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(54) Title: ION BEAM SPUTTER DEPOSITION ASSEMBLY, SPUTTERING SYSTEM, AND SPUTTER METHOD OF PHYSICAL VAPOR DEPOSITION

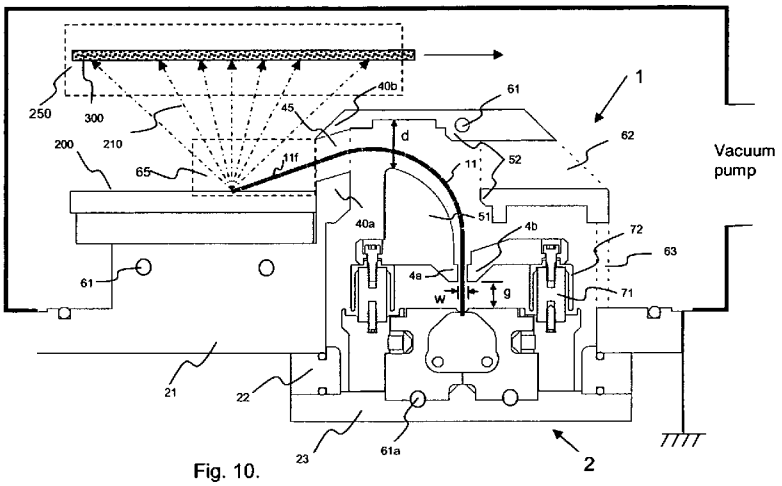


Fig. 10.

(57) Abstract: The present invention provides a superior ion beam sputtering system, assembly and methodology, with unique capabilities for film coating the exposed surface(s) of a workpiece or substrate by physical vapor deposition. The system can have far higher throughput than existing ion beam sputtering systems, while being constructed as a drop-in module, giving it a flexibility more typically found in magnetron systems. The operational system generates and initially extracts a ribbon shaped ion beam, typically of argon, whose breadth can be extended from about 150 mm to about 3 meters; then accelerates, deflects, and then decelerates the beam to form a spacecharge neutralized high current very broad ribbon ion beam; directs this resulting ion beam to strike the exposed face surface of a sputter target at a pre-chosen oblique incidence angle near 70 degrees; and consequently q: wises the formation and release of a plume of sputtered atoms from the target.

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Ion Beam Sputter Deposition Assembly, Sputtering System, and Sputter Method of Physical Vapor Deposition

PRIORITY CLAIM

The present invention was first filed as U.S. Provisional Patent Application Serial Number 61/966,808 on March 4th, 2014. All the legal benefits and advantages of this first filing are expressly claimed herein.

CONTINUATION-IN-PART STATUS & CROSS-REFERENCE

The present invention is a Continuation-In-Part of PCT International Patent Application No. PCT/US2014/000216 having an international filing date of 26 November 2014, presently pending. The legal benefits and advantages provided by a Continuation-In-Part application are expressly claimed herein for the present invention.

FIELD OF THE INVENTION

The present invention is concerned with the deposition of thin films of diverse materials upon various kinds and types of substrates in vacuum by physical vapor deposition (PVD). It is noted that the relevant technical field today conventionally includes both ion beam sputtering deposition processes and magnetron diode sputtering deposition procedures as well-established and often used PVD methods.

Nevertheless, the instant invention brings recent new developments in broad beam ion sources to organized assemblies capable of performing ion beam sputtering at much higher throughput rates; and addresses a number of long-existing shortcomings of the magnetron sputtering deposition technique - such as the control of insulating materials as thin film layers, and permitting the use of

magnetic substances as thin film coatings. The unique apparatus and singular methodology of the invention optionally also allows the user to exploit other known techniques such as Ion Beam Assisted deposition and reactive physical vapor deposition.

BACKGROUND OF THE INVENTION

The practice of depositing discrete film layers as coatings composed of varying materials upon differing types and shapes of solid substrates or workpieces has a long and extensive history, offers a wide range of alternative uses, and is used in many kinds of commercial applications. These practices typically include and are exemplified by depositing: Optical films for controlling reflection on optical elements and windows; hardness and anti-wear coatings of machinery and machined parts; magnetic films for electronic memory devices; conductive films used in microcircuits; dielectric films for microelectronics; as well as purely decorative films, antimicrobial and germicidal films, and the color coatings for many other constructions.

Within this broad technical field of depositing film coatings generally, however, the present invention is directed to and is primarily concerned with one particular sub-field: The deposition of solid thin film layers whose measurable thickness dimension ranges from a less than 1 nm to several microns in size; and which can be deposited as a discrete layer of material in a uniform and consistent manner repeatedly; and which are condensed upon the exposed surface(s) of a solid substrate or workpiece by physical vapor deposition in a limited vacuum environment whose measurable pressure ranges from about 20 Pa down to about 10^{-3} Pa. However, because the relevant technical field today provides a surprising variety of superficially similar film deposition methods, a substantive review of this broad technical field is appropriate.

Conventionally Known Substrates and Coating Materials

§ The shapes, compositions, and nature of the substrates and workpieces suitable for coating by PVD methods, and the intended capabilities and functions of the chosen films and coatings deposited upon the exposed surfaces of the substrates or workpieces, can vary widely. Such film coatings typically range from decorative coatings on ceramic or pottery materials, to electrically conductive circuit interconnection wiring paths on the surfaces of semi-conductor chips, to wear-resistant protective coatings on cutting tools and load bearing surfaces. Similarly, the nature, characteristics, and properties of the coating materials used as films and overlays can vary widely in their chemical composition (such as formula and stereochemical structure); and in their physical traits (such as crystallinity and stress); and in their intrinsic properties and functional capabilities (such as electrical conductivity, magnetic properties, and toxicity). Thus, for example, the chosen thin film coating material can range from electrically conductive materials, to semi-conductive compositions, to magnetic films, to electrical insulators.

Ink and Spray Coating Processes:

§ Paints and inks are conventionally used for applying thin films of certain compounds as spray solutions and suspensions; and vacuum roll-to-roll coatings for large sized substrates are frequently used in spray applying metal and oxide films for various products. In some specific applications, atmospheric pressure inert gas environments are used for spray film coatings of sensitive reactive materials; and in other circumstances, screen printing can be used for patterning of a film coating.

However, in all such spray deposition instances, the control of the coating thickness is relatively imprecise, and the microstructure of the film layer is not controlled as part of the coating process. Plasma spray coatings are applied by injecting a fine powder of the material to be coated into an intense plasma jet, whereby a spray of molten droplets is formed and directed, usually at atmospheric pressure - but in an inert gas atmosphere, and with a cold substrate condition, the spray of molten droplets solidifies on contact and upon impact with the cold exposed surface(s) of the substrate or workpiece.

Each of these aforementioned processes deposit macroscopic particles, and thus are outside the field of current interest even though the end uses of these films may be superficially related to those new processes described hereinafter.

Chemical Vapor Deposition Procedures and Other Conventionally Known Classes of Thin Film Deposition Processes:

A diverse range of other conventionally known thin film depositions processes are well known and long established in the technical field. However, each of these different kinds of deposition processes relies upon the formation of a film coating on the exposed surface of a substrate or workpiece via the repetitive placement of one atom or a single molecule of matter at a time; and therefore all these different deposition processes commonly share certain operational characteristics and modes of action within overlapping areas of use and application.

Among these known film depositions processes which are conventionally available and traditionally used within the technical field today are the following.

• Chemical Vapor Deposition (CVD) processes: The CVD class of processes embraces a variety of differing techniques for depositing films using a vapor.

Perhaps the simplest CVD process instance is a thermal decomposition of a gaseous chemical precursor composition to deposit a film of the desired coating material upon a heated substrate. This can be achieved, for example, to deposit solid film carbon coatings using a preselected hydrocarbon gas as the precursor composition.

In a similar manner, many individual CVD processes place the substrate or workpiece in a high vacuum chamber (the term 'high vacuum' indicating that the pressure within the closed chamber is well below about 10^{-2} Pa); and these involve injection of chosen chemical precursor species into the high vacuum environment, using various means of initiating and accelerating the intended chemical reaction. It is the intended chemical reaction in-situ and the series of chemical reaction events within the high vacuum environment which causes the deposition of the desired chemical species as a solid film coating upon the surface(s) of the substrate or workpiece.

The range and variety of known CVD processes today include Plasma Enhanced Chemical Vapor Deposition (PECVD), which uses plasma to enhance the deposition rate of the chosen chemical species; and Atomic Layer Deposition (ALD) which cycles different kinds of gases through the high vacuum chamber to catalyze the deposition of single atomic layers of the desired chemical species. These particular CVD processes allow remarkable precision in depositing a solid film layer of the desired thickness.

• Wet Electroplating processes: These processes offer a means of depositing precise amounts of certain metals on certain kinds of substrates; and such wet electroplating processes have found recent

increased use in patterned microcircuits. Under suitable conditions, electroplating can conform to fine surface topology.

• Ion or electron-beam induced deposition processes: An ion or electron-beam induced thin film deposition procedure is in fact a form of CVD process which is mediated by a charged-particle beam. Ion or electron-beam induced deposition is specifically considered here because this type of process can be exploited using a finely focused ion beam (FIB).

As typically employed today for sub-micron-scale mask repair, the focused ion beam is scanned to induce film deposition using a gaseous precursor as the source of the coating material; and this ion or electron-beam induced deposition technique can be done over a very fine scale of film thicknesses as the result of the direct contact of the scanning focused ion beam upon the gaseous precursor. As a consequence of this technique and mode of operation however, neither the ion nor the electron-beam induced deposition techniques is suitable for use as a large-scale process.

Physical Vapor Deposition Processes:

Physical Vapor Deposition (PVD) is a category of distinct vacuum processes in which the chosen coating material condenses from a vapor state onto the exposed surface(s) of the substrate or workpiece; and constitutes procedures which are typically performed in a moderate vacuum environment at a temperature typically held at between 30°C and 400°C. The condensed solid film coating is built up to a desired thickness using one atom or molecule at a time – an event similar in some respects to the CVD processes and wet electroplating techniques - but markedly unlike the mode and operational manner of the spray and ink deposition procedures.

Nevertheless, there are many different procedural formats and distinctive variant protocols which collectively constitute the PVD category of processes; and each of the major variants are well recognized individually and are firmly established as such within the technical field.

It sometimes can be difficult to separate certain variations of a PVD process from particular kinds of CVD processes. This is the subclass of reactive (typically gas) PVD processes, which involves the simultaneous (or alternated) exposure of the substrate to a chemically reactive species which is the source of one element of the coating material used to be deposited as a film, for example exposure to an oxidizing species while sputtering a metal, to create a film of the metal oxide. These procedures are an important variant of various PVD techniques, including sputtering. Merely exemplifying such reactive PVD deposition systems are U.S. Patent Nos. 4,392,931; 5,423,970; 6,217,720; 6,537,428; and 8,597,473 respectively.

For clarity of understanding as well as in furtherance of the purposes of the present invention, the controlling principle and rule of process difference and distinction is consistently as follows: If the manner of depositing a thin film coating upon the exposed surface(s) of a substrate or workpiece depends upon the *condensation* of a vapor produced by physical methods, the practitioner will consider and accept that deposition procedure to be a true PVD process. Condensation is defined as the change of the physical state of matter from a gas phase into a liquid or solid phase; clearly here we are concerned with the solid phase as the endpoint of the process.

The Conventionally Known PVD Systems

The essentials of the PVD discipline were known since as early as 1857; and since about 1912, the available PVD processes have

most often been performed in a vacuum environment, both experimentally and commercially, for applying solid film coatings. However, over the approximately 150 years of its known usage, the basics of the PVD process have been added to, altered, modified, and expanded in a number of different ways in order to meet the ever-changing needs of science, industry and commerce; or to meet and satisfy a diverse range of specific needs and goals. The many publications available in the scientific and technical literature, as well as the many authoritative books published in the field, cumulatively and collectively describe and illustrate the unusually broad range and surprising variety of the many innovations and developments which have occurred in PVD procedures over time.

Accordingly, a representative (yet still incomplete) listing of relevant technical and scientific publications is provided by the following: Donald M. Mattox, Handbook of Physical Vapor Deposition (PVD) Processing, Elsevier Publishing, 2010; Powell, *et al.*, Vapor Deposition, Wiley, New York, 1967; Westwood, W. D. Sputter Deposition; AVS Education Committee book series, v. 2. New York: Education Committee, 2003; Mattox, D. M., Handbook of Physical Vapor Deposition (PVD) Processing: Film Formation, Adhesion, Surface Preparation and Contamination Control; Noyes Publications, New Jersey,1998; Geng, H., Semiconductor Manufacturing Handbook; McGraw-Hill: New York, 2004; Helmersson *et al.,Thin Solid Films*, *513*:1, 2006; and Uhlenbruck *et al., ECS Transactions*, *35*: 2275, 2011; Eckertova, L., Physics of Thin Films, Springer, 1986 & 2012; Chapman, B.N. and J.C. Anderson, Science and Technology of Surface Coating, Academic Press, 1974; and Ohring, M., The Material Science of Thin Films, Academic Press, 2001.

£ The simplest format of PVD processing can be performed by heating a suitable material to be vaporized in a crucible made of a more refractory material: for example, zinc may be vaporized in an electrically heated crucible in vacuum, and condense on a glass substrate placed above it to form a conductive film. If the vacuum pressure is moderately low, the zinc atoms which evaporate will collide with several molecules of residual gas, and are likely to react and form oxide, which may not be desired. But if the pressure is sufficiently low, pure zinc can be deposited as a thin film coating.

Unfortunately, it has been found that deposited PVD film coatings may sometimes peel from their substrate surface. The reasons for such peeling include film stress (the condensed film is not in mechanical equilibrium with the substrate), and poor bonding (caused by voids and surface contamination).

£ Among the conventional enhancements to the basic methods of PVD process coating are: pre-cleaning the substrate surface by ion bombardment, and simultaneous bombarding of the substrate surface with low energy argon or other low energy ions during film deposition. As used herein the term 'low energy' means ion energies less than about 200 eV.

For the Ion Assisted Deposition (IAD) technique, such low energy ions originate in a plasma already present in the environment; whereas in the Ion Beam Assisted Deposition (IBAD) technique, the low energy ions are emitted from an ion source specifically provided for the purpose. It has further been found that shallow-angle, low-energy ion bombardment during deposition can cause the resulting film coating to form oriented crystallites, and in various other ways also markedly affect the growth and stress of the deposited film layer.

As some representative publications describing the IBAD subclass applications, see for example: P. J. Martin *et al.*, "Ion-beam-assisted deposition of thin films", *Applied Optics 22: 1,* pp. 178-184 (1983); Wang *et al.*, "Deposition of in-plane textured MgO on amorphous Si3N4 substrates by ion-beam-assisted deposition and comparisons with ion-beam-assisted deposited yttria-stabilized-zirconia", *Appl. Phys. Lett.* 71:2955 (1997); and Hak Ki Yu and Jong-Lam Lee, "Effect of ion beam assisted deposition on the growth of indium tin oxide (ITO) nanowires", *Cryst Eng Comm.* 16:4108-4112 (2014).

Traditional Methods and Systems for Performing Physical Vapor Deposition

(1) Pure Thermal Systems

In all the varieties of thermal vapor generation systems which are identified below, as well as in certain other variant methods, the key distinguishing feature of the method and system is that the gaseous vapor of coating material particles is formed by thermal sublimation or evaporation from a heated quantity of the desired material, often in liquid form in a crucible. Different means for providing adequate quantities of heat and quantitatively containing the gaseous vapor cloud of desired coating material exist and are frequently employed.

- As previously discussed above, one common method for vaporizing the desired coating material is simply to place the solid material in a suitable resistively heated crucible, where it may safely melt if direct sublimation does not occur. A simple example of a suitable crucible is a concave 'boat' made of a sheet of tantalum through which an electric current is passed in order to heat it. Tantalum has low vapor pressure and relatively low thermal

conductivity, so the process is simple and the contamination risk is low.

▪ Another common commercially used method is electron beam bombardment (EBVPD) in a vacuum environment, illustrated in Prior Art Fig. 1a. In the EBPVD method, intense heat is delivered by electron beam to the center of a solid piece or molten pool of the desired target material to be vaporized. A magnetic field directs the electron beam to its target. As representative instances of these resistance and induction heating procedures, see U.S. Patent Nos. 5,718,946; 6,368,404; 6,878,909; and 7,687,746 respectively.

▪ Molecular Beam Epitaxy (MBE) is still another form of PVD processing which can only be properly performed under 'ultra high vacuum' conditions. The term 'ultra high vacuum' (UHV) is generally understood to mean an environmental negative pressure below about 10^{-7} Pa.

In these MBE systems, the rate of film deposition is extraordinarily low – only about 1 nm per second maximum. Multiple crucibles containing individual solid materials (for example gallium and arsenic) are heated in-situ to vaporize their contents through collimating orifices; and the individual resulting vapor jets of different coating material are allowed to simultaneously deposit onto a suitable substrate surface, usually heated. Under the right circumstances and strictly controlled operational conditions, epitaxial growth of single-crystal stoichiometric films can be obtained - in this example, solid crystal gallium arsenide.

The MBE procedures thus can be regarded as a form of reactive PVD, relying on a UHV environment and heat - rather than using other

means for obtaining cleanliness and bonding, and optimizing the conditions for crystallinity of the deposited solid film coating.

(2) Ionized Cluster Beam Deposition Systems

A 'cluster' is defined in this context to be a grouping of 100 to 2000 atoms bonded weakly; and commercially is a practice in which a suitable material vapor expands under partial vacuum through a nozzle into a high vacuum environment to cause solid film deposition on a substrate. During the act of vapor expansion under vacuum, and before the mean-free-path within the high vacuum environment becomes too large, the vapor expansion allows adiabatic cooling; and thereby permits the in-situ formation of very small droplets, in a gaseous jet stream. These very small droplets may be ionized by electron impact and then accelerated to strike a substrate.

The energy per atom can be quite low, but the momentum of the cluster is markedly high. Thus, the total energy delivered to the surface by one cluster of atoms is sufficient to move the exterior surface atoms of the substrate; which in turn, can result in the formation of exceptionally smooth films of deposited material with this method [see for example, Takagi, *Pure & Appl. Chem.,* Vol. 60, No. 5, pp. 781-794, 1988].

(3) Cathodic Arc Methods and Systems

For depositing certain kinds of coating materials, the cathodic arc method can be used. In the traditional cathodic arc procedure a high current electric arc from an anode held at a suitable voltage is created is used to vaporize a coating material target. The arc discharge has a high level of ionization and excitation, and a plume of plasma is emitted. This vapor and plasma is condensed onto the target. By including nitrogen gas, for example, and using a titanium target, titanium nitride vapors can be created and deposited onto a

substrate.

The atoms so formed have high thermal energy, but may include clusters of many atoms and macroscopic particles which are undesirable for some applications; and a method of ducting the ionized atoms in the plasma through 90 degrees by means of a solenoid coil has often been used to separate them from the larger particles. As merely representative examples of the cathode arc procedure, see U.S. Patent Nos. 3,625,848; 3,793,179; 4,673,477; 4620913; 4,849,088; 5,037,522; and 5,972,185 respectively.

(4) Sputtering Deposition Methods and Systems

¶ Sputter deposition processes constitute a separate and distinct class of PVD procedures in which the following sequence of events occurs: the ions emitted from an ion source or a plasma discharge apparatus bombard a solid material to be used for coating (the "target") to cause sputtering – *i.e.,* the stream of charged ions (typically from an inert gas plasma) strike a solid material target with energies >500eV and dislodge atoms from the face surface of the target as a plume of vaporized atoms and small molecules - wherein the released plume of vapor generally travels toward, and is then condensed and deposited onto, the exposed surface(s) of a glass, metal, plastic, or other tangible workpiece as an adjoined film or layer of solid material (the 'substrate').

The sputter process is the emission of atoms, molecules and ions of material from a target, caused by the impact of energetic ions, usually of another species. Prior Art Fig. 2 illustrates the mechanism.

¶ When an energetic atom or ion hits a solid target, it can penetrate the surface. If the projectile ion has an energy value greater than a few hundred eV, that ion has a significant chance of

causing the ejection of one or more atoms of the target material. The rate rises exponentially with projectile energy up to a first low energy threshold, then rises very slowly to a peak.

The mechanism of sputtering is not thermal heating and consequent vaporization; but instead is due to a collision cascade, as illustrated in Prior Art Fig. 2. The incoming ion projectile displaces atoms within the solid target material; and by successive collisions, the momentum imparted to this cascade quickly becomes randomly directed, and a portion becomes directed toward the surface, where a near-surface atom or group of atoms of the coating material may be ejected by such a collision and released as a sputtered particle contained within a gaseous vapor or plume.

The atoms/molecules contained within a sputtered vapor plume typically have a distribution of energies which has a maximum value at several times the surface binding energy - i.e., several eV; and these atoms also have a high-energy tail, such that the mean energy value may be as much as 20eV for some atom or molecule species.

According to the detailed theory of Sigmund, the ejected particles have a distribution of random kinetic energies U, described by

$$\frac{dN}{dU} \propto \frac{U}{\left(U + U_b\right)^3} \qquad \text{[Equation 1]}$$

which means that the average energy of an ejected atom is several times U_b, where U_b is the surface binding energy, which is generally taken as the sum of the enthalpies of fusion and vaporization.

Thus the plume of atoms and/or molecules has significantly greater kinetic energy than thermal values, and notably is not in thermal equilibrium.

¶ In a high vacuum environment (pressure below about 10^{-2} Pa), the sputtered atoms in the plume of vapor can reach a substrate surface where most will strike with insufficient energy to penetrate; but still have more than sufficient energy to displace neighboring atoms - which in turn will cause dissociation of adsorbed gas atoms/molecules, and does cause significant densification of the film and enhanced bonding.

The yield of sputtered particles is generally greater when there is an approximate match between the projectile and target atomic masses. It depends on the atomic species of the projectile and of the target. The sputter yield further depends on the angle of incidence of the incoming ion. The dependence of yield on projectile energy also depends on the projectile mass: the peak yield is at a higher energy for projectiles of higher atomic mass, and is higher at higher angles of incidence. The use of argon gas is common, while krypton and xenon are less frequently used because their high cost may not be offset by their greater sputter yield. Prior Art Fig. 3 shows the sputter yield of almost all different ions at a particular energy on targets of three specific materials.

In practical terms this means that if the most common commercially exploited projectile ion, argon, is selected, then the highest sputter yield will depend on the target, the angle of incidence, and the energy.

¶ The ion species which is accelerated to the target and used to sputter atom and molecules to be used for coating, will usually be a noble gas. The best momentum transfer (and hence sputter yield) depends on several factors - but is best when the projectile ion and target material atom/molecule have a fairly similar mass. For most purposes, argon ions are deemed to be both effective and

inexpensive; but for certain heavy target metals, it may be preferable to use xenon or krypton ions. Neon and helium are not often used, since they are far lighter than most target material coatings of interest.

¶ For a normal incidence of the incoming ion onto the target, the sputter yield in atoms/ion for argon peaks at several tens of keV; but most of this ion energy is wasted as it is deposited too far below the target material surface to eject any atoms or molecules.

A quantity of greater relevance is the number of atoms/molecules released from the target material for each eV of kinetic energy delivered by the incoming ions. This quantity factor is generally at a maximum value for incoming ions whose energies are below 1 keV, and by which the depth of ion penetration into the target material is ~ 20 Å or less. Thus, this quantitative value is a reliable measure of how much ion energy must be delivered in order to generate and release one atom as a freely mobile particle from the target surface.

Clearly, the efficiency of mobile particle release is best when the ions do not penetrate too deeply into the target material and waste their energy, which is then simply converted into heat. It is well known by ordinary practitioners working in this field that sputtering as a method is energetically very inefficient, at best about 5%; but the films deposited by sputtering have in most instances far better properties than those coatings delivered by thermal methods.

¶ The sputtering deposition process can be modeled as desired, as for example by the Monte Carlo computer model: The Stopping and Range of Ions in Matter, SRIM 2000, Version 2000.38, International Business Machines, 1984-2000. Such models clearly show that the

interactions between the plasma generated ions and the target are limited to only those atoms/molecules lying at or close to the exposed topographical surface area of the target.

¶ The angle of incidence has long been defined as the angle between the incoming trajectory and the normal to the surface. When the angle of incidence of the ion is increased from zero, the resulting sputter yield rises dramatically – as is illustrated by Prior Art Fig. 4.

From the data of Prior Art Figs 2 and 4, it is recognized that a larger part of the collision cascade will intercept the surface if the angle of incidence is raised, thus causing more atoms to be ejected. The sputter yield of argon on an aluminum target is ~9 times greater at 70 degrees than at normal incidence. Furthermore the optimum incident energy is now higher, so that far more aluminum target material can be sputtered by 70 degree incidence 5 keV argon than by 800eV normal incidence; and as a result, the process is a little more efficient.

The heat delivered to a surface by the arrival and condensation of each atom in these thin film deposition processes always includes the surface binding energy (the sum of the enthalpies of fusion and vaporization), and for sputtered atoms also includes the kinetic energy 'U' given by Equation 1 above, which may be about ten times as much. The energy carried to the substrate surface by the sputtered atoms is sufficient to raise the temperature of the host substrate significantly during the film deposition; and in the case of plasma sputtering (and particularly rf plasma sputtering), other energetic particles may carry significant power to the substrate - such that final deposition temperatures are often in the range of from 150°C to 500°C. This is particularly important for films deposited on plastic

sheets. For temperature sensitive substrates (such as plastic sheets), these workpieces may be cooled in-situ, for example by tensioning the substrate matter over cooling drums during the deposition.

¶ The success of thin film deposition using sputtering methods is primarily due to the fact that the atoms in the sputtered plume themselves carry and bring sufficient energy and momentum to the exposed surface(s) of the substrate or workpiece - where upon impact, such sputter particle energy and momentum can and will dissociate loosely adsorbed impurities and displace host surface atoms at the substrate structure, particularly where the topographical features of the surface structure of the substrate are defective, or are irregular, or are incomplete. This sputter particle energy and momentum result in a cleaner and more uniform interface without the existence of voids between the host substrate matter and the deposited film layer. Some methods (such as IBAD shown by Prior Art Fig. 1b, IAD, and IBD) seek to add further energy by accelerating ions to strike the substrate surface.

