April 21, 1970 E. C. MULY, JR 3,507,774

LOW ENERGY SPUTTERING APPARATUS FOR OPERATION BELOW ONE MICRON PRESSURE

Filed June 2, 1967 3 Sheets-Sheet 1

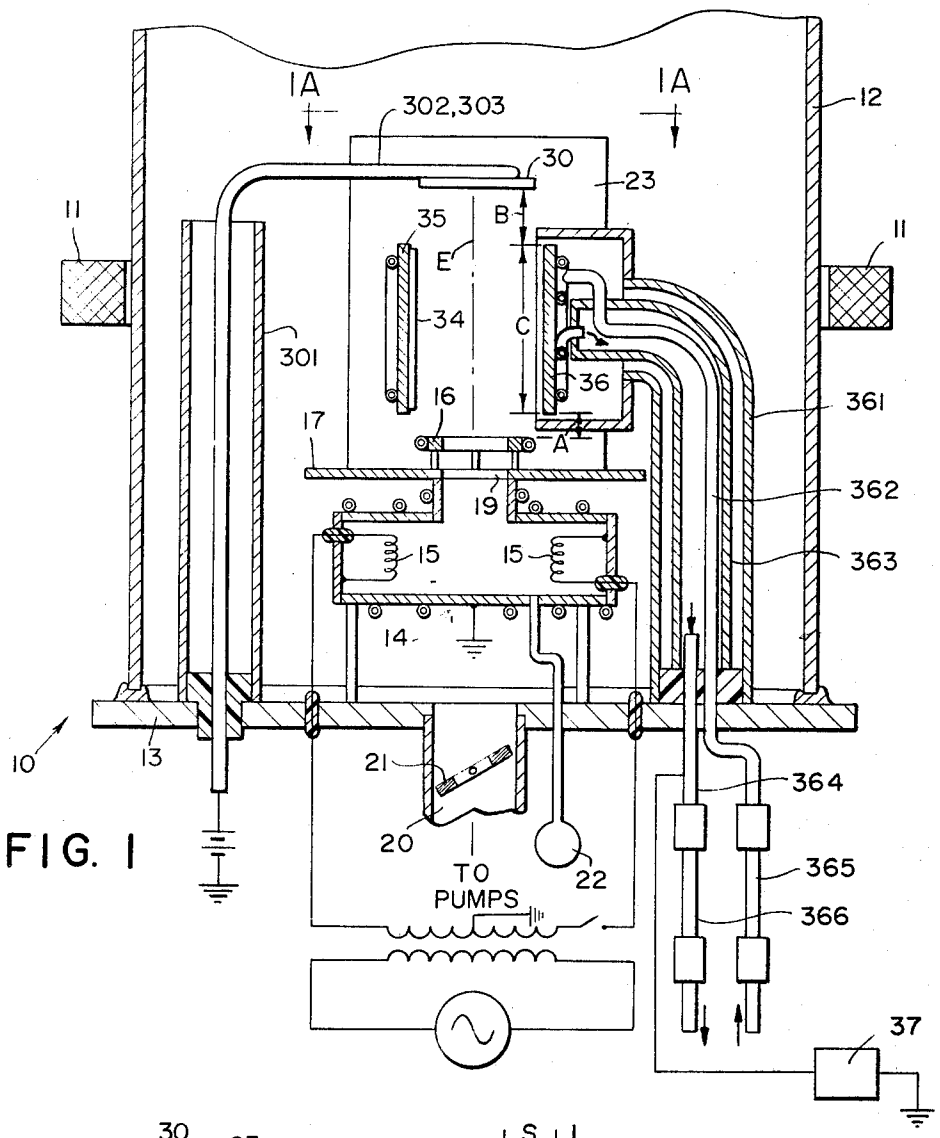


FIG. 1

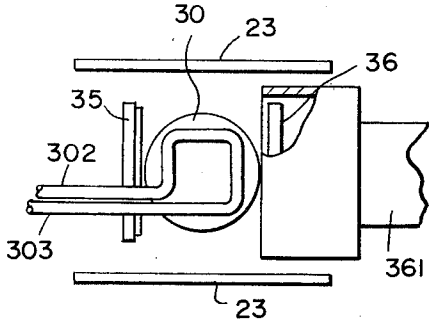


