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Discharge parameters and dominant electron conductivity mechanism in a low-pressure planar magnetron discharge

O. Baranov, M. Romanov, and Kostya (Ken) Ostrikov

1 Plasma Laboratory, National Aerospace University “KhAI,” Kharkov 61070, Ukraine
2 CSIRO Materials Science and Engineering, Plasma Nanoscience Centre Australia (PNCA), P.O. Box 218, Lindfield, New South Wales 2070, Australia

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Parameters of a discharge sustained in a planar magnetron configuration with crossed electric and magnetic fields are studied experimentally and numerically. By comparing the data obtained in the experiment with the results of calculations made using the proposed theoretical model, conclusion was made about the leading role of the turbulence-driven Bohm electron conductivity in the low-pressure operation mode (up to 1 Pa) of the discharge in crossed electric and magnetic fields. A strong dependence of the width of the cathode sputter trench, associated with the ionization region of the magnetron discharge, on the discharge parameters was observed in the experiments. The experimental data were used as input parameters in the discharge model that describes the motion of secondary electrons across the magnetic field in the ionization region and takes into account the classical, near-wall, and Bohm mechanisms of electron conductivity. © 2009 American Institute of Physics. [DOI: 10.1063/1.3153554]

I. INTRODUCTION

Low-pressure discharges in crossed electric and magnetic fields have been extensively investigated for several decades. In these discharges, the discharge structure is governed by the magnetic field magnitude and topography. The electrons and ions gyrate in the magnetic field, which greatly influences their mobility perpendicular to the magnetic field lines, while their mobility along the magnetic field is not affected. In low-temperature processing plasmas, the magnetic field is usually weak and cannot magnetize the ions, i.e., the ion gyroradius is large compared to the system size. As a result, in these systems the electrons are considered to be a magnetized component, whereas the ions are not. Furthermore, crossed electric and magnetic fields are created causing a closed-path electron drift, which prevents the electrons from escaping from the system. Under the condition of limited electron mobility across the magnetic field, each magnetic field line can be considered as an electric equipotential line. Thus, the electric potential changes strongly across the magnetic field; hence, a strong electric field can be generated and used for ion acceleration in the direction perpendicular to the magnetic field. This effect results in various important practical applications such as ion thrusters and spacecraft propulsion, magnetron discharges, plasma confinement in fusion experiments, controlled material sputtering for material synthesis and nanoscale applications, and the electromagnetic focusing and transport of the plasma ions in vacuum arc sources.

The \( \mathbf{E} \times \mathbf{B} \) discharge is a self-igniting system, which initializes by an avalanchelike ionization process and then maintained by electron emission from the cathode, with the energetic electrons providing the ionization required to sustain the plasma. This energetic electron flux can be generated in a number of different ways, e.g., by thermal electronic emission from the cathode (Hall thrusters) or secondary electron emission (magnetrons). The presence of the magnetic field significantly changes the discharge parameters. The Lorentz force causes a circular motion of the electrons with the cyclotron frequency (we will only consider the case of the discharges with unmagnetized ions). A magnetic field perpendicular to the electric field increases the path length of the electrons and ensures a sufficiently high ionization rate. A strong confinement of the secondary electrons by the magnetic field in a region near the cathode (closed drift) in turn results in a high plasma density. Thus, electron conductivity across the magnetic field determines the plasma parameters and still remains one of the main points of intense debates in the areas related to the devices with crossed electrical and magnetic fields.

Up to now, the physics of \( \mathbf{E} \times \mathbf{B} \) discharges, particularly, the electron transport in crossed \( \mathbf{E} \) and \( \mathbf{B} \) fields, are not completely understood. It was observed that the classical collisional mobility mechanism cannot adequately describe the levels of electron currents observed in the experiments. Several other conductivity mechanisms were proposed, namely, the Bohm-type mechanism, the near-wall conductivity (NWC) mechanism based on the assumption about electron reflection from dielectric walls, as well as the electron conductivity mechanism based on the ion flux neutralization on the nonconductive walls. Both classical and Bohm conductivity mechanisms need to be considered for the accurate description of magnetron discharges. With the properly chosen parameters, these conductivity mechanisms can explain the observed electron currents and discharge structures. However, these mechanisms are based on numerous different parameters that cannot be directly measured in the experiments. Thus, an experiment that can identify the process conditions when one or the other mechanism dominates is vitally needed.

