Outstanding Properties of Tungsten Material with Fiber-form Nanostructured Subsurface for the Wall of Fusion Reactor

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1. Introduction

Plasma heat control at plasma-facing components is one of most urgent subjects to be solved in fusion reactors. Tungsten material has been expected to be a most promising candidate for wall material in ITER and DEMO owing to relatively low tritium retention and the high melting temperature. However, there would be still essential enormous concerns on the employment of that as wall material in DEMO since the enormous heat pulse would bring a melting by ELM or other transient phenomena.

Especially, the tungsten material with nanostructured subsurface produced by helium irradiation on the tungsten with the ion energy above a few tens of eV and at the surface temperature 1000～1500K [1, 2] has been considered as “helium defect” so far since the thin fiber-form nanostructure may be easily melted by plasma heat flux [3]. In addition, it is considered that such nanostructured surface may enhance the probability of unipolar arcing [4] so that some recovery prescriptions have been tried [5, 6].

On the other hand, it should be considered that outstanding properties have been found for the wall of fusion reactor, which is the main subject of the present work.

2. Characterization

Figure 1 shows the fiber-form nanostructured tungsten surface made in AIT-PID where we have high density (～$10^{18}m^{-3}$) helium plasma with the ion bombardment energy of 50eV and the starting surface temperature of 1420K [5,7]. The helium ion fluence is ～$10^{26}m^{-2}$. The specimen is a cold-worked powder metallurgy tungsten. One of the outstanding characteristics of AIT-PID is the presence of hot electron component (T_h～30eV, α～5%) where T_h and α are the temperature and the fraction of hot component while the bulk electron temperature is around 4eV.

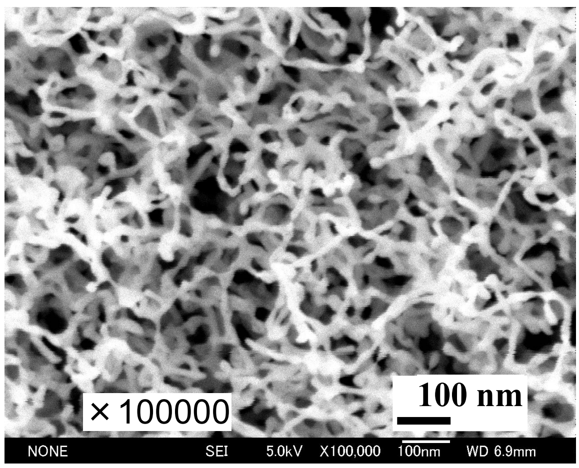

Fig.1 Fiber-form nanostructured tungsten surface obtained with helium plasma bombardment in AIT-PID. It is obtained with FE-SEM.

2.1 Surface cooling

The tungsten surface temperature has been measured with a radiation thermometer assuming a fixed radiation emissivity, for example $\varepsilon = 0.43$ at the wavelength of 0.9 μm. However, the surface morphology is substantially changed so that the emissivity approaches to almost unity due to a blacking on the way to fiber-form nanostructured surface formation. Although some cooling has been found to occur clearly [5], we cannot obtain the surface temperature definitively and quantitatively. This is overcome by employing R-type thermocouple made of platinum-rhodium fixed to the back surface of tungsten plate shown in Fig.2 together with the temporal variation of floating potential where the plasma potential is around +5 V. The temperature reduction up to 200K was clearly observed.

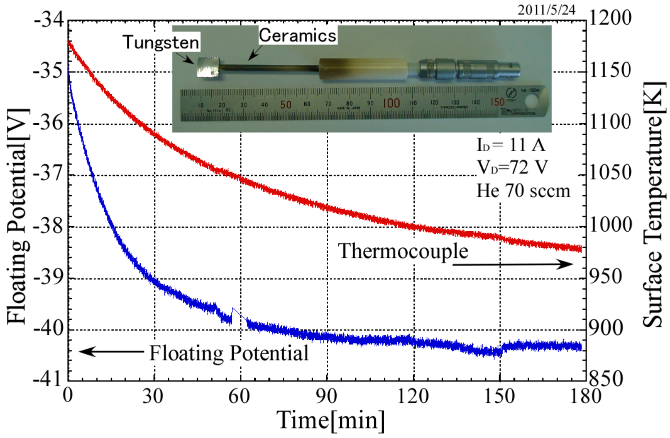

Fig.2 Temporal evolutions of surface temperature measured with thermocouple and floating potential of tungsten specimen (10×10 mm). Insertion shows how to fix the tip of thermocouple on the tungsten sheet.

