Technical Physics Letters, 2024, Vol. 50, No. 10

04.2;13.2

Radiation-induced effects in wide-gap dielectrics

© *I.A. Baryko*[1,2], *V.I. Zaytsev*[1], *A.A. Kartashov*[1], *A.A. Samokhin*[1], *I.A. Tarakanov*[3], *V.E. Tcherkovec*[1]

[1] Troitsk Institute for Innovation and Fusion Research, Russian Academy of Sciences, Troitsk, Moscow, Russia
[2] Russian Peoples' Friendship University, Moscow, Russia
[3] Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, Russia
E-mail: barykov@triniti.ru

Received May 2, 2024
Revised June 3, 2024
Accepted June 5, 2024

The results of studies of electron emission (photoelectric effect) from a wide-gap SiO_2 dielectric under the influence of electromagnetic radiation in the quantum energy range of 10–1000 eV are presented. Experimental studies were carried out on the ANGARA-5-1 facility. It is shown that the interaction of radiation with the surface of a dielectric is accompanied by electron emission from the dielectric and the appearance of an electric field in the dielectric. The measurement technique used is described. The experimental results are compared with mathematical modeling data.

Keywords: Plasma, x-ray, dielectric, surface.

DOI: 10.61011/TPL.2024.10.59687.19980

The implementation of new technologies, such as controlled thermonuclear fusion and nanoelectronics, requires the production of sources of intense electromagnetic radiation fluxes, where traditional methods of measurement of radiation parameters are often either inapplicable or too difficult to use. For example, just $\Delta E \sim 1-3$ eV [1] is spent on production of a pair of charge carriers (electron + ion) with traditionally used semiconductor detectors. A series of experiments on the interaction of bremsstrahlung radiation of an electron beam with an energy of 300–600 keV with dielectrics were performed at the Sandia Laboratory (United States). Pilot studies into the processes of interaction of electromagnetic radiation with dielectrics at the Angara-5-1 facility revealed the possibility of measuring the parameters of megawatt radiation fluxes with dielectric detectors [2]. In the present study, we report the results of further experiments with a quartz sample aimed at characterizing the processes of interaction of soft X-ray radiation with dielectrics.

Radiating plasma was generated at the Angara-5-1 facility that houses eight megavolt generators with a common radiating load. The parameters of generated radiation are governed by the load design. An assembly of coaxially arranged thin metal wires was used as a load in the experiments under consideration. Under the influence of megaampere currents (3–4 MA), tungsten wires ($D \leqslant 10\,\mu$m) are compressed toward the axis and enter a plasma state that consists of free electrons and stationary ions and emits quanta within the 10–1000 eV energy range with a power of 1–2 TW for 10^{-8} s. The time-integrated spectrum of a radiation pulse is shown in Fig. 1. Radiation with this spectrum has a fairly small depth of penetration into a solid dielectric (the radiation intensity is attenuated by 95% at a depth of $1\,\mu$m), and the produced ions may be regarded as a surface charge. Dielectric samples were positioned at a distance of 2 m from the source, where the radiation power was $W = (1-2) \cdot 10^6$ W/cm^2 at the maximum of a pulse. it is known [3] that quantum energy $\Delta E_1 = 17$ eV is spent on forming an electron–ion pair in quartz. Electronic work function ΔE_2 of quartz is close to 3 eV. Thus, the lower boundary of the electromagnetic radiation spectrum for inducing photoemission in quartz is $E \sim 20$ eV. It can be seen from the electromagnetic radiation spectrum that all quanta incident onto the dielectric satisfy this criterion. However, the electric field of produced ions and the field of electrons accumulated near the surface (especially under intense radiation fluxes) dilute this potential. The effect in question was described in detail in [3].

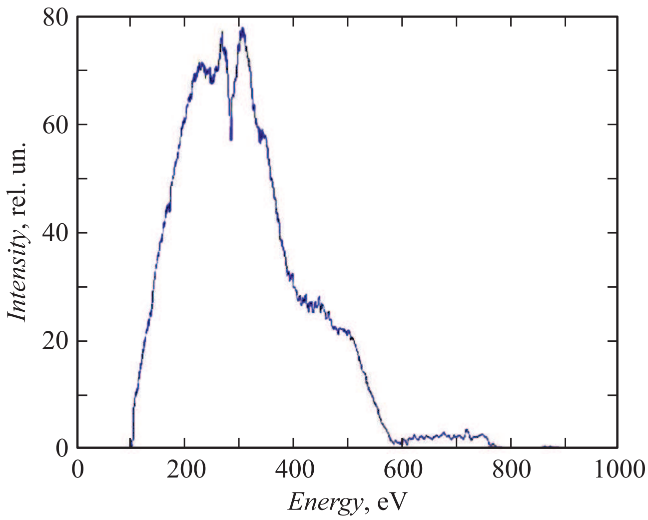

Figure 1. Integral spectrum of radiation of the plasma load state in a pulse at the Angara-5-1 facility.

