HE SELF-PUMPING BY TOKAMAK PUMP LIMITER MATERIALS:
Al, V, Ni, and Ni/Al Alloys

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An ECR plasma and Colutron ion gun were used to study He self-pumping by several possible pump-limiter materials: Ni, V, Al, and Ni/Al multi-layers. Ni and V exhibited similar pumping capacities (6×10^{15} He/cm², 200 eV) whereas Al showed a reduced capacity (6×10^{14} He/cm², 200 eV) due to increased sputtering. A He retention model based upon ion implantation ranges and sputtering rates agreed with the experimental data. The pumping efficiency increased significantly with ion energy. A new multilayer/bilayer pumping concept showed improved pumping above that for single element films.

I. INTRODUCTION

Pumping the He ash from burning DT plasmas of future tokamaks will be necessary to realize fusion energy. One possible pumping scheme is the use of a He implantation/gettering material. An electron cyclotron resonance (ECR) plasma and a low energy ion gun (Colutron) were used to determine the pumping efficiency for a range of ion energies present at the edge of an operating tokamak. For this study, the following possible limiter materials were chosen: Al, V, Ni, and Ni/Al alloys. Ni is being used currently [1] as a pump limiter material; however, the data is limited on the pumping characteristics of Ni. In addition to Ni, new materials were investigated to find the best pumping material and to test fundamental physical principles of He retention (i.e., ion implantation, sputtering, and grain boundary trapping). Elevated temperatures are expected during the pumping operation in tokamaks; therefore, the sample temperature, ion energy, and ion beam damage were varied. The results showed that Ni and V had similar pumping capacity in pure He plasmas; however, V pumping capacity decreased in H/He plasmas relative to Ni. Thin metal films were exposed simultaneously to H⁺ and to He⁺ ion beams/plasmas to determine the competition for trapping of H and He.

II. EXPERIMENT

Thin films (≈ 100 nm thick) were made by electron beam evaporation of the constituent metals onto sapphire substrates. These films were then exposed to either an ECR plasma or a Colutron ion beam, which were used separately in order to produce a wide range of ion energies. An ECR plasma is a source of 35-535 eV ions (by applying a 0-500 V bias to the sample) and a Colutron ion gun is a source of 100-3000 eV ions (either He or D ions). Also, the ECR source produced a high ion-density plasma (10^9 - 10^{10} /cm³) using either pure He or a mixed D/He plasma. A complete description of the ECR source operating at

2.45 GHz with a magnetic field ≈ 875 Gauss was given previously [2]. The ECR plasma characteristics were determined with a Langmuir probe, carbon resistance probe [2], and optical emission spectrometer. The sample temperature in the ECR system was controlled by radiative heating of the sample whereas the sample temperature in the Colutron was controlled by resistive heating of the sample mount. Following exposure of the samples to the low energy ions the amounts of D and/or He retained in the sample were measured via elastic recoil detection (ERD) utilizing a 20 MeV Si⁴⁺ ion beam. The D isotope was used in the exposures to allow for the separation of the D signal from that of H in the ERD spectra.

III. RESULTS

A. Simple Model for He Retention

Figure 1 shows the amount of retained He in pure Ni films as a function of the incident He fluence for 175 eV ions. In this figure, the upper curve represents the optimum case of 100% retention of He in Ni. However, the actual He retention is limited by the number of available trapping sites and the sputtering of the Ni. The lower curve models this situation. The slope of the lower curve before reaching saturation (saturation fluence $> 10^{18}$ He/cm²) is the pumping efficiency of Ni ($r \approx 2\%$) at 175 eV. The pumping efficiency, r , is the probability that at low fluence an implanted He⁺ ion will remain trapped.

Fig.1. Application of model of He retention in metals to Ni. Incident He⁺ energy is 175 eV.

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The basic physical mechanisms is governed by the competing physical processes of saturation implantation and physical sputtering. The rate of He retention in a metal exposed to D/He plasma can be represented using:

$$\frac{dN}{dt} = \phi f r \left(1 - \frac{N}{qN_s}\right) - \phi S_f \frac{N}{N_s} \quad (1)$$

where,

$$S_f = fS_{He} + (1 - f)S_D \quad (2)$$

and

- N - # He atoms retained in the metal
- ϕ - Incident plasma (or ion) flux (#/cm²-s)
- f - Fraction of He in plasma
- q - Saturation fraction of He in metal
- N_s - Implantation zone (# metal atoms/cm²)
- S_{He} - Sputtering yield of metal atoms by He
- S_D - Sputtering yield of metal atoms by D
- S_f - Effective sputtering yield.

