Wall sheath and optimal bias in magnetic filters for vacuum arc plasma sources

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A plasma diffusion model is established to determine the optimal bias and sheath patterns in a positively biased magnetic filter of a metal arc plasma source. We determine the equation for the optimal bias on the magnetic filter. According to our model, the optimal bias is related to the electron speed, ion speed, ion mass, ion charge state, and plasma density in the filter. The optimal bias increases as these variables are increased with the exception of the electron speed. Even though the magnetic field is taken into account, it is not a variable in the final equation. Our experimental results confirm that the magnetic field has almost no influence on the optimal bias. An alternate design approach is suggested that leads to enhanced plasma transport through the filter. © 2002 American Institute of Physics. DOI: 10.1063/1.1431690

Cathodic arc plasma is of increasing importance in thin-film deposition of metals, oxides, nitrides, semiconductors, and amorphous carbon,1–5 beam-line metal ion implantation,6 as well as metal plasma immersion ion implantation (PIII).7–9 The favorable characteristics of a cathodic arc plasma source are the high ion flux and high degree of ionization of the metal plasma. However, cathodic arc plasmas suffer from macroparticle contamination. Several techniques have been proposed to mitigate or eliminate the undesirable effects.10,11 The most common method to remove macroparticles is to insert a curved magnetic filter between the source and samples. The two most important parameters in designing magnetic filters are the biasing voltage and magnetic field. The magnetic field is necessary to effectively transport the plasma through the filter, and a proper bias on the filter increases the plasma output by an additional factor of 3 to 5.12,13 This is because the magnetic field limits electron motion in the radial direction and the positive bias deters ions from colliding with the filter wall. The positive bias value must be carefully selected to optimize the plasma output, and in order to do so, one needs to know how these parameters are interrelated and how they influence the optimal bias. In this work, we investigate plasma diffusion in the sheath and the relationship between the bias and plasma diffusion in order to determine the parameters impacting the optimal bias.

Based on previous results, the cathodic arc plasma is essentially fully ionized and the arc electron current is about ten times higher than the arc ion current. Hence, there is a net current in the arc discharge plasma.14 The electron thermal velocity and ion drift velocity are typically 7–9 × 10^5 m/s and 1–2 × 10^4 m/s, respectively.12 The directed velocity of the cathodic arc plasma plume is about 1 × 10^4 m/s.14 For a Ti cathode, the ion drift energy is in the range 16–66 eV. The experimental apparatus including a magnetic filter and cathodic arc plasma source has been described previously.13 The duration of each cathodic arc pulse is 0.3 ms, and the time for the plasma plume to move from the cathode to the exit of the filter is about 0.01 ms. Therefore, the plasma is formed as soon as the cathodic arc is ignited and acts as a conductor throughout the duct space to carry a net electron current emitted from the cathode. Our previous experimental results show that a positive bias improves the efficiency of the filter13 and simultaneously increases the electron current,15 thereby confirming that there is a net electron current in the plasma when both the magnetic field and electric field are on.

Generally, in a magnetic filter, electrons are tightly bound to the magnetic field lines whereas ions are not. The ion Larmor radius is of the same order as the filter minor radius. Therefore, the effects of the magnetic field on the ion motion can be neglected compared with the electron motion. Collisions between particles in the plasma result in electron transport across the magnetic field lines. Electron–electron collisions give rise to very little transverse diffusion since the center-of-mass of the guiding centers of the colliding electrons remains stationary. Transverse diffusion of electrons is mainly caused by electron–ion collisions.12 In this work, we assume that: (a) the plasma is quasineutral and fully ionized, (b) the plasma comprises only electrons and ions with one charge state, and (c) the magnetic field established by the external source is a good approximation to the actual mag-
A sheath is formed between the plasma and filter wall when a positive bias is applied. The potential in the sheath accelerates the electrons towards the wall and deters the ions, and the general method of sheath analysis can be adopted here. The ability of the electrons to traverse the magnetic field is much smaller than that of the ions, and so the electron and the ion roles are reversed when compared with the conventional sheath of a floating object in a plasma without the magnetic field. In our derivation, the electrons can be treated as stationary while the ions are in motion in the direction perpendicular to the magnetic line, and the Debye length in the direction perpendicular to the magnetic field is given by

$$\lambda_\perp = (T_e e^2 / n_0 e^2)^{1/2},$$

where $T_e$ is ion temperature, $z$ is the charge state of the ions, and $n_0$ is plasma density. The potential in the interface of the sheath and plasma (Fig. 1) is

$$V(x) = V_0 \exp(-x / \lambda_\perp),$$

where $V_0$ is the potential difference between the filter and the plasma. Hence, the electric field is given by

$$E(x) = -\lambda_\perp^{-1} V_0 \exp(-x / \lambda_\perp).$$

According to Poisson's equation,

$$d^2 V / dx^2 = e_n(x) / e_0,$$

where $e_n(x)$ is net electron density in the sheath. Consequently, we can derive the electron flux towards the filter wall in position $x$ under the influence of the electric field as

