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R. L. HALLEN ET AL
CATHODIC SPUTTERING APPARATUS INCLUDING THERMIONIC MEANS
FOR INCREASING SPUTTERING EFFICIENCY
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FIG. 1

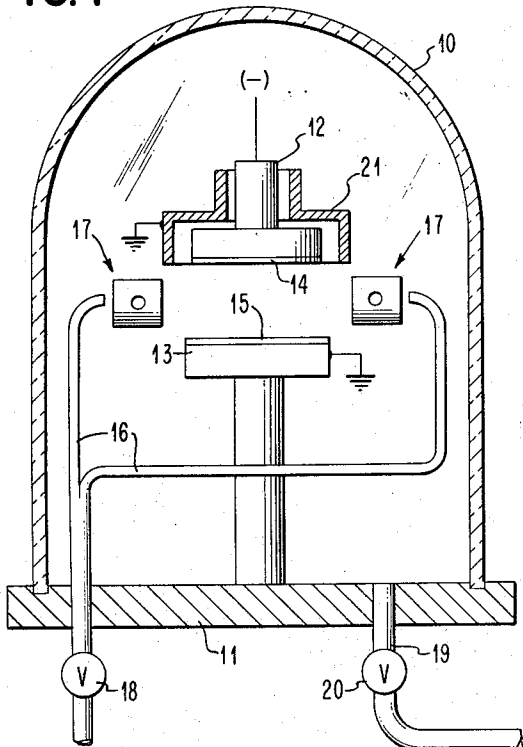


FIG. 3a

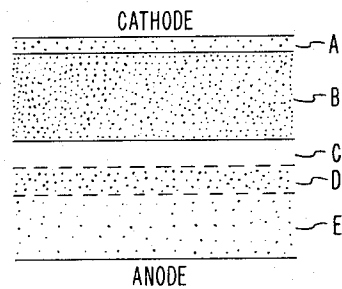


FIG. 3b

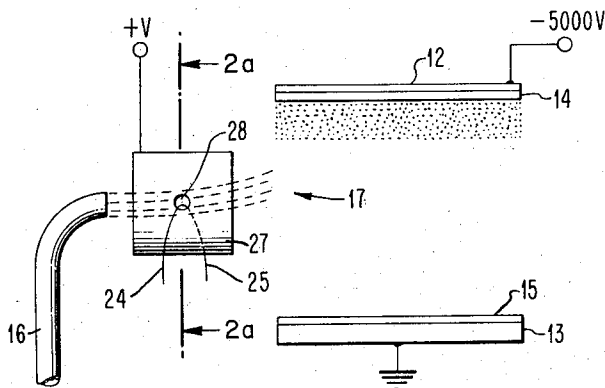
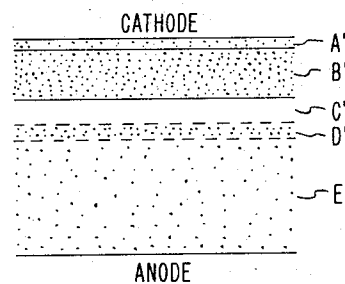
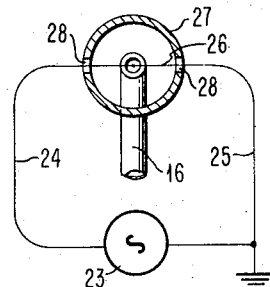


FIG. 2

FIG. 2a



INVENTORS
ROBERT L. HALLEN
ROBERT M. VALLETTA

BY

Marion D. Yancy

ATTORNEY

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CATHODIC SPUTTERING APPARATUS INCLUDING THERMIONIC MEANS FOR INCREASING SPUTTERING EFFICIENCY

Robert L. Hallen, Colonie, and Robert M. Valletta, East Fishkill, N.Y., assignors to International Business Machines Corporation, Armonk, N.Y., a corporation of New York

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This invention pertains to apparatus wherein ionic bombardment or sputtering of a cathode is employed for the deposition of thin films and the like and more particularly to such apparatus wherein the ionic bombardment is markedly increased to achieve a higher deposition rate.

Although the phenomenon of cathodic sputtering has been known in the art of deposition of thin films for many years, the employment of such techniques has not been as popular as thin film deposition by vacuum evaporation. However, in recent years, there has been an increased interest in the deposition of thin films other than conductive metal films particularly in the field of micro-electronic and monolithic circuit art. Cathodic sputtering is particularly advantageous over other techniques in the deposition of films of refractory materials including oxides, carbides and the like.

