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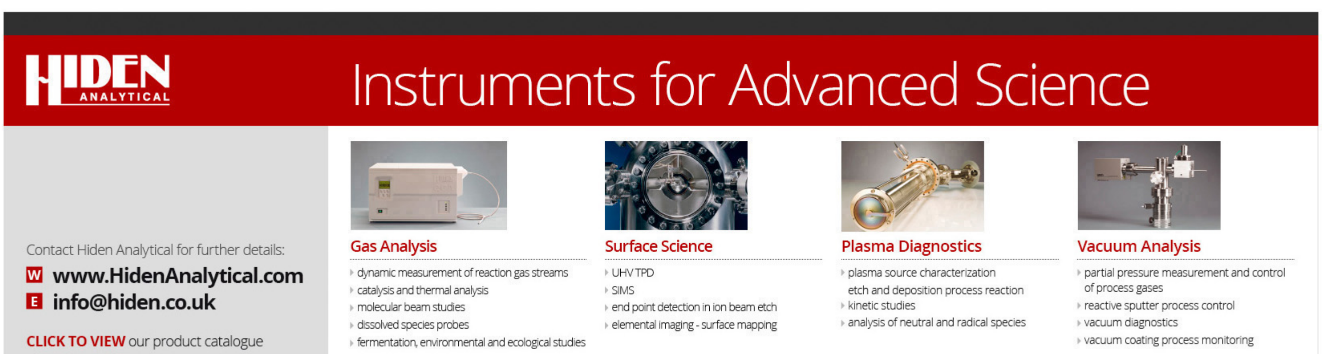

Charged particle fluxes from planar magnetron sputtering sources

B. Window and N. Savvides
CSIRO Division of Applied Physics, Sydney, Australia 2070

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We have investigated the charged particle fluxes from circular planar magnetrons with different magnetic field configurations and report measurements of the currents to earthed substrates, the substrate self-biasing voltages, the ion currents to substrates at − 100 V, and deposition rates as functions of axial and radial positions with respect to the target. The magnetrons fall into two classes, whose characteristics are explained in terms of electron motion in inhomogeneous magnetic fields. Both low and high electron/ion bombardment of the growing film can be achieved by small alterations to the magnetic field configuration.

I. INTRODUCTION

Magnetron sputtering has achieved widespread use in the past 10 years in the production of thin films at both the research and the industrial level.[1–5] One feature of magnetron sputtering which explains its wide use for the coating of plastic film is the low charged particle fluxes reaching a substrate. The charged particles in the plasma, particularly the electrons, are confined by the magnetic field at the cathode surface, and few electrons and ions reach the substrate. However, this is not true of all planar magnetrons, as we show in this paper, and care must be taken in designing a magnetron if this property is desired.

There is another class of industrial application, where there is a need for combined sputter sources—ion sources to deposit thin films with ion-beam assistance.[6,7] It is generally recognized that ion bombardment during the growth of thin films produces changes in the nucleation characteristics, in morphology, in composition, in crystallinity, and in the film stress. The changes are usually attributed to resputtering of the condensing species, or to increasing the adatom mobility, leading to modified microstructure of films at a given substrate temperature.[3,8] Particular processes where ion-beam assistance has proved valuable are the deposition of thin films for hard protective coatings,[9] for optical filters,[10] and for hard and wear resistant metallurgical coatings.[11–13]

We report here the results for seven planar magnetrons of essentially the same geometry but using different magnet designs. By altering the magnetic field configuration, thin film growth can be achieved with either low ion and/or electron bombardment, or bombardment by ions and/or electrons at a flux greater than, or equal to, that of the depositing neutral species. Parameters studied for the various designs include the deposition rates, the currents to probes at anode potential and at − 100 V bias, and the self-bias voltage acquired by a floating substrate.

II. EXPERIMENTAL TECHNIQUES

The aim of the experiments was to determine the effect of changing the magnetic field configuration in planar magnetrons while holding other parameters constant. The experiments were performed in a diffusion pumped chamber of dimensions 300 mm in diameter and 300 mm long, under an atmosphere of 1 Pa of argon. The target was a copper disk masked by an anode ring with an aperture of 75 mm diam. This diameter is an important dimension with respect to the geometry of the magnetic field. The discharge current was maintained at 300 mA (nominal) unless otherwise noted.

