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Cr/Sc multilayer radiator for parametric EUV radiation in "water-window" spectral range

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Abstract. The results of experimental investigation of parametric radiation generated by 5.7 MeV electrons in a multilayer structure consisting of 100 Cr/Sc bi-layers deposited on a Si_3N_4 membrane are presented. The multilayer structure was specially created for generation of parametric radiation with photon energy in "water-window" spectral range. First test measurements of angular distributions of radiation have been done and discussed.

1. Introduction

In a number of papers [1 – 6] it was shown that artificial periodic structures, as well as crystals, are suitable to generate tunable quasi-monochromatic X-rays by relativistic electrons. The energies E_{ph} of the photons emitted from the periodic structure lie in a narrow spectral range which is determined by the Bragg diffraction law. The mechanism of radiation generation in multilayer X-ray mirrors (MXM) is similar to the mechanisms of Parametric X-ray Radiation (PXR) and Diffracted Transition Radiation (DTR) generations in periodic crystal structures. Experiments [4 – 7] have been carried out for generation in MXM of X-rays with photon energies $E_{ph} = 6 – 15$ keV.

Recently in [10], it was experimentally shown that a multilayer mirror may be used for generation of quasimonochromatic radiation in the range of extreme ultraviolet (E_{ph} around 70 eV). So, by using structure with shorter period, one can get the quasimochromatic tunable source of photons in "water-window" spectral range. The "water-window" spectral range lies between the carbon and oxygen K absorption edges (284 and 543 eV, respectively). Radiation in this domain is required for many scientific and industrial applications, in particular, for the soft X-ray microscopy of biological objects.

This paper presents the construction of a multilayer radiator for generation of tunable radiation with photon energy in "water-window" spectral range and first results concerning the radiator test using the 5.7 MeV electron beam of the microtron M-5 of the Tomsk Polytechnic University. The multilayer radiator was specially prepared for generation of the parametric radiation (PR) in the "water window" spectral range with very thin substrate in order to decrease the contribution of background radiation.

2. Cr/Sc radiator

In the experiment, the radiator consists of a pile of 100 Cr/Sc bi-layers with a period d = 2.34 nm caped by a 2.5 nm thick B_4C layer; the whole stack is deposited onto a 0.5 μm thick Si_3N_4 membrane. The thickness of Cr and Sc layers, a and b, respectively, are the same. Scheme of the Cr/Sc multilayer radiator is shown in figure 1.

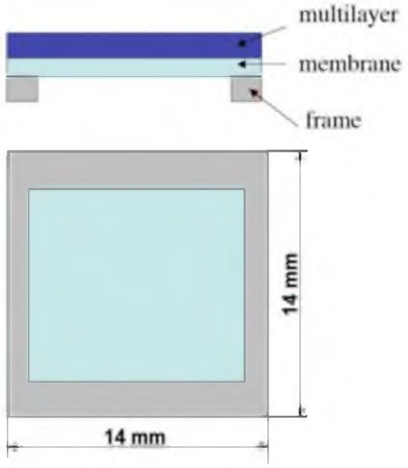

Figure 1. Scheme of Cr/Sc multilayer radiator. The thickness of B_4C cap layer is 2.5nm; Si frame is 500 μm thick.

The multilayer structure was prepared using the facility of the Laboratoire Charles Fabry by magnetron sputtering technique under constant argon pressure using plasma discharges by radio frequency power [11]; it was characterized by grazing incidence X-ray reflectivity GIXR and X-ray emission spectroscopy XES. Interfacial imperfection of Cr/Sc systems are mainly due to roughness with a typical rms roughness height of about 0.5 nm at each interface as indicated by GIXR; the analysis of Cr 3d valence states by XES does not evidence the presence of interfacial compounds resulting from the interdiffusion of the Cr and Sc layers [12].

