ELECTRON EMISSION UNDER SPACE CHARGE LIMITED CONDITION WITH AN OBLIQUE MAGNETIC FIELD

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It is well known that the electron emission from materials surface plays a very important role in the plasma-surface interaction and influences boundary plasma. Experiments verify that a large number of electron emission reduces the sheath potential [1]. This should result in the decrease of both ion energy flux to the surface and sputtering yield. At the same time electron flux to the target should be enhanced. As a result, a local hot spot is likely produced and large amounts of thermal electrons are emitted. However, the effect of virtual cathode formation and existence of an oblique magnetic field on thermo-electron emission has not been discussed yet. In the present work, we have made a computer simulation for secondary and thermo-electron emissions under space charge limited condition (SCLC) with an oblique magnetic field in the sheath taking into account the occurrence of a virtual cathode. Emission characteristics under the virtual cathode regime are compared for various conditions such as, different potential distributions, different target materials, different incident angles of the magnetic field and so on. For the calculation of the potential distribution in the sheath, the initial energy of emitted electrons was also taken into account.

Model

To describe the potential distribution $\varphi(x)$ in the sheath considering the occurrence of the virtual cathode near surface, we modified the Poisson equation given in [2] by adding a parameter ε_e for the initial energy of emitted electrons: $\varepsilon_e = v_{oe}^2 m_e / 2kT_e$, where v_{oe} is the mean velocity of electrons emitted from the surface, T_e is the plasma temperature at the sheath edge. We introduced the effective emission coefficient γ as a function of an effective electron emission coefficient Γ_e and angle α between the magnetic field and the target surface, $\gamma = \Gamma_e / [\sin \alpha + \Gamma_e (1 - \sin \alpha)]$, which represents the dependence of the potential distribution on electron emission and magnetic field. When Γ_e is small, coefficient γ can be large for small α. This is the effect of the "effective electron emission", that is, the emitted electron flux is suppressed by magnetic field and electron density increases near the surface.

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The effective electron emission coefficient $\Gamma_e = (\gamma_e + \gamma_t) / (1 + \gamma_t)$ includes secondary electron emission γ_e and thermo-electron emission coefficient $\gamma_t = k_t \gamma_j$. The reducing factor k_t presents suppression of thermo-electron emission by negative electric field of a virtual cathode and the gyration of electrons in an oblique magnetic field. We define the coefficient of thermo-electron emission in ordinary regime as $\gamma_j = j_t / e n_o v_{oi}$, where j_t is the thermo-ionic current, and $n_o v_{oi}$ is the average ion flux to the surface. The self consistent solution of Poisson equation determines the potential distribution in the sheath $\varphi(x)$ as a function of γ in the same manner as described in Ref. [3]. When γ exceeds the critical value 0.905, a virtual cathode is formed in front of the surface and the electric field there becomes negative.

For the calculation of the secondary electron emission coefficient γ_e ($\gamma_e = \int \delta_e(E_p) f(E_p) dE_p / \int f(E_p) dE_p$; the number of electrons returning to the boundary plasma per primary electrons with an incident energy distribution $f(E_p)$), basic data of the effective secondary yields $\delta_e(E_p)$, reflection coefficients and energy distribution of emitted electrons for Be, C, Mo and W are used as in Ref. [3]. The electron motions in the sheath were followed by using the Runge-Kutta method with an integration step automatically chosen to ensure an error less than $10^{-4}\lambda_D$, where $\lambda_D = (e_o kT_e / n_o e^2)^{1/2}$ is the Debye length. Calculations were made for primary electrons having the Maxwellian velocity distribution modified by the sheath potential for velocity component v_x in front of the surface in perpendicular to the surface direction: $dN(v_x) = (m_e n_o / kT_e) \exp(-m_e v_x^2 / 2kT_e) v_x dv_x$. The sheath thickness was set to $d = 5 \lambda_D$.

Thermo-electron current depends on the surface temperature T_s and the work function φ_a and current density of emitted electrons j_t can be described by the Richardson-Dushman equation: $j_t = A T_s^2 \exp(-\varphi_a/kT_s)$. We used the basic date for the temperature dependence of both Dushman's constant A and the work function given in [4]. Calculations were made using the modified Maxwellian distribution of thermo-electrons for velocity component v_x in front of the surface in normal direction: $dN(v_x) = (m_e n_o / kT_s) \exp(-m_e v_x^2 / 2kT_s) v_x dv_x$, where $N = j_t / e$.

