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Trapping of eV deuterium ions by niobium at glancing incidence

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Abstract

Trapping of low energy deuterium ions is investigated at inclined ArD^+ bombardment of Nb target. The trapping coefficient η, which is found from the thermal desorption spectra after implantation, is measured for the energy range of 5–120 eV per deuteron at 60°angle of incidence. The value of η measured for target cleaned with Ar bombardment and temperature treatment decreases with energy from $\eta \sim 0.3$ at the primary energy $E_0 = 120$ eV to $\eta \sim 0.15$ at about $E_0 = 5$ eV. Computer simulations based on the binary collision approximation and performed with taking into account the real target micro relief measured with STM agree with the experimental data rather well. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Argon; Niobium

1. Introduction

As it was shown earlier [1], trapping of eV range deuterium ions by metal surfaces strongly depends on the energy of ions and presence of impurities on the surface. This effect must influence hydrogen recycling, retention and permeation. Our previous experiments were carried out only for the normal incidence of the beam. Both D_3^+ and ArD^+ ions were used as projectiles to decrease the primary energy of deuterons. Bombardment by ArD^+ heteronuclear ions is of interest also in application to radiating divertor where argon is seeded into the divertor region to reduce localised high heat loads [2]. Therefore, one can expect ArD^+ species be formed in the divertor plasma, which also interact with PFC.

The inclined incidence can be typical for ions interacting with solids in divertor. It is necessary to take into account in this case that low energy particle reflection and trapping are much strongly influenced by the surface composition and roughness in comparison with the case of the normal incidence (see, for example, [3]). One must mention also that various molecular effects related to the chemical bond of atoms in the impinging ions can be important at inclined bombardment [4,5]. Therefore, in this work we used in situ sample surface analysis based on the momentum spectroscopy of reflected and emitted ions during glancing ion bombardment of the target and checked the target roughness with STM before and after irradiation.

2. Experimental

The mass-monochromator ‘Medion-2’ with ion decelerating system was used as for experiments performed earlier [1,6]. The experimental procedure of the trapping coefficient measurements corresponded to the previous work [1]. The main difference of the experimental procedure was connected with in situ measurements of the target surface composition during ion implantation and gas release. For this purpose, an electromagnetic spectrometer installed at 60° relative to the primary ion

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Table 1
Mass spectrum of ion in the duoplasmatron plasma

Ions	HD^+	D_2^+	D_2H^+	D_3^+		H_2O^+ DO^+ $CD_2H_2^+$	Ar^{2+} D_2O^+ CD_4^+			CO^+, N_2^+	Ar^+	ArH^+	ArD^+
M/Z	3	4	5	6	12	18	20	21	22	28	40	41	42
Relative content (%)	0.1	0.3	2.4	11	0.5	1.3	6.3	0.7	6.6	16.1	19.8	1.1	33.9

beam direction was used for analysis of ionised recoils and scattered atoms during inclined bombardment of the target. Resolution of the spectrometer $\Delta P/P$ (where P is momentum) varied in the range of 0.05–0.1, solid angle of registration is $\sim 10^{-2}$ sr. The ioniser of the residual gas molecules and secondary particles emitted by the target was installed between the target and the electromagnetic spectrometer. Target was a 0.1 mm thick Nb strip, which was ohmically heated and tilted relative to the beam direction.

At low deuterium fluences $\Phi_0 < 10^{15}$ cm^{-2} and low temperatures $T < 500$ K, no subsequent re-emission of deuterium during its implantation into niobium was detected after the reflection pressure jump. This meant that all the implanted particles were retained in Nb, so the number of trapped particles Φ_t was measured by integrating the TDS spectrum obtained during linear heating of the target up to 1600 K after implantation. The trapping coefficient can be then determined as $\eta = \Phi_t/\Phi_0$, while the particle reflection coefficient corresponds to $R_N = 1 - \eta$.

For ion beam production, a duoplasmatron ion source was used, and bombardment of the target was performed under 60° of incidence. Fluences were $(2\text{–}6) \times 10^{14}$ cm^{-2}. We used the mixture of deuterium and technical argon with varying ratio of deuterium to argon to carry out implantation and surface cleaning in different experimental series. The ion composition of the duoplasmatron plasma is shown in Table 1. Parameters of plasma in the ion source were optimised to achieve the highest signal of ArD^+. It is interesting to note that dense cold plasma of duoplasmatron can relate to some zones of the divertor with gas feeding, so ArD^+ can be the dominant fraction in such plasma.

