Suppression of secondary electron emission from the material surfaces with grazing incident magnetic field in the plasma

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Suppression of secondary electron emission from the material surfaces with an obliquely incident magnetic field is demonstrated experimentally in a plasma containing hot electrons. © *1996 American Institute of Physics.* [S1070-664X(96)01612-6]

Secondary electron emission (SEE) is one of the most important processes in plasma–surface interactions in fusion devices, flying objects in space, plasma processing, and so on. In the scrape-off layer (SOL) plasma of toroidal fusion devices with magnetic divertors, the magnetic field lines connect to the divertor target plate with grazing incidence. The SEE decreases the sheath voltage ϕ_s on the surface of the target plate so that the heat flux to the surface increases by dropping the thermal insulation across the sheath. The emitted cold electrons go upstream and cool down the plasma. Therefore, the suppression of SEE substantially changes the SOL plasma energy balance, and influences the erosion property of the target material and impurity contamination. However, there has been no experimental demonstration on the suppression of SEE coming from the electron gyromotion around the grazing incident magnetic field lines, especially in a plasma environment, in which a strong electric field associated with the plasma sheath accelerates the emitted electrons *away* from the target surface. The electric field force in the sheath could be greater than the Lorentz force for those emitted secondary electrons and might break down the return of them to the material surface. This is completely different from the condition of the electron beam experiment in a vacuum.

We have investigated the orbits of emitted electrons in various conditions to estimate what fraction of them can escape from the sheath region and if the electric field increases the fraction.[1] It is noted that some suppression should be observed at the angle θ close to 90°, where θ is the angle between the surface normal and the magnetic field line, as shown in Fig. 1. A space charge effect on the electron emission current through the sheath into the plasma, the so-called virtual cathode effect, has been studied empirically[2,3] and by a particle in cell simulation code,[4] since the sheath voltage, ϕ_s, is critically influenced by the electron emission.

The experiment was done in the Current Sustaining Tokamak in Nagoya University, CSTN-III, with a high repetition rate, 10 Hz.[5] The working gas was hydrogen with the low pressure of 6×10^{-5} Torr. The toroidal plasma current of 600 A with the toroidal magnetic field of 0.086 T gave us the modest peak plasma density of 1×10^{12} m^{-3}. The bulk electron temperature T_c was about 10 eV, and the ion temperature was much lower than that of electrons. The high repetition mode of the present low-temperature tokamak device ensures the technique of rapid sampling and averaging for data processing. In addition, the plasma is very reproducible and, therefore, is quite appropriate for fundamental research.[6–8] Contributions to the SEE from photons and ions as well as of the field electron emission are negligible in such a very low-temperature plasma with modest electron density.

A group of hot electrons is generated by accelerating thermoelectrons emitted from a LaB$_6$ cathode ($50\times20\phi$ mm) with a form of double spiral cylinder installed inside the tokamak vacuum chamber as shown in Fig. 1. The low gas pressure ensures a successful electron acceleration without any discharge. Using an electrostatic energy analyzer, the hot electrons thus produced were found to have a velocity distribution approximated as a Maxwellian along the magnetic field line with a cutoff corresponding to the biased voltage between the cathode and the plasma potentials. The plasma potential is changed little by the cathode biasing. The cutoff energy could mean almost the same total energy for all accelerated electrons. The distribution of parallel velocity comes from the fact that the electrons are emitted from the three-dimensional structure of the cathode surface with various angles, although the total energy should be the biasing voltage. The effective temperature of hot electrons, T_h, is determined by the exponential decay slope of the parallel electron energy distribution. We should note that the distribution of parallel velocities is important for the plasma sheath formation, although the total energy and the angle of incidence decide the SEE yield. The hot electrons are localized inside a flux tube in the tokamak plasma since the rotational transform on the drift orbit determines the trajectories of hot electrons. In this flux tube the hot electron abundance α is about 40%–50% of all electrons, weakly dependent of T_h, where the emission current from the cathode is 20 A.[8] We note that the cross section of the tube is larger than the size of the target plates.

Two-component electrons will bring some complications for sheath voltage formula. However, when the condition

$$\alpha>(T_{\mathrm{eff}}/T_h)^{1/2}(2\pi m_e/m_i)^{[1-(T_{\mathrm{eff}}/T_h)]/2}, \tag{1}$$

is satisfied, the sheath voltage is given by the following equation for the target with a normally incident magnetic field:[9]

$$\phi_s\approx-\frac{T_h}{e}\ln\left[\frac{1}{\alpha(1-\delta)}\left(\frac{T_{\mathrm{eff}}}{T_h}\,\frac{2\pi m_e}{m_i}\right)^{1/2}\right], \tag{2}$$

where δ is the sum of true SEE and backscattering, and T_{eff} is defined by $T_{\mathrm{eff}}^{-1}=(1-\alpha)T_c^{-1}+\alpha T_h^{-1}$. It shows an almost

