Simple way to determine the edge of an electron-free sheath with an emissive probe

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A new technique to determine the edge of an electron-free sheath is presented. The technique takes advantage of the variation of the inflection point of the emissive probe *I-V* characteristic with electron emission. The edge of the electron-free sheath is identified as the position where the inflection point changes from increasing with emission to decreasing with emission. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2195103]

A non-neutral sheath forms when a large negative potential is applied to a portion of a plasma boundary; The electron density can be neglected when the potential drop is much greater than T_e/e in the sheath, where T_e is the electron temperature, since the electron density decreases exponentially with the decreasing potential and the ion density decreases much less rapidly. This region is the so-called electron-free or ion sheath. The electron-free sheath is a critical region in plasma processing in which a large negative bias is normally applied to a wafer.

Emissive probes have been developed to measure plasma potential. The probe is heated to thermionically emit electrons. When the probe bias is more negative than the plasma potential, electrons can enter the plasma. On the other hand, when the probe bias is above the plasma potential, electrons cannot enter the plasma. An emissive probe is a reliable diagnostic for measuring plasma potential in many plasmas in which plasma flow and rf are present[1,2] since its current-voltage (*I-V*) characteristic depends on the plasma potential and only weakly on the electron velocity distribution function. Langmuir probes depend on the electron velocity distribution function to determine the plasma potential and can confuse electron drifts and plasma potential. In addition, an emissive probe is not easily contaminated due to the continuous heating.

It has been shown that plasma potential can be estimated by the floating potential of the emissive probe for strong electron emission.[3] However, the accumulation of electrons near an emitting wire can result in a potential dip near the probe. This potential dip reflects some of the electrons released from the emitting probe. This potential dip increases in size and the fractional reduction in emitted current increases as the heating increases. This is called space-charge-limited electron emission. The method of identifying the plasma potential from the inflection point of the emissive probe *I-V* characteristic in the limit of zero emission[4] was developed to eliminate the effects of space charge. The inflection point method follows the inflection point of *I-V* characteristic as the emission is varied to the point of zero emission. The inflection point is determined by taking the derivative of *I-V* characteristic. By graphing the inflection point as a function of the electron emission, the plasma potential is identified as the intersection of a straight line fit to the data with zero emission. This approach has the additional advantage that it does not require strong electron emission compared to electron collection.

In bulk plasma, the emissive probe has to be biased more negative than the plasma potential to emit electrons as the emission increases since the potential dip near the probe increases in size as the heating increases. Therefore, the inflection point becomes more negative with the increased emission. Data taken in a multidipole dc plasma device shown in Fig. 1 are given in Fig. 2. The chamber is a 90 cm long and 60 cm in diameter stainless steel cylinder. The argon gas was ionized by energetic electrons emitted from hot thoriated tungsten filaments biased at −60 V with respect to the chamber wall. Permanent magnets are mounted around the outside of the chamber wall to create multidipole magnetic fields, but not on the both ends, to confine the plasma. The base pressure is 1.0×10^{-6} Torr. A stainless steel plate of 15 cm in diameter biased at −30 V was placed in the axial direction to establish an electron-free sheath. Plasma potential was measured by an emissive probe using the method of the inflection point in the limit of zero emission.

The electric field is large in the electron-free sheath. Therefore, all electrons released from the probe surface are accelerated into the plasma and there are no space charge

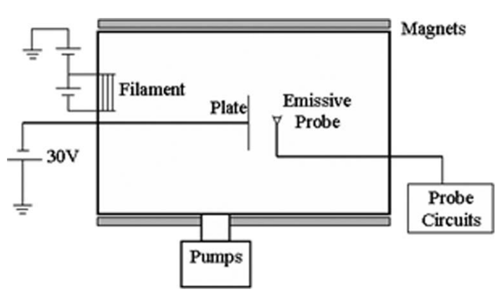

FIG. 1. A schematic of the experimental setup.

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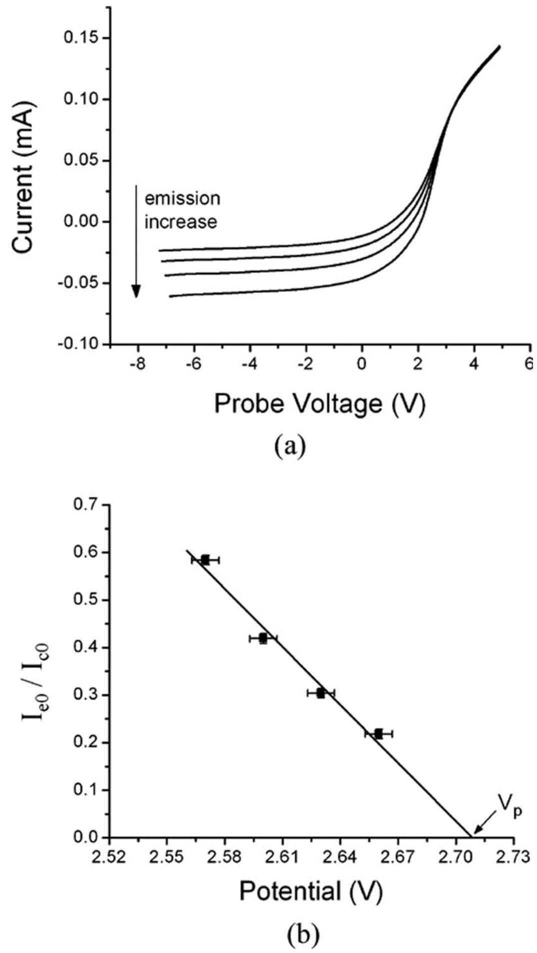