FIG. 1A

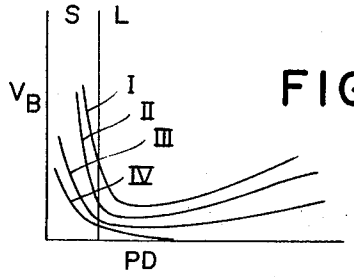


FIG. 2

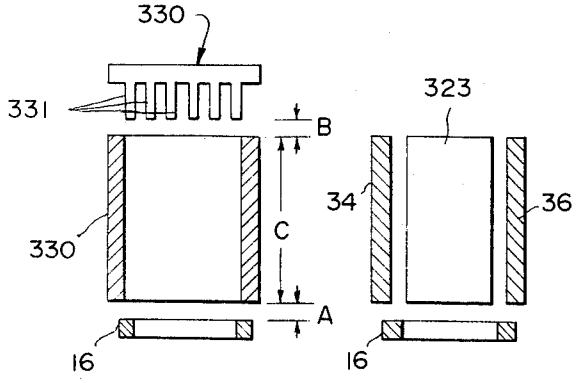


FIG. 3

FIG. 3A

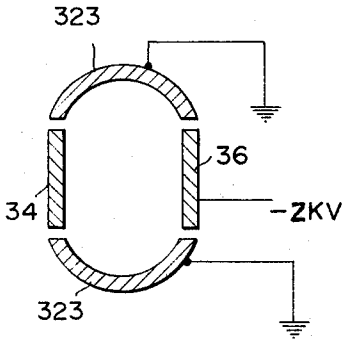


FIG. 3B

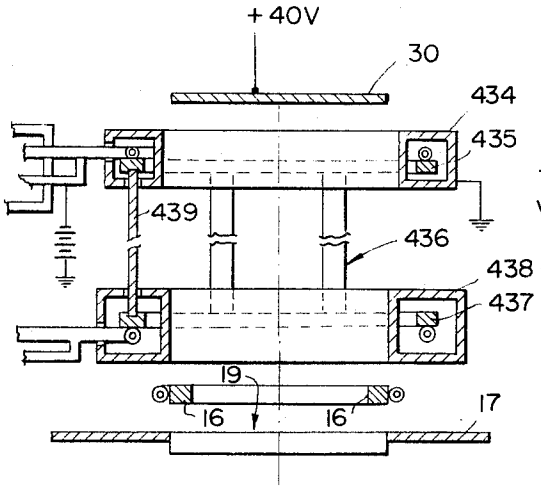


FIG. 4

