Influence of the presence of deuterium on displacement damage in tungsten

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Abstract.

The influence of the presence of deuterium on displacement damage in tungsten is studied by implanting 20 MeV tungsten ions to a fluence equivalent to 0.23 dpa in the damage peak maximum into already displacement-damaged tungsten containing 1.7 at.% deuterium. SDTrimSP calculations reveal that for the tungsten implantation fluence used, on average each D atom is recoiled once and hence mobile deuterium should be present simultaneously while displacing tungsten atoms. Nuclear reaction analysis after the tungsten implantation shows that no deuterium is lost from the sample and the depth profile is unchanged. However, deuterium must have been de-trapped and is effectively re-trapped again because temperature programmed desorption spectroscopy (TPD) reveals that deuterium is redistributed from the low temperature de-trapping peak to the high temperature de-trapping peak. Rate equation modelling can describe the measured deuterium desorption with the same de-trapping energies as for the initial material but with increased trap densities only. Decorating the samples after the additional tungsten ion implantation again with a low energy deuterium plasma shows increased deuterium retention beyond the saturation value that is known for initially deuterium free, displacement-damaged tungsten by nearly a factor of two. Both observations together indicate that deuterium is stabilizing the defects created within the collision cascade.

Keywords: defect stabilisation, deuterium retention, self-damaged tungsten, Displacement damage, Ion radiation effects, Nuclear Reaction Analysis, temperature programmed desorption

1. Introduction

In order to achieve tritium self-sufficiency in a future fusion reactor, the limitation in terms of tritium uptake needs to be very stringent [1]. Among many other favourable properties intrinsically low fuel retention makes tungsten, therefore, one material of choice as plasma-facing material. However, during plasma operation defects in the tungsten lattice will evolve that will trap hydrogen isotopes. While for present day experiments this increased fuel retention is only limited to the near surface it will take place throughout the whole bulk in future nuclear devices as a consequence of the 14 MeV neutron irradiation. High energy ion implantation is often used as a surrogate to study the effect of displacement damage on fuel retention [2,3,4,5]. Understanding hydrogen isotopes uptake, transport, retention and release in such displacement damaged tungsten is necessary to extrapolate to reactor conditions. Experiments with fission-neutron-irradiated samples as well as MeV-energy ion-implanted samples showed that hydrogen isotope retention can reach values of the order of 1 at.% due to the displacement damage [4,6]. However, nearly all these experiments were done sequentially: First, damage was produced and only then transport and retention of deuterium in this material was studied by exposing it to hydrogen plasmas, ions or atom beams. In order to extrapolate to reactor conditions experiments are lacking where displacement damage is created simultaneously under the presence of hydrogen. Theoretical work by Kato et al. [7] as well as Middleburg [8] showed that hydrogen can stabilize vacancies and lower the formation threshold for vacancy formation and hence it is expected and often speculated that defect densities and as a consequence hydrogen isotope retention increases for simultaneous exposures. First beam experiments where displacement damage was created with MeV tungsten ion implantation while simultaneously dosing the samples with atomic deuterium revealed that even the presence of very small amounts of deuterium in the bulk can increase defect density and hence retention noticeably [9,10].

Here a different approach is presented that allows to study the influence of hydrogen isotopes on damage creation: by implanting 20 MeV tungsten into already displacement-damaged and deuterium containing tungsten. The idea behind it is that within the collision cascade not only tungsten atoms are displaced but also trapped deuterium is de-trapped and hence displacement damage takes place simultaneously under the presence of deuterium. In the first part of this manuscript the experimental procedure is outlined. Afterwards calculations about the expected amount of de-trapped deuterium are presented. In the following the measured total amounts of deuterium and the depth distributions are presented and discussed as obtained with nuclear reaction analysis (NRA) and temperature programmed desorption (TPD). Finally, rate equation modelling is presented to derive the de-trapping energies and describe the observations and discuss the results.

