Magnetron sputtering: basic physics and application to cylindrical magnetrons

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Magnetron sputtering sources can be defined as diode devices in which magnetic fields are used in concert with the cathode surface to form electron traps which are so configured that the **E**×**B** electron-drift currents close on themselves. Coaxial cylindrical magnetron sputtering sources in which post or hollow cathodes are operated in axial magnetic fields have been reported for a number of years. However, their performance is limited by end losses. A remarkable performance is achieved when the end losses are eliminated by proper shaping of the magnetic field or by using suitably placed electron-reflecting surfaces. High currents and sputtering rates can be obtained, nearly independent of voltage, even at low pressures. This characterizes what has been defined as the *magnetron mode* of operation. This paper reviews the basic principles that underly the operation of dc sputtering sources in the magnetron mode with particular emphasis on cylindrical magnetrons. The important attributes of these devices as sputtering sources are also reviewed.

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I. INTRODUCTION

Magnetron sputtering sources can be defined as diode devices in which magnetic fields are used in concert with the cathode surface to form electron traps which are so configured that the **E** × **B** electron-drift currents can close on themselves.[1] Cylindrical sputtering sources with post[2–10] or hollow[11] cathodes, coaxial anodes, and axial magnetic fields have been reported for a number of years. Their configurations, shown in Figs. 1(a) and (b), are of a general magnetron form, but their performance is limited by end losses. Remarkable performance is achieved when the end losses are eliminated by proper shaping of the magnetic field, as for example in the configurations shown in Figs. 1(c) and (d), or by using suitably placed electron reflecting surfaces as shown in Figs. 1(e) and (f). High currents and sputtering rates can be obtained, at moderate and near constant voltages, even at low pressures. This characterizes what has been defined as the *magnetron mode of operation.*[1] It can also be obtained for plasma rings magnetically confined over planar surfaces (planar magnetrons)[12] or over short cylinders or within cylindrical surface cavities (sputter guns).[13]

Cylindrical magnetron configurations have been used for microwave oscillators,[14–16] pressure gauges,[17–20] and sputter ion pumps.[21–23] The first operation in the magnetron mode for sputtering appears to have been achieved by Penning and Moubis using the configurations of Figs. 1(e)[24] and (f).[25] Very active development of cylindrical magnetron sputtering technology has occurred over the period from 1969 to the present.[1] This work has involved primarily the dc operation of apparatus of the basic types shown in Figs. 1(c),[26–28] (d),[26,28] (e),[27,28–36] and (f),[28,29,31–33] although rf operation has been explored with both the post- and hollow-cathode configurations.[1,28]

This paper reviews the basic principles that underlie the operation of dc sputtering sources in the magnetron mode. The discussion concentrates on the cylindrical magnetrons with post cathodes and electrostatic reflecting surfaces [Fig. 1(e)] because these devices possess a relatively simple geometry. Following previous nomenclature[1] these devices, and their inverted counterparts [Fig. 1(f)], will be referred to as cylindrical-post and cylindrical-hollow magnetrons, respectively. However, the discussion also applies to other cylindrical magnetrons and generally to planar magnetrons and sputter guns.

SI units are used except for electron energies and temperatures which are expressed in eV. (1 eV = 11 600 K.)

II. SOME BASIC CONCEPTS FROM PLASMA PHYSICS

A glow discharge plasma can be defined as a region of relatively low-temperature gas in which a degree of ionization is sustained by the presence of energetic electrons. Such plasmas are neutral and their state is characterized by (1) the degree of ionization $\alpha = N_e/(N_i + N_A)$, where N_e is the electron density, $N_i = N_e$ is the ion density, and N_A is the gas density; and (2) the electron energy distribution, which can often be approximated by an electron temperature T_e. The long-range Coulomb forces between charged particles give plasmas a propensity for collective behavior.[37,38] A condition for dominance of Coulomb collisions is that $\alpha \gg 1.7 \times 10^{16}\sigma_{eA} T_e^{\,2}$, where σ_{eA} is the electron–atom collision cross section.[39] Electrostatic waves can be expected to develop if the plasma angular frequency, defined as $\omega_p = 56.4\, N_e^{1/2}$, is much larger than the electron–atom collision frequency. Another important parameter, the Debye length $\lambda_D = 7430\ (T_e/N_e)^{1/2}$, provides a measure of the distance over which significant

