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Influence of the working surface roughness of the pulsed X-ray radiation galvanic sensor on its performance

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A new design of a galvanic sensor of pulsed X-ray radiation is proposed, which is a flat electric capacitor with a window in one metal lining and a solid dielectric made of a single-crystal sapphire with a thickness of $200-300\,\mu$m inside. The influence of the surface roughness of the sapphire in the window area on the galvanic linear sensor of X-ray radiation has been established. Tests have shown that, with ultra-smooth polishing of the sapphire plate working surface in the window area to a roughness of $R_q \leqslant 0.2$ nm, it is possible to provide the galvanic linear detection of X-rays with an energy in the range of $0.1-1$ keV and power density of $1-2\,\mathrm{MW}\cdot\mathrm{cm}^{-2}$ with a sensor response time of about 8 ns. Sensors of this type can be used in studies of inertial nuclear fusion processes.

Keywords: X-ray radiation, galvanic sensor, sapphire, dielectric, flat capacitor.

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Detection of high-power X-ray fluxes in experimental investigations is one of the important tasks in the field of nuclear physics and physics of ionizing radiation interaction with solids. There have been proposed and applied a number of methods for measuring radiation parameters [1], which are mainly based on the effect of the radiation-induced ionization of atoms. Investigations in the field of inertial fusion synthesis have defined new diagnostics tasks [2], for instance, a task of developing a method for detecting plasma electromagnetic radiation, which is to meet the following basic requirements:
i) the operating measurement range should be within the photon energy range of $0.025-10$ keV;
ii) the time resolution should be about units of nanoseconds;
iii) the sensor sensitivity should remain within the linear region when the radiation flux power density exceeds $1\,\mathrm{MW}\cdot\mathrm{cm}^{-2}$.

Studies devoted to searching for materials and circuitry for such detectors of pulsed high-power-density X-ray radiation which are simple, reliable, and able to ensure fast response and linearity of the response signal, are in progress. Measurements of the pulsed X-ray radiation intensity are typically performed by using solid-state semiconductor detectors whose sensitivity is defined by energy consumption ΔE necessary for formation of a pair of charge carriers: $\Delta E \sim 3$ eV for silicon, $\Delta E \sim 13$ eV for diamond [3]. Among the drawbacks of semiconductor detectors there is the fact that investigation of inertial fusion synthesis needs for detecting radiation in the linear sensitivity range under vacuum conditions and removal of the detector (even the diamond one) to the distance of a few tens of meters from the radiation source; this makes the design of the fusion facility much more complicated and, sometimes, is merely impossible. In addition, filters used to reduce the intensity of incident radiation at the same time distort its spectral composition, which prevents identification of processes taking place in the fusion target.

Detection of pulsed ionizing radiations with high power densities is possible also based on other physical principles, e.g. by using scintillation counters. For instance, disordered arrays of ZnO single crystals on substrates produced intense luminescence in the UV spectral range with the attenuation time below 1 ns in a high-power X-ray beam [4]. The disadvantages of this radiation detection method are small area of the array working surface and considerable nonuniformity of the X-ray luminescence parameters over the area and complexity of the detector hardware. In addition, as tentative data showed, ZnO single crystals, contrary to diamond and sapphire crystals, cannot reach the required radiation resistance.

Besides semiconductor detectors, inertial fusion synthesis facilities use for routine measurements of high-power X-ray fluxes secondary-emission X-ray detectors (SEDs) whose sensitivity may be varied by changing the cathode material [5]. However, SEDs application in detecting high-power-density X-ray radiation, as well as application of semiconductor detectors, is restricted because of saturation effects. SEDs may be used only jointly with various

