Developing in-situ Ellipsometry for Tokamak Discharges in KSTAR

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Abstract. An in-situ ellipsometer based on four-detector polarimeter (FDP) is under development at KSTAR. In-situ ellipsometer for tokamak discharges will measure the characteristics of thin films deposited onto a quartz window near the edge region in real time. These characteristics contain local deposition/erosion rates as well as hydrogen to carbon ratio, which have to be measured in-situ, for more clear insight view of plasma-wall interaction in tokamak edge plasmas. This paper reports the status of in-situ ellipsometer development for tokamak discharges at KSTAR, to study plasma-wall interaction and fuel retention. Basic concept, design and construction of the ellipsometer are described.

1. Introduction
Ellipsometry is an optical technique for the characterization of an interface or a film between two media. It is based on exploiting the change of polarization state of a beam that is reflected or transmitted through the media. An ellipsometric measurement does not destroy the sample surface or interface during the measurement: It does not disturb deposition/etching processes, hence it is suitable for in-situ measurements. Also, the change of film properties can be characterized during the process with ultra high sensitivity for the change of the surface condition (accuracy of a monolayer detection). Thus, ellipsometry is a standard diagnostics in low temperature processing plasmas to control the thickness of thin films fabricated.

Why we need in-situ ellipsometry for tokamak discharges? Plasma-wall interactions during the tokamak discharge lead to the erosion of plasma facing components (PFCs) [1]. Eroded materials are transported to relatively cold area of the vacuum vessel and re-deposited as thin layers on the surface. Erosion and re-deposition of PFC materials, especially carbon containing materials cause several issues on the operation as well as safety. As the thickness of layers grows up, the flaking of thick layers leads to the creation of carbon dusts in the vacuum vessel during the plasma operation [2]. Furthermore, since carbon is always deposited as hydrocarbon molecules, fuel retention in the layer is another important issue [3]. ITER has set safety limit of tritium in the vacuum vessel [4], thus fuel retention has to be controlled effectively when it is necessary: Exact erosion and re-deposition rate of PFC materials have to be studied quantitatively. Furthermore, output of an in-situ ellipsometry provides complex refractive indices of the deposited layers. In the case of carbon materials, complex refractive indices are directly connected to hydrogen to carbon ratio in the layer [5]. Thus, measuring complex refractive indices give direct information on the fuel retention.

We have designed and constructed a four-diode-ellipsometer for tokamak discharges to measure the re-deposited layer thickness and optical constants in-situ. Basic concept is based
on the use of four-detector photopolarimeter (FDP) suggested by Azzam et al [6]. The FDP consists of four photo-diode detectors and a laser, that measure complete polarization state of laser light reflected by substrate-thin film system. Dittmar et al. have constructed an in-situ ellipsometer based on FDP for TEXTOR, but the measurements during the tokamak discharge have little success due to the thermal erosion of protective coatings on the mirror [7]. In order to control the temperature of the optical components, we have used cooling units, that are based on thermoelectric effect. We have finished the design and construction of the ellipsometer, and planned to be tested at a small vacuum vessel. After the test of the ellipsometer, it will be installed in KSTAR at a mid-port location to measure the growth of re-deposited a-C:H layers in-situ.

2. Principle: Four-Detector Polarimeter

In order to measure the optical characteristics of film-substrate system, it is needed to know complete polarization state of a light beam reflected by the surface. There are numbers of methods to measure the polarization state [8]. These devices measure the polarization state as ellipsometric angles $\Psi$ and $\Delta$, that are connected to Fresnel’s coefficients

$$\tan \Psi e^{i\Delta} = \frac{r_p}{r_s} e^{i(\delta_p - \delta_s)}, \quad (1)$$

where $r_p$ and $r_s$ represent the reflection coefficients of parallel(p) and perpendicular(s) polarization state, and $\delta$ is the phase difference. Ellipsometric angles $\Psi$ and $\Delta$ provide characteristics of sample under study. Note that, in tokamak environments we are dealing with high level of heat flux and magnetic fields. Thus, the use of conventional optical components will face problems such as Faraday effect, cooling problem, and experimental setup using stepper motors will not be available. To overcome these problem a static photopolarimeter, so-called “four-detector polarimeter (FDP)” can be used: The state of polarization is measured by splitting light by diffractive elements onto four photodetectors and measuring their response. The concept of FDP is described by Azzam in 1985, for the first time [6], and used for various polarization measurements, e.g., for Kerr effect measurement [9]. The incoming light is reflected under an oblique angle by the first three detectors and finally absorbed by fourth detector at normal incidence. At each detector a part of light will be absorbed and generate photocurrent $I_k$, where $k=0,1,2,3$. Azzam has showed a linear relation between photo-current I and stokes vector S,

$$I = AS \quad (2)$$

where A is a $4 \times 4$ matrix called instrument matrix, which describes the relation between I and S. Instrument matrix contains all characteristics of the response of the FDP to incident light. Once the matrix A is determined, complete polarization state of the light can be determined.

