Channeling of 20-35 MeV electrons in Si substrates of multilayer structures

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Abstract. Studying on X-rays generation by 20 – 33 MeV betatron electrons at its grazing incidence on a 56 μm Si plate with 1.5 mm length along the electron beam are presented. The plate was prepared from the Si samples used as substrates to create the multilayers on their surfaces. The photos of the angular distributions of generated X-rays show its concentration along atomic axis [110] and atomic planes (110) and (111). That is due to electron channeling when electron moves along atomic axis or plane and radiates in a narrow cones along its directions. As a result, that forms the narrow spot and bands of intensity within the broad cone of ordinary bremsstrahlung. A capture of electrons in the channeling mode at large angles between crystallographic planes and electron beam takes place due to multiple scattering of electrons in the bulk of the crystalline plate. The orientation dependence of angular pattern and spectra of radiation in the intensity spot and bands were measured. Such a complicated “background” is necessary to take into account at studying the X-rays generated in the layered structures created on Si plates, which manifest itself also in the bands of intensity oriented along the layers.

1. Introduction
Studying on X-ray generation by fast electrons in single crystals and periodic stacks of micro-thick crystals or amorphous foils performed at the Tomsk synchrotron [1, 2] led to the investigations of artificial nanostructured radiators such as multilayer X-ray mirrors and X-ray waveguides. Multilayer X-ray mirrors are widely used in X-ray optics for producing the X-ray beams with required parameters under Bragg reflection of real photons. The experiments at the synchrotron showed that they can also be as effective X-rays generators excited by 300–900 MeV electrons. The experiments were carried out with the use of X-ray mirrors consisting of several hundreds of layers of tungsten W and boron carbide B₄C with the thickness of 1.2–4.0 nm. When a fast electron crosses such structure at a certain angle to a set of layers, X-rays are emitted in a narrow cone in the Bragg direction due to the diffraction of pseudophotons of the fast electron field at a periodic layered structure. Later, the studies were carried out with regard to the characteristics of radiation generated by the 15–33 MeV electrons in the X-ray multilayer mirrors and waveguides which were installed inside the chamber of the 35 MeV betatron [3–5]. X-ray waveguides consisting of a pair of thin layers and in-between channels made of lighter material, are actively investigated in X-ray optics [6] as one possible way to generate microbeams for practical purposes. By compressing the broad beams of the primary X-rays that is directed towards the waveguide surface and then passes it through a channel in waveguide modes, a secondary source of narrow focus radiation can be generated at the output waveguide. In our experiments such structures were used as the waveguide radiators with new X-ray emission which occurs when electrons cross the radiator at sliding angles to the layer structure consisting of two 100
nm layers of tungsten and in-between 50 nm carbon gap. X radiation generated by electron in the material of the radiator or at the interfaces is captured into the waveguide channel and propagates it in the waveguide modes, forming the output sharp focus source with a narrow angular distribution of radiation, determined by the angle of total reflection of photons from the waveguide walls. The size of the source focus equals to the waveguide width which can be reduced to the value of about 10 nm, according to Heisenberg's uncertainty relation for the transverse photon momentum and coordinate. We presently investigate the generation of X-rays by fast electrons in more complex structures then a homogeneous multilayer mirror or simple waveguide. These structures consist of layered periodic substructures, i.e. X-ray mirrors, separated by waveguide channels. Currently such structures are referred to as non-uniform X-ray photon crystals in the X-ray optics. The use of these structures as new X-ray source provides the combination of the effect of parametric X-ray radiation in the channel walls layered structures with the waveguide effect for X-rays generated in the substructures and penetrating the radiator in the waveguide modes similar to the Borrmann effect with low absorption. Such structures are created on single-crystal silicon substrates. To determine the influence of possible "disturbing" effects by X-rays generated by fast electrons in a crystalline substrate on the pattern of generation of radiation in the layered structure, the study [7] was carried out. The angular distributions and spectra of radiation generated in the "bare" silicon plate with a thickness of 200 microns and a length of 4 mm along the electron beam were investigated. The sample was identical to those we used to produce layered structures on their surfaces. The influence the plate crystal structure on the formation of the angular distribution of generated radiation was shown. Concentration of radiation intensity in the direction of crystallographic planes (111) was observed. The intensity bands follow the directions of the atomic planes at tilting the crystal relative to the direction of electron beam. This effect was assigned to the fast electron channeling along crystal atomic planes (111). At channeling, electrons move for a time along the atomic plane in the bound states of transverse motion [8], emitting X-rays in a narrow cone along the planes due to spontaneous transitions between the levels of bound states [9] and bremsstrahlung, born on the nuclei of the plane atoms. Therefore, the effect manifests itself within a broad cone of usual bremsstrahlung from electrons scattered in the crystal in chaotic manner. The existence of the bands at electron beam disorientation relative to the atomic plane at the angle exceeding critical channeling angle $\theta_c$ shows that electrons are captured into the channeling mode within the crystal volume due to their multiple scattering [10].

