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In situ silicon and lithium coating and its removal in the HL-1M tokamak

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Abstract

Siliconization and lithium coating of the wall in the HL-1M tokamak were performed by means of DC glow discharges with a mixture of SiH_4 and He and lithium evaporation in a He glow discharge, respectively. With the wall conditioning, impurities and radiation power losses are generally lower than those with boronization, and strong wall pumping and low hydrogen recycling occur in these tokamak discharges. The excellent wall conditions lead to great progresses in such experiments as the multi-shot pellet injection, LHCD and long pulse discharges. Removal of these coatings by DC glow discharges with H_2 and He was demonstrated.

Keywords: Hydrogen recycling; Impurities; Lithium coating; Siliconization

1. Introduction

The wall coating in fusion devices plays a key role in controlling plasma impurities and hydrogen recycling. Following carbonization and boronization, the wall coating with silicon or lithium containing materials has appeared in the recent years and displays a potential superiority. In TEXTOR [1] and FTU [2] better results were achieved with siliconization instead of boronization. An appropriate deposition method and its characteristic on lithium coating are being surveyed. The best plasma performance and highest value of $n_i T_i \tau_E$ were achieved with lithium pellet injection, but the effect lasts only one discharge in TFTR and DIII-D [3]. Wall conditioning with lithium evaporation was applied to JIPP T-IIU and leads to 20–50% reduction in oxygen and carbon impurities with less hydrogen recycling in ohmic and NBI discharges [4]. Among the in situ coating materials for plasma facing walls, lithium has the lowest atomic number and highest reactivity, so lithium coating may be developed to the best wall conditioning method. Now, the key question is how to prolong its effective service time.

The use of boronization in HL-1M plays an important role in the improvement of the operational process and plasma performance [5]. To fit special requirements for wall conditions in various tokamak experiments, we have employed siliconization and lithium coating techniques since 1994. In the paper, we present the siliconization and lithium coating experiments and their influences on tokamak plasmas in HL-1M. In addition, the removal of deteriorated or contaminated coatings is also reported.

2. Experiments

The siliconization in HL-1M is performed by a DC glow discharge with a mixture of (5–10)% SiH_4 + (95–90)% He. The thickness of silicon containing coating measured by Secondary Ion Mass Spectroscopy (SIMS) is about 100 nm. Major components in the coating are silicon, carbon and SiC by means of X-ray Photoelectron Spectroscopy (XPS) analysis. Irradiation experiments with 3 keV D^+ ions at temperatures from room temperature to 800°C have proved that the stability of the coating against D^+ chemical erosion is similar to SiC and superior to graphite.

Lithium is deposited on the metal walls and graphite limiters in HL-1M by means of plasma-assisted deposi-

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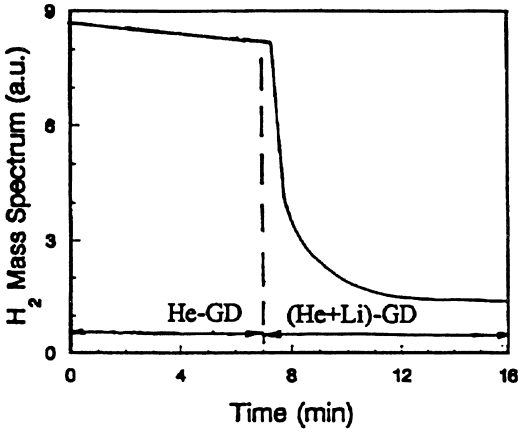

Fig. 1. Variation of the hydrogen partial pressure in the vacuum chamber during Li deposition.

tion. A few blocks of solid lithium (99.9% purity, about 2 g) are put in an oven under Ar gas flow to prevent the lithium surface from oxidation. The oven assembly is mounted on a long shaft which can be moved radially inwards and outwards. Ordinarily the oven is behind the limiters. During Li coating it is moved to the central part of the discharge chamber and lithium is heated up to 600°C with a resistively heated tungsten spiral wire, thus evaporated into a He glow discharge where it is ionized and finally deposited on the wall serving as the discharge cathode. The discharge pressure ($P_{He} + P_{Li}$) is 5×10^{-2} Pa and the current density equals 10–12 μA/cm^2 with 400–500 V anode voltage. The deposition run for about 10 min at room temperature. About 1 g lithium is deposited onto the wall. The average film thickness estimated from the deposited Li mass and wall areas (~13 m^2) is about 10 nm.