In this work, electron conductivity is studied experimen-
tally in a planar magnetron system, which features the crossed electric and magnetic fields and the associated closed electron drift. The NWC is likely to play a role due to the presence of the cathode surface and the cathode sheath near it; hence, possible electron elastic collisions with the sheath can be interpreted as the “wall” collisions. We estimated the ionization region width by studying the structure of the sputter trenches along a cylindrically symmetric cathode of the magnetron, in particular, the trench width dependence on the working gas pressure and the cathode voltage. A model of the electron transport describing the motion of secondary electrons emitted from the magnetron cathode is also developed and the results of the calculations are compared with the data obtained in the experiment. The model is primarily aimed at elucidating the dominant conductivity mechanism, as well as to better understand the physics of the gas discharge in crossed electric and magnetic fields.

II. CONDUCTIVITY MECHANISMS: A COMPARISON

The difference between the classical and Bohm conductivity is in the mechanism of the electron motion across the magnetic field. The classical conductivity mechanism assumes that the electron diffusion across the magnetic field is due to collisions of the electrons with neutral atoms. On the other hand, Bohm conductivity assumes that the field turbulence is the main reason for the effective electron motion across the magnetic field.

The classical cross-field diffusion scales with magnetic field as $B^{-2}$, whereas the Bohm diffusion scales as $B^{-1} \cdot 10^{-1}$. This circumstance results in a much lower electron mobility across the magnetic field and, hence, much higher electron energy loss per unit of length across the magnetic field for classical conductivity. Since magnetron discharges are sustained by the secondary electrons that gain the energy in a sheath and lose it in the ionization region, the ionization region should extend closer to the cathode if the classical conductivity mechanism is dominant rather than the Bohm mechanism. However, additional effects of the NWC (due to, for example, electron elastic collisions with the nonconducting walls, as well as the plasma sheath) may result in increasing the ionization region size. In this case one can conclude that collisional mechanisms (classical and NWC) play the leading role in the range of the discharge operating parameters concerned.

Ion fluxes directed toward the cathode of a magnetron cause sputtering of the cathode surface. The ion flux distribution along the cathode surface is determined by superposition of elementary ion fluxes that originate from different magnetic field lines and follow a Gaussian distribution. A relatively strong ambipolar diffusion of ions and electrons generated within the ionization region results in the expansion of the ionization region along the curved magnetic field lines and the projection of this region onto the cathode surface. At this projection on the cathode surface, the ion fluxes created by the motion of the high-energetic secondary electrons across the magnetic field within the ionization region affect the original Gaussian distribution. It is reasonable to assume that the superposition of the two ion distributions may be visualized when the sputter trench divides into the “main” sputter trench (determined by the Gaussian distribution only) and the “additional” sputter trench (controlled by the superposition of the initial Gaussian distribution and ion distribution generated during the expansion of the ionization region). Thus, this difference in the sputter traces can be effectively used to study the discharge structure and to determine the predominant electron conductivity mechanism.

III. EXPERIMENTAL SETUP AND PROCEDURES

The experimental system and the topography of the magnetic field are shown schematically in Fig. 1(a). A planar cylindrical-shaped magnetron system with a diameter of 235 mm and a height of 180 mm was mounted on a cylindrical vacuum chamber (500 $\times$ 500 mm$^2$). The magnetron was provided with a disk-shaped cathode made of polished copper. The cathode diameter was 235 mm; its thickness was 10 mm. A magnetic field of the magnetron was $B_{z0}=0.02$ T above the cathode near its surface, where the magnetic field lines...
are tangential to the substrate surface (in a region of magnetron discharge ignition). The radius of curvature of the magnetic field lines was about 60 mm.

