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Study of hot tungsten emissive plate in high heat flux plasma on NAGDIS-I

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Abstract

The high heat flux plasma in fusion devices sometimes makes a local hot spot on a plasma-facing material, generating sufficient electron emission from the surface to reduce the sheath voltage, resulting in a reduction in thermal insulation across the sheath. Experiments on hot tungsten emissive plate are performed in the linear divertor simulator NAGDIS-I with a steady state high heat flux plasma. Phase transitions due to the electron emission have been observed in the experiments. Results from SEM micrographs of the tungsten surface show that the microstructure of the tungsten surface is changed after the low energy and high flux plasma irradiation. An interesting ion species dependent surface modification is observed in experiments.

Keywords: NAGDIS-I; Divertor simulator; High Z material; Bifurcation and multistate solutions

1. Introduction

At high plasma heat flux density, erosion of the divertor target plate is a crucial point for an advanced divertor scheme. Tungsten has been considered to be a good candidate for the material of future divertor target plate because of its high threshold energy and low yield of sputtering as well as low hydrogen retention. In addition thermoelectron emission is one of the important characteristics to be studied in energy transmission through sheath in high heat flux plasma [1-5]. The thermoelectron emission gives a much reduced sheath voltage which suppresses the impurity generation by physical sputtering [6]. A general nonlinear dynamic relation between high heat flux plasma and electron-emissive hot material surface has been studied in the experiments and also in the numerical analysis [7].

In this paper we describe experimental results of a study on hot tungsten emissive target plates installed in the linear divertor simulator NAGDIS-I. It is shown that the thermoelectron emission leads to a strong reduction of the sheath voltage and a large enhancement of the heat flux density on the tungsten surface. The experimental results are compared with a simple numerical analysis. In addition, an interesting ion-species dependent surface modification due to high heat flux plasma irradiation is observed in the experiments.

2. Experiments

2.1. Experimental setup

The experiments have been performed in NAGDIS-I, in which a high heat flux plasma is generated by Philips ionization gauge (PIG) discharge with working gases of helium, hydrogen and argon [8,9]. The experimental setup is shown schematically in Fig. 1. In the experiments, the plasma with a length of 2 m and a diameter of 6 cm is confined by an up to 1.5 kG axial magnetic field. A rectangular tungsten target plate ($100 \times 100 \times 0.1$ mm) with a work function of 4.54 eV is installed on the water cooled end plate and set normally to the magnetic field. The voltage of the tungsten plate with respect to the vacuum chamber, the floating potential, is one of key parameters to be observed. The tungsten plate temperature is monitored with an infrared thermometer with the wave-

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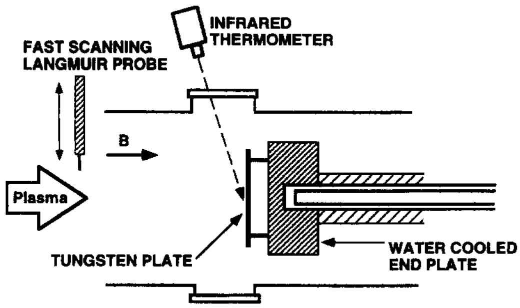

Fig. 1. Schematic drawing of the experimental device.

length of 0.8–1.1 μm through a vacuum window. The plasma parameters on a cross section are measured by a fast scanning Langmuir probe at 0.2 m from the tungsten target.