This paper presents the results of observing the influence of volume capture of 20 – 33 MeV electrons into the channeling along the atomic planes (111), (110) and along atomic axis [110] of Si plate with the thickness of 56 microns and a length $L = 1.5$ mm in the direction of the electron beam. That is ultra-thick crystal for the channeling effect because its length exceeds the channeling length $L_{ch}$ in a few hundreds times. This plate was cut from the 0.28 mm Si substrate of X-ray mirror and polished to the required thickness.

2. Experimental setup

Figure 1 shows the scheme of experimental setup established on the basis of the B-35 betatron. The betatron was equipped with a special experimental chamber (1). Under the action of additional magnetic field created by a special coil for 30 ms, the orbit radius for accelerated electrons decreased and the electron beam hit the radiator (2) placed in the goniometer (3). The goniometer was located inside the chamber but had an external control system of the radiator attitude relative to the electron beam. The recurrence rate of acceleration cycles is 50 Hz, the divergence of the electron beam incident on the radiator is 0.3 mrad, and the electron energy spread is about 0.5%. The radiation emitted from the radiator was transmitted through 50 $\mu$m Mylar window and hit the X-ray film (4) or the Si detector (5) located at a distance of 105 cm from the radiator. The detector aperture is 13 mm$^2$, and the energy resolution for the line Am (13.95 keV) is 250 eV. The detector can be displaced relative to the axis of the generated radiation cone.
Silicon wafers are traditionally used as substrates designed for building on their polished surfaces of layered periodic structures by deposition of alternating layers of heavy and light materials. Such plates were used by the authors [5] to fabricate the W-C-W waveguide structures. Figure 2 shows a scheme of the Si plate location relative to the direction of the electron beam (solid arrow) hitting the plate surface. The dotted arrow shows the direction of crystallographic axis [011] of the crystal plate, and its lateral surface coincided with the (100) crystallographic plane. The crystal plate with a thickness of 56 ?m, vertical and horizontal (along the electron beam) sizes of 5 and 1.5 mm, respectively, was placed on a vertical thin holder of the goniometer that enabled the crystal rotation around the vertical axis. At changing the angle of electron incidence on the crystal, the electron beam was directed along the horizontal dotted line in such a way that consistently coincided with the direction of the crystallographic planes (-1-11) and (001). In experiment, the angular length of the line was 6.4°.

3. Experimental results
The angular distributions of radiation were photographed with X-ray Retina films at a distance of 44 cm from the crystal plate. Photographs were processed with a scanner to obtain intensity profiles in the angular distribution of radiation. Photos of the radiation angular distributions for three orientations of the crystal plate relative to the direction of electron beam, shown in figure 3, demonstrate the influence of crystal structure on the formation of the angular distribution, with its form varying versus the crystal orientation. The radiation concentration is observed in the directions of crystallographic planes.

Figure 1. Experimental setup: 1 – betatron chamber, 2 – crystal, 3 – goniometer, 4 – photofilm, 5 – detector, Bs – bremsstrahlung, CR – X-rays from channeling electrons.