The automatic gas-supplying system maintained nitrogen pressure in the range from 0.01 to 10 Pa. The pressure was measured with the help of the ionization gauges. The cathode was under a negative potential relative to the grounded vacuum chamber walls. Before each experimental run, the magnetron cathode was heated and exposed to atmospheric pressure to blacken the cathode surface. The experiments were performed under the following conditions. The working gas pressure was varied in the range of 0.1–4.0 Pa. The negative voltage $V_c=300–1000$ V was applied to the cathode. Under these conditions, a self-sustained magnetron discharge was ignited through the sputtering process occurring on the cathode surface. The duration of each experimental run was 3 min at a constant sputtering power. For all pressures, the discharge voltage was raised to 1000 V and the corresponding discharge currents were measured. The magnetron was left in the depressurized vacuum chamber for several hours to prevent oxidation of the heated cathode and then the width of the sputter trenches was measured. In these experiments we did not use any special igniting electrodes or electron fluxes to initialize the discharge; the discharge reliably and reproducibly self-ignited in the whole range of the parameters used in the experiments.

IV. RESULTS

The discharge appeared in the form of a brightly glowing circular plasma ring hovering above the cathode. Ions created in this region are accelerated to the cathode, causing the erosion of the target in an area known as a “race track” or a sputter trench. Three main and two additional erosion zones were observed on the cathode surface after the treatment, as illustrated in Figs. 1(b)–1(d). A visual comparison of these zones with the discharge structure shown in Fig. 2, as well as microphotographs of these zones [Fig. 1(b)] shown in Fig. 3, allows one to differentiate the main and the additional sputter trenches.

The photos of the discharge above the planar cathode are shown for three pressure values (0.5, 1.0, and 1.4 Pa) for a discharge voltage of 1000 V. From these photos it is seen that the brightness of the discharge (and hence the plasma density) strongly depend on the pressure, with the most dense plasma obtained in the higher-pressure environment. It is also notable that the visual size of the discharge does not change significantly with the pressure.

Figure 3(a) shows that only the oxidized (black) layer is sputtered when the copper cathode remains intact [the intersected lines in Fig. 3(a) are scratches after polishing]. Figures 3(b) and 3(d) are associated with the cathode sputtering in the additional sputter trenches; this sputtering is less significant than the sputtering of the main sputter trench shown in Fig. 3(c). Furthermore, Fig. 3(e) shows very weak sputtering of the oxidized (black) layer.

The measured current-voltage characteristics of the discharge are shown in Fig. 4(a). The maximum ion current of the magnetron discharge reached 6.5 A at a bias voltage of 1000 V and a gas pressure of $p_0=0.5$ Pa [Figs. 2(a) and 4(a)] and 17 A at $p_0=1.4$ Pa [Figs. 2(c) and 4(a)]. The intermediate values of the current have been reached at pressures between 0.5 and 1.4 Pa. A photograph of the discharge at $p_0=1.0$ Pa is shown in Fig. 2(b). From these figures it is seen that the brighter discharge corresponds to higher discharge currents.

The measured values of the sputter trench width and radius at different gas pressures are shown in Fig. 4(b) for discharge voltages of 800 V (circles) and 1000 V (squares). It can be seen that increasing the pressure in 2.8 times (from 0.5 to 1.4 Pa) results in a reduction in the sputter trench width $w_s$ by about 1.26 times for a voltage of 1000 V (from 82 to 65 mm). This reduction is approximately 1.28 times for $V_c=800$ V (from 77 to 60 mm). The sputter trench radius $R_{min}$ shows an opposite trend. Increasing the pressure within the same pressure limits results in widening the sputter trench radius by about 1.28 times for a voltage of 1000 V (from 32 to 41 mm) and about 1.27 times for $V_c=800$ V (from 33 to 42 mm). In all discharge modes the main sputter trench width $w_0$ was about 50 mm. In contrast with that, the width $w_s$ of the additional sputter trench strongly varied with the gas pressure. For pressures above 1.6 Pa the additional sputter trench was not observed.
V. MODEL OF PLASMA TRANSPORT

In order to describe the observed dependence of the additional sputter trench on the discharge parameters, a model of the plasma transport in the crossed magnetic and electric fields was developed. This model is based on the assumption of plasma quasineutrality in the ionization region.