¶ The gaseous plume of sputtered material is usually *isotropically* distributed through almost 2π steradians; and being largely uncharged, cannot be directed to the target. Therefore the proximity of the target to the substrate is a critical and controlling factor. Relatively small changes and variations in distance and orientation between the target and the location of the substrate or workpiece will greatly affect the quality, consistency, and uniformity of thickness of the deposited film (as is equally true for the thermal methods discussed above).

Different Varieties of Sputtering Deposition Methods and Systems

Several subsets and class varieties of PVD systems have been identified and summarily described above. Such process variants can in principle be used with any form of sputter deposition procedure. However, many of the sputter deposition class members are distinguished by the individual particulars for the production of ions, which then strike the target material and create the plume of sputtered atoms/molecules employed for film coating a substrate or workpiece.

Accordingly, it is deemed useful here to describe briefly at least some of the present members constituting the sputtering deposition process as a class, a membership which today includes each of the following variant families of procedures.

(i) DC Diode sputtering deposition systems, as shown in Prior Art Figs. 5a and 5b and which include:

Simple planar diodes; and

DC magnetrons.

(ii) AC, RF, and pulsed sputtering deposition systems, as shown in Prior Art Fig. 6 and which include:

Pulsed magnetrons; and

MF twin magnetrons.

(iii) Ion beam sputtering deposition systems, as shown in Prior Art Fig. 7 and which include:

Discrete external ion beam systems.

(i) DC Diode Sputtering Deposition Systems

Simple Planar Diodes

As shown and summarily described by Prior Art Fig. 5a, a simple planar diode system is illustrated in which the plasma is generated and sustained by the electrical breakdown of an inert gas.

However, several rigorous operating conditions must be met in order to create a plasma for DC diode sputtering. The sputter deposition chamber must be generally evacuated to a base pressure below 10^{-3} Pa, in order to ensure that most volatile surface impurities are removed. However, once a satisfactory base pressure is present, the working gas (usually argon gas) is introduced into the vacuum chamber, thereby raising the pressure to a value where an electrical discharge is most easily established – *i.e,* approximately 3-10 Pa. This relatively high pressure is essential to the operative system.

In addition, the sputter target (made of material which it is desired to coat on the substrate) is biased to a negative potential V of several hundred volts with respect to the substrate on which it is desired to coat a film of target atoms. In the resulting electrical discharge, electrons strike the gas atoms and ionize them; and the electrons and ions are then accelerated in opposite directions, creating a plasma whose potential will become sufficiently positive to retain a high density of electrons. Ions are accelerated from this plasma to strike the target with an energy of qV, where q is their charge; and sputter material flowing from the target (mainly neutral atoms) also generate secondary electrons, which serve to sustain the ionization in the plasma. The sputtered neutral atoms then will travel to the substrate and condense on its surface to form the deposited film coating.

Illustrative of and exemplifying the conventionally known DC diode sputtering systems are U.S. Patent Nos. 3,968,018; 4,717,462; and 7,850,828.

DC Magnetrons

§ The DC magnetron sputtering method and system is a class of DC diode which adds a static (or sometimes moving) magnetic field. As shown in Prior Art Fig. 5b, the generated magnetic field serves to confine electrons in a plasma and to increase greatly the density achieved at a minimal pressure (i.e, markedly less than 10 Pa). Thus, a typical operating pressure is only 0.1 Pa for most magnetron sputtering systems – compared to >3.0 Pa pressure for DC diode sputtering systems.

Also as shown by Prior Art Fig. 5b, the specific magnetic field configuration of a magnetron sputtering system creates a closed loop region in front of the target material surface where the direction of the magnetic field is parallel to the surface. This event is accomplished by placing a pole of one polarity at a central location behind the target material surface, and enclosing the centrally located pole with a loop-shaped magnetic pole of the opposite polarity.

Consequently, in the racetrack-shaped spatial zone which exists between the poles and near the target material surface, the magnetic and electric fields are largely orthogonal; and this circumstance creates a spatial zone in which a particularly efficient trapping and circulation of free electrons occurs. The free electrons travel in tight spirals, the radius being determined by the ratio of the momentum of the electron to the magnetic field; but they drift around the racetrack path (with a velocity equal to **v= ExB**). The trapping of the secondary electrons allows the magnetron sputtering system to surpass traditional diode sputtering systems in many regards including

increased deposition rate and decreased impurities in coatings, and achieving depositions at lower substrate temperatures.

§ A major drawback of most magnetron sputtering systems is a characteristic high erosion rate of the target at the zone where the magnetic field is parallel to the surface of the target material – while being characteristically at a low erosion rate elsewhere. This leads to an inefficient use of the target material. Consequently, in order to increase target material utilization for magnetron sputtering systems, either the target material or the magnetic field generating apparatus is often kept in constant motion - in order to change physically and spatially the sputtering site location of the target and to distribute the erosion effect upon the target material more evenly over time and usage.

As representative working examples of the conventionally known magnetron sputter deposition systems, see PCT Patent Publication WO1982002725, and U.S. Patent Nos. 5,169, 509; 5,645,699; 5,399,252; 5,338,422; 5,618,388; 5,855,745; 5,968,328; 6,988,463; and 7,166,199 respectively.

Additional Pertinent Points Of Information

1. As illustrated by Prior Art Fig. 5b, each conventional magnetron sputtering deposition system comprises at a minimum: a water-cooled target mounting; a target of material for coating which is biased to a negative potential by a high-power power supply, a set of permanent magnets located behind the working surface of this target; the assembly being electrically insulated from a mounting flange by which it is attached to a vacuum chamber, into which a gas such as argon is introduced. Given the correct pressure and appropriate voltage, the magnetron system produces a stable plasma discharge,

and flux of particles moving energetically away from the target surface.

2. As concerns the conventionally known magnetron sputtering deposition systems, there are methods to increase the density of charged sputter particles impinging on the substrate surface, thereby increasing the energy deposition on the substrate, which changes the film properties. This sometimes desirable effect can be achieved, for example, by intentionally unbalanced magnetic field at the target site.

In an unbalanced magnetron system, one of the magnets producing the magnetic field above the target is given a decreased field strength compared to the field generated by the other magnets. The weaker magnetic field cannot compensate for all of the field lines resulting in the redirection of some of the field lines towards the substrate. The stray field allows a greater percent of electrons and charged ions to escape towards the substrate - where collisions with the growing film promote densification through re-sputtering and re-absorption of the film coating, but also increase heating of the substrate.

3. The most commonly used and commercially favored sputter deposition systems today are the magnetron sputtering methods. Most of the commercial and high volume sputter deposition applications today use magnetron sputtering techniques, be it in a DC, a RF, or an AC format.

4. The commercial success today for magnetron sputtering deposition systems rests primarily upon their having a good balance of film output rate and film quality. But their substantive disadvantages, limitations and severe operating requirements are well known and established, and must be recognized for what they are:

(α) A magnetron system operates at 10^{-1} Pa or higher. It cannot operate in a high vacuum environment [a pressure well below about 10^{-2} Pa] in the processing chamber.

(β) A magnetron will usually expose the substrate to an intense and hot stray plasma, particularly when the produced magnetic field is unbalanced, causing unintended and undesirable heating, and undesired interactions between the sputtered flux and the residual gas and the plasma can be significant.

(γ) The requisite pressure environment [about 10^{-1} Pa] of magnetron systems often results in some gas incorporation into the deposited film; and on such occasions, maintaining a consistent overlay thickness and bonding of thin films can be very challenging.

(δ) With magnetron sputter deposition systems, there are always exposed electric and magnetic fields within the spatial region of the substrate site; and this unavoidable circumstance means that there is likely to be imbalanced charge transport, leading to surface potentials on any insulating surface. This event in turn leads in many cases to small surface arcs, which can cause defects in the deposited films.

(ε) For magnetron systems, there are noted difficulties with using sputtering insulating material as films. The difficulties can be largely overcome by using one of several varieties of AC, or of RF, or of pulsed plasma systems. But such alternative sputtering systems are more complex in their operation.

(η) When target sputtering of an insulating material for coating is performed using a magnetron deposition system (such as reactive gas sputtering of a target insulator oxide compound), the surface of the target becomes insulating - except in the zone of intense sputtering; and the insulation material can encroach on this intense zone. In addition, insulating material films will condense and deposit

upon the ground surfaces, resulting in the 'lost anode' effect, where the discharge shuts down.

(θ) A magnetron deposition system cannot in any straightforward manner sputter magnetic materials for coating, since a magnetic target kills and effectively destroys the in-situ magnetron generated magnetic field on which the sputtering discharge relies.

(ii) AC, RF, And Pulsed Magnetron Sputtering Systems

AC Sputtering Systems

When the target is an insulator, the DC discharge mechanism cannot operate; but, by applying medium or high frequency AC current to the target mount, the displacement current during negative-going half-cycles can sustain sputtering. Capacitive coupling allows a useful current to flow and effectively sustains a plasma, thereby allowing sputtering to occur during parts of the AC cycle.

RF Sputtering Systems

As illustrated by Prior Art Fig. 6, the basis for the use of radiofrequency with a plasma deposition system is the large mass difference between the ionized gas atoms and the electrons in the plasma. If the frequency of the alternating frequency is high enough, a plasma can be sustained by continually accelerating and reversing the direction of the electrons through long enough distances such that they gain the quantum of kinetic energy required to ionize the sputter gas through collisions.

The radiofrequency required to sustain the plasma is generally above one MHz; but RF sputtering systems are generally operated at 13.56 MHz (which is the maximum allowed frequency in the United States by the Federal Communications Commission). It is noted also that the net average current from the target can and must be zero if the target is an insulator.

The main drawbacks with RF sputtering protocols are the decrease in deposition rate due to lack of secondary electrons for gas ionization; the tuning systems required to couple the alternating potential to the plasma; and the monetary expense associated with radiofrequency power supplies.

As illustrative and representative examples of the RF sputter depositions assemblies and protocols, see U.S. Patent Nos. 4,572,759; 4,579,618; 4,584,079; 4,802,968; 5,891,350; 6,446,572; and 6,710,524.

Pulsed Sputtering Systems

Also as shown by Prior Art Fig. 6, when a conductive target is used, and reactive sputtering is used wherein a gas such as oxygen modifies the film to create an insulating film, the areas of the target less deposited and the anode surfaces of the magnetron and the vacuum chamber can become insulating. This effect can lead to decreased deposition rates, and to the 'lost anode' effect, in which the anode becomes oxidized and therefore insulating, suppressing the discharge. The use of pulsed or medium-frequency switched power supplies can be used to mitigate this problem, and some systems use a pair of targets connected to opposite terminals of an AC power supply. [See U.S. patent refs 6,451,180, 5,789,071, 6,620,299]

(iii) Ion Beam Sputter Deposition Systems

◊ Ion beam sputtering (IBS) deposition systems as a family of protocols all utilize a discrete ion source to generate an ion beam; which is then extracted from the source and directed at the sputter target, made of the desired material for coating; from which energetic atoms are sputtered into a plume; which in turn impinges upon the exposed surface(s) of a substrate or workpiece, upon which it

condenses as a solid film coating. Attention is directed to Prior Art Fig. 7 which shows a representative ion beam sputter deposition system.

In these conventionally known IBS systems, the ion source is typically a gridded Kaufman source (see U.S. Patent No. 3,156,090). The ion beam emanates from an internally generated plasma; and is accelerated between multi-aperture grids in a triode arrangement to an energy value typically ranging from 1 to 10 keV. The emergent ion beam is then directed towards a positioned target formed of the desired material for coating. Material from the target is sputtered by these ions and released isotropically into a controlled vacuum environment as a vaporized plume of freely mobile atoms and molecules.

The target is generally aligned to face towards a specific deposition zone in which is located the exposed surface(s) of a substrate or workpiece (upon which it is desired to deposit a film layer), and this results in the condensation of the sputtered atoms, and the deposition of a solid film of material onto the exposed surface(s) of the substrate or workpiece.

Most ion beam sputtering systems are also equipped with means of IBAD and/or other enhancements. These enhanced IBS systems generally create the highest quality films.

◇ The desirable properties of IBS methods and systems are well known: They can operate in high vacuum; they can deposit insulating target materials as thin films; and they are not vulnerable to many of the difficulties of magnetron systems when depositing magnetic or insulating materials as coating layers. The precision of the control of the thickness of the film is very good. In many systems, as illustrated, means are provided to rapidly switch between targets, so that the

deposition of multi-layer films can be accomplished with relative ease.

One major drawback of IBS systems generally, however, is that their overall areal throughput rate is much lower than many other kinds of sputter deposition methods; and thus IBS systems, while highly desirable for multilayer optical coatings, remain today unused in many commercial and industrial applications requiring high throughputs.

A Point of Caution

Strictly speaking, the term 'sputtering' is properly limited in its meaning to the process described above for emitting material atoms from a target surface. But much confusion arises within the technical field when the term is unfortunately also used to mean the act of physically depositing the sputtered atoms as a film of coating material.

The same kind of linguistic confusion exists for a specific technology commonly termed 'Ion Beam Figuring' in the technical literature; and which, to the uninformed, may appear to be superficially similar to the IBS systems described above. The technique of 'Ion Beam Figuring' does indeed use "sputtering" – but clearly *is not* a thin film deposition process of any kind. Similarly, 'Ion Beam Milling' is a technique which uses "sputtering" to remove unwanted solid material, but is never a process or means for physically depositing thin films.

The Differences and Advantages of Ion Beam Sputter Deposition Systems over other Sputtering Methods

§ A primary advantage of all sputter deposition systems is this: since the target is converted into a vapor or gaseous phase by a mechanical act rather than by any chemical or thermal event, virtually any formula or combination of elements can be sputtered and then

deposited onto the substrate or workpiece.

§ In contrast to conventionally known magnetron sputter deposition systems, ion beam sputter deposition systems provide many unique advantages and desired benefits, including the following:

(1) Introduced gas is mainly confined to the interior of the ion source, whereas the general environment is a high vacuum. Straight line collision-less transport of the vapor from target to substrate will occur. A magnetron discharge requires a higher pressure in which collision-less transport is unlikely, in order to function.

(2) Ion beam sputtering systems allow for a reduced heating of the substrate, relative to plasma sputtering systems including simple diodes and magnetrons, since the only significant source of heat can be the energy of the sputtered atoms/molecules themselves. There is no intense plasma or other heat source near the substrate site.

(3) Ion beam sputtering is a highly controllable technique - owing in part to the fact that the ion current and energy are easily measured with precision; whereas in DC magnetron sputter systems the deconvolution of ion and electron currents is difficult and problematic.

Thus, ion beam sputtering can be more precisely controlled, and if the throughput were higher, this level of control would make ion beam sputtered films ideal for use with a variety of applications used commercially today in the making of precision instruments for optics, analysis, and electronic circuitry.

IBS film deposition systems and methods are restricted to high-precision niche applications. For example, this capability is a noted advantage in certain scientific applications which require the coating of test or empirical samples with ultra-thin films for high resolution SEM (scanning electron microscopy) and various TEM (transmission

electron microscopy) applications. For these reasons, ion beam sputtering is the preferred method for depositing thin film coatings onto samples for EM (electron microscopy), especially where high resolution quality and reduced artifacts are of primary concern.

THE VARIETY OF PRESENTLY KNOWN ION BEAM SPUTTER DEPOSITION PROTOCOLS

It is deemed useful and valuable to provide here a true and accurate listing of prior art references, patents and patent applications; which while necessarily incomplete - nevertheless properly covers the history of development for the IBS protocols, establishes the strengths and weakness of the different IBS techniques, and clearly establishes the continuing desirability for an ion beam sputtering system that overcomes their long known limitations and disadvantages.

A chronological summary of the more relevant patent publications is therefore presented below.

◊ *U.S. Patent No. 3,472,751 Of William J. King Issued October 14, 1969:*

A basic method and operational apparatus is disclosed by King for forming a highly tenacious deposit of material on a substrate by directing a high energy ion beam against the target – composed of the coating material to be deposited – in a vacuum environment of less than 10^{-3} Pa. The King technique causes atoms of material for coating to be removed by sputtering; and allows them to impinge upon the substrate surface.

◊ *U.S. Patent No. 4,108,751 Of William J. King Issued August 22, 1978:*

An ion beam implantation-sputtering method is described by King in which material is deposited onto and implanted into a substrate by directing a beam of ions against a target, comprised of

the material to be deposited, so as to sputter neutral particles and ionized particles from the target towards the substrate. In this disclosed King method, the ionized sputtered particles are accelerated to energies which are sufficient to penetrate the substrate and be implanted therein and provide a strong bond. In addition to this result, however, sputter cleaning and sputter deposition of the substrate surface by particles of sufficient energy also takes place.

◊ *U.S. Patent No. 4,142,958 of Wei et al. Issued March 6, 1979:*

As disclosed, the Wei *et al.* invention is a method for fabricating multiple layer interference optical films by ion beam sputtering, wherein the interfering optical films are used as mirrors in a ring laser apparatus. In this method, an ion beam strikes a target material obliquely, dislodging molecules of the target so that they can be deposited on a chosen surface serving as a deposit base for a multiple layer interference coating. The thickness of the coating material is monitored so that the proper thickness of a given interfering optical film layer can be optimized to obtain the type of reflectance desired for a given light wave length. The surface to be film coated is rotated during the deposition of the multiple layering of target material. A stack of multiple film layers having alternating indices of refraction comprises the optical interference film.

The coating process occurs in a vacuum chamber - where the partial pressures of the gases are carefully controlled to insure the proper ion beam intensity and optimum stoichiometry of the deposited optical films. Prior to beginning the deposition of the multiple optical films, the ceramic substrate comprising the mirror base is bombarded by the ion beam at an oblique angle to remove surface anomalies and clean it.

◊ *U.S. Patent No. 4,250,009 Of Cuomo et al. Issued February 10, 1981:*

In this Cuomo *et al.* sputter deposition system, the coating material target is located at an angle to the travel pathway of the energetic ion beam (although it need not be); and the material which is dislodged by the ion beam can be directed towards a substrate.

The Cuomo *et al.* target is composed of atoms forming both positive and negative ions. The voltage difference between the target and the substrate can be adjusted to be positive or negative so that either positive ions or negative ions can be accelerated to the substrate by means of adjusting the target-substrate voltage difference.

In addition, Cuomo *et al.* provides means for collecting electrons included with the ions moving towards and away from the target. Such means can comprise a grid located adjacent to the coating material target. It is disclosed that electrons can be collected by means of an electric field confining structure which permits the ions to pass through while the electrons are deflected.

Thus, the major advantage of the disclosed Cuomo *et al.* system is that the sputter deposition makes it possible to deposit positive and negative ions alternately or in a desired graded mixture at an interface under gradually changing voltage control.

◊ *U.S. Patent No. 4,424,103 of Barrett Cole Issued January 3, 1984:*

The Cole method and apparatus for thin film deposition comprises bombarding a target obliquely in a vacuum chamber using a linear ion gun. The Cole linear ion gun generates an ion beam which impacts the target over an area having a width dimension which is substantially greater than its height dimension. The coating material in the impacted area of the target is sputtered; and the sputtered material is then deposited onto a surface of a substrate by moving (or

'translating') the substrate surface at a controlled rate of speed through the sputtered material.

◊ *U.S. Patent No. 4,923,585 Of Krauss et al. Issued May 8, 1990:*

The Krauss *et al.* system of ion beam sputter deposition is performed using a single ion beam and a multi-component target; and is capable of reproducibly producing thin films of arbitrary composition, including those which are close to stoichiometry. The Krauss *et al.* system uses a quartz crystal deposition monitor and a computer controlled, well-focused ion beam; and this sputter deposition method is capable of producing metal oxide superconductors and semiconductors of the superlattice type (such as GaAs-AlGaAs), as well as layered metal/oxide/ semiconductor/ superconductor structures. By programming the dwell time for each target according to the known sputtering yield and desired layer thickness for each material, it is possible to deposit composite films from a well-controlled sub-monolayer up to thicknesses determined only by the available deposition time.

In one Krauss *et al.* system embodiment, an ion beam is sequentially directed via a set of X-Y electrostatic deflection plates onto three or more different element or compound targets which are constituents of the desired film. In a second Krauss *et al.* system embodiment, the ion beam is directed through an aperture in the deposition plate and is displaced under computer control to provide a high degree of control over the deposited layer. In a third Krauss *et al.* system embodiment, a single fixed ion beam is directed onto a plurality of sputter targets in a sequential manner where the targets are each moved in alignment with the beam under computer control in forming a multilayer thin film. These sputter deposition formats may also be used with laser and electron beams.

◊ *U.S. Patent No. 5,080,455 of King et al. Issued January 14, 1992:*

The King *et al.* invention describes the surface treatment of substrates wherein coating material is sputtered from a target by bombardment with ions which have preferably been accelerated to high energies - *e.g.,* one to fifty kilovolts or more. King *et al.* specifically discusses the advantages of high incidence angles, at energies of several keV, in a relatively moderate to high vacuum system typically held at a pressure of under about 10^{-2} Pa.

However, the disclosure of the King *et al.* '455 patent additionally sets forth two points of information which are believed to be highly questionable scientifically. These are: That using high energy ions to sputter a target material results in higher energy sputtered particles, and that the resulting sputtered coating material impacts the surface of the substrate with a kinetic energy which may be several orders of magnitude higher than in prior sputtering methods conventionally employed in industrial processes. Both of these technical points are directly contradicted by (i) the Sigmund theory (Phys Rev., Vol.184 (1969), p. 383) and by Equation 1 as given above; (ii) the results of the SRIM computer model; and (iii) the data measurements published by G. Doucas in 1977 in Intl. J. Mass Spec. & Ion Phys. Vol.25, p. 71. For these reasons therefore, the practitioner working in this technical field present invention cannot substantively rely upon either of these two technical points as being correct or as having scientific merit.

Notably also, the disclosure of the King *et al.* '455 patent further states that the sputtered coating material travels along trajectories having a substantial component normal to the surface of the target, thereby allowing for a more precise control of sputter deposition conditions. In reality however, this King *et al.* viewpoint appears to be

a mild exaggeration because any such effect has been found to be marginal at best.

◊ *U.S. Patent No. 5,089,104 Of Kanda et al. Issued February 18, 1992:*

A method and apparatus for forming a multiple-element thin film based on ion beam sputtering is disclosed by Kanda *et al.* In this Kanda *et al.* system, ion beams drawn out of a plurality of ion beam sources or neutralized beams derived therefrom are projected to a plurality of coating material targets; and the sputtered particles discharged from the multiple targets are directed in their travel to a substrate. The composition of sputtered particles is measured in the vicinity to the substrate. Sputtered particles having a controlled composition distribution are deposited on the substrate to form a multiple-element thin film.

◊ *U.S. Patent No. 5,492,605 to Mustafa Pinarbasi Issued February 20, 1996:*

An ion beam sputter deposition system and method for the fabrication of multilayered thin film structures is described. In this Pinarbasi system, selected combinations of ion beam gases and energies matched to the selected target materials optimize the physical, magnetic and electrical properties of the deposited thin film layers. By matching the ion beam gas atomic mass to the target material atomic mass, thin metal films are provided which have densities and resistivities which are very close to their bulk property values. The Pinarbasi system also utilizes low ion beam energies in combination with high-mass ion beam gases to obtain thin film deposits having low internal stress.

In addition, the ratio of the ion beam gas mass to the target material mass is shown to be the determining factor for achieving the desired thin film properties in the Pinarbasi ion beam sputtering

system. Both the mass of the ion beam sputtering gas and the energy of the ion beam is controlled as a function of the target material to provide single-layered and multilayered structures.

◊ *U.S. Patent No. 6,086,727 To Mustafa Pinarbasi Issued July 11, 2000:*

A method and apparatus to improve the properties of ion beam deposited films in an ion beam sputtering system is disclosed by Pinarbasi. This ion beam sputtering system has a chamber; an ion beam source; multiple targets; a shutter; and a substrate stage for securely holding a wafer substrate. The substrate stage is made to tilt about its vertical axis such that the flux from the targets hit the wafer substrate at a non-normal angle; and this results in improved physical, electrical and magnetic properties as well as in improved thickness uniformity of the thin films sputter deposited on the substrate surface.

◊ *U.S. Patent No. 6,224,718 of William Meyer Issued May 1, 2001:*

As disclosed, the Meyer ion beam sputtering system has six sputter targets arranged in pairs on three paddles, which are disposed upon the circumference of a circular holder. The circular holder can be rotated about its axis in such a way as to bring any one of the target pairs into exposure for impact with an ion beam; and each paddle is rotated to bring the desired target in the pair into position for sputtering. An alternative Meyer embodiment provides an enlarged spatial region - which allows one of the target paddles to be rotated about its axis while that target paddle is in an inactive, non-sputtering rotary position.

◊ *U.S. Patent No. 6,402,901 Of Baldwin et al. Issued June 11, 2002:*

A system and method for simultaneously performing sputter deposition on a plurality of planar substrates is disclosed by Baldwin *et al.* In this system, an ion source generates an ion beam in which ions are directed toward a target which is formed from a first section of a sphere. Each of the plurality of planar substrates has a deposition surface that is tangent to a surface of other sections of the same sphere.

In one Baldwin *et al.* embodiment, the plurality of planar substrates is arranged as a mosaic of tiles arranged generally about the surface of another section(s) of the sphere. As a result of the spherical shape of the target and the arrangement of the planar substrates on the surface of the same sphere, substrates that are small in size compared to the radius of the sphere will receive a substantially uniform deposition thickness that is substantially the same for each of the plurality of planar substrates. In accordance with other Baldwin *et al.* embodiments, a plurality of targets is used, each of which is formed from a section of the sphere; and each of the multiple targets is negatively biased.

◊ *U.S. Patent No. 6,669,824 Of Sferlazzo et al. Issued December 30, 2003:*

A dual-scan thin film deposition system is described by Sferlazzo *et al.* which includes a deposition source that generates deposition flux comprising neutral atoms and molecules. A shield defining an aperture is positioned in the path of the deposition flux; and this shield passes the deposition flux through the aperture and substantially blocks the deposition flux from propagating past the shield everywhere else. A substrate support is positioned adjacent to the shield. A dual-scanning system scans the substrate support relative to the aperture with a first and a second motion.

◊ *U.S. Patent No. 6,783,637 of Slaughter et al. Issued August 31, 2004:*

The Slaughter *et al.* '637 patent discloses a high throughput dual ion beam deposition system for sputtering material layers. This Slaughter *et al.* system comprises a vacuum chamber; a substrate positioned in the vacuum chamber; a first target holder capable of holding at least one target of a first material, wherein the first target holder is positioned in the vacuum chamber; a second target holder capable of holding at least one target of a second material, wherein the second target holder is positioned in the vacuum chamber; a first ion beam source for directing ions at the at least one target of the first material for depositing said first material onto the substrate; and a second ion beam source for directing ions at the at least one target of the second material for depositing said second material onto the substrate. The Slaughter *et al.* deposition system also includes a control system that allows materials to be deposited from the first and second target holder with negligible delay between the depositions.