2. Experiment

Hot-rolled tungsten specimens were used in this study, 12×15×0.8 mm^3 in size. All samples were taken from the same manufacturing batch produced by Plansee AG (Austria) with a purity of 99.97 wt.%. [11]. The surfaces were mechanically polished down to 5 µm grit and subsequently electro-polished in 1.5 % NaOH solution to a mirror-like finish [12]. As the aim of this study was to investigate the effects of the MeV ion implantation within the ion range of about 2 µm samples were heat treated to reduce the intrinsic defect density and hence retention in the bulk. Specimens were heated at 2000 K for 2 min by electron bombardment in vacuum at a pressure below 10^{-8} Pa. Afterwards the material exhibits grains with a size distribution ranging from 10 µm to 50 µm as observed by confocal microscopy [13] and the initial dislocation density of $2×10^{12}$ m/m^3 is reduced by two orders of magnitude compared to the as-delivered state [14].

Displacement damage was created by tungsten self-implantation with 20 MeV W^{6+} ions at the TOF beamline of the IPP tandem accelerator laboratory at room temperature. Details of the setup and the procedure can be found in [13]. The 'quick calculation of damage' option in the Monte-Carlo-based code SRIM-2008.04 (Stopping and Range of Ions in Matter) [15] was used to calculate the damage profile as well as the damage dose in the same way as described in [13]. As this calculation option is based on the modified Kinchin Pease formalism a subscript 'KP' will be used in the following when stating the calculated damage dose in displacements per atom dpa_{KP}. A value for E_d of 90 eV was used as recommended by the American Society for Testing and Materials [16]. For 20 MeV W the calculated damage profile shows a maximum around 1.4 µm and extends up 2.3 µm as can be seen in figure 1. Deuterium retention is known to saturate at large damage doses [4 and references therein] and the aim of this study was to work with samples damaged to this level so that further damaging conducted later on would not increase deuterium retention. As in most of the articles in literature the actual input parameters used to derive the stated dpa values are missing a preceding study was conducted to measure the actual value were saturation sets in for the experimental parameters used in this study. Saturation was observed above 7.87×10^{17} W/m^2 which converts to a calculated damage dose at the peak maximum of 0.23 dpa_{KP} [17]. For the present study this tungsten fluence was chosen. Homogeneous implantation was obtained by scanning the beam over other the whole sample area. The time needed to acquire the desired fluence was 50 min and hence the average damage rate was 8×10^{-5} dpa/s.

Defects were decorated with deuterium by exposing them to a well characterized low-temperature electron-cyclotron-resonance deuterium plasma [18]. To minimize the possible production of additional trapping sites during deuterium loading and to decorate only the existing defects plasma exposure was performed with floating target holder. At a D_2 background pressure of 1.0 Pa this results in an ion energy below 15 eV. Because the ion flux consists mainly of D_3^+ ions (94 %) with minor contributions of D_2^+ (3 %) and D^+ (3 %) we refer to this setting as

<5 eV/D. For this condition the resulting D flux in the form of ions is 5.6×10^{19} D/m^{2}s. Five samples were loaded at the same time for 72 h which corresponds to a fluence of 1.5×10^{25} D/m^2. Each sample was tightly screwed at the four corners to a tungsten coated copper target holder with molybdenum screws. A sample temperature of 370 K was chosen small enough to avoid any defect annealing during D loading yet large enough to allow for D diffusion into the depth. The temperature was maintained by a liquid heating circuit connected to thermostats operated with silicon oil at 373 K. A thermocouple pressed against the back of the target holder and an IR camera was used to monitor the temperature evolution as well as the lateral homogeneity during the experiments. The IR camera was calibrated directly before plasma operation using the thermostat at the desired temperature. As it is essential in this study that not only the applied tungsten fluence is high enough to reach the level saturation of displacement damage but also that the created damage zone is completely filled one sample was decorated for a second time for another 72 h. The deuterium depth profiles for that sample is shown in figure 1 (2nd decoration) together with the one for a sample that saw deuterium plasma only once (1st decoration). In both cases deuterium has diffused down to two micrometer depth and the maximum concentration is 1.7 at-%. The difference in the depth profiles are marginal. Hence, one can conclude that the damage zone for all samples is completely filled after 72 h.