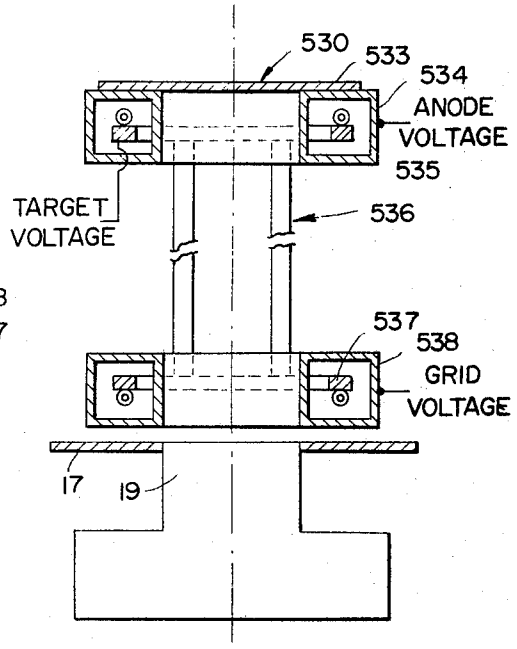


FIG. 5

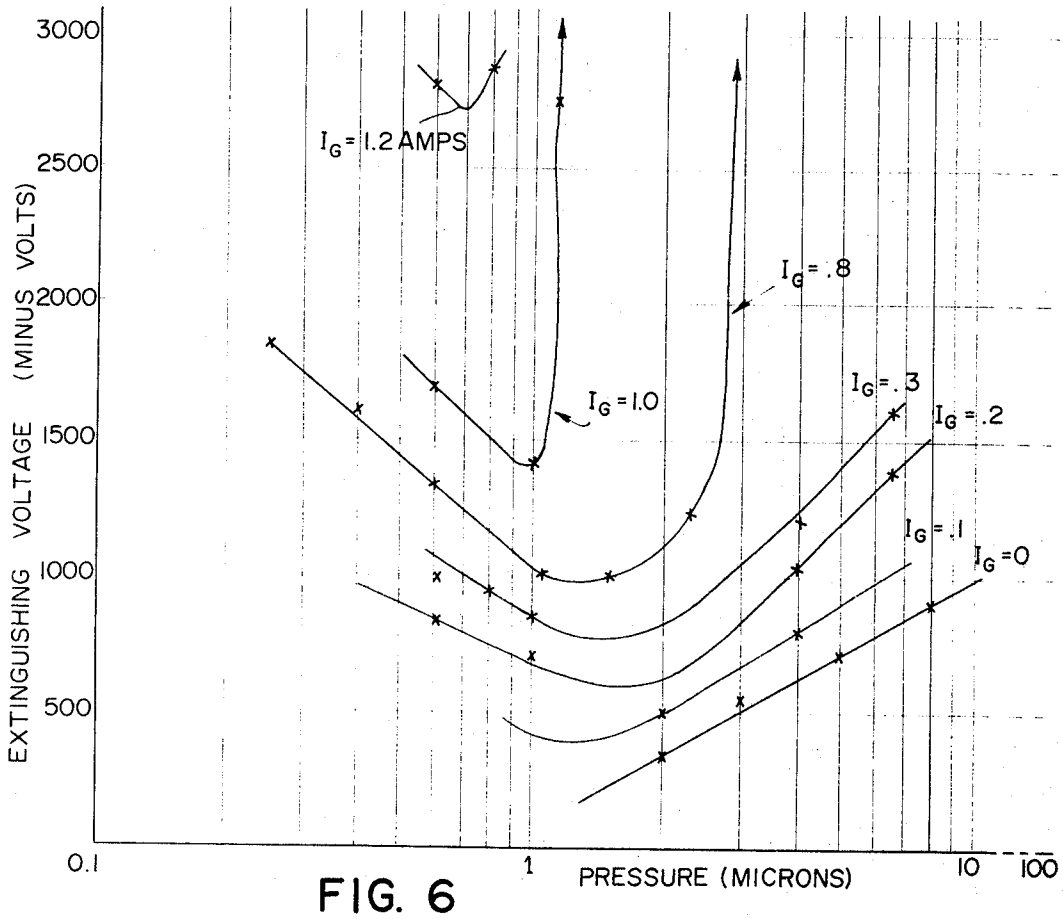

EXTINGUISHING VOLTAGE (MINUS VOLTS)
3000
2500
2000
1500
1000
500
0.1
1
10
100
PRESSURE (MICRONS)
I_G = 1.2 AMPS
I_G = .8
I_G = 1.0
I_G = .3
I_G = .2
I_G = .1
I_G = 0

