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Magnetron sputtering

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ABSTRACT

Magnetron sputtering developed rapidly in the 1980s for semiconductor, hard coating, and architectural glass applications. While the general operating principles were well known, subtle issues relating to cathode material, operating parameters, and deposition processes were only empirically understood. A sequence of magnetron measurements is described, which helps develop a more general understanding. The plasma is mostly conventional but is strongly perturbed by the large fluxes of energetic, neutral atoms sputtered from the cathode, which alter the gas dynamics as well as the discharge impedance. These studies have led to practical innovations, such as collimation and ionization of the sputtered atoms, which have been widely used for semiconductor manufacturing applications.

I. INTRODUCTION

Magnetron sputter deposition, after a contentious start, developed rapidly in the late 1970s and early 1980s for the high deposition rate of blanket metal films. Three major applications drove this development: integrated circuit metallization, hard coatings on cutting tools, and coatings on glass for architectural and heat management purposes. Most of the work to be discussed here relates to the first topic.

Magnetrons have a long history and the term has had several meanings. Originally, the devices were radar sources at microwave frequencies in the years prior to and during World War II. Later, the term was used broadly for the 2.45 GHz sources in conventional microwave ovens, of which more than a billion have been fabricated. The term is sometimes used for a magnetic electrical transducer used in small gasoline engines, and I once owned a gas lawnmower with a magnetic inductive coil, which was labeled as "magnetron-powered."

This manuscript will focus on the early understanding of magnetrons used for sputtering, followed by several diagnostic measurements undertaken to enhance this understanding. The implications and impact on thin film processing will be described followed by how this may have led to later developments in wide usage today. This work, which was recognized for the 1990 Peter Mark Award, was primarily focused on the diagnostic studies in the late 1980s.

II. EXPERIMENT

A. Plasma background

The plasmas used for thin film deposition have typically a cathode and anode configured in a vacuum system filled with a sub-atmospheric pressure of gas. In the DC version, the cathode is metallic, the anode is often the grounded chamber walls, and the cathode is biased negatively to many hundreds or thousands of volts. At a high voltage, some of the gas atoms or molecules in the chamber are ionized (positively) and accelerated at high energy to the (negative) cathode surface. As the ion impacts the cathode surface, it may physically erode or sputter neutral atoms from the surface. A small fraction of the bombarding ions may also generate a secondary electron, which is then accelerated away from the cathode and into the plasma at high energy. This energetic electron can cause additional ionization of the gas, which replaces the ions lost to the cathode and forms a steady state plasma.

The secondary electron yield, gamma, is low, typically a few percent. At steady state, for a given power supplied to the cathode, the voltage on the cathode adjusts such that the secondary electrons receive enough energy to lead to the ionization of 1/gamma atoms or molecules. The ionization cross section for most gases is low,[1] so for a simple DC diode, a high gas pressure (density) is needed, typically many Torrs and a voltage of >-1000 V. In a practical sense, high voltages cause safety issues, but more importantly, the high gas pressure strongly inhibits the sputtered cathode atoms from getting to the sample location due to scattering, resulting in a low deposition rate.

A magnetron refers to a diode plasma cathode in which a magnetic field is configured parallel to the cathode surface. This lateral magnetic field induces a Hall Effect, or **E**x**B** (**E** cross **B**) drift of electrons parallel to the cathode surface, but orthogonal to the magnetic field. In a magnetron plasma device, this drift path is organized to close on itself, forming a loop of drifting electrons (Fig. 1).[2] The result of this trap for electrons is a much longer path length for the energetic electrons in the region near the cathode, and this results in much higher levels of ionizing collisions with gas atoms or molecules than with an unmagnetized cathode. The higher ionization efficiency allows up to a 1000× reduction in gas pressure, greatly facilitating the transport of sputtered atoms and hence the deposition rate. The operating voltage is also lower, typically −300 to −500 VDC, which reduces some, but not all, electrical safety concerns. The discharge currents can be fairly high, amperes to tens of amperes. It is this large current that leads to the high sputtering and hence deposition rates desired for practical applications.