Deuterium depth profiles were analysed ex-situ with the D(^{3}He,p)α nuclear reaction with eight different ^{3}He energies ranging from 500 keV to 4.5 MeV to probe a sample depth of up to 7.4 µm. The D concentration within the near-surface layer at depths of up to about 0.3 µm was determined with ^{3}He energies of 500 keV, 690 keV and 800 KeV by analyzing the emitted α particles with a surface barrier detector at the laboratory scattering angle of 102°. A rectangular slit in front of the detector reduces the solid angle to 9.16 msr but increases resolution. For determining the D concentration at larger depths, the high energy protons were analyzed using a thick, large angle PIPS (Passivated Implanted Planar Silicon) detector at a scattering angle of

135°. A nominal pre-set charge of 10 µC was accumulated for each energy. Backscattered ^{3}He particles were detected with another PIPS detector positioned at 165° in Cornell geometry to

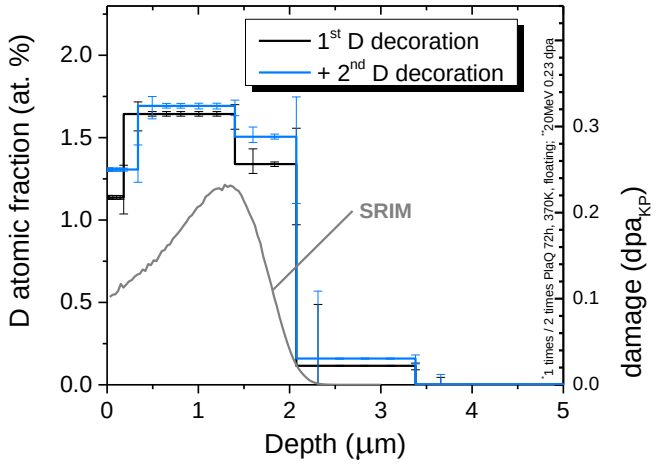

Figure 1: Deuterium depth profiles for two self-damaged tungsten samples decorated once (1st D decoration) and twice (+ 2nd D decoration) with 1.5×10^{25} D/m^2. The calculated damage profile for the applied W fluence of 1.87×10^{17} W/m^2 is shown in addition (grey line, right scale).

determine the actual accumulated charge for each individual energy. SIMNRA 6.06 was used to simulate the RBS spectra with SRIM stopping powers [15]. Details of the setup can be found in [13] and [19]. NRADC [20] and SIMNRA [21] were used to deconvolute the NRA spectra measured at different ^{3}He ion energies. As input data for NRADC all α and proton spectra measured at the different energies were analyzed simultaneously. Details about the data evaluation using NRADC can be found in Ref. [21]. The cross section published by Wielunska et al. [22] and Besenbacher and Möller [23] were used. The total amount of D retention was finally determined by integrating the D profile over the measured depth. To check the performance of the detectors and to minimize the scatter in absolute D areal densities in our measurements a gold coated, amorphous, deuterated carbon thin film calibration sample (*a*-C:D) of known D content

