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Ionisation response in semiconductor structures exposed to the X-ray radiation of a femtosecond laser-plasma source

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Abstract. **The possibilities of applying a femtosecond laser-plasma source of X-ray radiation for modelling the effect of single nuclear particles based on the principle of equivalent charge generation are analysed. The parameters of femtosecond X-ray radiation for the experimental modelling of individual radiation effects are validated. The experimental setup forming the X-ray radiation is described. The results of comparative ionisation response modelling in simple electronic devices using the FLUKA and FEANT codes are presented.**

Keywords: *X-ray radiation, femtosecond laser plasma, single event effects, semiconductor devices.*

1. Introduction

The miniaturisation of modern microelectronic devices related to the necessity of increasing the operation rate and packing density of individual elements is achieved at the expense of reducing the dimensions of these elements and using smaller currents and charges for data processing, transmission and storage. Generally, this essentially enhances the sensitivity of modern microelectronic devices to the influence of single nuclear particles of natural environment and increases the urgency of developing experimental methods aimed to estimate this sensitivity [1,2]. The necessity of such estimates is most evident for microelectronic devices intended for exploitation on board the spacecrafts. In many cases the single event effects (SEEs) caused by individual nuclear particles are responsible for the spacecraft functioning failures or even the loss of spacecrafts [3].

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In this connection, the traditional estimation of the probability and the consequences of SEEs is carried out at the ion accelerators, which often complicates the interpretation of results because of the stochastic nature of the interaction between the ionising radiation and the matter (relatively long exposure to radiation and high fluence of particles). An alternative approach is to use the focused pulsed laser radiation of picosecond duration with the photon energy exceeding the bandgap of the semiconductor used in the microchip [4, 5].

The main advantages of the laser methods of testing and experimental studies of microelectronic devices are

(i) the possibility of operative estimation of the sensitivity of microelectronic devices under the laboratory conditions without the experiments at high-cost accelerators of ions and protons;

(ii) the continuous variation of the laser radiation energy over the entire necessary range of linear energy transfers (LETs) of heavy charged space-born particles;

(iii) the localisation of sensitive regions of SEE origin directly at the surface of the microchip crystal;

(iv) the possibility of synchronising the laser pulse with the measured signal, corresponding to the microchip response to the laser action, which eliminates the influence of stochasticity on the interpretation of the results;

(v) the tryout of circuit-design and hardware-software methods of minimising the consequences of SEEs occurring in the spacecraft equipment, etc.

At the same time, the use of focused laser radiation of the optical range faces serious problems due to the presence of multilayer metallisation, covering up to 99% of the total area of the microchip crystal and shielding the laser radiation, thus preventing the penetration of the focused optical radiation into the sensitive semiconductor regions. A serious obstacle for using laser radiation is also the absence of the possibility to generate electron–hole pairs in dielectric media having relatively broad (above 4 eV) bandgap, the ionisation of which is possible only in multiphoton regime. However, the implementation of such a regime of impact requires focusing the radiation up to the intensities above 10^{13} W cm^{-2}, which is undesirable since it may cause the material destruction.

In this connection, in recent time there has been growing interest in the possibility of using ion, electron and X-ray pulsed beams, formed upon irradiation of special targets by high-power laser radiation [6–9], for testing microchips in the regime of single-event failures. The use of ultrashort laser pulses, generated by commercially available lasers, provides a small (to a few picoseconds) duration of the pulse acting on the microchip and the lockstep synchronisation of the events, i.e., possesses almost all key advantages, inherent in the direct laser irradiation of microchips. The energy of protons in this case can achieve a few MeV [10], for electrons, the energy can be as large as 10 MeV [11], and the spectrum of X-ray radiation (XRR) continues from a few keV to a few MeV [6, 7]. At the same time, the generation of proton and electron beams with an energy of a few tens or hundreds of MeV, sufficient to test microchips, is a complex problem, being solved to date only using expensive high-power laser facilities with a peak power of a few tens or hundreds of TW [12]. At the same time for generating high-power pulses of hard XRR (with the energy of photons ~10 keV) it is quite sufficient to have a moderate laser 'tabletop' system, the cost of which at present is rapidly decreasing and the overall dimensions are being reduced due to the introduction of fibre and laser diode technologies.

In our opinion, the approach based on the use of X-ray radiation of the laser plasma is most promising for applications, including the manufacturing of microelectronic devices. However, in this case a number of serious scientific and technical problems related both to the optimisation of the XRR ultrashort pulses and to the focusing of this radiation are to be solved. In the present paper, we study the possibility to observe the response of relatively sensitive semiconductor devices to the pulsed XRR generated using the compact femtosecond laser facility with the peak power 0.1 – 1 TW.