◊ *PCT Patent Publication No. WO 2002099155 Of Barrett E Cole & Christopher J Zins Published December 12, 2002:*

The Cole & Zins publication discloses a method for depositing an oxide material in an ion beam sputter deposition process, the method comprising: sputtering a target with ions in a chamber containing oxygen; and controlling a partial pressure of the oxygen in the chamber during the sputtering of the target, wherein a material having a non-stoichiometric composition is deposited. The material is for use as microbolometer. The sputter deposited film material is a VOx composition where x is such that the thermal coefficient of resistance is between 0.005 and 0.05; and the sputter deposited film material may be formed on a wafer.

The Cole & Zins method is a low temperature process (performed at less than 100 degrees C); and argon gas is used for sputtering a target of vanadium in an environment wherein the oxygen level is controlled to determine the x of VOx. The thickness of the deposited film is controlled by the performance time of the sputter deposition; and the VOx material properties can be changed or modified by controlling certain parameters in an ion beam sputter deposition environment. Also, there is sufficient control of the oxidation process to permit non-stoichometric formation of VOx films. Other layers may be deposited as needed to form pixels for a microbolometer array.

◊ *U.S. Patent Publication No. 2007/0051622 of Tang et al, published March 8 2007.*

This Tang *et al.* publication discloses a magnetron sputter reactor including an ion beam source producing a linear beam that strikes the wafer center at an angle of less than 35 degrees. The linear beam extends across the wafer perpendicular to the beam but has a much short dimension along the beam propagation axis while the wafer is being rotated. The ion source may be an anode layer source having a plasma loop between an inner magnetic pole and a surrounding outer magnetic pole with anode overlying the loop with a closed-loop aperture. The beams from the opposed sides of the loop are steered together by making the outer pole stronger than the inner pole. The aperture width may be varied to control the emission intensity.

◊ *U.S. Patent Publication No. 2009/0020415 of Gutkin et al. published January 22, 2009. (Abandoned)*

The Gutkin *et al.* innovation is described as a sputtering apparatus containing an ion source and a magnetic assembly called an

Iontron - wherein the magnetic assembly is configured to be positioned between a target and a substrate, and wherein the target comprises a chosen material which is to be sputter deposited within a magnetic field by means of one or two racetrack ALPA ion sources generating an ion beam with an energy of less than 1 keV onto the surface of the substrate.

As disclosed, the Gutkin *et al.* apparatus is a self-contained ion beam deposition source which can be attached to or positioned inside of a closed vacuum chamber where substrates are located. The pressure is 8×10^{-2} Pa. The ion beam source itself is formed of one or more ion beam sources; and is combined with one or more sputtering targets and a magnetic assembly able to provide a unified magnetic field for the controlled delivery of the charged particles to a workpiece (the substrate of choice). The Iontron includes a magnetic field assembly positioned between the target and a work piece (substrate), whose explicit purpose is to generate a magnetic field able to control the flux of charged particles. The target can be electrically biased, which modulates the energy of the ion beam and allows for modulation of the spatial location where the charged ions impinge the target. Additionally, the position of the target can be adjusted relatively to the ion beam.

◊ *U.S. Patent 8,821,701 Of Higdon et al. Issued September 2, 2014.*

An unique target suitable for use in any PVD sputtering apparatus is disclosed by Higdon *et al.* The target is formed of at least two target tiles, wherein at least two of the target tiles are made of different chemical compositions; and are mounted on a main tile; and are geometrically arranged on the main tile to yield a desired chemical composition on a sputtered substrate.

In an alternate Higdon *et al.* embodiment, the tiles are of varied thickness, according to the desired chemical properties of the sputter deposited film. In yet another alternate Higdon *et al.* embodiment, the target is comprised of plugs pressed in a green state, which are disposed in cavities formed in a main tile (also formed in a green state); and the target assembly is then compacted and sintered.

The Long-Standing and Continuing Problems Commonly Shared by IBS Systems

A wide variety of ion beam sputter deposition techniques can be performed with great success today; but existing families of IBS systems all exhibit and impose a series of continuing limitations deficiencies, which are as follows:

(i) The available sputtered particle flux has a low intensity compared to large commercially available magnetrons. One reason is that for a single circular ion beam of argon at an energy of a few keV, the space-charge limit is of the order of 1 mA, determined by Child's Law, and this has long necessitated the use of multi-aperture extraction electrodes, where hundreds of small beamlets are extracted and accelerated. This approach is expensive, and difficult to maintain, but has been very successfully commercialized.

(ii) Typical ion beam energies for IBS are in the range 500-800 eV, sometimes a few keV, and multi-aperture gridded sources as described above are usually used.

(iii) The desirable emittance and brightness properties of the ion beams are not quantitatively adequate to raise the beam's current to the necessary and appropriate values. Multi-aperture sources have high emittance; it is not possible to merge the beamlets and keep them merged. Thus the transport and focusing of large high current beams onto smaller sized targets is hardly feasible.

(iv) The apparatus organizational layout, as well as the site positioning of the substrate to be film coated, within the confining spatial limits of the high vacuum environment where the ion beams are employed has often been awkward and inconvenient.

Φ Although the film quality of thin coatings deposited using IBS protocols can be excellent, the uniformity of the resulting film layer is intrinsically poor if the substrate is large and flat, and the entire volume of the vaporized coating material comes from a small sized impact site where the (usually circular) ion beam actually strikes the target material. The film thickness is inversely proportional to the square of the distance from any point on the substrate to the target; so for large substrates it is necessary to use means such as mechanisms (*e.g.,* planetary arrangements) by which to move the same workpiece in two dimensions in order to allow all points on the substrates to experience the same overall time-averaged deposition in spite of large local variations within the deposition field. Controlling both the uniformity and consistency of the deposited single covering layer is thus a routine, major and continuing problem.

Φ The throughput rate for film coated products offered by conventional IBS systems is quite poor, relative to the throughput rate of other physical vapor deposition procedures. As a consequence, the use of the ion beam sputtering deposition technique has not yet met commercial throughput expectations of many manufacturing industries and businesses; and for this conventional IBS systems to date have only had commercial success in certain niche applications and product formats.

THE PRACTITIONER'S VALUATION OF THE AVAILABLE ION BEAM SPUTTER DEPOSITION PROTOCOLS

£ Of the alternative apparatus and differing methods for performing sputter deposition of thin films on various substrates, Ion Beam Sputtering ("IBS") is generally regarded today by ordinarily skilled practitioners within the technical field as the technique which provides the finest precision, offers the greatest versatility, produces the best thin film quality, and is able to rapidly switch targets in order to produce multilayer films.

However in actual practice, the technique requires apparatus which is overly complex in its component parts; and is frequently convoluted in its assembly organization and orientations; and its protocols are cumbersome to use and often awkward to perform; and the throughput of the available apparatus is low relative to that of magnetron sputtering systems.

£ There are many hitherto unavailable features which would make the technique of ion-beam sputtering much more suitable for large-scale production of thin films. Above all, an extended linear sputter zone, combined with an orthogonal substrate conveyor mechanism is a well known method in PVD to address the uniformity issues mentioned above; but such equipment using ion beam sputtering has not been available.

A list of other highly desirable, but presently unavailable, features today includes each of the following:

(i) Extension of the system's apparatus to create an extended linear gaseous plume or vapor for the coating of substrates on a conveyor system; and which is able to move in one direction through the gaseous plume and cause the deposit of thin films having a

measurable breadth dimension of 1 meter, 2 meters, or even 3 meters in size.

(ii) Simplification of the controls needed to perform ion beam sputtering.

(iii) Elimination of the expensive and difficult multi-aperture electrodes, and the concomitant difficulties of alignment and handling such electrodes.

(iv) Integration of a complete means for generating the sputtered plume of atoms/molecules, including ion source, acceleration and sputter target, upon a single structure mounted on a flange within a closed vacuum chamber in high vacuum.

(v) A throughput film deposition rate which is substantially equal to and thus is competitive with the throughput of magnetron sputter deposition systems.

SUMMARY OF THE INVENTION

The present invention has multiple aspects and presents alternative formats.

One aspect is a system for coating a substrate with a thin film of material from a sputter target provided for that purpose, said system comprising:

an ion source generating a high-current ribbon-shaped ion beam accelerated to an energy in the range of 10 to 50 keV;

an electrostatic deflector comprising two electrodes at different potentials, one on either side of the ribbon-shaped ion beam, effective to deflect the ribbon beam through an angle between about 60 and 160 degrees;

a slot-shaped electrode through which the deflected ribbon-shaped ion beam passes, at a potential which decelerates the ion beam to a final energy in the range of 2 to 10 keV;

a sputter target made of a material of which it is desired to deposit a film and placed in the path of the ribbon ion beam such that the angle of incidence of the ribbon-shaped ion beam is in the range of 50 to 85 degrees, whereby atoms will be sputtered from said target by said ion beam at its final energy and be emitted as a plume of mobile atoms traveling away from the target surface;

at least one substrate placed in the travel pathway of the emitted plume of mobile atoms, whereby said substrate receives a thin film deposition of sputtered coating material.

The ion source can optionally generate a ribbon-shaped beam whose linear current density is non-uniform, being significantly higher at the two extremes, thereby raising the quantity of material sputtered from the edges of the target relative to the center; this non-linearity is operative to offset the tendency of the deposited thin film to be thinner at the two edges for geometric reasons.

A second aspect is a method for performing ion beam sputter deposition whereby a solid film coating is deposited by physical vapor deposition upon at least one exposed surface of a tangible substrate or workpiece, said method comprising the steps of:

generating a ribbon-shaped ion beam comprising noble gas ions, with a breadth of from 150 to 3000mm in an ion source;

extracting and accelerating said beam to an energy greater than about 10 keV, with a linear current density of from 0.1 to 1.5 mA per mm of beam breadth;

deflecting said ion beam promptly through an angle of between 60 and 160 degrees;

decelerating said ion beam to a chosen final energy in the range from 2 to 10 keV;

directing said accelerated/deflected/decelerated ion beam through a drift region within the vacuum housing which is shielded from any significant electric fields, thereby allowing said resulting modified ion beam to become space-charge neutralized;

directing said resulting modified ion beam to strike a face of a sputter target of a material with which it is desired to coat a substrate, said resulting modified ion beam striking the target surface at an angle of incidence between 50 and 85 degrees, thereby sputtering a plume of energetic vapor traveling away from the sputter target surface;

permitting said plume of energetic vapor to travel toward a dedicated spatial zone situated at a central region of the vacuum housing; and

placing a tangible substrate or workpiece into said dedicated spatial zone for exposure to said plume of energetic vapor for controlled physical vapor deposition of a solid film coating of at least one exposed surface.

A variant of the above method uses a ribbon ion beam whose linear current density varies across the breadth, and is higher at the two extremes, up to 2.5 mA/mm at the extremes. This variation of linear current density is the means to reduce the variation of the thickness of the deposited thin film on the substrate, which, if the beam was entirely uniform, would for purely geometric reasons be thinner at the edges of the deposited zone than near the center.

BRIEF DESCRIPTION OF THE DRAWING

The present invention can be more easily understood and better appreciated when taken in conjunction with the accompanying drawings, in which:

Prior Art Fig. 1a shows an electron beam evaporation apparatus for PVD;

Prior Art Fig. 1b shows a PVD system with a vapor source and a separate ion source for Ion Beam Assisted Deposition (IBAD);

Prior Art Fig 2 illustrates a collision cascade leading to sputtering;

Prior Art Fig. 3 is a graph which shows the sputter yields of the elements for 45 keV sputtering on three different targets;

Prior Art Fig. 4 is a graph which illustrates the sputter yield (at low dose) of argon on aluminum at different angles;

Prior Art Fig 5a illustrates a simple sputter diode system for PVD coating;

Prior Art Fig. 5b illustrates a magnetron sputter diode system;

Prior Art Fig 6 illustrates AC or pulsed DC magnetron sputtering of dielectrics;

Prior Art Fig. 7 illustrates an Ion Beam Sputtering apparatus for PVD;

Fig. 8 illustrates the concept of the present invention at the most basic level;

Fig. 9 illustrates the present invention as a whole with its major components individually delineated;

Fig. 10 illustrates a preferred compact and integrated embodiment of the present invention, which is capable of producing and using an ion beam up to 3 meters in breadth;

Fig. 11 illustrates the concept of using a multi-faced sputter target in the present invention;

Fig. 12 is a graph which shows the projected angular distribution of sputtered atoms for a 70 degree angle of incidence and compares it with the $\cos^2$ function;

Fig. 13a illustrates the geometry and defines the terms used for calculating the relative deposited film thickness at any point;

Fig. 13b is a graph which shows a modeled example of tailoring the ion beam to optimize uniformity of deposition;

Fig. 14 is a graph which shows a measurement taken with the present invention of the mean energy for argon-sputtered iron atoms, by plotting the temperature rise of a deposited iron film; and

Fig. 15 is a graph which demonstrates the achieved rate of direct sputtering from an Al_2O_3 target, an insulator.

DETAILED DESCRIPTION OF THE INVENTION

Proper Terminology & Nomenclature:

1. The method and system of the present invention is performed in a high vacuum environment; but individual protocols often allow for or explicitly demand operation at different pressures and environmental vacuum conditions. To consistently describe and define the vacuum conditions used, the following terms and meanings will be strictly and consistently employed herein:

The term 'vacuum' as used herein shall be understood to mean that the measurable pressure of the particular chamber environment is less than about 50 Pa. In comparison, the term 'partial vacuum' will indicate and denote the existence of a measurable pressure which is higher than about 50 Pa. In marked difference, the term 'high vacuum' shall generally mean that the absolute pressure is below about 10^{-2} Pa. Lastly, the term 'ultra high vacuum' (UHV) will generally be understood to mean an absolute pressure below about 10^{-7} Pa.

One additional point of information concerning vacuum environments is deemed to be valuable here. Under high vacuum conditions, the mean free path for collisions of gas and vapor molecules is larger than the mean separation of the components in the chamber. In consequence, the mobile vapor atoms and molecules of coating material can and will travel directly from the location of the target to the site of the substrate without any interaction as such; and because their energy even at room temperature conditions is sufficient for the purpose, the vaporized atoms and molecules travel in essentially straight lines from target to the exposed surface of the substrate. These considerations are important when considering the vaporized atoms' and molecules' direction of approach, conformal coating, shadowing, etc.

2. For IBS deposition procedures and systems, it is important to recognize the differences in the energies of the particles employed. For these reasons, only the following terms and meanings will be routinely employed herein: When describing or discussing particle energies, the term 'thermal' will be used to denote solely those energies below about 0.2 eV. In contrast, the term 'low energy' will be used to denote exclusively those energies below about 200 eV. Sputtered atoms have low energy - their mean energy is typically 10 to 20 eV, but ~1% can exceed 100eV. Finally, for all higher energy ions whose energy values are meaningfully greater than about 200 eV, the ion energy range will be specified and explicitly stated.

I. The Invention as a Whole

The present invention is an ion beam sputtering assembly, system, and methodology using a high current ribbon ion beam which has a carefully controlled set of operating parameters; and is unique in its capabilities for coating the exposed surface(s) of a workpiece or

substrate with a film by physical vapor deposition.

The assembly and system of the invention is installed onto a port on a vacuum chamber pumped by high vacuum pumps. There, the assembly and system generate a traveling ribbon-shaped ion beam whose measurable breadth dimension may vary from about 150 mm to about 3 meters in size; initially extract, then accelerate, then deflect, and then decelerate the ribbon beam into a resulting modified ion beam; direct the resulting modified ion beam to strike and penetrate the surface of a sputter target at a pre-chosen oblique incidence angle; and cause the sputtering of mobile atoms and/or molecules of the target as an emitted plume of vaporized atoms having energies of several electron-volts, which then travels isotropically in the high vacuum environment toward the exposed surface(s) of a preselected substrate or workpiece, located within the high vacuum environment.

In this operative system, the sputter target formed as a solid rectangular block of material for coating is mounted onto the assembly at a location within the closed high vacuum chamber at a pre-chosen, fixed and limited distance from a dedicated spatial zone in which a tangible substrate or workpiece can be positioned for film coating. This dedicated spatial zone is situated nearer to the center of the vacuum chamber; and the assembly of the invention is mounted so that an isotropic plume of atoms emitted from the target would be travelling generally into the dedicated spatial zone where the workpiece is sited.

A. UNIQUE TRAITS OF THE PRESENT INVENTION

1. Recent developments and improvements in ion beam source equipment have provided an unforeseen opportunity to improve and upgrade the conventionally known ion beam sputtering protocols. In

particular, via a recently filed PCT International Patent Application [having the priority of U.S. Provisional Patent Application Serial No. 61/964,001 filed December 20th, 2013], an ion source capable of producing a ribbon-shaped ion beam of arbitrary breadth is now available; which is uniquely able to deliver ion beams having an electric current of about 1 ampere per meter of positive ions at energies of several keV, with good uniformity along the length of the ion source, and with a beam divergence of +/- 2 to 3 degrees.

The present invention preferably employs such a broad-beam ion source, and provides a single integrated assembly and system which can be installed through a port on a separate vacuum chamber. The system has very high throughput compared with diode sputtering systems or with conventional ion beam sputtering systems, and comparable to magnetron systems.

Also like some commercially available magnetron deposition systems, the present invention can be mounted within the limited confines of a vacuum chamber on a single port - whereas conventionally known ion beam sputtering systems require multiple individual components mounted in a complex geometry on several ports. However, most unlike magnetron systems, the invention typically operates in a high vacuum environment (a vacuum of about 2-5 x 10^{-3} Pa).

2. The present invention combines a broad beam ion source and ribbon ion beam extraction with discrete deflection, deceleration and charge-neutralization components; and structurally presents a fixed mounting flange for a cooled target of the material for coating desired for ion beam sputtering as an integrated assembly; and produces a broad, linear plume of sputtered atoms/molecules which are mobile and travel isotropically away from the target mounting flange into the

available interior volume of the high vacuum environment in the closed vacuum chamber.

In preferred embodiments of this assembly and system, a plasma is generated within a broad ion source, from which an initial ribbon-shaped ion beam is extracted. The initial extracted ion beam is sequentially accelerated, deflected and decelerated using a shaped set of acceleration/deceleration electrodes; and then enters a magnetic- and electric-field free zone where the traveling ions in the beam become space-charge-neutralized. Thus, after being accelerated and before being fully decelerated by the electrodes, the ion beam is purposely deflected in its travel pathway sharply through at least 60 degrees, and preferably more than 100 degrees, before being fully decelerated to its final ion energy value. In this manner, the resulting modified ion beam has a retrograde component of motion; and is directed at a pre-selected oblique incident angle onto a target of pre-chosen coating material, which is oriented to face into the available interior volume of the high vacuum chamber.

3. The ions in this resulting modified beam penetrate the face surface of the sputter target to a depth approximately equal to the range of the ions in the target multiplied by the cosine of the angle of incidence; and via a cascade of collisions within this near-surface region, impart kinetic energy and momentum to atoms near the surface of the target. This event, in turn, causes sputtering - the emission of low energy target atoms from the target surface - which form a gaseous plume. The directions of travel of individual atoms are random, but on average are approximately normal to the surface of the sputter target. The emitted plume of vaporized atoms and/or molecules (the mobile atoms of sputtered coating material) then isotropically travel to and at least in part enter that dedicated spatial

zone within which the tangible substrate or workpiece is sited.

4. In the assembly and system of the present invention, a preselected workpiece or substrate lies situated within, or is individually traversed at a controlled velocity through, a distinct and clearly identifiable dedicated spatial deposition zone of preset dimensions and limited volume, located a small distance from the sputter target; and most desirably is placed only a few inches from the target in order that the substrate or workpiece therein receive and accept on its exposed surface(s) a thin film deposit of condensed atoms and/or molecules of sputtered coating material.

The dedicated deposition zone of the invention is dimensioned to allow the plume of sputtered atoms/molecules to extend in dimensional size for approximately the full width of the broad-breadth ribbon beam extracted from the ion source; and thus the plume of vaporized coating material will typically be from about 0.15 meters to 3 meters or more in breadth.

Such a broad deposition zone is very desirable and suitable for depositing a thin film coating upon the surface of large substrates or workpieces in a uniform and consistent manner, for example such as large sheets of glass; and uniform thin film coating deposits are made by passing the chosen substrate (or workpiece) at a controlled velocity through the deposition zone in a passage direction orthogonal to the breadth dimension of the gaseous plume. The thickness of the film will be proportional to the flux of atoms, and inversely proportional to the velocity of the substrate. The particle flux is proportional to the sputtering current. The non-uniformity of the deposited film thickness will be determined in the direction of travel by any variations in the sputtered flux, and this may be compensated by changes in the travel velocity. The uniformity in the breadth dimension (orthogonal to the

travel direction) is determined by the intrinsic uniformity of the sputtered plume, which is discussed below, but which will tend to fall off toward the edges of the plume.

This uniformity issue is entirely analogous to spray painting with a broad spray.

5. The present invention presents an assembly and system which institute a series of major operational changes and substantive practice modifications to the traditional practice of ion beam sputtering deposition. Hitherto it has not been practical to use a broad ribbon beam for ion beam sputtering, because a suitable ion source was not available; the earliest systems used a duoplasmatron ion source which produced a small, intense but spatially limited ion beam, and later commercial systems have generally used a Kaufman source, which is a circular multi-aperture ion source. The use of broad linear deposition zones in sputter deposition has hitherto been mainly restricted to linear magnetrons.

With this invention, it becomes viable for the first time for the substrate or workpiece to be moved at a slow and uniform pace through a linear deposition zone in high vacuum and there encounter and be passed through a broad plume of ion-beam sputtered material for coating capable of coating large areas at viable throughputs, with the recognized benefits of ion beam sputtered films.

B. MAJOR ADVANTAGES AND BENEFITS OF THE INVENTION

(a) Practitioners in the technical field will consider it a great advantage to be able to mount a complete and integrated ion beam sputter deposition system upon one supporting flange as a discrete organized assembly within a closed high vacuum chamber of limited internal volume, in the same manner that they have been able to

install magnetron and other deposition systems. The ion beam sputtering protocols provided by the present invention can on-demand become a 'drop-in' technique suitable for use with those sequential processing production systems which apply a series of different application procedures in series to a workpiece in order to produce a single product.

One immediate instance of use is with those machines and treatment lines now used to coat rolls of flexible sheeting of metal or plastic. The breadth of the rolls of material can be large, up to 2 or 3 meters if desired.

(b) The present invention addresses, confronts, and overcomes many long-standing limitations of the IBS systems known to date. This is achieved in part by using an improved ion source having a narrow slit ion beam extraction geometry. This improved ion source overcomes the limit (Child's Law) without resorting to the complexity of multi-apertures. The realistic availability of a single narrow slit opening of extended size to extract and produce very broad ion beams is itself a unique feature and major advance in the technical field. It will be noted and appreciated that the use of such a single extended slot-based ion beam source avoids or simplifies many alignment issues, expense, wear, and beam quality issues of multi-aperture ion sources commonly used today for ion beam generation and extraction in sputter systems.

(c) Furthermore, the alternative types of conventional ion systems which have no separate acceleration electrode as such (and which are highly desired for producing IBAD ion beams for certain other applications) - cannot and do not deliver ion beams of sufficient quality (*e.g.,* a low energy spread and divergence) within an operative compact assembly and system as is offered by the present invention.

Typically, such alternative types of ion beam systems provide only low ion energies of ~600eV.

Commonly such alternative types of ion sources are a variant of an end Hall (*e.g.* U.S. Patent No. 4,862,032) or an Anode Layer Plasma Acceleration source (*e.g.* U.S. Patent No. 5,973,447) - which, as the name explicitly notes, accelerates the ions within a plasma; and such systems generate very broad energy spreads extending from near zero value to the maximum energy value, and thus at present have difficulty delivering a tightly controlled ribbon beam with the desired precision even if accelerating/focusing structures are added.

(d) By now exploiting the new broad ribbon ion beam source capabilities for the organized assembly, the present invention is able to satisfy and fulfill all of the following operational needs:

- The present invention allows much higher areal throughput with good uniformity than existing ion-beam sputtering systems.
- The present invention operates in a high vacuum environment - *i.e.,* at markedly lower pressures than those vacuum conditions used by magnetron sputter deposition systems.
- The present invention provides a consistently smoother and more uniform film quality than plasma sputtering techniques.
- The present invention provides an efficient means of controlling the deposition uniformity across a very broad linear deposition zone.
- The present invention offers precise monitoring and stabilization of the thin film deposition rate.
- The present invention allows the application of ion-beam sputtering to bulk processing of linear and planar substrates, such as roll-to-roll coating of sheet materials.

- The present invention enables the sputtering of either dielectric films or of ferromagnetic films at high throughput with all the advantages of ion beam sputtering.

(e) Further advantages of the present invention involve optional combination with a second linear ion source mounted on an adjacent flange, either of the same new type, or in an existing style such as ALPA. The optional use of multiple ion sources offers the capability of directing one beam of ions at the substrate while the other beam is independently directed at the sputter target. Such an optional combination of two or more ion beams can be used to:

□ Pre-clean the substrate with an oblique incidence beam of ions, either argon ions or a reactive species such as O+, F+, etc.; to desorb surface gas contamination; to detach particulate contamination; and/or to volatilize trace contaminants initially present,

□ Perform IBAD (Ion Beam Assisted Deposition) using simultaneous sputter coating and ion beam impact - as by example, for known processes where the crystallinity and/or density of the film is thereby enhanced, all in a high vacuum closed environment,

□Perform reactive sputtering by simultaneously (or alternately) delivering one ion species by sputtering and delivering another reactive ion species as either a low-energy ion beam to the surface of the substrate, or as a plasma, or even as a jet of neutral gas - all in a high vacuum closed environment, while avoiding the 'lost anode' problem (which afflicts magnetron systems).

II. The Minimal Structural Components comprising the Assembly and Operational System of the Invention

The assembly and system of the present invention will produce an unique ribbon shaped ion beam which presents specific traits and

particular attributes which are deemed advantageous and superior for use in a sputter deposition system performed within a closed vacuum environment -whereby a pre-chosen sputter material is deposited as a solid film coating by physical vapor deposition onto at least one exposed face surface of a tangible substrate or workpiece. A simple embodiment of the arranged assembly and of the operative system is illustrated by Fig. 9, and demonstrably includes all of the following.