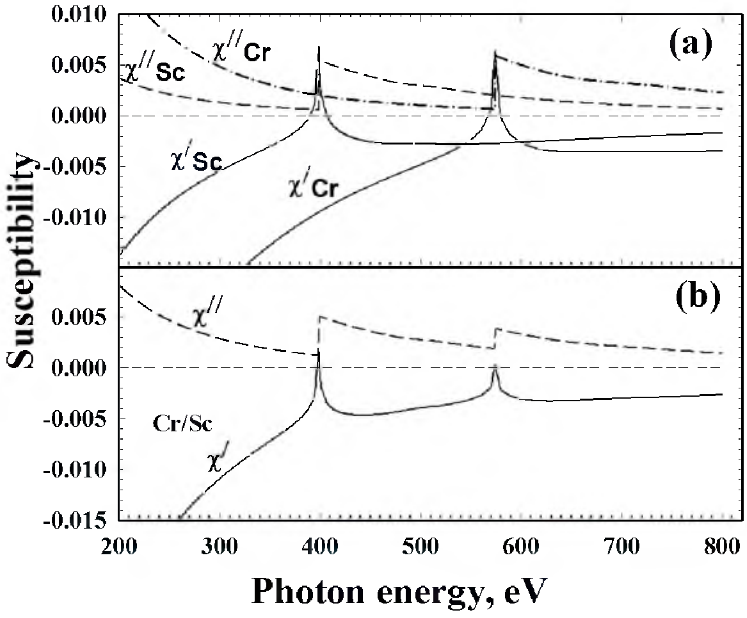

Figure 2. Dielectric susceptibilities: (a) Cr and Sc layers; (b) Cr/Sc bi-layer.

The global multilayer radiator (multilayer + substrate) was also tested using the X-ray diffractometer “Shimadzu XRD 6000”. The width of rocking-curve measured using the Cu K X-rays was about 0.2° that is in about 10 times more than that of theoretical one. All these characterizations indicate that the optical quality of this radiator is yet very far from perfection which has likely affected its PR emissive properties as shown hereafter. The mechanical properties of the Si_3N_4 membrane acting as substrate have not yet been studied in details; nevertheless it is likely that a large part of the relatively poor optical quality of the radiator can be attributed to the substrate.

Real $\chi^{/}$ and imaginary $\chi^{//}$ parts of the dielectric susceptibilities $\varepsilon_{a\ b}(\omega) = 1 + \chi^{/}(\omega) + i{\cdot}\chi^{//}(\omega)$ of Cr, Sc layers and average one $\varepsilon_{Cr/Sc}(\omega)$ of Cr/Sc bi-layer are shown in figure 2. The value of $\varepsilon_{Cr/Sc}(\omega)$ was calculated as $(a{\cdot}\varepsilon_{Cr} + b{\cdot}\varepsilon_{Sc}) / (a + b)$. The reflectivity of our Cr/SC multilayer structure supposed to be ideal (no interfacial roughness and interdiffusion) was calculated using the Parratt-method [13] for a number of Bragg angles and photon energies and shown in figure 3. The calculation evidences the reflectivity enhancements just below the L edge of Sc (398 eV) at the Bragg angle $\theta_0 = 42°$ and around L edge of Cr (574 eV) at $\theta_0 = 27°$ as a result of the anomalous scattering [14]

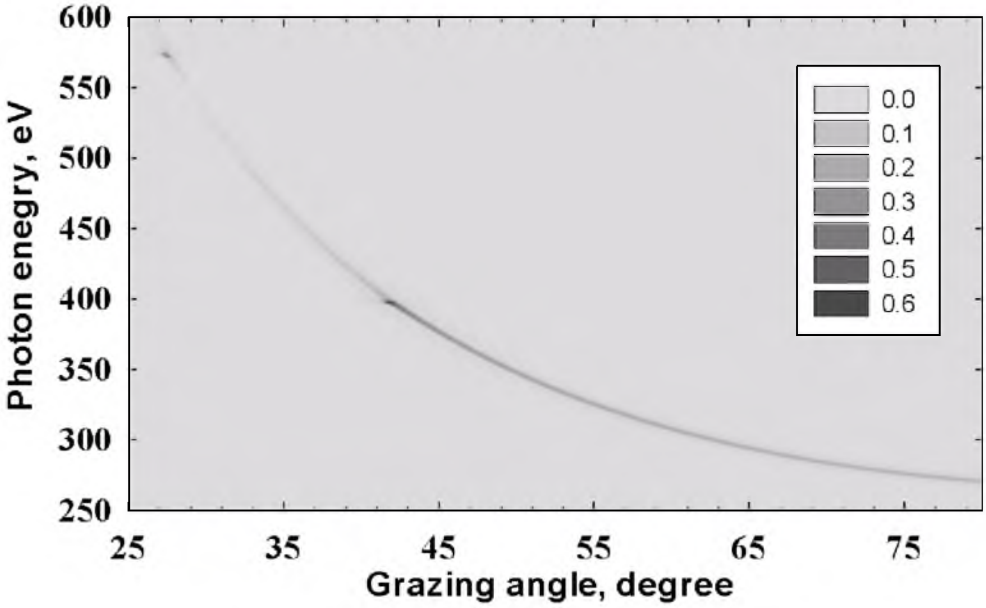

Figure 3. Reflectivity of ideal Cr/Sc mirror as function of Bragg angles and photon energies.