The basic magnetic geometry studied is shown in Fig. 1. It was achieved using electromagnets or permanent magnets, with soft iron where required. Situations covered by the two limiting cases shown in Fig. 1 were studied. In one extreme (type I), all the field lines originate from the central magnet, with some not passing into the annular magnet, and in the other extreme (type II), all the field lines originate on the

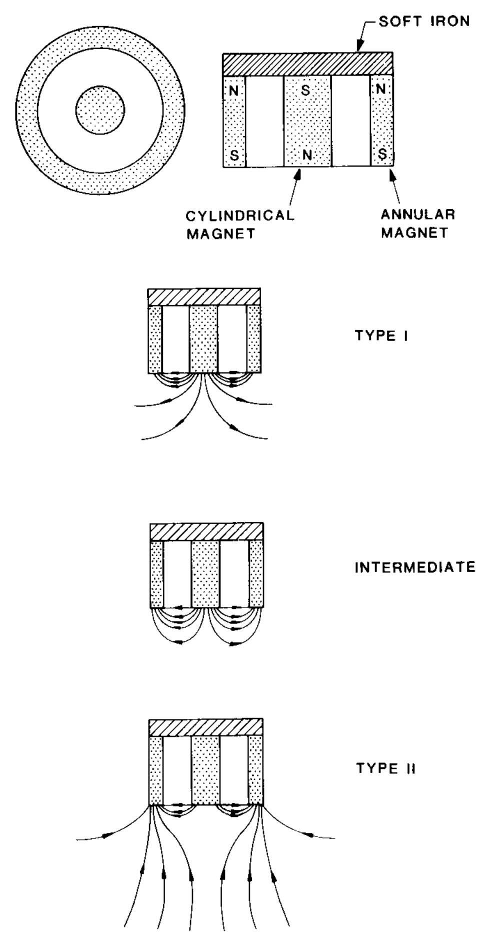

FIG. 1. Basic magnetic design used is shown at the top, in plan and in section. The three cases, type I, intermediate, and type II give different magnetic field patterns as shown.

annular magnet, with some not passing into the cylindrical central magnet. The intermediate special case, where all the field lines starting on the central pole finish on the annular pole, as shown in Fig. 1, cannot be achieved in practice, but can be closely approximated, particularly in larger magnetrons, by ensuring equal strength for the inner and outer poles.

The various configurations studied in detail or in part are shown in Fig. 2, together with a number code to identify them. Fixed magnetic field patterns close to type II were obtained using annular Alnico V permanent magnets (two sizes) (configurations 1 and 2) and electromagnets (configurations 6 and 7). Situations close to type I were obtained using electromagnets (configurations 3, 4, and 5); the magnetic material was mild steel. The back of the targets and the coils were water cooled. The geometry of the two electromagnet systems and the permanent magnet systems were kept similar to facilitate comparisons.

The charged particle fluxes from the discharge at various positions in the chamber were measured by probes designed to give results which would be meaningful in thin film depositon applications. The probe assembly consisted of a 100 mm diam metal disk which was attached to a 6 mm diam stainless steel tube as shown in Fig. 3. This tube entered the chamber through an electrical isolation feedthrough which kept it aligned along the axis of the sputter source, and allowed both translational and rotational motion. The behavior of such a probe represents the average behavior over a 100 mm diam disk substrate, except that charged particles also reach the back of the disk. This disk also was provided with five small probes, of 8 mm diam, which were electrically isolated from it. Their leads were brought out of vacuum by electrical feedthroughs (Fig. 3). One of the small probes was placed in the center of the 100 mm disk, and the four others were placed 10 mm apart along a radius of the 100 mm disk. These small disks were shielded at the back by the rest of the probe. When the average behavior across the 100 mm disk was required, all the probes were electrically connected to the 100 mm disk.

Deposition rates were determined by weighing 12.5 mm diam aluminium foil disks before and after coating.

