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[54] SPUTTERING METHOD AND APPARATUS

17 Claims, 10 Drawing Figs.

[52] U.S. Cl. 204/192, 204/298
[51] Int. Cl. C23c 15/00
[50] Field of Search 204/192, 298

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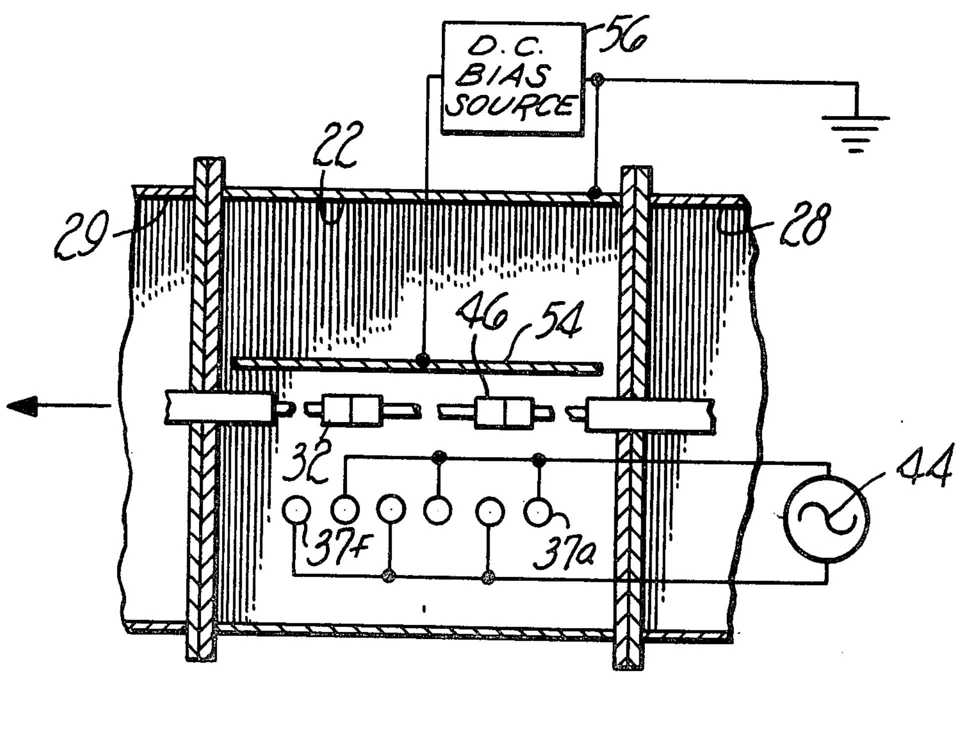
ABSTRACT: Substrate heating by plasma electron bombardment during the sputtering of a thin film in a deposition chamber is considerably reduced by utilizing, as the sputtering target, an AC-excited array of parallel tubes formed from the film material. An oscillating electric field of large amplitude is established between adjacent ones of the tubes to entrap free electrons of the chamber gas and to thereby prevent the electrons from reaching the substrate. An auxiliary conductive member mounted adjacent and parallel to the array is biased with a DC voltage of selectable polarity for increasing the deposition rate of the sputtered material without altering the chamber pressure.