In this case, the magnetic field lines are circular with the radius of curvature \( R_c \) as was used by Lieberman and Lichtenberg.\(^{20}\) A schematic of a planar magnetron discharge main physical processes involved are shown in Fig. 5. We recall here that under the conditions typical for magnetron and thruster discharges the ions are not confined by the magnetic field (ion gyroradius is much larger than the characteristic size of the discharge) and hence can be effectively accelerated by the electric field toward the cathode. Secondary electron emission and cathode material sputtering are produced during the interaction of the ions with the cathode. The electrostatic sheath potential reflects the electrons from the cathode surface; there can also be some mirroring due to the nonuniform magnetic field effects.\(^{20}\)

Secondary electrons pass the sheath and gain energy \( \varepsilon_e = U_s - V_c \), where \( U_s \) is the voltage drop across the sheath and \( V_c \) is the discharge voltage. The Child–Langmuir law determines the sheath width,\(^4\)

\[
s = \left( \frac{4}{9} \varepsilon_e \right) \left( \frac{2e}{m} \right)^{1/2} \left( \frac{U_s^{3/4}}{J_i} \right)^{1/2},
\]

(1)

where \( s \) is the sheath width (m), \( e \) is the electron charge (C), \( m \) is the electron mass (kg), \( J_i \) is the density of the ion current entering the sheath (A/m\(^2\)). The ion current density is determined through the ion current \( I \) and the configuration of the main and additional sputter trenches \( (R_{min}, w_x) \) as

\[
J_i = \frac{I}{\pi[(R_{min} + w_x)^2 - R_{min}^2]},
\]

(2)

thus assuming that total discharge current \( I \) is collected by the cathode surface in the sputter trench with the width \( w_x \).

After the secondary electrons have crossed the cathode sheath and enter the plasma, they become energetic primary electrons.\(^8\) The primary electrons are trapped by the magnetic field \( B \) and gyrate with the gyroradius \( r_{ce} = \sqrt{2m_e \varepsilon_e / eB^2} \).\(^{10}\) While gyrating, these electrons ionize the working gas, thus generating additional electrons.\(^8\)

In this paper, the two possibilities are discussed for the primary electrons: diffusion across the magnetic field due to collisions with neutral atoms and the cathode sheath and diffusion due to the field turbulence (Bohm conductivity). Since, for both mechanisms, the ionization frequency is much less than the frequency of the scattering collisions leading to the diffusion across the magnetic field, the ionization region is hovering above the area of width \( r_{ce} \), where nonscattered secondary electrons move as shown in Fig. 5.

The primary electrons diffuse across the magnetic field lines and lose their energy by ionizing the neutral atoms, thus determining the ionization region width \( L_{ion} \). The electron energy losses in the ionization region can be determined from\(^{22}\)

\[
\frac{\partial \varepsilon}{\partial z} = E - \frac{v_i}{V_{ed}} \varepsilon_i,
\]

(3)

where \( \varepsilon \) is the electron energy (eV), \( E \) is the electric field in the ionization region (V/m), \( V_{ed} \) is the electron drift velocity (m/s), \( v_i \) is the neutral atom ionization frequency (1/s), \( \varepsilon_i \) is the collisional energy loss per electron-ion pair created (eV).

In Eq. (3), the energy losses of the highly energetic primary electrons due to collisions with the plasma bulk electrons

FIG. 3. Magnified image of the selected areas in Fig. 1(c): (a)–(e) correspond to 1–5 in Fig. 1(b), respectively.

