

X-RAYS PRODUCED BY MEANS OF A PROTON BEAM FOR ANALYSIS OF THE MULTILAYER X-RAY MIRRORS

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Abstract

We used the proton accelerators as a source of the monochromatic X-rays to perform analysis the multilayer structures in the long-wavelength range. The monochromatic X-rays were induced by the accelerated protons from solid targets: carbon, aluminum and copper. A Soller type X-ray spectrometer was used to measure the intensity of lines. To determine the reflection coefficient of the mirrors we measured the intensities of the X-ray lines without the mirror and with the different mirrors. We induced the characteristics X-rays from the quartz substrate by the protons passing through the multilayer structure in order to measure the transmission coefficient of the mirror. The results of these measurements shown that the PIXE method can be employed for the investigation of the multilayer structures.

1 INTRODUCTION

Particle induced X-ray emission (PIXE) has now become a well-established technique for multielemental analysis of materials. Proton induced X-ray emission can be also considered as a source of monochromatic X-rays for a number of applications. The properties and possible applications of a very intense source of monochromatic X-rays excited by proton impact were discussed by Arduini et al. [1]. A very intense source of monochromatic X-rays, tunable in the 1 - 100 keV range, can be obtained by coupling a low energy (2 - 4 MeV) high current proton accelerator with an irradiation chamber. The generation of nuclear background is avoided by keeping the proton energy below the Coulomb barrier. Experimental results have shown that the monochromaticity of the source is generally better than 99 % [2]. We used the proton accelerator as the source of the monochromatic X-rays to perform comparative analysis of the nickel-carbon (Ni/C) multilayer structure and a new diamond-like carbon-carbon (DLC/C) multilayer structure in the long-wavelength range.

Long period crystals, multilayer molecular structures and multilayer interference mirrors are used as dispersive elements in optics and spectroscopy. Each of them has a number of advantages, apparent in certain spectral range, and disadvantages restricting its application [3]. Usually X-ray mirrors are formed of two different materials by sequential deposition of absorber (usually metallic) and spacer layers (such as B, C or Si). Essential characteristics

important for all optical elements are the reflection coefficient R and the resolution $\Delta E/E$.

As we know, the transmission coefficient of the multilayer structures, deposited on thick substrate, is not measured by ordinary methods of the X-rays optics as the thick substrates are opaque for X-rays. The utilization of the PIXE method for studying multilayer structures permits to measure the transmission coefficient of those mirrors.

2 EXPERIMENT

Multilayer carbon interference structures (DLC/C) were made by ion-plasma methods by sequential deposition of carbon layers from two sources placed in the same technological chamber. Mixtures $C_6H_{12} + Ar$ were used as the working gases [4]. The mirrors were deposited on silicon, quartz and float glass substrates with means-square roughness 0.6-0.8 nm. The layers parameters were measured using X-ray reflectometer at the wavelength $\lambda = 0.15$ nm. To perform comparative analysis the RAP crystal, Ni/C mirror and new DLC/C multilayer structure were studied. The Ni/C bilayer consists of 60 layers with the period spacing $d = 7.2$ nm. The period spacing of the new DLC/C structure is of 10 nm and 40 layers have been coated. The reflection coefficients and the shape of the first Bragg peak of all the three samples were investigated under the same conditions.

Measurements of the optical elements characteristics in the long-wavelength range were carried out at the 0.5 MV Cockroft-Walton generator at the Institute of Nuclear Physics of Moscow State University. The monochromatic X-rays are induced by the accelerated protons from the thick solid targets. The experimental setup has been described in detail previously [5] and is shown in Fig. 1. Here we mention only the main features. Protons of 0.45 MeV energy have been used. The target is positioned at 45° with respect to the incoming ion beam. The incident beam intensity is monitored by the current integrator. The spectra of $K\alpha$ lines of carbon ($\lambda = 4.47$ nm) and aluminum ($\lambda = 0.834$ nm) and $L\alpha$ line of copper ($\lambda = 1.334$ nm) are excited by protons in order to measure the reflection coefficient. The X-rays emitted from the excited target atoms are observed at an angle of 90° relative to the ion beam by the spectrometer. A Soller type (flat crystal) X-ray spectrometer is used to measure the intensity of X-rays. To determine the reflection coefficient R we measure the intensities of the

X-ray lines without the analyzers in the position of counter $\theta = 0^\circ$ and with the different analyzers. The rubidium biphthalate RAP ($2d = 2.61$ nm), DLC/C ($d = 9$

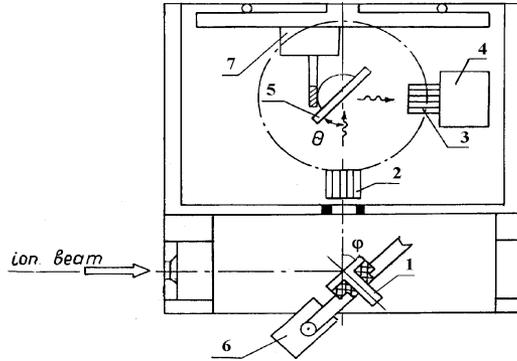


Figure 1: Schematic view of the experimental setup. 1 - target; 2,3 - Soller collimators; 4 - counter; 5 - crystal-analyzer; 6,7 - step motors.

nm and $d = 10$ nm) and Ni/C ($d = 7.2$ nm) mirrors are used as analyzers. The reflection coefficient is calculated from the results of these two measurements. Errors in the reflection coefficient are mainly due to errors in the determination of the K and L yields, which are caused by statistical fluctuations, background subtraction and fitting procedures. The EWA code [6] was used for the evaluation of the spectra. As a rule, the statistical error in the measurements of the reflection coefficient does not exceed 10%.