2.2 Reduction of secondary electron emission

The surface cooling comes from two reasons [8]: an increase in emissivity and a deepening of floating potential. The latter comes from a reduction of secondary electron emission, whose physical mechanism was already discussed in reference [8]. The forest made of tungsten nano-fibers inhibits the emission of secondary electrons from such subsurface, which was already suggested analytically [9]. We note that the secondary electron emission is induced by hot electron component in AIT-PID. Such a condition is much more common in boundary plasma encountered in fusion reactors.

We can demonstrate the effect of secondary electron emission in a different way as shown in Fig.3. It is a kind of recovery process for a tungsten plate with a black surface by increasing the plasma electron heat flux which was obtained by approaching the biasing potential to nearly 0 V. In this case the ion incident energy is about 5eV which is less than the potential barrier at the tungsten surface for helium ion to enter into the bulk tungsten [11]. The surface temperature increases in time because the nano-fibers on the surface shrink by outgassing of connotative helium [5, 6] so that the emissivity decreases. The remarkable phenomenon is a reductions of biasing electron current even under an almost a fixed or even decreasing biasing voltage. It is believed that the reduction of biasing current is caused by a recovery of secondary electron emission because the tungsten surface is gradually smoothed in time. The incident energy of hot electrons is larger than that in floating

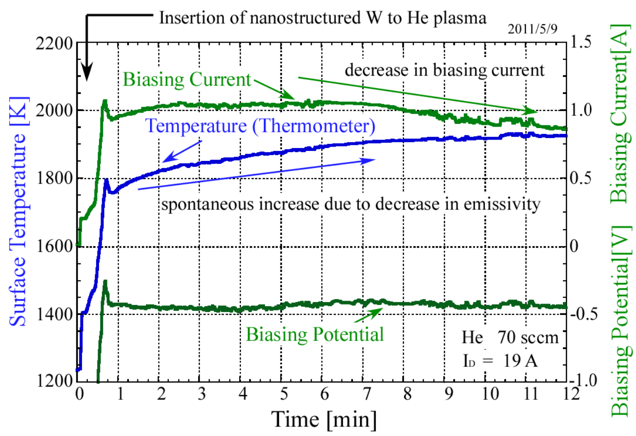

Fig.3 Temporal evolutions of surface temperature measured with radiation thermometer, biasing current and biasing potential.

condition.

2.3 Reduction of sputtering yield

It has been found that the nanostrucured tungsten surface gives a substantially reduced sputtering yield [12]. We have also demonstrated such effects as shown in Fig.4 where the triangular biasing voltage (see Fig.5) is applied to the nanostructured black tungsten specimen in an argon plasma, and the intensity of tungsten atomic line (498.26nm) is plotted as a function of time together with the surface temperature measured with a radiation thermometer ($\varepsilon = 0.43$). The envelope of light intensity gives a time-behavior of sputtering yield due to argon ion bombardment. At t ~ 150s, it has a minimum, and then increases up to a saturation intensity corresponding to the normal sputtering yield for Ar → W. Detailed traces are available at the beginning as well as almost final stage in Fig.5. At the moment the physical mechanism why the sputtering yield has a minimum is not clear although the surface morphology changes at this timing, fattening the thickness of tungsten nano-fibers.