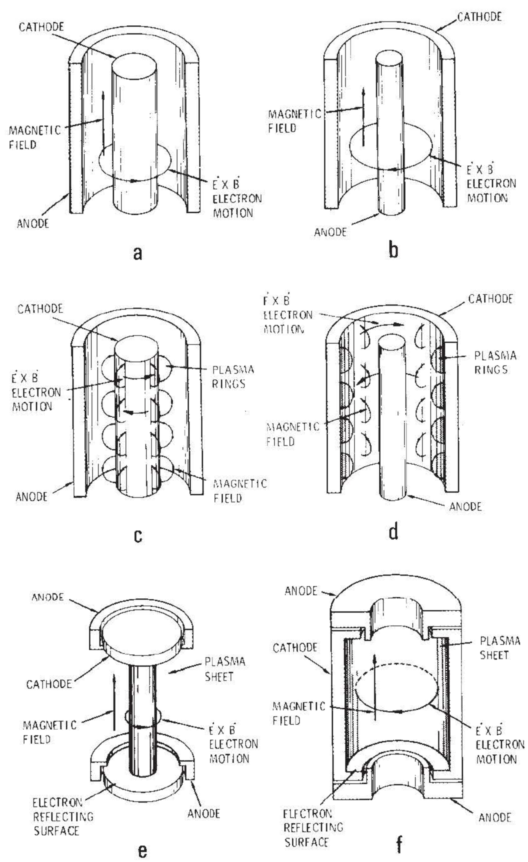

FIG. 1. The configuration of various cylindrical magnetron sputtering sources. (a) and (b) have general magnetron configurations but do not operate in the magnetron mode because of end losses. (b), (d), and (f) are often called inverted magnetrons and sometimes hollow cathodes. e is referred to here as a cylindrical-post magnetron and f as a cylindrical-hollow magnetron.

departures from charge neutrality can occur. Magnetron plasmas generally have higher degrees of ionization and are much richer in collective behavior than are the plasmas in conventional planar diode sputtering sources.

Despite the importance of collective phenomena an examination of single-particle motion[37–42] provides useful insight into the behavior of magnetron plasmas. Only the electrons are significantly influenced by magnetic fields of the strengths used in magnetron mode sputtering sources. An electron in a uniform magnetic field B will drift along the field lines with a speed $v_{\|}$ that is unaffected by the field, and orbit them at a gyro or Larmor radius ($r_g = 3.37 \times 10^{-6} W_{\perp}^{1/2}/B$), and with a gyro or cyclotron angular frequency ($\omega_c = 1.76 \times 10^{11} B$), where $W_{\perp}$ is the energy associated with the electron motion perpendicular to the field [see Fig. 2(a)]. When there is a component of electric field $E_{\perp}$ perpendicular to **B**, a drift of speed $v_E = E_{\perp}/B$ develops in a direction perpendicular to both $E_{\perp}$ and **B** and combines with the orbiting motion as shown in Fig. 2(b). This is the **E** × **B** drift. The motion of an electron created at rest in uniform and perpendicular **E** and **B** fields is the cycloid generated by a circle of radius $r_g(v_E)$ moving with velocity v_E as shown in Fig. 2(c), where $r_g(v_E)$ is the value obtained by setting $W_{\perp} = \frac{1}{2} m_e v_E^2$. Electrons are emitted from a magnetron cathode with energies that are small compared to that acquired as they are accelerated through the cathode dark space (CDS). However, their motion is not exactly cycloidal because the CDS electric field is not uniform. In general, the distance to the turning point d_t will exceed the CDS thickness d_s, as shown in Fig. 2(d). For planar cathodes, d_t equals the r_g value that is obtained with $W_{\perp}$ set equal to the CDS voltage drop.[43] For thin sheaths ($d_s \ll r_g$) over cylindrical cathodes of radius R_0, the turning distance d_t varies from r_g, when $R_0 \gg d_t$, to $2r_g$, when $R_0 \ll d_t$ as shown in Fig. 2(e).[43]