1. A Discrete Ion Beam Source

¶ As shown by Fig. 9, a discrete ion source 2 is a requisite component of the assembly and operative system. The ion source 2 will comprise a closed, solid wall, arc discharge chamber of extended dimensional size; and present a measurable length dimension which greatly exceeds the measurable width and height dimensions of the arc chamber; and have a discrete exit aperture or open slot in its front wall for the extraction and emergence of an ion beam 11.

Inside the interior cavity volume of the arc discharge chamber, a plasma is generated; from which an ion beam of known breadth and thickness dimensions is subsequently extracted, wherein the thickness dimension is typically 5mm or less and the breadth dimension is unusually large and ranges from several hundred millimeters to 3,000 mm or more. It is well-known that the total charged particle current which may be extracted or transported in a space-charge-limited beam is proportional to the aspect ratio (breadth/thickness) of the beam (Forrester), and this is one reason for the given choice of dimensions.

The arc chamber of the ion source 2 is also biased at a positive voltage V_0 with respect to ground; and with respect to a sputter material target mounted and grounded to the interior of a metal vacuum chamber, thus the term qV_0 defines the energy which the

streaming ions of charge *q* shall have upon reaching the sputter target.

¶ In the present invention, any ion beam generating source of any known type can be employed so long as it is capable of producing all of the following traits and features: A bright, low divergence, ribbon-shaped beam which possesses a linear ion current density of about 0.1 to 1.5 ampere per meter of positive ions; a well-controlled ion energy of several (5-40) keV; good uniformity of linear ion current density over its breadth dimension; and an ion beam divergence limited to +/- 2 to 3 degrees. Furthermore the ion source cannot produce a large external magnetic field; and it cannot have any component of magnetic field extending in its major beam breadth dimension, since such fields would interfere with the operations and functions of the assembly and interfere with its use in depositing magnetic films.

¶ Typically, the ion beam generating source 2 will emit a flowing stream of positive ions as a ribbon-shaped beam 11 from the arc chamber's open slot or exit aperture. The stream of ions will typically be about 2mm to 10 mm in its narrow dimension; and will allow an ion beam to be extracted from its full breadth, which can vary in measurable size from about 150 mm to more than 3,000 mm.

In addition, the ion beam generating source 2 will typically be biased at a known positive potential V_0 with respect to ground; and this positive voltage value will control and quantitatively determine the kinetic energy that the traveling ions will possess when they reach the exposed surface of the sputter target (which is also held at ground potential).

¶ A most suitable ion source is described more fully in a co-pending patent application based upon U.S. Provisional Patent Application Serial No. 61/964,001 filed December 20th, 2013, and of PCT International Application No. PCT/US2014/000216 filed 26 November 2014, the individual texts of which are expressly incorporated by reference herein. At the present time, there is no other suitable ion source which meets and satisfies all the necessary requirements stated above.

2. An Extraction/Acceleration Electrode

£ Within the limited dimensions and volumetric confines of the closed chamber and high vacuum environment illustrated schematically in Fig. 9, the ion beam is initially extracted from the ion source 2 by an adjacently located extraction/acceleration electrode 4 comprising two straight half-electrode structures 4a and 4b.

The identifiable extraction/acceleration electrode 4 is a discrete structure aligned with and positioned at a predetermined distance from the exit aperture of the ion source 2. Also, the extraction/acceleration electrode is biased at a negative potential V_{ex} with respect to the potential of the sputter target material; acts to extract the ion beam from the plasma generated within the interior of the arc chamber and immediately accelerate the traveling ions to an energy of $q(V_0 - V_{ex})$. A 0kV to -20kV power supply can provide this negative potential value.

Structurally, the extraction/acceleration electrode 4 typically comprises two straight half section structures 4a and 4b, wherein each of the two straight half sections 4a and 4b have an individual section thickness dimension of about 2 to 15 mm; and wherein the two half sections 4a and 4b are tangibly separated by a measurable distance h also ranging from about 2mm to 12mm, but preferably is a fixed

separation of about 4mm. Extraction electrode sections 4a and 4b are tangibly separated from the exit aperture of the ion source by a preselected gap *g,* which is typically about 10 to 20mm.

£ Operationally, the extraction/acceleration electrode 4 accelerates the ion beam 11 initially extracted from the ion source 2 to a high kinetic energy value which in an exemplary system is ~25 keV, but may be from about 10 to about 60 keV.

£ It is well known (based on Child's Law) that when ions are extracted from a plasma through an ion source's exit aperture, the divergence of the ions in the extracted beam is strongly dependent on the magnitude of the accelerating electric field; which, in turn, is an inverse function of the gap between the electrodes. The gap distance *g* between the electrodes must in practice be greater than the width dimension *w* of the exit aperture in the ion source, and also greater than the separation *h* of the two parts 4a and 4b of the extraction electrode. Then, the extracted beam is very near its minimum divergence values when the following mathematical relationship is met:

$$I = \frac{b^2}{g^2}\frac{4\varepsilon_0}{9}V_{ex}^{3/2}\left(\frac{2q}{M}\right)^{1/2} \qquad \text{[Equation 2]}$$

where the terms have the following meanings:

b is the total breadth (dimension into the page) of the ion beam;

V_{ex} is the total voltage across the extraction gap;

g is the extraction gap;

q is the charge of the ions;

M is the mass of the ions;

and all units are SI.

There is in general a numerical correction factor to Equation 2, which is based on detailed geometry, and is close to unity provided $g>>w$ and $g>>h$ in value; but for high current applications, one usually needs g to be fairly small in value, so the mathematical approximation recited by Equation 2 is subject to geometrical corrections, but correctly describes the scaling laws.

3. The Electrostatic Deflector

§ As shown in Fig. 9, the electrostatic deflector comprises two substantially parallel aligned electrodes– an inner electrode 51 and an outer electrode 52 - which are separated by a distance d. Together, two electrodes 51 and 52 provide a substantially uniform directed open passageway for ion beam travel there-through, in which they generate an electric field transverse to the beam direction, with the form of cylindrical sector. These electrodes could have a cylindrical shape, but in practice outer electrode 52 preferably incorporates some apertures such as 62 and 63 in Fig. 10, and a stepped profile rather than a smooth curve, while still functioning to define the outer limit of a generally cylindrical electric field zone. The reasons are discussed below.

The preferred electrostatic deflector comprising electrodes 51 and 52 is closely-coupled in distance, timing, and action to the ion source 2 and extraction/acceleration electrode 4a and 4b; imposes a transverse electric field upon the accelerated ions in the traveling ion beam; and will deflect the accelerated ions of the beam through a controlled deflection angle ranging between about 60 and 160 degrees from their initial travel direction.

§ The inner electrode 51 of the deflector must be biased at a negative potential value with respect to the potential of the outer

electrode 52, in order to create the required electric field. For added convenience, space-saving economy and efficient function, the inner electrode 51 is set at a potential value of V_{ex} while the outer electrode 52 is set to ground; and the electrode separation distance 'd' is selected so that the generated electric field has the desired value.

Note also that the outer electrode 52 intentionally deviates from a purely cylindrical shape for the reasons discussed below.

§ As seen in Fig. 9, the ion beam 11 passing through the extraction electrode 4 is directionally moving away from the mounting flange of the assembly and heading towards the interior center of the closed vacuum chamber. Given the physical constraints and limited confines of the closed high vacuum chamber, it is therefore necessary to deflect the traveling ion beam through an angle of preferably about 110 degrees; but at any rate more than about 60 degrees of deflection and less than about 160 degrees - so that it can eventually strike the face of a sputter target which is facing toward the interior of the vacuum chamber.

§ The necessity for ion beam deflection in the present invention is the consequence of not less than four different needs and events:

(i) The placing the ion source in its easily-serviced location on an exterior wall of the closed vacuum chamber;

(ii) The requirement for placing the sputter target so that its exposed face surface points inwardly into the center of the chamber;

(iii) The requirement that the ion source be located out of direct line-of-sight from the substrate site and the sputter target location; and

(iv) The desirability of a minimally short travel path for the ion beam.

Thus, in order to achieve these four purposes, an electrostatic deflector comprising electrodes 51 and 52 with cylindrical symmetry is provided. By deflecting the traveling ion beam through a controlled deflection angle ranging between about 60 and 160 degrees, the assembly and operational system remains very compact; and space-charge expansion within the deflector is largely overcome by means of the intrinsic focusing effect of such a deflector [see Anderson *et al., IEEE Trans NS-30*, No. 4 (1983), p.3215].

The deflector can be designed for convenience to use two already available potentials, as shown in Fig. 10 - a preferred compact and integrated embodiment of the present invention is shown which is capable of deflecting and utilizing an ion beam up to 3 meters in breadth - wherein the inner (negative) electrode 51 is simply connected to the negative extraction electrode 4a, and the outer (positive) electrode 52 is connected to ground. A first advantage of this compact organization is economy – *i.e.,* no extra power supplies are needed or used. Second, the desired final energy of the ion beam is about 5 keV - but by deflecting the ion beam at an energy of ~ 20 keV, the effect of space charge is reduced by a factor of about 8 and the current can be much higher, for a higher throughput rate.

In addition, it will be noted that in this electrostatic deflector, the inner trajectories have a higher energy than the outer trajectories because of the transverse electric field. The innermost energy is about 25 keV, but the mean energy is close to 20 keV under preferred conditions.

§ Although the outer electrode 52 preferably has a cylindrical-shaped geometry, it is sufficient for its deflection purpose if the outer electrode alternatively is configured to present an array of lines, rods or similar shapes, much like a grid in an electron tube; and thereby

defines a potential at multiple discrete positions on an approximately cylindrical shaped surface, while leaving empty gaps between the elements of the grid. It is also desirable that passages exist between the grid elements which allow residual gases to escape with high conductance toward vacuum pumps, for the purpose of maintaining good vacuum between the electrodes. It is further possible that although the desired shape of the electric field should approximate the shape of the field between two cylinders, at least within the volume occupied by the ion beam - the outer electrode should avoid providing surfaces directly parallel to the inner electrode so far as possible, because electric discharges between the two electrodes can become more intense by electron/ion multiplication if the electrodes are parallel.

This is the primary reason that the outer electrode will comprise a series of stepped shapes machined into the metal from which it is constructed. Such features are also valuable for capturing charged and neutral particles, which are for whatever reason, not taking the intended path; and preventing them from bouncing in the forward direction, thereby improving the purity of the process. However, whatever its detailed shape might be, the gap distance of the deflector structure must be uniform along the breadth dimension of the traveling ion beam.

4. An Integrated Ion Deceleration Electrode

Θ Within the arranged assembly and operative system shown by either Fig. 9 or 10, a discrete or integrated ion deceleration electrode comprising half-electrodes 40a and 40b is present, and is set at the same electric potential as the sputter target (and also of the vacuum chamber and the substrate) - i.e, the local ground potential. The

accelerated and deflected ion beam is directed to pass through this closely-coupled and aligned deceleration electrode 40.

Θ The discrete ion deceleration electrode 40 has a slot-shaped opening 45 in its structure, which is sufficiently large to accommodate the breadth dimension of the ion beam and through which the broad beam of deflected ions will pass. Because the deceleration electrode 40 is at ground potential, the ions are decelerated from their high value to an energy of qV_0- i.e., the final energy is solely defined by the ion charge and the ion source potential. In general therefore, the measurable size of the slot-shaped opening 45 will be not less than 150mm and will often be greater than 3,000mm; and the final kinetic energy of the ions will be in the range of from about 2 keV to 10 keV.

Θ Since this deceleration electrode 40 can be, and preferably is, set at the same electrical potential value as the potential of the outer deflector electrode 52, these two individual structures can be constructed in common to appear as a single tangible entity.

Furthermore, it is most beneficial if the outer deflection electrode 52 and the deceleration electrode 40 are integrated together into the housing which encloses the ion source and deflection system. Such an integrated housing format is illustrated by Fig. 10 and provides an organized and properly aligned structural framework for the whole assembly. This housing format can also integrate essential channels and circulating passageways for cooling water to keep the structure temperature cool despite very high power levels being used by the assembly.

Θ In addition, because the deceleration electrode 40 is at ground potential - i.e., the same potential value as the closed vacuum chamber, the assembly mounting flange, the outer electrode 52 of the

electrostatic deflector, and the sputter target 200 - it is convenient and good practice to integrate the assembly's mounting flange and structure, the deceleration electrode, the outer electrode of the deflector, and the necessary grounded electrostatic screening. All of these components can be machined from or cast as a single piece of material, such as aluminum alloy. Within the embodiment of Fig. 10, it can be seen that deceleration electrode halves 40a and 40b are machined from one piece of metal, along with outer deflection electrode 52 and the base flange 21; and that this monolithic housing structure also incorporates a number of circulating water passages 61 through which water flows to remove heat.

5. A Discernible Spatial Corridor Region For Ion Beam Travel Which Is Devoid Of Either Electric Field Or Magnetic Field Influences

After passage through the deceleration electrode, the ion beam enters a 'drift space' or virtually field-free zone which is substantially devoid of either electric or magnetic fields (reference numeral 65 in Fig.10). Almost every surface exposed to the decelerated beam at this point is a grounded conductor; the sputter target and the substrate may be insulators, in which case their surface potential cannot be predefined.

Two criteria must be met by this discernible spatial corridor region and drift field-free zone in every embodiment of the invention:

(i) The beam must be space-charge neutralized (i.e. possess no significant electrical charge); and

(ii) the beam must be current-neutralized (i.e., transport no net charge to the sputter target).

Note that a failure to space-charge neutralize the ion beam will lead to the beam expanding uncontrollably ('space-charge blowup')

and failing to deliver more than a fraction of the intended current to the target; and a failure to current-neutralize the ion beam will result in high surface potentials on insulating targets, resulting in many added problems including a failure to sputter, and damaging surface electrical discharges.

These criteria can be met by this discernible spatial corridor region and field-free drift zone 65. A necessary precondition for space-charge neutrality within the ion beam is that any electron initially attracted by un-neutralized positive charge of the initial ion beam be trapped, and not be accidentally accelerated out of the beam by an exposed positive potential. There is a positive potential on the ion source, but this is shielded from the decelerated beam by the negative potential *Vex* on discrete electrodes 4a, 4b, and 51. Thus this precondition is satisfied in full.

It is usual that high current ion beams can self-neutralize by trapping a population of free electrons, which reduce the potential within the ion beam to a few volts. This process occurs as a result of electrons generated by ionization and by beam strike on grounded surfaces, but needs to be further enhanced by providing a deliberate source of low-energy electrons, by means of a hot filament or plasma source, as is well-known and discussed in prior art patents.

These electrons can come to thermal equilibrium and together with the beam ions constitute a cool plasma with an electron temperature of typically 2eV to 5eV, which serves to maintain space-charge neutrality and permits current neutrality to be maintained.

Should a small positive surface potential appear on the target, it will attract copious extra electrons from the ion beam plasma, reducing it to a low equilibrium potential value. If a small negative

potential appears, the ions will continue to arrive, but electrons will be repelled, returning the surface potential to its equilibrium value.

A convenient source of electrons is a small auxiliary version of the same ion source design, perhaps 100mm long, with no acceleration electrodes, from which neutral plasma can issue, located close to the decelerated ion beam. The position is not critical.

6. The Traits And Attributes Of The Final Ion Beam

When the resulting modified ribbon-shaped ion beam emerges from the environment of the deceleration electrode and enters into the discernible spatial corridor region and drift field-free zone 65, this final ion beam has the following traits and characteristics:

(α) The final ion beam will have a breadth ranging from about 150 mm to more than 3,000 mm;

(β) The final ion beam will comprise at least one ion species which has an electric current density of approximately 0.1A to 1.5A per meter of beam breadth, in a beam thickness ranging between about 5 mm and 15 mm. The linear current density profile of the final ion beam may be deliberately altered, to make the current density slightly greater near the ends, in order to improve the uniformity of sputter deposition - which for purely geometrical reasons tends to be lower near the two ends of the deposition zone. This control may be accomplished by means appropriate to the ion source used; an example is to modify the internal gas density within the ion source using an internal array of gas feed ports, causing the pressure to be slightly higher near the ends of the arc chamber.

(γ) The trajectories of the ions in the final beam will be parallel within about +/- 6 degrees in its thickness direction, and about +/- 0.5 degrees in its breadth direction.

(δ) The final ion beam is directed to strike the exposed face surface of a sputter target at a controlled incidence angle ranging from not less than about 50 degrees to not more than about 85 degrees; and preferably strikes the sputter target obliquely at 70 degrees to the normal. This optimal circumstance at a 70 degree incidence angle means results in a strike surface area on the sputter target which has a measurable width ranging from about 17 mm to 51 mm in size.

(ε) The space-charge forces within the final ion beam will have been substantially neutralized - via the electrostatic trapping and the subsequent thermalization of an almost equal density of electrons within the beam.

(θ) The final ion beam will have a kinetic energy selected to optimize the yield of sputtered atoms per unit energy delivered. For a 70 degree incidence angle using argon ions as the chosen ion species, this ion kinetic energy is preferably about 5 keV; but this kinetic energy value may change depending on the ion species to be employed and the preselected material of the sputter target.

7. A Pre-chosen Sputter Target

ϕ As shown by Figs. 9, 10 and 11 respectively, the final ion beam is directed onto and penetrates the exposed surface of a fixed sputter target 200, which is composed of the pre-selected material from which it is desired to sputter atoms in order to coat the surface(s) of a substrate or workpiece 300. The sputter target 200 is a tangible solid block of a pre-chosen substance or chemical composition; is positioned at a set linear distance and fixed spatial location within the high vacuum environment; and presents an exposed face surface which is aligned at an oblique incidence angle with the travel pathway of the resulting modified ion beam.

The sputter target will typically be bonded to a fixed support base – a mounting flange which is often water-cooled to remove the substantial thermal energy imparted by the strike and impact force of the resulting modified ion beam. The fixed sputter target will preferably be oriented parallel to its mounting flange, and thus face directly inwardly toward the spatial interior of the closed vacuum chamber.

The sputter target will appear and be mounted in the field-free region where the final ion beam - after being deflected and directed by the electrostatic deflector electrodes 51 and 52, decelerated by electrode 40, and then space-charge neutralized - can drift at its final kinetic energy value and strike the sputter target surface.

ϕ The incident angle for the strike of the final ion beam upon the sputter target face surface in this arrangement is deemed to be a critical and controlling factor. It will be appreciated that a normal incidence angle (0°) is impractical because the ion beam would be coming from where the substrate should be positioned. An oblique angle of incidence which is less than 90 degrees is convenient; and the preferred 70 degree incident angle is deemed to be optimal.

Also, if the sputter target is mounted parallel with the front of the ion source (*i.e.,* the open exit aperture of the arc chamber), and if the accelerated ion beam is deflected through an angle of 110 degrees, then the resulting ion beam has a measurable angle of incidence α (measured to the normal plane) - which in this instance is 70 degrees. This 70° angle of incidence is illustrated by the angle α in Fig. 9.

Furthermore, it is generally true that the yield of sputtered atoms is maximized at an angle of incidence of about 70 +/- 5 degrees. For these reasons, a 70 degree angle of incidence +/- 5

degrees is deemed to be a near optimal choice. Moreover, at 70 degrees the optimum kinetic energy for incoming ions is higher than for normal incidence; and although the ion energy is higher, each ion is more productive of sputtered material; and there is a net gain.

Thus, an incident angle of 70 degrees and an ion energy of 5 keV using argon ions is presently considered to be near optimum for projecting and distributing the released vaporized cloud of mobile sputtered atoms into a desired flow pattern away from the sputter target.

ϕ Accordingly, the sputter target will present or demonstrably provide all of the following traits:

(i) The sputter target is to be substantively composed of at least one material substance which it is desired to sputter and use to coat a workpiece or substrate by physical vapor deposition (or possibly as one component of a film produced by reactive PVD);

(ii) The sputter target is to be electrically grounded. If the sputter target material is an insulator, it is to be held within a few volts of ground potential by neutralizing electrons. Note that practitioners working today in the commercial industry often refers to sputter targets as 'cathodes' because in all diode sputtering systems, they serve as the system's cathode terminal, being struck by 'cations' or positive ions. Nevertheless, the present system in its simplest form is in fact a triode arrangement (or has yet even more than three electrodes), and the sputter target is set at a potential between the positive and negative extremes.

(iii) The sputter target shall have an exposed face surface, which is obliquely exposed to the resulting modified ion beam; and also shall directly face toward a dedicated deposition zone, via a short

unobstructed travel pathway, wherein a substrate or workpiece can be placed for thin film coating.

(iv) The sputter target is fixed in distance and spatial location from the site and position of the deceleration electrode within the vacuum environment such that the ions of the final ion beam will strike the exposed surface of the target material at a controlled angle of incidence between about 50 and 85 degrees, and preferably 70 degrees, to the normal plane of the surface face.

(v) The sputtering of the target's material will cause the release and emission of a distinct plume 210 of freely mobile vaporized atoms and/or molecules; and this sputtering event is illustrated by Fig. 9. These vaporized atoms and/or molecules are the immediate and direct consequence of the ions striking and penetrating the exposed surface of the sputter target.

(vi) Once created and released, the manner of travel for the gaseous plume of vaporized atoms/molecules is substantially isotropic – i.e., having physical properties that are the same regardless of the direction of measurement. The direction of travel of these atoms cannot be altered or changed other than by choosing the face surface orientation for the sputter target.

(vii) The mean travel direction and pathway for the vaporized cloud of mobile sputtered atoms/molecules is almost normal to the face surface plane of the sputter target (but typically slightly favoring a direction at a small angle to the normal directed away from the source of the incoming ions); and the flux in any measurable direction is approximately proportional to the *cosine* of the angle to the normal of the target surface.

Φ The particular chemical composition and formulation of the fixed sputter material target 200 will be pre-chosen in advance of use.

The range of possible choices of material for coating is very large and quite varied; and can be any solid substance, element, metal, metallic alloy, oxide or other kind or type of compound or matter which is needed or desired as a film coating (or component thereof) for a substrate or workpiece. In many cases, such as films of oxides and nitrides, the target material may be a metal or metallic alloy. Also, at one's option, an additional flow of slow oxygen or nitrogen ions and/or atoms may be directed at the substrate - where, as the film is deposited, a stoichiometric (or in some instances non-stoichiometric) compound is reactively formed and deposited at the surface as a solid film.

ϕ The sputter material target typically has a substantially flat or planar exterior surface face which is co-extensive with at least the full breadth dimension of the traveling ion beam; and this face is struck and penetrated by the ions in the beam at a controlled angle of incidence - which ranges from not less than about 50 degrees to not more than about 85 degrees with respect to the normal to the surface of the target, and is preferably set at about 70 degrees.

ϕ A further option is to provide a multi-faced sputter target, where each individual face surface is composed of a different material for coating. The multi-faced sputter target can be rotated as needed or desired to present alternative kinds of materials for coating to the striking ion beam at different times as a single assembly, for the purpose of depositing multi-layer structures.

Such a polygonal shaped format is exemplified by a square target 201 illustrated by Fig. 11. In these particular embodiments, the polygonal shaped sputter target is positioned and actuated so that the beam impacts any one of the multiple face surfaces when selected at a similar angle of incidence.

8. The Formation and Release of a Gaseous Plume of Vaporized Atoms and/or Molecules

The immediate and direct result of the ion beam 11 penetrating the surface of the sputter target is the formation is the sputtering therefrom of a plume 210 of vaporized atoms and/or molecules having an average kinetic energy of about 20 eV. This value can be calculated by using Equation 1 (as given above) with data readily available for most elements; and for verification a measurement of this kinetic energy was made for the sputtering of iron using 5 keV argon ions at an angle of incidence of 70 degrees. The result is graphically shown in Fig. 14a.

If a sputtered atom is released from the target surface at an angle to the normal of a surface of ϕ, and at an azimuthal angle in any convenient frame of θ - then the *projected* angle (as viewed in the direction of the azimuthal θ axis) is $\beta = \phi \sin \theta$. The effect of taking a weighted average over all values of θ is that the distribution of sputtered atoms appears from any given direction to be proportional to $\cos^2(\beta)$. Thus the distribution of angles in which the atoms travel, if emitted completely randomly, projected onto a single direction, is a $\cos^2$ function. However in practice the direction of maximum flux is slightly inclined to the normal in the direction away from the incoming ion beam. This result is calculated using the computer program SRIM, and the calculated result matches the pattern of various results empirically reported by the relevant technical literature.

Furthermore, the apparent overall dependence of the flux on the *projected* angle β is proportional to $\cos^2\beta$. These relationships are graphically shown by Fig. 12.

Since the practitioner is concerned with the angular distribution about a line uniformly extending in the beam breadth direction, one uses the *projected* angular distribution to describe the direction and flux of the sputtered atoms. This distribution of emitted sputtered atoms is shown graphically by Fig. 12. This graph may be used with care to describe the flux from different directions in which atoms approach the target, except near the endpoints of the sputtered zone - because no sputtered atoms can originate beyond the endpoints of the sputtered zone; and near the endpoints of the linear zone, this has a material effect on the angular distribution of the atoms reaching the substrate; and unless compensated, leads to a lower flux and a thinner film on the substrate near the edges.

In this manner, this arranged system and oriented assembly generates a flux of flowing vaporized sputtered atoms which dimensionally extends somewhat more than the actual breadth of the traveling ion beam; and is substantially as uniform over its breadth distance as the sputtering current density applies in this breadth dimension - except in a zone near each extreme of the breadth of the plume, where the density falls significantly and reaches ~50% at points aligned with the ends of the sputtered zone on the target.

Also, the extent of decrease in sputter particle density will be less if the substrate or workpiece to be coated is positioned relatively close to the sputter target.

9. A Dedicated Spatial Zone For The Film Coating Of A Substrate Or Workpiece

The last minimal requirement of the arranged assembly and operative system is a dedicated deposition zone 250 of predetermined dimensions and volume and is shown as such by the embodiments of

Figs. 9 and 10 respectively. The dedicated deposition zone 250 is situated in high vacuum within the vacuum chamber; and is a limited spatial volume through which a chosen substrate or workpiece 300 can be moved in a direction orthogonal to the breadth of the sputtering ion beam 11 and approximately parallel to the surface of the sputter target 200, for film coating by physical vapor deposition.