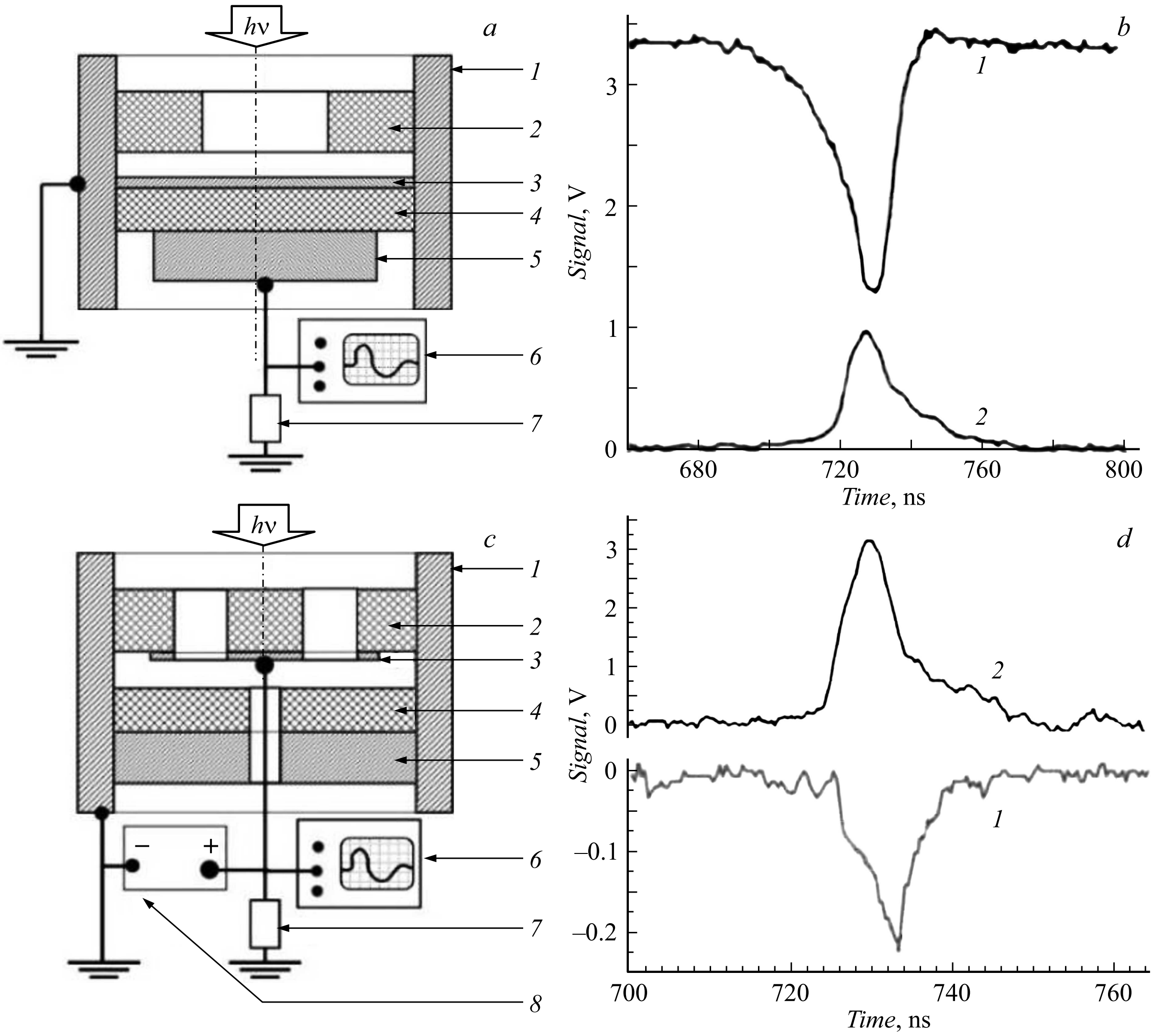

Figure 2. *a* — Diagram of the potential dielectric detector. *1* — Sensor housing (metal cylinder), *2* — collimator, *3* — input metal (Au) coating, *4* — dielectric, *5* — metal substrate, *6* — oscilloscope, and *7* — load resistance (50 Ω). *b* — Recorded signal of the potential dielectric detector. *1* — Response of the dielectric potential detector; *2* — response of the metal secondary-emission detector. *c* — Diagram of the current dielectric detector. *1* — Sensor body (metal cylinder), *2* — collimator, *3* — metal coating, *4* — dielectric (18 mm in diameter), *5* — metal substrate, *6* — oscilloscope, *7* — load resistance (50 Ω), and *8* — power supply. *d* — Recorded signal of the current dielectric detector. *1* — Response of the current dielectric detector; *2* — response of the metal secondary-emission detector.

