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Application of optical reflectivity measurements to diagnostics for plasma facing materials

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ABSTRACT

Optical reflectivity measurement is proposed as a convenient diagnostics method of surface modifications in plasma facing materials (PFMs) and its applicability to a plasma confinement device is evaluated. The optical reflectivity for mirror polished stainless steel (SUS316L) exposed to the Large Helical Device (LHD) plasma was examined with a spectroscopic ellipsometer. In-situ measurement of the reflectivity change under the glow discharge was also performed using a super continuum white laser.

The detectable change of the reflectivity was observed and the level of the degradation depended on the location, exposure period and employing wavelength. Microstructure observation of the mirror surface revealed that the behavior of the reflectivity change correlated closely with the ion-induced damages and the depositions thickness in the vicinity of the sample surface. Thus, the optical reflectivity measurement is considered to be a possible method for convenient in-situ diagnostics for PFMs.

1. Introduction

One of the key issues for maintenance of the high performance plasma in fusion devices is diagnostics of plasma facing materials (PFMs). Material probe experiments have been frequently employed as efficient methods to investigate the PFMs conditions in many plasma confinement devices [1–5]. However, most previous research has dealt with superimposed effects due to plasma exposures by postmortem analysis, and not examined the ever-changing PFMs conditions under various plasma surface interaction phenomena. In order to evaluate PFMs conditions, therefore, in-situ and real-time diagnostic methods of PFMs are highly desired as an alternative to the existing postmortem methods.

In our recent study, we reported the real-time change of the optical reflectivity for the metal mirror samples under irradiation with low energy helium (He) and deuterium (D) ions [6–8]. It was confirmed that the reflectivity under the irradiation decreases monotonically up to a rather high fluence depending on the ion energy, fluence and wavelength. In addition, it was revealed that He irradiation has a more dominant influence than D irradiation on the reflectivity reduction. In this study, optical reflectivity measurement is proposed as a convenient in-situ diagnostics of the surface modification in PFMs and its applicability to a plasma confinement device is discussed.

2. Experimental procedures

The Large Helical Device (LHD) is the world's largest heliotron-type plasma confinement machine with stainless steel (SUS316L) first wall and mainly carbon divertor tiles [9]. Due to the intrinsic divertor structure without additional divertor coils, LHD allows disruption-free steady-state plasma operation, which is a merit for the characterization studies of surface modifications of PFMs [10]. To examine the change of the optical properties due to plasma-surface interactions, the long-term material probe experiment was performed in LHD during the 15th experimental campaign. The plasma shots in the campaign were 7000 in total with each shot duration time lasting about 2 s, while total duration of glow discharge cleaning (GDC) was 325 h [11]. The expected average fluxes to the first-wall surface are evaluated to be $\sim 10^{18-19}$ ions/m^2 for the main plasma and $\sim 10^{17}$ ions/m^2 for the GDC, respectively [12]. The sample holders incorporating a set of mirror polished SUS316L sheets (see Fig. 1 for the photograph of the sample holder) were installed at various locations of the divertor region and exposed to LHD plasma. The details locations of the holders and the plasma parameters are described in Ref. [11,12]. The reflectivity change

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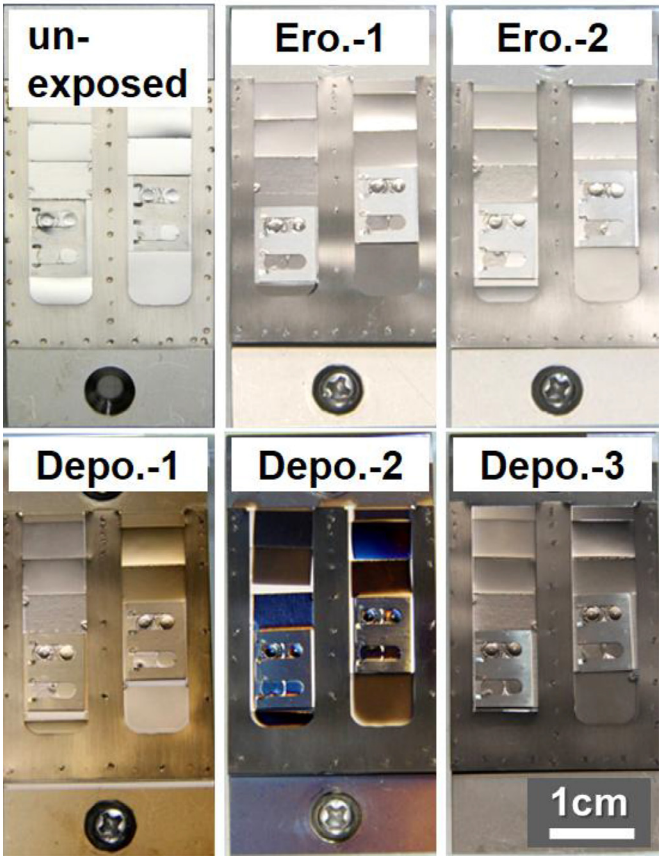