The closed-loop **ExB** effect can be organized for a surprising number of geometries and dimensions; the only design constraint is a magnetic field parallel to the cathode surface such that the Hall drift current closes on itself. A common configuration is a circular planar magnetron, which is a thin, circular cathode behind which is an array of magnets with a center pole of one polarity and the second pole near the perimeter of the disk. At intermediate cathode radius, the B field is parallel to the cathode and the drift path forms a circle. The drift path forms a locally very dense plasma near the cathode, and ions from this plasma that reach the cathode sheath are accelerated to the cathode to both sputter the surface and induce secondary electron emission, sustaining the plasma.

A variation on the circular planar device is the rectangular planar magnetron, which simply stretches the circular device to form a long rectangle with circular ends.[3] Devices as long as several meters are routinely used for coating large glass panels for windows or flat panel displays. Another, less common geometry is a cylindrical magnetron in which the cathode is a long, hollow cylinder with a single magnet inside, forming a North and South magnetic pole at each end of the cylinder (Fig. 2).[3] In this case, the **ExB** drift path is a sheet going around the cylinder. This gives a broad, uniform sputtered flux on the inside of a chamber or a large tube, for example, although the rate is low due to the geometry. A variation on this geometry uses segmented, offset magnets such that the **ExB** drift path is now a spiral around the cylinder. Rotation of the magnet assembly inside the cathode cylinder causes the spiral path to rotate, and the effect is like a "barber-pole" sign.[4] Intrinsic to all magnetron designs is the incorporation of water cooling of the cathode due to the high incident power. A general rule with

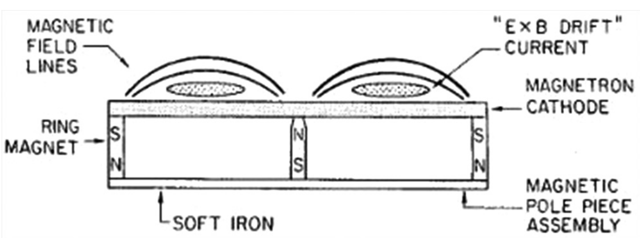

FIG. 1. Cross section of circular planar magnetron. Reprinted with permission from Rossnagel and Kaufman, J. Vac. Sci. Technol. A **5**, 88 (1987). Copyright 1987, American Vacuum Society.

magnetron sputtering systems is that 90% or more of the incident discharge power is used to heat the circulating water. Sputtering is a rather inefficient process.

B. Semiconductor processing applications

The earliest fabrication sequence for metal layers and connecting lines on a semiconductor wafer used thin film photoresist masks on the surface of the wafer. After optical exposure, wet chemical processing left a pattern opened in the resist with slight overhangs at the top edges of the resist, forming a re-entrant sidewall. Metal deposition, using evaporation at low pressure, is a line-of-sight process, which deposited films both on the resist surface as well as on the wafer surface in the openings. The top edges of the overhanging resist blocked metal deposition on the resist sidewalls. A subsequent wet chemical step could then dissolve the exposed resist via the sidewalls and removed or "lifted-off" the unwanted film on the resist surface, leaving the patterned deposit behind.

This technology did not scale well to either production or larger wafers. Evaporation was done in large, cubical systems known as "boxcar" evaporators, often larger than 1 m on a side with a sample-holding dome of over 1 m diameter with many tens of wafers at a time. Evaporative deposition requires low pressure, typically 10^{-7} Torr or better, to reduce in-flight gas scattering of the evaporated metal atoms. After loading a dome of samples, pump down times were often 10 h or more (typically overnight). Scaling to larger wafers required a larger source-to-wafer distance to preclude sidewall deposition and center-to-edge changes on a wafer, resulting in even larger chambers and longer pumping times. This type of batch processing also fell out of favor in manufacturing applications because of the risk of a problem compromising a large number of samples with a fault of some type and the lengthy pumping delays reducing throughput. A secondary limitation was the ability to deposit alloys, requiring careful, side-by-side operation of two sources at controlled rates to give the correct composition. While done routinely in a laboratory setting, this was very challenging for any manufacturing application.

The solution was a subtractive approach in which metal films are deposited as continuous blanket layers. These layers are then subtractively patterned with a resist and the unwanted areas etched away using reactive ion etching (RIE). It was this evolution that drove the rapid development of magnetrons in the 1980s, first as bulk systems with many wafers on a tray under one or more magnetrons and then as a single-wafer, integrated processing approach with deposition chambers only slightly larger than the wafers running at a high deposition rate.