Results

The secondary electron emission coefficient γ_e calculated for primary electrons with the modified Maxwellian velocity distribution is strongly reduced in SCLC compared with that in the ordinary regime, because of the prompt return of the secondary electron to the surface by their gyration. In the ordinary regime γ_e increases with plasma temperature due to the increase of the sheath potential and the electric field near the surface, whereas the electric field in the SCLC regime is so small in front of the surface that γ_e is nearly independent on the plasma temperature. Moreover, the difference in γ_e among target materials considered here (W, Mo, C and Be) are found to be small. For fusion plasma, for example, plasma

temperature $T_e = 40$ eV, plasma density $n_o = 10^{19}$m^{-3}, the strength of the oblique magnetic field more than T and the incident angle α of the magnetic field smaller than 10°, γ_e is significantly suppressed to the absolute number less than 0.1 for all of Be, C, Mo and W as already shown in [4].

The effect of the negative electric field of the virtual cathode is negligible for secondary electrons, because the kinetic energy of the secondary electrons is mostly higher than the height of the potential hill in the virtual cathode, but is very important for thermo-electrons. In Fig. 1, the reducing factor k_t as a function of initial energy of thermo-electrons is compared for different height of the negative potential hill $\nabla\varphi$ in the virtual cathode regime for $T_e = 40$ eV and $n_o = 10^{19}$m^{-3}. In the calculation we assumed a $\cos(\theta)$ dependence of the emitted electrons (the angle θ is respective to the surface normal). It can be noted that k_t is strongly reduced by only very small potential hill due to the reflect-back of low energy thermo-electrons by the negative electric field. As shown in Fig. 2, the suppression of the reducing factor k_t (calculated for thermo electrons with the modified Maxwellian velocity distribution) by the oblique magnetic field is very strong. However, the difference in the temperature dependence of k_t with and without the magnetic field is rather small. The temperature dependence of k_t is mainly controlled by the height of the negative potential hill, which varies with surface temperatures but not the magnetic field. The prompt return due to the magnetic field is appreciable only for higher energy electrons (Fig. 1).

As a whole, the temperature dependence of the effective emission coefficients γ including both secondary and thermo-electrons for C, Mo and W are given in Fig. 3. For C and W, both of which have high thermo-electron emission characteristics and high melting points, the SCLC is attained ($\gamma = 0.905$) before melting even in the oblique magnetic field. For low surface temperature, γ is determinate by the secondary electron emission, which is strongly suppressed by gyration in the oblique magnetic field. For higher surface temperatures, γ is dominated by the thermo-electron emission. Emitted electron flux is strongly suppressed by magnetic field itself and electron density increases in the sheath ("effective electron emission"). Then, the regime of SCLC is likely in the sheath with an oblique magnetic field.

References

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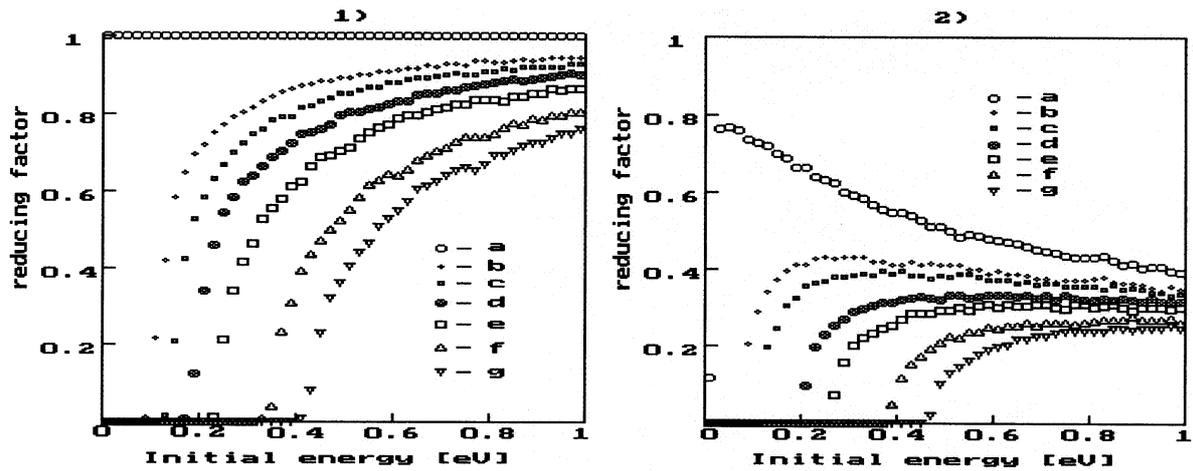[4] I.V. Tsvetkov and T. Tanabe: *Proc. of the 13th PSI*, May 18-22, 1998, San-Diego, California, USA, p.72.

