Observation of two-temperature electrons in a sputtering magnetron plasma

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We experimentally find that there are hot and cold electron components present in a sputtering magnetron plasma. The density of the hot component is greatest in the magnetic trap and decreases with the distance from the cathode. The cold electron density is negligible inside the trap and is approximately constant outside. The largest cold electron density is nearly as great as the hot electron density inside the magnetic trap.

I. INTRODUCTION

Sputtering magnetrons are used for sputter etching and thin-film deposition. In these devices a magnetic field is used to trap electrons above a cathode,[1,2] allowing operation at lower neutral pressures than similar unmagnetized discharges. These trapped electrons create ions that are accelerated into the cathode by the plasma sheath, causing the desired sputter etching. To balance the flux of ions to the cathode there must be an equal flux of electrons to the anode. However, to reach the anode, electrons must escape from the magnetic trap. Understanding electron transport in the sputtering magnetron is essential to understanding the operation of these devices.

In several recent experiments, the electron component of a magnetron plasma and mechanisms of electron transport have been investigated using Langmuir probes. Sheridan and Goree[3] found that electron transport is probably not a result of low-frequency turbulence. Sheridan, Goeckner, and Goree[4] demonstrated that electron and ion confinement are inextricably linked. Rossnagel and Kaufman[5] reported that the electron temperature and density decrease with distance from the cathode. They also noted the presence of a high-temperature electron tail under certain conditions (e.g., in a He discharge).

In this paper we investigate the origin and significance of this electron tail. By fitting Langmuir probe data with a two-temperature model, we find that the high-temperature tail reported by Rossnagel and Kaufman is made of electrons that have escaped from the magnetic trap and are traveling to the anode. Additionally, we find that outside the trap there is a dense, cold, background plasma through which these hot electrons move.

In Sec. II we describe the experimental conditions and the methods used to analyze Langmuir probe data. In Sec. III we present the results of this analysis, and demonstrate the presence of hot and cold electron components.

II. EXPERIMENT

A. Apparatus

These experiments were performed using the cylindrically symmetric planar magnetron described in Ref. 3. The computed magnetic field lines for this device are shown in Fig. 1. The etch track formed by ion bombardment is deepest at the radius $r = 1.7$ cm. Here the magnetic field has a magnitude of 245 G and is parallel to the cathode surface. The magnetic trap, which is shaded in Fig. 1, is approximately the largest region enclosed by field lines that begin and end on the cathode.

For the results reported here, we operated an 11-Pa He discharge with a copper cathode at a discharge voltage of -300 Vdc. (Though the data presented here is for a He discharge, we have found similar results in Ar.) Under these conditions the discharge current was 0.32 A, which corresponds to a current density at the cathode of 290 A/m^2 averaged over a collection area of 11 cm^2.

The discharge was diagnosed using a cylindrical Langmuir probe oriented parallel to the cathode. The tungsten probe tip had a diameter of 0.010 in. and a length of 3.5 mm. The probe bias $V_{\rm probe}$ was provided by a programmable bipolar power supply, and the electron current to the probe $i_e^{\rm probe}$ was measured with a resolution of 1 μA.

We measured the current-voltage characteristics of the probe for seven different heights z above the cathode at a fixed radial distance $r = 1.2$ cm. At this radius the magnetic