Magnetron sputtering was ideal for this fabrication approach. The depositing flux was from an extended area, not a point, with a short cathode-to-sample distance, and this led to a deposition that gently covered over edges and steps forming a continuous, smooth film. Magnetrons were also designed with a moving array of magnets behind the cathode, which enhanced uniformity and increased the useable lifetime and metal utilization of the cathode.[5] Sputter deposition also allowed the usage of alloy targets, which after an initial conditioning time deposited the bulk composition of the target as an alloy film. Magnetron sputtering became the standard approach for metal deposition for semiconductor wafers in the

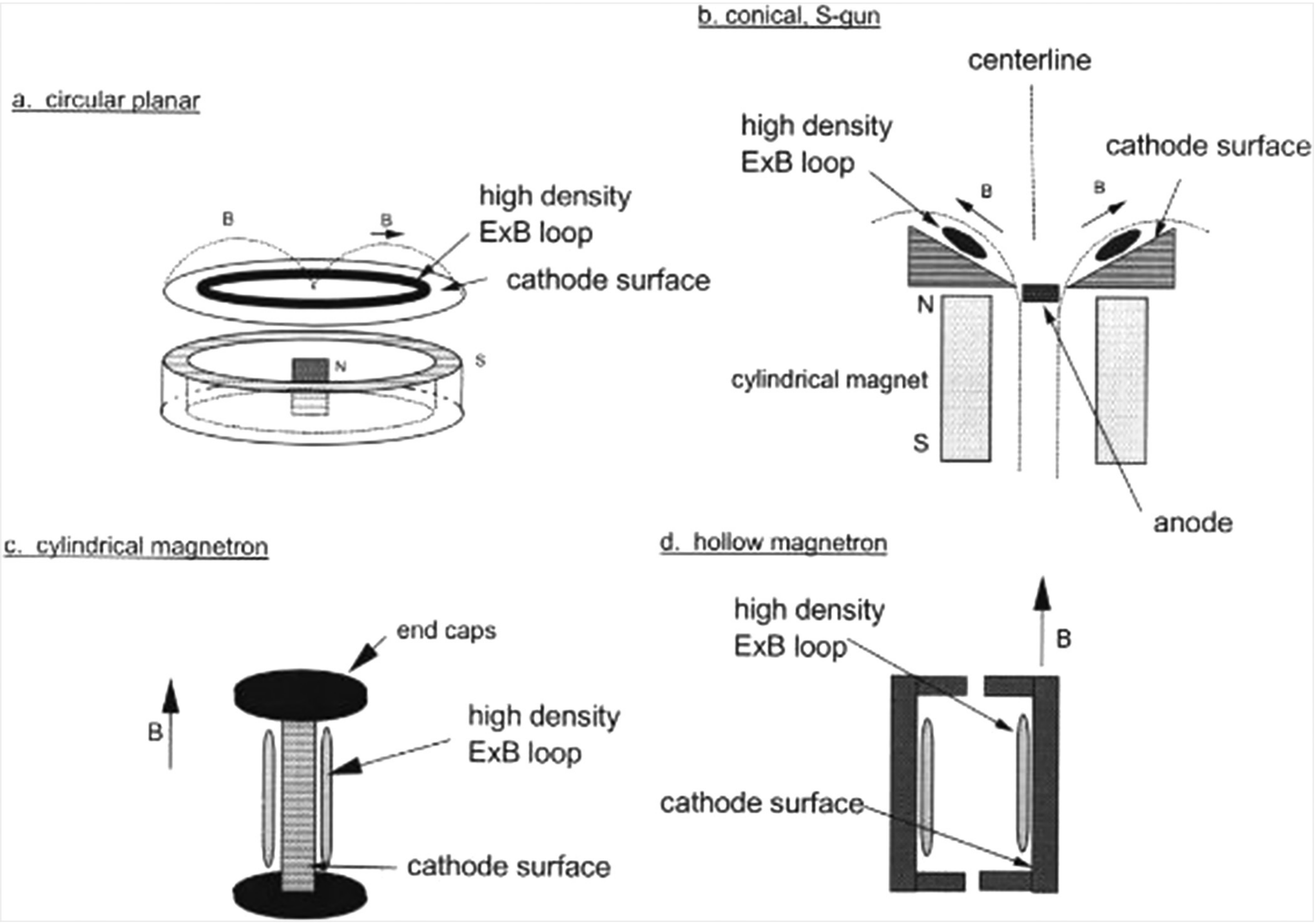

FIG. 2 Various geometries of magnetron sputtering devices. Reprinted with permission from Rossnagel, J. Vac. Sci. Technol. **21**, S74 (2003). Copyright 2003, American Vacuum Society.

