Ion implantation of helium and hydrogen in boron coatings

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Abstract. The work presents the calculated mean free paths of hydrogen, deuterium and helium ions in boron-carbon and boron-titanium films of various configurations. Has been rated impact of these coatings at various film thicknesses for ion capture in tungsten. The calculations were carried out using the software package SRIM-2012, for each mileage value was calculated by modeling of 10,000 cascades.

1. Introduction

One of the critical important problem in thermonuclear research is the protection of plasma-facing components from surface radiation damage. The first wall of the tokamak chambers must withstand loads of very high power (several MW/m²), high thermal stresses, and should not strongly pollute the plasma with impurities of elements with large atomic numbers [1, 2]. These impurities appear as a result of the interaction of the plasma with the first wall. In addition to radiation resistance, the capture and recirculation of hydrogen isotopes is also taken into account [3]. Similar requirements are also imposed on other reactor components that come into contact with plasma: limiters, plate targets in magnetic divertors, and antennas for auxiliary plasma heating.

The creation of materials that do not pollute the plasma is of fundamental importance to the physics of fusion. More suitable are surface-radiation-resistant materials with a low serial number: Be, Al, Ti, V and etc. as well as Li, B, C are also applies [4]. The compounds of these elements were investigated from the point of view of creating radiation-resistant coatings [5–8].

The harmful effects of heavy types of atomic nuclei appearing in the hydrogen plasma as impurities have already been noted in the early stages of thermonuclear research. The most dangerous phenomenon leading to plasma pollution is the cathodic sputtering of the wall material under the action of bombardment by flows of ions and atoms of deuterium and tritium, alpha particles and neutrons, as well as impurity ions and atoms.

For protection, the practice of boronization of the chamber walls is widely used [9]. The boron–carbon coatings obtained in this method reduce sputtering and affect the capture of hydrogen isotope ions by materials of the first wall and divertor. Nevertheless, in the process of work, they are quickly destroyed and lose their protective properties [10].

In this work it has been suggested that titanium boride-based coatings may have a longer life with protective properties similar to boron-carbon films. The resistance of titanium boride to ion sputtering...
was studied by us earlier in [11]. Also, the previously obtained results showed sufficient efficiency of using the DC-magnetron sputtering method of a composite cathode target to obtain coatings with the boron-titanium system [12].

2. Materials and methods

The boronization process is carried out in situ. The procedure for the deposition of boron – carbon films is constantly being improved; the difference in the methods used leads to different B/C ratios. The difference in the composition of coatings depending on the methods which are used in the synthesis plants, it is possible to trace in [13–15]. In this paper, we take the average values of the most common configurations of such films. The parameters of boron – titanium coatings correspond to a promising neutron absorbing titanium boride coating with a high boron content [12]. The elemental composition of the compounds is presented in Table 1. Coating No. 1–3 are B-C compounds with different B/C ratios; coatings No. 4–5 are B-Ti compounds with different B/Ti ratios. Pure tungsten is considered as a substrate as the main candidate of plasma-facing materials for structural elements.

| No. | B   | C   | H   | O   | Ti |
|-----|-----|-----|-----|-----|----|
| 1   | 41.6| 8.3 | 50  | –   | –  |
| 2   | 60.48| 27.11| 11  | –   | –  |
| 3   | 86  | 6   | 8   | –   | –  |
| 4   | 52  | 12.5| –   | 26.8| 8.7|
| 5   | 76  | 4   | –   | 4   | 14 |

Simulation of ion irradiation processes were carried out using the software package SRIM-2012, for each mileage value is calculated by modeling 10,000 cascades. The mean free paths of H\(^+\), D\(^+\), and He ions are calculated. The ion energy values characteristic of the fusion reaction were used. The energy of the isotopes of hydrogen is 14.8 MeV, helium is 3.25 MeV. The results obtained made it possible to evaluate the effect of coating parameters on the capture of H\(^+\), D\(^+\), and He\(^+\) ions in the tungsten.

3. Results and discussion

Coatings with high boron content are sufficiently transparent for the flow of high-energy ions of hydrogen and helium isotopes. This property helps to avoid intensive spraying of the coating. The performed model calculations confirmed this fact (Table 2).

| W   | 1     | 2     | 3     | 4     | 5     |
|-----|-------|-------|-------|-------|-------|
| H\(^+\)| 0     | 0     | 0     | 0     | 0     |
| D\(^+\)| 0     | 0     | 0     | 0     | 0     |
| He\(^+\)| 8×10\(^-4\) | 10\(^-4\) | 2×10\(^-4\) | 4×10\(^-3\) | 9×10\(^-4\) |

But at the same time, the passage of ions in the material leads to the appearance of cascades of collisions, leading to the redistribution of elements. In Figure 1a shows the distribution of boron-containing defects in coating 1 (thickness is 200 nm) and defects containing tungsten in the substrate. Defects in the coating formed at a depth of > 150 μm. The highest concentration of these defects is concentrated near the boundary with the substrate. A small amount of boron transferred in the substrate. In tungsten, a larger number of defects appear along the entire path of the passage of H\(^+\) ions. The main part of the displaced W atoms is concentrated at a depth of ~ 550 μm. The distribution of H\(^+\) ions is similar to the distribution of W atoms (Figure 1b).
Figure 1. The simulation results of irradiation by H\(^+\) ions of coating 1 on tungsten: (a) redistribution of B and W; (b) distribution of H\(^+\).

Figure 2. Difference in (a) H\(^+\) and D\(^+\) ions ranges (b) and He\(^+\) ions range in tungsten and in coatings 1–5.

Similar patterns are observed after irradiation by D\(^+\) and He\(^+\) ions also. The type of ion, composition and thickness of the coating mainly affect only the depth of concentration of ions implanted in tungsten.

Capture of hydrogen isotopes and helium of tungsten ions directly depends on the mean free path of the ion in the coating. The difference in the mean free path for hydrogen isotopes helium ions is shown in Figure 2. For all ions, the highest range is observed in coating with the lowest boron content (coating 1). In compounds B-C and B-Ti, the mean free paths are of the close order. It follows from the above that the amount of boron contained in the coating affects the mean free path of implantable ions. An increase in the amount of boron leads to a decrease in mileage in boron-carbon and boron-titanium coatings. In boron-titanium coatings, the range of ions is less than in boron-carbon coatings. The presence of hydrogen in the coating increases the range of ions.

Ions with a lower mass penetrate to a greater depth. The heaviest helium ions have an order of magnitude lower mean free path in coatings than hydrogen isotopes. The penetration depth of ions D\(^+\) is less than that of H\(^+\) ions by ~ 33%. 

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Titanium boride coatings affect the capture of hydrogen isotopes by tungsten to an equal extent with boron-carbon coatings (Figure 3). Complete absorption of H ions by a coating is possible at a thickness of 1200 μm, and D ions at a thickness of 800 μm. Compound B-C:H requires a thickness of 1.5 times greater for the complete absorption of implantable D ions and 1.8 times for H ions.

4. Conclusion
Studies have shown that titanium boride coatings have an effect on the capture of hydrogen and helium isotopes ions similar to boron-carbon coatings. Given the high stability of titanium boride to cathodic atomization, its thermal and corrosion resistance, such coatings can be used to protect plasma-facing materials.

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