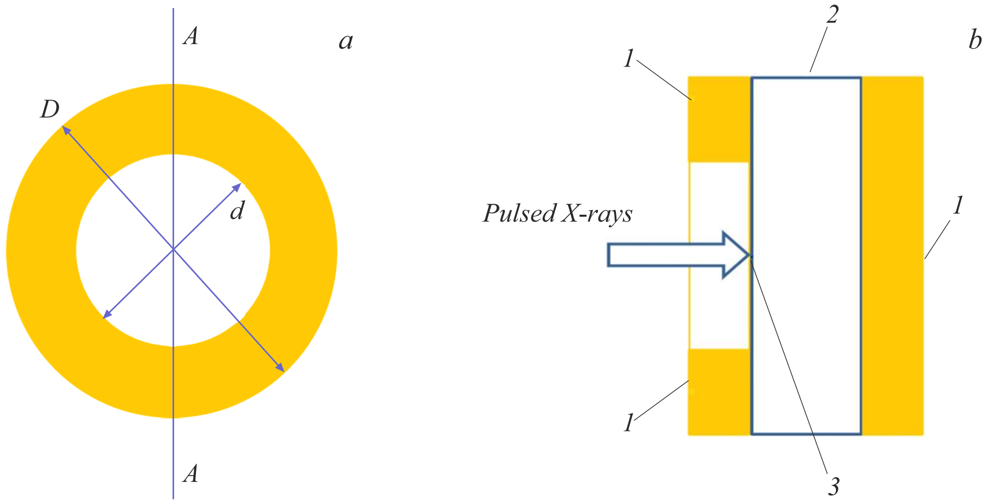

Figure 1. Design of the galvanic sensor of pulsed X-ray radiation (schematic diagram).*a* — frontal view, sensor diameter $D \approx 18-19$ mm, working window diameter $d \approx 14-15$ mm; *b* — section along *A–A*: *1* — golden electrodes $1-5\,\mu$m thick, *2* — single-crystal-sapphire dielectric plate $200-300\,\mu$m thick, *3* — front (working) surface of the dielectric plate.

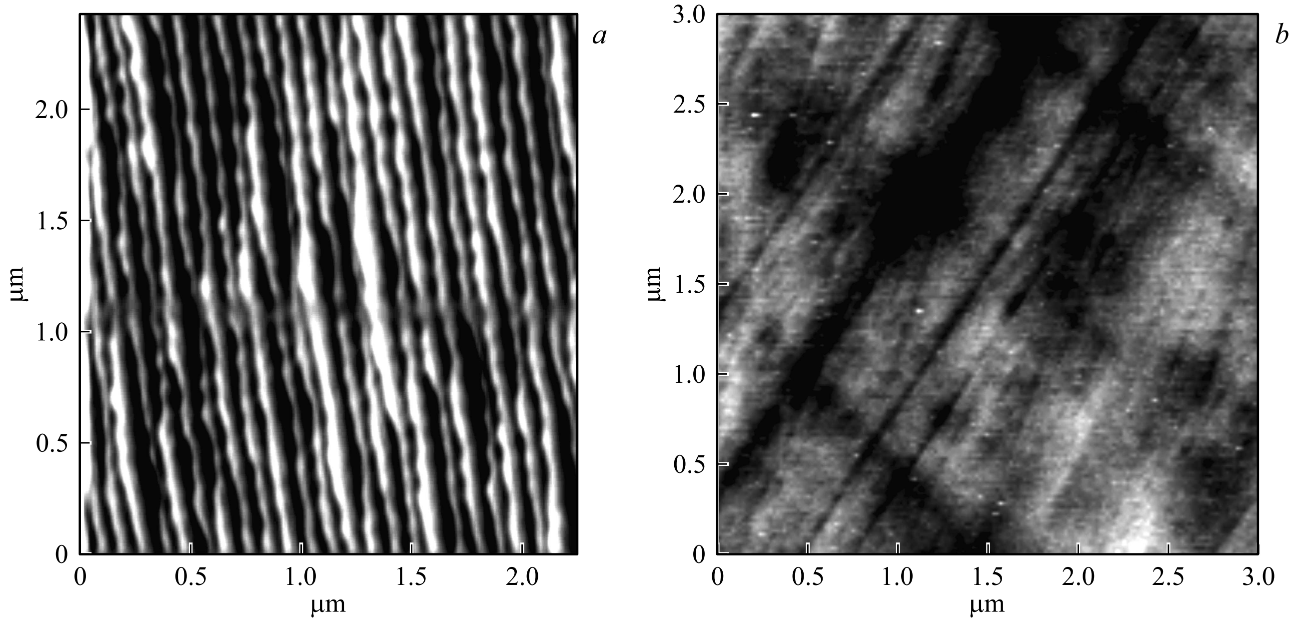

Figure 2. AFM images of surfaces of single-crystal-sapphire plates with working surface mean-square roughness of no more than 0.2 nm (*a*) and of 1–2 nm (*b*).

attenuating filters. Implementation of this method needs vacuum conditions, the presence in the measurement circuit of a high voltage source, and accounting for the emission response dependence on photon energies of the radiation to be measured. Along with this, degradation of the emitting surface takes place in the case of high power of the measured radiation fluxes.