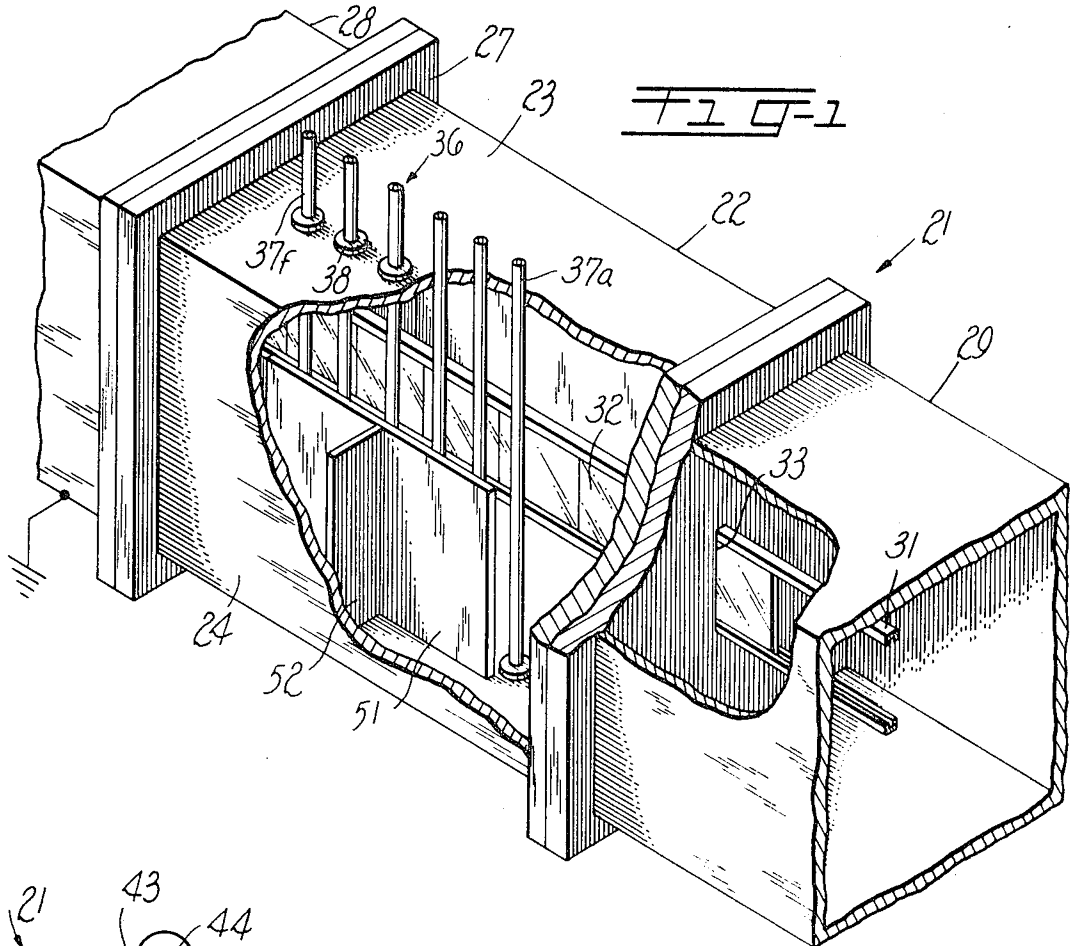


Fig-1

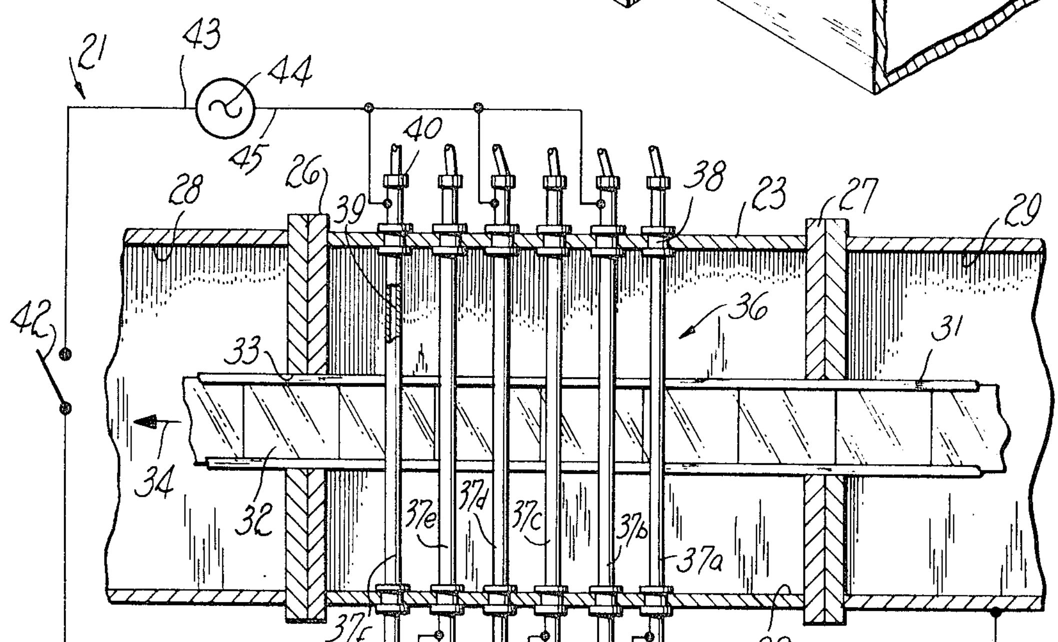


Fig-2

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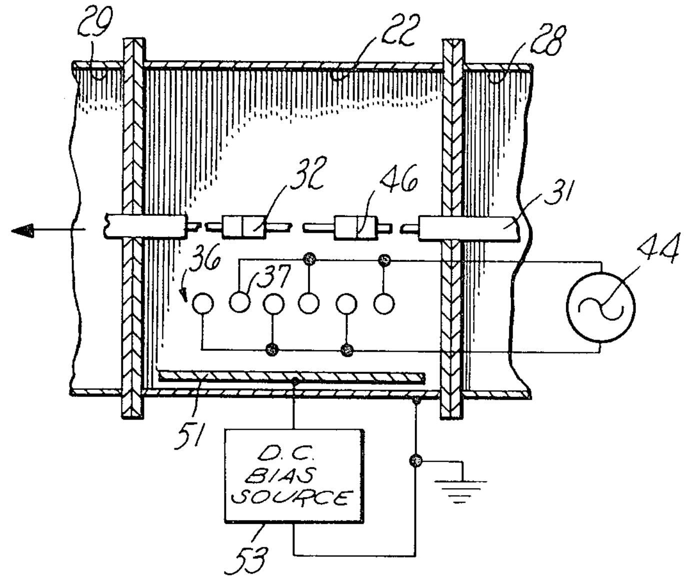
FIG-3