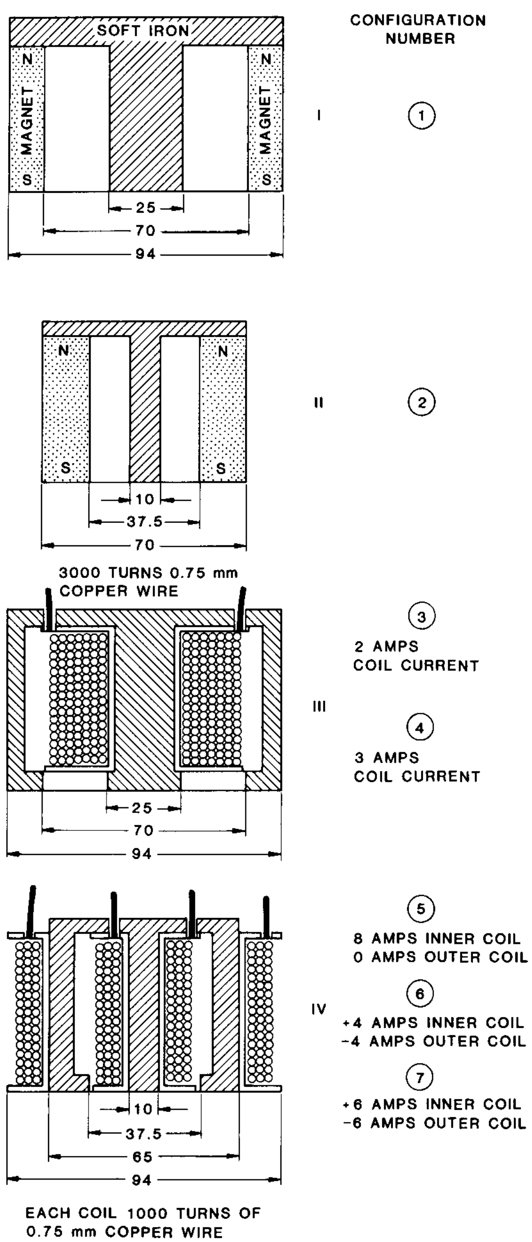

FIG. 2. Configurations studied are shown. They are identified by their configuration number later in the text. Configurations 1, 2, 6, and 7 are of type II, and configurations 3, 4, and 5 are of type I (see text).

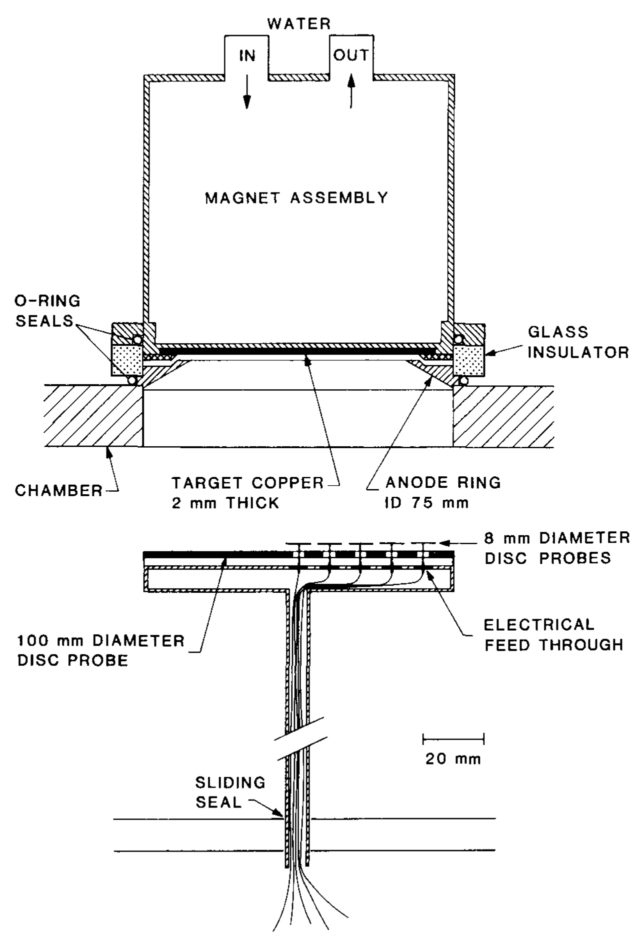

FIG. 3. Details of the magnetron design and the probe assembly are shown. The inner diameter of the anode ring was 75 mm. The electrical feedthroughs were cleaned regularly to maintain the insulation of the probes.