was measured for each energy in addition. The accuracy of the beam current measurement (typically 3-5 %) together with the counting statistics of about 1 % (counts depending on D content and energy) assures that the reproducibility of our measurements stays within 5 %. The absolute accuracy is dominated by the accuracy of the cross section which is stated as 5 %, too [23]. After the NRA measurement the retained D amount of the specimens was measured by temperature programmed desorption (TPD) in the quartz tube of the TESS device. A basic description of TESS is given in [24]. The temperature response of the samples to the linear oven temperature ramp was calibrated in independent experiments by a thermocouple spot-welded to a tungsten sample of identical size and surface finish. The samples were heated up to a sample temperature of 1010 K with an oven heating ramp of 3 K/min. This maximum temperature of 1010 K is high enough to ensure desorption of all retained D from the samples. The desorbed gases were measured with a quadrupole mass spectrometer (Pfeiffer/Inficon DMM 422). The secondary electron multiplier of the QMS was operated in single ion counting mode to minimize the background noise and to be able to apply Poisson statistics for determining the accuracy. Selected masses between 2 and 44 amu/q were recorded as a function of time (so called multiple ion detection mode of the QMS). The following 15 masses were recorded: 1, 2, 3, 4, 12, 14, 16, 17, 18, 19, 20, 28, 32, 40, and 44 amu/q. Release was dominated by mass channel 4 and 1. Mass channels above 4 showed no significant release of deuterium containing species other than HD and D_2. Background contributions were determined in a preceding and a consecutive temperature ramp without a sample or an outgassed sample in the heating zone, respectively. Measurements showed only negligible contributions in mass channel 4 and contributions on the percentage range for mass channel 3 which was subtracted in the latter case. For the quantitative analysis the QMS signal for D_2 was calibrated after each temperature ramp with a Laco leak bottle with a flow of 2.48×10^{19} D_2/s and a stated accuracy of 4.6 %. The calibration factor for HD was experimentally determined by flowing D_2 and HD gas through an orifice of know size from a calibrated volume. Based on the pressure recording of a spinning rotor gauge the calibration factor in QMS counts

per molecule for HD was 66 % of the one derived for D_2. Contribution of HD on the total D desorption was less than 2.4%. The reproducibility of the total signal heights of 3 % was derived by consecutive calibration measurements and is governed by the stability of the detector. The accuracy for the absolute amount for D is hence determined by the stated accuracy of the leak valve for the measurement shown here.

2. Results and discussion

3.1 Calculating deuterium de-trapping

The Monte-Carlo-based code SDTrimSP 5.07 (Static-Dynamic TRansport of Ions in Matter Sequential and Parallel processing) [25] was used to simulate the depth distribution of deuterium recoils generated during the implantation of tungsten into the deuterium containing tungsten. SDTrim.SP is typically used to describe physical sputtering of target atoms from the near surface. Recently Ziegler-Biersack stopping powers were implemented to be able to describe also displacement damage in the same way as SRIM [15] does. The dominant parameter in this case is the energy E_{dis} that is necessary to displace a tungsten atom from its lattice site and produce a stable Frenkel pair. In order to derive a value for the number of deuterium atoms that get displaced an adequate energy has to be chosen. Typical thermal de-trapping energies of deuterium from defects in tungsten as derived from rate equation modelling range between 0.8 eV and 2 eV [26].

Here we assume that the kinetic energy a tungsten atom has to transfer to a deuterium atom in order to de-trap it from its defect site is the same as this thermal de-trapping energy. For simplicity an average value of 1 eV was assumed for the calculation. Figure 2 shows the depth profile of the number of de-trapped deuterium atoms normalized to the initially retained deuterium for a tungsten sample containing 2 at-% of deuterium for the given tungsten fluence of

7.87×10^{17} W^{6+}/m^2 and energy of 20 MeV. Once can see that the fraction of de-trapped deuterium atoms varies by a factor of two between the surface and the peak maximum located around 1.5 µm. In the damage peak maximum on average every D atoms is replace once during the 50 minutes tungsten implantation. Hence, one would expect that mobile deuterium should be

