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Spatially Resolved Measurement of the Energy Influx in an RF-Plasma

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Abstract

The total energy flux for a typical radiofrequency process plasma has been measured by means of a simple thermal probe. The procedure is based on the measurement of temporal slope of the substrate temperature during the plasma process. A substrate dummy which is thermally isolated and inserted into the plasma at substrate position served as thermal probe. It can be moved in vertical and horizontal directions in order to measure the different energy fluxes and their distributions in the reactor vessel.

Different contributions to the total energy influx can be identified by different orientation of the thermal probe. For example, if the thermal probe is orientated to the rf-electrode ("down") the energy influx is much higher than in the opposite direction. This difference can be explained by an additional influx due to the secondary electron emission from the powered rf-electrode.

Experimental

The integral energy influx from the plasma towards the substrate was measured by a compact thermal probe [1]. A similar procedure for the determination of the total heat influx was proposed by [2] and [3]. A schematic sketch of the probe is shown in Fig. 1.

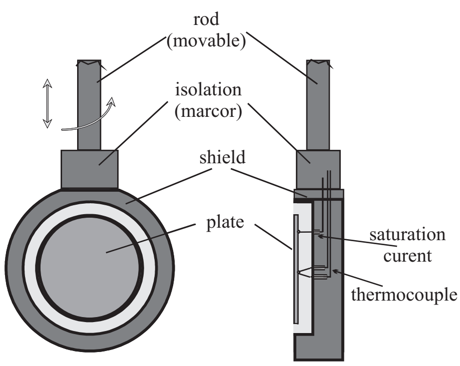

Figure 1: Schematic plot of the thermal probe.

The probe is mounted on a manipulator arm to allow for horizontal and vertical scans within the reactor. It can be also rotated in order to measure directional fluxes, e.g. secondary electrons coming from the electrode or radiation from a heated surface. In our experiments, the heat flux measurements are carried out by observing the rate of temperature change dT_S/dt of the substrate dummy which is brazed to a thermocouple and placed within a solid shield. The substrate is connected only to the thermocouple and a wire for additional biasing. For all experiments we used copper plate with d=20 mm and a thickness of 0.1 mm as substrate dummy.

The type J thermocouple has a sensitivity of 0.05 mV/K and the generated voltage is converted by an AD-converter. The measurement of the total energy influx Q_{in} is based on the determination of the difference between the time derivatives of the substrate temperature T_s during heating (which means the plasma-on phase) and cooling (plasma-off).

The thermal probe hardware and the designed evaluation software has been employed and performed in different experiments in the laboratory set-up "PerPlex". This is a common asymmetric rf-discharge which is normally used in complex (dusty) plasma experiments. In "PerPlex" we performed some test series in an rf-discharge with an argon pressure between 0.3 and 50 Pa and an rf-power between 5 and 100 W.

Results and discussion

In figure 2 a typical $T_S(t)$-curve measured by the thermal probe is shown. The start temperature in the vacuum chamber is 21.7°C. Then the plasma was switched on and the temperature of the thermal probe increases from 21.7 to 27.1°C within 75 s. After the plasma was switched off the system starts to cool down and after 170 s the temperature is again nearly the starting point (22.1°C). From the derivative of the heating and the cooling curve we can calculate the energy influx onto the thermal probe.

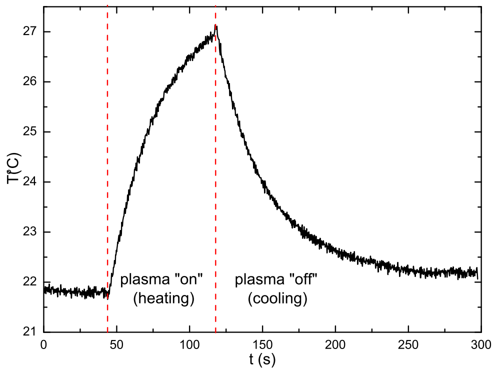

Figure 2: Typical measurement of raw data (10 W, 10 Pa, probe: z=20 mm and r=0).

Figure 3 shows the measurement of the energy influx for an argon plasma with a pressure of 10 Pa and at various rf-power between 1 and 100 W.

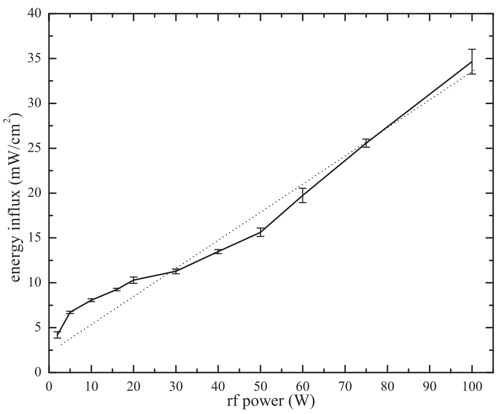

Figure 3: Dependence of the measured energy influx on the rf-power for an argon pressure of 10 Pa.

The thermal probe is located above the center of the powered electrode (r=0) in a height of z=20 mm. For this experiment, the thermal probe orientation is "down", e.g. the thermal probe is orientated into the direction to the electrode.

If we measure the energy influx for the same set of plasma parameters but for different orientation of the thermal probe we obtained quite different results, see figure 4.

The mean contributions for substrate heating are the energy transfer by electrons, ions and neutrals in the plasma volume and the radiation. In the plasma bulk these contributions are isotropic and, hence, the energy influx is almost independent on the angle of the probe orientation.