TABLE I. Results of 100 mm diam probe for 300 mA discharge current.

Configuration	Axial distance (mm)	Discharge voltage (V)	Probe self-bias voltage (V)	Probe earth current[a] (mA)	Probe − 100 V current[a] (mA)
1	60	400	− 25	264	− 22
	100	400	− 17	256	− 20
2	60	595	− 26	321	− 53
	100	595	− 16	318	− 30
3	60	410	+ 2.7	− 1.9	− 4.3
	100	410	+ 1.9	− 1.1	− 1.8
4	60	400	+ 3.3	− 1.9	− 4.6
	100	400	+ 2.4	− 1.1	− 1.9
5	60	595	+ 0.4	− 1.1	− 3.7
	100	595	+ 0.4	− 0.5	− 2.0
6	60	540	− 28	308	− 66
	100	540	− 20	311	− 25
7	60	490	− 33	307	− 94
	100	490	− 23	317	− 42

[a] Positive current corresponds to electron flow into the probe.

III. RESULTS

A. Initial observations

Two interesting features were noted in experiments on magnetrons of the type II design. First, earthed substrate platforms mounted on the target axis collected currents almost equal to the total discharge current, i.e., nearly all the electron current from the discharge reached this surface which was at the same potential as the anode. Second, when discharges from this type of magnetron were viewed side-on, a column of plasma could be seen extending down the axis towards the substrates. This column was sensitive to the presence of magnets near the substrate platform.

B. Studies with large probe

Using the 100 mm probe, measurements were made for source-to-substrate distances of 60 and 100 mm of the following quantities for the various magnetic field configurations: (i) The discharge voltage (cathode to anode) at a fixed cathode discharge current of 300 mA. (ii) The self-bias voltage of the probe. (iii) The current to the probe held at anode potential (ground). (iv) The current to the probe held at − 100 V bias.

The results are shown inTable I for the various configurations; certain results stand out. Type I (configurations 3, 4, and 5) systems have small positive self-bias voltages, low negative ground currents, and low negative currents at − 100 V bias. (The sign convention for Table I is such that electrons flowing to the probe from the discharge give a positive current.) Type II systems have large negative self-bias voltages, large positive ground currents, and appreciable negative currents at − 100 V bias.

C. Studies with small probes

These features were investigated on a finer scale using the small 8 mm probes to provide axial and radial information. All the probes were treated in the same way during any measurement, i.e., when determining the current into the central probe at − 100 V, all the other probes and the 100 mm diam probe were also biased to the same voltage.

The results for some of the magnetic field configurations shown in Fig. 2 are presented in Figs. 4–7. Figure 4 shows the currents into the central probe at − 100 V bias as a function of axial distance from the source, while Fig. 5 shows the