2. Estimation of necessary parameters

The modelling of the heavy charged particles effect is based on the principle of equivalent charge generation in the sensitive microscopic volume of the chip, the linear dimensions of which in up-to-date VLSI lie in the range from tens of nanometres to a few microns. The duration of the action should not exceed the characteristic formation time of the electric response of this microscopic volume, when a single event effect occurs. In modern VLSI, this condition is satisfied at the durations of the ionising radiation pulse less than 10 ps.

Under the direct laser action and in the absence of metallisation and other optical inhomogeneities on the surface of the integrated circuit crystal, in general, the linear relation between the energy of the focused laser radiation J and the LET L_z has the form [1, 4, 13]:

$$L_z(x) \approx \alpha_0 J(1 - R)\exp(-\alpha x)\varepsilon_i/h\nu, \quad (1)$$

where α_0 and α are the interband absorption coefficient and the total absorption coefficient, respectively; $h\nu$ is the photon energy; R is the coefficient of radiation reflection from the crystal; ε_i is the energy of electron – hole pair production in the semiconductor; and x is the coordinate in the direction, normal to the crystal surface.

One more important parameter is the SEE cross section σ, defined as the number of events N_s detected in the course of scanning the crystal area A:

$$\sigma = AN_s/N_{las}, \quad (2)$$

where N_{las} is the total number of laser radiation pulses in the process of full scanning of the area A of the integrated circuit crystal.

In the presence of multilayer metallisation, the laser radiation is unable to penetrate into the crystal volume directly, and the irradiation of the volume will occur due to the diffraction, repeated reflection and other analogous optical effects. Therefore, the application of the approach to up-to-date submicron VLSI with 3 – 5 layers of metallisation is extremely difficult. Additional complications arise due to inhomogeneous optical energy losses in the course of crystal scanning, although these effects can be partially taken into account using the technique of local laser irradiation with the measurement of ionisation response at each irradiated point [14].

Relations (1) and (2) will be also valid for the radiation, capable of penetrating through the metallisation layers. Since in the modern VLSI the equivalent thickness of the metallic layer can achieve 10 μm in the systems with classical aluminium metallisation and 5 μm in those with copper metallisation, the radiation able to penetrate through the layers with such equivalent thickness without significant losses is required. The radiation that satisfies these conditions is the XRR with the energy of a photon above 5 keV. The pulse duration of such radiation should not exceed 10 ps.

The estimate for the equivalent LETs for X-ray radiation can be obtained from Eqn (1) at $R = 0$:

$$L_z(x) \approx \mu_e E\exp(-\mu_t x),$$

where μ_e is the XRR absorption coefficient in the semiconductor; μ_t is the coefficient of the radiation attenuation by the additional layers of metals and dielectrics; and E is the energy of the X-ray pulse. Thus, to obtain the equivalent LET values of ~100 MeV cm^2 mg^{-1}, the energy of the focused XRR in the pulse for the photons having the energy 10 keV in the case of a package-free device should be at least 0.5 nJ for the thickness $x \approx 20$ μm.

The X-ray radiation arising under irradiation of dense targets with the femtosecond laser pulse having an intensity of $10^{17} - 10^{18}$ W cm^{-2}, possesses all parameters necessary for implementing the testing of integrated circuits. Its origin is related to free – free and free – bound transitions (bremsstrahlung and recombination components, possessing the continuous spectrum, exponentially decreasing with increasing energy) and bound – bound transitions (discrete spectrum component) [15]. Under a certain choice of such parameters as the laser radiation intensity, the target material, etc., the major contribution (up to 50% of the total emitted energy of the hard XRR) is provided by the K_α line of the target atoms. For typical copper and iron targets the energy of these photons amounts to 5 – 10 keV, i.e., completely corresponds to the above requirements. The efficiency of the laser radiation energy conversion into the energy of the X-ray pulse amounts to 10^{-5} [16], i.e., taking into account the solid angle, at which the integrated circuit crystal is seen from the plasma source, the energy of the laser pulse ~10 mJ is sufficient to provide the required flux of ionising photons. It is important to note that the duration of the X-ray pulse radiated by plasma in the hard X-ray range does not exceed 1 – 3 ps [17].