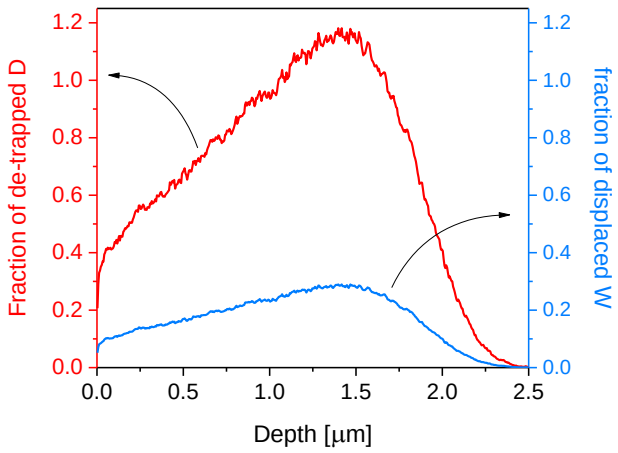

Figure 2: Dynamic SDTrimSP calculation of the number of de-trapped deuterium atoms normalized to the initially retained deuterium atomic fraction of 2% and the number of displaced W atoms normalized to the W bulk density as function of depth. Tungsten implantation fluence and energy are 7.87×10^{17} W^{6+}/m^2 and 20 MeV, respectively. Deuterium de-trapping and W displacement energies are 1.0 eV and 90 eV, respectively.

present simultaneously while the tungsten atoms are displaced. The number of calculated displaced tungsten atoms is also shown (right scale). However, care must be taken when comparing the number of displaced tungsten atoms with the number of de-trapped deuterium atoms. In the present case a displacement energy of 90 eV was used for tungsten as recommended by the American Society for Testing and Materials in order to compare with existing neutron irradiation results [16]. However, it is known that actual displacement energies are substantially lower and depend on crystal orientation [27]. If a value of 40 eV would have been used the

calculated displacement damage would be a factor of 2.2 higher. Hence, the ratio between de-trapped deuterium atoms per displaced tungsten atoms would not be four but only two. Given the uncertainties about the actual displacement energies in both calculations all what we want to conclude here is that the number of de-trapped deuterium atoms and displaced tungsten atoms is within the same order of magnitude.

3.2 W implantation into self-damaged, D-containing tungsten

Figure 3a shows again the deuterium depth profile from figure 1 for a sample implanted with 20 MeV tungsten to a fluence of 7.87×10^{17} W/m^2 and then decorated with deuterium for 72 h afterwards (1st D decoration, black line). In addition, the depth profile for a sample implanted with 20 MeV tungsten to a fluence of 7.87×10^{17} W/m^2 for another time is shown (+ 2nd W implantation, blue line). Both samples show the identical flat depth profile, ranging down to 2 µm. No deuterium is lost, neither to the surface, nor to the bulk. While the latter is expected as there is no creation of traps in the bulk where deuterium could be retained one could have expected that some deuterium is lost to the surface. Obviously re-trapping of the deuterium that is released by the tungsten bombardment is very effective. Figure 3b shows the corresponding deuterium effusion fluxes of these two samples as function of time during the heating ramp in the same colors together with the sample temperature (green line, right axis). For the sample decorated once desorption of deuterium starts around 345 K and ends at around 980K. It shows two distinct maxima, one at 560 K and one at 780 K. While the depth profile for the sample implanted additionally with tungsten did not show any difference to the initial one, the deuterium desorption is substantially altered by the tungsten implantation: The first desorption peak is significantly depleted while the second one is increased. Significant deuterium desorption does not start before 500 K and the peak maximum is shifted to 635 K. The position of the second

240 desorption maximum is not altered as well as the maximum temperature up to which desorption
241 takes place is also unchanged.

a)

b)