‡ The dedicated deposition zone 250 shown in Figs. 9 and 10 is closely located and aligned to the known location of the sputter target; and it is most desirable that the separation distance between these two components be as short as possible in order that the substrate receive a major fraction of the total mobile sputtered atoms then available as the gaseous plume of vaporized atoms and/ molecules.

‡ The plume of vaporized coating material atoms and/or molecules will travel isotropically towards and enter the dedicated deposition zone; strike the exposed surface(s) of the substrate or workpiece; and then become condensed and deposited upon the exposed surface of the substrate as a solid film coating. This sequence of events is illustrated by the embodiments of Figs. 9 and 10.

The substrate or workpiece to be film coated is moved into and subsequently moved out of the dimensional confines of the deposition zone, preferably in a direction normal to the extended breadth dimension of the gaseous plume, and preferably at constant velocity.

The thickness of the film layer deposited upon the surface of the substrate 300 will be proportional to the flux of sputtered atoms/molecules; which in turn, is proportional to the ion beam current and to other factors; and will also be proportional to the integrated time of exposure to the flux of sputtered atoms/molecules.

Therefore, it is inversely proportional to the velocity with which the substrate(s) is/are traversed through the plume of vaporized coating material; and accordingly for uniform coating, the substrate 300 should be moved at a slow single velocity consistently through the gaseous plume 210.

III. The Controlling And Critical Parameters Of The Operative System

The ordinarily skilled practitioner working today in this technical field will recognize and appreciate that a number of different parameters will critically control the invention's mode and manner of operation as a whole. Therefore, for the benefit and use of the working practitioner, some governing and decisive operative parameters are individually described in substantial detail below.

1. Controlling Parameters For Generating A Proper Ion Beam

The controlling parameters and critical variables of the ion beam source offers the system user an unique set of format variables for creating an initially extracted ion beam which then can be substantively altered and markedly changed in its attributes to yield the desired resulting modified ion beam characteristics.

(A). The characteristics of an initially extracted ion beam are:

Table 1: Initially Extracted Ion Beam Factors & Variables

Intrinsic current density:	From 2 to 50 mA/cm^2
Ion energy distribution range:	Less than 2 eV
Ion beam breadth range:	From about 150 mm to more than 3,000 mm
Ion extraction system:	Ribbon beam through one slot
Ion extraction energy range:	From about 5 keV to about 40 keV
Ion divergence range:	About +/- 3°
Output ion current range:	From about 0.1 to about 1.5 amperes per meter of positive ions

The output ion current is uniform to +/-1% in central zone; and at both extremes, the current density can be adjusted higher than the center by at least 25% if desired.

(B). After the initially extracted beam is accelerated to an increased kinetic energy, it is necessary to deflect the ribbon beam promptly to an optimal bent angle; and for this purpose a bend of about 110 degrees is highly preferred. A low-current ribbon shaped ion beam in a cylindrical electrostatic deflector would be strongly focused, but at the optimal high current the ribbon beam's space-charge within the deflector will offset this focusing, and the beam will emerge quasi-parallel, with some amount of increased angular variation.

The mean energy of the ions in the beam through the deflector electrode should be substantially higher than the desired final energy, in order to obtain a much higher current transmission - a factor of 8 being obtainable by deflecting the ion beam at ~ 20 keV before decelerating to 5 keV.

(C). The subsequent deceleration of the traveling ion beam occurs promptly after the act of deflection and must be carefully controlled - as it will focus, possibly steer, and probably generate aberration. The transition from deceleration field to field-free neutralized ion beam plasma is known as a plasma sheath, and calculating the precise trajectories requires computer models such as Cobham/Vector Fields 'SCALA'.

(D). A preferred ion beam sputter deposition system will present an argon ion current of about 1 Ampere per meter of dimensional beam breadth, in conjunction with a beam bending radius of about 35 mm; and thus uses a beam energy of about 20 keV within the bend

radius. The final kinetic energy for the decelerated ion beam is desirably around 5 keV. For this outcome, the extraction gap distance g is approximately 14 mm; and the cylindrical electrode gap d is about 23mm in distance.

(E). It is possible to use additional power supplies and separately control all the ion extraction and ion deflection voltages. In such instances, the negative electrode 51 in the assembly might be greater in negative potential than the extraction electrode 4; and the positive outer electrode 52 would be biased slightly negative with respect to ground and be positioned closer in distance to the negative inner electrode 51.

However, there does not appear to be any significant potential advantage to using such additional power supply apparatus, while the cost and complexity is substantial. For these reasons, preferred embodiments of the present invention require only two discrete high voltage power supplies, as shown in Fig. 9.

(F). The most uniform resulting sputtered films will be obtained if the ion beam linear current density profile is uniform in a central zone, but the current density at the two extremes is higher, by at least 25%, depending on the exact geometrical arrangement used.

2. Controlling Parameters For Properly Deflecting An Accelerated Ion Beam

(α.) The cylindrical sector passageway between the concave electrode portion and the convex electrode portion of the deflecting electrode is preferably shaped such that the traveling ion beam is bent over a wide cylindrical segment; and is deflected from its initial travel direction through an angle which is not less than 60 degrees, is

preferably a deflection angle of about 110 degrees, but is never more than about 160 degrees.

(β.) The initially extracted and accelerated ion beam is deflected by a radially directed electric field between the deflection electrodes 51 and 52; and the radius of the beam's central trajectory is conventionally calculated by

$$R = 2V_c/E_{rc} \qquad \text{[Equation 3]}$$

where the suffix c refers to the values of E and V which are encountered at the center of the ion beam, and the suffix r denotes that the electric field is radially directed.

(γ.) Operatively, as the beam current value is increased (which would necessitate reducing the sized gap g for the assembly of Fig. 9, other factors being held constant), the quantitative amount of repulsion among the charged ions within the extracted beam will increase until the repulsion value cancels (at least to first-order calculations) the focusing action of the deflector component, at which point the beam current is about optimum, since the divergence of the final beam will be minimized, and the transport of beam current to the target will be maximized.

(δ.) An algebraically complex relationship exists between the two voltages, the beam current, the proximity of the beam center to the inner electrode and the ratio of the deflector gap d to the electrode gap g. The complication lies in geometrical factors involving poorly known quantities - such as the maximum beam width w_{max} in the bend; which then determines the exact desired position of the inner electrode in the assembly.

However, this complicated relationship has a mathematically calculable form:

$$I = \frac{4kw_{\max}b}{r_0^2}\frac{4\varepsilon_0}{9}V_{ex}^{3/2}\sqrt{\frac{2q}{M}} \qquad \text{[Equation 4]}$$

where k is an unknown geometrical factor less than 1 which is affected by the choice of the radius of the inner electrode, and r_0 is the radius of the path of the central trajectory, and other terms were already defined.

As already mentioned, it is important that neither of the two curved electrodes acting in tandem to deflect the accelerated beam's travel pathway be at a positive potential value with respect to the potential of the sputter material target or to the potential of the vacuum chamber, and it is especially important that the positive potential of the ion source be electrostatically shielded from the remainder of the tangible components within the vacuum chamber. Such electrostatic shielding is conventionally known, and any mode or manner of electrostatic shielding is acceptable.

Given these two operating precautions and system requirements, no electric field or magnetic field capable of accelerating electrons away from the location of the fixed sputter target should exist; and the requirement of a field-free drift after deceleration should be met.

Thus, via such operational system controls, the traveling accelerated/deflected/decelerated ion beam also becomes space-charge neutralized; and the resulting final ion beam will then travel over a short and predetermined distance to the location of the fixed sputter target without experiencing significant space-charge blowup.

3. Critical Relationships among the Three Individual Electrode Components

§ Operationally, it will be appreciated also that there are, at a minimum, three different and discrete electrode potentials in the system.

(1) The potential V_0 of the ion source (reference numeral 2 in Fig. 10);

(2) The potential V_{ex} of the extraction electrode (reference numeral 4 in Fig. 10) and of the convex electrode (reference numeral 51 in Fig. 10). These may be mechanically joined together or physically integrated as shown in Fig. 10; and

(3) The potential value of the concave deflector electrode 52, which may be the local ground potential - that of the vacuum chamber- which is shared with the deceleration electrode, the target, the substrate, and the metal of the structured flange on which the assembly may be constructed.

§ This operational system of the invention uses an acceleration-deceleration sequence of actions, otherwise known as a 'triode' system, for creating and maintaining a space-charge neutralized ion beam. However, it will be appreciated that the incorporation within such a triode system of a powerful electrostatic deflector - without the addition of any new potentials or the use of magnetic fields - to create a high current and space-charge neutralized ion beam is, in and of itself, a notable and entirely new innovation.

Also, the act of ion beam deflection occurs only as the intervening event after ion beam acceleration, but before performing ion beam deceleration; and the sequence of events is strictly maintained in all use occasions. Its advantage is that beam deflection

occurs at the highest energy, and by Equation 4 as given above, the highest possible ion current is thereby deflected.

§ The output beam energy is determined solely by the voltage V_0 applied to the ion source with respect to the sputter target (and to the grounded vacuum chamber as a whole). The beam energy is selected for the chosen ion species (which will usually be argon) and the chosen angle of incidence (usually 70 degrees) to give efficient sputtering and high sputtering flux; and will typically be close to 5 keV, for the reasons given above.

§ The deflection angle of the traveling ion beam (presuming its output ion energy value to be held constant) can be adjusted by changing the voltage V_{ex} applied to the extraction electrode and to the inner deflection electrode.

§ The divergence of the output beam, and hence the width of its zone of impact on the sputter target, can be adjusted according to Equation 2 and Equation 4 as stated above. It is affected by a number of parameters. However, if the desired output beam energy is fixed, and if the geometry of the deflector cannot be adjusted (other than by changing its physical dimensions during manufacture), and if the gap between the extraction electrode is fixed (by the length, for example, of standoff insulators used to hold it in precise alignment to the ion source), the only remaining variable parameter which can be adjusted to vary the beam divergence is the ion current per unit length emitted from the ion source.

The beam's ion divergence is a steep function of beam current – see for example: White, N.R., *Nucl. Instr. and Meth., B55* (1991), pp. 287-295. Both Equation 2 and Equation 4 as stated above describe conditions where the beam divergence is minimized, and the designer

needs to make adjustments to the design to ensure that both equations are satisfied at the same beam current value.

§ In practice it is possible to make small adjustments to the electrode spacing from the ion source, and to determine the spacing which gives the lowest output beam divergence at the highest beam current.

If the beam deflection is adjusted a small amount during use (by changing the potential on the extraction electrode and inner deflector electrode), the divergence may not remain optimally low, but if this adjustment is made for the purpose of making the uniformity of erosion of the target more uniform, this would be an acceptable compromise, and good practice.

4. Critical Parameters for the Final Ion Beam when Striking a Sputter Target

It is generally true that the yield of sputtered atoms is maximized at an angle of incidence close to 70 degrees, so this is a near optimal choice of angle. It is reported that with a high incidence angle, the distribution of sputtered directions becomes narrower, and is slightly biased away from the incoming beam direction. These quantities vary slightly by target and projectile species.

Accordingly, in the present operating system, the angle of incidence – the angle at which the final ion beam strikes the exposed surface of a target – is controlled to be in the range of from about 50 degrees to about 85 degrees; and is optimal at about a 70 degree angle of incidence.

5. Operational Parameters For Maintaining A Uniform Deposition Zone

£ The present invention is optimally suited to coating substrates and other workpieces which are moved uniformly in a single direction through the dedicated spatial deposition zone, which would be arranged to extend transversely to the direction of motion. The proximity of the substrate to the location of the fixed sputter target will depend on many factors such as vacuum; other process needs (IBAD, cleaning, etc); but will typically be 50 mm to 100 mm in distance. The unobstructed clearance for out-gassing products to reach the high vacuum pumps will affect the true process pressure. In this way, uniform coating of large surface areas can be accomplished - the uniformity of the coating being limited only by the geometric falloff in the vapor flux near the edges of the deposition zone as described below.

For purely geometric regions, if a broad gaseous plume of sputtered material is generated by a uniformly broad ion beam striking a sputter target, and an substrate of equal breadth is slowly moved through the gaseous plume of sputtered material - some of the vaporized coating material will miss the edges of the substrate, simply because those atoms randomly moved from the target in a direction which failed to intercept the substrate.

£ The fraction of atoms from any point on the target which miss the substrate is proportional to the amount of solid angle beyond the substrate edge as seen from that point. Conversely, the amount of sputtered flux reaching any point on the substrate is proportional to the solid angle which the total sputtered zone on the target subtends at the point on the substrate.

Assuming that the emission of atoms is a perfect cosine distribution, i.e. perfectly randomly distributed in the forward direction from the target, one can calculate the film thickness variation purely based on calculating the solid angles in question. If the broad dimension of the sputter target is aligned with the *x*-axis of a coordinate system, extending from point *x1* to *x2*, and is uniformly sputtered over this precise length, and the substrate moves in the *z*-direction through the deposition plume at a distance *y* from the target as shown in Fig. 13a - then any point on the substrate with coordinates (*x,y*) will, after traveling through the deposition plume from point (x,y,z_1) to point (x,y,z_2) receive a deposit with a thickness t proportional to the following expression:

$$t \propto \int \left(\arctan\frac{x-x1}{y} - \arctan\frac{x-x2}{y} \right) \frac{\cos z/y}{v_z\sqrt{y^2+z^2}} dz$$

But, if one assumes that the substrate moves entirely through the plume in the *z*-direction at a constant velocity v_z and with all other conditions constant, this expression can then be simplified to the following function:

$$t \propto \arctan\frac{x-x1}{y} - \arctan\frac{x-x2}{y} \qquad \text{[Equation 5]}$$

This Equation 5 function is plotted graphically in Fig. 13b for the specific instance of a 400mm wide sputter zone on the target, 60mm from the substrate, and labeled 'Raw deposition profile'. It must be understood that the real distribution does not perfectly match this assumption; but the errors caused by the discrepancy are small; and as graphically shown by Fig. 13b, is an excellent guide to controlling the non-uniformity of the film deposited onto the substrate.

This data shows that the thickness of the deposited film layer will decrease at the margins of the substrate. It follows that the spatial deposition zone and the breadth of the ribbon beam and of the target must exceed the breadth of the substrates in order to maintain reasonably uniform deposition right to the margins and edge of the substrate. The amount of extra breadth required exceeds twice the target-substrate spacing at each end of the deposition zone.

£ This non-uniformity can be dramatically reduced if the ion beam current density varies in the opposite sense, and this can be accomplished in a number of ways. For example, if the gas feed into the long arc chamber of the ion source is distributed through an array of holes; and the flow rate is slightly higher near the ends of the arc chamber - then the beam current may rise by perhaps 30% at the edges relative to the center. This change will increase the quantity of sputtered atoms/molecules near the substrate edges; and produce a resultant deposited thickness profile similar to the profile in Fig. 13b labeled 'with ion beam contouring'.

By tailoring the current density in the ion beam with the profile labeled 'sputtering ion beam profile' in Fig. 13b, the deposition rate may be raised slightly at the edges to compensate this tendency. This means the excess deposition zone requirement can be reduced to a total of about one times the target-substrate spacing, instead of more than two times, and within this zone the uniformity can have a standard deviation of less than 1%.

If a greater increase in current density at the outer limits of the final broad ion beam can be achieved, the film uniformity can be made uniform over an even wider fraction of the total target width, and within the uniform zone, the variation can be reduced to a fraction of a percent, so long as the source profile can be controlled with

sufficient accuracy, and the film thickness sensed quickly enough to provide the necessary feedback.

6. Operational Parameters for Controlling the Deposit of Vaporized Sputtered Particles upon the Surface(s) of a Substrate or Workpiece

The quality of the deposited thin film coating is affected by the following factors:

(a) The atoms/molecules deposited on the surface of the substrate using this apparatus and methodology will include some dimers (a molecule containing two atoms), but relatively few larger sized clusters.

(b) The use of high vacuum during thin film coating ensures that the likelihood of incorporation of argon into the substrate surface is vastly reduced.

(c) The lack of intense hot plasma and strong electric fields (as in a magnetron discharge) means that the substrate is not receiving bombardment by large numbers of electrons and miscellaneous ions.

(d) The mean energy of the atoms created by sputtering at ~ 5 keV with argon ions at 70° incidence is around 20 eV.
This number is well substantiated; it varies with the target species according to the target surface binding energy, but will generally have a value of at least four times this energy. Fig. 14a shows a measurement of this energy per atom, made by depositing a film of iron atoms on a thin glass substrate while monitoring the temperature rise.

(e) Residual stress in the deposited film is a parameter which must be optimized for each specific situation. It is affected little by the primary beam energy, but in films formed by reactive sputtering, it is affected by the energy and flux of the reactive species. Thus changes

to the auxiliary ion source or sources, if used, may be an important control parameter.

(f) The use of an oblique IBAD beam tends to smooth the target surface.

(g) The use of a low energy argon or reactive beam to pre-clean the substrate can be beneficial to film quality and film adherence. Therefore the use of one or more auxiliary ion sources of the same or similar design to that described in the co-pending application cited is seen as a potentially beneficial combination.

(h) For high volume deposition of multiple layers, the substrate may be passed under a sequential array of similar apparatuses in a single large vacuum chamber to coat a succession of different films.

IV. The Methodology of the Present Invention

The methodology of the present invention, both by definition and by practice, points out the criticality and value of the final decelerated and neutralized ion beam, whose chosen characteristics are critical. The predominant part of the arranged assembly is dedicated to the production and output of a singular and unique ion beam, which is then used to perform ion beam sputtering in a geometry and compact arrangement never before reduced to practice or considered possible by practitioners working in this technical field.

Accordingly, two alternative protocol versions of the methodology as a whole accurately identify and precisely encompass the unique and unforeseen technique.

◇ The first protocol is a method for producing a broad plume of energetic vapor for use in physical vapor deposition, said method comprising the steps of:

operating an arranged assembly which includes

(i) a metal chamber at a local ground potential, able to provide a closed vacuum environment, provided with vacuum pumps capable of reducing the pressure to below 10^{-4} Pa ,

(ii) an ion source producing a ribbon beam of ions of a chosen species, commonly argon or a mixture containing argon, which can exit a slot-shaped aperture with a breadth of from about 150mm to 3000mm or more and a thickness of 2 to 5 mm, the broad ribbon beam having a current of about 0.1 to 1.5 mA per mm of beam breadth and an energy distribution of +/- 1 eV or less, the ion source being maintained at a first (positive) voltage,

(iii) an extraction/acceleration electrode aligned with and positioned at a predetermined distance from said arc chamber exit aperture, said extraction/acceleration electrode being biased at a second (negative) voltage with respect to the housing such that ions extracted from the plasma in said arc chamber are drawn through said open exit aperture as a broad ribbon-shaped ion beam having an ion energy determined by the difference of the first and second volta

(iv) an electrostatic deflector comprising two substantially parallel inner and outer electrodes extending in the beam breadth direction on either side of the ribbon beam wherein each discrete electrode in the pairing has an approximately reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectory of a ribbon-shaped ion beam then passing through said gap distance between said parallel electrodes at a deflection angle ranging from about 60 to 160 degrees,

(v) a deceleration electrode of preset dimensions which is connected to local ground potential, said deceleration electrode presenting a slot-shaped opening of sufficient size to allow a deflected

ribbon-shaped ion beam to pass there-through, whereby the energy of the ions is reduced to a final energy determined by said first positive voltage,

(vi) a short field-free drift space in vacuum in which the final ion beam at the final energy becomes space-charge neutralized,

(vii) a sputter target of a selected solid material with an exposed surface, mounted close to the deceleration electrode and shielded from the potentials of the ion source and extraction electrode, the exposed target surface facing into a central region of the vacuum housing;

producing a ribbon-shaped space-charge-neutralized ion beam at a chosen energy in the range from 2 to 10 keV from the exit of said deceleration electrode as a resulting modified ion beam, and

directing said resulting modified ion beam to strike said sputter target at an angle of incidence between 50 and 85 degrees, thereby sputtering a plume of energetic vapor from the target surface, the plume being generally directed toward the central region of the vacuum housing.

◇ In contrast, the second version protocol is a method for performing ion beam sputter deposition whereby a solid film coating is deposited by physical vapor deposition upon at least one exposed surface of a tangible substrate or workpiece, said method comprising:

operating an arranged assembly which includes

(i) a metal chamber at a local ground potential, able to provide a closed vacuum environment, provided with vacuum pumps capable of reducing the pressure to below 10^{-4} Pa,

(ii) a preformed sputter target formed of a desired material to be used for coating, said sputter target being held at a fixed location in the vacuum environment at the same potential as the vacuum

chamber, and having an exposed surface facing toward a central region of the vacuum chamber, and

(iii) an arc chamber of predetermined dimensions and limited internal volume in which a plasma is generated by electron bombardment of a gaseous substance introduced therein, from which an ion beam having a breadth size from about 150 mm to about 3,000 mm can be subsequently extracted, said arc chamber comprising

an anode, a cathode, and an open exit aperture whose breadth dimension greatly exceeds its width dimension, and being biased at a positive voltage with respect to said sputter target,

(iv) an extraction/acceleration electrode aligned with and positioned at a predetermined distance from said arc chamber exit aperture, said extraction/acceleration electrode being biased at a negative potential with respect to said vacuum chamber such that ions extracted from the plasma in said arc chamber are drawn through said open exit aperture as a broad ribbon-shaped ion beam and accelerated by said electrode to achieve an energy determined by the difference in potential of the ion source and the electrode,

(v) an electrostatic deflector comprising two substantially parallel inner and outer electrodes wherein each discrete electrode in the pairing approximates a reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectories of a ribbon-shaped ion beam then passing through said gap between said parallel electrodes through an angle ranging from about 60 to 160 degrees,

(vi) a discrete deceleration electrode of preset dimensions at the electrical potential of the vacuum chamber and the sputter target, said deceleration electrode presenting a slot-shaped opening of sufficient spatial size to allow a deflected ribbon-shaped ion beam to pass there-through, whereby the ions are decelerated to a final energy

determined only by the potential on the ion source,

(vii) a dedicated deposition zone of predetermined dimensions and volume into which a tangible substrate or workpiece can be precisely placed for controlled solid film coating, said dedicated spatial zone being closely placed in distance and adjacently aligned in position to said sputter target;

producing a ribbon-shaped ion beam from said operation of said arranged assembly within the limited confines of said closed vacuum environment, wherein said deflected and decelerated ribbon-shaped ion beam

(α) presents a beam breadth dimension ranging from about 150 mm to about 3,000 mm,

(β) carries a determinable electric ion current value ranging from about 0.1 to about 1.5 milliamperes per mm of breadth;

(γ) has a determinable final ion energy value deemed desirable for ion beam sputter deposition purposes, said final energy value ranging from about 2 to about 10 keV,

(δ) contains an equal density of free electrons to the ions, which electrons neutralize space-charge in the decelerated beam,

(ε) is substantially focused to a single direction of travel within about +/- 6°;

directing said produced ribbon-shaped ion beam to strike the exposed face surface of said sputter target within the confines of said closed vacuum environment at an angle of incidence in the range from not less than about 50 degrees to not more than about 85 degrees; and

causing the release of a vaporized plume of mobile sputtered atoms from said exposed face surface of said sputter target as the consequence of said ion beam striking wherein

(i) the average travel direction for said released vaporized plume of mobile sputtered atoms is approximately normal to the exposed face surface of said sputter target, and the atoms' directions have approximately a cosine distribution around this normal,

(ii) a dedicated deposition zone situated in front of said sputter target into which said plume will travel is maintained in high vacuum and free of obstruction;

moving a tangible substrate or workpiece into and out of said dedicated deposition zone for exposure to said vaporized plume of mobile sputtered atoms and for controlled solid film coating of at least one exposed surface by vapor condensation and material deposition of said sputtered atoms.

optionally measuring and controlling the total ion beam current delivered to the target, and controlling the velocity of the target so that the velocity is proportional to the ion beam current,

and optionally adjusting the linear current density of the final ribbon beam to be higher at the two extremes than in its center, the amount of non-uniformity being adjusted and/or selected to improve the uniformity of the deposited thin film.

VI. Illustrative Embodiments and Representative Practices

In order to demonstrate both the merits and value of the present invention, a series of performed experiments and empirical data are presented below. It will be expressly understood, however, that the experiments performed, as well as the empirical results described, are merely exemplary evidence of the subject matter as a whole which is the present invention; and that the such experimental information and data, albeit limited in content, is merely illustrative of the true scope of the invention envisioned and claimed herein.

A First Exemplary Assembly & Operating System

Fig. 9 shows the arranged assembly and operative system used for initial testing. The breadth dimension of the ion beam was 200mm; the energy was 5 keV; and the total beam current varied in the range from 80 to 150 mA.

Fig. 15 graphically shows data measured for a number of samples of films deposited with a prototype version of this embodiment. The sputter target used was formed of aluminum oxide; the incidence angle was 70 degrees; and the beam current was about 0.7 mA per mm of beam breadth. The beam energy was 5 keV, and the beam breadth was 200mm. The distance from sputter target to substrate location was 115 mm.

With aluminum oxide as the chosen coating material (which has a very low sputter yield and is an insulator), no serious problem was encountered and a stable operation without surface charging was performed. Films were deposited on glass slides, of which the temperature was sometimes monitored. Thicknesses were measured by profilometer, by ellipsometry, and by transverse SEM. The empirical results were in good agreement and are shown by the graph of Fig. 15.

Fig. 14a graphically shows the results of the temperature rise measurement for an iron film, and by measurement of the glass slide thermal mass it was possible to estimate the average kinetic energy carried per sputtered ion atom; this can be seen to be 20+/-2 eV, which is in good agreement with the predictions of sputtering theory. Fig 14b shows the predicted energy distribution for sputtered iron using CRC handbook values of the enthalpies of fusion and condensation, and the mean energy agrees within 1 eV with the value of 20 eV measured above.

A Second Exemplary Assembly & Operating System

Fig. 10 shows a preferred embodiment for a unitary drop-in sputtering system which has been built with a beam breadth and sputtering zone breadth of 350mm. This dimension is chosen to fit an existing vacuum chamber as a drop-in replacement for a commercially available linear magnetron. But the same cross-section can be used with very minor changes for systems with larger breadth dimensions, for example a breadth of 2 meters.

In this embodiment, a housing 21 is machined from solid aluminum; it could also be cast and post-machined. This housing also constitutes a rectangular flange which is mounted to a port on an existing vacuum chamber (shown only schematically) and sealed with o-rings. The closed vacuum chamber is pumped with two 1500 l/s high vacuum pumps.