The mechanism of cathodic sputtering is one in which a glow discharge is established between an anode and a cathode, the current therebetween being conducted by the flow of electrons to the anode and positive ions to the cathode. The glow discharge is maintained by ionization of gases existing within the glow discharge region which ionization is achieved by collisions of the gas particles with the electron flow from the cathode to the anode. As the positive ions are accelerated toward the cathode, they achieve sufficient energy to dislodge atoms or molecules from the cathode material upon impact with the cathode. In this manner, atoms or molecules of the cathode material are "sputtered" and deposited upon an appropriate substrate which in most situations is the anode. It is to be noted that the sputtered atoms are not ionized and that the mechanism by which such atoms are sputtered appears to be primarily one of a momentum and energy transfer. Because of this, the sputtering rate can be controlled by controlling the current density as well as the pressure of the gas in the glow discharge region.

Generally speaking, the deposition rate will increase with an increase of current density, that is to say with an increase in the rate of ionic bombardment of the cathode, and will decrease with an increase in pressure as the number of collisions encountered by the sputtered particles will be proportional to the number of particles in the plasma in the glow discharge region. In a closed system, for a given voltage drop, an increase in current can only be achieved by an increase in pressure and, at higher pressures, the percentage of sputtered atoms reaching the anode is greatly reduced. Various schemes have been proposed to increase the current density in a closed system by the employment of a magnetic field to deflect the ions and electrons to achieve a greater percentage of particle collisions and thus increased ionization. However, the number of ions created in this manner is limited and certainly cannot exceed the number of gas particles in the region for any closed system. Some sputtering apparatus supply a continuous stream of an ionizable gas into the glow discharge region with the pressure being maintained at a given level by exhausting gas from the region at a given rate. However, in such an apparatus the relationship between the current and the pressure of the region as well as the sputtering rate is the same as for a closed

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system and any increase in current is only achieved by an increase in pressure which ultimately reduces the deposition rate.

It is an object of the present invention to provide an improved sputtering apparatus wherein the deposition rate can be controllably increased.

It is another object of the present invention to provide an improved sputtering apparatus wherein the deposition rate can be controllably varied without varying the pressure within the sputtering apparatus.

It is still another object of the present invention to provide an improved sputtering apparatus for the deposition of films of oxides, carbides and other refractory materials.

In the present invention, increased deposition rates are achieved by supplying ionized gas or plasma to the glow discharge without relying upon the glow discharge phenomenon for the creation of such ions. In this manner, the pressure required for operation of the apparatus is only a minimum pressure required to sustain the glow discharge mechanism necessary to provide the appropriate electric field and current conductance. Once such a mechanism is provided, then the deposition rate can be increased by increasing the ion density in the glow discharge region and thus increasing the ionic bombardment of the cathode without increasing the pressure in the glow discharge region.

A feature, then, of the present invention resides in a cathode sputtering apparatus which is provided with one or more sources of an ionized gas or plasma and means to exhaust the apparatus to maintain a constant pressure in such apparatus. More specifically, a feature of the present invention resides in means for supplying a continuous flow of an ionizable gas to one or more positions adjacent the glow discharge region and in means to ionize the gas prior to its injection into the glow discharge region and to control the rate of such ionization.

Other objects, advantages and features of the present invention will become more readily apparent from a review of the following description when taken in conjunction with the drawings wherein:

FIGURE 1 is a cross-sectional view of a cathode sputtering apparatus employing features of the present invention;

FIGURE 2 is a detailed illustration of a source of ionizable gas and a gas ionizer such as is employed in the present invention;

FIGURE 2a is a cross-sectional view of the gas ionizer as shown in FIGURE 2;

FIGURE 3a is an illustration of the glow discharge region of a cathode sputtering apparatus not employing the present invention; and

FIGURE 3b is an illustration of the glow discharge region of a sputtering apparatus employing the present invention.