FIG. 6

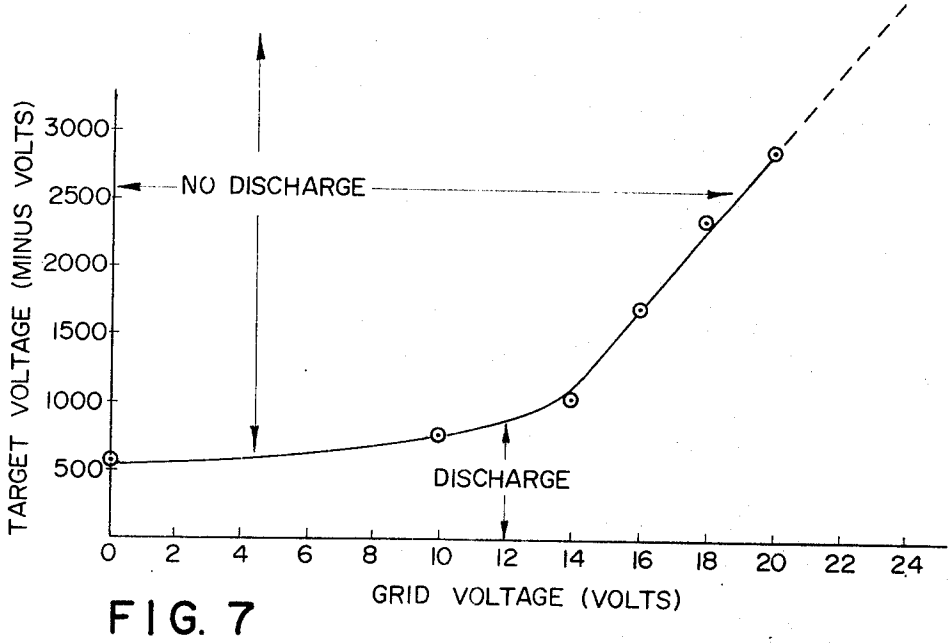

TARGET VOLTAGE (MINUS VOLTS)
3000
2500
2000
1500
1000
500
NO DISCHARGE
DISCHARGE
0
2
4
6
8
10
12
14
16
18
20
22
24
GRID VOLTAGE (VOLTS)

FIG. 7

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3,507,774

LOW ENERGY SPUTTERING APPARATUS FOR OPERATION BELOW ONE MICRON PRESSURE

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Int. Cl. C23c 15/00
U.S. Cl. 204—298 14 Claims

ABSTRACT OF THE DISCLOSURE

A low energy tetrode sputtering apparatus operating below one micron pressure with stability. The apparatus comprises a geometric enclosure substantially enclosing the plasma formed along the electron path from the electron source to the anode. An intermediate electrode is biased at a voltage of 10 to 40 volts positive relative to the voltage source and has the form of an annular ring.

The present invention relates to improvements in sputtering apparatus for use in coating and other applications such as crystal growing, sputter etching and spectroscopic emission.

BACKGROUND REFERENCES

U. S. Patents 3,021,271; 3,278,407; 3,294,669; 3,296,115 and 3,305,473.

It is the object of the present invention to provide an improvement in such sputtering apparatus characterized by high stability of the sputtering discharge and consistent with operation well below 1 micron pressure.

In general the object is achieved by constructing the apparatus so that extraneous voltage breakdowns are avoided. In this construction a geometric enclosure, including the sputter target, is provided around the plasma. In this way the escape of electrons from the plasma is minimized and a relatively high Paschen curve controls the formation of extraneous discharges between electrodes and metal parts around the electrodes. However, the enclosure is sufficiently open to allow low pressure operation in the sputtering zone with ease of pumping gas therefrom. The function of limiting escape of electrons is therefore carried out in part by electrostatic means which supplement the geometric enclosure means.

It is a further object of the invention to provide a sputtering apparatus also capable of stable and high sputtering rate operation at pressures well above 1 micron.

This object is achieved with the stability afforded by the above enclosed structure together with a novel form of grid for tetrode sputtering apparatus, the grid having an annular form enclosing a large electron escape area.