3. Theoretical background

The angular and spectral-angular densities of radiation were calculated using different theories [3, 5]. The calculation shows that the maximum PR intensity is emitted near the direction $\theta_{Dy} = 1/\gamma$ (γ is the Lorentz factor) with respect to the plane of diffraction. Therefore, the search for the PR effect should be carried out near the expected direction of maximum intensity of the radiation by scanning the detector through the angular distribution in a plane that is at an angle $\theta_{Dy} = 1/\gamma$ with respect to the diffraction plane **VN** (**N** is the normal to the target surface). As it is known, the back transition radiation (BTR) formed at the interaction of electrons with the input surface of the target is emitted also in the same direction. To suppress the BTR contribution, a filter (0.2 μm LiF + 0.1 μm Palyren) was used.

The angular distributions of 30 – 600 eV BTR and PR calculated for a number of Bragg angles θ_0 by taking into account the photon absorption in the filter are shown in figures 4(a) and 5. Figure 4(b) illustrates the influence of the filter on BTR intensity generated at $\theta_0 = 40°$ on upper Cr layer of the multilayer structure. The Cr surface was taken for calculation of the BTR contribution because the intensity of BTR from Cr surface is higher than that from B_4C, Si_3N_4 or Sc surfaces. The angular distributions of BTR were calculated using the Pafomov's theory [15].

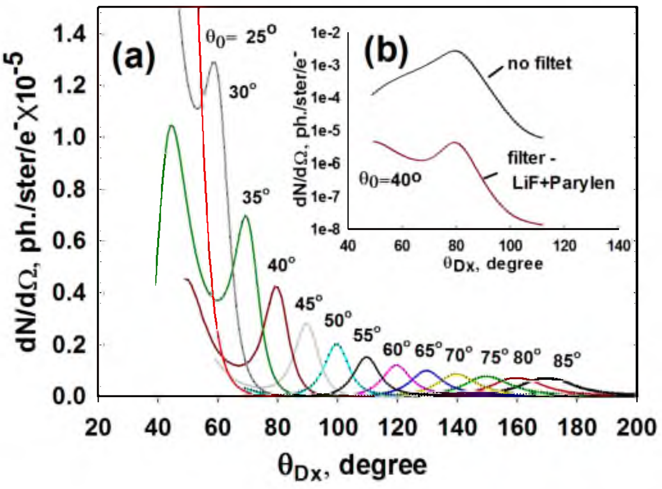

Figure 4. Angular distributions of 30 – 600 eV BTR: (a) θ_0 between 25° and 85°; (b) at $\theta_0 = 40°$, with and without a filter.

The angular distributions of PR were calculated using the theory [6]. The upper solid curve in figure 5 shows the dependence of photon energy versus $\theta_D = 2\theta_0$. As can be seen from a comparison of the data presented in figures 4(a) and 5, BTR contribution to overall radiation yield can be neglected at using the filter. Also is very important to note the difference of changing of the BTR and PR intensities via the angle θ_0. The BTR intensity increases with decrease of the angle θ_0, while PR intensity has a maximum around $\theta_0 \approx 40^{\circ}$.

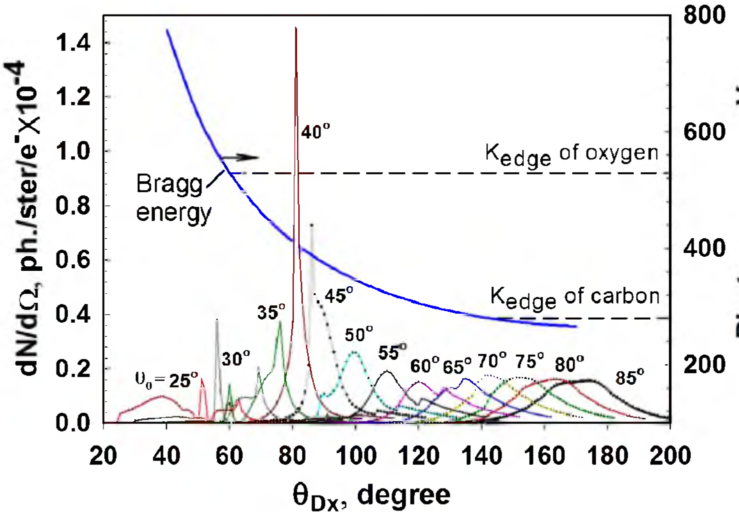

Figure 5. Angular distributions of PR for angles θ_0 between 25° and 85°.