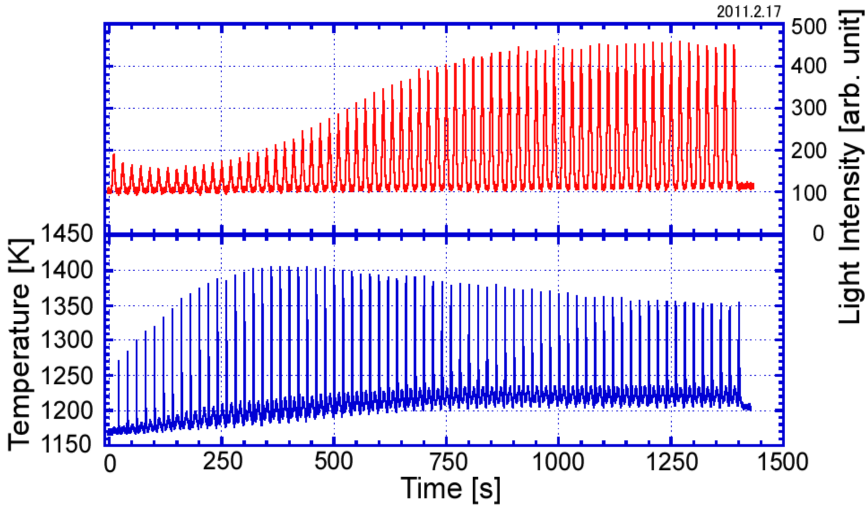

Fig.4 Temporal evolutions of sputtering yield and energy transmission behavior.

The temperature excursion is also plotted in Fig.4 and its detailed traces are in Fig.5. These are closely related to the energy transmission factor as a function of sheath voltage. The large temperature increase comes from the electron heat flux to the target and the tiny peaks correspond to the ion bombarding energy. We must be careful about the conversion of temperature change as a function of biasing voltage to the energy transmission factor because some calibration

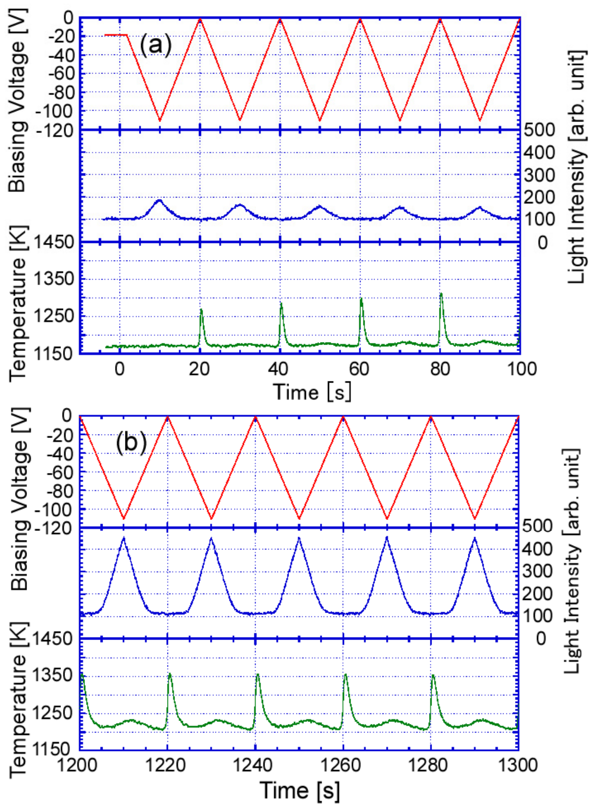

Fig.5 Detailed temporal evolutions of biasing voltage, WI light intensity and surface temperature measured with radiation thermometer.

may be needed and some phase delay is noticed due to rapid change of the biasing voltage.

3. Summary

Good properties of nanostructured tungsten surface as a plasma-facing wall in fusion reactor have been demonstrated, that is, a cooling function coming from the increase in radiation emissivity and the suppression of secondary electron emission, a suppressive behavior of sputtering. Moreover, a resistance against cracking produced by a pulsed heat load is also reported [13]. These outstanding characteristics are very favorable to the material surface. However, thin metal fibers through which the current flows are easily heated up by Joule process, which may trigger unipolar arcs [4]. This is an only minor property. We can say that nanostructured subsurface shows the outstanding self-defensive properties for a wall in fusion reactor if the triggering of unipolar arcing would be suppressed.

We have to say some words on the importance of suppression of secondary electron emission in relation to transient heat load. Bergman pointed out the role of hot electron component associated with ELM [14]. Hot electrons produce a substantial secondary electron emission bringing the sheath voltage small. It results in an enormous electron heat load to the plasma-facing material surface. Therefore we must be careful about the estimation of energy transmission factor through the sheath in order to estimate the heat flux to the plasma-facing component.

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