Fig. 1. Photos of the sample sets exposed to the LHD plasma.

after the exposures was measured by spectroscopic ellipsometer for the wavelength range of 280–820 nm. For comparison, reflectivity change by ion irradiation with 3 keV helium ions at R.T., up to a fluence of $\sim 1 \times 10^{23}$ ions/m^2 were also examined. While it does not necessarily simulate a particle load under the LHD plasma condition, an ion energy of 3 keV was applied due to the ion source stability of our irradiation device. The microstructure modification induced by the plasma exposure and the ion irradiation was investigated using a transmission electron microscope (TEM). The focused ion beam (FIB) technique was applied to make the sample ready for cross-sectional observation. The depth profile of the chemical compositions was also measured for some impurity deposition samples by Glow discharge optical emission spectrometry (GD-OES) which is a technique to measure the depth profiles of constituent elements in a solid specimen by detecting emissions from atoms implanted into plasma by specimen surface sputtering [13].

To investigate the applicability of the reflectivity measurement to future fusion device, in-situ measurements under the glow discharge in LHD was also performed using with the retroreflector (corner cube mirror), which consists of three orthogonal mirror surfaces and reflects laser light in parallel with the incident light [14]. A super continuum white laser source and a wide spectrum spectrometer were used for spectral reflectivity measurements with a wavelength from 360 to 1000 nm.

3. Results and discussion

3.1. Surface modification and reflectivity measurement

The long-term plasma exposure in LHD over an experimental campaign caused the apparent change on the material probe samples. Photos of the exposed samples at LHD 15th campaign are displayed while comparing the unexposed samples in Fig. 1. These exposed samples exhibit tarnish in metallic luster or various color changes depending on the location of the samples during the material probe experiment in LHD. This means that exposure conditions were different for each sample, and the optical properties could show the individual surface states of the samples. Because it is very important to evaluate the location dependence of surface modifications on these material probe samples, we focus on the investigation into the relation between the optical reflectivity and the surface condition in this study. Fig. 2 shows the cross-sectional microstructure of these samples obtained by TEM after the FIB processing. The tarnished samples (labeled “Erosion-1” and “-2”) show little deposition layer and the damaged layer including high density helium bubbles with the white circular contrasts is observed at the sub-surface region. On the other hand, the formation of impurity deposition is observed for the colored samples (labeled “Deposition-1”, “-2” and “-3”). GD-OES measurement showed the deposition consists mainly C, O and Fe, and their compositions were ~97%, ~2% and ~1%, respectively, on the average apart from the outermost surface. These compositions were almost same for the samples Deposition-1, -2 and -3. The deposition thicknesses on these samples are directly evaluated by the TEM images, and measured to be ~20, ~70 and ~400 nm for the samples Deposition-1, -2 and -3, respectively.

Fig. 3 shows the wavelength dependence of reflectivity obtained by the spectroscopic ellipsometer for these samples exposed to the LHD plasma. Compared with the reflectivity for the unexposed sample, various changes in the wavelength dependence are observed, especially drastic for colored samples such as Depo-1, -2 and -3. As describing below, the wavelength dependence of reflectivity strongly depends on the degree of microscopic damages and the thickness of the impurities depositions.

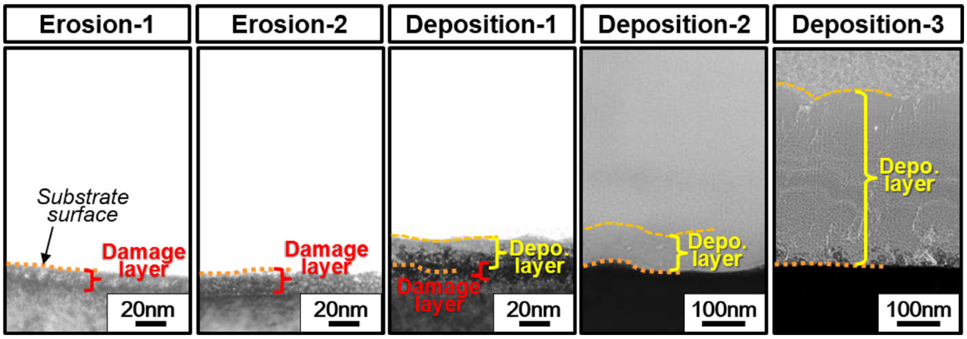

Fig. 2. Cross-sectional microstructure of the SUS316L samples exposed to the LHD plasma. The formation of the damage layer including high density helium bubbles and the impurity deposition layer are observed.

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