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Helium-Defect-Interactions in Tungsten Studied by Positron Annihilation Spectroscopy

Tungsten (W) is a promising candidate material for the plasma-facing surfaces of nuclear fusion devices. The interaction of helium (He) with W is of interest because the wall of a nuclear fusion device will be subject to high fluxes of He produced in the DT-fusion reaction. Furthermore, neutron irradiation will create He in the bulk by nuclear reactions.

Simulations on the atomic level predict a) that He can agglomerate in a W lattice, termed "clustering", b) how these clusters can create lattice defects, termed "self-trapping" [Boisse14], and c) that He traps in open-volume defects and can create additional defects in the lattice, termed "trap-mutation" [Henriksson06]. Self-trapping and trap-mutation are precursors to the creation of He-clusters. These clusters grow into macroscopic bubbles when more He atoms are added.
Unlike the growth of He-bubbles, these initial steps of He clustering have not been studied experimentally in W. Therefore, we have experimentally investigated the behavior of low-energy He in W samples with very low defect concentration ("defect-free") as well as in samples with deliberately introduced defects. The investigation is mainly performed by positron annihilation spectroscopy (PAS), specifically Doppler-broadening spectroscopy (DBS) and positron annihilation lifetime spectroscopy (PALS). These complementary methods are sensitive tools for the examination of the defect type and concentration.
The investigation was conducted as follows: First, high-purity W(111) monocrystals are cut, polished, annealed, and pre-characterized to ensure their defect density is below the detection threshold of PAS, i.e., less than about 10^{-6} vacancies per atom. Secondly, a subset of these crystals is irradiated with 4.5 MeV electrons to different fluences (corresponding to 3 × 10^{-5} and 15 × 10^{10-5} dpa). This treatment produces Frenkel pairs in the samples. Since interstitials in tungsten are much more mobile than vacancies, predominantly single-vacancies survive. The presence of single-vacancies only, facilitates an easy comparison with theory. Finally, all crystals are exposed to a low-temperature He plasma with ion energies of 50 eV or 100 eV while being cooled to 292 K. This energy is substantially below the threshold for the creation of lattice defects in the bulk by kinetic means, which is around 500 eV. Different combinations of He flux (1 × 10^{17} to 4 × 10^{19} He m^{-2} s^{-1}) and fluence (2 × 10^{18} to 9 × 10^{21} He m^{-2}) are explored.
In order to track the evolution of the type and concentration of the defects, the samples are characterized by PAS before and after each treatment. The effect of electron irradiation is probed by conventional Coincidence DBS (CDBS), conventional PALS, depth-resolved PALS, and depth-resolved DBS. The effect of He irradiation is then studied by depth-resolved PALS, and depth-resolved DBS.

In the defect-free samples we observe evidence (e.g., the creation of open volume defects) of self-trapping at a fluence of 9 × 10^{21} He m−2 with a flux of 9 × 10^{16} He m^{-2} s^{-1} and an energy of 50 eV, while no self-trapping was observed at a fluence of 2.0 × 10^{21} He m^{-2},. This observation gives a threshold for self-trapping and enables us to rule out trap-mutation for the parameter space we probed with the defect-free samples.
At an He energy of 50 eV, evidence of He clustering, the initial step of self-trapping, is observed at a lower fluence of 1 × 10^{21} He m^{-2}, only when we increase the He flux to 4 × 10^{19} He m^{-2} s^{-1}.
For the sample irradiated to the lower of the two electron fluences of 3 × 10^{-5} dpa, we observe by PALS that the vacancies near the surface of the sample are filled with more than four He atoms. Even in this saturation region, where the highest He-to-vacancy ratios of any sample of the entire study were induced, the He atoms were not found to give rise to trap mutations. This observation allowed us to rule out trap mutations for the entire He irradiation parameter space explored in this study.
In addition, our measurements showed that no lattice damage is caused by He irradiation at 50 eV energy. At 100 eV, however, we observed the creation of open volume defects by depth resolved DBS.
Taken together, these measurements allow us to constrain the limits of the flux-fluence combinations in which He clustering and He self-trapping are possible.

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