Curved magnetic fields of the type shown in Figs. 1(c) and (d) have a perpendicular gradient $\nabla B_{\perp}$ and a parallel gradient $\nabla B_{\|}$, as shown in Fig. 2(f). Electrons in such a field experience a $\nabla B_{\perp} \times \mathbf{B}$ drift that is proportional to $v_{\perp}^2$. This combines with an identically directed drift, due to the centrifugal force associated with the speed $v_{\|}$, and yields a drift identified as v_D in Fig. 2(f).[44] Electrons tend to conserve their magnetic moment μ_M ($\mu_M = m_e v_{\perp}^2/B$). Thus conservation of energy may cause electrons passing in the direction of $\nabla B_{\|}$ to be reflected by the magnetic field[45] before they reach the cathode surface.

Important collective behavior includes charged particle

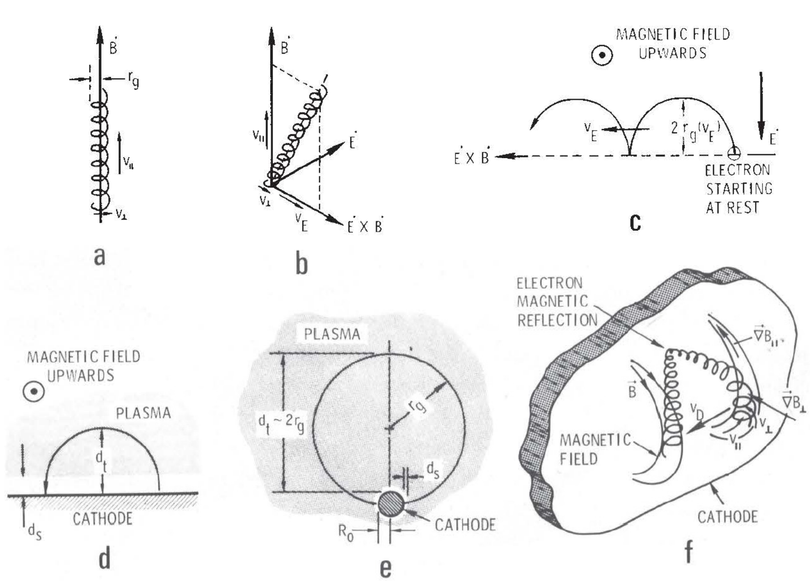

FIG. 2. Electron motion in static electric and magnetic fields.

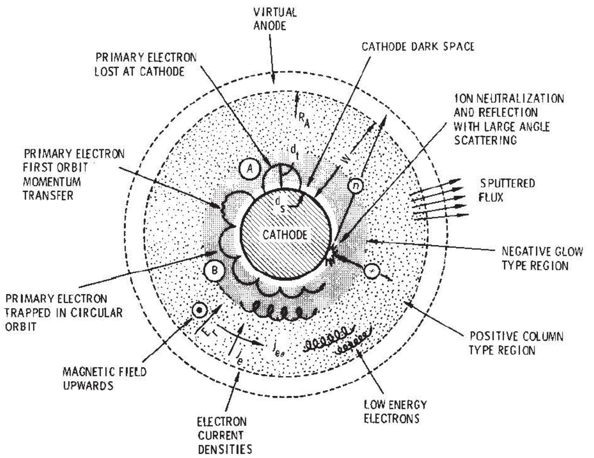

FIG. 3. Schematic representation of electron transport processes in a cold-cathode discharge between a cylindrical cathode and a coaxial anode in a uniform axial magnetic field [configuration shown in Fig. 1(e)].

current flow and diffusion, sheath formation, and plasma oscillations. When an electric field $E_\perp$ is applied perpendicular to a magnetic field of sufficient strength to affect the electrons but not the ions, a current density

$$J_\perp = eN_e\mu_{e\perp}E_\perp + eN_i\mu_{i\perp}E_\perp \qquad (1)$$

will flow in the direction of $\mathbf{E}_\perp$ and an electron Hall current[46]

$$J_H = \omega_c/\nu_e\, J_{e\perp} = \omega_c/\nu_e\, eN_e\, \mu_{e\perp}\, E_\perp \qquad (2)$$

will flow in the $\mathbf{E}\times\mathbf{B}$ direction. In Eq. (1) the mobility perpendicular to the magnetic field is given by[47]

$$\mu_\perp = \mu/[1 + (\omega_c/\nu)^2], \qquad (3)$$

where $\mu = e/(m\nu)$ is the mobility in the absence of a magnetic field or along a field line ($\mu_\|$) and ν is the collision frequency for the species in question (m and e are the appropriate mass and charge). The diffusion coefficients can be written as $D = \mu kT/e$ (k is Boltzman constant) and therefore obey relationships similar to Eq. (3).[47–48]

