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Dynamic transition between erosion and deposition on a tungsten surface exposed to edge plasmas containing carbon impurities

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Abstract

By the exposure of high-fluence deuterium (D) plasmas (10^{23}–$10^{26}\,\mathrm{m}^{-2}$) containing a small amount (<10%) of carbon (C), the dynamic transition from C deposition to the erosion of tungsten (W) with increasing plasma temperature from 10 eV to 100 eV is investigated using EDDY code. Above fluences of $10^{23}\,\mathrm{m}^{-2}$, there appears to be a fluence-dependent change in the C deposition rate as a function of plasma temperature. At a fluence of more than $10^{25}\,\mathrm{m}^{-2}$, a steady-state condition is reached where an abrupt transition is formed. This occurs due to temperature increases of only a few eV. The transition occurs as a result of small reflections in the incident C ions from a C-rich layer and the enhanced sputtering of the deposited C from a W–C mixed layer. This explains the very sharp boundary between the erosion and deposition zones observed on W test limiters exposed to TEXTOR edge plasmas.

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1. Introduction

Recent surface analyses of limiters and divertor tiles made of tungsten (W) used in present fusion devices have shown a pronounced deposition of carbon (C) impurity. There are several numerical calculations that have been carried out on C deposition on W using simple analytical models [1–3] and dynamic Monte Carlo simulation codes, e.g. TRIDYN and modified codes [4,5]. Compared with controlled C^+ and CH_3^+ ion beam experiments [3–5], the calculations have revealed a fluence-dependent transition from erosion to C deposition

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with increasing fluence of the order of 10^{22} m^{-2} and the impact of C diffusion in the W bulk at elevated temperatures ($\sim$ 1000 K).

In recent test limiter experiments in TEXTOR [6–8], the erosion area was clearly separated from the C deposition area that appeared at the edge of the W and tantalum (Ta) limiters. The total ion fluence was $\sim 10^{25}$ m^{-2}, which is much higher than found in the existing numerical studies mentioned above, but for much shorter exposure times. In previous studies [9,10], by modelling the plasma exposure to the W and Ta limiters of a hemi-spherical shape (radius of 7 cm) where the exposure conditions varied along the surface of the limiters, the erosion and deposition patterns on the limiter were calculated using EDDY code and some modifications [9,10]. The results revealed that when approaching the edge, the surface is covered by a thick C layer, which shows a very sharp boundary similar to observations made in surface measurements [7]. In this study, our simulation calculation concentrates on the transition behaviour between erosion and deposition during the exposure of high-fluence D plasmas (10^{23}–10^{26} m^{-2}), including C impurities.

2. Dynamic Monte Carlo code, EDDY

The EDDY code models the interaction of plasma ions, i.e. fuel D ions and impurity ions of different species, with material surfaces. In this study, C^{4+} ions are the only impurity in the plasma. The Maxwellian distribution of the ion velocities is taken into account and ions are accelerated towards a W surface by the sheath potential, V_{sh} which is the sum of the potential drops in an electrostatic sheath and in a magnetic presheath. The potential drops strongly depend on the normal distance from the material surface [11], however, they vary only in a thin layer above the surface; the widths of the electrostatic sheath and the magnetic presheath are of the order of 10 μm and 1 mm, respectively. In this study, therefore, the ions are accelerated by the total sheath potential, $V_{sh} = -(T_e/2)\ln(\pi m_e/m_i)$, just before the bombardment. Furthermore, for simplicity, equal temperatures of electrons and ions, $T_e = T_i$ are assumed; although $T_e < T_i$ for TEXTOR edge plasmas, in particular, during the neutral beam heated phase. The EDDY code simulates the slowing down of projectile ions in the material and the formation of recoil cascades leading to processes such as ion reflection and physical sputtering, in the same manner as the TRIDYN code [12]. According to TRIDYN, dynamic changes in the composition of the material arise from the deposition of C ions and collisional transport of the deposited C. The atomic density in each layer of the W–C mixed material is calculated by the reciprocal addition of the atomic densities of pure W and C materials with the compositions. The surface binding energy of the mixed material for sputtering varies linearly from the cohesive energies of W and C to the mean value according to the surface composition. In this study, thermal diffusion is not taken into account; some calculation results were presented in the previous paper [4]. For thermal processes such as C diffusion and chemical erosion discussed later in short, the flux of ions bombarding the material surface is also an important physical quantity in addition to the ion fluence, defined as the product of the ion flux and exposure time. However, collision processes such as physical sputtering and ion reflection may have much less of influence.

