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Positron annihilation lifetime measurement and X-ray analysis on 120 MeV Au^{+7} irradiated polycrystalline tungsten

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HIGHLIGHTS

- Simulation of neutron damage in W using 120 MeV Au^{+7} ion irradiation has been employed.
- The induction of damages is attributed to high electronic energy losses.
- Positron annihilation lifetime measurements confirm induction of bulk damages.
- The physical properties of damaged tungsten have been investigated.

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ABSTRACT

In order to simulate radiation damages in tungsten, potential plasma facing materials in future fusion reactors, surrogate approach of heavy ion irradiation on polycrystalline tungsten is employed. Tungsten specimen is irradiated with gold heavy ions of energy 120 MeV at different fluences. Positron annihilation lifetime measurements are carried out on pristine and ion beam irradiated tungsten specimens. The variation in positron annihilation lifetime in ion irradiated specimens confirms evolution of vacancy clusters under heavy ion irradiation. The pristine and irradiated tungsten specimens have also been characterized for their microstructural, structural, electrical, thermal, and mechanical properties. X-ray diffractograms of irradiated tungsten specimens show structural integrity of polycrystalline tungsten even after irradiation. Nevertheless, the increase in microstrain, electrical resistivity and microhardness on irradiation indicates creation of lattice damages inside polycrystalline tungsten specimen. On the other hand, the thermal diffusivity has not change much on heavy ion irradiation. The induction of damages in metallic tungsten is mainly attributed to high electronic energy loss, which is 40 keV/nm in present case as obtained from SRIM program. Although, concomitant effect of nuclear losses on damage creation cannot be ignored. It is believed that the energy received by the electronic system is being transferred to the atomic system by electron-phonon coupling. Eventually, elastic nuclear collisions and the transfer of energy from electronic to atomic system via inelastic collision is leading to significant defect generation in tungsten lattice.

1. Introduction

In future fusion reactors, a large number of high energy (14.1 MeV) neutrons will be generated by deuterium–tritium fusion reactions. These neutrons will irradiate the reactor wall and in turn the physical properties of reactor wall material will get modified [1,2]. Tungsten is considered as the most likely material to be used in divertor section of ITER-like Tokamak, because of its attractive physical properties e.g. it can withstand high temperatures, low activation, does not transmute into long-lived radioactive isotopes and has a low erosion rate [3]. All these properties make tungsten prime material for fabricating plasma facing components for fusion applications. However, in fusion reactor, the high

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flux of energetic neutrons (14.1 MeV) will create a large number of radiation damages in tungsten and it will lead to change in thermo-mechanical properties of tungsten [4,5].

Interaction of neutron with plasma facing material induces both elastic and inelastic nuclear reactions. Inelastic interaction of neutrons with solid activates transmutation process inside solid. During elastic interaction, an incident neutron transfers energy to a lattice atom, forming a primary knock-on atom (PKA). PKA dislodges neighbouring atoms, which results in an atomic displacement cascade and formation of point defects and defect clusters of vacancies and interstitial atoms inside the solid. The induction of damages modifies thermo-mechanical properties of tungsten and, thus, it is imperative to understand the effect of radiation induced damage, on thermo-mechanical properties of tungsten.

Neutron source of energy 14.1 MeV and required fluence is not yet available and existing neutron irradiation facilities are being used. Specimens irradiated with neutrons get radioactive in nature and needs dedicated laboratory set up to investigate the radiation modified physical properties [6], and it limits the number and types of test that can be performed on neutron irradiated specimens. Alternatively, high energy (nearly 1 MeV/amu) heavy ion beams can be employed to simulate similar kind of radiation damages inside plasma facing materials; so that damage induced modification in their properties can be studied [7].

During ion solid interactions, at low incident ion energy (up to 100 keV), ions transfer their energy mainly via elastic nuclear stopping (S_n), which leads to damage creation in solids. The damage creation in tungsten due to nuclear stopping is limited to top few nanometres only due to high density (19.3 g/cm^3) of tungsten. At high energies, ions can penetrate up to few micron deep in bulk and can lead to bulk damage creation via elastic and inelastic collisions [8,9].

However, neutron-solid and ion–solid interactions are different in nature. Since ions are electrically charged, their penetration inside solid is limited and depends on incident ion energy and mass. On the other hand, neutron (electrically neutral in nature) penetrates deep inside the solid and results in bulk damages. Oya et al. have reported different thermal desorption spectra for neutron and ion irradiated W specimens [10]. The additional desorption stage for neutron irradiated W specimen, had been attributed to deeper deuterium trapping in irradiated W specimens owing to bulk damages. In case ion irradiated W specimens, damages are limited to a depth of less than 1 μm and hence shallow trapping of deuterium, which gets reflected in desorption spectra [10]. Furthermore, neutron participates in nuclear activity, while ion–solid interaction is electrostatic in nature. Nevertheless, the damage creation due to elastic interaction of neutrons with solid is nearly similar to damage creation by ions via elastic and inelastic interactions, therefore, ions are being widely employed to simulate radiation damage inside solids.