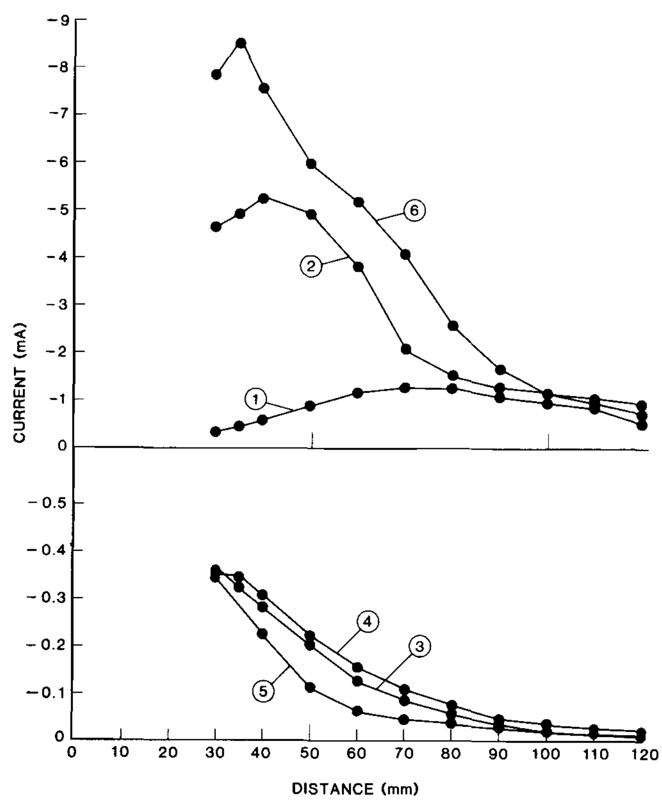

FIG. 4. Ion currents into the central 8 mm diam probe at − 100 V as a function of axial distance from the cathode surface are shown for the various magnetic field configurations. (Positive current corresponds to the electron flow into the probe.)

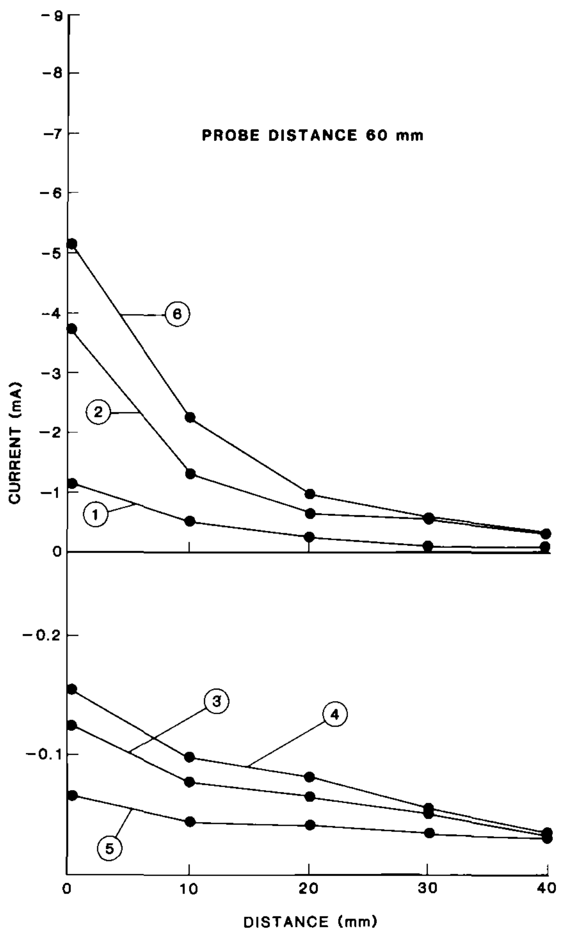

FIG. 5. Ion currents into the five 8 mm probes at − 100 V bias and 60 cm axial distance from the surface of the cathode are plotted against the radial position of the probe for various configurations.

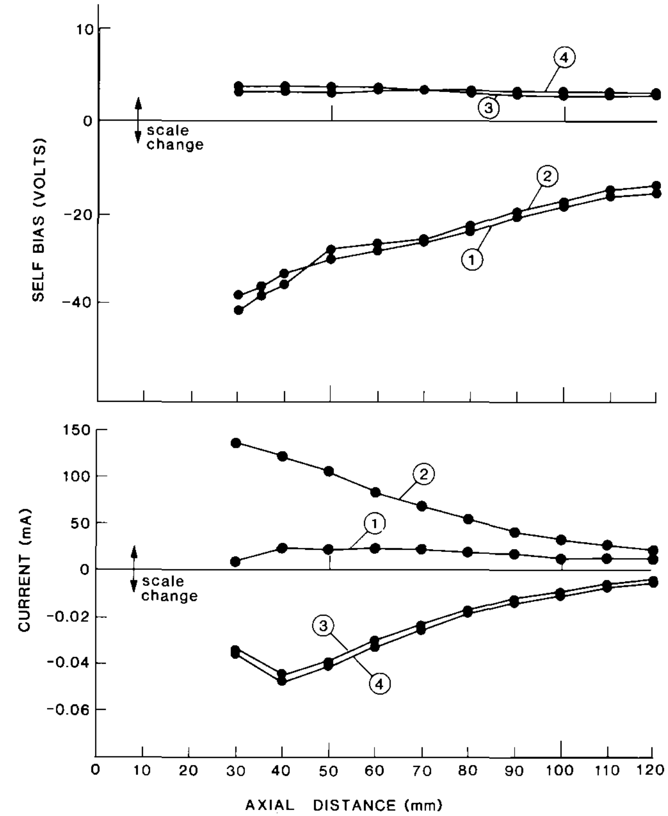

FIG. 6. Currents into the central 8 mm probe when grounded (at anode potential) and the self-bias voltages for this probe are shown as functions of the axial position of the probe from the cathode surface for various configurations.