3. Results

Fig. 1(a) demonstrates a typical momentum spectrum (high momentum part) measured for Ar^+ irradiation of the target. After long term bombardment (several hours) at high temperature, the surface oxygen content can be considerably decreased. Nevertheless, an oxygen peak observed after high temperature ion cleaning indicates that Nb surface contains some oxygen in the vacuum conditions of the particular experiment.

The low momentum part of the spectrum measured for Ar^+ and ArD^+ irradiation (Fig. 1(b)) represents ionised protium and deuterium recoils and scattered deuterium ions. One can see that during analysis of the target surface at room temperature with Ar beam before the irradiation and heating only H peak can be detected (it is thought to be due to hydrogen absorbed mainly in

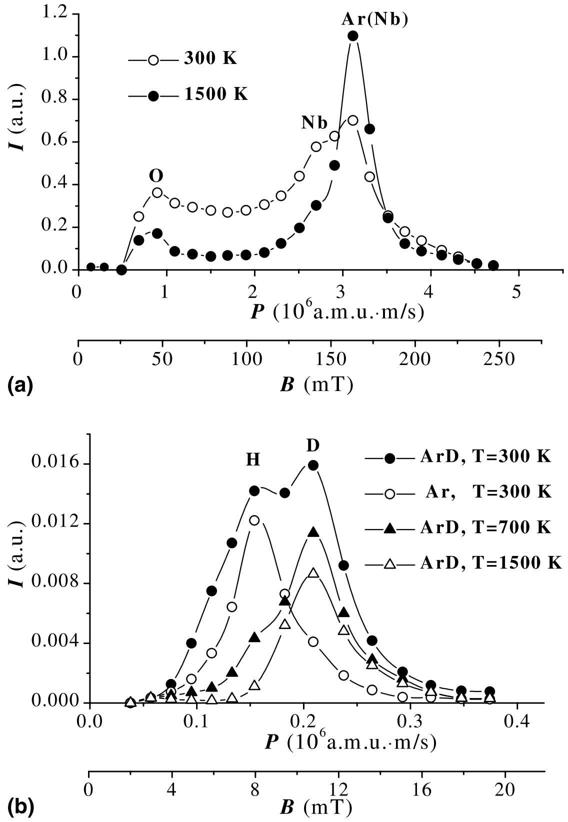

Fig. 1. The momentum spectra of the ionised recoils and scattered atoms for Ar^+ and ArD^+ bombardment of Nb target at different target temperatures. The ion energy $E_0 = 2.5$ keV, the angle of incidence $\Theta_0 = 60°$ (a) – high momentum part of the spectra, Ar^+ irradiation, (open circles – before heating and ion cleaning, closed circles – after several hours of Ar bombardment at 1500 K); (b) – low momentum part of the spectra for Ar^+ and ArD^+ irradiation before ($T = 300$ K) and after ion cleaning at different temperatures.

the form of water and hydrocarbons), while ArD^+ bombardment gives also another peak. Its position at $\Theta_0 = 60°$ correlates both with the position of deuterium knocked out from the surface and deuterium reflected from the surface after decomposition of the initial ArD^+ ion. As the magnitude of the peak depends only on the primary beam intensity and does not depend on the fluence, this peak is suggested to correspond to reflection of primary deuterium species. The bombardment with ArD^+ (or Ar^+) ions and heating leads to a decrease of protium peak to zero indicating cleaning of the surface. So, applying such a surface treatment, we assumed that the experiments on hydrogen trapping were performed with not contaminated, rather 'clean' surface (with small admixture of oxygen).

The energy dependencies of the trapping coefficient are shown in Fig. 2. The trapping coefficient decreases continuously with the energy decrease down to ~5 eV per deuteron, the lowest energy used. For comparison, the data for normal incidence of D^+ on clean niobium surface taken from [1] are also given in Fig. 2. At the energies below 20 eV, the ratio of the trapping coefficient at $\Theta_0 = 0°$ to that at $\Theta_0 = 60°$ is about 2. Due to the general considerations one can expect that for glancing incidence the rise of the trapping coefficient at decreasing of particles energy $E_0 \to 0$ should arise at higher energies than that for normal incidence as shown for example for glancing incidence of D_3^+ ions on W target where the increase of η takes place at 20–30 eV [7]. But in this experiment we did not found the low energy rise of the trapping efficiency down to 5 eV. The possible reason of the no-rise effect is the low value of binding energy E_S for clean Nb surface ($E_S = 0.4$ eV fitted computer simulations for clean Nb surface at normal incidence [1]). Computer simulations predict very strong influence of E_S on η rise at low energies. As one can see from calculations for smooth surface presented on Fig. 2, the small increase of η is seen below 5 eV. Another reason can be connected with surface roughness, which can decrease the average angle of beam incidence.