Because of their difference in mass, electrons and ions tend to pass from a plasma to an adjacent surface at different rates. Thus a space charge region or sheath, in which one species is largely excluded, forms adjacent to such surfaces.[49] The potential variation between the surface and the plasma is largely confined to this layer. The nature of the sheath depends on the current passing across it. Therefore the current density at the anode establishes the anode sheath voltage drop and thus the plasma potential. For floating surfaces the sheath potential drop is the well-known floating potential and is negative (relative to plasma potential) except for cases where the magnetic field causes the total electron flux to be less than the ion flux. The CDS is a positive space charge sheath (negative potential drop relative to plasma). The ion current density J_i is related to the sheath thickness d_s and potential drop V_s by the Child–Langmuir law[37] [first term at right in Eq. (4)] and approximately to the plasma electron density and temperature by the Bohm relationship[37,50] (second term at right):

$$J_i = 8.6\times10^{-9}\left(\frac{40}{M}\right)^{1/2}\frac{V_s^{3/2}}{d_s^2} = 1.48\times10^{-16}\,N_e\left(\frac{40T_e}{M}\right)^{1/2} A/m^2, \qquad (4)$$

where M is the ion molecular weight.

The plasma state is rich in wave phenomena, particularly when a magnetic field is present.[37,38,51] Electron electrostatic waves can propagate along field lines with frequencies of the order of ω_p, or across field lines with a frequency of the order of $(\omega_p{}^2 + \omega_c{}^2)^{1/2}$. Ion electrostatic waves can pass in all directions at a velocity of the order of $(kT_e/m_i)^{1/2}$. Electron drifts perpendicular to the magnetic field develop in the presence of a perpendicular electric field, as discussed above, or a density gradient.[37] Such drifts are inherently unstable, since any departure from charge neutrality in the form of charge bunching and separation (over distances of the order of the Debye length) create electric fields which cause second-order $\mathbf{E}\times\mathbf{B}$ drifts that can exacerbate the perturbation. These instabilities are often referred to as gradient–drift and neutral-drag instabilities.[52] Thus a charge perturbation associated with the azimuthal J_θ Hall current in a cylindrical magnetron can cause an E_θ perturbation field which interacts with the axial magnetic field B_z, to produce radial electron drift waves.[53–55] Drifts driven by the two density gradients associated with a maximum in the radial electron density distribution can interact to cause the diocotron instability.[56–58] If feedback mechanisms are present, the oscillations associated with these instabilities can grow to produce macroscopic motions capable of enhancing electron transport across the magnetic field.

Plasma instabilities can also be important in permitting a collisionless energy exchange within a plasma. Examples are the two-stream instability and Landau damping.[37,38] Evidence of such energy transfer has been seen between primary electrons and the negative glow over thermionic cathodes.[59,60]

Plasma oscillations and instabilities are believed to play an important role in the operation of magnetrons, as will be discussed in the next section.[61–71]

III. THE PLASMA DISCHARGE

Consider a cold-cathode magnetron mode discharge in a cylindrical-post magnetron of the type shown in Fig. 1(e). The discharge cross section in the r–θ plane (cylindrical coordinates) is shown in Fig. 3. The uniform axial magnetic field is assumed to be of such strength that $d_s < d_t < W$ and $\omega_c \gg \nu$, where W is the width of the end reflector.