3. Experimental technique

The studies were carried out at the experimental laser-plasma source of hard XRR of the International Laser Centre, M.V. Lomonosov Moscow State University. The key element of the setup is the terawatt Ti:sapphire laser facility generating femtosecond pulses (50 fs) with the energy up to 100 mJ at a centre wavelength of 805 nm with a repetition rate of 10 Hz. When such radiation is focused at the target surface with a peak intensity above 10^{16} W cm^{-2}, the superhot plasma is formed, in which the energy of electrons can be as large as tens of keVs [15, 18]. In the present facility, the used target was made of melted metal (gallium) at a temperature of about

200 °C. On the one hand, the approach using a liquid target has previously shown itself to be highly stable with respect to the source parameters from shot to shot [16] and simple in construction. On the other hand, the penetration of the fast electrons into the depth of the heavy target leads to the production of a large number of bremsstrahlung X-ray photons, against the background of which the excitation of the discrete component, namely, the K-lines of gallium (nearly 10 keV) occurs [16].

The experimental setup is presented in Fig. 1. The laser pulse with an energy of about 1 mJ was focused by an objective lens with the focal length 6 cm onto a target surface making an angle of 45° with its normal. The diameter of the beam waist amounted to nearly 4 μm, which provided a peak intensity of about 4×10^{16} W cm^{-2}. Since the study was aimed at clarifying the possibility of using the XRR for modelling the pulsed ionisation response in semiconductor devices, the experiments were performed with uniform irradiation of the entire surface of the studied object, placed inside or outside the vacuum chamber at a distance of 10–15 cm from the plasma.

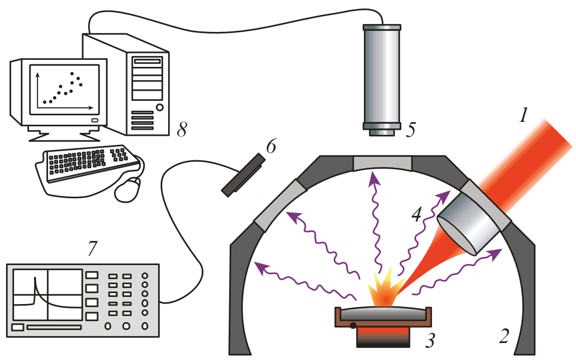

Figure 1. Experimental setup:
(*1*) laser radiation; (*2*) vacuum chamber; (*3*) cuvette with melted gallium; (*4*) focusing objective lens; (*5*) X-ray spectrometer; (*6*) studied object; (*7*) oscilloscope; (*8*) computer.

The spectrum of the X-ray source based on the laser plasma (Fig. 2) was measured by means of an Amptek PIN diode spectrometer with a resolution of 300 eV. Since the detector was located beyond the vacuum interaction chamber, the lower threshold for the energy of the detected photons was determined by the thickness and material of the vacuum window (100 μm of aluminium) and amounted to 3–5 keV. In the spectrum, against the background of the bremsstrahlung, the discrete components K_α (9.3 keV) and K_β (10.3 keV) were also present. For the first of them the generation efficiency could be estimated as $(5\pm2)\times10^6$ photons in the complete solid angle per one laser shot, which nearly coincides with the number of bremsstrahlung photons in the range 5–30 keV.

A key specific feature of the femtosecond laser plasma is the ultrashort X-ray emission time, which, as a rule, is determined by the nonequilibrium plasma thermalisation and amounts to about 1 ps. Thus, the studied sample exposed to radiation is subjected to the instantaneous impact of a high-intensity flux of photons, which can be estimated as 10^3–10^4 photons having the energy 10 keV (for the detector placed outside the vacuum chamber at 10–15 cm from the source) per one laser pulse. This corresponds to $L_z = 40$–400 MeV cm^2 mg^{-1}.

Additional experimental studies were carried out at the Research and Educational Centre 'Stoikost' of the National

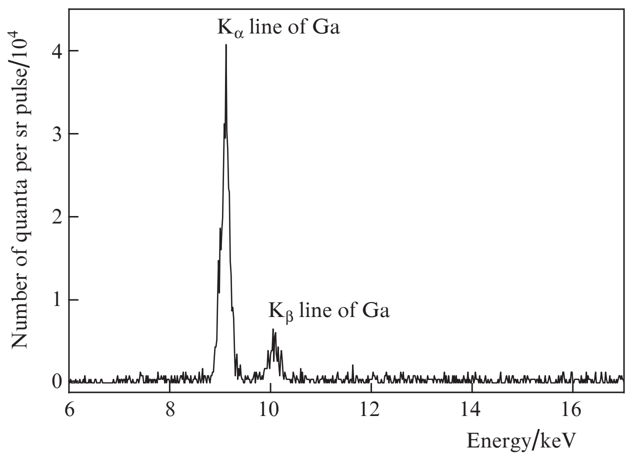

Figure 2. Spectrum of hard X-ray radiation from laser plasma in the range 6–17 keV.