The EDDY code also simulates the transport of sputtered and reflected impurities in the local plasma near the surface. Furthermore, by diving the whole limiter (or a divertor tile) surface into many segments along toroidal and poloidal directions, the two-dimensional erosion and deposition patterns are calculated [9], where some impurities redeposit promptly on the same segment as they are released, or redeposit on the other segment after migration in the plasma.

3. Results and discussion

As already mentioned in Refs. [1–5], the deposition of C ions on a W material causes serious changes in the plasma-surface interactions of the material. One of the changes arises from the large difference in the C reflection coefficient at the deposited C layer compared with that at the W bulk. As long as the deposited C is not strongly eroded by D ions, the deposition (reflection) of C ions on the surface is enhanced (suppressed), so that a thick C layer is formed with the thickness increasing proportional to the plasma ion fluence, as shown in Fig. 1. In this figure, a plasma containing 92% D^+ ions and 8% C^{4+} ions irradiated the W surface.

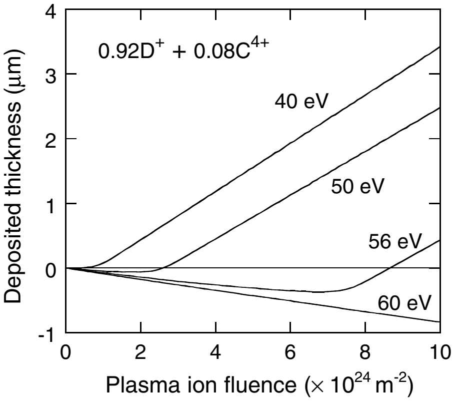

Fig. 1. Dependence of the deposition thickness on the plasma ion fluence. The negative values in the thickness represent the erosion depth.

The high concentration (8%) of C ions is used in the present calculation so as to show clearly the fluence-dependent change in the deposited thickness during the plasma exposure, in spite of the somewhat lower concentrations (2%–5%) of C ions for the TEXTOR edge plasmas. At high plasma temperatures, a steady-state condition is reached where the amounts of the deposited and released C are balanced, so that the W surface is slowly eroded by the impact of C ions. The eroded depth is also proportional to the plasma ion fluence. At intermediate temperatures (50 eV–56 eV), the transition from a state of erosion to a state of deposition occurs as a function of the ion fluence. Such a transition was calculated by Naujoks and Eckstein [1] for the first time, and has been discussed in several references for ion fluences in the order of $10^{22}\ \mathrm{m}^{-2}$ [1–5].

Fig. 2 shows the dependence of the deposition rate on the plasma temperature for various plasma ion fluences. The deposition rate for each ion fluence is defined as the increase in the thickness per $10^{23}\ \mathrm{m}^{-2}$ at the fluence. At very low ion fluences, the C atomic fraction in W is so small that the deposition of C ions has a much lesser influence on both the eroded depth and the thickness of the deposited C layer. Therefore, the deposition rate monotonously decreases at fluences of less than $1\times 10^{23}\ \mathrm{m}^{-2}$ with increasing plasma temperature. With further increases in ion fluence, the deposition rate changes dynamically, and finally, at fluences of more than $1\times 10^{25}\ \mathrm{m}^{-2}$, a steady state condition is reached where an abrupt transition from deposition to erosion is formed; the transition is caused by increases in temperature of only a few eV to around 55 eV. The abrupt transition is the formation mechanism for the sharp boundary between the erosion and deposition zones observed on the hemi-spherical surfaces of W test limiters, since the plasma temperature (of the order of tens of eV) decreases along the surface from the top to the bottom of the limiter. This also indicates that, depending on the plasma temperature above a material surface, the erosion and deposition zones are clearly distinguished from each other in the long-term plasma operation of fusion devices. The origins of the transition are investigated by analysing the fluctuations in the deposition rate, the C reflection coefficient and the C and W sputtering yield during the plasma exposure (not shown here). Around the transition temperature, the C reflection coefficient and both sputtering yields fluctuations are in opposite phase to the deposition rate. This indicates that when the C deposition thickness increases, the deposition (reflection) of C ions is increased (decreased) and the C sputtering yield and W sputtering yield are decreased; then, the C deposition thickness is further increased. Conversely, when the C deposition thickness decreases, the deposition of C ions is decreased and both the C and W sputtering yields are increased so that the deposition thickness is further decreased. The reason for the increase in the C (and W) sputtering yield with decreasing thickness of the deposited C is that the collision cascade of the deposited C is localized in the W–C mixed layer, so that the sputtering of the deposited C is more enhanced for the W–C mixed layer than for the thick C layer.