The invention is now described with reference to the accompanying drawings wherein:

FIG. 1 is a sectional view of the sputtering apparatus according to a preferred embodiment of the invention FIG. 1A being a top view of the same apparatus,

FIG. 2 is a graph qualitatively illustrating the factors favoring voltage breakdown,

FIGS. 3, 3A–3B, 4 and 5 are sectional views of portions of other embodiments of the invention,

FIGS. 6 and 7 are graphs showing the effect of the intermediate electrode on performance of the sputtering apparatus.

Referring now to FIG. 1 the sputtering apparatus **10** comprises a bell jar **12** on a base plate **13**. The bell jar is evacuated through a port **20** connected to vacuum pumps (not shown). A butterfly valve **21** with an orifice in it is in the port **20**. The position of the valve controls pressure in the bell jar. Argon or other inert or active gas bleeds into the bell jar from a supply **22**.

The electrodes of the sputtering system are one or more filaments **15** at ground potential, an intermediate electrode **16** (grid) biased at about plus 10–40 volts, an anode **30** biassed at plus 10–40 volts and a sputtering target **36** with a power supply **37** of minus 1500 to minus 2500 volts. The filament(s) **15** is contained in a grounded metal enclosure **14** of T form with an exit port **19** at the foot of the T. A flange **17** extends outwardly from the port to provide a ground plane.

The substrate **34** to be coated is mounted on a plate **35** which may also be thought of as the substrate for purposes of defining, together with the sputter target **36** a partial enclosure of the plasma zone P which is in the region of the linear electron path E between the electron exit port **19** and the anode **30**. The electron path E constitutes an extension of the axis of the exit port **19**.

The enclosure of the plasma is further supplemented by opposed glass plates **23** which straddle the plasma zone and are set-off to the sides of the opposed target and substrate. The anode **30** and electron source chamber **14** complete the substantial geometric enclosure of the electron path region where the plasma is to be formed. The tightness of the enclosure is critical in promoting stability of the discharge and this tightness is characterized by the dimensions A, B, C where A is the axial separation (along a line parallel to the electron path) of the target **36** from the electrode **16**, B is the axial separation of the target from the anode and C is the axial length of the target. The limiting condition is that neither A nor B shall be over two inches nor shall A and B together be over half C.

The geometric enclosure is supplemented by electrostatic enclosure effects afforded by the negatively biassed target **36** and the substrate and glass plates to the extent that these electrically floating members collect stray electrons and build up negative charge which tends to repel further electrons which may stray from the electron path. The magnet **11** around the bell jar **12** also assists in confining electrons to the zone of the electron path by accelerating the electrons spiral movement essentially about the electron path.

The biassing means includes a high tension power supply for biassing target electrode **36** to a negative voltage on the order of 1000 volts (as opposed to on the order of 100 or 10,000—typically 1500–2500) and comprising feed and return coolant pipes **362** and **363–364** which serve as the lead in conductor. These are surrounded by a metal shield **361** which is sufficiently close to the lead-in conductor and isolated therefrom by a vacuum gap to thereby suppress parasitic discharges. The spacing is preferably about .75 inch between the conductor **363** and shield **361** and preferably less, about .25 inch where the shield nears the edges of target **36**. Similarly a metal shield **301** closely surrounds lead-in conductors **302**, **303** across a narrow vacuum gap to suppress parasitic discharge. A similar lead-in conductor arrangement (not shown) is provided for the grid **16**. The shields and electron source chamber **14** are grounded. The substrate (holder) **35** is electrically floating, but may be biassed to a desired potential (e.g.

a negative potential for reverse sputtering) with similar lead-in conductor arrangements. The coolant feed paths **364, 362** are continued with plastic pipes **365, 366** to isolate the high voltage carried by pipes **364, 362.**

All of the electrodes **36, 30, 35, 16** and **14** are water cooled as indicated in the drawing to further ensure stability of the discharge. The annular single turn loop form of electrode **16** allows a thick conductive cross-section for effective cooling to ensure this stability to greater degree than is possible with the conventional mesh electrode used for this purpose.

