Heat flux measurements and plasma composition

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(Received 7 June 2006; accepted 20 July 2006; published online 3 November 2006)

Measurements of heat flux into a probe in plasma, combined with measurement of electron temperature, are used to extract information about the plasma composition. In particular, such measurements in oxygen and nitrogen plasmas at a pressure of several millitorrs indicate that these plasmas are composed mostly of molecular ions. The measurement is based on comparing the rates of heating and cooling of a probe during its exposure to and isolation from the plasma flow. The measured heat flux into the negatively biased probe is in good agreement with the calculated heat flux carried by the impinging plasma ions.
[DOI: 10.1063/1.2358317]

I. INTRODUCTION

Measurement of heat flux is an important tool in plasma diagnostics. There are several techniques for the measurement of heat flux: a water cooling probe,[1] a temperature-dependent resistance,[2] a temperature-gradient measurement,[3,4] heat flux compensation,[5] a time dependent temperature measurement,[6] and the measurements of the time derivatives of a probe temperature.[4,7] In this paper we describe measurements using the latter technique[4,7] which is based on comparing the rates of heating and cooling of a probe during its exposure to and isolation from the plasma flow. In the case of our plasma source this is accomplished by turning on and off the plasma flow. We combine the heat flux measurements with standard electron temperature measurements based on the current-voltage characteristics of the probe. The measurements were carried out in oxygen, nitrogen, argon, and xenon plasmas, while the probe was made of molybdenum. We calculate the energy deposited in the probe by the impinging ions, assuming binary collisions. The measured heat flux into the negatively biased probe is in good agreement with that calculated heat flux carried by the impinging plasma ions. From the measurements we conclude that the ions in the argon and xenon plasmas are atomic, while oxygen and nitrogen plasmas are made of molecular ions.

In Sec. II we describe the heat flux probe and the method of measurement. In Sec. III we present a theoretical modeling of the heat flux and compare the measurements with the theory. We conclude in Sec. IV.

II. HEAT FLUX MEASUREMENTS

The method of heat flux measurement is described in detail in Refs. 4 and 7. Rather than fitting the time-dependent temperature curve to solutions of the heat equation,[4] we employ the approximate method for finding the heat flux through the determination of the difference between the time derivatives of the probe temperature during the exposure to and isolation from the heat source,[4,7] in our case the plasma flow. Thus we write

$$q = Cm\left(\frac{dT^+}{dt} - \frac{dT^-}{dt}\right), \qquad (1)$$

where dT^+/dt and dT^-/dt are the time derivatives of the temperature, and C and m are the thermal capacity and the mass of probe, respectively. The derivatives denoted by plus and minus signs are measured when the probe is exposed to and isolated from plasma, respectively. This difference is taken at the same probe temperature and is found to be constant and independent of that temperature.

The heat flux probe (HFP) that we used in the experiments described here, shown in Fig. 1, consists of a molybdenum flat plate with glued Chromel-Alumel thermocouple. The probe is of dimensions 17.5×19 mm^2 and thickness of 0.25 mm. The experiments in which the HFP was employed were carried out in our plasma source.[8] Figure 2 shows the experimental system and the HFP is denoted. The vacuum chamber and Pyrex tube are pumped to base pressure of 5×10^{-6} Torr. The plasma is generated inside a Pyrex tube, 52 cm in length, 10 cm outside diameter, and 2.5 mm thickness. The radio-frequency generator radiates at 13.56 MHz. The antenna is a helix of six turns of 35 cm length and 10.5 cm diameter. In the experiments reported here no magnetic field was applied and the plasma source operated as an inductive plasma source. The HFP is positioned in the vacuum chamber, at a distance of 30 cm from the lower end of the Pyrex tube, and its plane is parallel to the axis of symmetry of the system. The HFP is protected by L filter (L=0.46 mH).

Figure 3 shows a typical temperature-time characteristic where the temperature increases when the plasma source operates and decreases when the source is switched off. Figure 4 shows the derivatives of the HFP temperature with respect

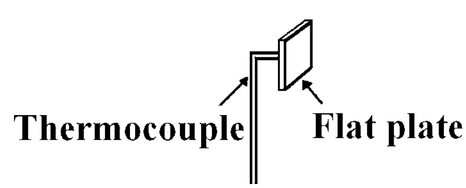

FIG. 1. The heat flux probe.