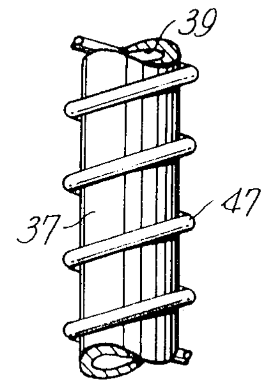


FIG-4

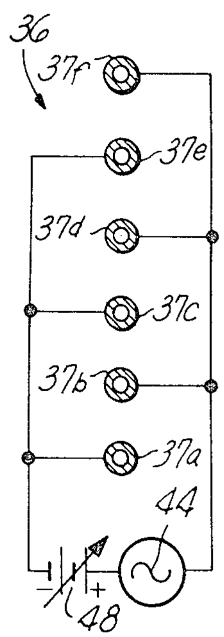


FIG-5

FIG-6

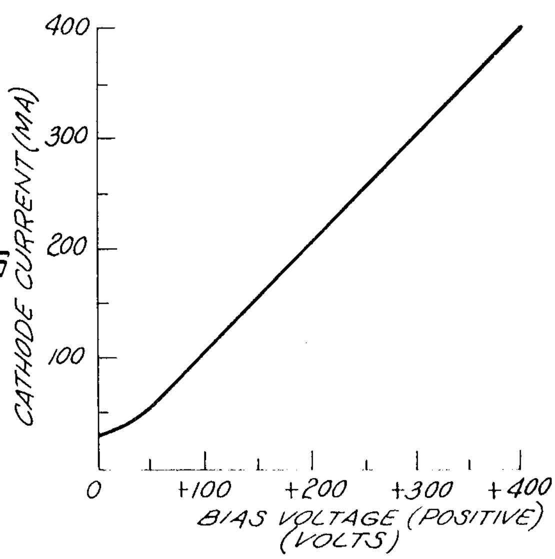


FIG-7

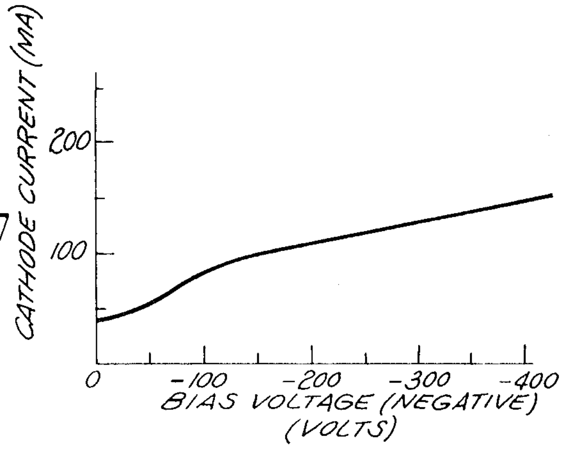


FIG-8

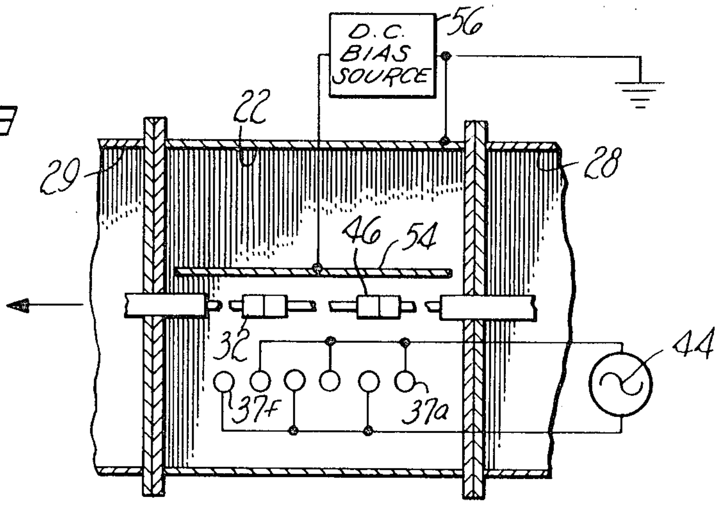


FIG-9

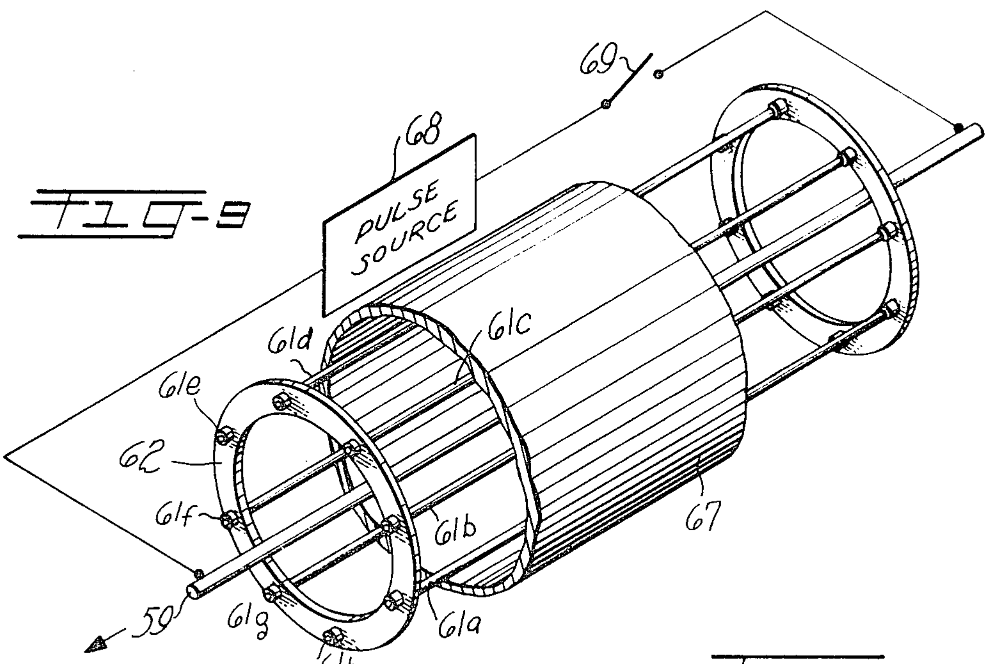
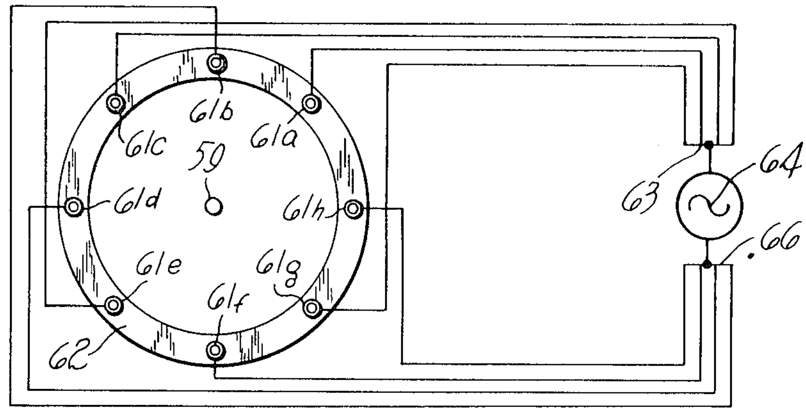


FIG-10



SPUTTERING METHOD AND APPARATUS

BACKGROUND OF THE INVENTION

In the well-known diode or cathodic sputtering technique for depositing thin conductive films on a substrate in a vacuum chamber, a glow discharge or plasma is established in the chamber gas upon the application of a high DC potential between a cathode formed from a source of film material and an anode, which supports the substrate. Positive ions of the gas in the discharge are attracted to and bombard the film source (hereafter "target") to dislodge atoms of the film material, which in turn form a coating on the adjacent face of the substrate.

Ordinarily, free electrons in the discharge are attracted to the sputtering anode and bombard the adjacent face of the substrate. Such bombardment causes localized heating of the substrate which in many cases impairs the quality of the coated film thereon. For example, in the case of deposition of aluminum films having an average thickness greater than 2,000A., deposition at such elevated substrate temperatures causes uneven film deposits and poor surface reflectivity.

In the past, certain expedients have been devised to combat this substrate bombardment problem. Probably the best known of these is to apply a negative DC potential on the deposited film during sputtering to repel plasma electrons from the substrate. This procedure, known as DC bias sputtering, has been satisfactorily employed in the batch-type generation of thin conductive films in bell jars and the like. However, it is awkward for use in the large-scale production of thin films on moving substrates, such as those processed by the in-line vacuum machine described in U.S. Pat. No. 3,294,670 issued to S. S. Charschan et al. on Dec. 27, 1966. The use of DC bias sputtering in such an arrangement involves the formidable engineering task of providing, within a vacuum chamber, satisfactory wiping contacts between the stationary biasing source and the film coating on the continuously moving substrates.