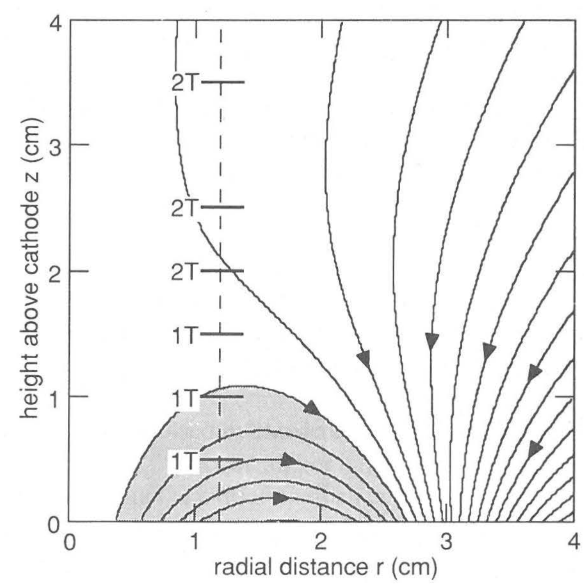

FIG. 1. Computed magnetic field lines for the magnetron, with the magnetic trap shaded. The positions at which probe measurements were made are shown by the horizontal lines at $r = 1.2$ cm. The length of these lines gives the length of the probe tip. At each of these points we have indicated whether one or two electron components were observed, using "1T" or "2T," respectively. Note that there are both hot and cold electrons outside the magnetic trap, while there are only hot electrons in the trap.

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trap is just over 1-cm tall. The locations where data were taken are shown in Fig. 1, as is the length of the probe tip. The disturbance of the discharge by the probe resulted in a decrease in the discharge current of 12% at $z = 0.5$ cm. At all other heights the decrease in discharge current was $<2.5\%$.

B. Data reduction

The probe characteristics were analyzed using a method suitable for two-electron temperatures. First, the plasma potential V_p was taken to be the voltage where the derivative of i_e^{probe} with respect to V_{probe} was a maximum. This estimate for V_p was improved using parabolic interpolation. Those points with $V_{\text{probe}} < V_p$ were then fit to the two-temperature model using nonlinear least squares.[6]

We assumed that the probe current could be written as

$$i_e^{\text{probe}} = C\sqrt{V_p - V_{\text{probe}}} + i_e^{\text{cold}} \exp\left[\frac{e(V_{\text{probe}} - V_p)}{kT_e^{\text{cold}}}\right] + i_e^{\text{hot}} \exp\left[\frac{e(V_{\text{probe}} - V_p)}{kT_e^{\text{hot}}}\right]. \quad (1)$$

Here T_e is the electron temperature, i_e gives the electron current when $V_{\text{probe}} = V_p$, e is the elementary charge, k is Boltzmann's constant, and the superscripts "hot" and "cold" refer to the hot and cold electron components, respectively. The term $C\sqrt{(V_{\text{probe}} - V_p)}$ is used to model the orbit-limited saturation ion current to the cylindrical probe.[7] Under idealized conditions, which are only approximately met in the magnetron, the constant C is given by

$$C = \frac{n_i A}{\pi}\sqrt{\frac{2e^3}{M}}, \quad (2)$$

where n_i is the ion density, M the ion mass, and A the probe area. If only a single electron component was present, we found that the fit converged to a single temperature: $T_e^{\text{hot}} = T_e^{\text{cold}}$.

Hot and cold densities, n_e^{hot} and n_e^{cold}, respectively, were found for each component using

$$n_e = \frac{i_e}{eA\sqrt{kT_e/2\pi m}}, \quad (3)$$

where m is the electron mass. Note that if $i_e^{\text{hot}} = i_e^{\text{cold}}$, then n_e^{cold} will be greater than n_e^{hot} by the square root of the temperature ratio. That is, small currents of cold electrons represent sizable cold electron densities.

III. RESULTS AND DISCUSSION

Outside the magnetic trap, probe characteristics with the signature of two electron temperatures were observed. Such a characteristic is shown plotted on linear axes in Fig. 2(a), and on semilogarithmic axes in Fig. 2(b). The two slopes evident in Fig. 2(b) for $V_{\text{probe}} < V_p$ are due to the presence of hot and cold electron components.[8] The two-temperature fit [Eq. (1)] is also plotted in Fig. 2, and it shows excellent agreement with the data. Reassuringly, the ion density computed using Eq. (2) agrees to within a factor of 4 with the total electron density found using Eq. (3). We have indicated in Fig. 1 at what heights the electrons were characterized

