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Retention properties of plasma particles in tungsten exposed to LHD divertor plasmas

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Abstract

To study retention properties of plasma particles in tungsten exposed to divertor plasmas, material probe experiments were carried out by exposing tungsten specimens to long pulse helium or hydrogen divertor plasma in LHD. After the exposure, the quantitative analysis of the implanted helium and hydrogen atoms were conducted by using ion beam analytical techniques. Though the incidence energies were very low, remarkable retention of plasma particles were confirmed. In the case of helium divertor experiment, the specimen which located at the strike point (highest retention), the total retained helium atoms were estimated to be 1.2×10^{20} He/m^2, and depth profile of helium atoms reached to about 25 nm. It is the much deeper range than that of the calculated results of 200 eV-He$^+$ irradiation by TRIM-code. In the case of hydrogen, the total retention of hydrogen at the strike point was estimated to be 3×10^{19} H/m^2 (lowest retention).

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1. Introduction

Divertor armor tiles in large-sized plasma confinement devices are exposed to heat and plasma particles with very high flux. Therefore, selection of divertor materials with high heat resistance and high plasma particle resistance is essential for advanced plasma confinement devices. Tungsten based materials are potential candidates of the plasma facing materials. In our previous study, details of the microscopic and macroscopic damage of tungsten exposed to the LHD divertor plasmas have been studied by using several analytical techniques [1]. However, in addition to the studies on

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the damage, characterization of the plasma particles injected in the divertor tiles is very important for the controls of impurities and hydrogen isotopes in the vacuum vessel.

The Large Helical Device (LHD) at NIFS is the largest heliotron-type plasma machine with superconducting magnetic coils. In heliotron-type devices, the edge magnetic structure is more complex than that of the scrape-off layer (SOL) in axisymmetric divertor tokamaks, and an intrinsic divertor exists without additional coils [2]. This magnetic structure is a large merit for current-less and disruption-free steady state plasma operation [3] and is also a great advantage for material exposure experiments to the divertor plasmas [1].

In the present work, material exposure experiments were carried out with helium divertor plasmas and also with hydrogen divertor plasmas in the LHD. Retention of the plasma particles was investigated by using ion beam analysis techniques.

2. Experimental procedures

Bulk tungsten plates of $35 \times 10 \times 1\ \mathrm{mm}^3$ (2-pieces) and pre-thinned vacuum annealed tungsten disks of 3 mm in diameter were mounted on the probe head shown in Fig. 1. They were transferred to the divertor-leg position by using the retractable material-probe system equipped with the LHD [1],

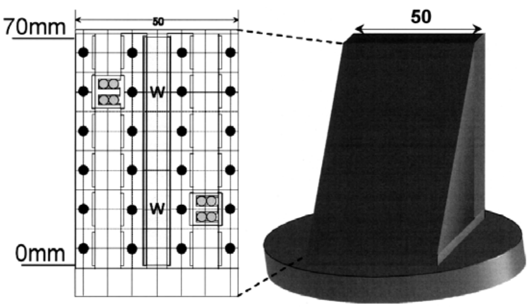

Fig. 1. Schematic view of the probe head and tungsten specimens.

and then exposed to a single helium plasma discharge for 30 s (shot-#56216) and a single hydrogen plasma for 30 s (shot-#52730). Typical plasma parameters are listed in Table 1. The material probe head made of SUS316L was designed so that the specimens and the magnetic field lines of the divertor-leg cross perpendicularly. The incident ion energy distribution at the specimens is shifted-Maxwellian (sheath-potential + T_i). In the present case, main component of T_e and T_i at the specimens were expected to be $T_e \sim T_i = 10$–20 eV. Taking into account the sheath potential, the actual incidence energy of the plasma bombarding the specimens is considered to be about 100–200 eV.

The temperature of the probe head was monitored by a thermocouple inserted just beneath the strike point. In actual it did not change much. The actual specimen temperature under the plasma discharges could not be measure in the preset experiment but it was roughly estimated from the defect accumulation as described in Section 3.