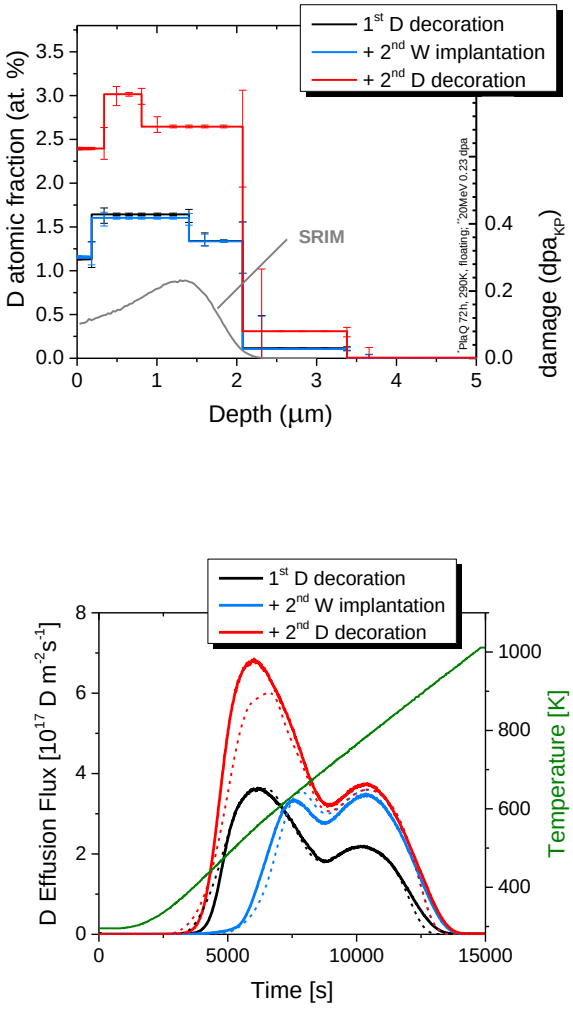

Figure 3: Deuterium depth profiles (a) and deuterium effusion flux as function of time (b) for self-damaged tungsten samples decorated once (1st D decoration, black line) and implanted again with 20 MeV tungsten to a fluence of 1.87×10^{17} W/m^2 (+2nd W implantation, blue line). In red, the data for a sample decorated with deuterium for 72 h again after the second W implantation is shown. In (a) the calculated W displacement damage is plotted in addition (grey line, right scale) and in (b) the sample temperature (right scale) and the results from the rate equation modelling are shown (dashed lines).

3.3 Reloading of self-damaged, D containing tungsten

In order to find out if additional trapping sites were created during the tungsten implantation of the deuterium containing, self-damaged tungsten one sample was exposed again to the low-temperature deuterium plasma. Exposure conditions were the same as for the initial defect decoration with floating target, exposed for 72 h at a temperature of 370 K. As shown before, no change in the deuterium depth profile was observed when only doubling the D fluence as for the given energy, flux and temperature no additional defects are observed. However for this sample that saw the additional W implantation there is a dramatic change in the depth profile as well as the desorption spectrum: While the overall shape of both stayed the same, the absolute intensities nearly doubled. The depth profile for this sample shows now a peak concentration of 3 at.%. The desorption spectrum indicates that the tungsten implantation did no create defects with substantially different de-trapping energies but it seems that only the total densities of defects were increased. This is at first glance surprising as the sample that also saw the additional W implantation but no additional D decoration afterwards did show a substantially altered desorption spectrum. Therefore rate equation modelling was conducted to describe the observed phenomena.

3.4 Rate equation modelling

The rate equation code TESSIM-X was used to describe the observed phenomena [28,29]. TESSIM-X can simulate the transport and interaction of different hydrogen isotopes in tungsten based on the physical model of de-trapping, diffusion and trapping. Two different physical models can be used: The first is the so-called classical model which is characterized by the assumption that each trap can be occupied by only one hydrogen atom and each trap type has a fixed de-trapping energy. The second option is the so-called fill-level model, inspired by DFT calculations [30 and references therein], which assumes that each trap can be filled with several hydrogen atoms simultaneously. Here the latter was used because the de-trapping energies necessary to describe thermal desorption were taken from an independent study were deuterium-hydrogen isotope exchange in self-damaged tungsten could be described quantitatively [31]. One trap with five fill levels with de-trapping energies of 1.18, 1.32, 1.46, 1.7, 1.84 eV, and a pre-factor of 10^{13} Hz were found to describe the thermal effusion spectra. The diffusion coefficient