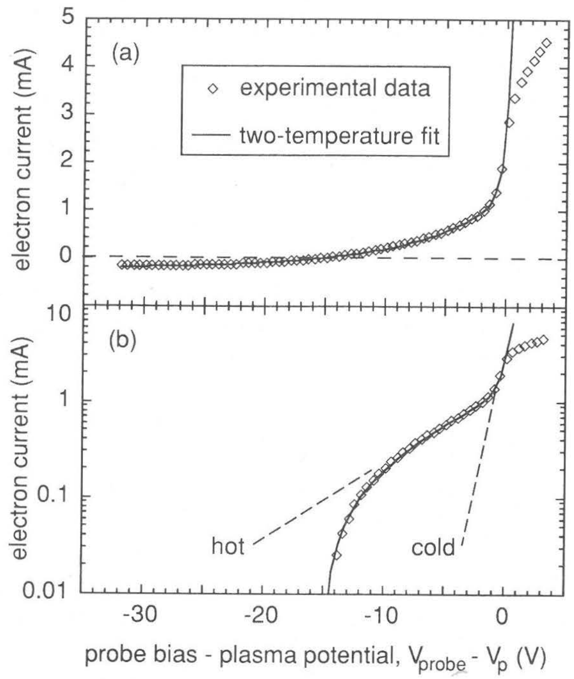

FIG. 2. Measured two-temperature probe characteristic taken at $r = 1.2$ cm, $z = 2.5$ cm. In (a) the electron current is plotted on a linear scale, and in (b) on a logarithmic scale. The two slopes shown by the dashed lines in (b) are due to the presence of hot and cold electron components. The solid line gives the fit to a two-temperature model for $T_e^{\text{cold}} = 0.47$ eV, $n_e^{\text{cold}} = 2.4 \times 10^{16}$ m^{-3}, $T_e^{\text{hot}} = 6.8$ eV, and $n_e^{\text{hot}} = 0.68 \times 10^{16}$ m^{-3}.

by a single temperature, and where they had two temperatures. Note that in the magnetic trap there is a single, hot electron component, but outside the trap there are both hot and cold electron components. To interpret the electron temperature and density profiles, we must first consider the plasma potential.

The axial plasma potential profile is shown in Fig. 3(a). Above $z = 2$ cm the plasma potential attains a nearly constant value of 1.8 V. Consequently, there must be a 1.8-V sheath at the anode. As the probe was moved into the magnetic trap the plasma potential decreased rapidly, reaching a value of -16.8 V at $z = 0.5$ cm.

We exhibit the hot and cold electron density profiles in Fig. 3(b). The density of hot electrons is greatest in the magnetic trap and decays as the height above the cathode increases, indicating that the source of hot electrons is in the trap. Note that n_e^{hot} is largest nearest to the cathode ($z = 0.5$ cm), where the plasma potential [Fig. 3(a)] is most negative. This is clear evidence that the magnetic field is trapping electrons close to the cathode. The steep potential gradients in the trap [Fig. 3(a)] will enhance the transport of hot electrons across the magnetic field.

The cold electron density [Fig. 3(b)] is negligible in the magnetic trap. However, outside the trap, it reaches a constant value almost as large as that of n_e^{hot} in the trap. In contrast to Rossnagel and Kaufman,[5] we find that when the cold electrons are considered the total electron density outside the trap is comparable to that inside. This cold dense