Amongst the features machined into this flange/housing 21 are an internal cavity which houses the ion source 2 and the deflector subassembly which is mounted to it as described below; and two linear arrays of rectangular ports 62 and 63. These arrays dimensionally extend into the page and are bridged at intervals by aluminum frames for structural stiffness; and the ports allow waste gas from the ion source to escape to the high vacuum pumps and lower the pressure in the internal cavity.

The housing 21 also contains a parallel-side slot 45 bounded by sides 40a and 40b which serve as the deceleration electrode, the slot 45 extending the full 350mm of breadth size and a little more. The inside of the cavity contains a stepped profile 52, which serves as the outer electrode of the electrostatic deflector.

The housing 21 also contains a number of passages for cooling water 61. These communicate with the atmosphere side of the flange, where cooling water can be connected. Different passages provide for

cooling the outer deflector electrode 52, and the mounting location for the sputter target (separate item 200). All the above features are contained in one monolithic item.

Into this flange/housing 21 is installed an insulator 22 upon which is mounted the ion source by means of flange 23. The ion source is fully described in a co-pending patent application of which this invention is a continuation-in-part.

However, note that while there are internal magnetic fields inside the ion source - these are very rapidly attenuated outside the source and are insignificant at the position of the target. This compact version of the ion source uses internal permanent magnets. Mounted onto the front of the ion source on ceramic insulators 71 shielded by metal shrouds 72 is the extraction electrode 4 comprising electrodes 4a and 4b, together with deflector inner electrode 51.

Note that each of 4a and 4b is mounted on its own row of ceramic insulators, so that even in a very long ion source producing a very broad ribbon beam, the alignment of the two halves of the extraction electrode is tightly controlled. Also note that in this embodiment item 4a and electrode 51 are in fact the same part, which is machined from solid graphite. Item 51 is the inner electrode for the beam deflector. The two halves of the extraction electrode are separated from each other by a distance *h*, through which the ion beam is accelerated from the ion source, and both are separated by a gap *g* from the front exit slot of the ion source, from which the ion beam 11 is schematically shown emerging.

Ion beam 11 is accelerated, deflected, then decelerated, and emerges through the slot bounded by 40a and 40b into a field-free drift zone 65, to strike sputter target 200 at an angle of incidence α of 70 degrees. The ion source is connected to a +5kV power supply (as in Fig. 9, but not shown in Fig. 10), and electrodes 4a and 4b are

connected (by an electrical feed-through which is not shown) to a potential with a maximum of -20kV but in practice about -18 kV.

Before striking the sputter target, the beam of argon ions at 5 keV passing through field-free zone 65 becomes space-charge neutralized. This occurs because the housing 21 completely shields the emerging beam from those components of the ion source at a positive voltage, and the negative potential on electrode 51 is interposed in between. As a result, the emerging ion beam will attract electrons (generated by collisions with both the target and traces of beam striking unwanted locations, also from residual gas ionizing collisions) for as long as its potential is a few volts positive with respect to ground, but the buildup of electrons will continue and create a beam plasma, with a potential of only 2 to 5V positive with respect to the vacuum chamber.

The gaseous plume of sputtered atoms 210 will travel through the vacuum environment as shown, with a mean energy of between 15 and 20 eV, enter deposition zone 250, and then strike substrate 300. The substrate can be introduced onto a transport system through an airlock, and can be moved at a slow constant velocity through the vapor plume 210; at a distance of 75mm from the target, which extends in and out of the page by a total breadth of 350mm at the target, expanding somewhat as it moves outward. By tailoring the beam uniformity of the ion source (for example by using the gas distribution as a control), the uniform region of the deposition spatial zone can have a breadth of about 275mm within which the thickness non-uniformity can be about +/- 1% or less.

VII. Some Particularly Notable Features of the Invention

1. An additional ion beam source or sources can be disposed within the limited confines of the closed vacuum environment, and the

additional ion source can be used for a number of different purposes relating to the PVD process, which include:

(i) An additional ion source can provide a source of cool plasma electrons to allow the beam to stably sputter a target made from an insulating material; such a plasma source clamps the potential on the target within a few volts of the potential on the chamber walls.

(ii) An additional ion source can provide an ionized reactant (such as oxygen) at a preselected energy, and directed onto the same workpiece that is being coated; in this way various new or known forms of reactive sputtering may be performed.

(iii) The additional ion source may be biased a few tens of volts positive for a limited period for the purpose of cleaning the surface of the workpiece by ion collisions, prior to commencing the coating process.

2. The ion beam source of the operative system may be integrated into a unified removable structure together with the electrostatic deflector and the sputter material target; and this structure, when mounted on a single flange in the vacuum chamber, is relatively easy to remove for service. This mounting flange would also allow for the mounting and integration of such items requiring 5kV isolation from ground as:

- Power supplies for the ion source;
- Cooling water or fluid to the ion source;
- Argon or other gas into the interior volume of the ion source;

All the above items are provided at the ion source potential of ~+5kV through an insulated set of vacuum feed-throughs;

In addition, the mounting flange would allow for:

- High voltage to the accel electrode, typically ~20 kV negative, through a dedicated high voltage vacuum feed-through

▪ Cooling water or fluid to the sputter target (which would otherwise be heated to a high temperature during ion bombardment).

3. The specific layout and orientations of the components in the operative system may be varied as needed or desired in order to satisfy the specific goals of:

◦ Delivering the sputtered material flux in the forward direction into the vacuum process chamber as efficiently as possible;

◦ Shielding the ion beam source from unwanted contamination by the vaporized sputter material;

◦ Minimizing the size (dimensions and volume) of the ion beam source;

◦ Increasing the efficiency of generating the final ion beam;

◦ Simplifying the manner of removal of tangible items and functional components for maintenance, repair, or replacement; and

◦ Reducing the total weight and volume of the system assembly as a whole.

4. Within the limited confines of the closed vacuum environment chamber, various components can be electrically isolated from the other system entities; and these arrangements then can be operationally connected to the other parts of the assembly through current-measuring devices. In this manner, the total electrical current can be measured; and the additional currents allow stray and parasitic ion and electron currents to be monitored. This measured and monitored information allows the traveling ion beam to be precisely controlled in current and energy; and allows a far greater overall precision of the amount of material sputtered than is typically available with magnetrons, because the energy and current of sputtering ions is poorly resolved from unproductive parasitic current.

Thus, in the present invention, the measured beam is a precise measure of the amount of material actually delivered to the substrate.

5. Within the system's organization, the useful life span of the sputter material target can be adversely affected by non-uniform erosion of the face surface (owing to the creation and release of vaporized sputter atoms). While this event may be less serious than in a magnetron system, any of the following life-enhancing procedures can be employed in the operative system to increase the useful life-span of the target.

- Using a rotatable cylindrical target and rotating it slowly and continuously or intermittently throughout its life to spread uniformly the erosion of the target surface.
- Adjusting the impact position of the ion beam striking the target, either by the use of either small adjustments to the beam deflecting voltage, or by changes to the mechanical position of the exposed face surface of the target. The voltage adjustment method can easily be pre-programmed and automated.
- Moving the target to alternative positions to compensate for uneven loss of coating material and undesired patterning effects.

VIII. Substantive Comparisons and Significant Contrasts of the Present Invention with Prior Art Systems and Methods

1. There is a merely superficial resemblance between the electron trajectories in certain well-known commercial electron beam evaporation systems for PVD and the present invention. The electron beam is typically deflected through a requisite angle of about 270 degrees before being focused onto the target material for evaporation.

Moreover, the substantive differences also include:

(a) The electron beam serves as a source of heat, not as a means of sputtering. Electrons do not cause sputtering.

(b) The energy of evaporated atoms is only ~1/100 of that of sputtered atoms, and this affects the film properties adversely.

(c) The deflection in the electron source is caused by a magnetic field, and the field orthogonal to the travel of the electrons and to the direction of deflection.

(d) This geometry precludes the development of an elongated broad source of vapor. It works well for a point source, but the magnetic field lines would be required to extend in the breadth direction of an extended source, and this is problematic for many reasons including those discussed in the co-pending ion source patent.

(e) In contrast, the deflection in the present invention is solely generated by electric fields lying in the plane of the trajectory, and this enables the creation of line PVD sources of arbitrary length.

2. In conventional prior art ion beam sputtering systems, a direct line of sight trajectory from the ion source to the sputter material target must exist. There is also commonly found a direct line of sight travel pathway from the ion source to the workpiece. Also, there is frequently an exposed and electrically heated tungsten wire filament used as a source of neutralizing electrons. Each of these commonly present system requirements is a source of cross-contamination - either of the ion source with sputtered material, or of the sputtered material with spurious sputtered or evaporated material. The present invention blocks each of these direct sight-line exposures, and thereby greatly reduces the amount of unnecessary cross-contamination in the system.

3. Also, when directly compared with a flange-mounted magnetron sputter deposition system, the present invention offers and exhibits all of the following highly desirable advantages:

□ The creation and extraction of a charged ion species as a ribbon-shaped beam occurs from within a separate closed housing and a discrete ion source. Because the ion source is an independently operating confined apparatus with a limited-size exit aperture, although it is physically situated within the same vacuum chamber as the entire sputtering assembly, this circumstance allows for the use of relatively high pressure (~1 Pa) within the ion source while maintaining much lower pressure ($<<10^{-2}$ Pa) at both the target sputtering and film deposition spatial zones,

□ The tightly focused broad ion beam has a precisely controlled energy. The ion energies in magnetron discharges span a wide range from near zero to about 800eV, depending on the applied voltage, and this range is many times greater – and thus are far less controlled or precise.

□ The resulting modified ion beam produced by the assembly and system of the present invention presents ion which are space-charge neutralized. Also, if desired or when deemed necessary, a separate cooling plasma source held at ground potential can and will reduce the residual space-charge potentials further;

□ Within the assembly of the present invention, the sputter target is mounted on a fixed location and is held at local ground potential – which is the same potential as the substrate to be coated. It is noteworthy also that both the sputter target and the substrate to be coated are situated in a region which is substantially free of electric fields. This fact and circumstance renders immaterial the issue of whether the material of the target is a conductor or an insulator.

□ For the assemblies and systems of the present invention, the immediate vacuum environment of the sputter target is also substantially free of magnetic fields. Thus, unlike the known magnetron sputtering systems, it now makes no difference whether the chosen coating material is magnetic or non-magnetic. If it is desired to apply a magnetic field at the substrate, this should cause no problem.

□ In the present invention, the final ion beam is directed to strike the sputter target at a predetermined incidence angle, which is optimally about 70 degrees. This requisite incidence angle raises the sputter particle yield; allows a higher ion energy for the resulting modified ion beam; and improves energy efficiency.

□ In the present invention, a wide range and chemical variety of insulating materials can be sputtered continuously using DC power without experiencing the difficult problems of overcoming electrostatic charging and a 'disappearing anode'.

□ In the present invention, a steady high rate of deposition of thin-film coatings is produced and can be electrically monitored.

□ By tailoring the ion beam current density profile, the present invention can tailor the uniformity of the sputtered plume along its major dimension, and hence improve both the uniformity of the deposited films and the relative breadth of the 'sweet spot'.

□ The present invention provides effective means for increasing the uniformity of erosion of the sputter target - by adjusting the potentials in the electrostatic deflection to scan the beam back and forth, thereby maximizing the utilization of target material,

The preset invention is not limited in form nor restricted in scope, except by the claims appended hereto.

What I claim is:

1. An assembly for producing a ribbon shaped ion beam which is suitable for sputter deposition within a closed vacuum environment whereby a chosen sputter material is deposited as a solid film coating by physical vapor deposition onto at least one exposed surface of a tangible substrate or workpiece, said system assembly comprising:

an ion source presenting an arc chamber of predetermined dimensions and limited internal volume in which a plasma is generated by electron bombardment of a gaseous substance in-situ and an ion beam having a breadth size from about 150 mm to about 3,000 mm can be subsequently extracted, said arc chamber comprising an anode, a cathode, and an open exit aperture whose breadth dimension greatly exceeds its width dimension, and being biased at a positive voltage with respect to the chosen sputter material which is to be deposited as a coating by ion beam sputtering;

an extraction/acceleration electrode aligned with and positioned at a predetermined distance from said ion source exit aperture, said extraction/acceleration electrode being biased at a negative potential with respect to a chosen sputter material such that ions extracted from the plasma in said arc chamber are then accelerated by said electrode to an initial energy;

an electrostatic deflector comprising two substantially parallel inner and outer electrodes wherein each discrete electrode in the pairing has a reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectory of a ribbon-shaped ion beam then passing through said gap distance between said parallel electrodes at a deflection angle ranging from about 60 to 160 degrees;

a deceleration electrode of preset dimensions and which has an electrical potential value similar to the measurable potential of a pre-

chosen sputter material, said deceleration electrode presenting a slot-shaped opening of sufficient spatial size to allow a deflected ribbon-shaped ion beam to pass there-through, whereby the ions are decelerated to a final value, and enter a region substantially free of electric and magnetic fields;

whereby a final ion beam of a chosen species is produced which is suitable for ion beam sputtering of a target formed of pre-chosen material for coating, and wherein said final ion beam

(α) presents a beam breadth dimension ranging from about 150 mm to about 3,000 mm,

(β) carries an ion current ranging from about 0.1 to about 1.5 amperes per meter of breadth;

(γ) has a determinable final ion energy value ranging from about 2 to about 10 keV,

(δ) becomes space-charge neutralized after emerging from the deceleration electrode into a field-free region,

(ε) is substantially focused to a single direction of travel within about +/- 6°.

2. An assembly for producing a broad gaseous plume of sputtered coating material atoms and/or molecules for physical vapor deposition as a solid film, said assembly being suitable for installation as an integrated unit through a port in a wall of a closed vacuum chamber, and comprising:

a sputter target made of a pre-chosen material, said sputter target having a face surface exposed toward the interior of the vacuum chamber and being mounted upon a support flange constructed for heat removal by discrete water passageways within the support flange structure, and wherein the broad ribbon-shaped ion beam penetrates said sputter target surface and causes by sputtering

the release of a gaseous plume of vaporized material therefrom, and said gaseous plume travels towards the interior of the vacuum chamber;

an arranged subassembly comprising an ion source, an extraction/acceleration electrode, a deflector, and a deceleration electrode, said subassembly being able to deliver a broad final beam of a selected ion species to the exposed surface of a sputter target, the exposed surface of the sputter target being slightly broader in linear size than the measurable beam breadth dimension, and wherein the resulting modified beam ions are space-charged neutralized, and will strike the surface face of the sputter target with an angle of incidence between 50 and 85 degrees, and will have a current between 0.1 and 1.5A per meter of beam breadth, and will have an ion energy between about 2 and 10 keV, and a substantially uniform linear current density profile which may optionally rise to significantly higher linear current density near the two extremes; and

a dedicated deposition zone which is positioned within the interior of the vacuum chamber in front of said sputter target, wherein at least one substrate is moved into said deposition zone for film coating by said plume of vaporized material.

3. An assembly for producing a broad plume of vaporized atoms and/or molecules to be used for physical vapor deposition of a solid film layer upon the surface of a substrate, said assembly being suitable for installation as a single unified entity to a port in a wall of a closed vacuum chamber, and comprising:

an ion source of predetermined dimensions and limited internal volume in which a plasma is generated by electron bombardment of a gaseous substance introduced therein, and from which an ion beam having a measurable breadth from about 150 mm to about 3,000 mm

can be subsequently extracted, said ion source including an arc chamber which has an anode, a heated cathode, and an open exit aperture whose linear breadth dimension greatly exceeds its width dimension, and which is biased at a positive voltage with respect to the chosen coating material;

an extraction/acceleration electrode presenting a slot aligned with and positioned at a predetermined distance from said ion source exit aperture, and which is biased at a negative potential with respect to the chosen material of a sputter target, whereby ions extracted from said ion source are accelerated to an initial kinetic energy value ranging from about 10 keV to about 50 keV;

an electrostatic deflector comprising two substantially parallel inner and outer electrodes wherein each discrete electrode in the pairing has a reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectory of a broad ribbon-shaped ion beam passing through said gap between said parallel electrodes at a deflection angle ranging from about 60 to 160 degrees;

a deceleration electrode of preset dimensions which presents a slot-shaped opening of sufficient size to allow a deflected broad ribbon-shaped ion beam to pass there-through, whereby the ions become decelerated to a final kinetic energy less than about 10 keV,

a field-free drift zone within said closed vacuum environment which linearly extends from said ion deceleration electrode to a fixed sputter target, which serves as a travel path for the final ion beam;

whereby a resulting final beam is produced which becomes space-charged neutralized, has an ion divergence less than about +/- 6 degrees, has a substantially uniform electric linear current density ranging from about 0.1 to about 1.5 amperes per meter of beam breadth, but which may optionally rise to higher values near the two

extremes, and travels so as to strike the face surface of a sputter target at an angle of incidence between about 50 and 85 degrees;

a preformed sputter target made of a pre-chosen material for coating, said sputter target having a face surface exposed toward the interior of the vacuum chamber and being mounted upon a support flange constructed for heat removal by discrete water passageways within the support flange structure, said final ion beam striking and penetrating said sputter target and causing the release therefrom of a plume of vaporized material, traveling towards the interior of the closed vacuum chamber; and

a dedicated deposition zone which is positioned within the interior of the vacuum chamber in front of said sputter target, wherein at least one substrate is placed within said dedicated spatial zone and wherein said plume of vaporized coating material encounters, condenses onto, and forms a solid film upon the substrate surface.

4. The assembly recited by claim 3 wherein the electric potential on the outer cylindrical electrode of the electrostatic deflector is that of the target.

5. The assembly recited by claim 3 wherein the electric potential of said inner cylindrical electrode in said electrostatic deflector is equal to the potential on said extraction/acceleration electrode.

6. The assembly recited by claim 3 wherein said assembly is held within a closed vacuum chamber equipped with vacuum pumps able to evacuate it to a pressure below about 10^{-4} Pa;

7. The assembly recited by claim 3 wherein the ion species in the extracted beam contains at least one ion species selected from the group consisting of neon, argon, krypton, or xenon ions.

8. The assembly recited by claim 3 in which the mounting flange, the outer deflector electrode, the deceleration electrode, and the housing for the ion source are all contained in one single unified metal part.

9. The assembly recited by claim 3 in which the ion source generates a ribbon beam with a substantially uniform linear current density in a central zone but which rises near the two extremes by at least 25% from the central value, the non-uniform overall profile being adjusted or selected to be effective to improve the uniformity of the deposited thin film, compensating the tendency for geometric effects to cause the film to be thinner at the edges.

10. An operative system for ion beam sputter deposition of a pre-chosen coating material upon at least one exposed surface of a tangible substrate or workpiece, said operative system comprising:

(i) a closed and pumped vacuum chamber able to provide a vacuum below about 10^{-4} Pa;

(ii) a discrete ion beam source situated within said closed vacuum environment and comprising a preformed arc chamber having predetermined external dimensions, a measurable interior volume, an internally disposed anode, an internally disposed cathode, and an open exit aperture whose breadth dimension greatly exceeds its width dimension, and wherein the interior volume of said arc chamber is employed to generate a plasma in-situ from a known gaseous substance, from which an ion stream having a breadth dimension ranging from about 150 mm to more than 3,000 mm can be extracted as an initial ribbon-shaped ion beam which then travels within the volume confines and limited dimensions of said closed vacuum environment;

(iii) an extraction/acceleration electrode situated within the confines of said closed vacuum environment and which is able to extract an ion beam from the plasma generated within the interior volume of said arc chamber, said extraction/acceleration electrode being placed adjacently in front of the open exit aperture of said arc chamber, and being able to accelerate the ions in the ribbon beam to a higher kinetic energy ranging from about 10 keV to about 50 keV;

(iv) An electrostatic deflector situated within said closed vacuum environment which is disposed adjacent to said ion source and is closely-coupled to said extraction/acceleration electrode, said electrostatic deflector imposing an electric field upon the traveling ion beam which is sufficient to bend the ribbon beam of accelerated ions through a controlled deflection angle ranging between about 60 and 160 degrees from the beam's initial trajectory;

(v) A discrete ion deceleration electrode placed adjacent to said electrostatic deflector, comprising a slot-shaped opening which is sufficiently large to accommodate the breadth dimension of the traveling ion beam and through which the broad beam of deflected ions will pass, whereby the ion beam is decelerated to a kinetic energy less than about 20 keV;

(vi) a resulting final ion beam produced by means of said ion source, said extraction/acceleration electrode, said electrostatic deflector, and said deceleration electrode within the limited confines of said closed vacuum environment, wherein said resulting final ion beam

(α) has a breadth dimension ranging from about 150 mm to about 3,000 mm,

(β) carries an ion current ranging from about 0.1 to about 1.5 milliamperes per mm of breadth;

(γ) has a determinable final ion energy value deemed desirable for ion beam sputter deposition purposes, said final energy

value ranging from about 2 to about 10 keV,

(δ) is substantially focused to a single direction of travel within about +/- 6°;

(vii) a substantially field-free drift region within said closed vacuum chamber which linearly extends from said ion deceleration electrode to a fixed sputter target and serves as a travel path for said final ion beam;

(viii) A preformed sputter target formed of a desired material for coating and having an exposed face surface, said sputter target being held at a fixed location within the closed vacuum environment and being aligned with the deflected ion beam's travel pathway wherein

(a) an unobstructed travel pathway exists between said exposed face surface of said sputter target and a dedicated deposition zone located in front of the target face,

(b) said exposed face surface of said sputter target is fixed in position such that said resulting modified ion beam will strike said target face surface at an incidence angle ranging between about 50and 85 degrees,

(c) the striking of said resulting modified ion beam upon said exposed face surface of said sputter target causes a release of a plume of vaporized atoms and molecules,

(d) the atoms within the released plume of vaporized material travel in random directions away from to the surface of the sputter target, and

(e) the flux in any travel direction for the released vaporized plume of mobile sputtered atoms is approximately proportional to the cosine the angle between its direction and the normal of the target's face surface; and

(ix) A dedicated deposition zone of predetermined dimensions and volume within the vacuum chamber environment into which a

desired substrate or workpiece can be precisely placed for controlled material coating by ion beam sputter deposition, said dedicated deposition zone being closely placed in distance and directly in front of the face of said sputter target, to facilitate condensation and deposition of the sputtered atoms and molecules as a solid film layer upon at least one surface of the substrate or workpiece.

11. The operative system recited by claim 10 wherein said ion source does not produce a large external magnetic field; and does not have any component of magnetic field extending in its major beam breadth dimension.

12. The operative system recited by claim 10 wherein said arc chamber of said ion source is biased at a known positive voltage with respect to the electrical potential value of a preselected sputter material target, said positive potential defining the initial energy value for the ions in the ribbon-shaped beam traveling within said closed vacuum environment;

13. The operative system recited by claim 10 wherein said initially extracted ion beam is a low divergence ribbon-shaped beam which possesses a linear ion current density of about 0.1 to 1.5 ampere per meter of positive ions; a well-controlled ion energy of several (10-50) keV; good uniformity of linear ion current density over its breadth dimension; and an ion beam divergence limited to +/- 2 to 3 degrees.

14. The operative system recited by claim 10 wherein said extraction/acceleration electrode is aligned with and is positioned at a predetermined distance from said ion source exit aperture; and said

extraction/acceleration electrode is biased at a negative potential with respect to the pre-chosen coating material of said sputter target.

15. The operative system recited by claim 10 wherein said extraction/acceleration electrode is biased with respect to ground at a negative potential value.

16. The operative system recited by claim 10 wherein said initially accelerated ion beam has a kinetic energy of about 25 keV.

17. The operative system recited by claim 10 wherein said electrostatic deflector is closely-coupled in distance, timing, and action to said ion source and said extraction/acceleration electrode.

18. The operative system recited by claim 10 wherein said electrostatic deflector further comprises an inner electrode and an outer electrode which lie substantially in parallel and wherein each electrode has a reciprocal cylindrical geometry and is separated from the other by a preset gap distance.

19. The operative system recited by claim 18 wherein said inner electrode of said electrostatic deflector is biased at a negative potential value with respect to the potential of said outer electrode .

20. The operative system recited by claim 10 wherein said electrostatic deflector bends the accelerated ribbon beam ions through a controlled deflection angle ranging between about 60 and 160 degrees from the beam's initial trajectory.

21. The operative system recited by claim 10 wherein said deceleration electrode has an electrical potential similar to the potential value of the pre-chosen material of said sputter target and the vacuum chamber.

22. The operative system recited by claim 10 wherein the normal to the exposed face surface of said sputter target is parallel to the initial direction of the extracted ion beam.

23. The assembly recited by claim 10 further comprising a second ribbon-shaped ion source which is independently mounted at an adjacent port within the closed vacuum chamber; and will produce a second beam of preselected ion species, ion energy, and linear current density; and is directed to strike the surface of the substrate then positioned within said deposition zone.

24. An improved method for sputtering a solid target made of a chosen material for coating, said method comprising the steps of:

operating an arranged assembly which includes

(i)) a metal chamber at a local ground potential, able to provide a closed vacuum environment, provided with vacuum pumps capable of reducing the pressure to below 10^{-4} Pa,

(ii) an ion source producing a ribbon beam of ions of a chosen species, commonly argon or a mixture containing argon, which can exit a slot-shaped aperture with a breadth of from about 150 to 3000mm or more, and a width of 1 to 5 mm, the broad ribbon beam having a current of about 0.1 to 1.5 mA per mm of beam breadth and an energy distribution of +/- 2 eV or less, the ion source being maintained at a first positive voltage,

(iii) an extraction/acceleration electrode aligned with and positioned at a predetermined distance from said arc chamber exit aperture, said extraction/acceleration electrode being biased at a second negative voltage with respect to the housing such that ions extracted from the plasma in said arc chamber are drawn through said

open exit aperture as a broad ribbon-shaped ion beam having an ion energy determined by the difference of the first and second voltages,

(iv) an electrostatic deflector comprising two substantially parallel inner and outer electrodes extending in the beam breadth direction on either side of the ribbon beam wherein each discrete electrode in the pairing has an approximately reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectory of a ribbon-shaped ion beam then passing through said gap distance between said parallel electrodes at a deflection angle ranging from about 60 to 160 degrees,

(v) a deceleration electrode of preset dimensions which is connected to local ground potential, said deceleration electrode presenting a slot-shaped opening of sufficient size to allow a deflected ribbon-shaped ion beam to pass there-through, whereby the ions are decelerated to a final energy determined by said first (positive) voltage,

(vi) a sputter target with an exposed face surface, mounted close to the deceleration electrode and shielded from the potentials of the ion source and extraction electrode, the exposed target surface facing into a central region of the vacuum housing; and

producing a ribbon-shaped space-charge-neutralized ion beam at a chosen energy in the range from 2 to 10 keV from the exit of said deceleration electrode as a final ion beam; and

directing said final ion beam to strike said sputter target at an angle of incidence between 50 and 85 degrees, thereby sputtering a plume of energetic vapor from the target surface, the plume being generally directed toward the central region of the vacuum housing.