Quantitative analysis of the implanted helium and hydrogen in the exposed specimens were carried out by means of Rutherford back scattering (RBS) and elastic recoil detection (ERD). Depth profile of helium was measured successfully by using an oxygen ($^{16}O^{4+}$) analyzing beam ERD technique with the energy of 5.0 MeV. Incident angle of the analyzing beam was 72° to the surface normal of the specimen. The back scattered ^{16}O atoms were detected with the RBS detector placed at an angle of 170° to the incidence direction. The recoiled helium atoms were detected by the ERD detector at the angle of 30° to the analyzing beam direction. An Al film of 4 μm thick was placed in front of the ERD detector to absorb the O ions scattered from the specimen surface. In this method the retained helium atoms can be analyzed very clearly, because the background signal of the measurement is very low.

Hydrogen atoms were detected by using the $^{4}He^{2+}$ analyzing beam with the energy of 2.8 MeV. The geometry of the RBS&ERD system is same as the case of helium measurement. An Al film of

Table 1
Typical core-plasma parameters of helium and hydrogen discharges

	Discharge time (s)	Electron density, n_e (m^{-3})	Ion temperature, T_i (keV)	Input power (MW)
He-plasma	30	1.3×10^{19}	1.6	0.5
H-plasma	30	1.0×10^{19}	1.7	0.8

12 μm thick was used to absorb the He ions scattered from the specimen surface.

Surface morphology and microscopic damage inside the materials were observed with scanning electron microscopy (SEM) and atomic force microscopy (AFM), and transmission electron microscopy (TEM) was applied complementally.

3. Results and discussion

3.1. Retention of helium atoms in tungsten

The line distribution of the retained helium in the tungsten specimen exposed to a single helium divertor plasma is plotted in Fig. 2. The specimen position noted in the figure corresponds to that in Fig. 1. As noted in the figure, 0 mm-side is the private side. Profile of the connection length (L_c) of the magnetic field lines calculated by the field line tracing method is also plotted in the figure. The high peak of the L_c indicates that the divertor strike point is at about 40 mm. It is clear that retention of helium is highest (1.2×10^{20} He/m^2) at the strike point. With increasing the distance from the strike point, retention of helium decreases and it is almost constant (2×10^{19} He/m^2) beyond 20 mm away in the private side. It is known that most of the injected helium ion is trapped in tungsten up to the fluence of 1×10^{21} He/m^2 even at rather high temperatures [4], because the binding of helium and defects is very high. Therefore, the average flux of helium bombarding the specimen can be estimated directly from the retention. The helium flux at the strike point is about 4×10^{18} He/m^2 s. This value is much lower than that of our expectation, which can be extrapolated from our previous study [1]. Probably, this difference results in from the difference in a core-plasma parameter during helium discharge, such as plasma density (n_e). In actual, n_e of the present discharge (#56216) is about 1/3 of the previous study (#43426) [1]. However, to clearly explain this difference, the further discussion will be required. In the right side of the strike point, the helium flux is higher than that of the left side (private side). This result can be explained from the calculation of the magnetic structure and plasma diagnosis conducted in LHD [2,5]. According to those results, the particle and energy deposition is relatively high in the right side of the strike point.

Depth distributions of helium at several positions are plotted in Fig. 3. Injected helium distribute up to 10–25 nm from the incident surface depending on the position. To know the details of the depth distribution, data at the strike point (1) and at the 4 mm-position (2) are plotted in Fig. 4 together with that of 200 eV-He$^+$ (3) and 2 keV-He$^+$ (4), estimated by TRIM-code. Peak of the distribution locates at about 2–3 nm for (1)–(3) cases. This fact indicates that the majority of the helium plasmas bombarding the divertor plate have energy of about 200 eV. One should note that the depth distribution at the 4 mm-position agrees quite well with that of 200 eV-He$^+$, while that at the strike point has a long tail beyond the projected range. One of the possible reasons causing such difference is the difference of ion flux. At high flux, helium which diffuse out from the injected range have more chance to meet other helium and thus they have more chance to form their clusters even in the area beyond the projected range. In actual, the ion flux at the strike point is about 6 times higher than that at the 4 mm-position.