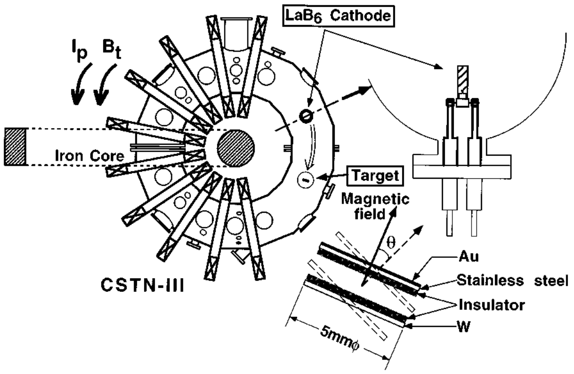

FIG. 1. Schematic view of experimental arrangement.

linear increase of sheath voltage with T_h, as shown by a solid line in Fig. 2. When δ increases, ϕ_s will approach zero. It means that the SEE makes ϕ_s small compared with the value without SEE. Oppositely, when the SEE is suppressed, ϕ_s becomes large and approaches the value without SEE. The above inequality condition, Eq. (1), is well satisfied in the present experiment.

We employed gold and tungsten for a target material, which have relatively high and low δ, respectively, in the energy range concerned, where SEE increases monotonically with the electron energy. The δ reaches unity when it is 80 eV for Au and 250 eV for W.[10] Both targets have the same size, 5 mm in diameter, and were set back to back with a vertical rotatable rod in between, as shown in Fig. 1. The size is large enough for the emitted electrons to return to the surface, which has been confirmed by the numerical orbit tracing.[1] Evaporated Au was deposited on a stainless-steel target plate with a surface roughness of less than half a micron; that is much smaller than the electron Larmor radius of a few tens microns for emitted electrons with the energy range of 1–10 eV. Moreover, the Au surface layer has a thickness of 20 microns, which is much greater than the few nanometers penetration depth of primary fast electrons into the solid surface layer. The reproducibility of the measured sheath voltage was quite good over many series of experiments so that a sputtering due to the high negative sheath voltage may clean the target surface. This meant that surface contamination, like oxidization, did not create any serious complications in the experiment. We should note that the precision of setting the angle θ between the B field line and the target surface normal may vary a few degrees due to the rotation mechanics, surface flatness, the curvature of B field lines, etc. Even the modest estimate gives the ratio of the electric field force to the Lorentz force in the sheath E/vB larger than 2 for the secondary electron's energy of 10 eV and the electron temperature of 10 eV. A possible lower energy of secondary electrons and a higher electron temperature due to hot electrons could give a greater value for the ratio.

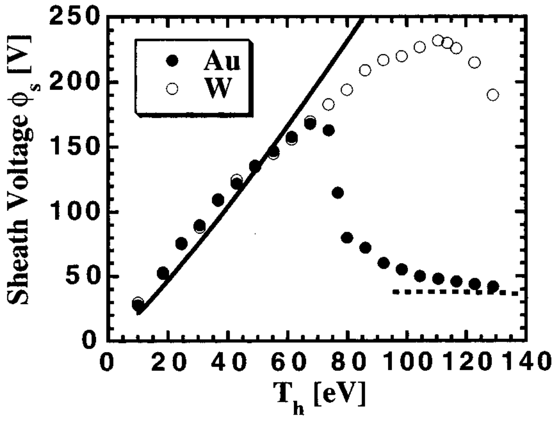

FIG. 2. Dependencies of sheath voltage on the effective parallel temperature of hot electrons. Solid line shows theoretical formula, Eq. (2), without SEE, $\delta=0$, where α is assumed 0.5. Dotted line is theoretically obtained by the floating condition using the modified Child–Langmuir formula for space charge limited emission current.

As described by Eq. (2), ϕ_s should be a very good measure of the electron emission. Figure 2 shows the sheath voltages on the surfaces of both metals with a normal incidence of B field as a function of T_h. Here ϕ_s is defined as the potential difference between the target and the plasma just in front of it. In the present case, the plasma potential is very close to the chamber potential. Therefore, the target floating potential with respect to the chamber potential is just the sheath voltage. The solid line shows the dependence given by Eq. (2) with $\delta=0$. Here, we assume a constant value of the hot electron population $\alpha=0.5$. Saturations and succeeding decreases in ϕ_s, followed by linear increases with T_h, come from a contribution of SEE. The reference δ data for Au[10] seem to be a little bit too large judging from our experimental measurement on the T_h dependence of sheath voltage. For the Au target a low but finite ϕ_s after a sharp drop was observed, approaching the dotted line obtained from the space charge limited emission current, $j=2.33\times10^{-6}\phi_s^{1.5}/d^2$, where d is chosen to be $3\lambda_D$.[2–4] The Debye length λ_D is calculated using T_{eff}.