SUMMARY OF THE INVENTION

A preferred technique for eliminating bombardment-induced heating of a moving substrate in a sputtered film deposition apparatus employs the sputtering target excitation of the present invention. In an illustrative embodiment suitable for use in sputtering aluminum films on moving planar substrates, the target is formed from a plurality of individual elongated aluminum tubes arranged in parallel spaced relation in a planar array and extending transversely through the chamber. The plane of the array is parallel to and spaced from the path of the moving substrates.

Sputtering is initiated by applying a relatively large AC voltage between adjacent ones of the tubes. Each tube functions as a film material source during the portion of the AC cycle in which it is relatively negative. Free electrons in the ionized chamber gas are entrapped in the oscillating electric field established between the adjacent tubes so that substrate heating due to bombardment from such electrons is obviated without the necessity of biasing the sputtered film on the moving substrates.

The current density in the cathode array and thus the deposition rate of the sputtered film may be greatly enhanced by distorting the oscillating electric field between the tubes. This may be accomplished, e.g., by mounting a conductive member behind the cathode array and applying either a positive or a negative DC bias to the member. For any given chamber pressure, the enhancement of the deposition rate is nearly proportional to the magnitude of the bias voltage applied to the member.

Target and substrate configurations other than planar may also be employed in the apparatus. For example, if the moving substrate is cylindrical as is the case, e.g. with copper wires to be coated with permalloy or other magnetically anisotropic material to form memory devices, the several tubes are arranged longitudinally in a circumferential array about the moving wire.

Alloy films may be conveniently deposited by forming alternate tubes of the array from one metal of the alloy and the remaining tubes from the other metal. In this case, a degree of composition control of the resulting sputtered film may be obtained by placing adjacent elements of the array at different DC potentials.