A low-pressure cold-cathode discharge is maintained primarily by secondary electrons emitted from the cathode by ion bombardment. These electrons are accelerated in the CDS and enter the plasma where, known as primary electrons, they must produce sufficient ions to release one further electron from the cathode.[72] This requirement can be expressed by the following relationship for the minimum potential to sustain such a discharge:[73]

$$V_{\min} = \mathcal{E}_0/\Gamma_i\epsilon_i\epsilon_e \qquad (5)$$

where Γ_i is the number of secondary electrons per incident ion which leave the cathode, $\mathcal{E}_0$ is the average energy required for producing ions (about 30 eV for Ar^+ [74]), ϵ_i is the ion collection efficiency, and ϵ_e is the fraction of the full complement of ions $V/\mathcal{E}_0$ that is made by the average primary electron before it is lost from the system. The primary electrons are emitted from the cathode with energies of a few eV[75] and move in cycloidal-like trajectories, as shown at A in Fig. 3. There is a strong probability of recapture at the cathode, since the path length is much smaller than the mean free path. Furthermore the retarding field reduces the returning electron energy to a value which is generally too low to produce significant secondary electron emission. It is believed that the recapture probability is reduced by interactions with plasma oscillations. On a random phase basis about one-half will undergo an interaction which promotes their return to the cathode, while about half will exchange sufficient momentum so that they cannot return. Γ_i is called the effective secondary emission coefficient.[76–78] It is equal to the secondary emission coefficient due to ion bombardment γ_i times a factor which accounts for the probability of recapture. γ_i is typically $1/10$ for low-energy argon ions incident on metal surfaces. Γ_i is perhaps close to $1/20$ for the cylindrical cathode surface. Secondary emission from the end reflectors (unaffected by the magnetic field) is of little significance in most geometries because of the relatively small end-reflector area in contact with the intense plasma.

Primary electrons which enter the plasma are believed to become trapped on cycloidal-like paths which orbit but do not reach the cathode, as shown at B in Fig. 3. Collisions in the radial electric field beyond the CDS and plasma oscillations cause the electrons to migrate to the anode. Such discharges exhibit a bright glow which extends a distance of about $2d_t$ from the cathode, and a dimmer glow from there to the anode. The bright glow is believed to be the main region of energy exchange for the primary electrons. Thus, following conventional terminology,[72,79] the regions can be identified as having negative glow and positive column-type characteristics, respectively. Since the primary electrons can escape the magnetic trap only by exchanging energy, $\epsilon_e \sim 1$; and since the primary energy exchange is close to the cathode, $\epsilon_i \sim 1$. Thus magnetron discharges are very efficient and operate in Ar at voltages near the $V_{\min}$ of 600 V predicted by Eq. (5) for $\epsilon_0 = 30$ eV/ion and $\Gamma_i = 1/20$ (see Sec. IV). The high operating voltages of conventional planar diode sources result from low values of ϵ_e and ϵ_i.[1]

A typical cylindrical magnetron discharge operates at a pressure of 0.13 Pa (1 mTorr) with a magnetic field strength of 0.02 T (200 G). Thus $\omega_c = 3.5 \times 10^9$ rad/s. The total electron–atom cross section of electrons of a typical energy of 10 eV in argon is about 2×10^{19} m^2,[1,74] and the collision frequency ν is about 10^7 s^{-1}. Thus $\omega_c/\nu \sim 300$. Accordingly, the Hall current density, Eq. (2), is significant and electrons circle the cathode many times in passing to the anode. The total Hall current is typically an order of magnitude larger than the discharge current and constitutes a solenoidal current that can cause a reduction of the magnetic field strength in the vicinity of the cathode by ~10%.

Equation (3) predicts $\mu_{e\perp} \sim 10^{-5}\mu_e$ at $\omega_c/\nu \sim 300$. If the electron mobility were this low, it would be less than the Ar ion mobility, and operation of the discharge in the positive space charge mode would be endangered.[1] Similarly, the radial current predicted by Eq. (1) (using measured values for $E_\perp$ and N_e in the vicinity of the anode) or by electron diffusion (using electron density gradients estimated from probe measurements) fails to account for the discharge current by a factor of more than two orders of magnitude.[80] The answer to these dilemmas is believed to be plasma oscillations which promote electron migration across magnetic fields strong enough to restrain the motion of the primary electrons.[1] Oscillations at frequencies in the 50–500 kHz range, with a maximum frequency that varies inversely with the square root of the working gas atomic mass, have been detected using electrostatic probes in cylindrical-post magnetrons operating with Ar, O_2, and He.[80] This frequency range is consistent with electrostatic ion waves oscillating in the discharge cavity and about equal to the ion–ion collision frequency.