Research Nuclear University 'MEPhI' and at the JSC 'SPELS' using an ARSA pulsed accelerator of electrons and a Radon-5M laser facility [19]. The duration of the pulse action in this case amounted to 10 ns, and the dose for silicon was 10^7 rad s^{-1}. The experimental studies were performed using the setups equipped in a similar way.

As an object of study, we used relatively simple but sensitive semiconductor devices, namely a PIN diode and a typical operation amplifier, fabricated using the bipolar technology. The devices under test are presented in Fig. 3. The operation amplifier (Fig. 3a) was switched in the voltage repeater mode. The oscilloscope measured output voltage of the amplifier. The PIN diode (Fig. 3b) was switched in inverse bias and the pulse voltage at the resistor mode was analysed. Before the experiment, the packages of the sample devices were removed to avoid their influence on the results.

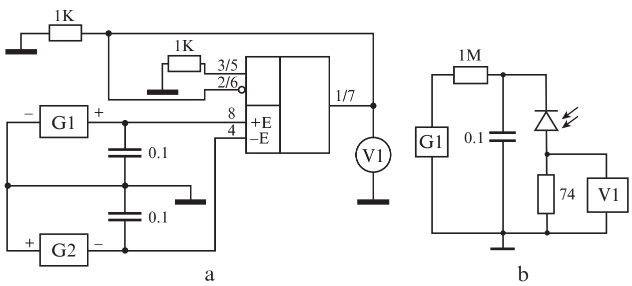

Figure 3. Electric circuits of connection for (a) the operation amplifier and (b) PIN diode: (G1, G2) voltage sources; (VI) oscilloscope.

4. Experimental results

In the course of experimental studies, the practical identity of the amplitude–time characteristics of the ionisation response in both samples (Figs 4 and 5) for all types of radiation impacts was observed. One can only note that for PIN diodes a small difference is observed at the initial stage of the pulsed response. This discrepancy is explained by the role of the pulse duration. In the case of the XRR action, the temporal pulse shape can be considered as a delta-function, while the effect of the bremsstrahlung in the ARSA setup with the pulse

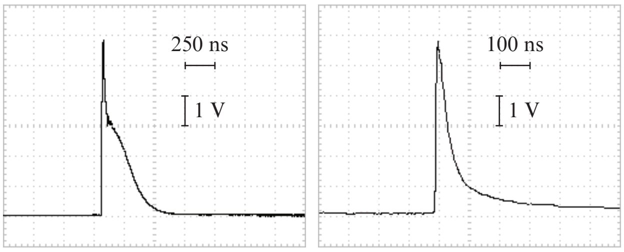

Figure 4. Oscillograms of injection current for the PIN diode, obtained using (a) the X-ray source and (b) the ARSA pulsed accelerator.

duration slightly shorter than 10 ns does not satisfy this condition.

If the response time of the semiconductor device is essentially greater than 10 ns, then no differences in the amplitude–time characteristics are expected. This behaviour takes place under the action of pulsed ionising radiation in the operation amplifier (Fig. 5). Unfortunately, for this case it is impossible to perform quantitative estimates, since the effect appeared to be too large and has driven the amplifier into the saturation mode (the amplitude of the signal being limited by the supply voltage). Some unessential differences in the signal shapes can be due to the difference in the level of impact.

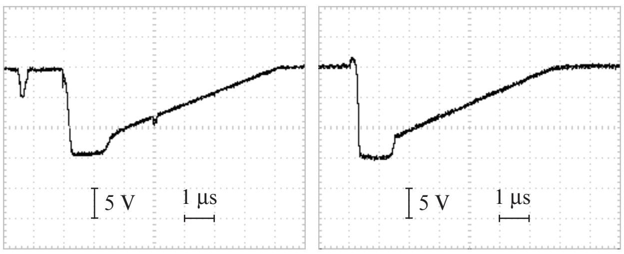

Figure 5. Oscillograms of output voltage changes for the operation amplifier, obtained using (a) the X-ray source and (b) the ARSA pulsed accelerator.

Some estimates of the possibility of using the XRR for SEE modelling can be drawn from the analysis of the PIN diode ionisation response. From the comparison of the signal amplitudes, which are practically equal among themselves, it is easy to see that the equivalent action level of XRR for silicon amounts to 0.1 rad. In other words, if it could be possible to focus all this radiation into a spot with the diameter of about 1 μm, then the LET values at the level of 10^3–10^4 MeV cm^2 mg^{-1} could be obtained. In this case, the possible losses of radiation in the X-ray optical focusing system can amount to two orders of magnitude, and the maximal level of LETs in the sample will achieve the required value of 100 MeV cm^2 mg^{-1}.