BRIEF DESCRIPTION OF THE DRAWING

The nature of the invention and its advantages will appear more fully from the following detailed description taken in conjunction with the appended drawing, in which:

FIG. 1 is a perspective view, partially broken away, of a sputtering apparatus employing a target array and auxiliary biasing plate constructed in accordance with the invention for use with a planar substrate;

FIG. 2 is a side elevation, partly broken away, of the arrangement of FIG. 1 with the biasing plate removed, illustrating a cooling arrangement for the target array;

FIG. 3 is a diagrammatic view of the sputtering apparatus of FIG. 2, illustrating the electrical connections for the array and the biasing plate;

FIG. 4 is an enlarged fragmentary view of a portion of one element in the array of FIG. 1, illustrating a wire formed from a "seeding agent" wrapped around the element;

FIG. 5 is a diagrammatic view of the array of FIG. 1, showing alternate electrical connections therefor;

FIGS. 6 and 7 are curves showing typical variations of cathode current as a function of positive and negative bias voltages, respectively;

FIG. 8 is a diagrammatic view similar to FIG. 3 but showing an alternative disposition of the biasing member and electrical connections therefor;

FIG. 9 is a perspective view partially in diagrammatic form and partially broken away, of an alternative form of target array and auxiliary biasing member suitable for use with a cylindrical substrate; and

FIG. 10 is an end view, partly in schematic form, of the arrangement of FIG. 9, illustrating the electrical connections for the array.

DETAILED DESCRIPTION

Referring now to the drawing, FIGS. 1-2 illustrate an elongated sputtering apparatus 21 which may form a portion of the in-line vacuum machine described in the above-mentioned U.S. patent. The apparatus 21 includes a rectangular sputtering chamber 22 (FIG. 1) formed from a conductive material such as steel and electrically grounded. The chamber 22 is defined by two pairs of opposed, mutually perpendicular sidewalls 23—23 and 24—24 which are disposed horizontally and vertically, respectively. The walls 23 and 24 are terminated at opposite longitudinal ends by a pair of end walls 26—26 (FIG. 2). The end walls are respectively fitted with a pair of flanges 27—27 for attachment to similar flanges on the end walls of a pair of similarly formed chambers 28 and 29, which abut respectively opposite ends of the chamber 22.

A pair of metallic, channel-shaped tracks 31—31 extend longitudinally through the sputtering chamber 22 for movably supporting a plurality of planar nonconductive substrates 32—32 mounted end-to-end in a vertical plane. The tracks 31 are fixedly supported in a pair of correspondingly shaped slots 33—33 centrally disposed in the mating end walls of the chamber 22 and the chambers 28 and 29, respectively. The substrates may be longitudinally advanced in the tracks in the direction of an arrow 34 (FIG. 2) by means not shown. Such means may include, e.g., a reciprocating pusher of the type described in U.S. Pat. No. 3,282,392, issued to W. H. Fowler on Nov. 1, 1966.

The chamber 22 is filled with an inert working gas, such as argon, at a pressure suitable for sputtering. The path of the substrates 32 in the chamber 22 extends past a fixed sputtering target, represented generally as 36 (FIG. 1), for receiving therefrom a uniform coating of the target material when sputtering conditions are established in the chamber as described below.

In accordance with the invention the target 36 is in the form of an AC-excited planar array of elongated, mutually parallel cylindrical elements 37*a*—37*f* (FIG. 2) extending vertically in the chamber 22. The elements 37 extend completely through the chamber and penetrate the opposed horizontal walls 23 thereof through an associated plurality of vacuum seals 38—38. As best shown in FIG. 3, the plane of the array is parallel to and transversely spaced from the plane of the moving substrates 32.

Each of the elements 37 is tubular in shape and includes a central bore 39 (FIG. 2) through which a suitable coolant (not shown) may be passed during the sputtering operation to prevent excessive heating and/or melting of the elements 37. The tubular shape permits the coolant to come into direct contact with the inner surface of each element and thereby promotes efficient heat transfer. The coolant may be introduced into the bore 39 of each element 37 through an associated inlet fitting 40 and withdrawn therefrom through an outlet fitting 41.

Alternate ones 37*a*, 37*c*., and 37*e* of the elements are electrically connected in common, through a switch 42, to one terminal 43 of a high voltage, low frequency AC source 44 that is electrically isolated from the walls of the chamber 22. The remaining elements 37*b*, 37*d*., and 37*f* are electrically connected in common to another terminal 45 of the source 44. Thus the entire source potential may be applied across adjacent elements 37 in the array to provide an intense oscillating electric field between the adjacent elements. During the half cycle of the applied AC voltage when the elements 37*a*, 37*c*, and 37*e* are negative with respect to the remainder of the elements, the elements 37*a*, 37*c*, and 37*e* constitute the instantaneous "cathode" of the sputtering apparatus. Similarly, when the elements 37*b*, 37*d*, and 37*f* are negative with respect to the remaining elements, the elements 37*b*, 37*d*, and 37*f* constitute the instantaneous cathode. In this way, each of the elements 37 constitutes a film source of the sputtering apparatus. No separate anode of the type generally employed to support the substrate in diode sputtering apparatus is required.

