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Retention and surface blistering of helium irradiated tungsten as a first wall material

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Abstract

The first wall of an inertial fusion energy reactor may suffer from surface blistering and exfoliation due to helium ion irradiation and extreme temperatures. Tungsten is a candidate for the first wall material. A study of helium retention and surface blistering with regard to helium dose, temperature, pulsed implantation, and tungsten microstructure was conducted to better understand what may occur at the first wall of the reactor. Single crystal and polycrystalline tungsten samples were implanted with 1.3 MeV ^{3}He in doses ranging from 10^{19} m^{-2} to 10^{22} m^{-2}. Implanted samples were analyzed by $^{3}He(d,p)^{4}He$ nuclear reaction analysis and $^{3}He(n,p)T$ neutron depth profiling techniques. Surface blistering was observed for doses greater than 10^{21} He/m^2. For He fluences of 5×10^{20} He/m^2, similar retention levels in both microstructures resulted without blistering. Implantation and flash heating in cycles indicated that helium retention was mitigated with decreasing He dose per cycle.

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1. Introduction

A proposed inertial fusion energy reactor operates at ∼10 Hz. Each cycle begins with the injection of a pellet with a deuterium–tritium (DT) core. Next, multiple high intensity laser beams are focused on this pellet, which leads to implosion and fusion in the core. Immediately following the fusion event, the chamber wall is subjected to intense radiation. X-rays arrive first, then reflected laser light, followed by high-energy neutrons, and finally fast and slow ion debris [1]. Most of the wall heating results from the energy deposition from X-rays and ion fluxes. Simulations of the thermal evolution at the first wall indicate that the maximum

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temperature reached will be 2000–3400 °C with an operating temperature greater than ~700 °C [2]. The intense radiation damage to materials directly facing the plasma, i.e., the first wall, has motivated widespread research. A major concern is erosion of the wall surface due to evaporation, physical and chemical sputtering, as well as blistering due to trapping of gaseous ions. Tungsten is a favorable choice for the material of the first wall because of its lower physical and chemical sputtering yields and high melting point of 3410 °C [1–3].

Implantation of helium, with energies on the order of 1 MeV, can give rise to the formation of He bubbles about 1 μm beneath the surface. As the helium bubbles grow they cause blistering of the surface, which leads to repeated surface exfoliation of ~1 μm thick layers [4]. In previous studies it was observed that blistering occurs in most helium-implanted materials at doses around 10^{21} m^{-2} and exfoliation occurs around 10^{22} m^{-2} [5]. If we consider, for example, a He flux of $\sim 3 \times 10^{18}$ ions/m^2 s, then a 1 μm thick layer would exfoliate about once per hour resulting in unacceptable surface erosion over the course of a year.

The objective of this study was to investigate the helium retention and surface blistering characteristics of tungsten with regard to helium dose and temperature. Ultimately, the goal was to determine if helium retention and its damaging effects can be mitigated by the cyclic nature of the helium irradiation and high temperature thermal spikes within the IFE reactor. Helium implantation and annealing conditions were chosen in an effort to imitate conditions at the first wall. In reality, the helium ion bombardment and heating would occur at much faster time scales. Also, the exact timing of the helium bombardment within the thermal evolution of the first wall is not well known. Tungsten samples were implanted at a temperature near the expected base operating temperature (850 °C) followed by flash annealing at 2000 °C. Implanting ^{3}He ions allowed the measurement of helium retention by ^{3}He(d,p)^{4}He nuclear reaction analysis and ^{3}He(n,p)T neutron depth profiling.

The study presented here consists of three major components as follows: (i) determination of the critical helium dose for which surface blistering occurs, (ii) investigation of the effects of microstructure (single crystal vs. polycrystalline) on helium retention, and (iii) a study of how helium retention is affected by cyclic implantation and flash annealing.

2. Experimental

The size of single crystal and polycrystalline tungsten samples were $\sim 8 \times 50$ mm^2 and ~1.0 mm thick. Preparation of the single crystal tungsten samples involved extensive grinding and polishing with a final step of 3 μm diamond polishing. All tungsten samples were implanted with a 1.3 MeV beam of ^{3}He with an incident angle of 4.5° from the surface normal. The slight tilt of the sample was to avoid accidental channeling of He in single crystal tungsten. According to SRIM-2000.40 code [6], the projected range of the ^{3}He ions in tungsten was 1.73 μm with a longitudinal straggle of 0.21 μm.

Use of a 5×5 mm^2 aperture in the beam line allowed selection of the implantation beam size. Due to beam spread between the aperture and target, the actual ^{3}He implantation area was approximately a 6×6 mm^2. Targets were implanted at a temperature of 850 °C. After implantation high temperature heating was conducted at 2000 °C. The helium doses ranged from 10^{19} He/m^2 to 10^{22} He/m^2. The ^{3}He beam currents used were 0.1–1.0 μA, depending upon the implantation dose. The effect of dose rate was not considered in this study. All implantation, flash heating, and analysis were conducted in an ultra high vacuum environment without breaking the vacuum.

A 2.5 MV Van de Graaff accelerator was used to generate the ion beams. A beam profile monitor (BPM) was used extensively for helium implantations to ensure that the beam profile was uniform over the 6×6 mm^2 implantation region. The water-cooled sample holder used in these experiments did not allow for measurement of the beam current hitting the target. Therefore, a Faraday cup located between the BPM and the target chamber (~0.5 m away from the target) was used to calibrate the BPM output. In addition, a surface barrier Si detector placed at 160° was employed to monitor the beam fluctuations. The BPM output maintained proportionality to the backscattered ion yield in the monitor. Error in the dosimetry was estimated to be ~10%.

The computer controlled implantation sequence involved a custom computer program with two separate threads running in parallel, one for temperature control, and the other for dosimetry control. The dosimetry control thread read the signals from two separate digital current integrators to calibrate the BPM/Faraday cup ratio, then removed the Faraday cup from the beam path until the proper dose