4. Experimental procedure

Experiment on the angular distribution of the radiation generated by the 5.7 MeV electrons into the Cr/Sc radiator was carried out using the electron beam delivered by the microtron M-5 at Tomsk. The radiation was detected by a channel electron multiplier (CEM-model VEU-6). A detailed description of the installation can be found in [8 – 10]. The geometry of the interaction between the electron beam and the target and of the generation of radiation is shown in figure 6.

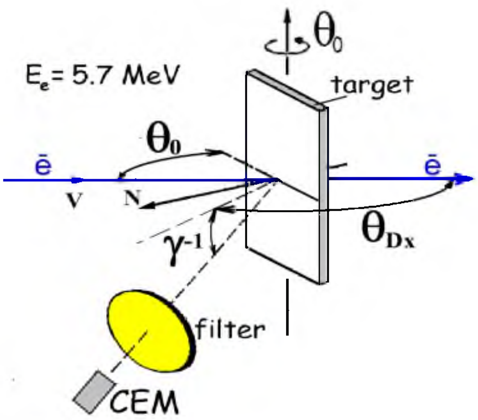

Figure 6. Scheme of geometry of the interaction of electron beam with the radiator and generation of radiation at experimental setup based on microtron M-5. Electron energy – 5.7 MeV; repetition rate – 25 Hz, pulse duration – 0.4 µs, electron current on target – 4 pC per pulse.

A series of angular distributions was measured for several angles between the electron beam and the radiator surface in the range of 35° – 72°. The distributions were measured in the diffraction plane **VN** and at the angle $\theta_{Dy} = 1/\gamma = 5.14°$ ($\gamma = 11.15$) with respect to this plane. To suppress the soft component of ordinary BTR, the measurements were carried out with the "LiF + Parylen" filter considered in section 3.

5. First experimental results and discussion

Angular distributions of radiation generated in the Cr/Sc structure are shown in figure 7 and 8. The black points in figure 7 show the angular distribution of density of radiation generated in the Cr/Sc structure at $\theta_0 = 41°$.

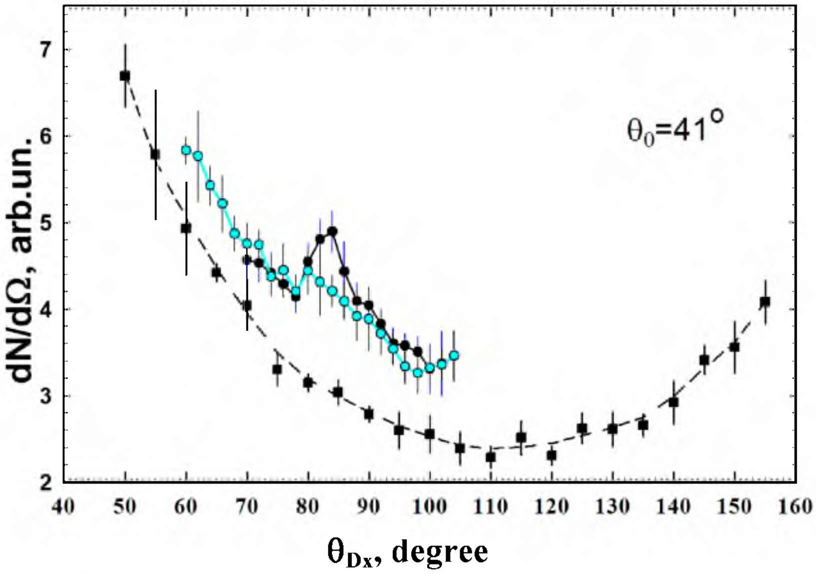

Figure 7. The black points are for radiation emitted from Cr/Sc structure at $\theta_0 = 41°$. The light points are for the Si_3N_4 substrate without Cr/Sc structure. Lower curve shows background level.

