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Application of spectroscopic imaging reflectometry to analysis of area non-uniformity in diamond-like carbon films

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ABSTRACT

Complete optical characterization of diamond-like carbon (DLC) films non-uniform in thickness is performed using spectroscopic imaging reflectometry (SIR). It is shown that by using this technique it is possible to determine the area distribution (area map) of the local thickness of these films with arbitrary shape of this thickness non-uniformity. Furthermore, it is shown that in principle it is possible to determine the distributions of the refractive index and extinction coefficient of these films simultaneously with the thickness distribution, if a suitable dispersion model of these optical constants is chosen. In this paper the dispersion model of the optical constants of the DLC films based on parameterization of density of electronic states (DOS) is used. The values of the material parameters of this dispersion model are determined too. It is shown that the DLC films studied do not exhibit the area non-uniformity in material parameters and optical constants. The method presented can be used to characterize the non-uniform films consisting of other materials.

1. Introduction

In practice one can encounter many thin films exhibiting non-uniformity. This is also the case of deposition in capacitively coupled RF plasma reactors equipped with parallel electrodes, which are often used to prepare DLC films. The changes of various technological parameters during the deposition can cause the existence of thickness non-uniformity of the DLC film prepared in this way (e.g. the changes in input power, gas flux, working pressure and substrate temperature stabilization often cause this non-uniformity). A very important effect causing the thickness non-uniformity of the DLC films is also the electric field distortion near edges and corners of substrates [1,2]. This is why it is very important to consider the non-uniformity of the DLC films in their optical characterization because without taking the non-uniformity into account misrepresented results are obtained in this characterization. Moreover, in general a certain non-uniformity of such DLC films can arise in the optical constants. So far several papers dealing with the optical characterization of various thin films exhibiting special wedge-shaped non-uniformity in thickness have been published (see e.g. refs [1–5]). In these papers, the optical characterization of the non-uniform films is based on interpreting standard spectrophotometric data, i.e. the data corresponding to spectral dependences of reflectance and transmittance measured by standard spectrophotometers. However, in the case of the general non-uniformity in thickness, the procedures presented in the papers mentioned above are not usable. Thus, other methods must be used to perform the optical characterization of the thin films exhibiting this general thickness non-uniformity. From our previous studies it followed that the methods based on employing spectral imaging reflectometry (SIR) were promising for this purpose. We developed a method employing the interpretation of the experimental data obtained using an imaging spectrophotometer operating in the reflectance mode [6,7]. This method enables us to determine simultaneously the area distributions of the thickness and optical constants (i.e. refractive index and extinction coefficient). Moreover, this method is usable for determining these distributions even when general shapes of these non-uniformities occur in thin films. Thus, SIR mentioned above is very suitable for the complete optical characterization of the non-uniform DLC films. The reason is that the uniformity in the optical constants of the non-uniform DLC films needs not be assumed *a priori* as in the spectrophotometric methods cited above and the area distribution of the thickness can be determined together with the distributions of the area non-uniformity of the optical constants simultaneously.

2. Sample preparation and experimental arrangement

The DLC films were prepared by PECVD in RF capacitive discharge at low pressure (16.5 Pa). The reactor was a glass cylinder with two, inner parallel electrodes, made of graphite. The bottom electrode, with a diameter of 150 mm, was coupled to the RF generator

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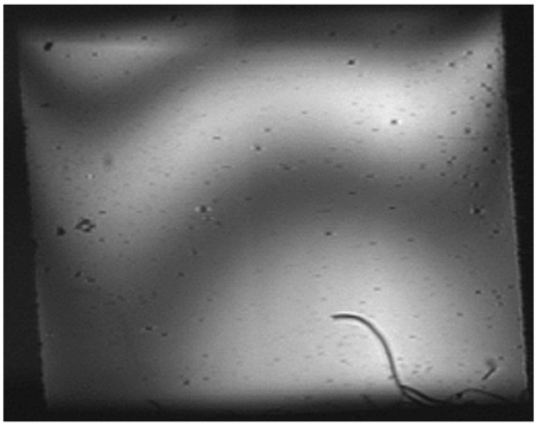

Fig. 1. Image of the DLC film investigated for the wavelength of 720 nm.

(13.56 MHz) via a blocking capacitor [8]. The depositions were performed at applied power of 50 W. The silicon single crystal substrates were placed on different substrate holders.

The substrate holders were situated on the bottom r.f. electrode made of graphite, the r.f. voltage of which was superimposed with a negative d.c. self-bias in the range from -300 to 350 V.

For measuring the experimental data the self-made two-channel spectroscopic imaging reflectometer containing a CCD camera as a detector was employed. The reflectance experimental data was measured at a normal incidence of light within the spectral region 320–850 nm. A detailed description of this arrangement is presented in our earlier paper [7].

3. Data processing

Owing to the fact that the dimensions of the local areas on the non-uniform film corresponding to individual pixels of the CCD camera are relatively very small, it is possible to assume that over these areas the film is uniform. This means that the spectral dependences of the reflectance $R^{i,j}$ measured by a pixel are given by the formulae valid for the uniform films (i and/or j denotes the ith row and/or jth column in which a certain pixel is placed in the matrix of the CCD chip), i.e.