When a sustained discharge is established in a gas at reduced pressures of from approximately 20 microns to a few millimeters of mercury and under a voltage greater than the breakdown voltage of the gas, the mechanism by which the discharge is sustained is referred to as the abnormal glow discharge phenomenon where the current through the gas is a function of the applied voltage. Under such conditions, two particular zones of the glow discharge are most important in the maintenance of the discharge. One such zone is referred to as the Crookes dark space or the cathode dark space and consists primarily of positive ions, the more mobile electrons having been more quickly accelerated toward the anode. Because of this positive region, the established field or voltage drop is primarily across this zone and extending to the cathode. The second zone of importance is adjacent the Crookes dark space on the anode side and is one in

which the major portion of the ionization takes place due to collision between gas molecules and the secondary electrons emitted from the cathode and accelerated through the above referred to field. This second region is referred to as the negative glow zone and is more thoroughly described in any standard text on glow discharges and gaseous conductors as is the entire glow discharge phenomenon. The secondary electron emission and the negative glow zone are essential to the sustaining of the glow discharge phenomenon.

Upon impact at the cathode surface by the positive ions accelerated through the electric field established across the Crookes dark space, atoms of the cathode surface material are ejected as are the secondary electrons required to maintain the sustained glow discharge phenomenon. The traverse of the glow discharge region by the ejected atoms is the result of the kinetic energy and momentum transferred to the ejected atoms at the time of the ejection and it is to be noted that the majority of the ejected or sputtered atoms are not ionized nor can it be said that their motion is in any way due to the electric field. Because of the momentum transfer mechanism by which the sputtered atoms are ejected, these atoms have energies which are many times greater than would be the case for thermally evaporated atoms which advantage is one of the important factors to be considered in choosing cathode sputtering over other vacuum deposition processes. Another consequence of the momentum transfer mechanism is that the sputtering rate is dependent on the mass of the bombarding ions as well as their energy.

To illustrate the type of apparatus embodying the present invention, reference is now made to FIGURE 1 wherein the sputtering apparatus is contained within a conventional bell jar vacuum system 10 such as might be employed for laboratory experiments or in the manufacture of discrete layers of sputtered films. However, it will be appreciated that such a system may be redesigned to accommodate the passage of a continuous substrate into and out of the vacuum system according to well known methods so as to achieve a continuous sputtering deposition process. It will be further appreciated that FIGURE 1 is intended to be illustrative and that the dimensions and spacings between the respective components do not necessarily correspond to the actual dimensions that would be employed.

To maintain a preselected pressure within bell jar 10, an ionizable gas is supplied by conduit 16 to regions adjacent the glow discharge maintained between sputtering cathode 12 and sputtering anode 13, conduit 16 extending through base plate 11 which completes the vacuum seal of bell jar 10. The pressure is controlled by regulation of valve 18 in the gas supply conduit 16 and by valve 20 in exhaust conduit 19 that also extends through base plate 11 into the interior of bell jar 10 and is connected to an appropriate vacuum pump. As the ionizable gas is injected into the glow discharge region, it is passed through plasma or ion generators 17, the number of such generators and conduits 16 preferably being so chosen and arranged as to be symmetrically disposed about the glow discharge region. Cathode shield 21 is so arranged about sputtering cathode 12 so as to prevent bombardment of the cathode except on the surface of cathodic material 14 which is the material chosen to be sputtered onto substrate 15 of anode 12.

Ion or plasma generator 17 is illustrated in more detail in FIGURES 2 and 2a, FIGURE 2a representing a cross-section of the plan view illustrated in FIGURE 2. Each of generators 17 include a metal cylinder 27 which serves as an electron collector or anode and contains two ports 28 through which is inserted a thermionic wire 26 to act as a cathode. This cathode is coupled across an alternating voltage source 23 by conductors 24 and 25 with one side of voltage source 23 being grounded. The frequency of voltage source 23 may be a standard 60 cycle fre-

quency and voltage magnitude may be of just sufficient voltage to heat thermionic wire 26, preferably 4 to 6 volts. Anode 27 is coupled to an appropriate positive voltage supply preferably approximately 50-100 volts.

When the thermionic cathode 26 becomes sufficiently heated, electrons are emitted therefrom and accelerated toward the cylindrical walls of anode 27. As the ionizable gas such as air or its constituents nitrogen and oxygen and the like is passed through the electron field, the resulting collisions between the gas molecules and the electrons result in ionization of the gas in the form of both positive ions and electrons which plasma is then introduced into the glow discharge region between sputtering cathode 12 and sputtering anode 13. Approximately the same number of electrons that are emitted from thermionic cathode 26 arrive at the cylindrical surface of anode 27 and the plasma emitted from generator 17 is essentially neutral, although ionized, as it enters the glow discharge region. By varying the voltage and current of anode 27 and the gas flow by variation of valve 18, one may control the ion flow into the glow discharge region.