The frequent deposition of fresh silicon or lithium films is probably necessary, in particular after each exposure to air. A serious problem is associated with repetitive deposits, i.e., multiple, thick silicon or lithium layers tend to peal off (flaking). In addition, the electrically insulating silicon wall may influence tokamak discharge. Therefore, in situ removal of the thick, deteriorated or contaminated films is important. Lithium coating is removed easily by hydrogen glow discharge, while it is difficult to remove silicon containing coatings. After each experimental period (about three months) with siliconization, the silicon containing layer was removed by a DC glow discharge cleaning with a mixture of 30% He + 70% H_2. The discharge pressure is about 0.1 Pa and the anode voltage is 500–600 V. The removed effect was measured with visible and vacuum ultraviolet spectrometers. Si II and Si XII lines were reduced 3 and 4 times after 36 h and substantially disappeared after 45 h, respectively. HL-1M is ordinarily exposed to atmosphere about half a year for servicing or installing equipment when an experimental period ends. The initial stage of next experimental period would experience 1–2 weekly disruptive discharges if the layer were not removed, but this condition only lasts one day when the above removal method is applied.

3. Results and discussion

After siliconization and lithium coating the wall displays a strong pumping effect for hydrogen ions and atoms leading to very low neutral hydrogen recycling. To achieve the same plasma density, the quantity of feeding hydrogen after these wall conditionings is 4–5 times as large as that after boronization. The hydrogen component in the vacuum chamber declines sharply during lithium deposition (Fig. 1), which implies that there is very strong wall pumping for hydrogen ions and atoms. In He glow discharge cleaning the mean desorption rates of hydrogen from the siliconized or Li-coated wall are generally higher than those from the boronized wall (Fig. 2). We interpret this as an indication that the former two coatings contained more hydrogen, owing to a stronger absorption in tokamak discharges. This absorption has generally a high bond energy in contrast to physical absorption as these energetic H^+ or H^0 not only can be absorbed chemically at the surface but also can penetrate into its interior to result in this absorption. The energy (~400 eV) of the impacting species during He glow discharge cleaning is much higher than average particle energy (~50 eV) in the scrape-off layer during HL-1M tokamak discharges. Thus He can displace a larger amount of bonded hydrogen, which can locally recombine forming H_2 which is then released, than the tokamak plasma species. He itself will not form a chemical bond to the layer and

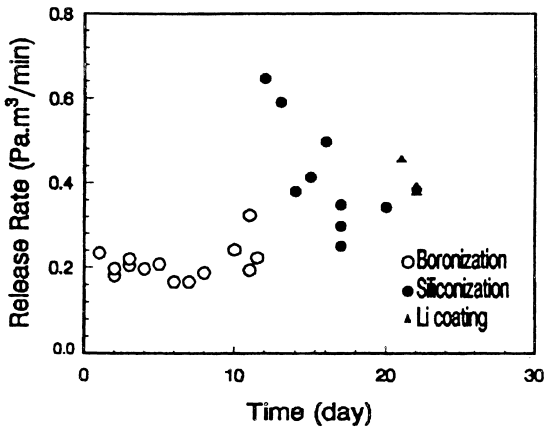

Fig. 2. Mean hydrogen release rates from the wall during each He glow discharge cleaning as a function of time and wall condition.

most of it will be released. This could explain why the layers absorb hydrogen during tokamak discharges and release it during He cleaning discharges. This is an important reason leading to the low hydrogen recycling.

Siliconization as well as boronization lead to an almost complete disappearance of metal impurities, but the carbon and oxygen intensities and the radiation power loss are further reduced with siliconized walls in contrast to boronization (Figs. 3 and 4). Particularly, the loop voltage (V_L) decreases to 0.2–0.5 V from more than 2 V and the core radiation power loss increases very slowly with shot numbers with siliconization, while the V_L changes from 1.5–2 V to about 1 V and the core radiation power loss rises rapidly with shot numbers with boronization. Lithium coating reduces the oxygen impurity to the lowest level, owing to the strong chemical reactivity of lithium with oxygen (Fig. 3). An important source of the carbon impurity is the chemical sputtering of graphite components by oxygen particles, so the carbon intensity is also lowered with the decrease of the oxygen impurity. Moreover, the sputtered lithium particles from the coating hardly harm the core plasma because of their low atomic number. Therefore, in contrast to boronization and siliconization, the core radiation power loss reduces to the lowest level with a fresh lithium coating under similar discharge parameters (Figs. 4 and 5), but the superiority lasts only several shots.