3. Design and Construction of in-situ Ellipsometer for Tokamak Discharges

As we have mentioned above, most of diagnostics for tokamak discharges have restricted access to the plasma due to the high heat flux and high magnetic fields: Areas in tokamaks at which physical quantities of plasma-wall interaction can be measured are relatively restricted. This leads to the limitation of size, design, geometry and installation of a diagnostic. An in-situ ellipsometry for tokamak discharge measures thin film formed by plasma-wall interaction at edge region. It can be installed at a vertical or at a mid-port. KSTAR has 24 vertical ports (12 at top and 12 at bottom) and 16 mid-ports. Because the size of mid-ports is much larger than vertical ones and they have more flexibilities, we have designed an in-situ ellipsometer which will be installed at a mid-port in KSTAR. A picture of designed and constructed prototype ellipsometer is shown in figure 1. The basic concept of the ellipsometer is to construct a simple FDP. Normally, conventional ellipsometers measure the polarization state of ambient-thin film-substrate system.
A laser beam is passing through the ambient and thin film and reflected by the substrate, then detected by a photodiode with an (rotating) analyzer. In order to measure a sample exposed to a tokamak edge plasma, the laser beam has to pass through and to be reflected back along a long path from the laser to the detector. Thus, it is impossible to construct an ellipsometer based on such a simple “reflection geometry” in a tokamak. An alternative configuration was suggested by Dittmar et al [7]: This is based on the backside reflection measurement. The laser is placed at the opposite side of the plasma and FDP measures the back-reflected laser beam. At KSTAR, we have adopted only the concept of Dittmat et al [7], and designed for KSTAR mid-port installation (see figure 1). The dimension of the ellipsometer part in figure 1 is 205 mm × 90 mm × 80 mm. A 35 mW green diode laser is horizontally mounted and laser beam is launched. The beam is reflected by a photodiode of the same type as detector (act as mirror). The beam passes through a linear polarizer to be sure of the polarization state of the incident beam. A part of the beam will be reflected at the surface of a 6 inch window (label

Figure 1. Picture of in-situ ellipsometer based on FDP constructed at KSTAR. Solid line represents the light beam from a green laser diode.

Figure 2. Picture of in-situ ellipsometer assembled into aluminum case attached to 6 inch window.
1 in figure 1) and the rest of the beam will pass through the window (label 2 in figure 1). At the backside of the window where the deposition occurs due to the plasma-wall interaction, a part of the beam is again reflected (label 3 in figure 1) and finally detected by FDP. The mirror and FDP are mounted on movable rods so that the incident angles and the horizontal/vertical position of each component can be adjusted in a fine scale. Light intensities at each detector will be recorded separately by a personal computer (5 channels). The acquisition speed will be in the kHz range. By analyzing the signal, the state of the polarization of the beam at the detector can be determined. Note that, lower power laser can be used for a conventional ellipsometer. Due to the concept of backside reflection, the light intensity reaching at the detectors is significantly reduced by a factor of $10^3$ [7]. Preamplifiers can be employed in case of bad signal to noise ratio at detectors. In order to test the ellipsometer before it is installed in KSTAR, further test and design optimization are needed. This is a reason for the use of a 6 inch quartz window: The constructed ellipsometer can be mounted easily to any vacuum system which has 6 inch port for further test. The case of the ellipsometer is made of aluminum. The outer part of the case will be covered by graphite tiles to protect system from high heat flux and a electrothermal cooling system will be installed inside.

4. Summary and Outlook

We have designed and constructed a prototype of an in-situ ellipsometer for tokamak discharges. Assembly and alignment of optical components were accomplished and the detectors are ready to record signals. The next step of the development is calibration of the ellipsometer. Using laser light of known polarization state, the response of FDP can be calibrated. This procedure determines the instrument matrix A [10]. For the calibration, we have constructed a “calibration unit” which is exactly the same as ellipsometer unit shown in figure 3, but assembled as mirrored at the upper part of ellipsometer unit without 6 inch window, with an additional $\lambda/4$ plate after the polarizer. This calibration unit produces any “known” polarization state for the calibration. After the instrument matrix A is determined, the system will be ready to measure any polarization state incoming towards FDP. The system will be mounted to a small device where a-C:B:H thin films are deposited to optimize the boronization in KSTAR, and the growth of thin film will be measured and the ellipsometer will be intensively tested and optimized. In 2010, the ellipsometer will be installed in KSTAR (Faraday effect on window has to be considered also) and plasma-wall interaction at edge region will be studied: Information on local erosion and deposition, hydrogen to carbon ratio can be directly obtained during plasma shots.

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