$$R^{i,j} = \frac{|\hat{r}_1^{i,j}|^2 + |\hat{r}_2^{i,j}|^2 (U^{i,j})^2 + 2|\hat{r}_1^{i,j}||\hat{r}_2^{i,j}|U^{i,j}\cos\left(X_0^{i,j} - \delta_1^{i,j} + \delta_2^{i,j}\right)}{1 + |\hat{r}_1^{i,j}|^2 |\hat{r}_2^{i,j}|^2 (U^{i,j})^2 + 2|\hat{r}_1^{i,j}||\hat{r}_2^{i,j}|U^{i,j}\cos\left(X_0^{i,j} + \delta_1^{i,j} + \delta_2^{i,j}\right)}, \quad (1)$$

where $\hat{r}_1^{i,j}$, $\hat{r}_2^{i,j}$, $X_0^{i,j}$, $U^{i,j}$, $\delta_1^{i,j}$ and $\delta_2^{i,j}$ denote the local complex reflection Fresnel coefficient of the upper boundary of the film, local complex reflection Fresnel coefficient of the lower boundary of the film, local phase change inside the film, local extinction factor, local phase shift corresponding to the upper boundary and local phase shift corresponding to the lower boundary, respectively. These quantities are expressed as follows [9,10]:

$$\hat{r}_1^{i,j} = |\hat{r}_1^{i,j}|\exp\left(i\delta_1^{i,j}\right) = \frac{n_0 - \hat{n}_1^{i,j}}{n_0 + \hat{n}_1^{i,j}}, \quad \hat{r}_2^{i,j} = |\hat{r}_2^{i,j}|\exp\left(i\delta_2^{i,j}\right) = \frac{\hat{n}_1^{i,j} - \hat{n}}{\hat{n}_1^{i,j} + \hat{n}},$$

$$X_0^{i,j} = \frac{4\pi}{\lambda} d^{i,j} n_1^{i,j}, \quad U^{i,j} = \exp\left(-\frac{4\pi}{\lambda} d^{i,j} k_1^{i,j}\right). \quad (2)$$

In Eq. (2) symbols $\hat{n}_1^{i,j}$, $\hat{n}$ and $d^{i,j}$ represent the local complex refractive index of the absorbing film studied, complex refractive index of the absorbing substrate and local thickness of this film corresponding to the (i,j)th pixel, respectively ($n_0 = 1$ because the ambient is formed by air). In our work we employed the following convention of the complex refractive indices $\hat{n}_1^{i,j} = n_1^{i,j} - ik_1^{i,j}$ and $\hat{n} = n - ik$, where $n_1^{i,j}$, $k_1^{i,j}$, n and k denote the local real refractive index of the film, local extinction coefficient of the film, real refractive index of the substrate and extinction coefficient of the substrate, respectively. Symbol λ represents the wavelength of incident light.

The least square method (LSM) is used to treat the experimental data using Eq. (1). Of course, the LSM must be applied for each local area on the film corresponding to the given pixel of the CDD camera. Within the LSM, the following merit function $S^{i,j}$ was employed:

$$S^{i,j} = \sum_{s=1}^{K} \left(\frac{R_s^{i,j} - R_s'^{\,i,j}}{\sigma_s^{i,j}}\right)^2, \quad (3)$$

where $R_s^{i,j}$ and/or $R_s'^{\,i,j}$ denotes the theoretical and/or experimental value of the local absolute reflectance corresponding to the (i,j)th pixel and wavelength λ_s. Symbol $\sigma_s^{i,j}$ and/or K represents the standard deviation of $R_s'^{\,i,j}$ and/or the number of the measurements of the absolute reflectance, i.e. the number of wavelengths, for which the absolute reflectance was measured in each pixel.

Within the processing of the experimental data, the dispersion model based on parameterization of DOS [11–13] was used to express the spectral dependences of the refractive index and extinction coefficient of the DLC films.

Thus, using the LSM the values of the local thickness $d^{i,j}$ and material parameters occurring in the dispersion model are determined for each local area. The dispersion model parameters are as follows [12,13]: the band gaps of σ and π electrons $E_{g\sigma}$ and $E_{g\pi}$, high-energy limits of σ and π electronic transitions $E_{h\sigma}$ and $E_{h\pi}$, and parameters proportional to the σ and π electron densities Q_σ and Q_π. Using the parameters found in the procedure described above one can calculate the true spectral dependences of the refractive index and extinction coefficient of the DLC films studied in all the local areas corresponding to the pixels of the CCD camera. This means that distributions (maps) of the thickness and optical constants are determined in this way.

Note that the spectral dependences of the optical constants of the silicon substrate were taken from the literature [14] and fixed within the LSM.

4. Results and discussion

In this section the results of the optical characterization of a selected non-uniform DLC film are presented. These results are typical of the optical characterization of DLC films being studied using spectroscopic imaging reflectometry (SIR) in this work.

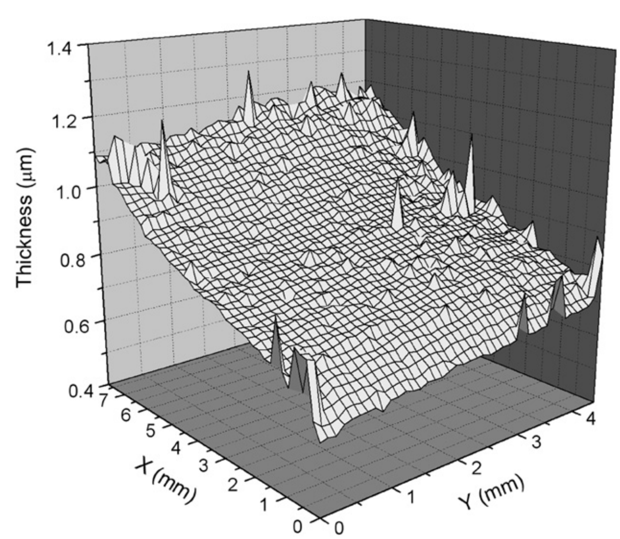

Fig. 2. The distribution of the local thickness of the film under investigation.