for protium $D_0 = 1.58\times10^{-7}$ m^2/s was divided by $\sqrt{2}$ to account for the higher mass of deuterium and a migration energy of 0.25 eV was used [32]. The trap profile were derived from the measured deuterium depth profiles and a trap density of 0.32 at. %, which corresponds approximately to one fifth of the measured D concentration, is chosen. The following sequence was modelled with TESSIM-X: First, a 100 µm thick tungsten slab with a 2.2 µm thick top layer was filled with D with the given flux and fluence. The deuterium flux distribution was taken from [18]. It was assumed that D_2^+ and D_3^+ ions can be described as D^+ ions with twice or three times the flux but only half or one third of the energy, respectively. The corresponding D implantation profile was approximated by truncated Gaussians fits to implantation profiles calculated with SDTrimSP. After the given D fluence the sample was cooled to room temperature and after a waiting time of 2000 s the temperature of the sample was ramped up according to the measured temperature. Figure 3b shows the obtained calculated deuterium desorption spectrum as a dashed black line. The description of the desorption is excellent. The peak positions as well as their width and height are very well reproduced. In order to describe the desorption spectrum of the sample that was additionally implanted with tungsten correctly, two effects had to be considered. First the creation of additional traps due to the displacement damage caused by 20 MeV W^{6+} ions and second the kinetic de-trapping of trapped D by collisions with energetic atoms in the tungsten ion collision cascade.

The effect of additional traps was approximated by increasing the trap density while leaving the de-trapping energies as well as the depth distribution of the traps unchanged.

The trap density was assumed to increase in the same way with irradiated tungsten fluence as observed in a preceding study with deuterium-free tungsten where it saturated at a fluence of 7.87×10^{17} W^{6+}/m^2 [17]. Based on these data the additional W self-damaging was simulated by an exponentially saturating increase of the trap density up to 1.8 times of the original trap density during the W implantation.

The kinetic de-trapping of trapped D by energetic W was investigated with SDTrimSP in which the implantation of 20 MeV W into D containing W was simulated. The D concentration was varied between 1 to 5 at. % and the displacement energy of D was altered within the range of the de-trapping energies of the fill-levels from 0.5 to 2.0 eV. For each SDTrimSP simulation the depth profile of the D recoils was extracted and normalized by the respective D concentration. The so obtained kinetic de-trapping profiles of D by W were fitted by an asymmetric Gaussian which allows the parameterization of the profiles with respect to the individual de-trapping energies of the fill-levels used in the TESSIM-X simulation. After the initial loading of the

sample with D and the subsequent waiting time of 2000 s the W self-damaging is simulated with a W flux of 2.62×10^{14} 1/m^{2}s for 3000 s at a temperature of 300 K. During this period the trap density was increased and the kinetic de-trapping of trapped D took place as described above. Once the W implantation was finished an additional waiting time of 2000 s was simulated before the temperature was increased. It can be seen in figure 3b that the simulation reproduces the measured desorption spectrum very well. The depletion of the first desorption peak as well as the increase of the second one are in good agreement with the experimental observation. It is important to stress that the shift in the release temperature is due to the increased trap density and not due to a different de-trapping-energy as would be typically concluded in the literature.

The D reloading of the additionally self-damaged, D-containing tungsten sample was simulated as above but with an additional D loading sequence following the additional W implantation phase after a waiting time of 2000 s. Once the second D loading was finished and 2000 s of waiting time passed, the temperature of the sample was ramped up. The simulated desorption spectrum is compared to the experimental data in figure 3b. Also in this case the agreement between simulation and experiment is very good. Especially the increase of the first desorption peak while the second one remains nearly unchanged is reproduced by the simulation.

Figure 4 shows the calculated deuterium solute concentration as a function of depth for different times during the 20 MeV tungsten implantation into the self-damaged tungsten containing 1.7 at.% D. Similarly as the W damage profile the solute concentration extends to 2.3 µm and shows a maximum at a depth of 1.4 µm. At the very beginning of the tungsten implantation the solute concentration builds up quickly and reaches a value of 5×10^{-8} at.%. It is worth mentioning that this solute concentration is within the same order of magnitude as calculated for the existing experiments with two beams [9,10]. Therefore it is important to note that the effect of de-trapping of retained deuterium within the collision cascade needs to be taken into account also when modelling such multi beam exposures when the amount of deuterium builds up over time. For the present experiment the solute concentration drops for two reasons as implantation continues. First, the number of newly created traps increases and with increasing amount of traps the solute concentration drops. Second, the average fill level drops and hence the effective de-trapping energy increases with evolving time.