Electrostatic probe measurements of the electron density in the discharge region are consistent with Eq. (4) and indicate that the degree of ionization is a few percent or less. At low pressures the primary electrons in a well-designed trap are estimated to travel as much as 100 m before their energy is totally exchanged although, as with conventional negative glows, the primary electron density is typically only a few percent of the density of ions and low-energy electrons. Atom flux calculations indicate that an average atom passing through the discharge region of a cylindrical-post magnetron must have a 1% to 30% chance of being ionized, depending on the discharge current.[1] Probabilities of being either excited or ionized arc about twice as large. This is particularly relevant to reactive sputtering.

The anode in a magnetron should be placed within the magnetic field so that it terminates the trap at a point where the primary electrons have dissipated their energy.[1] Anode placement is aided by the fact that $\mu_{e\parallel} \gg \mu_{e\perp}$. Thus all electrons reaching the radius R_A in Fig. 3 are swept into the anode; i.e., a virtual anode, that does not disrupt the sputtered flux, separates the substrates from the plasma and reduces plasma substrate heating (ions are electrostatically forced to stay in the vicinity of the electrons). An anode of insufficient size or with poor placement can cause a significant anode voltage drop.

IV. CURRENT–VOLTAGE CHARACTERISTICS

The current–voltage characteristic reveals a great deal about the ionization processes in a plasma discharge. Discharges operating in the magnetron mode obey an I–V relationship of the form $I \propto V^n$, where n is an index to the performance of the electron trap and is typically in the range 5 to 9. The voltage is related to the ionization mechanisms by Eq. (5).

Typical I–V curves for cylindrical-post magnetrons operating with various magnetic field strengths and pressures are shown in Fig. 4 and compared with a I–V curve for a planar diode. If the magnetic field is too weak, the discharge will leave the magnetron mode and the voltage will increase abruptly, as shown at A.[1,24,35] Figure 5 shows the variation in

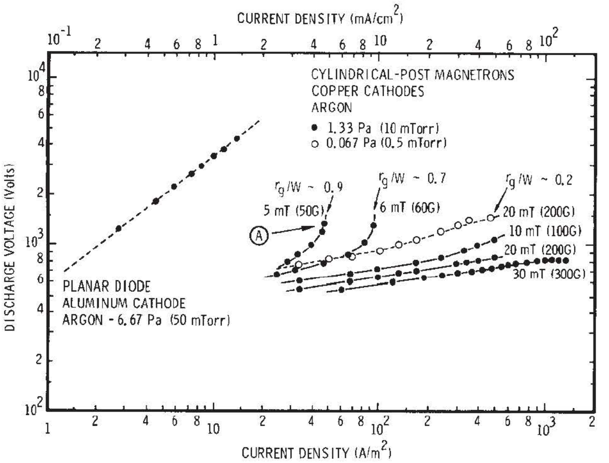

FIG. 4. Typical current voltage characteristics for a planar diode sputtering source and for cylindrical-post magnetron sputtering sources operating under various conditions of pressure and magnetic field strength.

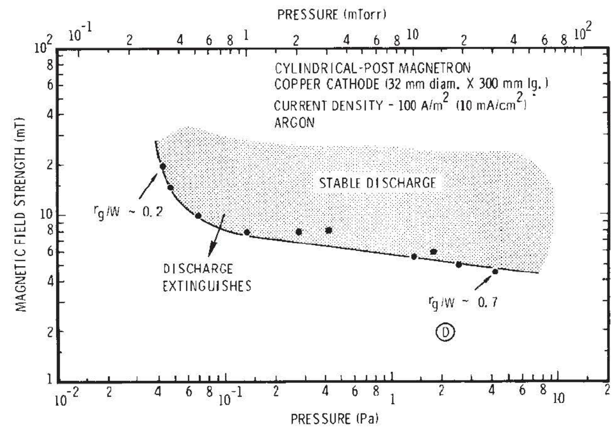

FIG. 6. Conditions of pressure and magnetic field strength for stable operation of a representative cylindrical-post magnetron at fixed current (from Ref. 1).