The light points are for radiation generated by the nude substrate (Si_3N_4 membrane) at the same angle $\theta_0 = 41°$. The black and light points in figure 8 correspond to the angular distribution of radiation generated in the Cr/Sc structure at $\theta_0 = 55°$ and $\theta_0 = 35°$, respectively. The lower dashed curves, shown in figures 7 and 8, present background level measured when the electron beam did not hit the target.

Comparison of the results of measurements, presented in figure 7 and 8, with the calculations presented in figures 4(a) and 5, shows that the experimentally observed trend of change of the intensity of the maxima of the angular distributions, namely the existence of the global maximum of radiation intensity near $\theta_0 = 41^\circ$, is in qualitative agreement with the PR calculations.

The FWHM of the PR angular distribution is about 6° that is about in 2 times less than typical value of FWHM of BTR one. As can be seen from figure 7, the Cr/Sc structure generates radiation with intensity more 2 times larger than the Si_3N_4 membrane, but this value is almost 10 times less than that derived from model calculations for an ideal periodic structure.

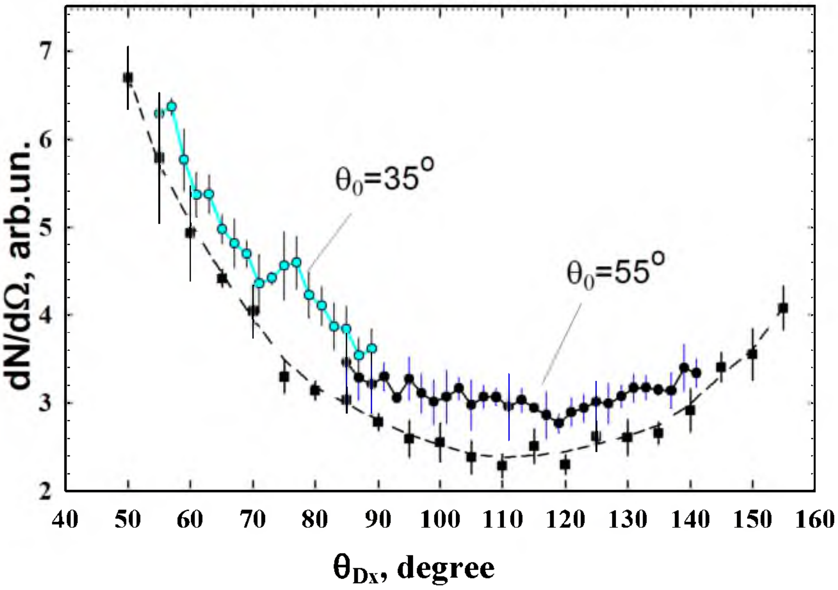

Figure 8. The black and light points illustrate the emission from Cr/Sc structure for the two angles $\theta_0 = 55^\circ$ and $\theta_0 = 35^\circ$, respectively. Lower curve shows background level.

In addition, due to the small thickness of the substrate, the electron beam is scattered weakly, even at high angles of inclination of the target, and completely falls into the aperture of the Faraday cup, that eliminates the need of correction of the value of electron current measured, that associated with a change in the thickness of the target when the target is rotated.

6. Conclusion

The presented results of the test experiment show the low yield of generated radiation. Probably, the reason of the essential difference between experimental and theoretical values of PXR yield results from interfacial roughness, mutual diffusion of layer materials and lack of flatness of the substrate because these factors can severely deteriorate efficiency of PXR generation, as it takes place concerning the decrease of reflectivity of real photons in X-ray optics due to imperfection of X-ray mirror. An improvement of the multilayer fabrication technique is necessary to minimize these radiator defects in order to create an effective source of radiation. Due to the thin (thickness – 0.5 μm) Si_3N_4 substrate of the multilayer structure, the contribution of background radiation generated in the target was less in about 3 times than that in experiments [9, 10] when a multilayer structures had the thick Si substrates. Additionally, the use of target with very thin substrates might be promising to increase the efficiency of this type of radiator when using cyclic accelerators because of possible multiple passes of electrons through them [16].

It should be noted that the structure composed of Cr and Sc layers is capable to generate the Cherenkov radiation because the values of $\chi'_{Cr/Sc}(\omega_{LCr})$ and/or $\chi'_{Cr/Sc}(\omega_{LSc})$ may exceed 0 near the L absorption edges of Cr and Sc (see figure 2b). By means of optimizing of the ratio of the thicknesses of Cr and Sc layers, the effect of diffracted Cherenkov radiation can be observed at the appropriate orientation of the structure with respect to an electron beam [17, 18].

Acknowledgements

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