FIG. 4. (a) Current-voltage characteristics of the discharge with the pressure as a parameter. (b) Parameters of the sputter trenches vs gas pressure.
have been neglected due to the relatively small cross section of the process.\(^8\)

Since the primary electrons lose almost all their energy in the sheath due to ionization, excitation, and polarization scattering against neutral atoms within the ionization region, the electron energy losses well exceed the energy gain and the following condition can be implied in the ionization region:

\[
E \ll \frac{v_i}{V_{ed}} e e_c,
\]

and Eq. (3) can be simplified,

\[
\frac{\partial e}{\partial z} = - \frac{v_i}{V_{ed}} e e_c.
\]

The neutral atom ionization frequency is determined\(^10\) as \(v_i = n_a \nu_i \sigma_i\), where \(n_a\) is the neutral atom density (m\(^{-3}\)), \(\nu_i\) is the electron velocity (m/s), and \(\sigma_i\) is the cross section for ionizing electron collisions with neutrals (m\(^2\)). The electron drift velocity is \(V_{ed} = \mu_e E\), where \(\mu_e\) is the electron mobility.\(^10\) The published data\(^26\) allow one to approximate the above cross section as \(\sigma_i = (-0.23[4.6 - \ln(e)]^2 - 273.4/e^2 + 1.86) \times 10^{-20}\) (m\(^2\)) for electron energies in the range between 16 and 1000 eV.

Considering the classical mechanism of the electron conductivity across the magnetic field, when the electron gyrofrequency \(\omega_e = eB/m\) is much larger than the electron collision frequency with neutrals \(\nu_i\), \(\omega_e \gg \nu_i\), the electron mobility can be expressed as \(\mu = \mu_0 (1 + \omega_e/\nu_i)^{10}\). Taking into account the primary electron reflection from the cathode sheath (NWC), we assume that these electron collisions can be quantified by the electron bounce frequency \(\nu_b\). The electron bounce is a fair approximation of the electron motion along the magnetic fields line and their mirroring due to interaction with the plasma sheath. Thus, the total frequency,

\[
\nu_{el} = \nu_i + \nu_b,
\]

of the electron elastic collisions resulting in the electron drift across the magnetic field incorporates both sorts of collisions. The electron-neutral collision frequency is \(\nu_n = n_a \nu_i \sigma_n\), where \(n_a\) is the neutral atom density (m\(^{-3}\)) and \(\sigma_n\) is the cross section for elastic electron collisions with neutrals (m\(^2\)). The published data\(^26\) allow one to approximate the cross section as \(\sigma_n = 89.4 \times 10^{-20} e^{-1/2}\) for electron energies \(\epsilon = 16\)–1000 eV. Since \(\nu_i = (2eB/m)^{1/2} = 5.93 \times 10^5 e^{-1/2}\), the electron-neutral collision frequency can be written as \(\nu_n = n_a \nu_i \sigma_n = n_a k_e^2\), where \(k_e = 5.3 \times 10^{-13}\) m\(^3\) s\(^{-1}\).

The electron-sheath collision frequency can be expressed as \(\nu_{s} = l_m^{-1} \sqrt{eE/3m}\), where \(l_m\) is the length of the magnetic field line between the two “mirroring” points (arc 1–0–2, Fig. 5); the elastic collisions of the electrons with the mirroring points can be interpreted as the “wall” collisions. To simplify the consideration, we assumed that \(l_m\) is constant through the ionization region and can be obtained by geometrical construction as \(l_m = 2R_e \arccos[(1-(1+s)R_e)/R_e]\).

The equation for the classical mobility\(^10\) becomes

\[
\mu_{el} = \frac{e \nu_{el}}{m \omega_e^2} = \frac{m}{eB^2} \left( n_a k_e + \frac{1}{l_m} \frac{eE}{3m} \right)
\]

after the addition of the NWC effects. Assuming that the Bohm conductivity is the dominant mechanism for electron conduction across the magnetic field, the fluctuations of the field with the frequency \(\nu_p = \omega_p / \omega_e\), lead to additional effective electron collisions.\(^2\)\(^10\) In this case the Bohm mobility can be written as

\[
\mu_{B} = \frac{e \nu_{B}}{m \omega_e^2} = \frac{1}{\alpha_B B},
\]

where \(\alpha_B = \text{const}\). Taking Eqs. (6)–(8) into account, Eq. (5) can be rewritten as

\[
\frac{\partial e}{\partial z} \bigg|_{CL} = -\frac{eB^2}{m} \frac{\sigma_i \sqrt{2eeE}}{m e_c E} = -\frac{e \nu_{el} \sigma_i \alpha_B B}{E} \sqrt{\frac{2eeE}{m}}
\]

for the classical mobility case and

\[
\frac{\partial e}{\partial z} \bigg|_{B} = -\frac{e \nu_{el} \sigma_i \alpha_B B}{E} \sqrt{\frac{2eeE}{m}}
\]

for the Bohm mobility case.