late 1980s through the mid-1990s, and most research focused instead on RIE, which was very challenging for some metals with low vapor pressure products, such as Cu. This subtractive integration approach was limited by the topographic modulation of the surface caused by dielectric deposition over lines and other structures. The surface modulation reduced the optical exposure precision for patterning, which limited the approach to two–three metal-insulator layers, adequate for some DRAM devices, but not sufficient for microprocessors.

The third, and current, generation of semiconductor integration is known as damascene and is based on a surface with a planar dielectric layer. Patterning and RIE are used to form vias and trenches in this dielectric layer.[6] The trenches and vias are then filled with metal and subsequently physically and chemically polished back to the original dielectric surface leaving an embedded metal via or line, or both (known as dual damascene). The result is a planar surface onto which the next dielectric film is deposited for the next metal layer. This self-planarizing approach allows fabrication of many tens of layers of metal lines and vias. Unfortunately, the same wide-angle deposition flux from the magnetron that made high step coverage films for RIE-based subtractive patterning is very poor at deposition into holes and trenches. Due to the wide range of arrival angles of the sputtered atoms, deposition at the top edge of the trench or via is very rapid and this quickly closes the feature leaving an embedded void. Thus, magnetrons required significant changes to be compatible with damascene processing. Much work was done to develop various CVD approaches to avoid this problem, but these were difficult for the materials needed for Cu interconnect integration.

The initial steps to address this new integration scheme were to develop a means to operate a magnetron in a more line-of-sight mode. Initially, this used a small magnetron and a much longer distance between the magnetron cathode and the sample (tens of cm),[7] known as "long-throw" deposition. However, it also required a much lower pressure to reduce gas scattering of the sputtered atoms. To counteract the reduced ionization efficiency of the secondary electrons at very low pressure, a second electron source was used to add many additional energetic electrons into the magnetron plasma.[7] A hot, hollow cathode source was used to add many amperes of 50 eV electrons near the cathode, and this allowed operation in the magnetron mode down to the 10^{-5} Torr range. This was sufficient to demonstrate a lift-off deposition, although lift-off was effectively obsolete by that time (1988). However, the directional nature of the deposition did turn out to be useful for damascene approaches, at least for thin films. Due to the lack of in-flight gas scattering and the long-throw geometry, the depositing atoms at the sample were mostly normal incidence. The overhang depositions on the top edges of the vias and trenches developed much more slowly or not at all, allowing deposition deep into features. In effect, the non-normal incidence sputtered atoms were deposited on the chamber walls and only the normally incident atoms made it to the sample.

To be compatible with large wafer, high rate single-wafer manufacturing, this long-throw, small magnetron enhanced plasma approach was insufficient: too slow and non-uniform. Two developments helped solve this: more efficient magnetron design with higher magnetic fields allowed somewhat lower pressure operation (1 mTorr),[5] and the use of a physical collimator between the cathode and the wafer collected the sputtered atoms, which were not vertically incident onto the wafer surface[8] (Fig. 3). For short throw distances (10 cm), pressures around 1 mTorr, and high powers, the deposition through the collimator was effectively line-of-sight. While used sparingly for filling via and trench features, it was widely applied to the thin adhesion, diffusion barrier, and seed layer films on the sidewalls, all required for damascene integration. A principal limitation was the deposition rate because 65%–95% of the sputtered atoms were deposited on the collimator, not the wafer. For thin (5–50 nm) barrier and adhesion layer films, this was not a problem, but for filling micrometer-scale vias and trenches, it was not practical and damascene technology used electroplated copper on sputtered seed layers for filling.

The intrinsic inefficiency of collimated sputter deposition was a production concern in manufacturing. The bulk of the sputtered atoms landed on the collimator, not the sample. As a result, the collimators clogged over time with deposited films, and the cathodes and collimators had to be changed much more often. Each effect led to increased cost and tool downtime for maintenance.