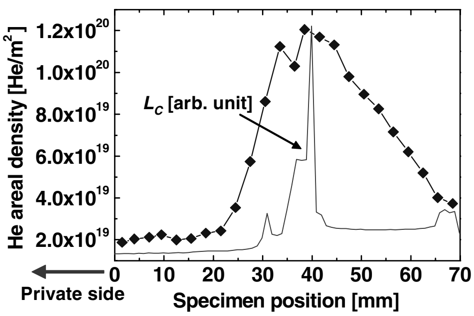

Fig. 2. Line distribution profile of the retained helium atoms in tungsten after exposed to the helium divertor plasma.

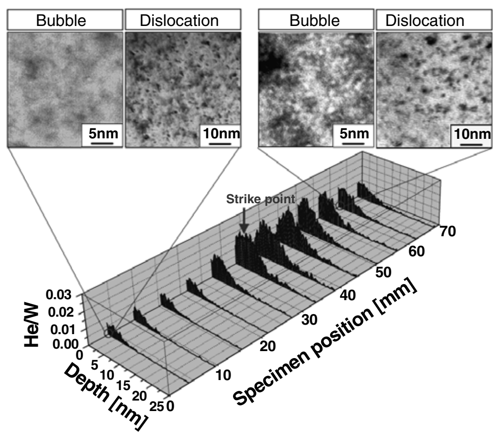

Fig. 3. Depth profile of the retained helium atoms in tungsten after exposed to the helium divertor plasma. TEM images were also shown; each image corresponds to the indicated position by solid line.

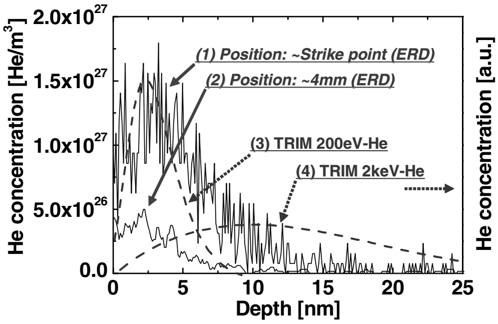

Fig. 4. Depth profile of helium atoms trapped in the tungsten after exposed to helium divertor plasma measured by ERD (solid line); data at the strike point (1) and at the 4 mm-position (2). Injected helium atoms profiles calculated by TRIM-code (200 eV-He^+ (3) and 2 keV-He^+ (4)) are also plotted together for comparison (dashed line).

The other explanation is the difference of the local temperature depending on the heating due to the plasma bombardment. It seems that increase of the temperature will enhanced the thermal aggregation of the helium.

Internal damage formed in the tungsten specimens by the helium plasma exposure is also shown in Fig. 3. They show typical damage structures formed by low energy helium ion irradiation. Fine defects with strong strain field around them are formed in the specimen placed at 4 mm (2×10^{19} He/m^2), while bubbles are formed in addition in the specimen at 62 mm (6×10^{19} He/m^2). According to the results in Ref. [6], where details of the damage accumulation in tungsten have been studied extensively as functions of helium ion energy, fluence and irradiation temperature, the former defects are platelets of helium atoms and dislocation loops. Size and density of the defects indicates that ion fluence is the order of 10^{19}–10^{20} He/m^2 and the expected temperature of the specimen during the plasma exposure increased up to the about 873 K. This temperature is not as high as that observed in the previous study [1]. Furthermore, the trace of the divertor strike point formed on the specimen surface was faint. This fact also indicates that the increase of the specimen temperature is not as high as that observed in the previous study [1]. The density of helium platelets and dislocation loop at the 62 mm-position in Fig. 3 is lower than that at the 4 mm-position even if the fluence of the helium ion is higher. This suggests that increase of the temperature at the strike point is higher than that at the 4 mm-position, where the ion flux is about 6 times lower.