voltage with pressure at constant magnetic field strength. A similar abrupt voltage increase is seen at B. These voltage behaviors are a result of electrons escaping from the trap without making sufficient ionization (low ϵ_e), because their gyro radii are too large compared to the end reflector size W. At high magnetic field strengths the discharge will extinguish if the pressure is too low, as seen at C in Fig. 5. This is believed to be the result of electrons not exchanging sufficient momentum with the plasma during their first cycloidal orbit (low Γ_i). Note that the low-pressure extinction is surprisingly independent of gas species (i.e., collision cross section). This is attributed to the role of plasma oscillations in establishing Γ_i. Figure 6 summarizes the pressure-magnetic field requirements of a small cylindrical-post magnetron operating at a current density of 100 A/m^2. Increasing the magnetic field strength lowers the allowable operating pressure until the length of the first cyloidal orbit becomes too small to permit adequate energy exchange. At normal operating pressures (>0.07 Pa) low field strengths can be used for larger devices (design requirement is that W be a mutliple of r_g[1,29]).

At a fixed voltage and magnetic field strength the current increases with pressure (more collision targets). At a fixed voltage and pressure the current increases with magnetic field strength (higher ϵ_i), at least for moderate fields (<20 mT). An electrostatic probe placed over the anode of a cylindrical-post magnetron operating at 700 V indicated that the primary electrons had exchanged essentially all of their energy in the discharge, therefore implying that $\epsilon_e \sim 1$.[81] Taking $\Gamma_i = 1/20$ and $\mathcal{E}_0 = 30$ eV/ion, in Eq. (5) yields $\epsilon_i \sim 0.9$. This ion-collection efficiency is generally consistent with electrostatic probe measurements at positions beyond the virtual anode.

With proper choice of magnetic field, magnetron mode operation with a near common I–V characteristic has been achieved for a wide range of apparatus sizes in both cylindrical-post and cylindrical-hollow configurations.[1]

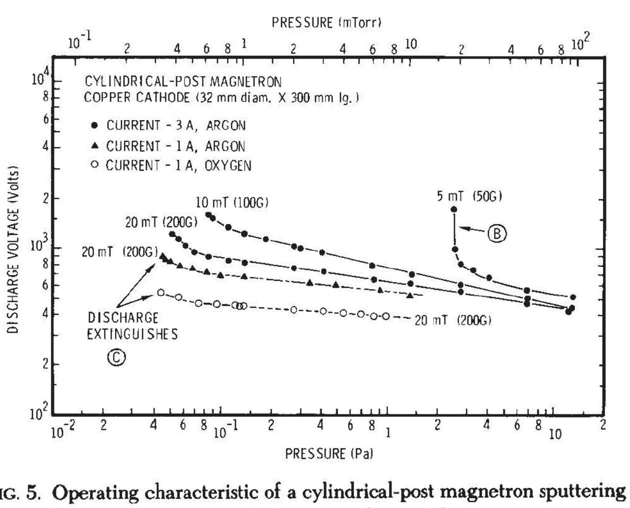

FIG. 5. Operating characteristic of a cylindrical-post magnetron sputtering source, showing the variation of discharge voltage with pressure at constant discharge current and magnetic field strength (from Ref. 1).

V. PERFORMANCE AS SPUTTERING SOURCE

With sufficiently uniform magnetic fields, the cylindrical magnetron configurations shown in Figs. 1(e) and 1(f) provide uniform sputtering over the cathode surface. This has been verified by measuring the cathode erosion profiles after extended sputtering.[1,82] (Reports of nonuniform erosion are believed to be due to nonuniform magnetic fields.[35]) A large inventory of coating material can be stored in a cylindrical target and used efficiently. Current densities are typically 50 to 500 A/m^2 with erosion rates of 33 nm/s and deposition rates of 3.3 nm/s (2000 Å/min). However, a copper cylindrical-post cathode has been operated with a uniform current density of over 2000 A/m^2 and an erosion rate of over 333 nm/s (200 000 Å/min).