25. An improved method for performing ion beam sputter deposition whereby a solid film coating is deposited by physical vapor deposition upon at least one exposed surface of a tangible substrate or workpiece, said method comprising:

operating an arranged assembly which includes

(i) a metal chamber at a local ground potential, able to provide a closed vacuum environment, provided with vacuum pumps capable of reducing the pressure to below 10^{-4} Pa;

(ii) a preformed sputter target formed of a desired material and having an exposed face surface, said sputter target being held at a fixed location in the vacuum environment at the same potential as the vacuum housing, and

(iii) an arc chamber of predetermined dimensions and limited internal volume in which a plasma is generated by electron bombardment of a gaseous substance in-situ from which an ion beam having a breadth size from about 150 mm to about 3,000 mm can be subsequently extracted, said arc chamber comprising an anode, a cathode, and an open exit aperture whose breadth dimension greatly exceeds its width dimension, and being biased at a positive voltage with respect to said sputter target,

(iv) an extraction/acceleration electrode aligned with and positioned at a predetermined distance from said arc chamber exit aperture, said extraction/acceleration electrode being biased at a negative potential with respect to a fixed sputter target such that ions extracted from the plasma in said arc chamber are drawn through said open exit aperture as a broad ribbon-shaped ion beam and accelerated by said electrode to an energy determined by the difference in potential of the ion source and the electrode,

(v) an electrostatic deflector comprising two substantially parallel inner and outer electrodes wherein each discrete electrode in

the pairing has a reciprocal cylindrical geometry and is separated from the other by a preset gap distance, said electrostatic deflector acting to deflect the travel trajectories of a ribbon-shaped ion beam then passing through said gap between said parallel electrodes through an angle ranging from about 60 to 160 degrees,

(vi) a deceleration electrode of preset dimensions which has an electrical potential value similar to the potential of the fixed sputter target, said deceleration electrode presenting a slot-shaped opening of sufficient spatial size to allow a deflected ribbon-shaped ion beam to pass there-through, whereby the ions are decelerated to a final energy determined by the potential of the ion source,

(vii) a substantially field-free region which linearly extends from said ion deceleration electrode to said sputter target,

(viii) a dedicated deposition zone into which a tangible substrate or workpiece can be placed for controlled solid film coating, said dedicated deposition zone being closely placed in distance and aligned in front of the face of said sputter target;

producing a final ion beam from said operation of said arranged assembly within the limited confines of said closed vacuum environment, wherein said final ion beam is a ribbon-shaped beam which

(α) presents a beam breadth dimension ranging from about 150 mm to about 3,000 mm,

(β) carries a determinable electric ion current value ranging from about 0.1 to about 1.5 milliamperes per mm of breadth;

(γ) has a determinable final ion energy value ranging from about 2 to about 10 keV,

(δ) becomes space-charge neutralized on entering the field-free region,

(ε) is substantially focused to a single direction of travel within about +/- 6°,

directing said final ion beam to strike the exposed face surface of a fixed sputter target within the confines of said closed vacuum environment at an angle of incidence in the range from not less than about 50 degrees to not more than about 85 degrees'

causing the release of a plume of sputtered atoms from said exposed face surface of said sputter target as the consequence of said final beam strike wherein said plume of mobile sputtered atoms will travel into said deposition zone, which is maintained in high vacuum and free of obstruction; and

placing a tangible substrate or workpiece into said dedicated deposition zone for exposure to said vaporized plume of mobile sputtered atoms and coating of at least one exposed surface by vapor condensation and material deposition of said sputtered material.

26. The method recited by claim 25 further comprising the additional step of:

adjusting the current density profile of the ion source so that the final ribbon beam has substantially higher current density at the two extremes of its breadth than in the center, whereby the variation of thickness of the deposited thin film on the substrate becomes reduced.

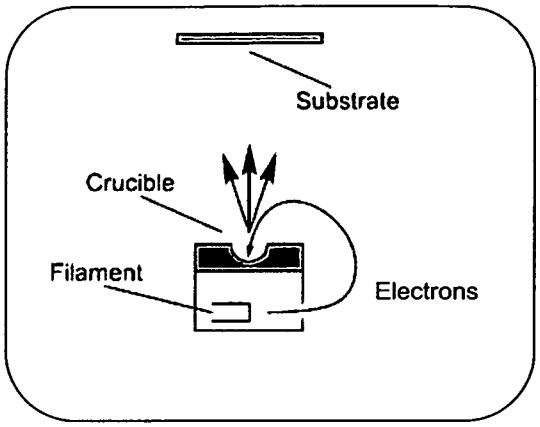


Fig. 1a – Prior Art
Electron beam evaporation

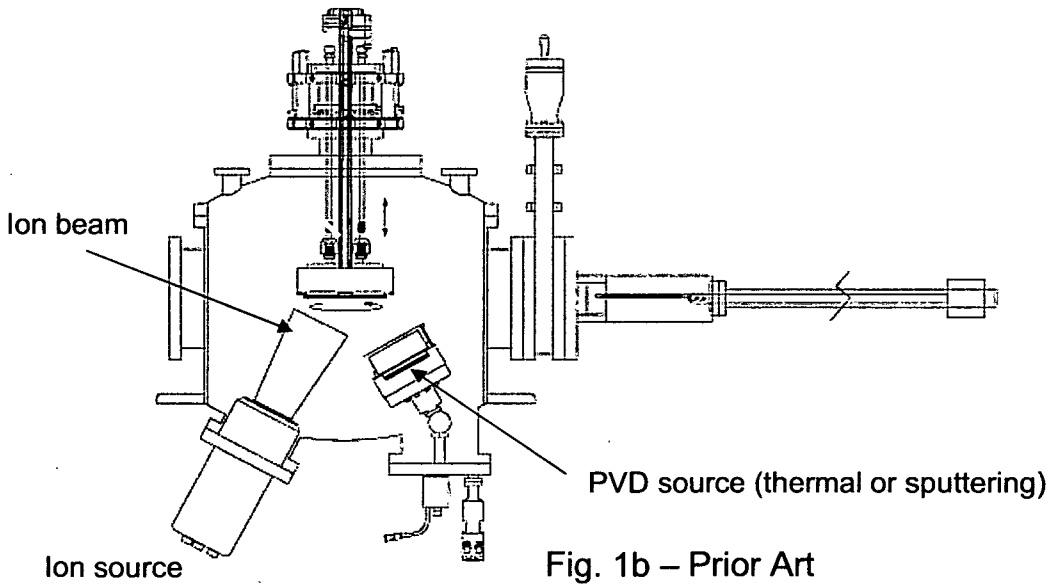


Fig. 1b – Prior Art
Ion Beam Assisted Deposition

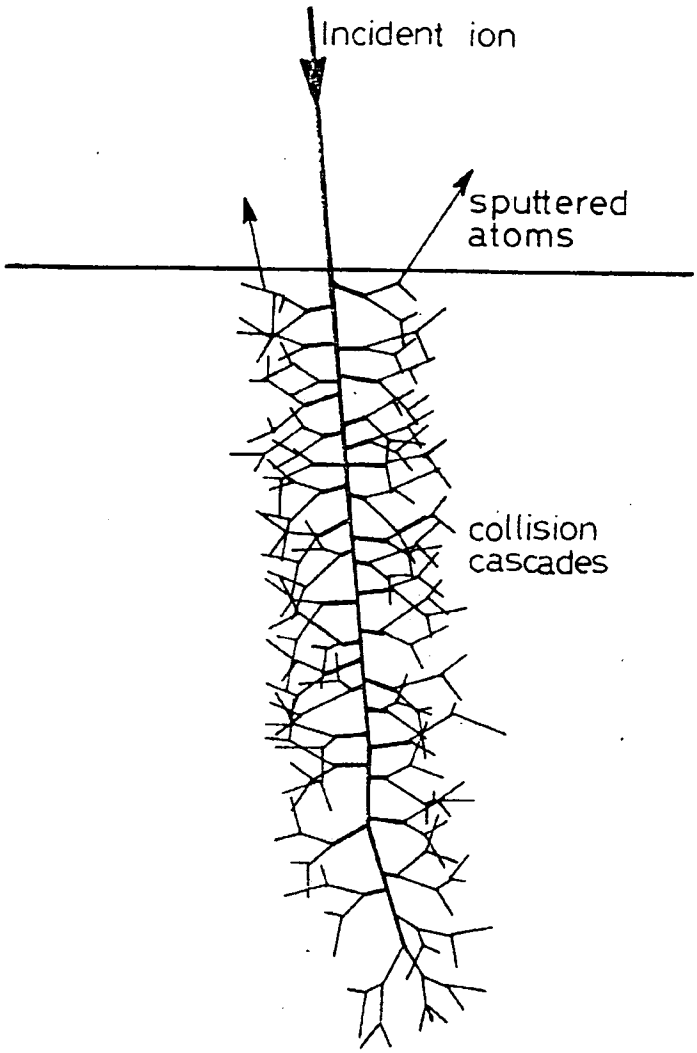


Fig 2.

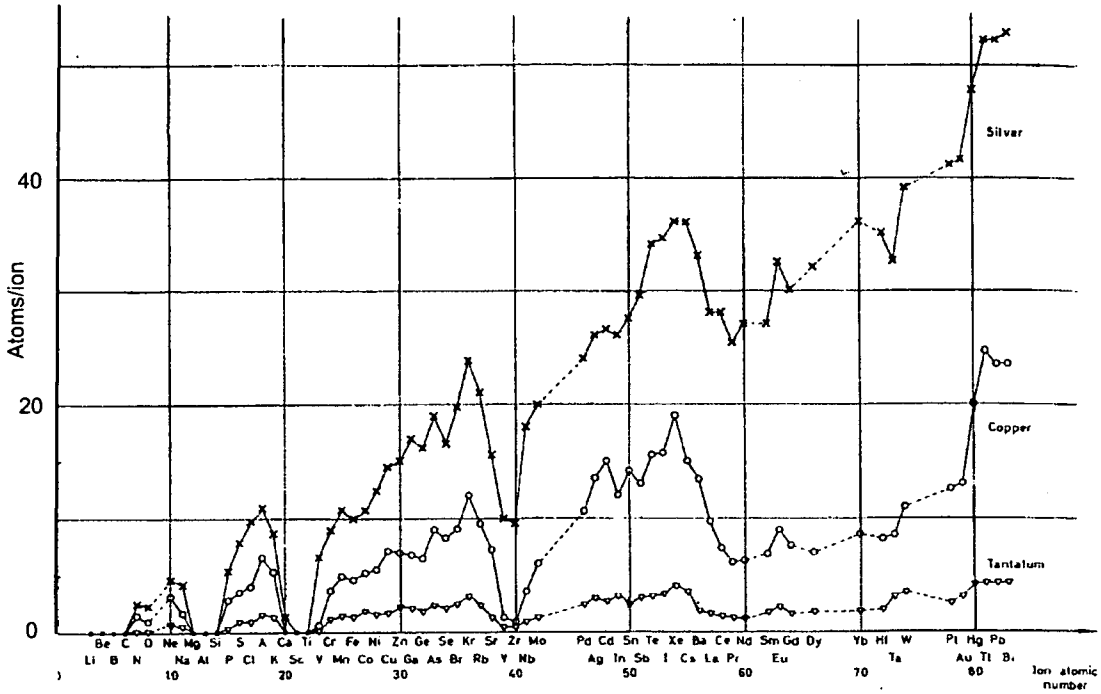


Fig. 3. Sputter yield by projectile, at 45 keV energy

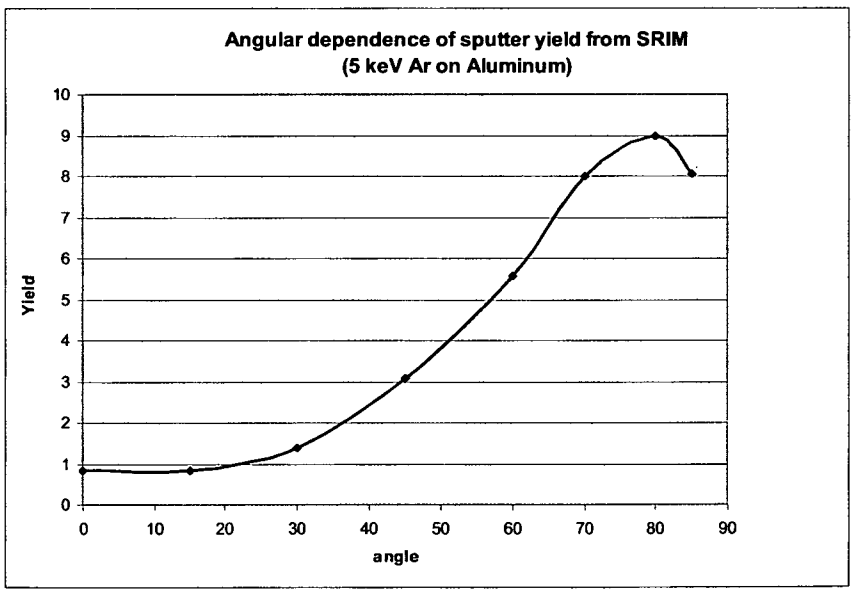


Fig. 4

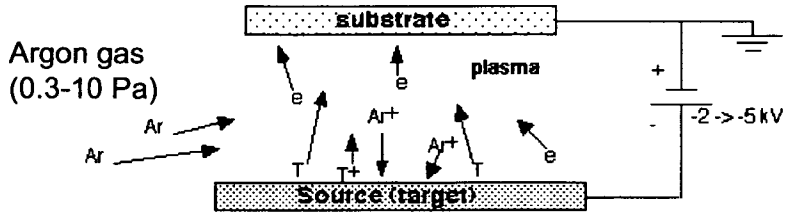


Fig 5a. Prior Art. Simple Sputtering Diode

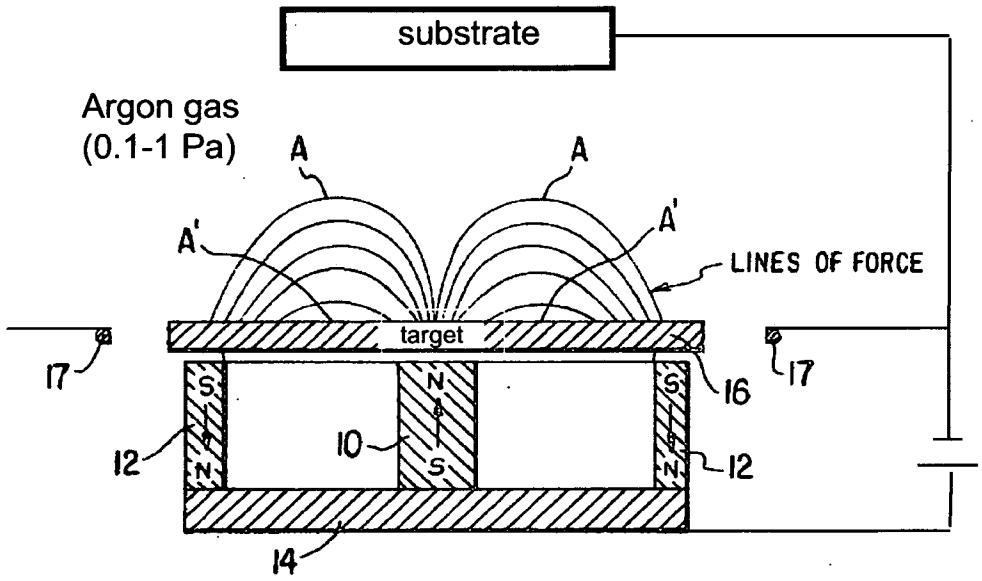


Fig 5b. Prior Art. Magnetron Sputtering Diode

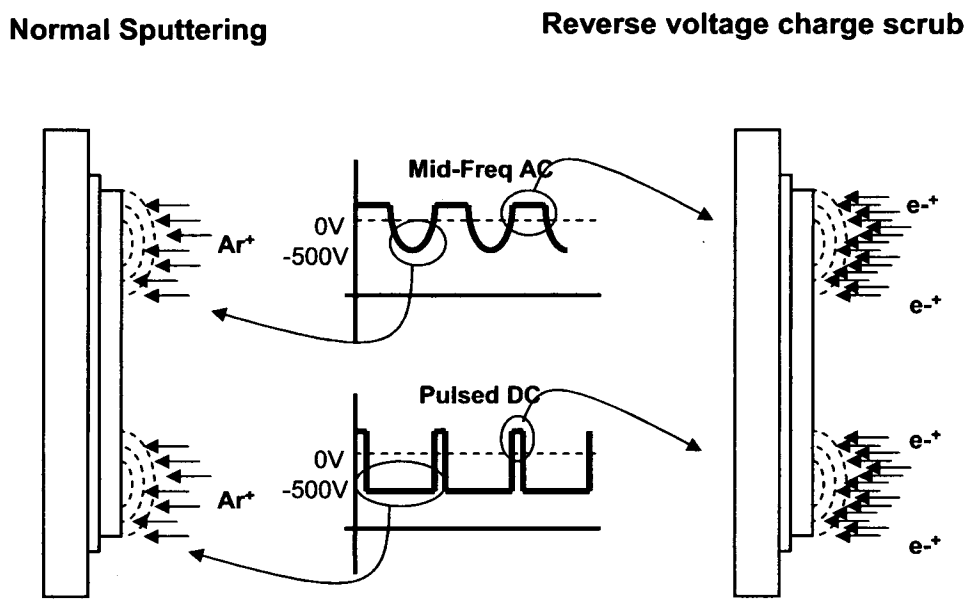


Fig 6. Prior art. AC and pulsed DC magnetron

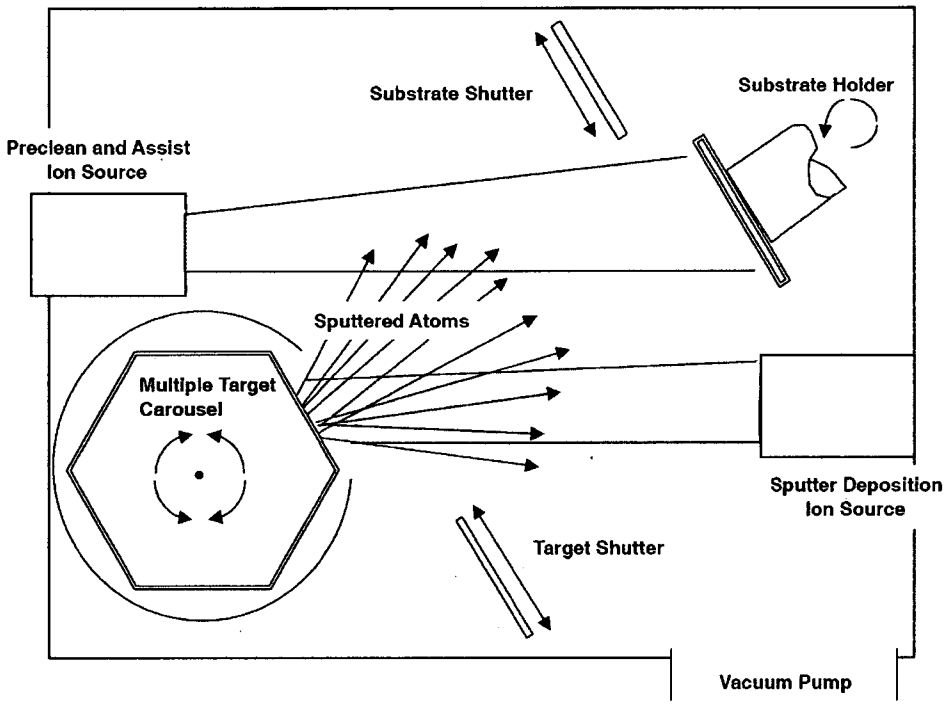


Fig. 7 – Prior Art
Ion Beam Sputtering Deposition

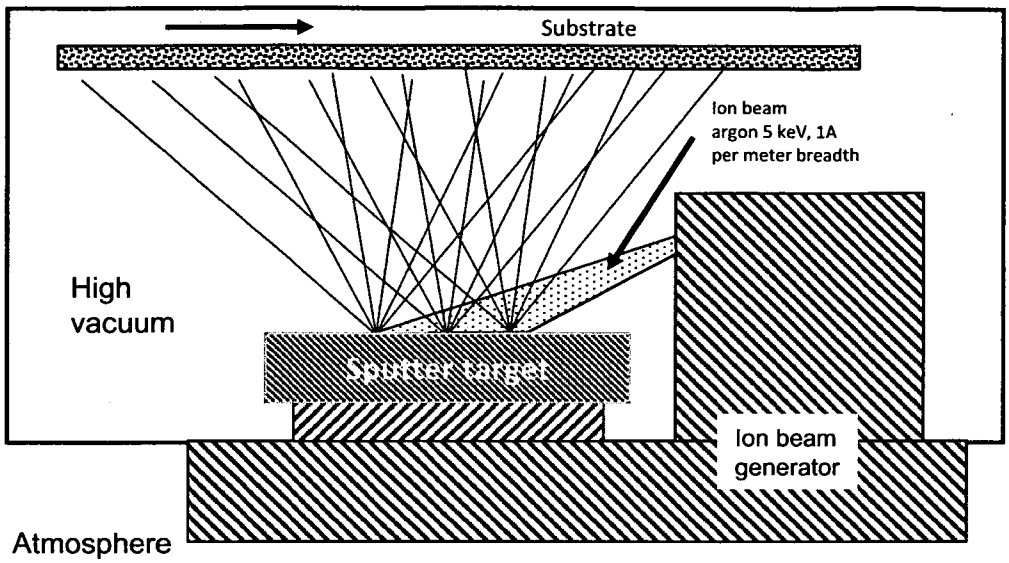


Fig. 8. Basic concept of oblique incidence line ion beam sputter source

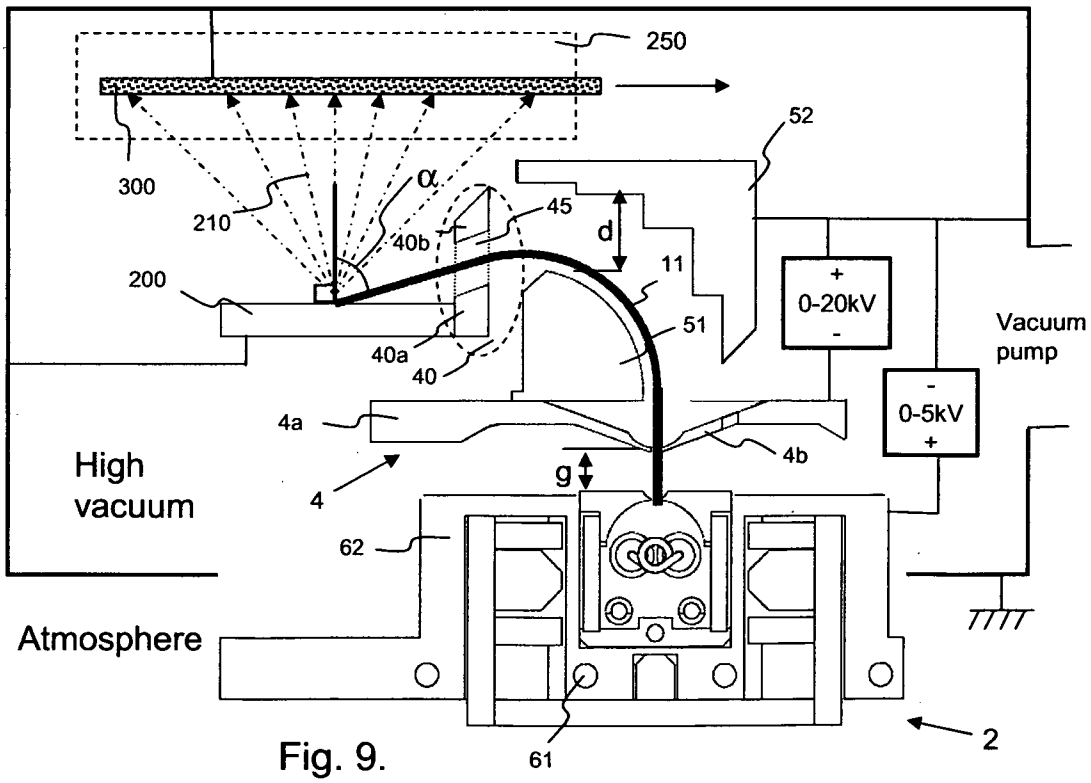


Fig. 9.

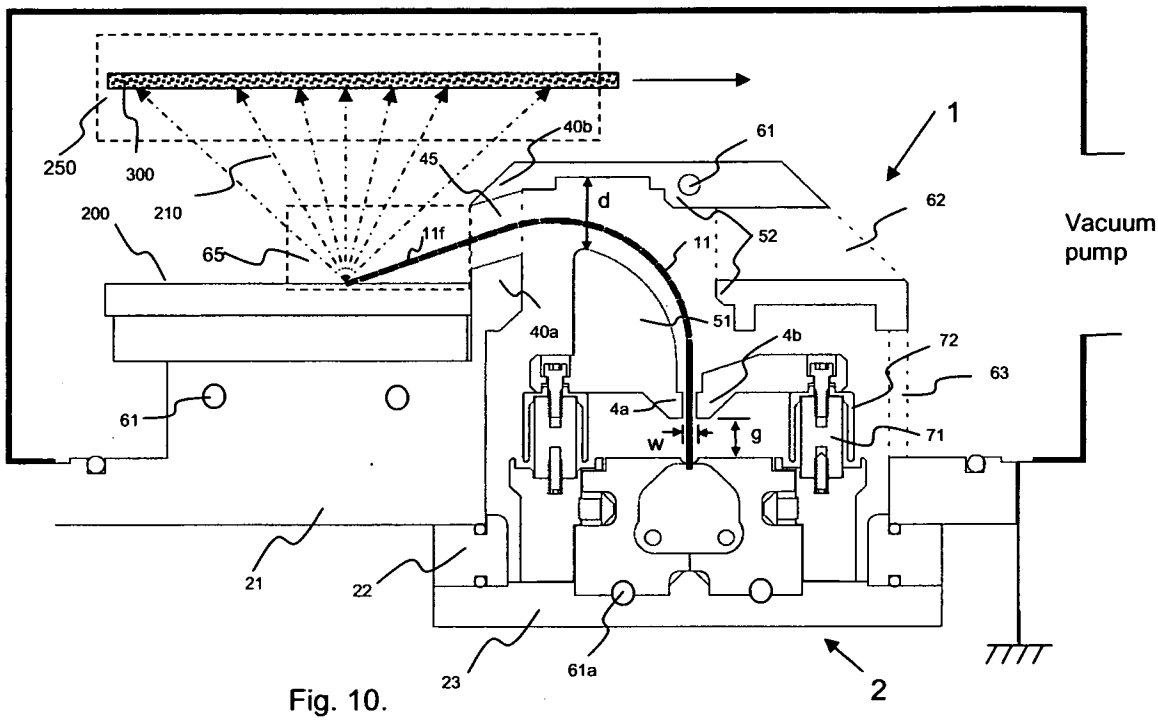

250
300
200
210
65
11f
40b
45
61
d
62
1
Vacuum pump
11
52
51
40a
4b
72
63
4a
w
g
71
61
21
22
23
61a
2

Fig. 10.