Figure 2. Scheme of [011] Si crystallographic direction and disposition of Si plate with respect to electron beam.
(011), (111) and axis [011] in such a manner that elements in the form of bands and spots are formed in addition to the usual bremsstrahlung cone. Decreasing the electron energy from 33 to 20 MeV, the width of the bremsstrahlung cone, as well as that of bands and spots are increased in about 1.5 times.

Figure 3. Photographs of X-ray distributions.

This means that both bands and spot are not formed by the diffracted bremsstrahlung. From the experience in studying the orientation effects for a few MeV electrons [9, 11], it was assumed that photos of the angular distributions of X-ray radiation of the accelerated electrons penetrating the crystal show the channeling effect of fast electrons along the atomic planes and axis. The channeling electrons move along the atomic plane or axis and generate radiation in a cone with a solution of about $\gamma^{-1}$ ($\gamma$ is an electron relativistic factor) along the axis or plane. Therefore, the effect manifests itself in the radiation angular distribution as an additional intensity band or a spot within the broad cone of bremsstrahlung from electrons that were repeatedly and randomly scattered during the penetration into crystal. As a result, the angular distribution of radiation consists of a cone of bremsstrahlung and the additional contribution of radiation from the channeling electrons, with its elements, given a thick crystal, being much narrower as compared to the bremsstrahlung cone with the width depending, apart from the relativistic factor, on the multiple scattering of electrons in the crystal. In the case of 33 MeV electrons, the angle $\gamma^{-1} = 15$ mrad, and the cone width of bremsstrahlung is much greater because the electron multiple scattering is quite large with the given crystal.

According to the scheme shown in figure 2, at crystal plate turning in the goniometer in a horizontal plane, electron beam is directed at different angular distances off the crystallographic planes. Figure 3 shows photographs of the angular distributions of radiation generated by 33 MeV electrons in Si plate at the angle $\theta = 115, 18$ and 4 mrad between the electron beam and the vertical atomic plane (001) – photos a, b and c, respectively. The directions of the main crystallographic planes are shown in each photograph, and the direction of electron beam is in the center of a wide dark spot caused by bremsstrahlung. The bands coincided with the directions of the crystal atomic planes and
displaced when tilted. At the same time, the direction of the cone axis of bremsstrahlung generated in the crystal as an amorphous medium remains constant. The top image of X-ray angular distribution generated at $\theta = 115$ mrad demonstrates mainly the effects defined by atomic planes (011) and (111), and the middle photo obtained at $\theta = 18$ mrad mainly contains bremsstrahlung and additional darkening in the direction of the crystallographic axis [011]. On their background, the effects from the crystallographic planes are less pronounced. The lower image shows only an intense spot of ordinary bremsstrahlung and less intense spot in the crystallographic axis [110]. Here, the effects defined by the atomic planes (011) and (111) are not evident.

Figure 4 shows the profiles of the density of blackening in the image of the angular distribution of radiation obtained by processing the image in figure 3c on the scanner, for horizontal scan lines - through a spot of bremsstrahlung, curve 1, and through the top spot, curve 2, formed by radiation from electrons channeling along atomic axis [011]. The width of a curve at half height of about $\Delta_1 = 2.1^{\circ}$ is greater than the theoretical estimation $\Delta_{Br} = \gamma^{-1} = 0.87^{\circ}$ for this parameter of the angular distribution of bremsstrahlung in the neglect of electron multiple scattering. This broadening of the distribution is determined by multiple scattering of electrons in the crystal plate. The width of curve 2 is about $\Delta_2 = 1.6^{\circ}$, which is less than $\Delta_1$ because this distribution consists of bremsstrahlung distribution with a width $\Delta = \Delta_1$ from the multiply scattered electrons and a narrower distribution of radiation from the electrons channeled along atomic axis [011] with a width $\Delta_{Ch} < \Delta_1$ due to the bound movement of channeling electrons along the atomic rows without random scattering. They radiate due to spontaneous transitions between the levels of bound states of its transverse motion in a pair of atomic rows [011], as well as emit bremsstrahlung at interactions with the atomic nuclei of the rows. In order to separate the contribution of radiation generated by the channeling electrons, the subtraction of curve 3 from curve 2 was made. Curve 3 represents the curve 1, but scaled so as to "seam" it with curve 2 on its “tails”. It was assumed that curve 3 could describe the contribution of bremsstrahlung from randomly scattered electrons in this case. The result of subtraction is represented by curve 4. The angular distribution of radiation from channeling electrons has a half-height width of about $\Delta K = 1.2^{\circ}$, which is somewhat higher than the estimate of $\gamma^{-1} = 0.87^{\circ}$. This is probably due to the fact that the distribution is "smeared" because of the transverse oscillations of electrons channeled along a pair of atomic rows [011].