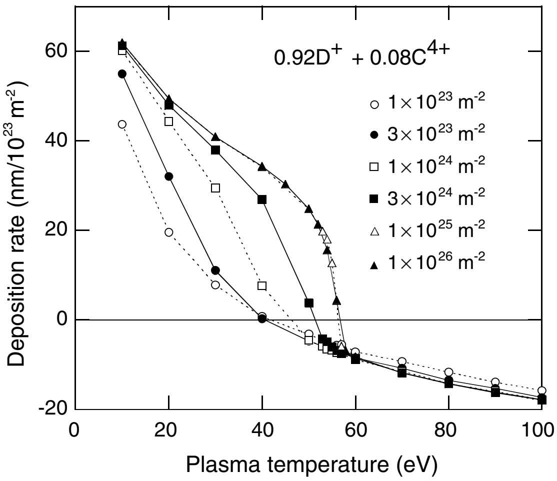

Fig. 2. Plasma temperature dependence of the C deposition rate on W.

Fig. 3(a) shows the decrease and increase in the C re-emission yield due to the formation of the thick C layer at low temperatures and the W–C mixed layer at high temperatures, respectively. The C re-emission yield is defined as the sum of the C sputtering yield and the C reflection coefficient multiplied by the C concentration in the plasma. The reduction in the W sputtering yield due to the deposition of C ions is also shown in Fig. 3(b) at different ion fluences. The formation of the thick C layer strongly suppresses both the C and W yields below the transition temperature. Due to the strong reduction in the C reflection coefficient, the C re-emission yield is dominated by the physical sputtering by D ions. Above the transition temperature, both C and W yields approach fluence-independent values at fluences of more than $1\times 10^{25}\ \mathrm{m}^{-2}$, whereas the C re-emission yield is equal to the amount (8%) of incoming C ions from the plasma.

Fig. 4(a) shows the change in the temperature dependence of the thickness of the deposited C with the C concentration of the plasma, where the ion fluence is $1\times 10^{25}\ \mathrm{m}^{-2}$. Both the deposited thickness and the eroded depth increase with increasing C concentration. The increase in the eroded depth above the transition temperature indicates that the erosion is dominated not by the D ions but by the small amount of impurity C ions (<10%). The transition temperature also increases with increasing C concentration, and at the highest C concentration, no transition occurs in the tem-

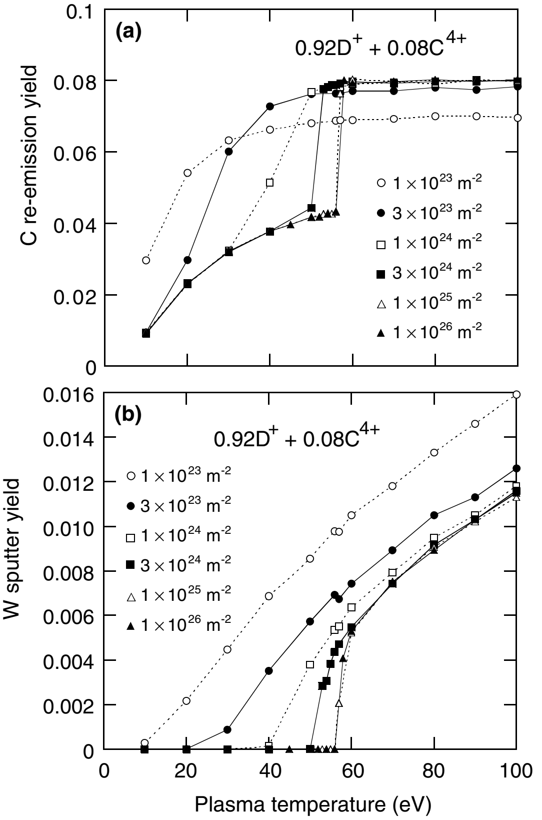

Fig. 3. Plasma temperature dependence of the C re-emission yield and the W sputter yield.