The maximum number of available trapping sites (qN_s) is balanced by the number of available trapping sites lost to sputtering ($S_f N$). Therefore, the equilibrium concentration of He trapped in the metal (N_0) is determined from setting $dN/dt = 0$:

$$N_0 = \frac{qN_s}{1 + \frac{qS_f}{rf}} \quad (3)$$

The solution of Equation 1 yields:

$$N = N_0 [1 - \exp(-\frac{t}{\tau})] \quad (4)$$

where,

$$\tau = \frac{N_0}{\phi f r} = \text{characteristic time to reach}$$

pumping saturation

The pump time is an important parameter to determine the amount of He pumped away from the burning plasma during a given tokamak shot. In the saturation limited regime where $qS_f/(rf) < 1$:

$$N_0 = qN_s \Leftrightarrow \tau = \frac{qN_s}{\phi f r} \quad (6)$$

In the sputter limited regime where $qS_f/(rf) > 1$:

$$N_0 = \frac{N_s r f}{S_f} \Leftrightarrow \tau = \frac{N_s}{S_f \phi} \quad (7)$$

The implantation zone (N_s) was calculated from Monte Carlo damage calculations (the TRIM computer code for energy ions [3]). Experimentally, r is an adjustable parameter determined from the slope of a fit to the data and q can be calculated from the saturation limited regime.

B. Influence of Ion Energy and Limiter Material on He retention

In order to test the importance of ion energy on He pumping, the fraction of retained He as a function of implant He energy is shown in Figure 2. The

capacity for He pumping increases significantly with increasing ion energy; therefore, future pump limiters should be designed with a capability to be biased.

In Figure 3, the pure Al shows the lowest He retention due to a large sputtering yield (S_{He}), whereas, the Ni/Al multilayer exhibits the best pumping ability by combining large N_s (Al) and small S_{He} (Ni). Preliminary results suggest that the dominant pumping mechanism is ballistic implantation rather than adsorption or grain boundary trapping. Further experiments will be done to examine these results more fully. The V, Ni, and Ni/Al bilayer all

Fig 2. Fraction of He retained in V(o) and in Ni(Δ) as a function of He energy.

Fig 3. Percentage of He retained in different materials. All of the materials were exposed to a 3 keV He⁺ the Colutron. The Ni/Al bilayer was composed of 10 nm of Al deposited on 100 nm of Ni. The Ni/Al multilayer was composed of 7 layers of 5 nm Al/5 nm Ni deposited on 100 nm of Ni.

show similar He pumping capacities. The fact that the bilayer is similar to the other two metals and different from the pure Al or multilayer is probably due to the high S_{He} of Al.

C. Competition for D/He Release from V and Ni

The competition for D/He release from V was studied as a function of anneal temperature and is shown in Figure 4. The transition from a D dominated trapping regime to a He dominated trapping regime occurs at ≈ 250 °C. At room temperature, V forms a hydride with the implanted D thus reducing the overall number of trapping sites (N_s) for He. Above 250 °C, the decomposition of the hydride is increased which causes the preferential release of the D. However, the overall pumping efficiency of He has been significantly reduced. As is shown in Figure 4, over 60% of the He has been released at 400 °C. To investigate He pumping ability of pure V and Ni in the He dominated regime ($T = 500$ °C), samples of Ni and V were exposed to a D/He ECR plasma identical to the one used in Figure 4. In this regime, a hydride is formed

Fig 4. Competition for D/He release from Vanadium. Vanadium sample exposed to ECR plasma containing 90% D and 10% He. The sample was biased to 100 eV. The samples were vacuum annealed (for 10 min @ Temperature) in the ERD analysis chamber.

Fig 5. Competition for D/He from Nickel. The Ni samples were implanted with 175 eV He⁺. The D⁺ (+) was implanted at 100 eV and the sample was heated to 500 °C before implant. An identical Nickel sample (o) was vacuum annealed at 500 °C.

in neither Ni nor V. The retention of He in both samples was almost identical. Therefore, the decomposition reaction of Vanadium deuteride is associated with a strong release of He. This suggests that V limiter materials must be operated above 400 °C to suppress hydride formation and achieve efficient operation.

The retained He fluence as a function of both D implant fluence and anneal temperature is shown in Figure 5. Although Ni does not form a hydride, other mechanisms for the competition for trapping sites must be investigated. From Figure 5, the competition for trapping sites is not important. These results are consistent with the experiments conducted by Pontau [4] which were conducted at higher implant energies.

IV. CONCLUSIONS

An ECR plasma and Colutron ion gun were used to study He self-pumping by several possible pump-limiter materials: Ni, V, Al, and Ni/Al multi-layers. Ni and V exhibited similar pumping capacities whereas Al showed a reduced capacity due to increased sputtering. A He retention model based upon ion implantation ranges and sputtering rates agreed with the experimental data. The pumping efficiency increased significantly with ion energy. A new multilayer/bilayer pumping concept showed improved pumping above that for single element films. Also, D/He trapping site competition is more important in V than in Ni. However, D/He site competition in V was shown to be less important above 400° C where hydride decomposition is enhanced.

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