Electron and ion transport in magnetron plasmas

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We demonstrate experimentally that there is a strong link between electron transport and ion transport in sputtering magnetron plasmas. Electron densities and discharge currents for He, Ne, Ar, Kr, and Xe discharges are measured and used to infer the charged particle confinement time. We find that the confinement time increases with ion mass. Further we find fair agreement between the experimental results and a model which assumes that ion motion is collisionless and unmagnetized, and that the spatial dependence of the electric potential and ion source are similar in the different discharges.

I. INTRODUCTION

Sputtering magnetrons are widely used for thin film deposition and sputter etching.[1] In these devices, electrons are confined by the electric sheath at the cathode and an externally imposed magnetic field. The magnetic field near the cathode is typically weak enough that electrons are magnetized, but ions, because of their much larger mass M_i, are not. The combination of the electric potential and the magnetic field forms an effective potential well,[2,3] or trap region. In the absence of collisions many electrons are unable to escape from the trap region to the anode. In contrast, the travel of ions to the cathode is not impeded by the magnetic field.[3] Maintenance of charge neutrality demands that electrons and ions leave the trap region at the same rate.[4] In this paper we clarify the mechanisms responsible for ion transport to the cathode and the concomitant escape of electrons from the trap region to the anode.

Previous authors[5] speculated that low frequency turbulence is the mechanism responsible for electron transport. By measuring the bulk electron confinement time τ and comparing it to the energy density in the turbulent waves at different discharge currents, Sheridan and Goree[6] demonstrated that low frequency turbulence is probably not responsible for the observed transport.

In previous work[3] we proposed a model where collisions with neutral gas particles play an important role in electron transport in a sputtering magnetron. Comparison with experiment confirmed that the model accurately predicts the spatial distribution of ionization events.[7] However, since the model deals only with the motion of single electrons in static electric and magnetic fields and does not include the interplay between electron and ion transport, it cannot predict the magnitude of the discharge current or plasma density.

A complete model for the sputtering magnetron cannot neglect ion transport, since in equilibrium one electron must escape from the plasma for each ion which is expelled from the plasma. To achieve this balance, the electric field in the plasma $\mathbf{E}$ (i.e., the negative gradient of the plasma potential) adjusts self consistently until it has a magnitude and shape such that ions are lost to the cathode, and electrons to the anode, at equal rates. This self-consistent electric field abets the collisional escape of electrons from the trap region. Since electrons and ions are created at nearly the same rate, the confinement time for electrons and ions must be nearly the same. Because heavier ions experience less acceleration in a given electric field, we expect that the charged particle confinement time and hence the plasma density will increase with ion mass.

In Sec. II we describe an experiment which demonstrates that electron confinement and ion confinement are inextricably linked, as discussed above. In Sec. III we present a simple model and compare it to the experimental results. We draw conclusions from this work in Sec. IV.

II. EXPERIMENT

For the experiment reported here, we have measured the scaling of the charged particle confinement time τ with ion mass M_i in our sputtering magnetron. We used either He, Ne, Ar, Kr, or Xe as the working gas. Before describing the particulars of the experiment, we need to explain how we determine the charged particle confinement time.

Here we show that the confinement time for charged particles is proportional to the ratio of the plasma density n, measured at a given location, to the discharge current $I_{\rm dis}$. Assume that there is some volume V enclosing a plasma source g, given as the number of ions created per unit time and volume. Since the plasma must be quasineutral, we let $n = n_e = n_i$, where n_e and n_i are the electron and ion densities, respectively. The number of ions or electrons in V, which we call N, is then given by

$$N = \tau \int_V g \, dV, \tag{1}$$

where the integral is over V. If the plasma is in equilibrium then the number of ions created in V per unit time [the integral in Eq. (1)] must equal the number of ions lost from V per unit time. This loss rate is $I_{\rm dis}/e$. Consequently,

$$\tau = eN/I_{\rm dis}. \tag{2}$$

Measurements performed in our magnetron earlier[6] indicate that $n \propto N$, no matter at which point the density is measured. Therefore, the charged particle confinement time must be proportional to the plasma density divided by the discharge current:

$$\tau \propto n/I_{\rm dis}. \tag{3}$$

Our magnetron, which is described in Ref. 6, has a planar copper cathode and a cylindrically symmetric magnetic field. The magnetic field is tangential to the cathode surface