Measuring of the transmission coefficient of X-rays for diamond-like carbon/carbon mirrors we induce the emission of $L\alpha$ line of Si from the quartz substrate by the protons passing through the multilayer structure. The protons energy is 0.45 MeV. The mirror in this case is used as a target and the intensity of X-rays is measured by spectrometer with the ADP ($2d = 1.06$ nm) as the analyzer crystal. The position of mirror is perpendicular to the ion beam axis. The intensity $N(\varphi)$ of line is measured as a function of the exit angle φ of the emitted X-rays with respect to the surface of mirror. Obviously, that

$$N(\varphi) = \varepsilon J_0 \exp(-\mu t / \sin\varphi), \quad (1)$$

where ε is the quantum efficiency of the spectrometer, J_0 is the yield of X-rays, excited by protons in the substrate, t is the multilayer structure thickness, μ is the linear absorption coefficient. To determine the transmission coefficient $T(\varphi)$ we measure Si $L\alpha$ line yield for two angles: $N_1(\varphi_1)$ and $N_2(\varphi_2)$. From these measurements the transmission coefficient is determined as

$$T(\varphi) = (N_2/N_1)[\sin\varphi_1 \sin\varphi_2 / (\sin\varphi_1 - \sin\varphi_2) \sin\varphi]. \quad (2)$$

3 RESULTS

The values of angular resolution $\Delta\theta$ for the RAP crystal, DLC/C and Ni/C mirrors are determined from measurements of energy resolution ΔE , respectively, K and L lines using the relation

$$\Delta E = E \operatorname{ctg}\theta (\Delta\theta + \Delta\theta_{\text{col}}), \quad (3)$$

where E is the energy of the line, θ is the Bragg angle and $\Delta\theta_{\text{col}}$ is the divergence angle of the Soller collimator before the analyzer of the spectrometer. Table 1 summarizes the data obtained. As shown in the table

Table 1: Experimental values of reflectivity R and resolution $\Delta\theta$.

	R (%)	R (%)	R (%)	$\Delta\theta$ (deg)	$\Delta\theta$ (deg)	$\Delta\theta$ (deg)
λ (nm)	RAP	Ni/C	DLC	RAP	Ni/C	DLC
0.15	12	92	65	0.008	0.05	0.13
0.83	0.1	9.9	10	0.017	0.17	0.05
1.33	0.2	7.4	7.8	0.013	0.23	0.1
4.47			0.4			0.9

the reflection coefficients of all studied structures decrease at longer wavelength due to greater absorption in this spectral range. The advantage of new DLC/C structure is relatively slow decrease of R . The wavelength $\lambda = 4.4$ nm is near the absorption edge of carbon atoms. It results in the abrupt reduction of reflectivity in this region of the wavelength. The table confirms that the advantages of carbon structures over metal/carbon ones take place in the long-wavelength range as well.

The transmission coefficient T of X-rays is measured at $\lambda = 0.71$ nm by the exciting K line of silicon by protons in the quartz substrate. Experimental results are presented in Figure 2 for two mirrors with the different

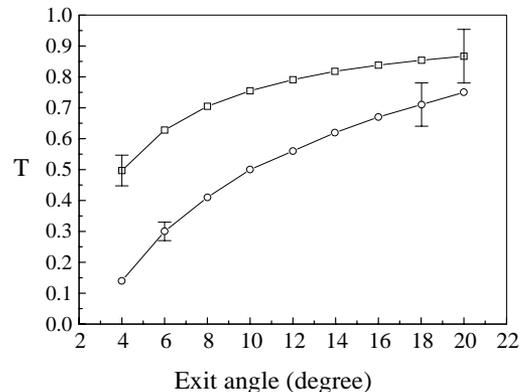


Figure 2: Angular dependence of the transmission coefficient of the mirrors for $\lambda = 0.71$ nm.

• - the mirror I; O - the mirror II.

periods: mirror I - the period $d = 9$ nm and number of layers $n = 30$; mirror II - $d = 10$ nm and $n = 40$. It can be seen that the transmission coefficient of the mirror I is larger than the transmission coefficient of the mirror II. We explain this difference by a different mirrors thickness and by different average density of the carbon layers.

4 CONCLUSION

It is shown that PIXE method can be applied for measurements of the optic features of the X-ray multilayer mirrors. Using of the PIXE method permits to measure the transmission coefficient of X-ray mirrors deposited at thick substrates. The reflectivity of the diamond-like carbon-carbon structures was proved to be comparable with the reflectivity of traditional metal-carbon structures. The resolution of DLC/C is significantly better. These advantages take place at least in the wavelength range $\lambda < 4.4$ nm.

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