Detailed angular dependence of ϕ_s for the Au and W target plates are, respectively, demonstrated in Figs. 3(a) and 3(b). The angle θ was changed from $-180°$ to $180°$. The range $90° \leqslant |\theta| \leqslant 180°$ means that the counterclockwise streaming electrons and ions come into the target. However, here we should concentrate the range $-100° \lesssim \theta \lesssim 100°$ because of some complications due to the hot electrons scattered into the shadow region of the target. In our experimental condition the emitted electrons always feel an accelerating field away from the target surface during at least the first gyromotion. The sheath thickness is larger than the Larmor radius of secondary electrons. At the hot electron temperature T_h below 65 eV, the voltage is almost the same for both materials where there are slow decreases of ϕ_s with θ from 0° toward ±90°, indicating the decrement of electron current compared with the ion current due to the decrease of effective perpendicular surface area $S\cos\theta$. Here S is the surface area of the target. The ion current does not decrease as much with θ, owing to the finite Larmor radius. In a middle range of T_h, 80 and 100 eV for W, a sharp drop in the voltage with the angle is attributed to the increase of δ by the oblique incidence of primary electrons to the target plate as the SEE coefficient is usually inversely proportional to $\cos\theta$. This is very much pronounced in T_h of 75 eV for Au

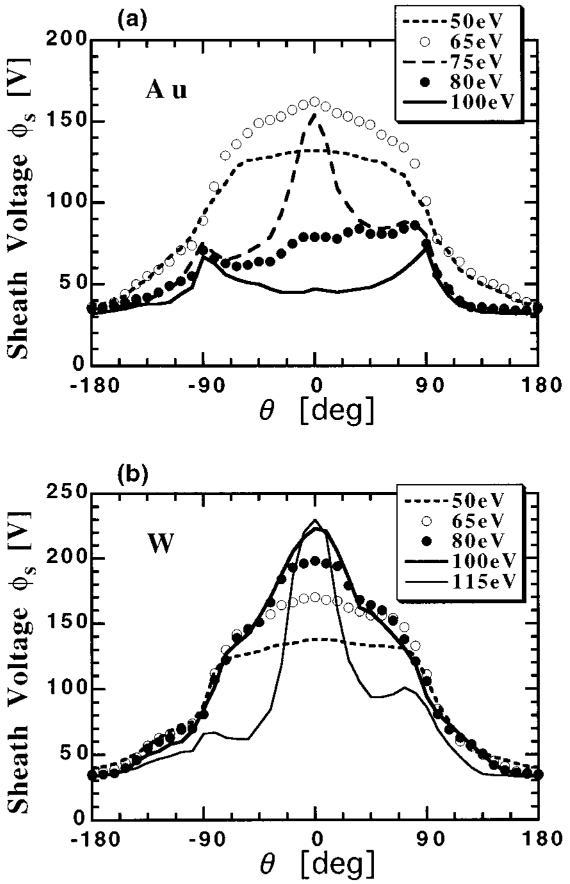

FIG. 3. Dependencies of sheath voltage on the angle θ between the surface normal and the magnetic field line for (a) golden and (b) tungsten targets taking effective parallel temperature of hot electrons as a parameter.

and 115 eV for W. The orbit calculation has really shown an increase of grazing incident primary electrons when the angle θ increases toward 90°. We note that a small increase of ϕ_s to be observed at θ close to 90°, where the target surface is nearly parallel to the magnetic field, showing some suppression of SEE, as discussed in explaining Eq. (2). This peak becomes very clear in $T_h=80$ eV for Au, where we do not have any peak around the normal incidence ($\theta\sim0°$). Finally, at $T_h=100$ eV for Au the voltage has two clear peaks only near $\theta\sim90°$, where the suppression of SEE overcomes the enhancement of SEE due to the oblique incidence of primary electrons.

To summarize, the suppression of SEE from metal surfaces with a grazing incident magnetic field in a plasma with hot electrons is demonstrated for the first time in the plasma environment under the condition that the sheath electric field force is greater than the Lorentz force in the course of gyromotions for secondary electrons. Electron gyromotion around the magnetic field line makes the emitted electrons return to the surface, although the sheath electric field makes those electrons go away from the surface and might break down the suppression of SEE. The experiment also shows an enhancement of SEE due to the oblique incidence of primary electrons on the surface. As the angle of the surface normal with respect to the B field line increases, the fraction of grazing incident primary electrons was really found, in a simple orbit tracing analysis, to increase.

In order to have a quantitative evaluation, it is necessary to get a correct δ using exact electron velocity distributions in parallel as well as in perpendicular directions with respect to the magnetic field line, together with the ratio of electron to ion current to the inclined target plate, and the space charge limited current. Those will be combined in the plasma–sheath analysis to get an exact analytical angular dependence, as well as the electron temperature dependencies of sheath voltage for a normally incident magnetic field on the target.

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