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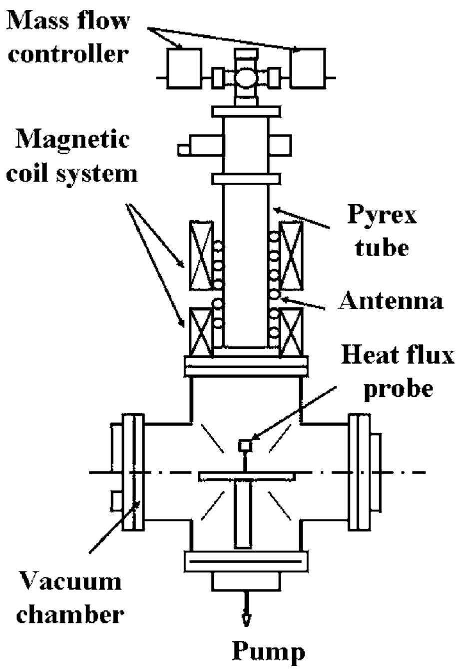

FIG. 2. The experimental system.

to time versus the HFP temperature. It can be seen in the figure that the difference between the derivatives varies very little with the HFP temperature. This approximately constant difference between the two curves demonstrates that the heat flux does not depend on the HFP temperature.

III. HEAT FLUX AND PLASMA COMPOSITION

We measured the temperature dependence of the HFP for various applied voltages at various gas plasmas, during exposure to and isolation from the plasma. From these measurements the heat flux from the plasma to the probe was calculated. Figure 5 shows the heat flux versus applied voltage of argon and xenon plasmas. Figures 6 and 7 show the heat flux for nitrogen and for oxygen.

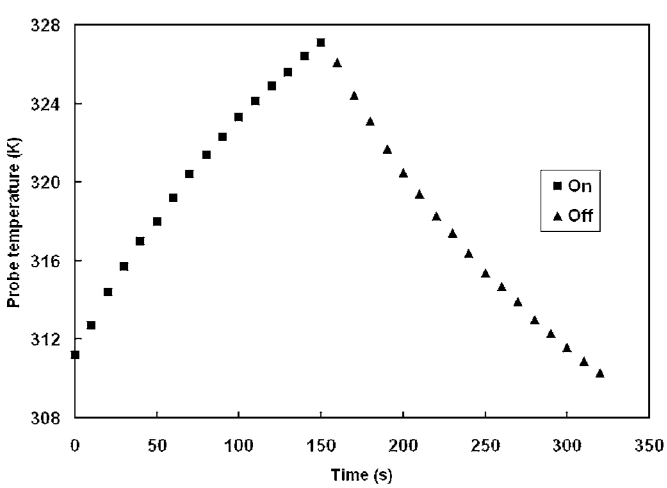

FIG. 3. A typical example of the temperature-time characteristic of the heat flux probe in the argon plasma. The heat flux probe has potential $V_p = -83$ V.

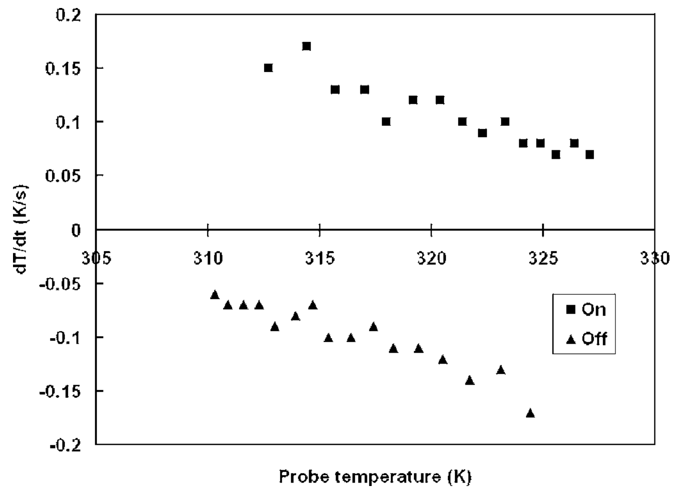

FIG. 4. The two derivatives of the probe temperature with respect to time vs the probe temperature, when the plasma source is on and when it is off.