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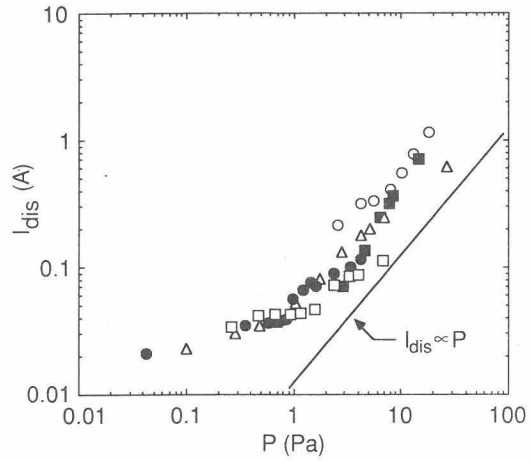

FIG. 1. Discharge current I_{dis} as a function of neutral pressure P for He(○), Ne(■), Ar(△), Kr(●), and Xe(□) discharges. A line showing the scaling $I_{dis} \propto P$, which is the signature of the normal operation regime, is drawn for comparison. Note the data for each gas exhibit this scaling.

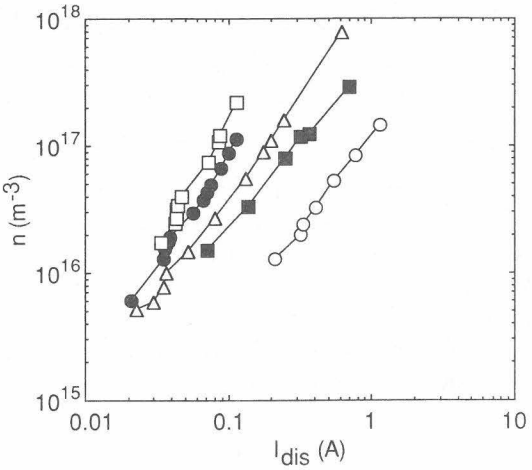

FIG. 2. Plasma density n measured at $r = 1.7$ cm and $z = 1.03$ cm, plotted against the discharge current I_{dis} for five noble gases. Note that as the atomic mass of the gas increases, the plasma density is always larger for the same discharge current, clearly indicating that the charged particle confinement time increases with increasing ion mass. Symbols are the same as those in Fig. 1.

($z = 0$) at $r = 1.7$ cm, and has a value of 245 G there. Here r is the distance from the symmetry axis of the magnetron, and z is the height above the cathode. In this experiment the cathode bias was provided by a linear direct-current (dc) power supply. Pressure measurements, which we corrected for gas type, were made using a Granville–Phillips Convectron gauge tube that was located well away from the magnetron.

A cylindrical Langmuir probe was used to measure the electron density,[6] which should be equal to the plasma density n. The diameter of the tungsten probe tip, which was parallel to the cathode surface, is 0.254 mm, and its length is 3.5 mm. Plasma parameters were extracted from the probe characteristic using the method described in Ref. 6.

In these experiments we varied the discharge current and the ion mass while measuring the electron density at a single point in the trap region. This point was located at $r = 1.7$ cm (over the deepest part of the etch track) and at $z = 1.03$ cm. The reduction in the discharge current caused by inserting the probe was less than 5%. Measurements for each gas (He, Ne, Ar, Kr, or Xe) were performed at a constant discharge voltage V_{dis} (see Table I). The discharge current was varied by changing the neutral gas pressure P from 0.04 to 16 Pa, with most of the data falling between 0.2 and 10 Pa (see Fig. 1). Higher discharge voltages were needed with Kr and Xe to get a good discharge.

Current-pressure curves for the five gases used are shown in Fig. 1. It has been reported that the relationship between discharge current and pressure is characterized by at least three distinct regimes.[8] In the normal "A" operating regime, I_{dis} varies approximately linearly with P, and the characteristic current–voltage scaling for dc magnetrons ($I_{dis} \propto V_{dis}^{x}$, where $x \approx 7$) is observed. Most of the data presented here is from this normal operating regime, in which it has been shown that ions travel collisionlessly through the sheath.[8]

In Fig. 2, which is a plot of the electron density versus discharge current, we see that the electron density increases with ion mass for a given discharge current. We must conclude from Fig. 2 that charged particle confinement times are longer for heavier ions. To gain a further understanding of the physics involved we next consider a simple model.