In the case of low energy helium ion such as 200 eV-He^+, injected helium atoms aggregate by themselves, because radiation induced vacancies are not formed due to lack of knock-on energy [6]. The helium atoms are trapped by the bubbles, helium platelets and dislocation loops. According to the discussion on the trapping sites for helium at high fluence [7], most of the injected helium are trapped not only by the helium bubbles but also among the lattice atoms in the heavily damaged subsurface area where the lattice is heavily distorted due to the dense defect clusters such as bubbles and dislocation loops. It has been reported that accumulation of the defects such as helium bubbles and dislocation loops change the properties of the surface such as embitterment and enhancement of the trapping of hydrogen isotope [8].

Present results indicate that accelerated helium ions of about 200 eV bombard the diverter plates. Their flux is about 4×10^{18} He/m^2 s at the strike point. They cause heavy irradiation damage such as bubble and dislocation loops.

3.2. Retention of hydrogen atoms in tungsten

In the case of a single hydrogen divertor plasma discharge for 30 s, a clear 'foot print' was formed as a trace of melting on the probe head and tungsten specimens. The evaporated elements from the foot print of the probe head (Fe, Cr and Ni) re-deposited on the tungsten specimens nearby. These results indicate that one should take into account the large temperature increase. Fig. 5 shows the line distribution of the retained hydrogen atoms in tungsten

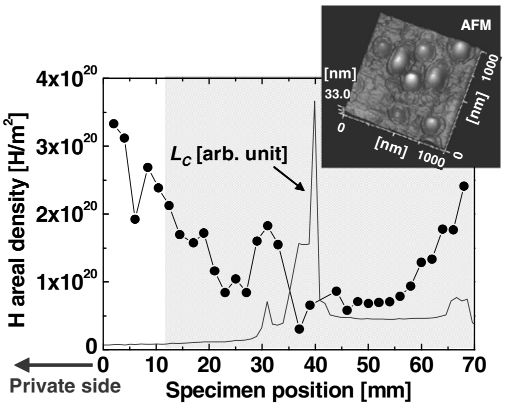

Fig. 5. Line distribution profile of the retained hydrogen atoms in tungsten after exposed to the hydrogen divertor plasma, hatched area means the deposition zone of Fe, Cr and Ni. AFM micrograph at the position of 10 mm is also shown.

specimen exposed to the hydrogen divertor plasma, AFM micrograph at the position of 10 mm was also shown. The hatched area in the figure indicates the zone covered by the re-deposition. It was identified by RBS that thickness and the major component of the deposition is 2–30 nm and Fe, respectively. The total retention of hydrogen at the strike point was estimated to be 3×10^{19} H/m^2. With departing from the strike point, the retention of hydrogen increases gradually. One should note that the position dependence is contrary to the case of the helium divertor experiment as described in Section 3.1. In the case of hydrogen, thermal detrapping occurs at much lower temperature than helium, because the interaction with defects is low. It was reported that helium once injected into metal is not easily released due to the strong interaction with the lattice defects even at high temperature up to about 1500 K, while, most of the injected hydrogen isotopes in tungsten are easily released up to 800 K [6,9,10]. Near the strike point, where specimen temperature increases very much due to the high flux plasma bombardment, most of the injected hydrogen is released during discharge and therefore only a small amount of hydrogen is retained. In contrast, at the periphery, where hear flux is lower, temperature of the specimen did not increase much, large amount of the injected hydrogen are retained.

From the AFM observation, small blisters with size of 200–300 nm were observed at the position of 10 mm as shown in Fig. 5. This result suggests that un-predicted hydrogen retention may occur in the tungsten divertor as well as carbon divertor.

4. Summary

Material probe experiments in LHD and subsequent material analysis were carried out by using RBS&ERD and several analytical techniques complementary. In the case of helium plasma experiment, the position of the highest retention of total retained helium atoms corresponds to the divertor strike point, which was contrary to a hydrogen plasma experiment.

Especially, in the case of helium plasma experiment, we have succeeded to estimate depth profile of the injected helium atoms in tungsten. The results showed that many of the helium atoms had diffused deeper into the material than that of the projection range, even though the major component of the injected energy is rather low. It was reported that helium bubbles and dislocation loops (see Fig. 3) act as the strong trapping site for hydrogen isotope [8].

It should be emphasized that even in the low energy divertor plasmas, such a large amount of plasma particles in tungsten divertor may be retained that we cannot expect.

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