A solution to this problem came with the use of a second plasma source in the chamber, this time configured in the volume between the magnetron and the sample[9,10] (Fig. 4). The role of this second plasma was to ionize the sputtered metal atoms in-flight from the cathode to the sample, a process known generically as I-PVD. Due to the nature of plasmas, a thin, low voltage sheath was present parallel to the wafer surface. When metal ions approached this sheath at any angle, they were accelerated at a few eV vertically to the wafer surface. In effect, their random, sputtered direction was straightened out by the wafer sheath, and the entire ionized flux arrived at normal incidence to the wafer surface. The operating pressure that led to the highest levels of ionization was typically 20–35 mTorr, which is much higher than the 1–3 mTorr used for conventional sputtering. This high gas pressure was needed to slow the energetic sputtered atoms by gas thermalization, allowing them to remain in the plasma region longer and have a higher probability for ionization (Fig. 5).[9,10] Ionization levels of nearly 90% of the depositing flux have been observed. An additional advantage of this approach was that the sample could be biased negatively of the plasma potential (near ground potential), and this accelerated the depositing metal ions to the sample surface at higher kinetic energy, potentially allowing resputtering and redistribution of the deposited films. A range of materials and deposition issues have been developed.[11,12] This I-PVD development allowed the wide usage of magnetrons for liner-seed films in interconnect and contact applications across the semiconductor industry. There were many later permutations of the basic I-PVD approach using alternate geometries and high-power pulsing.

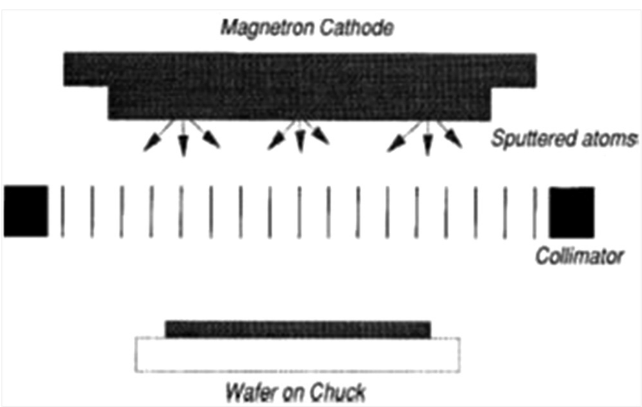

FIG. 3. Cross section of a collimator configured between the magnetron cathode and a sample. Adapted with permission from Rossnagel *et al.*, J. Vac. Sci. Technol. A **9**, 261 (1991). Copyright 1991, American Vacuum Society.

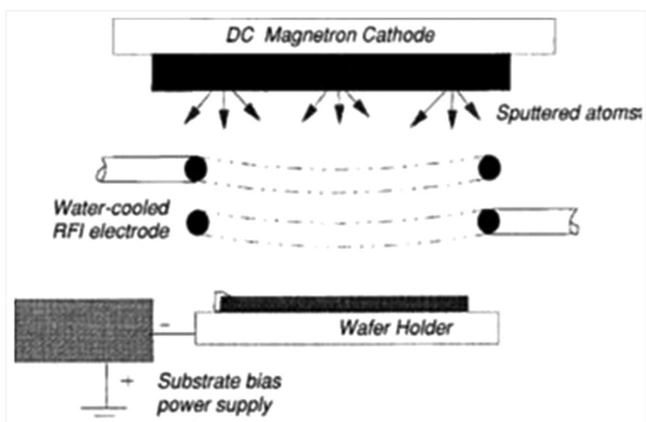

FIG. 4. Ionized magnetron deposition system (Ref. 9). Adapted with permission from Rossnagel and Hopwood, J. Vac. Sci. Technol. B **12**, 449 (1994). Copyright 1994, American Vacuum Society.

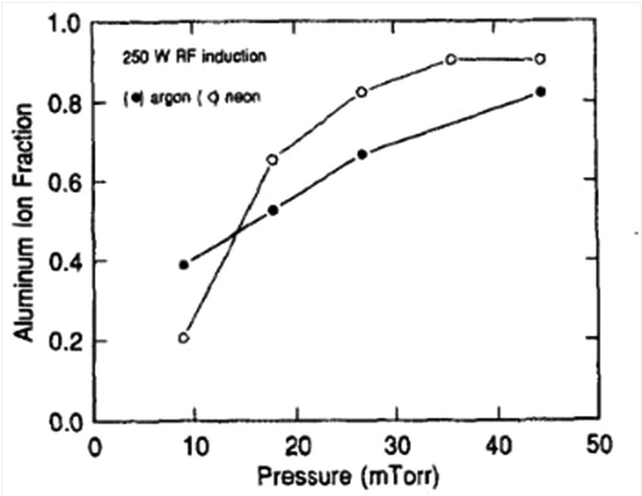

FIG. 5. Ionization fraction of depositing metal atoms as a function of chamber pressure for three magnetron powers (Ref. 9). Reprinted with permission from Rossnagel and Hopwood, J. Vac. Sci. Technol. B **12**, 449 (1994). Copyright 1994, American Vacuum Society.