III. DISCUSSION

As we have demonstrated experimentally, at a given discharge current the plasma density increases with ion mass. We have argued in general terms that this happens because heavier ions are accelerated more slowly in a given electric field. We now explore this idea in greater depth.

We examine a one-dimensional model where we assume that we are given the source and potential profiles. A complete model, which we do not present here, would include some way of calculating the source and potential self-consistently. We will show that if we assume that the source and potential profiles are similar in different discharges that τ should scale as the square root of the ion mass. Comparison with the experimental data presented in the previous section yields good agreement with this predicted scaling at higher discharge currents and for heavier gases.

A. Model with nonuniform source and potential

The motion of ions must be approximately one dimensional, as we explain here. In the presheath, the magnetic field must be nearly constant along any magnetic field line, and the electric field must therefore be nearly perpendicular to the magnetic field. Further, the plasma density on a magnetic field line must be fairly uniform, since the field line is approximately an equipotential. The motion of ions along a single electric field line thus should be modeled well using only one spatial coordinate.

We also assume that both the electric potential profile $\phi(z)$ and the source profile $g(z)$ along our chosen electric field line are known. As before, g is the number of ions creat-

ed per unit time and volume. The cathode is located at $z = 0$ and the plasma fills the volume for $z > 0$. The potential is taken to have a single maximum located at z'. For $z > z'$ ions are collected at the anode. The ion density at a given point can now be calculated.

The ion density for any $z < z'$ will be given by the following integral[9]:

$$n_i(z) = \left(\frac{M_i}{2e}\right)^{1/2} \int_z^{z'} \frac{g(\xi)d\xi}{[\phi(\xi) - \phi(z)]^{1/2}}, \quad (4)$$

if ions are born with zero initial kinetic energy and their trajectories are not affected by the magnetic field or by collisions.[3] Because of quasineutrality $n = n_i = n_e$ this is the density that would be measured by a probe placed at z. From Eq. (4), we conclude that the plasma density depends on the ion mass and on the source and potential profiles between z and z'.

The current density at the cathode, J, is given by

$$J = e \int_0^{z'} g(\xi)d\xi, \quad (5)$$

if we ignore the small current of electrons created at the cathode via secondary emission. Combining Eqs. (4) and (5) we find

$$\frac{n(z)}{I_{\text{dis}}} \propto M_i^{1/2} \left\{ \int_z^{z'} \frac{g(\xi)d\xi}{[\phi(\xi) - \phi(z)]^{1/2}} \int_o^{z'} g(\xi)d\xi \right\}. \quad (6)$$

Thus, the ratio $n(z)/I_{\text{dis}}$, which we have shown is proportional to τ, is a function of M_i, g, and ϕ. Note that Eq. (6) is independent of all constant factors, including the ionization cross section, that are implicit in g; therefore, one can compare values of τ mesured for different discharges with various gases.

If we assume that the profile of g, and the profile and magnitude of ϕ, are the same for different M_i, then Eq. (6) predicts the following scaling:

$$\tau \propto M_i^{1/2}. \quad (7)$$

Why would we expect g and ϕ to obey such assumptions? We have shown previously[3] that the location of ionizations events is determined by the motion of single electrons. This motion is dominated by the shape of the magnetic field as long as the sheath width is much narrower than the magnetic trap height. Since the magnetic geometry is fixed, we have good reason to expect that the profile of the source will not depend strongly on the type of gas used. Others have shown that under some circumstances the magnetic field can create a "magnetic presheath."[10,11] Thus, it does not seem unreasonable to expect that the profile, and possibly the magnitude, of ϕ in the presheath should be determined by the magnetic field and will not depend on the type of gas used. A comparison to our experimental results will indicate the extent to which this is true.

B. Comparison of experiment with model

We make a quantitative comparison between the scaling predicted in Eqs. (3) and (7) and the experimental data in the following way. Since the data points for each gas in Fig. 2 fall on nearly straight lines, a power law of the form

TABLE I. Ion mass M_i, discharge voltage V_{dis}, and fit coefficients a and b, tabulated for each of the five noble gases used. In the experiment, the plasma density n and the discharge current were varied by changing the neutral gas pressure, as shown in Fig. 1. Measurements of n were fit with a power law of the form $n = aI_{\text{dis}}^b$. The departure of b from the predicted value of unity [Eq. (7)] indicates the degree of validity of the assumptions about the profiles of g and ϕ that were made to obtain Eq. (7).