This paper presents the results of further studies into the effects induced in quartz under the influence of megawatt-level electromagnetic radiation. Experiments were carried out using two measurement techniques. In both cases, the „grounded“ cylindrical body of an RK-50 high-frequency cable connector was the basis of the experimental measurement design.

Figure 2, *a* shows one of the designs with a dielectric as a sensitive element. This (potential) method of measurement of electromagnetic radiation was discussed in more detail in [4]. Figure 2, *b* illustrates the corresponding detector response. It is evident that the signal is identical to the one of the metal secondary-emission sensor of the Angara-5-1 facility, confirming that this detector type is indeed suitable for detection of high-power pulsed X-ray radiation [5]. The detection sensitivity is $K_{h\nu} \sim 7.5$ V/MW. Note that the response is shaped in this case not by the electron current, but by the potential of produced ions (potential detector type). This detector type does not require an electric power supply, which is an additional advantage. It can be seen from Fig. 2, *a* that the crystal surface is coated with a thin (300 Å) Au layer. This coating is needed to collect electrons produced as a result of ionization of the dielectric and transport them to the load. However, it was discovered that the coating had evaporated under the influence of radiation after several cycles of operation of the facility. At the same time, the parameters of the detector response to the incident radiation flux did not change. Having discarded the mechanism of electron collection at the surface levels of the crystal, we concluded that a significant secondary emission from the crystal surface should be present.

A radiation detector presented in Fig. 2, *c* was designed to test this assumption. Since we were interested in determining the magnitude of electron emission only, it was decided against the use of well-developed methods of photoelectron spectroscopy in the discussed setup. The previous design was augmented with an electrode to which a voltage up to 500 V could be applied.

The additional electrode served to collimate the incident radiation flux and collect and transport the current of produced electrons to the load. This design ensures the detection of electrons located between the additional electrode and the dielectric, which can only be emission ones. The response to incident radiation is shown in Fig. 2, *d*. The obtained sensitivity is $K_{h\nu} \sim 10^{-2}$ A/MW. The irradiated surface area was 0.2 of the total surface of the dielectric. As in the case of the potential-type sensor, the response was virtually identical in shape to the pulse of the metal secondary-emission detector (Fig. 2, *d*), suggesting that the discussed current-type sensor design is suitable for measurements.

The primary process of interaction of emitted quanta (Fig. 1) with the dielectric material is photoionization, where a quantum is absorbed by an atom with the transfer of the atomic electron into a continuous spectrum. Since all processes proceed in a very thin near-surface dielectric layer ($\sim 10^{-6}$ m), the transport model is limited to electrons emitted from the surface and to calculation of the current density in the near-surface layer.

Electrons move under the influence of a self-consistent electric field. To model the electron kinetics, one needs to solve the non-stationary kinetic equation together with the complete system of Maxwell's equations. The electron scattering integral and the term containing the total macroscopic electron scattering cross section may be neglected in the kinetic equation:

$$\frac{\partial f}{\partial t} + \mathrm{div}_{\mathbf{r}}(\mathbf{v}f) + e\,\mathrm{div}_{\mathbf{p}}\left[\left(\mathbf{E} + [\boldsymbol{\beta}, \mathbf{H}]\right) f\right] = Q(t, \mathbf{r}, \mathbf{p})$$

where $\mathbf{E} = \mathbf{E}(t, \mathbf{r})$ and $\mathbf{H} = \mathbf{H}(t, \mathbf{r})$ are the electric and magnetic field strengths and $Q = Q(t, \mathbf{r}, \mathbf{p})$ is a source of electrons characterizing the intensity of their production at point $\mathbf{r}, \mathbf{p}$ in the phase space. The kinetic equations are closed by Maxwell's equations for the electromagnetic field components

$$\mathrm{rot}\,\mathbf{H} = \varepsilon \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}(\sigma \mathbf{E} + \mathbf{j}),$$

$$\mathrm{rot}\,\mathbf{E} = -\mu \frac{1}{c}\frac{\partial \mathbf{H}}{\partial t},$$

$$\mathbf{E}|_{t=0} = \mathbf{H}|_{t=0} = \rho|_{t=0} = 0,$$

where $\mathbf{j} = \mathbf{j}(t, \mathbf{r})$ is the electric current density set by the flux of particles in the interelectrode gap and the current in the near-surface dielectric region.