C. Magnetron plasma measurements

The first, nearly automatic measurement in a plasma uses a Langmuir probe, which is simply a small metal surface, often a wire, which is insulated, exposing just the tip of the wire to the plasma. By biasing the wire positive and negative of ground, in theory, it is possible to determine the electron temperature, density, and plasma potential. However, in a magnetron, there are numerous complications. The most severe is the strong lateral magnetic field, 0.1–0.5 T, which alters electron motion and causes a non-uniform flux of electrons to the tip based on the geometry of the tip and the magnetic field. A second complication is the rather high density of electrons, which results in a tip many times the dimension of the Debye length of the plasma. A third constraint is the thickness of the sheath at the magnetron cathode surface, typically a mm or less, meaning the tip has to get extremely close to the biased cathode to sample the sheath region, which is a safety issue due to the cathode voltage, which is biased several hundred volts negative, often with a power supply capable of many kW output. The final, more practical issue is the large flux of metal atoms sputtered from the cathode, which rapidly coats the insulator near the tip, dramatically increasing the active area of the tip and requiring a very fast measurement before metal coating of the insulating shield.

The results of this study showed a reasonably Maxwellian electron distribution with a temperature of a few eV.[13] The densities were high ($10^{16}/cm^3$), but it was difficult to be accurate due to the magnetic field corrections. Occasionally, a small peak in the electron distribution was seen at an energy close to the cathode potential, indicative of a few secondary electrons from the cathode. The most significant implication was that the plasma was mostly a conventional, steady state plasma. Ionization of gas atoms occurred mostly due to the energetic tail of the electron distribution and not directly due to the secondaries from the cathode. Their role was predominantly to heat the electron population, not ionize gas atoms. This is also consistent with the rapidly declining electron-ionization cross section for inert gas atoms as a function of energy.[1]

A second measurement approach was to determine the magnitude of the **ExB** drift current.[14] In a circular, planar magnetron, this current is in the form of a wide ring just above the cathode surface. This circulating current could be measured by observing the magnetic field it induced on the centerline of the cathode. A small magnetic probe was configured in a glass tube a few cm from the cathode. The electron motions in a magnetron are complex, with most electrons on radial field lines, occasionally hopping across field lines as they move in the drift loop. Geometrically, this did not alter the measured field perturbation, and the drift current could be determined. For the circular planar magnetron used, the drift currents scaled with discharge current and were 3×–9× larger (Fig. 6). This implied that rather than rapidly leaving the cathode surface region, the electrons effectively made several loops around the drift path before reaching the anode (chamber walls), resulting in significantly increased ionization and plasma density compared to a nonmagnetized case.

D. Current-voltage relations

An unusual observation with DC magnetron diodes was the relationship between discharge current and voltage (after ignition