Gas	M_i (amu)	V_{dis} (V)	a ($10^{16}\text{m}^{-3}\text{A}^{-b}$)	b
helium	4.003	−400	11.9	1.43
neon	20.18	−400	44.8	1.24
argon	39.95	−400	156	1.63
krypton	83.80	−500	586	1.84
xenon	131.3	−600	2490	2.18

$$n = aI_{\text{dis}}^b \quad (8)$$

can be used to approximate the relationship between the plasma density and discharge current. The parameters a and b, which we found using a nonlinear least squares fit, are shown in Table I.

Values of the exponent b range from 1.24 to 2.18. The departure of b from the predicted value of one [Eqs. (3) and (7)] indicates the extent to which the assumptions about g and ϕ used to obtain Eq. (7) are met. The highest values of b are found for the heaviest gases, Kr and Xe, for which we found it necessary to use higher discharge voltages. Note that for all gases $b > 1$. This indicates that τ increases with I_{dis}. At higher discharge currents the sheath width decreases. It seems likely that this decrease in sheath width leads to a decrease in the electric field in the presheath, and a corresponding increase in τ.

To determine the experimental scaling of τ with ion mass, we plot τ in units of n/I_{dis} against M_i for several values of I_{dis} in Fig. 3. Here n/I_{dis} is determined using Eq. (8) and the fit coefficients listed in Table I. Recall that our model predicts that the plasma density at a given discharge current (i.e., the confinement time) should scale like the square root of the ion mass provided that g and ϕ do not change. We find good qualitative agreement with the scaling predicted by our model, particularly for $I_{\text{dis}} = 1\text{A}$. This agreement indicates that the source and electric potential structure are similar for the different discharges in this case.

At lower discharge currents, and for He, Fig. 3 shows a nonignorable deviation from the predicted $M_i^{1/2}$ scaling [Eq. (7)]. Since the plasma density in these discharges is lower than for the heavier gases and higher currents, the sheath width will be larger. The failure to more closely follow the predicted scaling probably indicates that the sheath width has become a significant fraction of the magnetic trap width, significantly altering the profiles of both ϕ and g in these cases.

IV. CONCLUSIONS

We have experimentally demonstrated the importance of ions in regulating electron transport in sputtering magnetron discharges. Currents and electron densities for separate

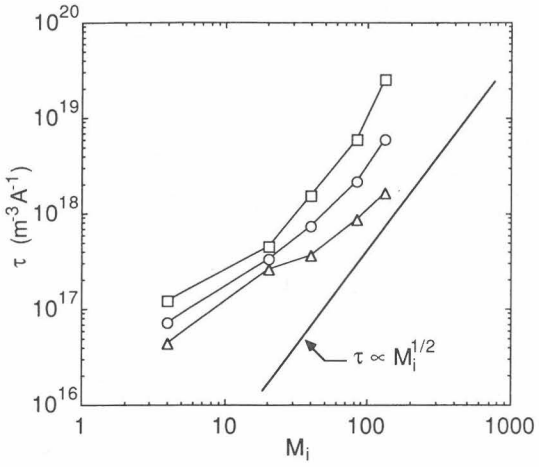

FIG. 3. Confinement time τ, in units of n/I_{dis} [Eq. (3)], plotted against the ion mass M_i for discharge currents of $I_{dis} = 0.1(\triangle)$, $0.3(\bigcirc)$, and $1(\square)$A. The scaling $\tau \propto M_i^{1/2}$ [Eq. (7)], found by assuming similar source and potential profiles in the different discharges, is shown for comparison. Good agreement is found at higher plasma densities, where we expect the sheath width to be much narrower than the magnetic trap height.

discharges using He, Ne, Ar, Kr, or Xe gases are reported. The electron density increases with increasing ion mass for the same discharge current, indicating that the confinement time of charged particles increases with ion mass. Assuming that ions travel collisionlessly in a one-dimensional electric potential and are not affected by the magnetic field, we predict that the confinement time should be proportional to the square root of the ion mass. To facilitate comparison betweeen the experiment and this prediction, we fit the data for each gas with a function of the form $n = aI_{dis}^{b}$. Good agreement with the predicted $M_i^{1/2}$ scaling was found for higher plasma densities.

Since we have shown that electron transport and ion transport are inextricably linked, we can predict that they must both be taken into account in any future model which purports to describe the global properties of the magnetron discharge.

ACKNOWLEDGMENT

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