In operation, the switch 42 in series with the AC source 44 is closed to apply the high AC voltage of the source 44 between adjacent ones of the elements 37. The resulting electric fields between the adjacent elements ionize the chamber gas so that positive ions of the gas bombard those elements 37 that are relatively negative at that moment. The resulting dislodgement of aluminum atoms from the bombarded elements are deposited on the moving substrates 32 opposite the target array in the form of a thin film coating 46 (FIG. 3). DUring the next half cycle of the source voltage, the positive gas ions bombard the remaining ones of the elements 37, which are now relatively negative so that aluminum atoms therefrom are dislodged and deposited in an identical manner.

Free electrons in the ionized gas are trapped in the AC electric field between the adjacent elements, and oscillate therebetween as the relative polarities within the array reverse. At any instant, such electrons will be attracted to those elements 37 in the array which are instantaneously positive rather than to the conductive film 46 on the substrates which are electrically isolated from the array. In this way, heating of the moving substrates 32 due to the electron bombardment is essentially precluded without the necessity of providing wiping contacts to the coated film to negatively bias the substrates. As a result, it has been possible to eliminate film deterioration caused by such heating during the continuous deposition of aluminum films thicker than 2,000A.

In some case, the adherence and uniformity of the aluminum film 46 may be enhanced by wrapping a wire 47 (FIG. 4) of a suitable "seeding agent", such as tantalum or titanium, around each of the elements 37 in the cathode array. Such seeding agents form extremely small grain deposits on the substrate during sputtering, and act as nuclei for the aluminum material deposited from the elements 37 which would otherwise form a coarser grained deposit.

The use of the AC-excited sputtering array of FIGS. 1–3 has also been found to virtually eliminate the delay (common in diode sputtering of aluminum) from the time that the sputtering potential is applied to the time the aluminum atoms are actually dislodged from the target surface. This so-called "induction period", which is thought to be caused by the presence of a natural layer of aluminum oxide on the surface of the target prior to sputtering, may normally last several hours.

The arrangement of FIGS. 1–3 is also useful for the deposition of alloy films, such as compositions of tantalum and silicon. In such a case, alternate ones of the elements 37 would be formed from one of the metals in the alloy, and the remaining elements from the other metal. Some control of the composition of the resulting alloy film may be obtained by including an auxiliary DC bias source 48 (FIG. 5) in series with the AC source 44. The alternate elements 37*a*, 37*c*, and 37*e* will be more negative on the average than the remaining elements, and will generally provide a larger portion of the sputtering film composition.

If the amplitude of the output from the AC source is reduced to zero and the voltage of the DC source 48 is suitably adjusted, a DC sputtering arrangement results in which the substrate (not shown) will be free from electron bombardment, since the DC field will be applied between adjacent tubes 37 rather than between the cathode array and a substrate-supporting anode. It will be understood that such effect will also take place when all the tubes 37 are formed from the same material.

With the AC-excited arrangements thus far described, the maximum "cathode" current, i.e., the total current drawn by the array of elements 37 (FIG. 3) from the source 44, will be determined by the chamber pressure in a manner analogous to diode sputtering. Because of this dependence, the deposition rate (which is determined largely by the cathode current) cannot be conveniently adjusted independently of the film density; the latter is a function of the chamber pressure, with lower pressures corresponding to higher film densities.

In further accordance with the invention the AC-excited apparatus of FIGS. 1–3 may be adapted to eliminate, to a large degree, the dependence of cathode current density on chamber pressure so that thin films with a prescribed film density can be obtained with much higher deposition rates (and thus speed of precessing) than is possible with normal diode sputtering. This is accomplished, as shown in FIG. 1, by providing an auxiliary conductive bias member 51 within the chamber 22 adjacent the plane of the array 36. The member 51 is a metallic plate which is supported in parallel and electrical coupling relation to the array by means of a dielectric bracket 52 affixed to the adjacent vertical wall 24 of the chamber 22. The member 51 occupies a major portion of the area of the chamber 22 in a plane parallel to the array 36 and the vertical wall 24.

As shown in FIG. 3, the member 51 is biased with a steady potential of selectable polarity from an adjustable, grounded bias source 53.

For any given pressure in the chamber 22, the use of the biased member 51 in conjunction with the AC-excited element array 36 has been found to increase the cathode current density during sputtering in direct proportion to the voltage of the bias supply source 53 up to bias voltages of several hundred volts. This phenomenon is similar to that obtained by relatively complex electromagnetic means in the so-called triode sputtering method, wherein a thermionic cathode and an independent anode are employed to establish the ionizing discharge. While the explanation of the phenomenon of current increase is not fully understood, it is believed that, in the context of the present arrangement, the distorting effect of the biased member 51 on the AC electric fields established within the array 36 increases the ionization concentration of the chamber gas in the region of the array plane. Typical variations in cathode current of the array 36 as a function of the magnitude of the positive or negative bias on the member 51 (with the effective AC source voltage and the chamber pressure held constant at 4.6 KV and 8.5 millitorr, respectively) are separately shown in FIGS. 6 and 7. It can be seen from FIG. 6, for example, that for a positive bias voltage of 400 v. the ionization enhancement is such that the cathode current increases by a factor of about 10 over the nonbiased state. In like manner, it can be seen from FIG. 7 that the ionization enhancement provided by negative bias voltages is somewhat less pronounced than with positive voltages, with the cathode current reaching a limiting value of about 2.5 times that of the nonbiased state at − 150 v. It should be made clear at this point that the graphs of FIGS. 6 and 7 are not intended to be universal current amplification plots applicable for all chamber pressures and cathode voltages. Rather, they are intended to show the general effect of applied bias voltages of selectable polarity. It is to be expected that the relative effect of applying bias voltages, as regarding numerical values of cathode current amplification, will be a function of chamber pressure, cathode voltage and the specific dimensions and geometry of the deposition apparatus. For example, the influence of cathode tube diameter, the spacing between adjacent tubes and the spacing between the bias plate and the tubes are among the variables in the apparatus which may influence the cathode current amplification effect.