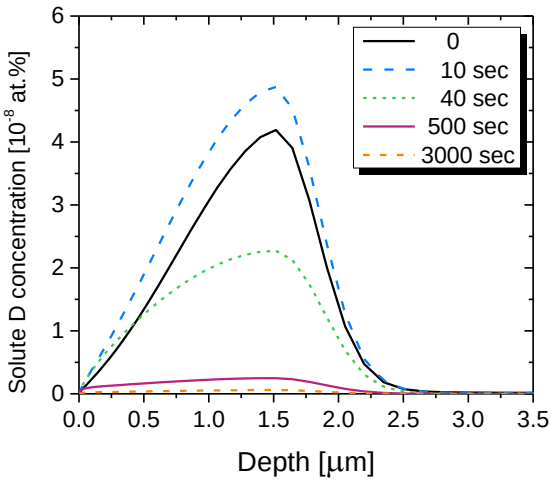

Figure 4: Calculated deuterium solute concentration as a function of depth for different times during the 20 MeV tungsten implantation into the self-damaged tungsten containing 1.7 at.% D.

In summary, both experiments can be explained by an increase in trap densities. The maximum deuterium concentration is nearly a factor of two higher as ever observed for self-damaged but initially deuterium-free tungsten. This clearly indicates that deuterium can stabilize defects. At present experiments are under way to study the effect of damage stabilization as a function of the initially retained deuterium amount. Next, it will be investigated up to which temperature this increased retention prevails.

4. Conclusions

An alternative experimental approach to study the influence of deuterium on displacement damage in tungsten is presented: In contrast to evolved dual beam experiments were damage is created within the displacement cascade of MeV energy ions while dosing the sample with deuterium atoms [9] or low energy ions [33] at the same time here only one beam is necessary. Deuterium containing self-damaged tungsten is used as starting material and bombarded with MeV energy ions. Due to the de-trapping of the retained deuterium from the traps within the collision cascade deuterium gets re-trapped and hence the newly created displacement damage also takes place simultaneously with mobile deuterium being present. Monte-Carlo based simulations of the collision process show that for the parameters used on average every retained deuterium atom is de-trapped once. Experiments reveal that no deuterium is lost from the self-

damaged tungsten sample when it is bombarded with 20 MeV tungsten again. However, deuterium is de-trapped and effectively re-trapped again. Temperature programmed desorption spectroscopy shows that deuterium is redistributed from the low temperature de-trapping peak to the high temperature de-trapping peak. Rate equation modelling can describe the change in deuterium desorption by assuming only an increase in trap density without changing the de-trapping energies compared to the initial material. Decorating the samples after the second tungsten implantation again with a low-energy deuterium plasma bolsters this assumption as deuterium retention increases beyond the value that is known for initially deuterium free, displacement-damaged tungsten by nearly a factor of two. Both experimental observations show that deuterium is stabilizing the defects created within the collision cascade. As a consequence this substantially increased retention must be considered when extrapolating to reactor conditions based on sequential experiments where displacement damage was created before deuterium exposure. The same effect of increased retention is not only expected for laboratory experiments but also for rector operation were displacement damage in tungsten will take place in the bulk of the material by fusion neutrons while deuterium and tritium will be present in the material from the plasma implantation.

Acknowledgments

The authors thank T. Dürbeck, J. Dorner and M. Fusseder, for their technical support. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No. 633053. Work was performed under EUROfusion WP PFC. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

387

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Note: *Unfortunately, the information given in the last paragraph of this article is not correct. The contribution of the molecular ions to the total ion flux for standard conditions is:* D_3^+ *= 94%,* D_2^+ *= 3%, and* D^+ *= 3%. Correspondingly, the contributions to the total deuteron flux in form of ions are: 97%, 2%, and 1% as expressed correctly in figures 5 and 6 in this reference.*
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