In the case where the thermal probe "looks" direct to the electrode (probe orientation "down") we get an additional energy influx form the anisotropic electrons which are released from the powered electrode by secondary electron emission (γ-effect). For a calculation of the energy influx we used k_BT_e=1.5 eV and n_e=2.5$\cdot 10^{14}$ m^{-3} as typical values for electron temperature and density. The plasma potential V_{pl} is 11 V. The potential $V_{fl} = V_S$ of the floating thermal probe is -4 V for the "down" direction and V_S = -0.4 V for the "up" alignment. The resulting bias-potential V_{bias} is 11.4 V and 15 V, respectively. Under these conditions the electron energy influx J_e is given by

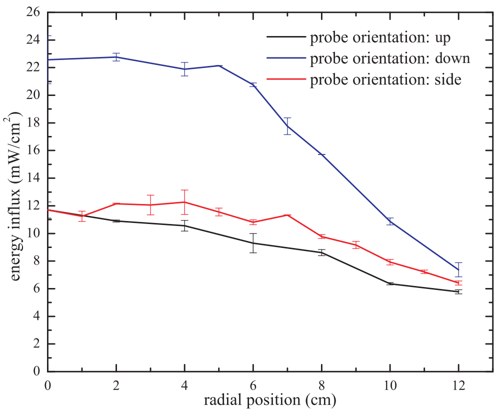

Figure 4: Dependence of the measured energy influx at constant plasma parameters (10 Pa, 50 W) from the orientation of the thermal probe. For the "side" and the "up" view of the thermal probe the energy influx is comparable.

$$J_e = n_e\sqrt{\frac{k_BT_e}{2\pi m_e}}\exp\left(\frac{-eV_{bias}}{k_BT_e}\right)\ 2k_BT_e \tag{1}$$

and the energy influx by the ions J_i is

$$J_i = n_e\sqrt{\frac{k_BT_e}{m_i}}\exp\left(-0.5\right)\ eV_{\text{bias}} \quad . \tag{2}$$

In the case of a floating probe the released energy influx J_{rec} by recombination of electrons and ions has to be considered

$$J_{rec} = j_iE_{rec} \quad , \tag{3}$$

where j_i = j_e and E_{rec} is the ionization energy, which is 15.7 eV for argon. The total energy influx for the "up" orientation of the thermal probe is then a combination of the eq.s 1, 2 and 3 to

$$J_{up} = J_i + J_e + J_{rec} \quad . \tag{4}$$

For the total energy influx for the "down" direction of the thermal probe we get an additional term $J_{e,direct}$ for eq. 4. $J_{e,direct}$ describes the flux of secondary electrons from the powered electrode to the thermal probe surface. The term can be estimated by

$$J_{e,direct} = \alpha j_iV_{electrode} \quad . \tag{5}$$

α is the secondary electron emission coefficient (α=0.1), j_i is the ion current density at the rf-electrode and $V_{electrode}$ is the voltage of the powered electrode. For the experiments which are shown in fig. 4 the total energy influx for the "up" case is calculated to J_{up}= 12.6 $mW cm^{-2}$ and for the "down" case to J_{down}= 21.1 $mWcm^{-2}$. The reason for this difference is the additional energy from the anisotropic secondary electrons originating from the electrode.

Finally, in figure 5 the spatial distribution of the energy influx $J = J(r,z)$ in the r-z-plane (r=0: axis of symmetry) is plotted.

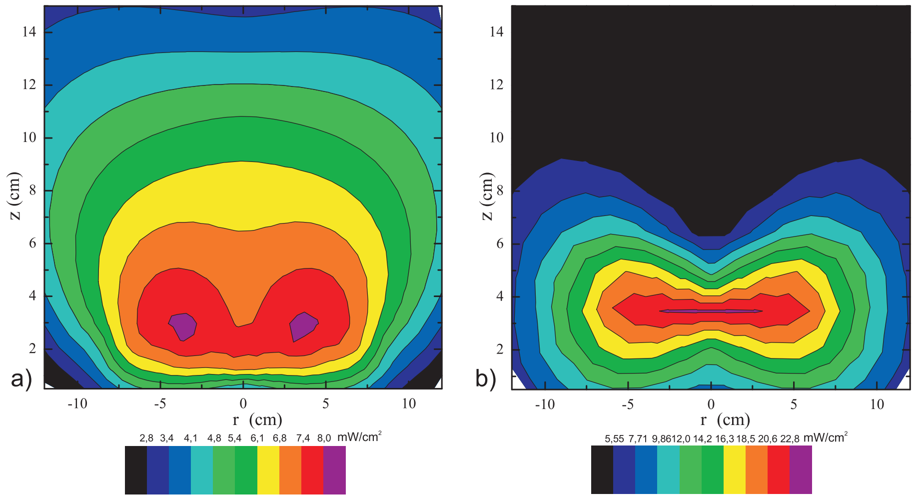

Figure 5: Radial and axial (2D) distribution of the energy influx for an Argon plasma with 10 Pa and an rf-power of 10 W (a) and 10 Pa and an rf-power of 50 W (b), respectively.

Figure 5a) shows the results for a pressure of 10 Pa and an rf-power of 10 W. In the region z=30 mm above the electrode and r=30 to 40 mm from the center we obtain the maximum of the energy influx ($\approx$ 8.1 mW/cm^2). Outside the electrode to the walls of the vessel we can identify a coil-like shape in the spatial distribution of the energy influx.

In figure 5b) the rf-power is 50 W at the same argon pressure as in figure 5a). Here, we got a different shape. On the one hand side the energy influx is increased by a factor of 2.8 in the center of the electrode. There is only one region with a maximum around the center position. On the other hand side it is clearly seen that the energy influx decreases dramatically towards the walls of the vessel. In a height of z=90 mm above the electrode the value of the influx is almost zero. The reason for this dip is the shape of the used electrode for particle trapping [4].

Acknowledgements

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