2.2. Phase transition of the plate due to thermoelectron emission

An initial steady state of He gas discharge with a discharge current of $I_p = 46$ A and a discharge voltage of $V_p = 158$ V gives a tungsten plate temperature $T = 2100$ K, electron density $n_e \approx 2.5 \times 10^{18}$ m^{-3} and electron temperature $T_e \approx 6$ eV. Then, the tungsten plate was heated up gradually from the above state by increasing plasma heat flow. A change of temperature near the center of the tungsten plate and the floating voltage of the tungsten plate were obtained as a function of time, as shown in Fig. 2. At $t = 24$ min, corresponding to $I_p = 98$ A, $V_p = 190$ V, $n_e \approx 4.0 \times 10^{18}$ m^{-3}, the tungsten plate is heated up to a temperature of 2600 K, sufficient for thermoelectron emission. At this point, the floating voltage V_f of the tungsten plate decreases abruptly from 69 to 42 V, and the tungsten plate temperature T increases suddenly from 2600 to 3200 K, which means a triggering of a phase transition of the tungsten plate from the cold (2600 K) to the hot phase (3200 K). After the transition, the quasi-equilibrium temperature remains near 3200 K, and the floating voltage stays near 42 V. When the tungsten plate was heated up to a high temperature, tungsten impurities injected into the plasma caused an unstable discharge. The instability is indicated by some peaks appearing on the temperature and the floating voltage. From $t = 45$ min the plasma heat flow is decreased gradually. At $t = 52$ min, although the discharge power has decreased to the same level as that at $t = 21$ min, the tungsten plate temperature is still higher than that at $t = 21$ min. This means that the tungsten plate can be kept hot because a large enhancement of plasma heat flow to the tungsten plate is maintained, associated with the plasma electron influx to the tungsten plate due to the small sheath voltage compared with that in the case of the cold phase. In fact, the sheath voltage in front of the tungsten plate can be obtained by $V_f - V_s$, where V_s is the plasma potential with respect to the vacuum chamber, which can be measured from the characteristic curve of the single probe. In the experiments, it is shown clearly that the sheath voltage in front of the tungsten plate decreases when the phase transition occurs. At the region near the center it is about −40 V before transition and around −10 V after transition.

The experiments were also carried out for H plasma. In the experiments it is difficult to get a high heat flux uniform plasma in NAGDIS-I. Phase transition of the tungsten plate has not occurred in H plasma discharge with hollow plasma profile even if the local temperature of the tungsten plate is up to 2800 K.

2.3. Modification of tungsten surface

Surface analysis was made with SEM for tungsten irradiated by the helium plasma with a diameter of about 6 cm and a flux of 2.4×10^{22} He^+ ions m^{-2} s^{-1}, corresponding to a tungsten plate temperature of up to nearly 3200 K. Fig. 3 shows clearly that the microstructure of tungsten surface is modified due to the helium plasma irradiation. The dune-like relief exhibits many holes of 1–4 μm in diameter which appear in the tungsten surface after the helium plasma irradiation, as shown in Fig. 3(c) and (d). The size of holes is small and the density of holes is low at the position of the tungsten surface near the center of the irradiation region, as shown in Fig. 3(c) compared with that in Fig. 3(d). This positional dependence may be due to the plasma nonuniformity, which affects the incident ion energy as well as the surface temperature distribution on the tungsten surface. To obtain a comparison with different ion-species, the tungsten plate was irradiated by the hydrogen plasma with 3.3×10^{22} H^+ions m^{-2} s^{-1}, corresponding to a tungsten plate temperature of nearly 2800 K. The surface morphology of tungsten irradiated by the hydrogen plasma is found to be quite different from the helium case. A large crystal struc-

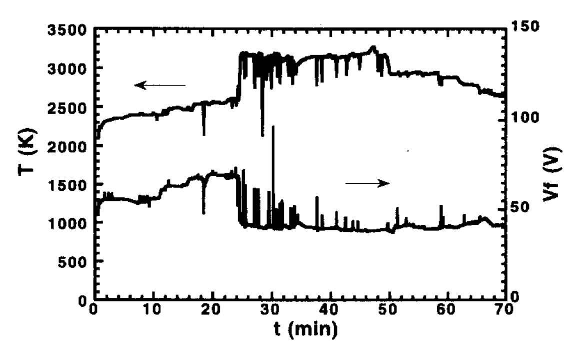

Fig. 2. The experimental results for tungstep plate in helium plasma. At $t = 24$ min, corresponding to $I_p = 98$ A, $V_p = 190$ V, $n_e \approx 4.0 \times 10^{18}$ m^{-3}, the tungsten plate is heated up to a temperature of 2600 K, sufficient for thermoelectron emission, and a phase transition occurs.