An alternative manner of employing an auxiliary biasing plate in connection with the AC sputtering array of FIGS. 1–3 is shown in FIG. 8. In this case the biasing plate (now designated by the numeral 54) is disposed behind and adjacent the plane of the substrate 32 and is provided with a negative or positive DC bias from a second grounded bias source 56 of adjustable output. This arrangement provides ionization enhancement in a manner similar to that obtained with the biased member 51 of FIG. 3.

In the previous discussion, the sputtering target array 36 and the substrates 32 were assumed to be planar in shape. However, other substrate and target array configurations (e.g. cylindrical) may be employed. In the arrangement of FIG. 9, wherein the sputtering chamber is omitted for clarity, the advancing substrate is a wire 59 (formed from beryllium copper or the like) which is to receive a sputtered coating of an uniaxially anisotropic magnetic material such as permalloy. As is well known, such coated wires are useful, e.g., in magnetic memory applications.

Ordinarily the wire 59, like the planar substrates 32 or FIG. 1, may be impaired by excessive heating caused by electron bombardment during sputtering; however, in a manner analogous to that described in connection with FIG. 1, this problem is avoided by utilizing, as the sputtering target, a plurality (illustratively eight) of elongated cylindrical permalloy elements 61*a*—61*h*(FIG. 9) extending longitudinally in parallel relation to the wire 59 and arrayed circumferentially at equally angular intervals about the wire 59. The elements 61 are supported at longitudinally opposite ends by a pair of insulating rings 62—62.

As shown schematically in FIG. 10, the elements 61*a*, 61*c*, 61*e*, and 61*g* are connected in common to one terminal 63 of an AC source 64. The remaining elements 61*b*, 61*d*, 61*f*, and 61*h* are connected in common to another terminal 66 of the source 64. An auxiliary biasing cylinder 67 (FIG. 9), analogous to the biasing plate 51 of FIGS. 1 and 3, is disposed outside and coaxial with the circumferential array of the elements 61 (FIG. 9). While not specifically illustrated, the cylinder 67 is assumed to be connected to one terminal of a DC bias power supply with the other terminal grounded to the metal chamber wall of the vacuum enclosure. Because of the closed structure of the bias electrode (i.e., the cylinder 67) in this arrangement, the high voltage AC source 64 (FIG. 10) used to supply the elements 61*a*—61*h* is preferably a transformer with a grounded center tap (not shown) in order to allow the establishment of a stable ionization of the inert gas in the volume within the cylinder 67 (FIG. 9), and further allow (When desired) an electrically floating substrate.

The required magnetic anisotropy of the coated wire 59 is provided by subjecting the wire to an orienting circumferential magnetic field during deposition of the permalloy film. The field may be established, with a minimum of wire heating, by passing pulsed DC current of low duty cycle through the wire 59 from a suitable pulse source 68 via a switch 69.

Without in any way limiting the generality of the foregoing, an example of the use of the DC bias-enhanced, AC sputtering technique of the present invention will now be described to illustrate its ability to sputter uniform planar aluminum films greater than 2,000 angstroms in thickness.

EXAMPLE

The apparatus of FIGS. 1–3 was employed to deposit an aluminum film on 2-inch×3-inch glass substrates supported within a 12-inch×12- inch×12-inch vacuum chamber in an in-line vacuum machine. The chamber was filled with argon at a pressure of 8.5 millitorr.

The target consisted of 6½-inch diameter, 99.99 percent pure aluminum tubes arranged in a planar array. Each tube had a 3/16-inch diameter central bore therein for water cooling. The tubes were spaced apart by a center distance of 1¼inches. The plane of the array was located a distance of 2½inches from the plane of the substrates. An auxiliary biasing plate consisting of a sheet of stainless steel 11-inch×11-inch×1/16-inch was placed in back of the array and was spaced from the array by 3¼inches.

AC sputtering was accomplished with a 60 Hz. cathode voltage of 4.6 kv. RMS applied between adjacent tubes in the array. The cathode current was 300 ma. The auxiliary plate was biased at 400 volts positive and drew a biasing current of 1.01 amps. Cooling water at an inlet temperature of 19.5° C. was passed through the tubes at a rate of 11.44 cc. per second.

Under these conditions, an aluminum film that was nominally 4,280A. thick was sputtered on two substrates disposed opposite the central tubes in the array. The substrate was held stationary during the deposition.