Fig. 1. Reducing factor k_t against initial energy of termo electrons for regime of virtual cathode without (1) and with (2) an oblique magnetic field at different height of the negative potential hill $\Delta\varphi$: a) $\Delta\varphi = 0$, b) $\Delta\varphi = 0.05$ eV, c) $\Delta\varphi = 0.1$ eV, d) $\Delta\varphi = 0.15$ eV, e) $\Delta\varphi = 0.2$ eV, f) $\Delta\varphi = 0.3$ eV, g) $\Delta\varphi = 0.4$ eV. Plasma temperature T_e=40 eV, plasma density n_0=10^{19}m^{-3}, magnetic field strength B=2T, angle between magnetic field and surface α=10°.
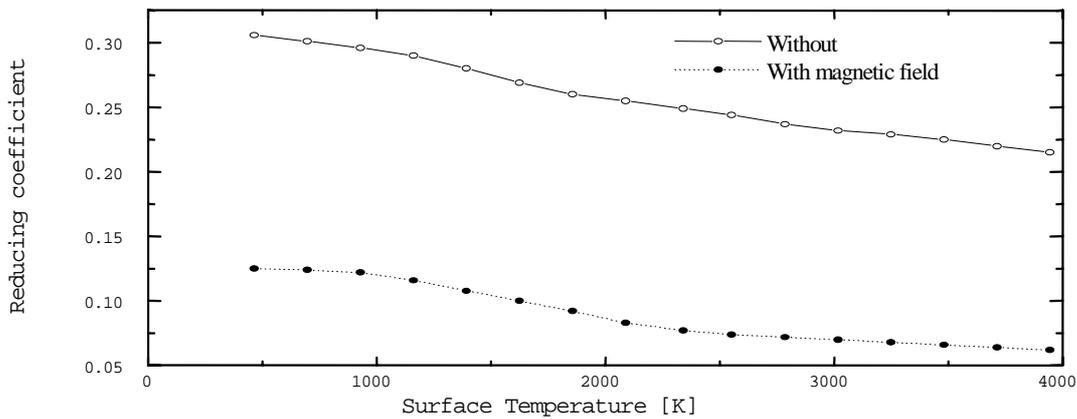

Fig. 2. Reducing factor k_t as a function of the surface temperature T_s for regime of virtual cathode without and with an oblique magnetic field. Plasma temperature T_e=40 eV, plasma density n_0=10^{19}m^{-3}, magnetic field strength B=2T, angle between magnetic field and surface α=10°.
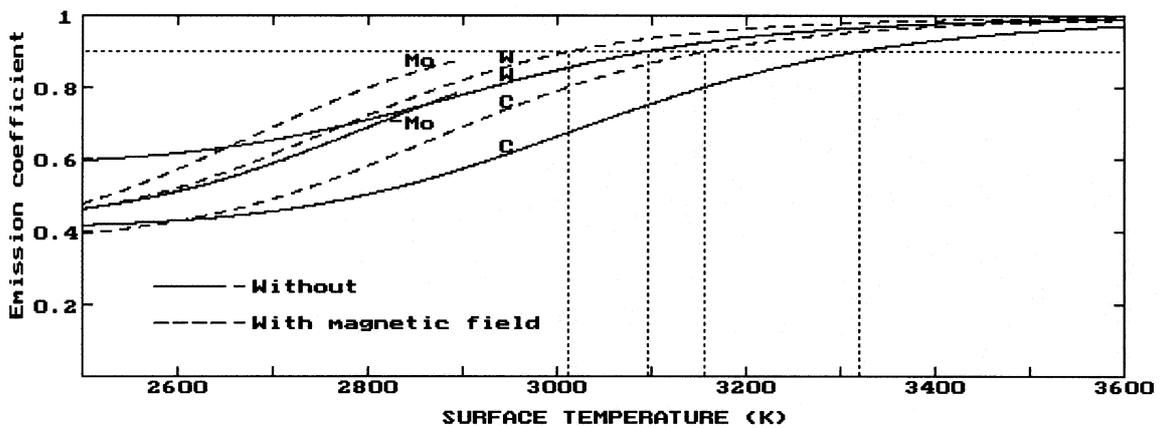

Fig. 3. Effective emission coefficient γ for thermo emission plus secondary electron emission of C, Mo, W as a function of the surface temperature T_s for SCLC without and with an oblique magnetic field. Plasma temperature T_e=40 eV, plasma density n_0=1019m-3, magnetic field strength B=2T, angle between magnetic field and surface α=10°.