5. Computer simulation of the effect of X-ray photon flux on the PIN diode

To illustrate the processes that occur in the microchip material under the effect of the incident X-ray pulse, we performed the mathematical modelling of the interaction between the X-ray pulse and the photodiode. Since the process of energy accumulation is stochastic, it is natural to use the Monte Carlo statistical trial method for its mathematical modelling. The result of the modelling depends on the physical models incorporated in the code; however, for the electromagnetic interaction these models are specified rather unambiguously. For the considered X-ray photon energy (below 50 keV), the basic mechanism of interaction with silicon is the photoelectric effect (the formation of electron–hole pair). Besides that, the contribution of Compton scattering and the secondary electrons is essential.

The threshold values of the transmission and particle production energies used in the programmes are essential factors that affect the adequacy of the applied physical model. For the simulation, we used the open FLUKA [20, 21] and GEANT codes [22].

To perform the simulation, the following data are necessary:

(i) the energy distribution density of the particles in the pulse, normalised to unity;

(ii) the number of particles per pulse and their spatial distribution in the source; and

(iii) the photodiode geometry.

For accelerating the calculations, the source, placed at the distance 1 m from the diode, was assumed point and isotropic (the energy spectrum of XRR is presented in Fig. 2). The number of particles $N_{\rm d}$, hitting the photodiode, is determined by the relation $N_{\rm d} = NS/(4\pi r^2)$, where r is the distance between the source and the diode, and S is the diode area. The photodiode was presented in the form of a silicon plate measuring 0.014×0.014×0.21 mm with the protecting copper layer 35 μm thick. The energy cut-off parameters were chosen equal to 1 keV in the FLUKA calculations and 16.7 eV in the GEANT calculations. The results of the calculations presented below are normalised to one incident gamma-quantum.

Both transport-modelling codes yielded almost similar results for the number of gamma-quanta passed the silicon zone without interaction, the number of photoabsorption events, and the energy released in silicon (6.38 keV photon^{-1} for FLUKA and 6.24 keV photon^{-1} for GEANT). The corresponding maximal number of electrons produced in the silicon zone amounted to ~1700 electrons/photon. With the

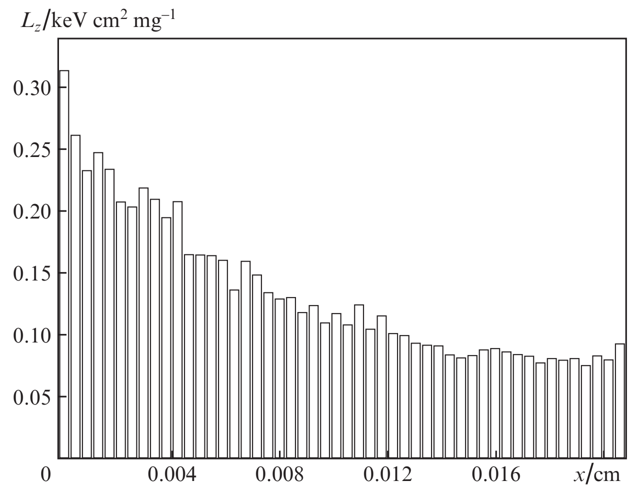

Figure 6. Density of the energy released in silicon versus the depth, calculated using the FLUKA code.

total number of X-ray photons hitting the diode aperture during one laser pulse taken into account, we arrive at the estimate of about 1 V for the photodiode output voltage, which is in reasonable agreement with the experimental results.

Figure 6 presents the depth dependence of the energy density, released in silicon, calculated using the FLUKA code. The analysis of Fig. 6 shows that the mean LET per one photon of radiation with the energy 10 keV in our case amounts to 5–7 keV cm^2 mg^{-1}, which, with the diode area and the experimentally estimated flux of LET yields the total LET equal to 100 MeV cm^2 mg^{-1}. This value is also in agreement with the experimentally estimated ones.

6. Conclusion

The performed numerical and experimental studies of the impact of laser plasma X-ray radiation have shown that the use of the terawatt femtosecond laser facility can provide the equivalent LET levels for silicon up to 10^4 MeV cm^2 mg^{-1} per pulse. Such values potentially allow the use of this radiation for modelling the SEE, if it is focused into a spot with the size of a few micrometres. Therefore, at the next stage it is necessary to solve the technical problem of focusing the X-ray radiation into a micron-size spot with the X-ray radiation energy losses not exceeding two orders of magnitude.

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