The existence of bands at the electron beam disorientation relative to the atomic plane at an angle $\theta$ significantly exceeding the critical angle $\theta_{cr}$ for channeling shows that electrons are captured into the channeling mode within the crystal volume with their multiple scattering. In addition, the crystal thickness exceeds the length of the electron channeling in about 300 times, which also excludes a significant role of direct electron capture into the channeling mode on the crystal surface.

The experiment also included the measurement of the spectra of radiation generated by 33 MeV electrons channeling along the crystallographic axis [011] and also by electrons multiple scattered in the bulk of the Si plate. Figure 5 shows the spectra of radiation emitted by 33 MeV electrons in the
direction of the center of the top spot in figure 3c, curve 1, and in leftward direction of 9 mrad off, curve 2. The spectra are normalized to the yield of radiation at photon energies > 55 keV in order to allow determining changes in the spectrum shape at the alteration of the electrons penetration mode in the plate thickness. The emission spectrum measured along the axis [011] shows no obvious peaks due to spontaneous transitions between the bound states of channeling, which occur in the case of thin crystals [9] with the thickness being of the order of channeling length. But at the same time, the spectra comparison shows the difference in the X-ray photon energy range of about 10–25 keV. Estimates show that it can be defined by the spontaneous transitions of electrons between the topmost levels of their motion states bound with atomic rows [011] during the crystal penetration.

4. Conclusion
The experiments have shown that the effect of electron channeling significantly changes the general form of the distributions of radiation generated in the crystal plate even if angular distances between electron beam and crystallographic planes or axis are greater then $\theta_c$, and $L \gg L_{ch}$. But, in this case the electrons can be captured in the channeling along the crystal atomic planes or axis by the effect of volume capture [10] at a multiple small-angle scattering, when the electron trajectory gradually turns to the direction of the atomic plane or axis, as well as at a strong single scattering when an electron abruptly changes its trajectory to the direction along the atomic plane or axis. In both cases, having been capturing into the channeling mode the electrons move for some time along the atomic plane or axis in the bound states of transverse motion in a potential of atomic plane or axis [8]. The channeling electrons generate bremsstrahlung on the nuclei of atoms of the atomic plane or axis, as well as spontaneous radiation due to transitions between the levels of the bound states of transverse motion. The cones of these emissions from the channeling electrons are much narrower than that of ordinary bremsstrahlung of electrons randomly scattered in the bulk of the crystal. The cone of ordinary bremsstrahlung is strongly broadened by multiple scattering of the electrons, and the widths of both cones of radiations from the channeling electrons are defined by the electron relativistic factor. As a result, the channeling effect provides additional elements having the forms of narrow stripes and spots in addition to a wide spot of ordinary bremsstrahlung. These studies were undertaken to determine the possible role of any effects in the crystals, which can prevent the observation of radiation generated by electrons in layered structures created on the surface of these crystals as on substrates. Non-uniform photonic crystals that are currently studied by the authors as a new X-ray radiator, are periodic structures consisting of a lot of alternating layers of tungsten and carbon, which have the non-uniformity inside in the form of the channel through which the radiation generated in periodic structures passes in the waveguide modes and forms the output angular distribution in the form of intensity bands oriented along the structure layers. Therefore, it is important to consider the interfering
factors determined by the crystalline substrate when studying the effects in the radiation generated in the layered structure created on the substrate.

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