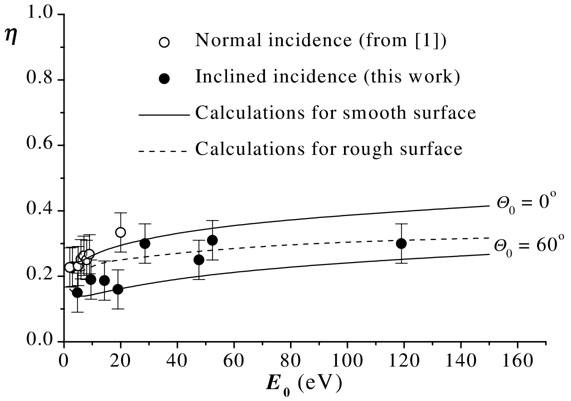

Fig. 2. Deuterium trapping coefficient as function of primary energy of D for ArD^+ irradiation of Nb surface. Closed symbols correspond to $\Theta_0 = 60°$ (this work); open – $\Theta_0 = 0°$ (from [1]); solid lines – computer simulations for smooth surface, dashed line – computer simulations for rough surface using STM scans.

Computer simulations were performed with the upgraded Monte-Carlo code SCATTER-R based on the binary collision TRIM code. The upgrade of the SCATTER code is in taking into account the real surface topography in calculations. The data about the topography of the sample (see Fig. 3) have been obtained by using the scanning tunnelling microscope SMM–2000T. Size of STM images varied from 0.1 × 0.1 to 6 × 6 μm^2. Maximum resolution achieved was about 0.3 nm for all three directions (X, Y, Z). Computer file of STM scan consisted of measured points co-ordinates was introduced into the program as it is. Results of computer simulations were averaged over several STM scans taken for various parts of the irradiated target. This procedure differs from other simulations of the surface roughness [8–10] by the more realistic taking into account target micro topography. The surface binding energy was set to be 0.4 eV in accordance with previous measurements [1]. As one can expect, the calculations for real surface performed for 60° lie higher that the respective values for the smooth surface. The results of same procedure made for the non-irradiated parts of the sample within the statistical error of simulations coincide with the dashed curve in Fig. 2. The errors of the trapping efficiency measurements are too large to make the accurate quantitative comparison with computer simulations, but one can see that for $E_0 > 30$ eV the experimental values correspond better to the modified computer code taking into account the real surface topography. But for low energies computations seem to overestimate a little experimental points. The details of the interactions at the lowest energies need further investigation.

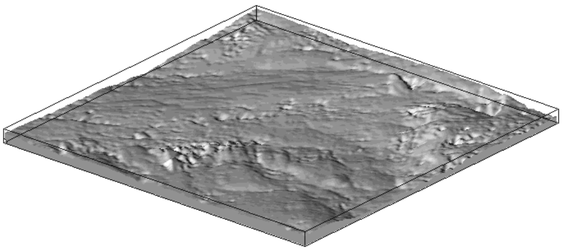

Fig. 3. Sample of the Nb surface scanned with SMM-2000T. The profiles obtained were used for computer simulations. The plotted surface has the size of 5.432 × 5.412 μm^2; the maximum difference in height is 0.215 μm.

4. Conclusion

The low energy deuterium trapping efficiency in Nb was measured at the angle of incidence of 60°. It was found to be twice less than the value obtained previously for normal incidence at energies $5 < E_0 < 20$ eV.

The experiments were performed with ArD^+ ions, so in situ surface control and analysis became available during low energy deuterium implantation.

The simulation of deuterium trapping using the computer code based on the binary collision approximation with incorporation of the real target micro relief measured with STM has given a reasonable agreement with the data measured. This upgraded code can be used for more realistic calculations of various parameters of ion–solid interaction.

It is necessary to note that for small energies of impinging particles when its range in solid is very small the STM relief measurements become crucially important for the analysis of fuel particles reflection and trapping in fusion materials.

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