Siliconization significantly improves the performance of the plasma and leads to the important progresses of some tokamak experiments in HL-1M. Despite good results that have been obtained by boronization in the device, unstable wall conditions appear after several boronization cycles as the boronization material contains carbon and the coating is deposited at the room temperature [3]. As a result, the wall outgassing and impurity intensity rise sharply, leading to disruptive shots when pellets are injected in the pellet fueling experiment or the higher driving power (about 500 kW) is fed in the LHCD experiment. In addition, the plasma pulse length (t_P) only achieves 2.1 s and its reproducibility is poor in the long pulse discharge experiments with boronization. By means of siliconization, the wall conditions stay stable over a long period so that the wall outgassing and impurities are controlled effectively in the experiments. Almost no disruptive shots occur in the pellet fueling experiment. The driving power in the LHCD experiment rises to 850 kW and reproducible long pulse discharges with t_p of up to 4 s are obtained. These parameters are approximately twice as those obtained with boronization.

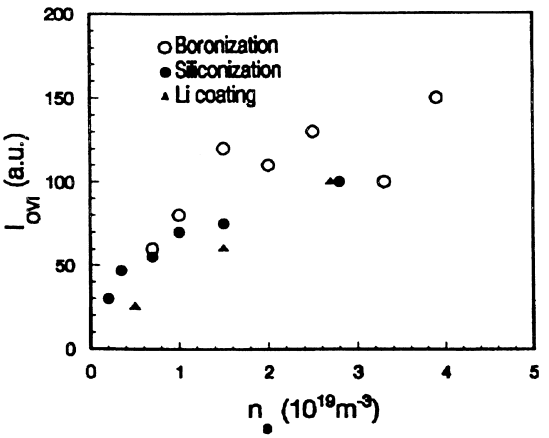

Fig. 3. OVI line radiation intensity as a function of the line averaged central electron density with similar discharge parameters.

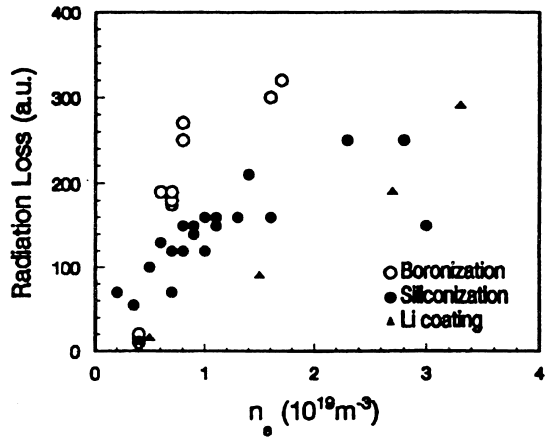

Fig. 4. The core radiation power loss as a function of the line averaged central electron density with similar discharge parameters.

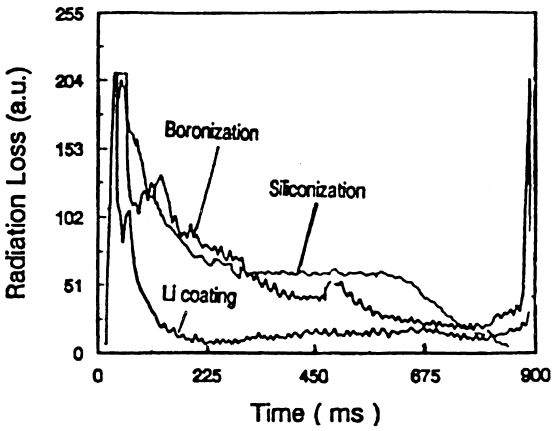

Fig. 5. The core radiation power loss in the first shot after the different wall coatings with the same discharge parameters.

The lithium coating in HL-1M is a preliminary test, but it has shown its potential. Its rapid deterioration may be related with the physical and chemical properties, namely low melting point, low hardness and strong reactivity of lithium leading to the rapid damage of the coating in the plasma irradiation. To remedy the defects, silicon or carbon containing lithium coating may be excellent alternatives, and we are developing these techniques.

4. Conclusions

The siliconized wall shows a strong stability against plasma irradiation damage and a high capture effect to H^+ or H^0. Therefore, it leads to a low hydrogen recycling and a substantial decrease of impurities so that plasma performance is greatly improved. Li coating resulted in even better results in several discharges, but its effective service time is still short and needs to be improved.

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