Following deposition, the film thickness was measured at three positions on the film by conventional profilimeter (Talysurf) techniques. The sheet resistivity of the film was also measured at three positions on the film with a four point probe technique.

It was found that the total variation of thickness on the AC sputtered aluminum film was ±1.9 percent while the variation of sheet resistivity was negligible. The substrate temperature rise during the deposition was also negligible.

During sputtering, the outlet water temperature stabilized at 41.0° C., or 21.5° C., higher than the inlet water temperature. For a cathode input power of 4.6×3=1.38 kw., this was equivalent to the removal of 74 percent of the cathode input power in the form of heat by the cooling water.

If desired, the AC-excited element array of the invention may conveniently be adapted for the sputtering of insulator films, such as silicon dioxide. This may be done by providing suitable conductive backing members to act as terminals for the dielectric elements in the array, and superimposing a radio frequency AC voltage on the 60 cycle AC sputtering voltage. Additional modifications such as the use of external magnetic fields, electrically floating substrates (with or without applied bias), and variations in the geometry of the cathode elements and biasing electrodes may also be made.

What is claimed is:

1. In an apparatus for sputtering a conductive coating on a substrate situated in an enclosed sputtering chamber:

a composite sputtering target comprising a plurality of parallel mutually spaced elongated elements arrayed symmetrically with respect to the substrate within the sputtering chamber and formed from the coating material to be sputtered;

means for applying opposite polarities of an AC voltage to adjacent ones of the elements in the array to establish an oscillating electric field between the adjacent elements;

an auxiliary conductive member disposed in spaced relation to the array for altering the oscillating electric field when a biasing voltage is applied to the member; and

means for applying a DC biasing voltage to the conductive member.

2. Apparatus as defined in claim 1, in which the element array is disposed between the conductive member and the substrate.

3. Apparatus as defined in claim 2, in which the DC bias voltage is positive

4. Apparatus as defined in claim 1, in which the elements are arranged in a planar array about the substrate.

5. Apparatus as defined in claim 1, in which the elements are arranged in a circular array about the substrate and are disposed coaxially therewith.

6. Apparatus as defined in claim 1, further comprising means for selectively passing a succession of electrical pulses through the substrate.

7. Apparatus as defined in claim 1, in which alternate elements in the array are formed from a first metal and the remaining elements are formed from a second metal, and the apparatus further comprises means for placing the alternate elements at a different DC potential than the remaining elements.

8. Apparatus as defined in claim 1, in which each element has a centrally disposed, axially extending bore for receiving a cooling fluid.

9. Apparatus as defined in claim 1, in which the conductive member is disposed on the side of the substrate opposite from the element array.

10. A method of sputtering a conductive film on a substrate from a plurality of pairs of parallel, mutually spaced conductive elements that are arrayed symmetrically with respect to the substrate within an enclosed sputtering chamber and are made from the material to be sputtered, the steps comprising:

applying an AC sputtering voltage of opposite polarities between the elements in each pair of sufficient magnitude for establishing a current density in each element to sputter material on the substrate from the instantaneously negative element of each pair at a prescribed rate for sputtering and for establishing an oscillating electric field between the elements in each pair to prevent bombardment of the substrate by any free electrons within the field; and

distorting the oscillating electric field in the region between the elements by applying a DC bias voltage to a conductive plate disposed parallel and in spaced relation to the array to increase the current density in each element and raise the sputtering rate.

11. A method as set forth in claim 10 which further includes the step of imparting relative movement between the substrate and the element pairs to coat successive regions on the substrate with the sputtering material.

12. Method as defined in claim 10, in which the elements are formed from aluminum.

13. Method as defined in claim 10, in which the substrate is formed from a copper-based conductor, and each of the elements in the array is formed from a magnetic material.

14. Method as defined in claim 10, in which each element is an aluminum rod covered with a material selected from the group consisting of tantalum and titanium.

15. In an enclosed vacuum chamber for sputtering a conductive coating upon a substrate;

a sputtering target comprising a plurality of parallel, mutually spaced cylindrical elements arranged in a symmetrical array about the substrate, each element being formed from the coating material to be sputtered;

means for applying opposite polarities of an AC voltage to adjacent elements in the array;

a conductive plate disposed parallel and in spaced relation to the array;

means for applying a DC bias voltage to the conductive plate; and

means for supporting the substrate for movement through the vacuum chamber along a path parallel to the plane of the array and disposed on the opposite side thereof with respect to the conductive plate.

16. Apparatus as defined in claim 15, in which adjacent pairs of the elements include a common element.

17. In an enclosed apparatus for sputtering a conductive coating onto a surface of a substrate situated within the apparatus;

a sputtering target comprising a plurality of pairs of conductive elements arrayed in a configuration about the substrate, each of the elements being constructed of the coating material;

means for applying between alternate elements of each pair an AC voltage of sufficient magnitude to sputter material from one element in each pair.

an auxiliary conductive member disposed in coupling spaced relation to the conductive elements;

means for applying a DC bias voltage to the conductive member; and

means for supporting the substrate for movement passed the sputtering target to receive therefrom a coating of the sputtered material.

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