radial dependence of this current at an axial distance of 60 mm from the source. Figure 6 shows the current into the central probe when earthed, and its self-bias voltage, both as functions of the axial position. Figure 7 shows the deposition rates (only for configurations 1 and 2), the self-bias voltages, and the current to an earthed probe as a function of the radial position of the probe at a source-to-probe distance of 60 mm.

IV. DISCUSSION

The data presented in Table I and Figs. 4–7 are essentially three points on the voltage–current characteristic of the probe inserted in the plasma. The theory of probes in plasmas, particularly when magnetic fields are present, is complex,[14–17] and we have chosen this rather limited set of data rather than the full probe characteristic on the basis of their relevance to thin film deposition.

A simplified probe characteristic typically of that observed is shown in Fig. 8, with the three special points marked. The physical interpetation and significance of these quantities are as follows:

(i) Current at − 100 V bias. This current is essentially just the flux of ions diffusing to the probe from the plasma region, which is typically an approximate equipotential area with a voltage of + 2 to + 20 V above the anode voltage.[16,17] A bias voltage of − 100 V is adopted for this measurement, as it is sufficiently negative to repel nearly all the electrons in the plasma and yet not so negative that ions bombarding the probe produce significant secondary electron emission. This ion current persists at all voltages up to the plasma potential, and is approximately constant (Fig. 8). These particles are most effective in modifying thin film growth, dissipating their energy close to the surface.

(ii) Floating probe potential. As the potential approaches the plasma potential from − 100 V, the probe starts to collect electrons as well as ions. At zero net current to the probe, the ion current will be approximately as measured in (i), and the electron current will be equal to it.

This self-bias voltage is important in thin film deposition because it gives the potential reached by an insulating substrate. The growing film will then be bombarded with ions of energy equal to their charge times the voltage difference between the self-bias potential and the plasma potential, and by an equal flux of electrons.

(iii) Current into probe at anode potential. This is the net difference between the electron and the ion currents reaching the probe. Many depositions are made on grounded substrates, and the growing film will be bombarded with approximately the same number of ions as when biased at − 100 V, each with an energy corresponding to the plama potential, which is typically 2–10 V,[17] and a compensating number of electrons. A small current does *not* mean no bombardment.

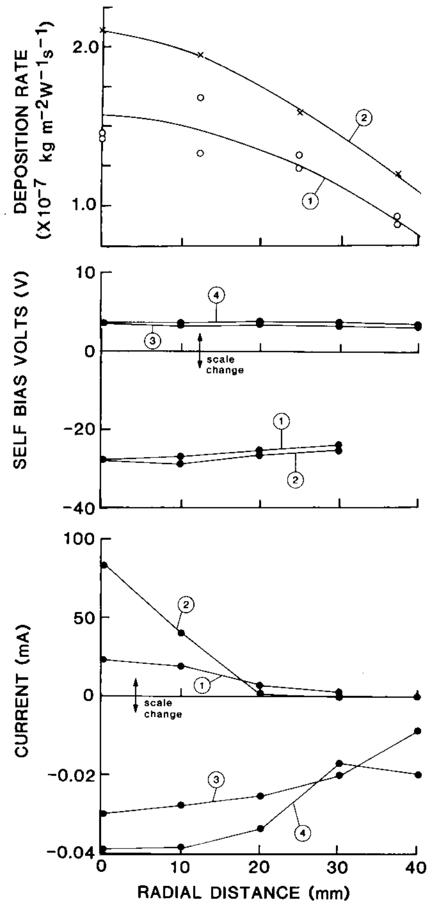

FIG. 7. Deposition rates per unit discharge power for copper films, the probe currents when grounded (at anode potential), and the probe self-bias potentials are shown as functions of the radial position for an axial distance of 60 mm from the cathode for the various configurations.