To calculate the ionization region width, the following assumptions have been made: (i) Primary electrons can ionize the neutrals until the electron energy is decreased from \(U_s\) to \(e_{ion}\), this can be used to determine the ionization region width \(L_{ion}\) and (ii) the electric and magnetic fields are constant \((E,B = \text{const})\) throughout the ionization region. The first condition implies that the additional electrons, created as a result of impact of the energetic primary electrons, cannot gain energy from the electric field within the ionization region directly. This also means that the primary electrons are the main species that sustain the glow in the ionization region. The assumptions made allow one to apply the following boundary condition, which relates the ionization energy with the distribution of the electric field:

\[
\int_{0}^{L_{ion}} E dx = E L_{ion} = \epsilon(L_{ion}) = \epsilon_{ion},
\]

where \(\epsilon_{ion}\) is the ionization energy. Condition (11) sets the dependence of width \(L_{ion}\) on parameter \(E/e_c\) to solve Eqs. (9) and (10). Since the collisional energy loss per electron-
pair created $e_-$ approaches to just below $2e_\text{ion}$ at high temperatures, one can obtain $E/\varepsilon_0 = E/(2e_\text{ion}) = 1/(2L_\text{ion})$.

Taking into account that $n_\text{e} = p_0/kT$, where $p_0$ is the gas pressure, $k$ is Boltzmann’s constant, and $T$ is the gas temperature, and integrating Eqs. (8) and (9), one can estimate the width of the ionization region,

$$L_\text{ion}|_{\text{cl}} = \frac{1}{B} \left( \frac{m}{8e} \right)^{3/4} k \int_{e_\text{ion}}^{U_\text{i}} \frac{d\varepsilon}{\sigma_\text{e}(\varepsilon)} + \frac{kT}{p_0 B m} \int_{e_\text{ion}}^{U_\text{i}} \frac{d\varepsilon}{\sigma_\text{e}(\varepsilon)}^{1/2},$$

in the classical mobility case, and

$$L_\text{ion}|_{B} = \left( \frac{kT}{\alpha_\text{B} B p_0} \right)^{1/2} \left( \frac{m}{8e} \right)^{1/4} \left( \int_{e_\text{ion}}^{U_\text{i}} \frac{d\varepsilon}{\sigma_\text{e}(\varepsilon)} \right)^{1/2},$$

for the case when Bohm’s mobility is dominant.

The additional electrons generated in the ionization region move along the magnetic field lines and affect the ions that follow the electrons by ambipolar diffusion to conserve the plasma quasineutrality. The ions being accelerated in the sheath strike the cathode and sputter its surface thus forming the additional sputter trench observed in our experiments.

We estimated that the plasma torus has the mean height from the cathode equal to the sum of the sheath width $s$ and the electron gyroradius $r_\text{e}$. Hence, primary electrons are trapped on a magnetic field line and can oscillate between the reflections from the cathode sheath. The energy losses of the electrons during the drift across the magnetic field $B$ determine the ionization region width $L_\text{ion}$ (Fig. 5). Thus, considering the projection of the ionization region onto the cathode surface due to the curvature of the magnetic field lines, one can express the width of the additional sputter trench as

$$w_1 = \alpha_\text{m} L_\text{ion},$$

where the coefficient $\alpha_\text{m} = \text{const}$ can be determined from the geometrical construction for the measured and calculated values of $r_\text{e}$, $s$, and $R_c$.

The width of the main sputter trench can be calculated as $w_0 = 2(2r_\text{e} R_c)^{1/2}$. The measured radius of curvature of the magnetic field and its strength near the cathode were used to calculate the electron gyroradius $r_\text{e}$ for cathode voltages of 800 and 1000 V. The configuration of the sputter trench was used to calculate the ion current density $J_i$ and sheath thickness $s$ using Eqs. (1) and (2). The results of the calculation are shown in Fig. 6(a). The width $w_1$ of each additional trench was calculated as a difference between the measured values $w_i$ and $w_0$: $w_1 = (w_i - w_0)/2$. The results of calculations are shown in Fig. 6(b) (bars are for $U_s = 1000$ V and circles are for $U_s = 800$ V).