At a negative enough voltage, when plasma electrons do not reach the probe, the ion heat flux to the probe is related to the plasma parameters through

$$q = (\delta E_i + E_{\mathrm{ion}} - e\Phi)\Gamma_i, \tag{2}$$

where e is the elementary charge, Γ_i is the ion particle flux to the probe, E_i the energy of the ion impinging on the probe, E_{ion} the ionization energy of the gas particles (atoms or molecules), and Φ is the work function of the probe material. The difference $E_{\mathrm{ion}} - e\Phi$ expresses the energy deposited at the probe by a recombining ion. Here δ is the energy transfer coefficient. The energy of the impinging ion is written as[4]

$$E_i = K_i + T_e \ln\left(\frac{M}{2\pi m_e}\right)^{1/2} - eV_p, \tag{3}$$

where V_p is the voltage relative to the floating potential, T_e (in eV) is the electron temperature in the plasma, and M and m_e the masses of the gas particles (atoms or molecules) and of the electron, respectively. We take K_i, the kinetic energy of the ions when they arrive at the presheath-sheath edge, to be $K_i = T_e/2$, the energy gained in the presheath. The heat

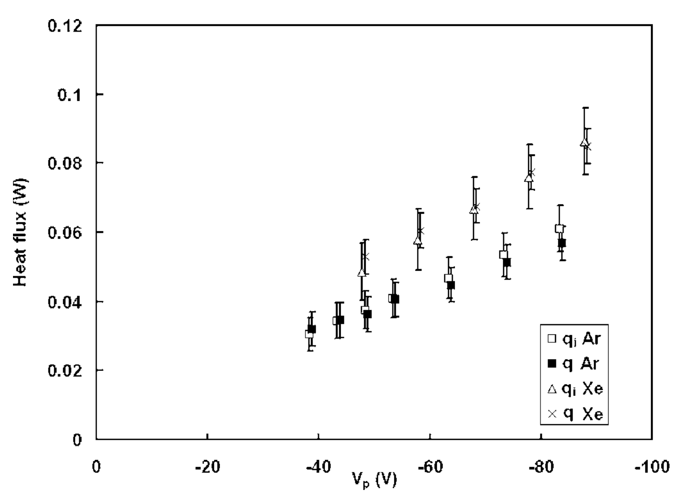

FIG. 5. The two calculations of the heat flux for argon and for xenon, where q and q_i are calculated according to Eqs. (1) and (2).

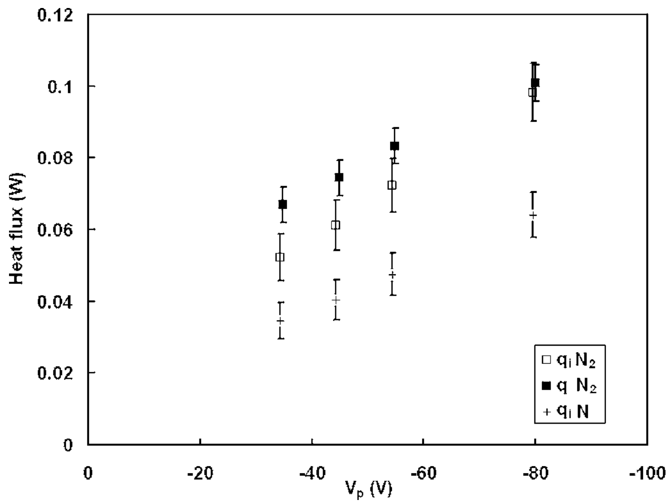

FIG. 6. The calculations of the heat fluxes for nitrogen, where q and q_i are calculated according to Eqs. (1) and (2). Here q_iN_2 and q_iN are the calculated heat fluxes according to Eq. (2) if ions are assumed molecules or atoms, respectively.

flux due to radiation and due to neutrals is negligible. An expression for the heat flux similar to Eq. (2) has been used in Ref. 7.