The gas medium in which sputtering is to be conducted (generally argon) is bled into chamber **14** from a source **22** and then exits out through the electron exit port **19** and then through the above described geometric enclosure and out into the ambient vacuum of the bell jar for removal by the vacuum pumps via port **20**, the speed of gas removal being determined by the setting of valve **21.** Generally, the valve is set to allow a pressure of 2×10^{-4} mm. Hg abs. as measured by a gauge not shown located at baseplate **13.** The dimensions of port **19** and escape paths through the geometric enclosure are of course sufficiently large that the same pressure prevails throughout the bell jar **12** including the spaces inside the electron source chamber **14** and the shields **361, 301,** etc. under the applicable conditions of pressure and pumping speed.

An understanding of the invention is assisted by considering the conditions required for an extraneous sparking voltage discharge with reference to FIG. 2 which is a curve indicating the necessary voltage V_B to achieve a spark breakdown in a given gas medium. The curve I indicates the ideal situation for two parallel plate electrodes. The curves II, III, IV, etc. indicate how the breakdown voltage curve is reduced by various factors which are typically encountered in a vacuum system—principally sharp projections on one or both electrodes between which breakdown is considered and the presence of stray electrons between the electrodes. These curves are called Paschen curves after D. F. Paschen, a German scientist who first analyzed Townsend discharges in this fashion circa 1890. The ordinate of the Paschen curves is the voltage required to initiate spark breakdown and the abscissa is the product PD where P is pressure and D is the distance between electrodes. There are two distinct regions of the abscissa, S corresponding to a low PD product where V_B is on a steep negative slope and L corresponding to a large PD product where minimal voltage can set off a spark discharge. In all sputtering apparatus of interest the product PD is within the region S, especially in low energy sputtering apparatus where pressures on the order of $\leqq$10 microns are used and more so in the instant apparatus wherein pressures of .2 to .5 micron are typical. The object then, is to create a situation in which the likelihood of extraneous breakdown is controlled by a relatively high Paschen curve (e.g. curve II) rather than a relatively low curve (e.g. curve IV).

The essence of the present invention, then, is the above described tight geometric enclosure arrangement in combination with the tetrode sputtering apparatus. The geometric (and electrostatic) enclosure limits the loss of stray electrons from the region of the electron path E and thereby leads to a relatively high Paschen curve operation. The target **36,** when placed close in to the electron exit port **17** and/or when biassed as highly negative as is desired for high speed sputtering, tends to extinguish the plasma discharge which supports sputtering. This is resolved herein by the grid **16** which supports the plasma discharge independently of the anode and target electrodes. Collateral benefits of the grid in this context are that it attracts electrons that would otherwise escape in the space A and that it provides a very low voltage drop between itself and anode **30** and acts as a Paschen shield for the electron source chamber **14,** particularly its flange **17.**

In typical operation of the apparatus of FIG. 1, the grid **16** draws 4 amperes electron current and the anode **30** draws about 8 amperes electron current. The plasma around the electron path is stable and well confined and the entire bell jar has a remarkable absence of extraneous sparking.

Several variations may be made from the above described apparatus within the scope of the present invention.

FIGS. 3 and 4 for instance illustrate alternate sputter targets **336** and **436** which could replace the target **36** of FIG. 1. The substrate could be within either annular target **336** or **436** or outside the annular target **436.** Another variation is shown in FIGS. 3A–3B wherein the target **36** and substrate **34** are as in FIG. 1, but wherein curving metal side walls **323** are provided at ground potential or a low negative potential (e.g. minus 40 volts or less) to supplement the geometric and electrostatic enclosure. The FIG. 3 embodiment also shows a modified anode 33° with concentric cylindrical fins **331** extending therefrom. For purposes of defining the tight enclosure of the invention, the dimension B would be taken from the ends of fins.

Returning to FIG. 4, the modified target **436** comprises a cage made of rods **439** in a cylindrical array and mounted on two rings **435** and **437.** Coolant pipes are attached to each ring and the target voltage is applied to the coolant pipes. Doughnut form Paschen shields **434, 438** at ground potential surround the pipes.