The coefficient $\alpha_\text{m} = 16$ was used in calculations that involve Bohm’s conductivity mechanism; the gas temperature $T = 300$ K and the ionization energy $e_\text{ion} = 16$ eV for nitrogen $N_2$ were also used as parameters. The integrals $\text{Int}_1(U_s) = \int_{e_\text{ion}}^{U_\text{i}} (d\varepsilon/\sigma_\text{e}(\varepsilon))$ and $\text{Int}_2(U_s) = \int_{e_\text{ion}}^{U_\text{i}} (d\varepsilon/\sigma_\text{e}(\varepsilon))$ were calculated numerically. These parameters allowed us to calculate the ionization region width $L_\text{ion}$ for collisional (classical and near-wall) and Bohm conductivities according to the developed model.

The calculated parameters $r_\varepsilon$, $s$, $R_c$, and $L_\text{ion}$ and the geometry of the discharge region were used to determine the constant $\alpha_\text{m} = 1.5$ to calculate the width of the additional sputter trench $w_1$ using Eq. (14). The results of the calculations are shown in Fig. 6(b), which displays the dependence of the additional sputter trench width on the gas pressure at different cathode voltages (solid line is for $U_s = 1000$ V and dotted line is for $U_s = 800$ V) for the collisional and Bohm electron conductivity mechanisms.

VI. DISCUSSION AND CONCLUSIONS

The measured width of the main sputter trench $w_0$, shown in Fig. 3(b), was compared with the value calculated by the expression $w_0 = 2(2r_\varepsilon R_c)^{1/2}$, 48 mm for the cathode voltage 800 V and 51 mm for the voltage 1000 V. This comparison shows that the observed width of the main sputter trench is in a good agreement with the theoretical predictions. One can thus conclude that the motion of the energetic electrons in the magnetic field controls the creation of the plasma ions and hence the distribution of the ion current density $J_0$ over the cathode surface and eventually the main sputter trench width $w_0$.

Considering the additional sputter trench width $w_1$, one can see that an increase in the gas pressure causes this trench to be shifted toward the main trench. Since the magnetron discharge of our interest is essentially a glow discharge, all
the discharge layers (e.g., near-cathode sheath, etc.) become thinner and shift closer to the cathode as the pressure increases. This is why one can conclude that the region where the primary electrons ionize neutral atoms (i.e., the ionization region) contracts due to faster ionization at higher working gas pressures.

Comparing the results obtained for the additional sputter trench, one can conclude that the experimental data are best fitted by the curve corresponding to the turbulence-driven Bohm conductivity of electrons across the magnetic field. This works very well for the low-pressure operating regimes up to gas pressures of about 1 Pa. At the same time, the mechanism involving elastic collisions of primary electrons with the neutrals and the cathode sheath is more likely to play a major role in the electron conductivity at operating pressures above 2 Pa.

The underlying mechanisms for the electron conductivity in crossed $E \times B$ fields were investigated by considering the sputter trenches that revealed the structure of the ionization region of the planar magnetron discharge. A model describing the motion of energetic primary electrons in the ionization region was developed to determine whether the classical and near-wall or, alternatively, turbulence-driven Bohm mechanisms of the electron conductivity across the magnetic field best describes the experimental observations. The width and the structure of the additional sputter trench varied with the operating gas pressure and were found in excellent agreement with the results obtained for the Bohm conductivity case, in particular, in the low-pressure (below 1 Pa) discharge mode. These results suggest that the classical and near-wall collisional mechanisms for electron conductivity across the magnetic field are dominant at higher pressures (above 2 Pa). The results of this work are particularly important for the development of highly effective material sputtering equipment, as well as nanoscale and plasma propulsion applications. Future work will focus on revealing the dominant conductivity mechanisms in a wider range of the process parameters.