To take into account only that fraction of ion energy that is deposited at the probe,[9] we employ a simplified form of the energy transfer coefficient δ,[4,10]

$$\delta=\frac{4MM_W}{(M+M_W)^2}, \tag{4}$$

in which M_W is the atomic mass of the probe material. This form of the coefficient is a good approximation when head-on collisions are dominant. When the electron flux is neglected, the ion particle flux is

$$\Gamma_i=\frac{I_m}{e(1+\gamma_{se})}. \tag{5}$$

Here I_m is the measured current into the probe and γ_{se} is the coefficient of secondary electron emission. The current I_m increases when $-V_p$ increases due to the increase in sheath area.[11]

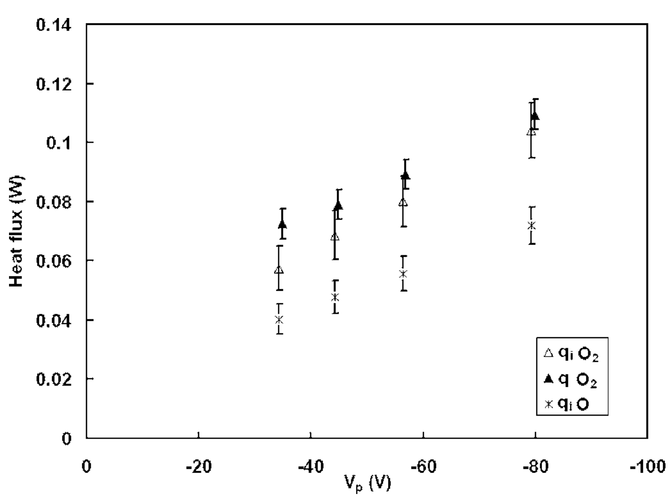

FIG. 7. The calculations of the heat fluxes for oxygen, where q and q_i are calculated according to Eqs. (1) and (2). Here q_iO_2 and q_iO are the calculated heat fluxes according to Eq. (2) if ions are assumed molecules or atoms, respectively.

Here we compare, for several gases, the heat flux calculated according to Eq. (1) with the heat flux calculated according to Eq. (2), both as a function of the applied voltage. For the calculation according to Eq. (1) we measure the varying temperature of the HFP during its heating and cooling off and use its measured mass, $m=0.931$ g, and $C=264$ J/(kg K) (molybdenum). For the calculation according to Eq. (2) we first measure the current into the HFP for a varying applied negative voltage to determine the ion flux through Eq. (5) and also use $M_W=96m_p$ (m_p is the proton mass), $\Phi=4.3$ eV for the molybdenum probe, and the measured electron temperature. The experiments were conducted at 3 mTorr gas pressure and 200–300 W wave power.

In Fig. 5 are shown the two calculations for argon ($T_e=9\pm3$ eV) and for xenon ($T_e=4.5\pm1$ eV). The electron secondary emission coefficient was taken as $\gamma_{se}=0.115$ for argon ions and $\gamma_{se}=0.056$ for xenon ions.[12] The error bars in the figures reflect the inaccuracy in the measurement of the electron temperature used in Eq. (2) and the inaccuracy in the calculation of the time derivatives of the probe temperature used in Eq. (1). There is a good agreement between the measurement and the calculation.

In Figs. 6 and 7 measurement and theory for nitrogen plasma and for oxygen plasma ($T_e=11\pm3$ eV for both plasmas) are shown. Since oxygen and nitrogen are molecular gases, two calculations were made for each gas: one calculation with the assumption that the gas is composed of atomic ions and a second with the assumption of molecular ions. The agreement between experiment and theory is better when molecular ions are assumed. The measurement enabled us to determine the dominant cation. Thus, this measurement turned out to be a simple and robust diagnostic tool for extracting information about the plasma composition.

IV. DISCUSSION

In this paper we described measurements with a heat flux probe in plasma. We showed that by relating these measurements to other measurements in the plasma, information about the plasma composition can be extracted. An estimate of the heat flux by neutrals and by radiation can improve the accuracy of the measurement. We will make such an estimate in the continuing research. The method can be applied with more accuracy to denser plasmas in which the sheath area varies less when the applied voltage increases.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Y. Raitses, Dr. J. Ashkenazy, and G. Appelbaum, for helpful discussions. This research has been partially supported by the Israel Science Foundation (Grant No. 99/59).

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