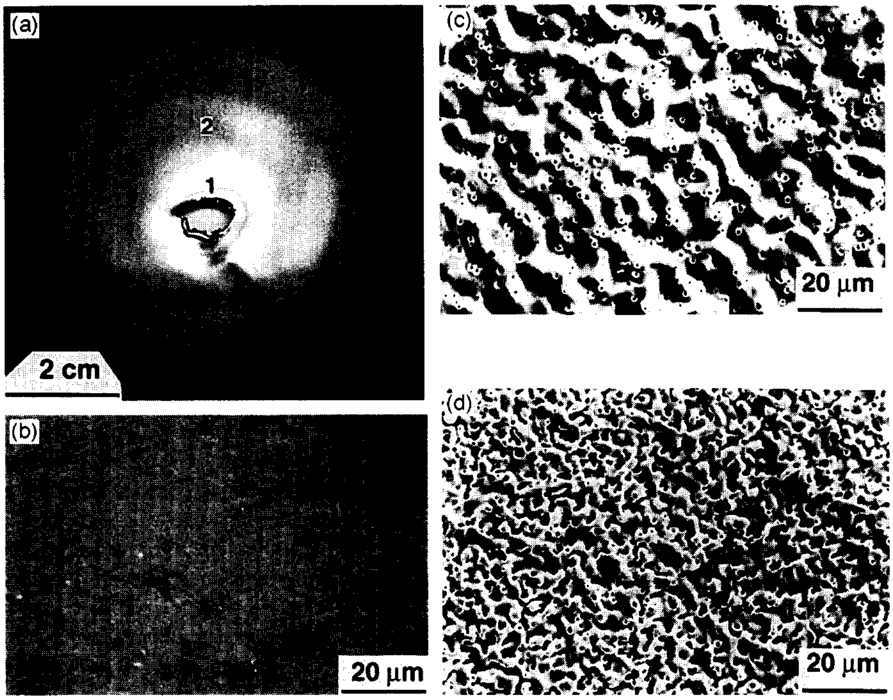

Fig. 3. (a) Picture of tungsten surface after the helium plasma irradiation with 2.4×10^{22} He^{+} ions m^{-2} s^{-1}. The irradiation region is bright corresponding to a surface temperature of up to nearly 3200 K. (b) SEM micrograph of tungsten surface before the plasma irradiation. (c, d) SEM micrographs of tungsten surface after the helium plasma irradiation at two different positions on the tungsten surface, indicated by 1 and 2 in (a), respectively.

ture appears in the tungsten surface without any holes appearing, as shown in Fig. 4. Such a different surface modification of tungsten may be explained in terms of the different properties of He and H implantation in tungsten. In the case of the helium plasma irradiation, the implanted He ions result in larger clustering of trapped He by vacancies with higher surface binding energies, and the helium gas forms relatively large and stable bubbles in the tungsten. When the tungsten plate is heated to very high temperature these bubbles break and make holes. In the case of the hydrogen plasma irradiation, the implanted H ions are trapped in the tungsten surface with a lower surface binding energy, which means that hydrogen eventually escapes from the surface.

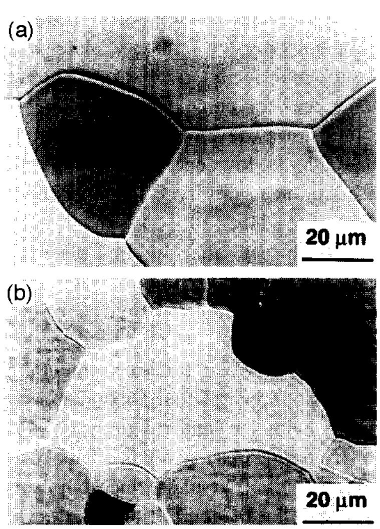

Fig. 4. SEM micrographs of tungsten surface after the hydrogen plasma irradiation with 3.3×10^{22} H^{+} ions m^{-2} s^{-1}, corresponding to a surface temperature of up to 2800 K at two different positions of tungsten surface (a, b).

Some similar blistering phenomena have been reported in many experiments on He implantation in metals [10,11], in which the incident ion energy is very high, in the range of 20–300 keV. There is very little known about blistering at low ion energies or at high target plate temperature. Our experimental results give some understanding of the morphology of tungsten irradiated by a low ionic energy and a high ion flux at a high target plate temperature.

3. Simple numerical analysis and discussion

Concerning the phase transition in such a nonlinear system, a simple analysis is given here for a hot emissive tungsten target plate by considering the system modeled as consisting of a uniform homogeneous plasma adjacent to the target plate heated to a temperature sufficiently to emit thermoelectrons which are accelerated across the sheath into the plasma. The phase transition is analyzed by using a series of simple equations describing sheath formation, including a new Child–Langmuir expression for an electron emission from the material surface into the plasma. The temperature of tungsten surface is determined by a balance between the plasma heat flow to the tungsten plate and the heat losses due to radiation cooling of the tungsten plate and thermoelectron emission [7].