The spacings between conduit 16 that ejects the ionizable gas through generator 17, generator 17 and the glow discharge region between sputtering cathode 12 and anode 13 are not particularly critical although the orifice of conduit 16 should be positioned as close as practical to plasma generator 17 which in turn should be positioned as close as practical to the glow discharge region without actually extending into that region.

In a particular embodiment of the present invention the sputtering anode is grounded and the sputtering cathode is maintained at a negative potential of 5,000 volts with the spacing between the cathode and anode being approximately one and one-half inches although the values of these dimensions may be varied.

As the plasma enters the glow discharge region, it is similar in character to that portion of the region that is closer to the anode (the positive column that will be more thoroughly described below) and the plasma has a marked effect upon the structure of the glow discharge region although the gas pressure is not varied. As has been pointed out above, the gas pressure in the sputtering apparatus is controlled by controlling the amount of gas that enters the apparatus as well as the amount of gas exhausted therefrom. For the purposes of the following description of this effect and operation of the apparatus of the present invention, it is assumed that pressure is maintained constant and is preferably between 20 and 100 microns of mercury.

FIGURE 3a illustrates a glow discharge for a situation in which there is no external source of ions and the characteristics of this region will now be briefly described in order to distinguish from the characteristics of the glow discharge of apparatus employing the present invention. As illustrated in FIGURE 3a the region between the cathode and anode is divided into five zones labeled A, B, C, D and E. The respective zones are denoted by various degrees of stippling to indicate differences in magnitude of light intensity of each zone in such a manner that the more heavy stippling represents darker zones and the lesser degrees of stippling represent brighter zones. Region B represents the Crookes dark space which was briefly described above and which consists primarily of positive ions with the heaviest positive density being at the anode side of the zone. The major portion of the voltage drop and thus the electric field is established between the anode side of this zone and the cathode, the remaining zones between zone B and the anode being approximately at the same potential (that is the anode potential) and having little field. As was stated above, the major portion of the ionization takes place in the negative glow zone which is represented in FIGURE 3a by zone C which has the brightest glow of any of the zones in the glow discharge and which is characterized by a slight excess of negative charges due to the electrons having been accelerated from

the cathode across the voltage drop through zones A and B. Zone A is generally referred to in the literature as the cathode glow zone and contains an excess of negative charges due to the secondary electron emission resulting from the ionic bombardment of the cathode surface. Zone D has less intensity than the negative glow zone and is referred to in the literature as the Faraday dark space while zone E is referred to as the positive column, the Faraday dark space and the positive column being essentially neutral although ionized. Any ion motion in zone D and zone E is primarily by diffusion as there is little or no field in these zones. The boundaries between zones C and D and between zones D and E are indicated by broken lines since at the reduced pressures employed in apparatus of the present invention the existence of these zones is difficult to detect. It is also because of the reduced pressures employed in the present invention that the zones of the glow discharge as represented by FIGURE 3a will appear to be distorted compared to illustrations found in standard textbooks which are generally for glow discharges at higher pressures.

Although there are still other zones existing in a glow discharge which have particular characteristics of their own, such zones have not been illustrated in FIGURES 3a and 3b as their significance with respect to the present invention is not important.

The above described stratification of zones results at the instant of the breakdown of the gas to establish the glow discharge at which time the electrons are accelerated out of the cathode dark space with the major portion of the field being established across the dark space to the cathode, the zone in which ionization occurs being that region ahead of the electrons as they accelerate out of the cathode dark space with the respective dimensions of the different zones adjusting to achieve the optimum potential distribution for the ionization process which is a function of the applied voltage and the pressure. When an increased number of positive and negative ions are introduced into the system as in the present invention, this potential distribution will readjust just as it will readjust upon variation of one of the other parameters such as pressure.

The thickness of the Crookes dark space is inversely proportional to the pressure and some authors attribute this to the fact that the mean free path of electrons traversing the Crookes dark space make a fixed number of collisions before passing out of the dark space into the negative glow zone where they play a part in the establishing of additional ionization.

Just as an increase in pressure results in an increase in current density as a result of increased ionization in the negative glow zone, so too does the increase in ionization result in increased current density having the apparent effect of an increased pressure even though the pressure is kept constant. This is illustrated in FIGURE 3b which is an illustration of the glow discharge region for apparatus employing the present invention.

When the plasma generator of the present invention is employed in the sputtering apparatus, the increase of ions in the glow discharge region has the effect of increasing the conductivity and the current density without any increase in pressure being required. The change observed in the glow discharge region is that the Crookes dark space B' of FIGURE 3b is decreased with the negative glow zone C' being moved upwardly with an apparent expansion of the positive column E'.