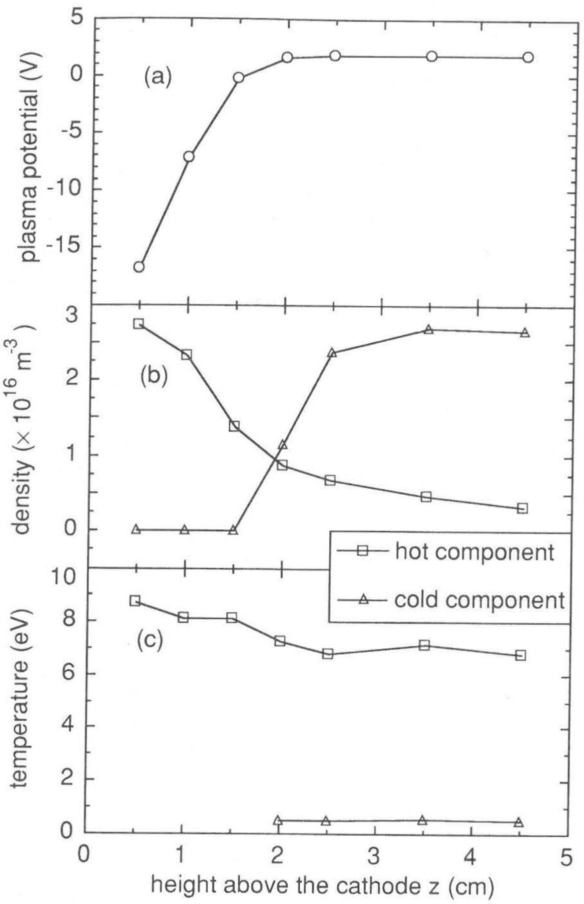

FIG. 3. (a) Plasma potential, (b) electron density, and (c) electron temperature plotted against the height above the cathode, z. There is a steep potential gradient (i.e., large electric field) in the magnetic trap. The hot electron density is largest in the magnetic trap and decreases as z is increased. In contrast, the cold electron density is large outside the trap and negligible inside. The average hot electron temperature is 7.6 eV, while the average cold electron temperature is 0.50 eV.

plasma provides a charge-free background through which the hot electrons travel to the anode.

The temperatures of the hot and cold electrons are shown in Fig. 3(c). The hot electron temperature has an average value of 7.6 eV, and is nearly independent of z. The small increase in $T_e^{\rm hot}$ in the trap may be due to inaccuracies in the fit, since the electron distribution there is non-Maxwellian. These hot electrons are not, of course, the electrons created at the cathode, which would be much more energetic. The temperature of the cold component appears to remain constant near the average value of 0.50 eV even as the density goes to zero. Because the average energy of a cold electron is much less than the excitation potential of He, these cold electrons will not produce any visible glow, in contrast to the hot electrons.

Unlike Ar, He lacks a Ramsauer minimum in its scattering cross section,[9] so some other mechanism is needed to account for the cold temperature. The data suggests that the cold electron component consists of low-energy electrons from the hot component that are trapped between the anode sheath and either the cathode sheath or the magnetic trap. We cannot distinguish between the latter two possibilities using the data presented here.

IV. SUMMARY

Sputtering magnetrons confine electrons in a magnetic trap next to the cathode. Using Langmuir probes in a − 300-Vdc, 0.32-A, 11-Pa He discharge, we have observed a hot electron component ($T_e^{\rm hot} \approx 7.6$ eV) which is sourced in this trap and leaks out of it to the anode. The least energetic members of this hot component are reflected by the anode sheath and become trapped in the plasma, forming a cold electron component ($T_e^{\rm cold} \approx 0.50$ eV). The density of the cold electrons outside the trap is nearly as large as the total density in the trap.

ACKNOWLEDGMENT

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[1] A. E. Wendt, M. A. Lieberman, and H. Meuth, J. Vac. Sci. Technol. A **6**, 1827 (1988).

[2] T. E. Sheridan, J. Goree, and M. J. Goeckner, J. Vac. Sci. Technol. A **8**, 30 (1990).

[3] T. E. Sheridan and J. Goree, J. Vac. Sci. Technol. A **7**, 1014 (1989).

[4] T. E. Sheridan, M. J. Goeckner, and J. Goree, J. Vac. Sci. Technol. A **8**, 1623 (1990).

[5] S. M. Rossnagel and H. R. Kaufman, J. Vac. Sci. Technol. A **4**, 1822 (1986).

[6] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes: The Art of Scientific Computing* (Cambridge University, Cambridge, 1986), pp. 289–293.

[7] E. Eser, R. E. Ogilvie, and K. A. Taylor, J. Vac. Sci. Technol. **15**, 199 (1978).

[8] F. F. Chen, in *Plasma Diagnostic Techniques*, edited by Richard H. Huddlestone and Stanley L. Leonard (Academic, New York, 1965), p. 136.

[9] S. C. Brown, *Basic Data of Plasma Physics, 1966* (MIT, Cambridge, 1967), p. 17.