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Effect of helium implantation on deuterium permeation behavior in tungsten
タングステンにおける重水素透過挙動に及ぼすヘリウム照射影響

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Gas-driven deuterium permeation experiments were performed for helium implanted and un-implanted tungsten foils. The permeability of un-implanted tungsten was in good agreement with Zakharov’s results, and the activation energy was estimated to be 1.04 eV. The permeability of helium implanted tungsten is lower than that of un-implanted tungsten at the temperature below 1023 K, and higher at the temperature above 1073 K and the activation energy is calculated to be 2.10 eV. The activation energy of helium implanted tungsten is higher than that of un-implanted tungsten, indicating that the activation energy is influenced by the defects produced by helium implantation, such as helium bubble.

1. Introduction

Tungsten is considered as a plasma facing material (PFM) in fusion reactors due to its favorable properties, such as higher melting point, lower hydrogen retention and lower sputtering yield. However, during plasma operation, the irradiation damages will be introduced in the PFM by the exposure of various energetic particles, such as helium, hydrogen isotopes and neutron from plasma. It is expected that dissolution, diffusion and permeation behaviors of hydrogen isotopes for damaged tungsten would be different from those for undamaged tungsten. Therefore, elucidation of hydrogen isotope transfer dynamics for the damaged tungsten is quite important from a view point of fuel control.

In our previous study [1,2], the helium ion irradiation experiment showed that the helium bubble was formed on the tungsten surface. The TDS (Thermal Desorption Spectrometry) spectra for helium implanted tungsten indicated that the retention of deuterium as both of Peak 1 (400 K) and Peak 2 (580 K) were increased. It was known that the deuterium desorption as Peak 1 was induced by that trapped by grain boundaries and dislocation loops. For Peak 2, the deuterium desorption was caused by that trapped by dislocations and vacancies near helium bubbles. These results indicate that implantation defects affect on the deuterium permeation behavior because the implantation defects would work as deuterium trapping sites and helium bubbles become deuterium diffusion barrier. In this study, the deuterium gas-driven permeation behaviors for tungsten damaged by energetic helium ion implantation were studied at 673 - 1173 K, and the permeability, diffusivity and solubility were also evaluated. The influence of the implantation damages on the hydrogen permeation behavior was discussed.

2. Experimental

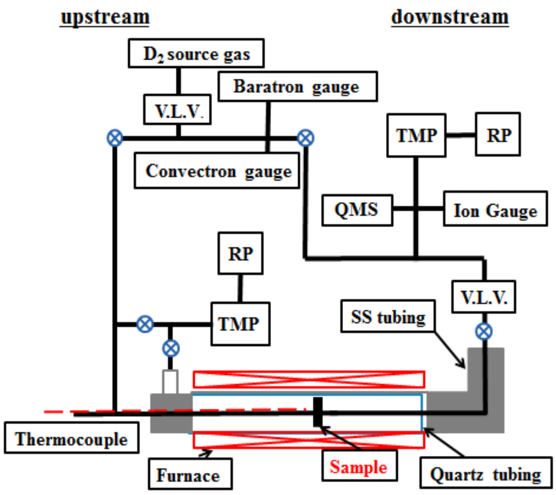

Fig.1. Schematic diagram of the deuterium permeation system.

Figure 1 shows the schematic diagram of

deuterium permeation system used in this study. It consisted of two different vacuum pumping systems; namely downstream side for permeation signal monitoring and upstream side for gas supply. To prevent the oxidation of sample holder at higher temperature and prevent the deuterium permeation to the environment, the sample holder was covered by quartz tubing and pumped out with the pressure less than 10^{-4} Pa. The vacuum pressure for both of upstream and downstream sides was kept ~10^{-6} Pa. Thereafter, the deuterium gas was installed in the upstream side. The amount of deuterium permeated through the sample was evaluated by a quadrupole mass spectrometer (QMS).

In this study, deuterium gas-driven permeation experiments were performed for two type samples. One was the nickel foils (10 mm × 10 mm × 0.1 mm^t, Nilaco Co. Ltd.) to check soundness of the permeation system using in this study, and the other was tungsten foils (10 mm × 10 mm × 0.035 mm^t, Nilaco Co. Ltd). The samples were cut in a circle and preheated at 1173 K for 30 minutes under ultrahigh vacuum (< 10^{-6} Pa) to remove the impurities. The 3.0 keV helium implantation for tungsten was performed to introduce the damage of helium implantation characteristic such as helium bubble with the ion flux of 1.0×10^{17} He^+ m^{-2} s^{-1} and the ion fluence of 1.0×10^{21} He^+ m^{-2}. These samples were introduced into permeation system and sealed with silver coated gaskets. The helium implantation side of sample was placed at the upstream side. The deuterium permeation experiments were performed with the pressure of 10.00 - 100.0 kPa and temperature range of 673 - 1173 K.

3. Results and Discussion

The accuracy of the permeation system was proved by permeation experiments for nickel and un-implanted tungsten. The deuterium permeability for the nickel sample was determined to be

$$P = (2.87 \pm 0.81) \times 10^{-7} \exp(-0.58 \pm 0.01\, eV/kT) \quad [\mathrm{mol\ m^{-1}\ s^{-1}\ Pa^{-0.5}}].$$

This permeability was consistent with the previous results derived by S.J. Noh [3], and T. Shiraishi [4], showing the experimental setup is ideal for deuterium permeation test for tungsten.

Figure 2 shows the deuterium permeabilities for the un-implanted and 3.0 keV helium implanted tungsten samples. The permeabilities for the un-implanted sample was determined to be as follows;

$$P = (3.99 \pm 0.76) \times 10^{-8} \exp(-1.04 \pm 0.04\, eV/kT) \quad [\mathrm{mol\ m^{-1}\ s^{-1}\ Pa^{-0.5}}].$$

The present permeability for un-implanted sample was in good agreement with Zakharov's result, whose permeability was expressed by following equation [5],

$$P = 3.65 \times 10^{-8} \exp(-1.04\, eV/kT) \quad [\mathrm{mol\ m^{-1}\ s^{-1}\ Pa^{-0.5}}].$$

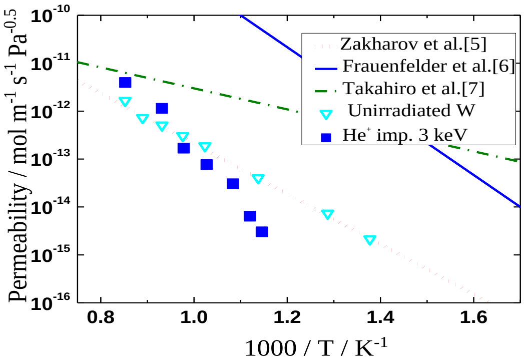

Fig.2. Arrhenium plots of deuterium permeability for the un-implanted W and 3 keV He^+ implanted W.

As shown in Fig. 2, the deuterium permeability for the helium implanted sample was different from that for un-implanted sample. The permeability was significantly reduced at the temperature below 1023 K and increased at the temperature above 1073 K compared to that for un-implanted tungsten. The permeability can be evaluated to be as follows;

$$P = (3.03 \pm 0.81) \times 10^{-3} \exp(-2.10 \pm 0.07\, eV/kT) \quad [\mathrm{mol\ m^{-1}\ s^{-1}\ Pa^{-0.5}}].$$

It can be said that the activation energy for helium implanted sample is higher than that for un-implanted sample, indicating that the rate determination step for helium implantation sample would be the deuterium detrapping by helium implantation defects.

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