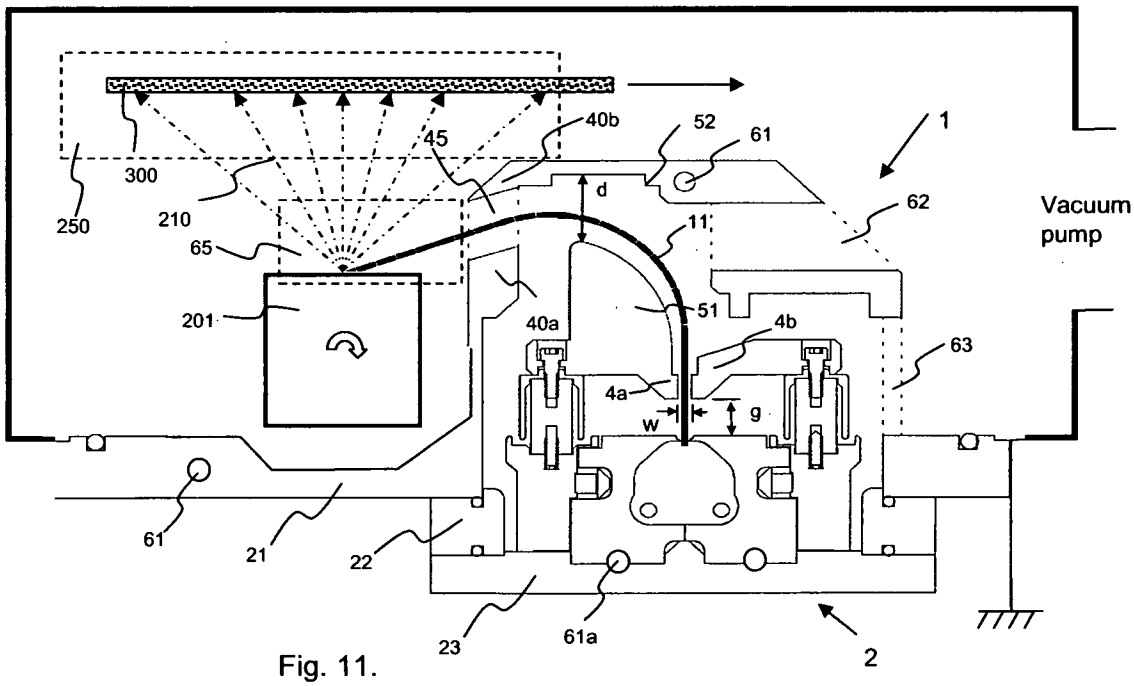

250
300
210
65
201
40b
45
52
61
d
62
1
Vacuum pump
11
51
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4a
w
g
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61a
2

Fig. 11.

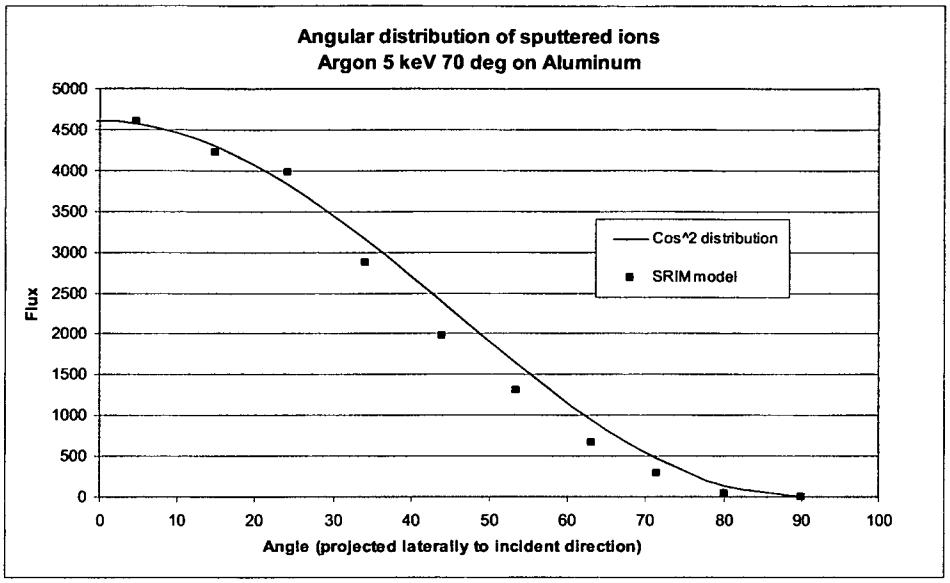
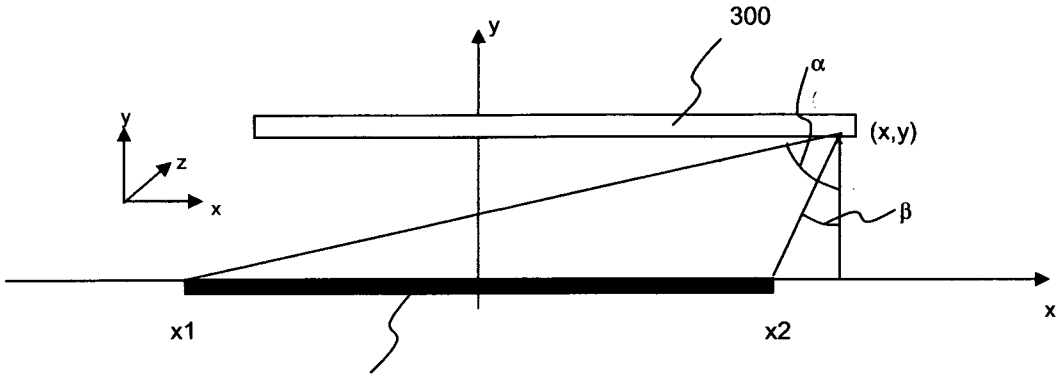

Angular distribution of sputtered ions
Argon 5 keV 70 deg on Aluminum
Flux
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
100
Angle (projected laterally to incident direction)
Cos^2 distribution
SRIM model

Fig. 12



Film thickness t at (x,y) for any point in plane of substrate which moves orthogonally through deposition zone in z direction

$$t \propto (\alpha - \beta)$$

Fig. 13a

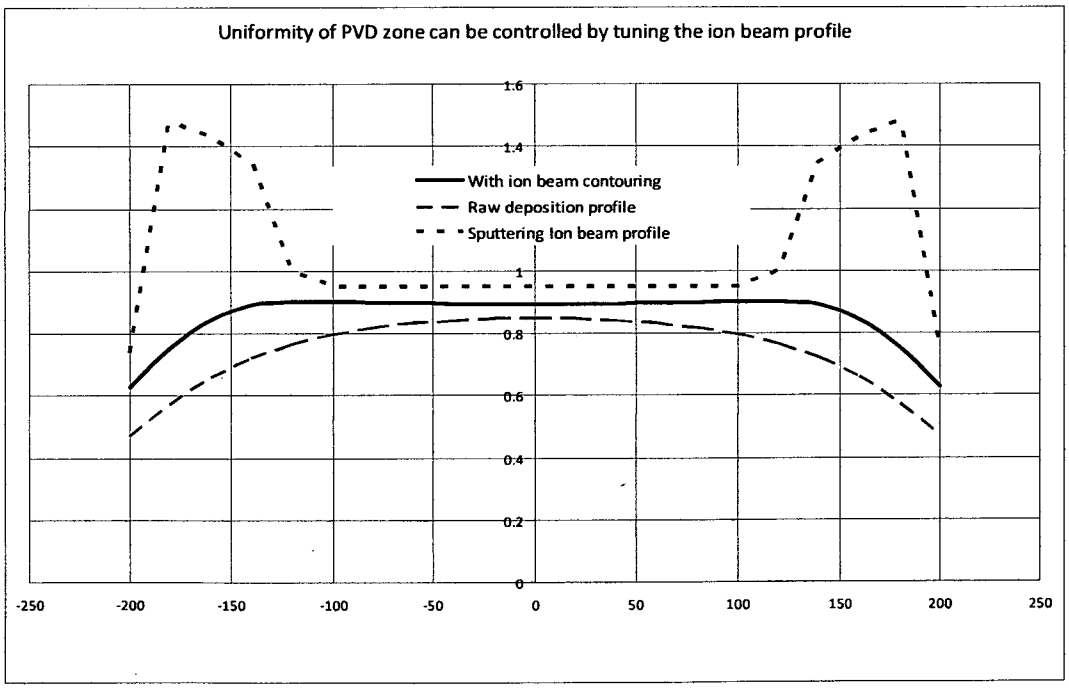


Fig. 13b

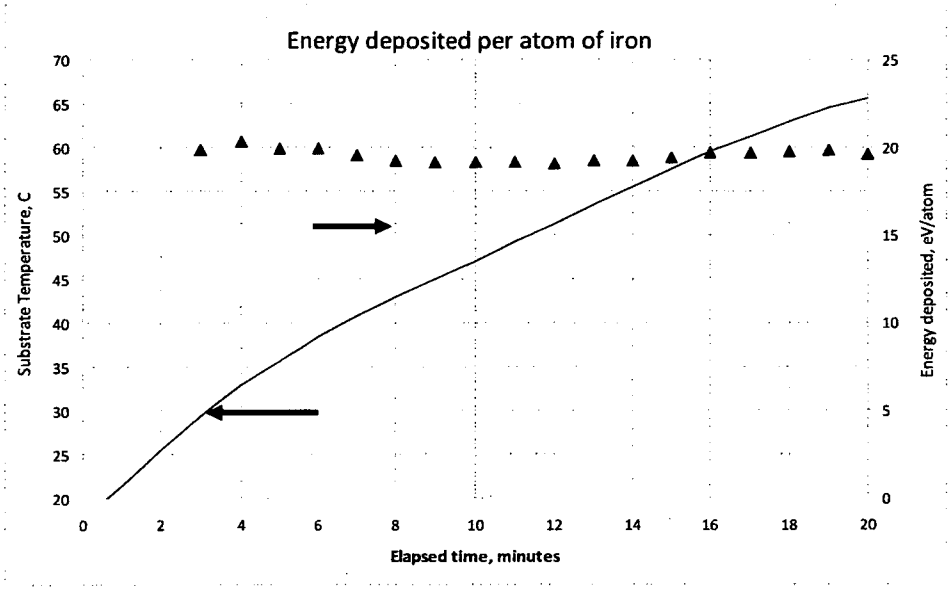


Fig. 14a

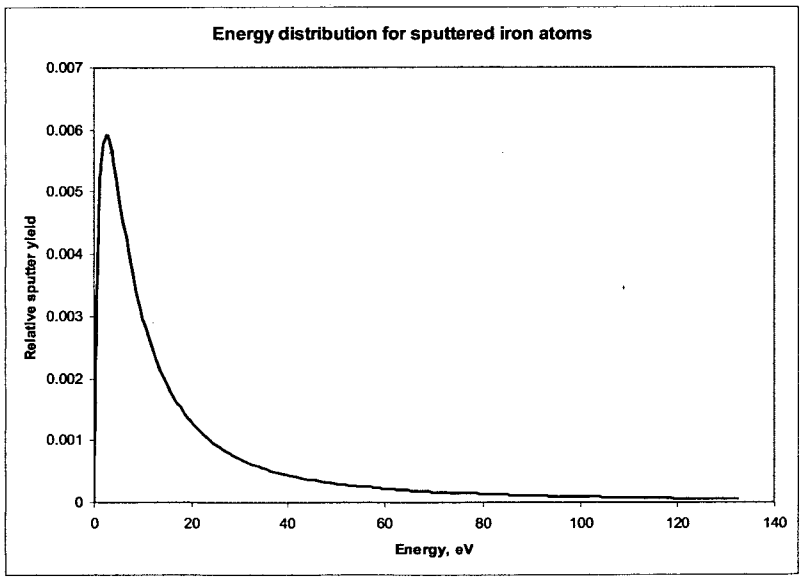


Fig. 14b

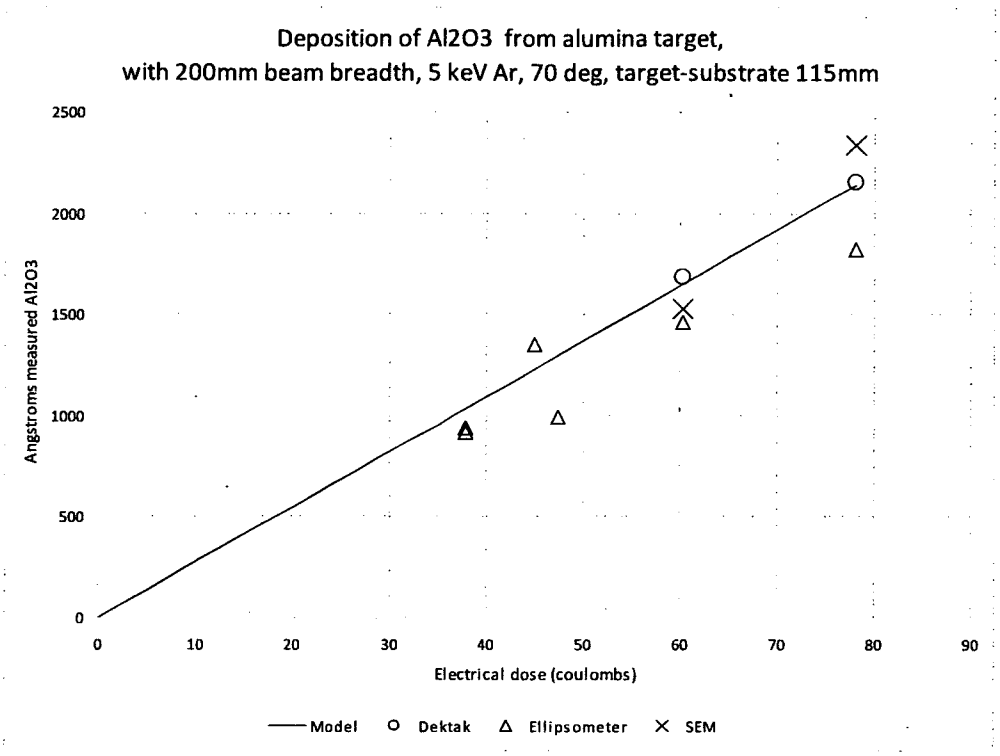

Deposition of Al2O3 from alumina target,
with 200mm beam breadth, 5 keV Ar, 70 deg, target-substrate 115mm
Angstroms measured Al2O3
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
Electrical dose (coulombs)
Model
Dektak
Ellipsometer
SEM

Fig. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/00023

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - C23C 14/00 (2015.01)
CPC - C23C 14/54, H01J 37/34, C23C 14/0042
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - C23C 14/00 (2015.01)
CPC - C23C 14/54, H01J 37/34, C23C 14/0042

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 204/192.1, 204/192.13, 204/298.07, 204/192.15, 204/192.11, 204/192.12
Patents and NPL (classification, keyword; search terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Pat Base (AU BE BR CA CH CN DE DK EP ES FI FR GB IN JP KR SE TH TW US WO), Google Patent, Google Scholar, Free Patents Online; Search Terms: sputtering, physical vapor deposition, ion, plasma, beam, electrostatic deflector, angular energy filter, accelerator, decelerator, electrode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2007/0114455 A1 (Naito et al.) 24 May 2007 (24.05.2007) Fig 1; para [0039], [0102], [0112], [0126]	1
A	US 4,885,070 A (Campbell et al.) 05 December 1989 (05.12.1989) Fig 1; col 1, ln 19-22; col 2, ln 38 to col 3, ln 14; col 4, ln 67 to col 5, ln 4; col 7, ln 52-55	1
A	US 6,583,427 A (Edmonds et al.) 24 June 2003 (24.06.2003) col 1, ln 23-49	1
A	US 7,304,319 B2 (Kawaguchi et al.) 04 December 2007 (04.12.2007) Fig 2A; col 4, ln 43 to col 5, ln 7	1
A	US 4,775,789 A (Albridge, Jr. et al.) 04 October 1988 (04.10.1988) Fig 6, col 1, ln 7-10, col 2, ln 8-57, col 4, ln 25 to col 5, ln 31	1
A	US 2009/0114815 A1 (Vanderberg et al.) 07 May 2009 (07.05.2009) Fig 1, abstract, para [0005] -[0014]	1
A	US 2006/0113493 A1 (Kabasawa et al.) 01 June 2006 (01.06.2006) Fig 5A, para [0139]-[0146]	1

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 May 2015 (27.05.2015)	24 JUN 2015
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/00023

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

---please see continuation in supplemental box ---

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/00023

Box III: citations and explanation:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, Claim 1, drawn to an assembly for producing a ribbon shaped ion beam which is suitable for sputter deposition within a closed vacuum environment whereby a chosen sputter material is deposited as a solid film coating by physical vapor deposition onto at least one exposed surface of a tangible substrate or workpiece.

Group II, Claim 2, drawn to an assembly for producing a broad gaseous plume of sputtered coating material atoms and/or molecules for physical vapor deposition as a solid film, said assembly being suitable for installation as an integrated unit through a port in a wall of a closed vacuum chamber.

Group III, Claims 3-9, drawn to an assembly for producing a broad plume of vaporized atoms and/or molecules to be used for physical vapor deposition of a solid film layer upon the surface of a substrate, said assembly being suitable for installation as a single unified entity to a port in a wall of a closed vacuum chamber.

Group IV, Claims 10-23, drawn to an operative system for ion beam sputter deposition of a pre-chosen coating material upon at least one exposed surface of a tangible substrate or workpiece.

Group V, Claim 24, drawn to an improved method for sputtering a solid target made of a chosen material for coating.

Group VI, Claims 25-26, drawn to an improved method for performing ion beam sputter deposition whereby a solid film coating is deposited by physical vapor deposition upon at least one exposed surface of a tangible substrate or workpiece.

The inventions listed as Groups I-VI do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

Groups II-VI do not require an assembly comprising a deceleration electrode having an electrical potential value similar to the measurable potential of a pre-chosen sputter material, as required by Group I.

Groups I and III-VI do not require an assembly comprising an arranged subassembly capable of delivering a modified beam ion having a substantially uniform linear current density profile which may optionally rise to significantly higher linear current density near the two extremes, as required by Group II.

Groups I, II and IV-VI do not require an assembly comprising an ion source including a heated cathode, as required by Group III.

Groups I-III, V and VI do not require an operative system comprising a preformed sputter target wherein the flux in any travel direction for the released vaporized plume of mobile sputtered atoms is approximately proportional to the cosine the angle between its direction and the normal of the target's face surface, as required by Group IV.

Groups I-IV and VI do not require an improved method comprising operating an arranged assembly which includes an ion source producing a ribbon beam of ions which can exit a slot-shaped aperture with a width of 1 to 5 mm, as required by Group V.

Groups I-V do not require an improved method comprising operating an arranged assembly which includes a preformed sputter target being held at a fixed location in the vacuum environment at the same potential as the vacuum housing, as required by Group VI.

Shared Common Features

The only feature shared by Groups I-VI that would otherwise unify the groups, is the technical feature of physical vapor deposition; a ribbon-shaped ion beam; and an extraction/acceleration electrode. However, this shared technical feature does not represent a contribution over prior art, because the shared technical feature is anticipated by US 4,885,070 A to Campbell et al. (hereinafter 'Campbell').

Campbell discloses a coating apparatus for sputter coating or vapor deposition of a target material 7 to a substrate 15, comprising a plasma generating chamber 37 including an electron emitter 9 for accelerating ions in a ribbon-shaped plasma beam against the target material 7 in a vacuum chamber 1 having an opening in a wall 28 which is connected to the plasma beam generator 37, thereby sputtering or vaporizing the target material to form sputtered or vaporized particles for sputter coating or vapor deposition of the target material 7 to the substrate 15 disposed in the vacuum chamber 1 (col 1, ln 19-22; col 2, ln 38 to col 3, ln 14; col 3, ln 57 to col 5, ln 4; col 9, ln 33-36; Fig 1).

--PLEASE SEE SUPLEMENTAL BOX --

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/00023

CONTINUATION LACCK OF UNITY:

The only feature shared by Groups I, IV, and VI that would otherwise unify the groups, is the technical feature of ion beam sputter deposition. However, this shared technical feature does not represent a contribution over prior art, because the shared technical feature is anticipated by Campbell. Campbell discloses a coating apparatus for sputter coating or vapor deposition of a target material 7 to a substrate 15, comprising a plasma generating chamber 37 including an electron emitter 9 for accelerating ions in a ribbon-shaped plasma beam (col 1, ln 19-22; col 2, ln 38 to col 3, ln 14; col 9, ln 33-36; Fig 1).

The only feature shared by Groups I and II that would otherwise unify the groups, is the technical feature of sputtered coating material atoms and/or molecules for physical vapor deposition as a solid film, said assembly being suitable for installation as an integrated unit through a port in a wall of a closed vacuum chamber. However, this shared technical feature does not represent a contribution over prior art, because the shared technical feature is anticipated by Campbell, as set forth above.Campbell discloses a coating apparatus for sputter coating or vapor deposition of a target material 7 to a substrate 15, comprising a plasma generating chamber 37 including an electron emitter 9 for accelerating ions in a ribbon-shaped plasma beam against the target material 7 in a vacuum chamber 1, thereby sputtering or vaporizing the target material to form sputtered or vaporized particles for sputter coating or vapor deposition of the target material 7 to the substrate (col 1, ln 19-22; col 2, ln 38 to col 3, ln 14; col 3, ln 57 to col 5, ln 4; Fig 1).

The only feature shared by Groups IV and VI that would otherwise unify the groups, is the technical feature of an extraction/acceleration electrode; vacuum pumps capable of reducing the pressure to below 10-4Pa; an ion beam having a breath dimension ranging from about 150 mm to about 3,000 mm; an ion beam carrying an ion current ranging from about 0.1 to about 1.5 milliamperes per mm of breadth; an ion beam having a determinable final ion energy value ranging from about 2 to about 10 keV. However, this shared technical feature does not represent a contribution over prior art, because the shared technical feature is obvious over Campbell in view of US 2007/0114455 A1 to Naito et al. (hereinafter 'Naito').

Although Campbell discloses an extraction/acceleration electrode (col 4, ln 67 to col 5, ln 4; col 9, ln 33-36; an electron emitter 9 for accelerating ions in a ribbon-shaped plasma beam), and a pressure of 10-4 mbar (i.e., 0.0001 mbar = 0.01 Pa or 10-2 Pa) (col 8, ln 13-23), Campbell does not specifically disclose vacuum pumps capable of reducing the pressure to below 10-4 Pa; an ion beam having a breath dimension ranging from about 150 mm to about 3,000 mm; an ion beam having a determinable final ion energy value ranging from about 2 to about 10 keV; an ion beam carrying an ion current ranging from about 0.1 to about 1.5 milliamperes per mm of breadth. However, it would have been obvious to a person of ordinary skill in the art arrive at a vacuum pressure of below 10-4 Pa through routine experimentation of the pressure disclosed in Campbell in order to optimize plasma density and deposition efficacy and efficiency onto the surface of the target (col 8, ln 13-23).

However, Naito discloses an assembly for producing a ribbon shaped ion beam which is suitable for deposition onto at least one exposed surface of a tangible substrate or workpiece (Fig 1; para [0002], [0003], [0015], [0016], [0102], [0105], [0160]; ion beam apparatus comprising an ion source 2 which extracts an ion beam 4 having a cross-sectional profile in the shape of a rectangle for injection and implantation of an ion beam 4a of desired energy into the surface of the target 50), said system assembly comprising: an ion source presenting an ion beam having a breadth size from about 150 mm to about 3,000 mm can be subsequently extracted, and an open exit aperture whose breadth dimension greatly exceeds its width dimension (Fig 1; para [0102], [0105], [0139]-[0141]; ion source 2 which extracts an ion beam 4 having a width of 300 mm); and a final ion beam at the exit of an electrostatic deflector 30 (Fig 1; para [0003], [0126]; ion beam 4a of desired energy), wherein said final ion beam: presents a beam breadth dimension ranging from about 150 mm to about 3,000 mm (para [0139]-[0141]; ion beam 4 having a width of 300 mm), and
has a determinable final ion energy value ranging from about 2 to about 10 keV (para [0192]; ion beam 4a having an energy of from 1keV to 300 keV). It would have been obvious to a person of ordinary skill in the art to utilize an ion beam having a breath dimension ranging from about 150 mm to about 3,000 mm, and a determinable final ion energy value ranging from about 2 to about 10 keV, as disclosed in Naito in order to optimize deposition efficacy and efficiency onto the surface of the target, because Campbell and Naito are directed toward ion beam generating apparatuses for implanting a desired material onto the surface of a substrate.

Although Naito discloses an ion beam at the exit of the electrostatic deflector 30 having an ion beam current density of 25 mA/m (i.e., 0.025 A/m) (para [0252]), Naito does not specifically disclose an ion beam carrying an ion current ranging from about 0.1 to about 1.5 amperes per meter of breadth. However, it would have been obvious to a person of ordinary skill in the art arrive at an ion beam carrying an ion current ranging from about 0.1 to about 1.5 A/m of breadth through routine experimentation in order to optimize deposition efficacy and efficiency onto the surface of the target.

As the technical feature was known in the art at the time of the invention, this cannot be considered a special technical feature that would otherwise unify the groups.

Groups I-VI therefore lack unity under PCT Rule 13 because they do not share a same or corresponding special technical feature.