The resultant increased sputtering rate with such an increase in current density without a pressure increase is illustrated by the data listed below for the deposition of silicon dioxide (SiO₂) where the cathode material is silicon and the gas supplied through the respective plasma generators consists of approximately 99 percent Argon (A) and 1 percent of oxygen (O₂). The cathode voltage was held at a negative potential of 5,000 volts and the pressure was approximately 60 microns of mercury. Under these conditions the current established in the glow

discharge region was approximately 100 milliamperes and the rate of silicon dioxide deposited upon the anode substrate was measured at approximately 500 Angstroms per minute. Under similar conditions without the ion generator, a current of only 65 milliamperes was established and the deposition rate was only approximately 100 Angstroms per minute.

Although oxygen is employed to react with the silicon to form silicon dioxide, a small percentage of oxygen is employed in the above described atmosphere since an increase in the amount of oxygen results in an excessively thick layer of oxide being formed on the cathode to the detriment of the sputtering rate.

It will be understood that other reactive gases such as nitrogen, chlorine and bromine may be employed in place of oxygen to deposit layers of nitrides, chlorides and bromides respectively. Furthermore, other nonreactant gases such as helium, neon and xenon may be employed in place of argon.

In order to ionize the gas as it is passed through the plasma generator, the thermionic cathode constructed of a tungsten wire is supplied with an alternating current of 60 cycles and approximately 4.5 volts and anode 27 is maintained at approximately 80 volts to establish an anode current of approximately 500 milliamperes.

For plain cathodes and common gases, the abnormal cathode drop is expressed by the relation

$$V = E + \frac{F\sqrt{j}}{p}$$

where E and F are constants, j is the current density and p is the gas pressure.

This equation readily points out that for a given voltage in a closed system, not employing the present invention, the current density can be increased only by increasing the pressure. However, with the present invention for a given V and p, a variation in the current density such as is achieved in the present invention results in the change in one or both of the respective constants.

The sputtering rate has been determined empirically to be expressed by the relation

$$M = C_1 \left(\frac{j}{p} \right) C_2$$

Thus, for a constant pressure the sputtering rate is observed to increase as the current is increased while an increase in pressure is detrimental of the sputtering rate.

While the pressure in the sputtering apparatus should be greater than 20 microns of mercury in order to achieve sufficient current density, it has been observed that the sputtering rate decreases markedly when the pressure is increased above 100 microns as the "sputtered" molecules encounter too many collisions on their way to the anode.

While the present invention is particularly adaptable for the sputtering of refractory materials and various glasses by reactive sputtering wherein a constituent of the ionized gas is employed to react with the material sputtered from the cathode to form the deposited layer as is the situation in the above described example, the present invention is also readily adaptable to other applications of ionic bombardment of a cathode such as might be employed in cleaning a substrate positioned on the face of the cathode and other similar applications.

While the invention has been described and illustrated in the form of one particular embodiment, it will be understood by those skilled in the art that variations and modifications may be made without departing from the scope of the invention as claimed.

What is claimed is:

1. In an apparatus for the deposition of thin films on a substrate in a space having a reduced pressure upon the establishment of a glow discharge in a region between a sputtering cathode and sputtering anode resulting from ionic bombardment of a layer of material placed on the cathode, the improvement comprising:

an ionizing means positioned adjacent said region and including a thermionic cathode, an electron collector positioned adjacent said thermionic cathode, and positively biased with respect thereto to establish an electron stream between said thermionic cathode and said collector, a gas supply conduit in said space having an orifice directed toward said region to continuously supply an ionizable gas generally transversely through said stream,

said ionizing means positioned with the electron stream outside said region and traversing the flow of gas from said orifice of said gas supply conduit thereby causing the ionization of said gas.

2. Apparatus according to claim 1 that includes at least two of said supply conduits and ionizing means which are positioned symmetrically about said region and in a plane residing between said anode and said cathode.

3. Apparatus according to claim 1 including at least two of each of said ionizing means and conduits symmetrically positioned about said region and in a plane residing between said layer and said substrate.

4. Apparatus according to claim 1 wherein said thermionic source of electrons is an electrically heated wire.

5. Apparatus according to claim 1 wherein said electron collector is comprised of a generally cylindrical element which receives the gas from said gas supply conduit.

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