Another embodiment of the invention based on FIG. 4 is shown in FIG. 5. In this embodiment a target **536** is formed of a cylindrical array of rods **539** mounted from rings **535, 537,** this arrangement for structural support, cooling and bias being the same as in FIG. 4. The toroidal Paschen shields **534, 538** are used here for anode and grid however, in addition to their shielding function. It is preferred however to add a plate **533** to the toroidal electrode **534** to make a complete anode assembly **530** which limits axial escape of electrons. But the top plate **533** can be omitted. Cooling pipes may now be provided for the "electrodes" **534, 538.** But it has been found that for many purposes radiation cooling to the cooled target rings **535, 537** is sufficient. In this FIG. 5 embodiment, of course, the above defined dimensions A and B approach zero and a very tight geometric electrostatic enclosure, consistent with large gas escape areas is obtained. Insulating supports (not shown) are used for mounting the target assembly from flange **17.**

TETRODE GRID STRUCTURE

The structure of the tetrode grid requires special attention. This contributes to the above described stability of operation and also plays a part in extending the operating range of the apparatus as now described.

The grid is the annular element **16** in the FIG. 1, FIG. 3, FIGS. 3A–3B and FIG. 4 species and the annular element **538** of the FIG. 5 species. This annular structure is in contrast to the mesh grid structure of the tetrode sputtering apparatus of Wehner described in the above cited U.S. Patent 3,021,271.

It has been discovered that the annular grid of the present invention, in addition to promoting operation of the system at pressures below 1 micron, also promotes operation at higher pressures. This behavior is illustrated in the curves of FIG. 6 wherein test data taken with the apparatus of FIG. 1 is plotted with operating pressure as the x-axis and maximum target voltage (before the discharge is extinguished) is shown. The various curves are taken with the grid currents indicated thereon. Grid voltages were varied to achieve these measured controlling currents. The bottom curve (I_G=0) is not part of the present invention. Rather, it indicates the base line from which to measure the contribution of the present invention shown by the upper curves. The performance of the apparatus above 2 microns pressure is a surprising benefit

of the annular grid structure not obtainable with the mesh grid structure of Wehner.

The reasons for these results are not entirely understood but can at least be generally attributed to two distinct functions of the grid which are in addition to starting and maintaining the electron discharge and shielding as described above. First the grid acts to reduce the length of voltage drop path from anode **30** to filament(s) **15**. Second the grid acts as an accelerator to extract electrons from the electron source structure **14**. The second characteristic is of prime importance at pressures below one micron. The first characteristic, together with a highly transparent grid structure (e.g. an annular grid), is of prime importance at pressures above one or two microns. The transparency of the grid allows a majority of accelerated electrons to get past the grid and into the plasma region despite higher gas density and diffusion obstacles.

FIG. 7 is a curve replotting the FIG. 6 data in terms of allowable target voltage range (*y*-axis) versus grid voltage (*x*-axis) at 3 microns pressure.

Many variations within the scope of the present invention will now be obvious to those skilled in the art. It is therefore intended that the above disclosure shall be read as illustrative and not in a limiting sense.

What is claimed is:

1. In a sputtering apparatus for use in a vacuum chamber with vacuum pumping means connected thereto, the combination comprising:

(a) an enclosed electron source chamber with an electron exit port, electron forming means inside said chamber,

(b) an anode electrode spaced from said electron exit port to form an electron path therebetween,

(c) a sputtering target electrode parallel to and spaced from said electron path,

(d) an intermediate electrode adjacent to the electron exit port for starting a discharge within the electron source chamber and drawing electrons therefrom,

(e) means including said target electrode forming a geometric and electrostatic enclosure for limiting loss of electrons from the zone of the electron path to provide a high Paschen curve location limiting extraneous voltage breakdowns in the vacuum chamber, and

(f) means for electrically biassing each of said anode and intermediate electrodes to about 10 to 40 volts, positive relative to said electron source and biassing said sputter target negative on the order of 1000 volts with respect to said electron source.