World wide efforts are being made to correlate heavy ion induced damages to neutron induced damages. Kirk et al. [11] attempted to simulate neutron induced damages by employing Kr ions irradiation in Mo and further research is in progress to establish correlation between two methods. Armstrong et al. used 2 MeV tungsten ion beam to simulate neutron damage in tungsten alloy, subsequently, damage induced change in mechanical properties had been investigated [5,12]. Takagi et al. employed 1.5 and 5 MeV self-ion irradiation on tungsten to study deuterium trapping in damaged tungsten [13]. Shimada et al. have performed series of extensive studies on fuel retention, their depth profiling and fuel desorption in damaged tungsten [14–16]. Hatano et al. have also carried out deuterium retention studies on the neutron and ion irradiated tungsten specimens [17]. Khripunov et al. utilized high energy light ions helium and carbon, to produce displacement damage in tungsten [18]. Recently, Ogorodnikova et al. have used 20 MeV self-ion irradiation in tungsten to perform study on accumulation and recovery of radiation defects in tungsten [19]. They have also performed TEM and fuel retention study in self-ion damaged W [20,21].

At high energies, incident energetic ions deposit their energy in electronic system of target atoms and the deposited energy gets transferred to atomic system of target atoms through electron–electron and electron-phonon coupling. The electron-phonon coupling strength plays important role in defect generation in solids. Metals such as Ti and Fe exhibit strong electron-phonon coupling and electronic stopping lead to defect creation in these materials. Increase in defect-production efficiency in metal system e.g. Bi, Ti, and Fe is well evidenced [22]. The electron-phonon coupling strength of materials defined as $g = D_e C_e/\lambda^2$ (*De*: electronic diffusivity, *Ce*: electronic specific heat and λ is electron mean free path), depends on electronic parameters [23]. Daraszewicz et al. have estimated the effective electron-phonon coupling constant (g) for tungsten from *ab initio* calculations and high-resolution pump-probe reflectivity measurements and it is found to be $1.4{*}10^{17}$ Wm^{-3} K^{-1} [24]. The significant value of g indicates efficient energy transfer from electronic to atomic system in case of tungsten.

It has been reported that, in conductors, the energy stored into the electronic excitation can affect materials properties depending upon the value of electronic stopping power (S_e) of the ion. If S_e value, which depends on the material, exceeds a certain threshold (~10–40 keV/nm) then electronic stopping can also contribute to additional disorders in the material i.e. atomic displacements can occur due to electronic energy losses as well under certain conditions e.g. in case of Ti metal [25], the S_e threshold for defect creation is reported to be 11–14 keV/nm [26,27]. Electronic stopping power (S_e) of 120 MeV gold ions in tungsten is evaluated from SRIM/TRIM simulation software [28]. The obtained energy loss spectrum of gold ions in tungsten is shown in Fig. 1, and it shows electronic energy loss of ~40 keV/nm for 120 MeV gold ions. Therefore, in the present work, 120 MeV gold ions have been chosen to get high value of S_e~ 40 keV/nm, so that electronic stopping can contribute significantly in bulk damage creation in tungsten. At the same time gold and tungsten have nearly similar atomic mass/size and no known phases of gold and tungsten exist, therefore, gold implantation in tungsten will not give any modification in properties due

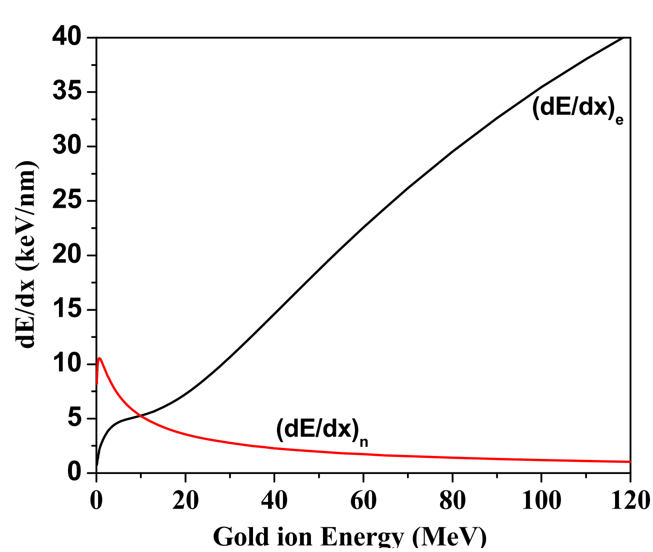

Fig. 1. Energy loss spectra of gold ions in tungsten obtained from SRIM software.