Fig. 5 shows the temperature of the tungsten surface, the plasma heat flux and the sheath voltage as a function of the helium plasma density, where Te is assumed to be 10 eV. We assume that the power input introduced into plasma region from discharge region is kept constant irrespective of the condition of the target plate, that is, phase transition. These typical S curves of bifurcation suggest the presence of transitions from the cold (without thermoelectron emission) to the hot phase (with thermoelectron emission) of the tungsten plate. The sheath voltage and the plasma heat flux to the tungsten plate also have transition characteristics. In the case of a very low density ($n_e < n_{el}$) and a very high density ($n_e > n_{eh}$), only a single solution is obtained, corresponding to the cold and hot phases, respectively. In the case of medium density ($n_{el} < n_e < n_{eh}$), there are triple solutions corresponding to cold and hot phases as well as a transient solution. When the tungsten plate is heated up to a high enough temperature ($T > 2600$ K) sufficiently to emit thermoelectrons, the sheath voltage decreases to a third of the value in the cold phase and remains at the small value of -10 V due to the space charge limited electron emission. The plasma heat flux to the tungsten plate in the hot phase increases to a value about twice as large as that in the cold phase. Such a large enhancement of the plasma heat flux to the tungsten plate comes from an increase of the plasma electron influx going to the tungsten plate due to a strong reduction of the sheath voltage.

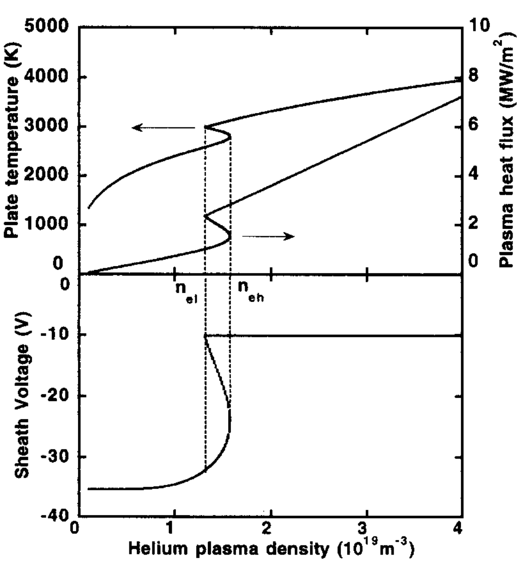

Fig. 5. Analytically obtained bifurcation S curves for tungsten plate temperature, plasma heat flux to the plate surface and sheath voltage as a function of the helium plasma density. The sheath thickness is assumed to be 3 times as large as the Debye length of the plasma. Dushman's constant $A = 6.0 \times 10^5$ A/(m^2 K^2), the work function is 4.54 eV and the emissivity is 0.4 for tungsten.

The simple analysis indicates the phase transition phenomena in such a nonlinear system. But a quantitative comparison of experimental and numerical results indicates that the plasma density triggering the phase transition in the numerical analysis is about 3 times as large as that measured in experiments. This difference seems to be large, and may be due to several factors. One is that the Richardson–Dushman constant A in the expression for the temperature-limited electron emission current changes strongly with the state of tungsten surface [3], which means that A may increase with increase of the temperature of material surface. Another possible factor comes from the fact that a uniform plasma column and uniform heating of the target plate is assumed in the numerical analysis. However, in the actual experiments, the present DC discharge produces a nonuniform plasma, which introduces a nonuniform heat flow to the target plate. In the experiments the probe data show that the plasma potential is not constant over the plasma cross section, which makes the sheath voltage distribution on the electrically conductive tungsten plate. This leads to plasma heat contraction on tungsten plate [12].

4. Summary

Sufficient thermoelectron emission produces a phase transition in a hot tungsten emissive plate–high heat flux plasma system, and leads to a strong reduction of the sheath voltage and an enhancement of the plasma heat flow to the tungsten plate. For a high temperature tungsten plate irradiated by a low energy and high flux plasma, surface modification is observed in experiments. A dune-like relief and many holes of 1–4 μm in diameter appear in the tungsten surface after helium plasma irradiation. This phenomenon has an obvious relation to the incident ion species, energy distribution, and temperature of the material surface.

The difference between the experimental results and numerical analysis indicates that Dushman's constant may change strongly with the state of tungsten surface, and a nonuniform discharge plasma tends to make plasma heat contraction on conductive plate due to plasma potential distribution across the magnetic field. Further experiments and 2D numerical calculation including 2D heat conduction equation on the target plate will be carried out on the nonlinear dynamics of plasma–surface interaction as well as interesting ion species dependent surface modification.

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