Our data show the wide range of ion currents and electron currents that is attainable in planar magnetron systems, depending on the magnetic field pattern. The general assumption that magnetron deposition is accompanied by minimal substrate bombardment is clearly false for type II systems. The maximum electron current flowing to a large substrate can be all the discharge current, and the available ion flux can exceed the actual deposition flux. For example, a deposition rate of 2×10^{-7} kg m^{-2} W^{-1} s^{-1} for copper (Fig. 7) corresponds to a flux of copper atoms on an 8 mm diam disk of 1.4×10^{16} s^{-1}, for a discharge power of 150 W (500 V at 0.3 A). Under these conditions, dense copper films would be deposited at 0.2 μm/min. An ion current of 5 mA (Fig. 4) corresponds to a particle flux of 3×10^{16} s^{-1}. Thus, for a substrate mounted on the axis of the magnetron and at a distance of 60 mm from it, the ion flux density for configuration 2 is twice the deposition flux density, and for configuration 5 it is only 0.025% of the deposition flux density. Away from the axis, the ion current is still substantial for the type II magnetrons. The high fluxes are sufficient to modify growth, and are comparable to what can be achieved with the smaller Kaufman ion sources, i.e., 20 mA/cm^2.

Published work on ion fluxes from magnetically confined discharges is minimal. Schiller *et al.*[18] reported that for most dc magnetrons, presumably of the balanced type, the ion fluxes are typically 5%–10% of the deposition flux. There have been some studies using rf magnetrons of the effect of extra magnetic fields on the bombardment of substrates[19,20]; the details of the supply of ions and electrons are different for the rf and dc discharges. The only relevant work on dc magnetrons is that by Fraser and Cook,[21] who report using magnets under the substrate in "aiding" or "opposing" configurations to affect the ion flux at the substrate. It is not clear whether the basic magnetron was of type I or II in these experiments.

The behavior of the probes in the glow discharges of the two different types of magnetrons can be understood in terms of the motion of electrons in the inhomogeneous electric and magnetic fields. The theory is covered in a number of texts.[22,23]

The discharge in the type I magnetron is confined basically in the magnetic tunnel defined by the cathode surface and the surface defined by the last field line which cuts the anode surface. The electrons move from near the cathode to this surface by collisions, and should be collected by the anode. In agreement with the observations, few electrons should reach the substrates. However, we have ignored what is probably an important effect. The anode ring is in a region of high magnetic field (Figs. 2 and 3), and many electrons approaching the anode would be reflected by the magnetic mirror back towards the central pole. Collisions will result in their moving outwards, and ultimately they will reach the anode and the walls of the chamber. This effect will produce a small flux at the substrate or probe. Because the flux of electrons is low, the probe self-biases only slightly negative with respect to the plasma (it is above anode potential) (Figs. 6 and 7). This self-bias voltage increases slightly towards the plasma potential (Fig. 7) and the ion flux decreases (Fig. 5) with radial distance. This means that the electron flux must decrease from the center of the target. This is consistent with the magnetic field pattern; at the edge of the 100 mm disk, the magnetic field lines are approximate-

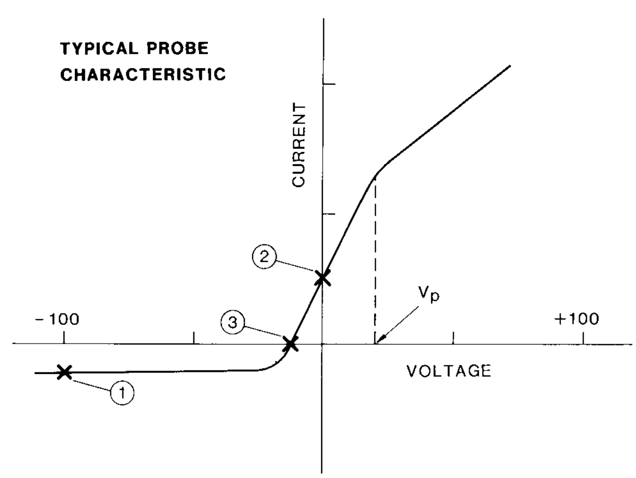

FIG. 8. Form of probe characteristic curve expected in a typical magnetron system is shown. The special points marked are (1) probe current at -100 V bias, (2) probe current at zero bias, and (3) self-bias potential of the probe. The plasma potential V_p is typically $+5$ to $+20$ V.

ly parallel to the probe, giving low fluxes because the electron mobility across the field lines is low.