$$\Gamma = E(\lambda_\perp) \mu_e [n(\lambda_\perp) + zn_i(\lambda_\perp)],$$

where $\mu_e$ is the electron transfer rate perpendicular to the magnetic field and $n_i(x)$ is the ion density in the sheath. Using Boltzmann's distribution,

$$n_i(x) = n_i \exp(-zeV(x)/T_i),$$

where $n_i = n_0 / e$. So, $n_i(\lambda_\perp) = n_i \exp(-zeV(\lambda_\perp)/T_i) = n_i \exp(-zeV_0/2.72T_i)$. Sometimes the plasma in the magnetic field shows Bohm diffusion.\(^{16}\) Anders et al. studied the plasma transport in a magnetic filter and observed that the plasma in the magnetic filter had the Bohm diffusion coefficient\(^{12}\)

$$D_0 = T_0 / 16eB,$$

where $T_0$ is the temperature of the particles in the plasma, $B$ is magnetic field, and according to Einstein's formula,

$$\mu_e = 1/16B.$$

In the presence of a magnetic field but with no wall bias, the average velocity of the electrons towards the wall (grounded) at position $x = 0$ (that is the wall) is $\rho v_{ei}$,\(^{17}\) where $\rho$ is the electron Larmor radius and $v_{ei}$ is the electron–ion collision frequency. The highest flux of electrons lost to the wall should be

$$\Gamma_0 = g \rho v_{ei} n_0,$$

where $g$ is the ratio of the electron current to the ion current in the cathodic arc.

The transport efficiency of the filter increases as the positive bias increases at the beginning because the positive bias deters ion from diffusing to the wall. When the positive bias is so high that the electron flux in the sheath surpasses the normal electron flux that the plasma can supply, that is, $\Gamma > \Gamma_0$, the electron loss is high in the filter leading to increased ion loss to the wall. Thus, the transport efficiency of the filter begins to decrease and the optimal potential difference between the wall and the plasma should make $\Gamma = \Gamma_0$. That is,

$$E(\lambda_\perp) \mu_e [n(\lambda_\perp) + zn_i(\lambda_\perp)] = g \rho v_{ei} n_0.$$  

From Eq. (10), the equation

$$V^2 e_0 / 2.72 e_\perp^2 + V n_0 \exp(-zeV/2.72T_i) = 43.52 g n_0 \rho v_{ei} \lambda_\perp B$$

(11)

can be derived, and

$$1.05 \times 10^8 \frac{z}{Mu_i^2} V^2 + \exp\left(-1.05 \times 10^8 \frac{z}{Mu_i^2} V\right) V - 0.625 \times 10^{-10} v_{ei} u_i u_e \sqrt{Mn_0z} = 0,$$

(12)

where $V$ (in units of volts) is the optimal potential difference between the wall and plasma, $M$ is the atomic number, $u_i$ and $u_e$ (in m/s) are the ion and electron velocities, respectively, and $n_0 = n_e$ where $n_e$ is the electron density of the quasineutral plasma in m$^-3$. Equation (12) indicates that $V$ is affected by the electron velocity, ion velocity, mass and charge state, and plasma density. If the influence of magnetic field on $v_{ei}$ is neglected, then $V$ is not affected by the magnetic field. If the plasma has a zero potential, $V$ is the optimal bias of the filter. Experimentally, our results show that the optimal bias remains at 20 V when the magnetic field is changed from 100 to 500 G. Anders et al. have also confirmed that the magnetic field has almost no influence on the optimal bias in the range of 170–1700 G.\(^{12}\)

The relationship between $u_i$, $V$ and between $z$ and $V$ determined by Eq. (12) is shown in Fig. 2. $V$ increases with $u_i$ and so does $z$ in the range studied in this work. It should be noted that the electron velocity, ion velocity, and charge state in the cathodic arc plasma are not singular but have distributions. The optimal bias is the composite result of these distributions. Our results indicate that $V$ increases with $n_0$ (Fig. 2). For a certain cathode material, the atomic number is known and its ion charge state as well as the ion and electron energy distributions in the cathodic arc plasma are stable.\(^{14,18}\) This therefore suggests that the optimal bias can be determined easily for a given cathode material. However, when the plasma is transported through the filter, the $n_0$ distribution is not the same in the radial and azimuthal direc-
tions. In addition, $n_0$ changes with the axial distance along the filter length. Hence, $n_0$ and $\nu_{ei}$ are not evenly distributed and very difficult to determine in the filter. The measured optimal bias takes into account all these distributions and parameters. As $n_0$ becomes smaller as the plasma is transported through the filter, the optimal bias decreases with distance. Hence, our results suggest that an improved filter could be designed to have several sections along the axial direction, with each section independently biased. The overall plasma transport of such a filter should be significantly enhanced.

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