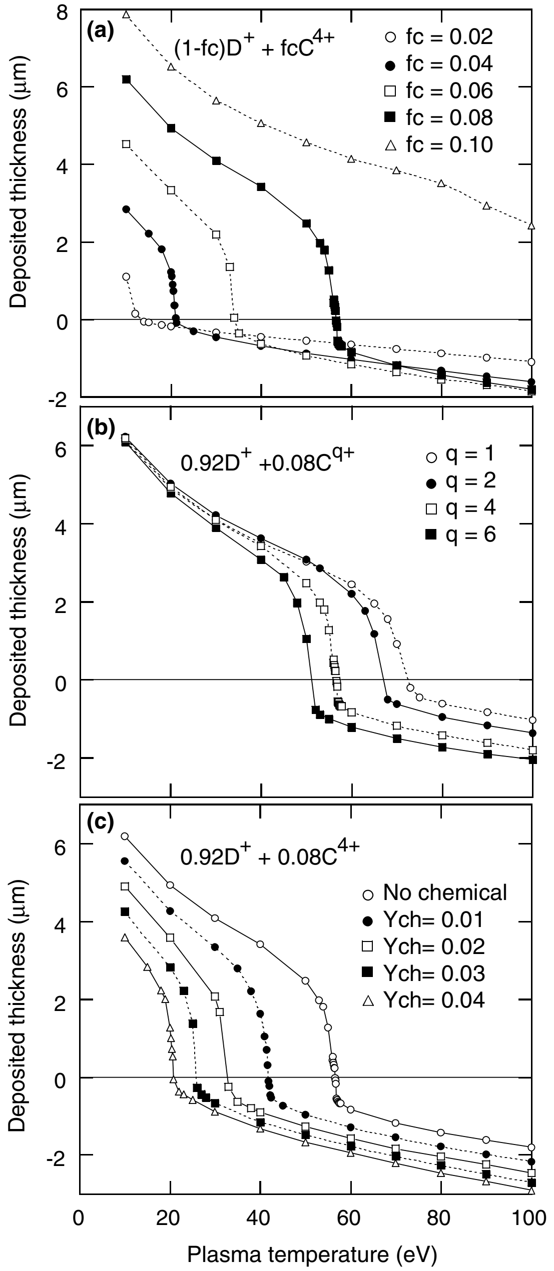

Fig. 4. Plasma temperature dependence of the deposition thickness on W at different concentrations and the charge state of C ions in the plasma, and at different chemical erosion yields.

perature range of tens of eV. Fig. 4(b) shows the plasma temperature dependence of the deposited thickness for different charge states of C ions ($q = +1 \sim +6$). Above the transition temperature, low charged C ions cause the eroded depth to decrease due to a decrease in the sputtering yield. Below the transition temperature, the sputtering of the deposited C is much less influenced by the charge state of C ions because it is dominated not by the small amount (<10%) of C ions but by the D ions (>90%). As a result, the transition temperature increases with decreasing charge state of the C ions.

In addition to the chemical erosion of the deposited C, the transition behaviour changes drastically, as shown in Fig. 4(c). When a D ion is implanted in the deposited C layer, the areal density of the deposited C is reduced by the D ion fluence multiplied by a chemical erosion yield. In TEXTOR, the chemical erosion yields measured for pure C materials have a maximum value of 0.04 at around 800 K and decrease to 0.01 at elevated material temperatures (1300 K) [13]. Due to the increase in the C re-emission yield, a steady-state condition is reached at lower plasma temperatures compared with no chemical erosion. Therefore, the transition plasma temperature is clearly decreased and the thickness of the deposited C layer is decreased below the transition, whereas the eroded depth is increased above the transition plasma temperature. However, the C implanted in the W bulk will lead to significantly different chemical properties from pure C materials due to the different chemical bonding state. In a previous study [5], a comparison of the calculated width of the deposition zone on the limiter surface with experimentally determined values (~ 2 cm) predicts a small chemical erosion yield of <0.01 for the C–W mixed material.

The surface temperature during plasma exposure depends strongly on the position on the limiter surface; the maximum temperature was ~ 1600 °C which was measured far from the top along the limiter surface, $d = 2$ cm. As described in a previous paper [4], a surface temperature of 1300 K near the boundary ($d = 4 - 5$ cm) between the erosion area and the deposition area was assumed, and a relevant total exposure time of 100 s in the test limiter experiments was used for the EDDY calculation including the one-dimensional Fickian equation. The exposure time is much shorter than 10^4–10^5 s in the experiments by Schmid and Roth [5]. The calculated results indicate that the thermal diffusion only slightly affects the eroded and deposited thickness due to the small diffusion coefficient ($\sim 1.1 \times 10^{-14}\,\mathrm{cm^2\,s^{-1}}$) of C in W. This was estimated by Schmid and Roth [14] by extrapolating the observed values at around 1000 K.

4. Conclusions

At fluences of more than $10^{25}\,\mathrm{m^{-2}}$, an abrupt transition from deposition to erosion is calculated as the plasma temperature is increased from 10 eV to 100 eV. A steady state condition is reached where a transition occurs due to a temperature increase of only a few eV at around tens of eV. When the deposited C thickness increases just below the transition temperature, the C reflection and sputtering are suppressed so that a thick C-rich layer is formed on W. Conversely, when the deposited C thickness decreases above the transition temperature, the C reflection and sputtering are enhanced so that there is only a thin W–C mixed layer.

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