2. The apparatus of claim **1** comprising a coating substrate holder facing the sputter target electrode and forming part of said geometric enclosure.

3. The apparatus of claim **2** comrising plates arranged parallel to and straddling the electron path and forming, together with said target electrode and substrate holder an approximate annular enclosure.

4. The apparatus for claim **3** wherein said plates are constructed to be electrically floating to build up an electrical charge as stray electrons collect thereon to repel further stray electrons.

5. The apparatus of claim **1** wherein the said intermediate electrode has the form of a single turn loop of thick cross-section and cooling means connected to the intermediate electrode.

6. The apparatus of claim **1** with cooling means connected to said anode, target and intermediate electrodes and said electron chamber.

7. The apparatus of claim **1** with means for bleeding gas into said electron chamber.

8. The apparatus of claim **1** wherein said biassing means includes lead conductors passing into the vacuum chamber and extending to said anode, target and intemediate electrodes, at least said target electrode lead conductor being surrounded by a spaced conductive shield held at essentially the same potential as said electron chamber to avoid substantial voltage drops therebetween, and the said shield-conductor spacing being in the low PD region of the Paschen curve controlling discharge between shield and conductor whereby parasitic shield to conductor discharges are substantially avoided.

9. The apparatus of claim **1** wherein said geometric enclosure is formed by an annular target electrode.

10. The apparatus of claim **1** wherein said geometric enclosure is formed by supplementary electrode means which are negatively biassed to repel electrons leaving the zone of said electron path.

11. The apparatus of claim **1** further comprising a magnet producing a field in the zone of the electron path to further confine electrons to said zone.

12. In a sputtering apparatus for use in a vacuum chamber with vacuum pumping means connected thereto, the combination comprising:

(a) an enclosed electron source chamber with an electron exit port, electron forming means inside said chamber,

(b) an anode electrode spaced from said port to form an electron path therebetween,

(c) a sputtering target electrode parallel to and spaced from said electron path,

(d) an intermediate electrode adjacent to the electron exit port for starting a discharge within the electron source chamber and drawing electrons therefrom, the intermediate electrode being transparent to pass a majority of electrons into the electron path at pressures above one micron said intermediate electrode being at a voltage 10 to 40 volts positive relative to the voltage source.

13. The structure of claim **12** comprising an annular electrode as said intermediate electrode.

14. In combination,

(a) an enclosed electron source chamber of metal, said chamber having a T form with an exit port at the foot of the T and a flange extending outwardly from the port at least one electron emitter within said chamber,

(b) an anode electrode spaced from and opposing said electron exit port to form an axial electron path conforming to an extension of the exit port axis, means for cooling said anode,

(c) a sputtering target electrode parallel to and spaced from said electron path,

(d) an intermediate electrode of single turn loop form adjacent to the electron exit port for starting a discharge within the electron source chamber and drawing electrons therefrom,

(e) means including said target electrode forming a geometric and electrostatic enclosure for limiting loss of electrons from the zone of the electron path to provide a high Paschen curve location limiting extraneous voltage breakdowns in the vacuum chamber, the said enclosure being axial within two inches of the anode and within two inches of the electron exit port and with the total of said distance being less than about half the length of said target parallel to the electron path,

(f) electrical bias means for said electrodes comprising means for biassing said target to a high negative voltage on the order of 1000 volts with respect to ground, biassing said anode and intermediate electrode to a positive voltage on the order of 10 to 40 volts with respect to ground, said means including conductors extending to said electrodes, surrounded by metal shields, the said conductors being coolant carrying conduits and conductive shield means surrounding said conductors, and means for grounding said shields and electron chamber,

(g) means for bleeding gas into said electron chambers for exiting through said electron exit port and out through said geometric enclosure into the ambient region outside said enclosure,

(h) a vacuum chamber surrounding said enclosure and vacuum pumping means for removing gas from said chamber to define an ambient vacuum.

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