FIG. 2. Inflection point in the limit of zero emission method. (a) Emissive probe *I-V* characteristics at four-probe temperatures in a bulk plasma. (b) Ratio of emitted to collected saturation current vs the inflection point.

effects near the probe. However, these emitted electrons reduce $n_i - n_e$ in Poisson's equation.

$$-\varepsilon_0 \frac{d^2\phi}{dx^2} = e(n_i - n_e), \tag{1}$$

where n_i is the ion density, n_e is the electron density, x is the position, and ϕ is the plasma potential. This reduces the curvature of potential, which makes the local potential higher

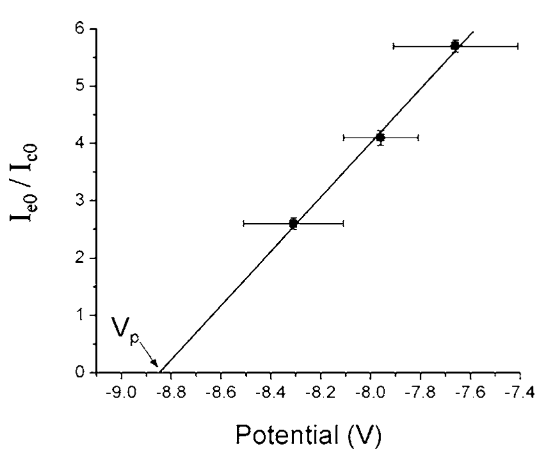

FIG. 3. Ratio of emitted to collected saturation current vs the inflection point in an electron-free sheath.

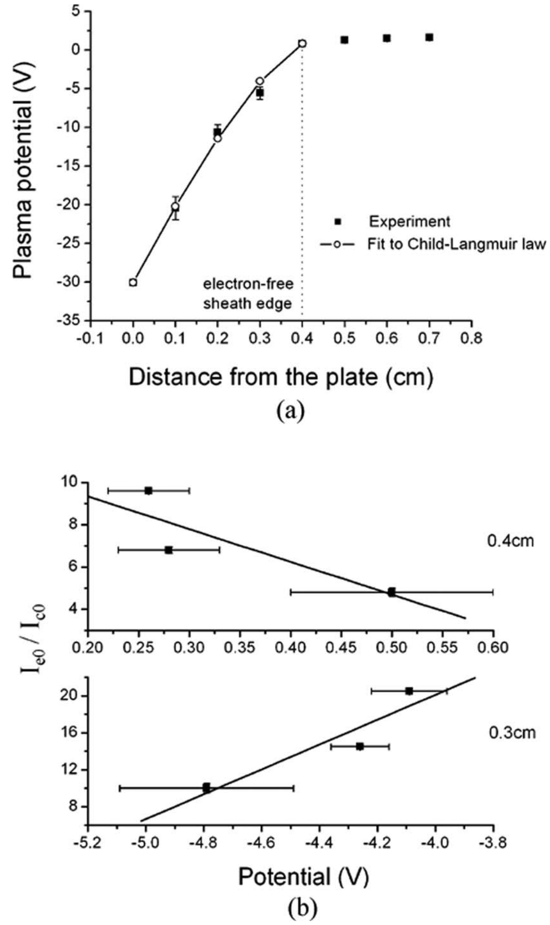

FIG. 4. Determination of the edge of an electron-free sheath. (a) Plasma potential profile in an electron-free sheath. (b) Ratio of emitted to collected saturation current vs the inflection point.

than the true plasma potential. The reduction in the curvature of the potential increases as the emission increases. Therefore, the inflection point becomes more positive with the increased emission. Data taken in the electron-free sheath are shown in Fig. 3.

By taking advantage of the variation of the inflection point of the emissive probe *I-V* characteristic with the electron emission, the edge of an electron-free sheath is identified as the position where the inflection point changes from increasing with the emission to decreasing with the emission. The plasma potential profile in a one-dimensional electron-free sheath can be fit by the Child-Langmuir law,[5]

$$\phi(x) - \phi_0 = (\phi_w - \phi_0)\left(\frac{x_0 - x}{s}\right)^{4/3}, \tag{2}$$

where x_0 is the position of the sheath edge, s is the sheath thickness, and ϕ_0 and ϕ_w are the potential at the sheath edge and the wall, respectively. Fitting to Eq. (2) gives $x_0 = 0.4 \pm 0.1$ cm, as shown in Fig. 4(a).

The inflection point as a function of the emission at 0.3 and 0.4 cm are shown in Fig. 4(b). It is apparent that the inflection point increases with the emission at 0.3 cm in the electron-free sheath and decreases with the emission at

0.4 cm in the Debye sheath where n_e is not negligible. This indicates that the edge of an electron-free sheath is between 0.3 and 0.4 cm, which agrees with the sheath edge predicted by the Child-Langmuir law.

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