The boundary conditions are specified by the cylindrical design of the potential detector: the potential of the cylinder bottom is set by the sum of the field of ions on the dielectric surface and the electric field of the electron cloud near the dielectric surface, while the cylinder walls are grounded (zero potential). The collimator potential is determined by the voltage developed across the load resistance. Photoelectrons are knocked out of the dielectric surface under exposure to plasma photons (with a photon flux intensity of $\sim 6 \cdot 10^{22}\,\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$) at the Angara-5-1 facility. The produced electrons generate a current density component normal to the dielectric surface, forming an electric field that, working alongside with the field of ionized ions, decelerates photoemission electrons. This field reaches fairly high strength levels (approximately 45 kV/m) within the first 5 ns from the start of an X-ray radiation pulse and is sufficient to stop photoelectrons with an energy of 100 eV near the dielectric surface within a distance shorter than 500 μm. The maximum strength of the barrier electric field in the dielectric is on the order of 4.5 kV/cm.

The experimentally measured current was compared with the calculated current density in an equivalent conductor. The current was calculated according to Ohm's law with account for the cross-section area and a finite conductivity of the wire. Figure 3 presents a comparison of the experimentally measured current and the current calculated at a voltage of 100 V (as in the experiment) and at 0 V. A rather satisfactory agreement is seen in the region of maximum X-ray flux intensities.

Let us list the key findings of this study.

1. It was demonstrated that self-consistent electric fields are generated when soft X-ray radiation interacts with dielectric structures.

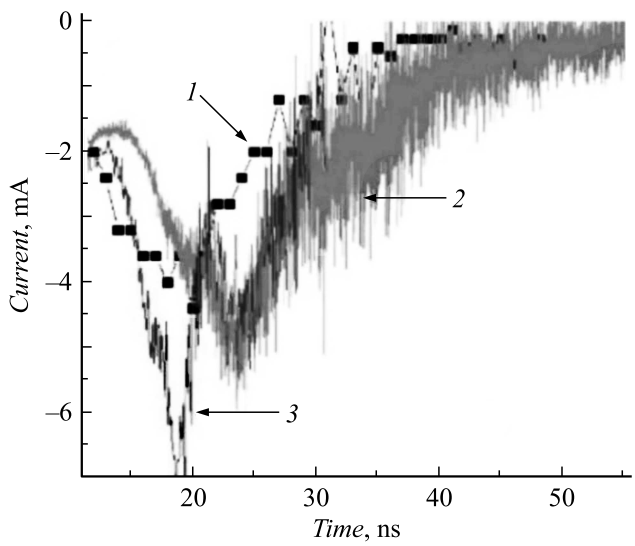

Figure 3. Comparison of time dependences of experimentally measured and calculated currents. *1* — Experimental current, *2* — Calculated current with zero voltage, and *3* — calculated current for a voltage of 100 V.

2. It was established that photoelectron emission is the primary mechanism of formation of electric fields.

3. Two types of dielectric detectors (potential and current) were designed and tested experimentally in the soft X-ray range.

4. A mathematical model for calculating radiation-induced processes in dielectrics and the environment was developed, and the results of its application are consistent with experimental data.

Note that since the spectral composition of radiation used in the experiment is close to the one of solar radiation in „storms" (when the intensity of soft X-ray radiation increases by several orders of magnitude), the discussed effects need to be taken into account in practical astronautics.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Yu.K. Akimov, A.I. Kalinin, V.R. Kushniruk, H. Jungclaussen, *Poluprovodnikovye detektory yadernykh chastits i ikh primenenie* (Atomizdat, M., 1967) (in Russian).

[2] V.I. Zaitsev, I.A. Barykov, A.V. Kartashov, O.V. Terent'ev, N.B. Rodionov, Tech. Phys. Lett., **42**, 1134 (2016). DOI: 10.1134/S1063785016110225.

[3] I.A. Barykov, I.Yu. Vichev, Yu.A. Volkov, V.I. Zaitsev, N.V. Zalozhnyi, V.M. Kanevskii, I.A. Tarakanov, V.A. Fedorov, *Matematicheskaya model' radiatsionno-indutsirovannoi provodimosti v kvartse pri vozdeistvii moshchnogo rentgenovskogo izlucheniya,* Preprint No. 18 (Inst. Prikl. Mat., 2021) (in Russian). DOI: 10.20948/prepr-2021-18

[4] I.A. Barykov, A.N. Gritsuk, S.A. Danko, V.I. Zaitsev, A.V. Kartashov, S.A. Meshchaninov, N.B. Rodionov, O.V. Terentev, Phys. Atom. Nucl., **82** (7), 1072 (2019). DOI: 10.1134/S1063778819070032

[5] I.A. Barykov, I.Yu. Vichev, V.I. Zaitsev, V.M. Kanevsky, I.A. Tarakanov, V.A. Fedorov, Surf. Investig., **16**, 693 (2022). DOI: 10.1134/S1027451022050020.

Translated by D.Safin