The type II magnetrons are more complex in their behavior. As already mentioned, a discharge is clearly visible below the usual magnetron trap. The results in Table I show that a current equal to the discharge current passes through the 100 mm probe when it is at anode potential. Calibration of the meter used to measure the discharge current yielded a current of 310 mA rather than the nominal 300 mA, i.e., the probe collected more current than was flowing through the cathode for the configuration 2. Considering that the ion flux was also present, the current of electrons to this probe must be considerably higher than the cathode current. Photoelectrons from the walls of the chamber produced by radiation from the glow discharge must find their way to the probe (the back is not shielded).

The discharge is basically operating in the magnetron mode in the tunnel region over the cathode. Electrons are scattered out of the tunnel region, and the first surface at anode potential cutting the field lines will be the anode ring for configuration 1, and the probe electrode (substrate) for configurations 2, 6, and 7 (Figs. 1, 2,3). Thus it is expected for configurations 2, 6, and 7 that a probe at anode potential at the substrate position will collect all the electron current, as is observed. Even for configuration 1, the compression of the magnetic field lines towards the anode ring will reflect most electrons, resulting in a probe at anode potential at the substrate position gathering nearly all the electrons; this is also observed (Table I). In both situations, the highest flux will be in the center, as field lines at the center are the first encountered by the electrons as they scatter out of the magnetic tunnel. In the case of configuration 2, a current equal to the entire cathode current passes through a 40 mm diam disk.

The motion of electrons will act to increase the ion flux at the probe because of the ambipolar nature of the diffusion.[17] However, there is yet another important effect operating to produce a secondary discharge in front of the magnetron tunnel discharge. Besides the constriction of field lines at the anode, there is also a constriction of field lines towards the probe past the minimum in the field (Fig. 1). This compression, the cathode surface, and the anode compression will form an electron trap, and electrons being scattered from the main magnetron discharge will oscillate along the field lines between these regions. They will further ionize the argon gas, leading to a secondary discharge supported by electrons from the main discharge.

This supported discharge is near the substrates or probe, and contributes to the ion flux. The glow produced by this discharge is readily observable. The axial dependence of the ion current has a maximum for these configurations (Fig. 4). As the probe approaches the cathode the ion current increases until the probe starts to interfere with the magnetic mirror geometry.

Because of the flux of electrons, floating substrates self-bias strongly negative with respect to the plasma (Figs. 6 and 7). Assuming the plasma is at $+10$ V with respect to the anode,[16] the ions striking a self-biased substrate will have about 40 eV of energy, sufficient to modify substantially the growth of films. For magnetrons of type I, the ion current is smaller by a factor of nearly 100, and the self-bias energy is about 7 eV. Thus the ratio of energies delivered by ions to insulating films by the two types of sources is 400.

V. CONCLUSIONS

These results have important ramifications for magnetron designs. We have shown that on each side of a balanced magnetic arrangement there are two classes of unbalanced magnetic designs which we have called type I and type II. Type I, with a strong central magnet, gives low ion and electron fluxes at substrates and low self-bias potentials. Type II, with a strong outside magnet, gives large ion and electron fluxes at substrates and high self-bias potentials, but with considerable variation across the substrate plane. The magnetic field configuration can be varied to change the operation between type I and type II and to adjust the flux of electrons or ions.

Planar magnetrons giving either low bombardment of growing films (as is required for critical electronic applications), or very high bombardment of growing films (to promote chemical reactions, and to modifiy the structure or preferred orientation as is required for metallurgical coatings), can be designed. The energy of ions incident on conducting substrates can be varied independently of the ion flux by biasing the substrates with respect to the plasma. It is also possible to change the type of operation during deposition as required. For example, the deposition can be started in type II mode to clean the substrates, to promote adhesion or to produce preferred orientation, and changed to type I mode during the depostion to encourage the growth of a columnar microstructure.

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