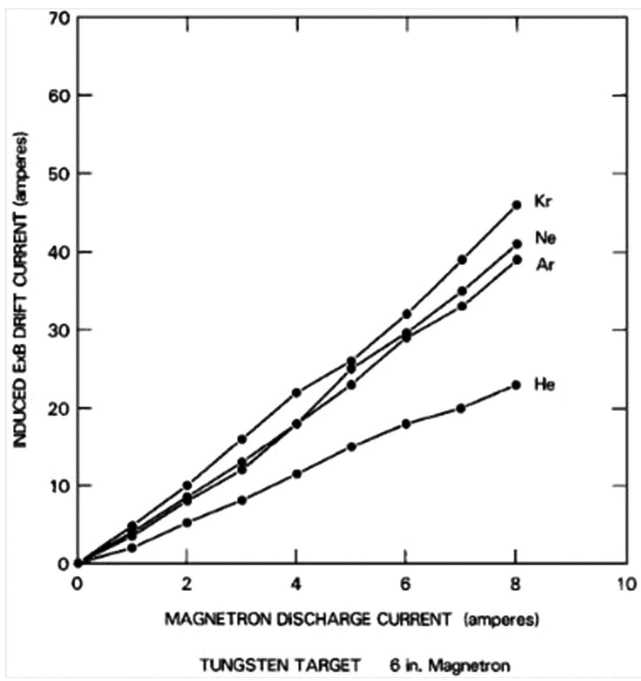

FIG. 6. Measured **ExB** drift currents in a circular planar magnetron using several inert gases and a tungsten target. Reprinted with permission from Rossnagel and Kaufman, J. Vac. Sci. Technol. A **5**, 88 (1987). Copyright 1987, American Vacuum Society.

of the plasma), which usually took the form of

$$I = kV^n,$$

where k is an arbitrary constant and the exponent, n, was typically 5–10. The ignition voltage of the plasma scaled inversely with the secondary electron coefficient. The exponent, n, did not seem to have any relationship with the cathode secondary electron yield, but varied by cathode metal, chamber pressure, and even the background gas species.

A clue to this relationship came out of an interesting paper by Dave Hoffman called "the Sputtering Wind."[4] The magnetron used was unusual: a rotating barber-pole cylindrical cathode. The experiment measured radial pressure at a tube-probe near the cathode varied as the cathode rotated, and the explanation described the pressure caused by the sputtered atom flux as the cathode rotated within the chamber. A simpler experiment followed, using an open-ended tube positioned on the axis of a circular planar magnetron, parallel to the cathode surface, several cm away from the cathode.[15] The other end of the tube went to a capacitance manometer (Baratron) mounted outside the vacuum chamber.

Rather than the expected increase in pressure in this manometer as the magnetron increased in power, the observed pressure dropped significantly. This drop depended also on chamber pressure, cathode species, and background gas species. The observed drop can be explained using thermal transpiration. The pressure in an open chamber (where the magnetron is) cannot really depend on the position, or gas flow would occur, as seen by Hoffman.[4] However, the presence of sputtered atoms can, through in-flight gas-phase collisions, lead to heating the gas atoms. As the gas heats, it rarefies, even though the pressure does not change. This was initially observed by Langmuir nearly 100 years ago[16] and is consistent with ideal gas laws. In the current experiment, the capacitance manometer is sampling this rarefied, hot gas, but the gauge temperature outside the chamber is 25 °C. Using thermal transpiration equations, the observed pressure drop in the external gauge pressure can be converted to a reduced gas density in the region in front of the cathode. The gas density in the cathode region drops rapidly as discharge current is increased before saturating well below the initial level (Fig. 7). The gas density at high powers can be as low as 20% of the starting density.

Gas heating and rarefaction depend strongly on the flux and energy of the sputtered atoms, which depend on the discharge current and sputter yield of the cathode, coupled with the average kinetic energy of each of the sputtered atoms, usually a few eV.[1] This begins to explain why different cathode metals in the same magnetron result in different current-voltage (I–V) relationships, i.e., a different exponent n. As the working gas rarefies, ionization becomes less efficient, requiring an increase in cathode voltage as the discharge current increases.[17] This increase will be higher for high sputter yield materials or those with more energetic sputtered atoms because of increased rarefaction. Hence, higher sputter yield or high emitted energy means a lower exponent, n. This same rarefaction effect was used by Hopwood and Qian to explain the reduced ionization levels for sputtered metal atoms as the discharge power was increased in an I-PVD device.[18]