Search for new engineering solutions in the field of detection resulted in developing a method for reliable measurement of high radiation intensities $I \approx 10^5-10^7\,\mathrm{W \cdot cm^{-2}}$ characterized by a simplified measurement circuit and reduced cost [6]. In implementing this method, the sensitive element was made as a thin dielectric plate with the first and second metal contacts applied on two opposite larger-area planes of the plate; thickness of the first contact was so that it was transparent for the ionizing radiation. The detector based on that radiation-sensitive element will be installed on the way of the ionizing radiation to be detected so that the plate side with the first contact is oriented towards the ionizing radiation. The method consists in measuring an electrical signal induced by the radiation in the solid radiation-sensitive element made from quartz glass KU-1 with relatively high energy of the free charge carrier formation $E \sim 150$ eV. Among the method [6] disadvantages there is a quite long signal rise time (40 ns) characterizing the method performance, as well as a greatly extended response to the pulsed X-ray radiation.

In order to overcome those disadvantages, i. e. to improve the performance of the high-power-density X-ray detector, this paper proposes a novel detector circuitry. In fabricating this detector, dielectric plates from another dielectric were used, namely, from single-crystal sapphire. In addition, the effect of the sapphire surface roughness on the X-ray detector performance was studied.

In this work, the galvanic sensor design was modified as compared with that presented earlier in [6]: one of the sensor electrodes was made in the form of a ring (Fig. 1). In the process, dielectric single-crystal-sapphire plates 200−300 μm in thickness and 18−19 mm in diameter were used; their working surfaces were polished according to the earlier-developed technique [7] (Fig. 2, *a*, *b*): Type I — with atomically smooth steps and mean-square roughness R_q of no more than 0.2 nm; type II — with traces of polishing and mean-square roughness of 1−2 nm. Golden electrodes 1−5 μm thick were applied on the sapphire plates by thermal deposition.

Then the sapphire sensors (Fig. 1) were tested as part of a trivial electrical detection unit consisting of a load resistor and pulsed oscilloscope-voltmeter similar to that described in [6]. As a source of X-ray radiation (with the total peak power of up to 10^{13} W), mega-ampere *Z*-pinch plasma was used, which was obtained at a specialized fusion facility Angara-5-1 [8]. The X-ray photon energy was 0.1−1 keV, the pulse power density was 1−2 MW · cm^{-2}. Microscopic measurements were performed using atomic force microscope (AFM) „Integra Prima" (NT-MDT, Zelenograd).

Testing of sapphire sensors designed and fabricated according to the circuit diagram shown in Fig. 1 was carried out. As expected, SED sensors distinguish themselves in high performance (curves *0* in Fig. 3, *a*, *b*); however, they possess the drawbacks mentioned in the introductory part of the paper. Among the sapphire-based new-type sensors studied in this work, the best performance (pulse rise time of about 8 ns) under irradiation with pulsed X-ray radiation from *Z*-pinch was offered by the type I sensor (Fig. 3, *a*). The type-II sensor (Fig. 3, *b*) characterized by a higher roughness R_q of the front (working) surface exhibited a lower performance (the front rise time of about 32 ns). For comparison, sensors based on glass KU-1 with uncontrollable surface roughness [6] exhibited under irradiation with pulsed X-rays from *Z*-pinch the signal rise time of $\sim$ 40 ns. It is also worth-noticing that the galvanic signal from the type-II sensor (Fig. 3, *b*) evidently differs in length and shape from the X-ray pulse. The proposed modification of the sensor design (Fig. 1), including replacing glass KU1 with single-crystal sapphire with the working surface roughness of no more than 0.2 nm, provides a multiple increase in the sensor performance.

Phenomena observed in the sensor of the proposed design under high-power X-ray irradiation may be interpreted in the framework of the following model. Electromotive force