At typical operating pressures the sputtered flux passes to substrates with little gas scattering. This has been verified by observing the post-cathode images that are formed by the coatings on substrates placed behind shields with small apertures in pin-hole camera configurations.[1] Thus mechanical masks can be effectively used to accurately define deposition areas. The deposition flux at various points surrounding a post cathode can be predicted with considerable accuracy by assuming a uniform cathode current density and a cosine emission of sputtered flux with collisionless transport.[83]

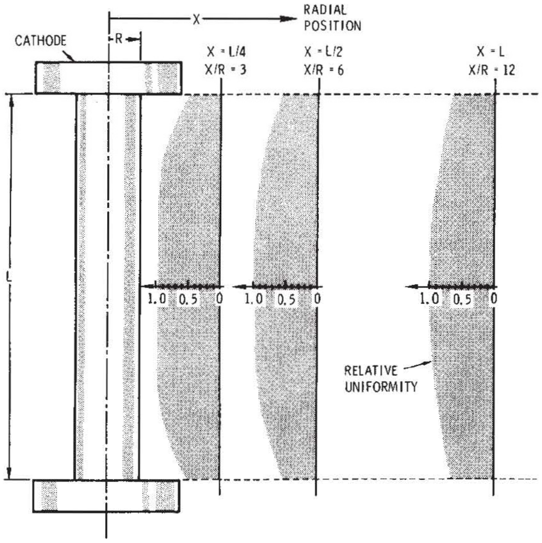

FIG. 7. Theoretical coating uniformity profiles at various radii surrounding a cylindrical-post magnetron sputtering source with a uniform cathode current density. Cosine emission and collisionless transport are assumed. Profiles show the influence of end effects. Absolute deposition rate incorporates an X/R dependence not shown. Such profiles have been verified experimentally.[83]

Typical calculated profiles are shown in Fig. 7. A hollow cathode with uniform cosine emission has the interesting characteristic that the coating flux at all points within the cathode that are unaffected by end losses is equal to the cathode erosion flux, independent of the working gas pressure.[84] This behavior has been experimentally verified.[84] It makes hollow cathodes particularly effective for coating objects of complex shape. All surfaces having an unobstructed view of the cathode receive a uniform coating.

An important attribute of magnetrons is the reduced substrate plasma bombardment. No primary electrons reach substrates located at radii beyond the virtual anode of a cylindrical post magnetron. Floating potentials are a few volts positive with respect to the anode. Ion densities are typically 50–100 times less than in the discharge. When sputtering metals, ion bombardment fluxes are typically only about 1/10 to 1/5 of the deposition flux, even with a negative substrate bias. Therefore, auxiliary discharges are generally required for sputter cleaning and bias sputtering.[34] In the case of cylindrical-hollow magnetrons the charged particle density on the axis is typically 1/3 that adjacent to the target surface. Floating potentials are −20 to −50 V relative to the anode. For metals the ion diffusion flux to the substrate is typically 1/5–1/3 the sputtered atom flux.

The substrate heating is much reduced in cylindrical-post magnetrons by the absence of plasma bombardment. Plastics and other heat-sensitive substrates can be effectively coated.[85] The heating flux has been found to be proportional to the sputtered flux and to vary from 15 to 25 eV/atom for metals such as Ti, Cr, and Cu, to about 50 eV/atom for heavy metals such as Mo, Ta, and W, where ion neutralization and reflection[86–89] become more significant and where the sputtered atom KE is larger.[90] Atom reflection is believed to be relatively important for cylindrical-post magnetrons because of the low operating pressure and the fact that ions undergoing reflections of considerably less than 180° pass in the direction of the substrates[1] as indicated in Fig. 3.

VI. SUMMARY

An operation defined as the magnetron mode can be achieved in diode sputtering sources that are configured so that magnetic fields in concert with the cathode surface form electron traps of such geometry that the **E** × **B** electron-drift currents close on themselves. The ionization process is very efficient, and high currents and sputtering rates can be achieved at relatively low voltages, even at low pressures. Plasma collective behavior is believed to play an important role in the discharge operation.

Uniform current densities can be achieved over post or hollow cathodes, thereby permitting a large inventory of coating material to be stored and efficiently used. Post cathodes can be scaled to large sizes, permitting large areas to be uniformly coated. Hollow cathodes are effective for coating substrates of complex shape. Substrate plasma bombardment is much reduced, particularly with cylindrical-post magnetrons.

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