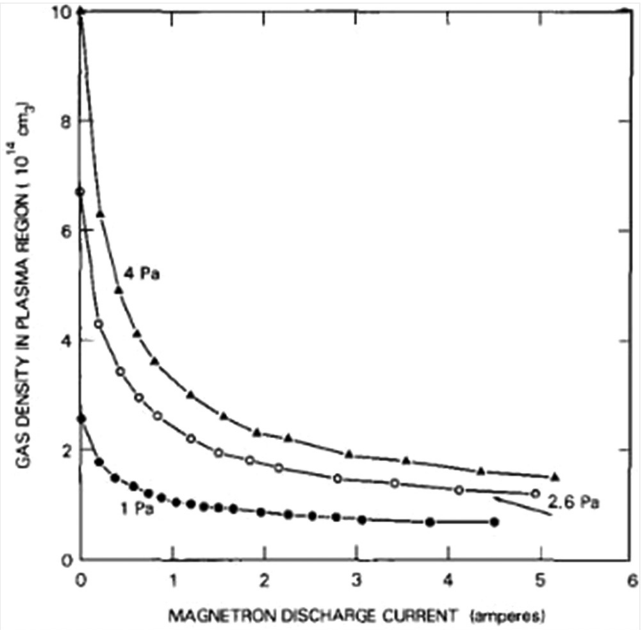

FIG. 7. Gas rarefaction in front of a circular planar magnetron as a function of discharge current for 1–4 Pa (7.5–30 mTorr) Ar with a Cu target. Reprinted with permission from Rossnagel, J. Vac. Sci. Technol. A **6**, 19 (1988). Copyright 1988, American Vacuum Society.

The background gas species also matters in this relation. At lower pressures, the number of sputtered atom-to-gas atom collisions declines. In effect, the mean-free-path of the sputtered atoms increases,[1] and rarefaction decreases. Lower pressure results in a higher exponent, n, i.e., a more efficient diode. The thermal conductivity of the gas also influences the degree of rarefaction. A higher thermal conductivity, typically associated with a lighter mass gas species, allows the gas heating to be dispersed to the walls more rapidly. Moving from Kr to Ar to Ne to He results in less rarefaction and hence a higher I–V exponent.

An extreme example of this exponential relationship is the case of sputtering a W cathode in He at a low pressure. The sputter yield is effectively zero and the gas thermal conductivity is very high. In this case, the I–V exponent, n, becomes 50–100 or more, effectively a perfect diode. Of course, the sputter yield and net deposition rate is zero, which for thin film applications is not useful. However, it could be useful for cases where a dense plasma is required without erosion of the cathode. An example of this might be in a plasma thruster for spacecraft applications or a light source.

The general conclusion of these measurements is that the magnetron plasma is mostly unsurprising: it is like other chamber-based plasmas at moderate discharge voltage. The novel difference is the strong influence of the large fluxes of sputtered atoms from the cathode. As this flux increases, it heats and effectively drives away many of the background gas atoms. It is this reduction in density that alters the plasma impedance, the transport of the sputtered atoms (including composition), and the deposition process.

Once the rarefaction is understood, many of the other deposition-related effects are obvious.

III. CONCLUSION

The resultant model of the magnetron plasma operation is one where the sputtering process at the cathode process strongly alters the working gas in the cathode region, which alters the impedance of the plasma or, in effect, its voltage. These relationships are much less likely to be seen in either a nonmagnetized diode plasma or an RF plasma simply because the flux to the cathode is much lower and the sputtered flux less important, but they are useful in explaining why simply changing the metal species of the cathode can have a significant effect on the plasma properties and film deposition issues.

On a personal note: I had the pleasure of working with Professor Peter Mark at the Princeton University shortly before his death in 1979. At the time, I was a junior faculty member exploring surface analysis of the walls of tokamaks at the Princeton University Plasma Physics Laboratory. I had a very unique, high resolution Scanning Auger Microscope (and SEM), and Professor Mark spent several afternoons working with me on surface analysis topics.

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Stephen M. Rossnagel is currently a research professor in the Department of Materials Science and Engineering at the University of Virginia in Charlottesville. Previous positions were at the IBM T. J. Watson Research Center in Yorktown Heights, NY, for 35 years, and shorter positions at the Princeton University Plasma Physics Laboratory and the Max Plank Institute for Plasma Physik in Garching bei München. His Ph.D. was in physics from the Colorado State University, and BS and MS in physics from the Penn State University. Much of his work since the 1980s has been in the interplay between plasma, sputtering, and film deposition. Significant developments include a series of magnetron studies, ranging from plasma measurements to gas dynamics to film applications. This includes development of new technologies, such as collimated sputtering and ionized sputter deposition, which are widely used for interconnect and contact applications for semiconductors. He also codeveloped plasma enhanced atomic layer deposition. More recent work was with DNA nanopore devices and the materials and integration for quantum computing devices. In the AVS, he has been Director, Plasma Division Chair, Annual Symposium Chair, head of Publications, President, Treasurer, and co-founder of the ALD meeting. Awards include the Peter Mark award, the Bunshah Award, Fellow, and Honorary Member.