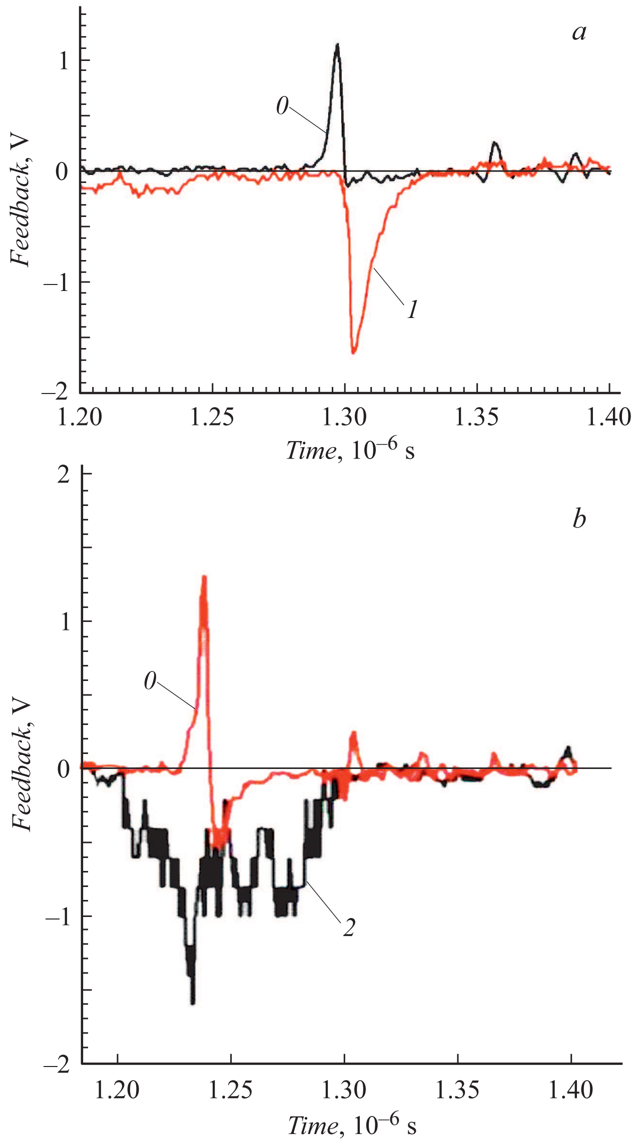

Figure 3. Comparison of signals (X-ray pulse power density of $\sim$ 2 MW · cm^{-2}) of radiation sensors of types I (*a*) and II (*b*) with those of SED. *0* — SED, *1* — type I, *2* — type II.

gets generated at the metal−semiconductor interface due to radiation-induced conductivity caused by the motion of nonequilibrium charge carriers, namely, conduction electrons. Nonequilibrium distribution of excess charge carriers in dielectrics emerges under X-ray irradiation. X-ray radiation gets absorbed in a quite thin (about 1 μm) near-surface layer of dielectric and generates electrons. This process is described by the classical photon- and electron-transport equations. Photons and photoelectrons lose their energy which is sufficient for exciting electron-hole pairs. In the conduction band there arise excess electrons with the mobility quite higher than that of valence-band holes. High-power X-ray radiation produces in dielectric sensors a sufficient number of electrons. The generated strongly nonuniform electric field initiates directed radial motion of electrons emerging in the near-surface layer. In this case, physical processes may be described in terms of radiation-induced conductivity. It is known that, being mechanically polished, the near-surface layer of the type-II sapphire crystals is „distorted" [7], i.e. contains point, linear and three-dimensional defects characteristic of sapphire. In this crystal region there can occur additional long-living energy levels able to capture both electrons and holes generated by an X-ray pulse, which finally leads to an increase in the relaxation time of a cloud of electron-hole pairs (curve *2* in Fig. 3, *b*). The same arguments are applicable also to glass that is, contrary to single crystals, micro-nonuniform in its nature. Theoretical fundamental principles of emergence in a crystalline dielectric of radiation-induced conductivity and electric field are considered in more details in [8,9].

Thus, the paper proposes a new design of a galvanic sensor of pulsed X-ray radiation, that is, a flat electric capacitor with a window in one metal lining and solid single-crystal-sapphire dielectric $200-300\,\mu$m thick inside the capacitor. Sensors of this type can be used in studying inertial nuclear fusion processes. We have established that, to make possible the galvanic linear detection of X-ray radiation with the energy of $0.1-1$ keV and power density of $1-2\,\mathrm{MW}\cdot\mathrm{cm}^{-2}$ at the detection response time of about 8 ns, the dielectric plate front surface facing the source of pulsed X-ray radiation through the window in the metal lining should possess low roughness $R_q \leqslant 0.2$ nm. In experiments on detecting high-power pulsed X-ray fluxes, an increase in surface roughness R_q of the dielectric plate front side leads to a significant increase in the sensor response time, just due to which delinearization of the sensor response to the X-ray pulse takes place.

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Conflict of interests

The authors declare that they have no conflict of interests.

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