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Microarticle

Measurement of heat diffusion across fuzzy tungsten layer

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ABSTRACT

Heat diffusion across the fuzzy nanostructured tungsten (W) layer formed by helium plasma irradiation was measured using a pulsed light heating thermoreflectance method. By observing the heat diffusion across the nanostructured tungsten layer with a short (1 ns) laser pulse heating, the averaged thermal conductivity of the nanostructured layer was deduced to be ~1.5 W/mK, which is ~1% or less of that of pure (ideal) W.

One of the serious issues in the plasma material interaction in fusion reactors is the effects of transients on materials accompanied by the edge localized modes and disruptions [1]. It has been identified that helium (He) plasma irradiation on tungsten (W) leads to formation of fiberform nanostructures, so called tungsten fuzz, on the surface [2]. It could initiate various phenomena in response to transients. E.g., melting/annealing of the nanostructures occurs with a significant low energy in response to transients [3–6], and, also, initiation of a unipolar arcing is enhanced by the nanostructures [7–9]. In this study, we focus on the thermal conductivity of the nanostructured layer, which is one of the key parameters to determine the impact of the transients on the surface. For ion irradiated/implanted surfaces and porous tungsten samples, 3Ω method [10], non-contact method measuring transient grating pattern on the surface [11], and rear face flash method [12] have been used to measure the thermophysical property. Recently, in [13], pulsed light heating thermoreflectance method was applied to the fuzzy W nanostructured layer with so called rear heating/rear detection (RR) configuration, in which a pump and probe laser beams were both focused on the rear surface. In this study, we will extend the previous study by applying front heating/rear detection (FR) configuration, in which the heating laser focuses on the front side to observe heat diffusion across the fuzzy layer. It is expected that we can deduce the thermal conductivity in a more accurate manner.

W nanostructured layer was formed on a quartz glass substrate with a W deposition layer on the surface. The thickness of the W deposition layer was 1 μm. A chrome layer with a thickness of ~50 nm was first deposited on the quartz glass before the W deposition to enhance adherence to the substrate. The W nanostructure layer was formed in the divertor simulator NAGDIS-II (Nagoya Divertor Simulator). The surface temperature was ~1500 K during the irradiation, and the He fluence was 6.2×10^{25} m^{-2}. Fig. 1(a) shows a cross sectional scanning electron microscope (SEM) micrograph of the sample. A 3.6-μm-thick nanostructured layer can be identified on the W deposition layer.

The thermal conductivity was measured using a pulsed light heating thermoreflectance apparatus. In Fig. 1(b), a schematic of the configuration was shown. A pump laser beam, of which the wavelength, the averaged power, the pulse width, the pulse frequency, and the modulation frequency were 1550 nm, 15 mW, 1 ns, 100 kHz, and 1 kHz, respectively, was focused on the front face of the sample. For the probe laser, the wavelength, the pulse width, and the averaged power were 775 nm, 1 ns, and 1 mW, respectively. The incident angle of the heating laser was 45 degree. The spot size of the laser on the sample was ~200 μm in diameter.

Fig. 1(c) shows temporal evolutions of the normalized thermoreflectance signal. It is presented that the temperature gradually increased with time and saturated at ~2 μs. The areal heat diffusion time method [14] was used to evaluate the thermal conductivity. (The details of the method are in Appendix.) In this method, unknown thermophysical properties can be calculated from the area A (see an inset in Fig. 1(c)) obtained from the normalized temperature evolution to the maximum value. Two different locations were chosen to measure A, and the values were 7.0×10^{-7} and 5.6×10^{-7} s. The gap between the two different locations are several mm. The value was altered approximately 20% by changing the location. This was probably because the thickness of the layer alters by position. For later calculation, we use the averaged values at $A = 5.6\times10^{-7}$ and 7.0×10^{-7} s, and the measure-

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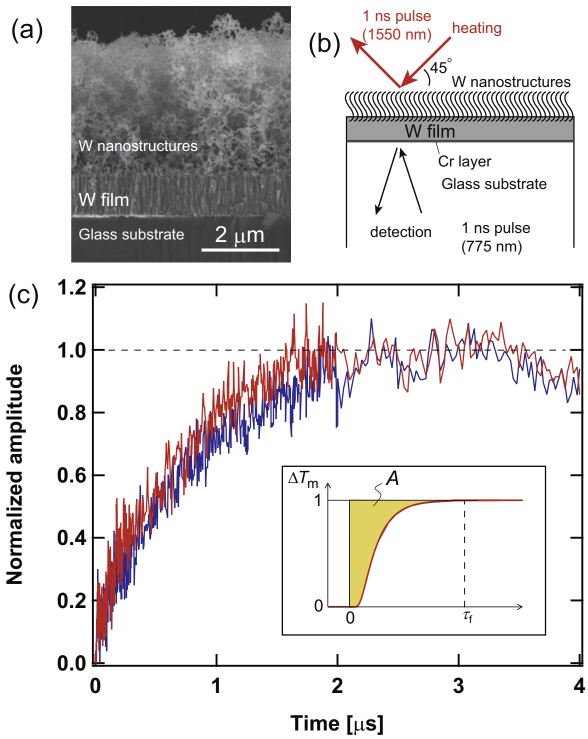

Fig. 1. (a) A cross sectional SEM micrograph of the sample, (b) a schematic of the measurement configuration, and (c) temporal evolutions of the normalized thermoreflectance signal.

ment errors are deduced by considering the ambiguity in the thickness. Concerning the porosity, we used the value measured in [15].

To obtain the thermal diffusivity of the nanostructured layer, an improved areal method including the penetration of heating laser beam to the surface was used [16]. We first considered to perform coating on the fuzzy layer to eliminate the ambiguity in the penetration of photons. However, previously, it was observed that the carbon deposition penetrated into deeper region [17]; we chose direct heating method in this study. It was assumed that deposition power decay exponentially in the fuzzy nanostructured layer and that no penetration occur to W film layer. It is noted that the estimated λ_e by considering the porosity dependence of σ [18,19] was in the range of 37–141 nm (detail is in Appendix). In this λ_e range, the variations in the thermal conductivity and thermal diffusivity are less than 1%, which is much smaller than the measurement errors. We can omit the ambiguities caused by the penetration depth in the present study.

The obtained thermal diffusivity and thermal conductivity were 9.2 (+4.2, −3.5)$\times 10^{-6}$ m^2/s and 1.5 (−0.6, +0.7) W/mK, respectively. (The values in the parenthesis are the errors considering the ambiguity in the thickness). In the previous RR configuration [13], thermal diffusivity and thermal conductivity were deduced to be 1.9$\times 10^{-5}$ m^2/s and 3.1 W/mK, respectively. The analytical error in RR configuration was typically $<$ 10%. It can be seen that the FR configuration deduced lower thermal diffusivity, say ∼50% or less, compared with RR method. This is probably because the W density in the nano-layer has non-uniformity in height [20], and the RR configuration does not have a sensitivity in the top of the structure, where the density is lower. From the results of FR configuration, the deduced thermal conductivity is ∼0.6% or less of the pure (ideal) W. This value should be closer to the actual averaged thermal conductivity of fuzzy nanostructure tungsten layer. The thermal conductivity of fuzzy layer could be altered when the thickness of the layer was changed; the further measurements using different samples are our future work. At the moment, from the ambiguity in the layer thickness, the measurement errors were approximately 50%. By forming a uniform fuzzy layer or increasing the measurement position, it is expected to reduce the errors in the thermophysical properties in future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.rinp.2016.10.025.

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