

Study of the sensitivity of semiconductor pixel structures using focused laser irradiation

Artyom A. Sharapov^{1,2}, Alexey V. Sidelev¹, Konstantin I. Tapero^{1,2}, Artyom E. Zemtsov^{1,2}

1 Research and Development Institute of Scientific Instruments, Joint-Stock Company, 8 Turaevo Industrial Area, Lytkarino, Moscow Region 140080, Russian Federation

2 National University of Science and Technology "MISIS", 4-1 Leninsky Ave., Moscow 119049, Russian Federation

Corresponding author: Artyom A. Sharapov (s.artem11@mail.ru)

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Abstract

Results of focused laser irradiation of semiconductor structures having relatively small sizes of discrete components on the crystal were presented. Different laser beam depth profiles were obtained in the experiments via different lenses. The focused beam size was varied in a range of 1.4 to 3.6 μm at the beam waist. The test specimens were position-sensitive detectors with small pixel size ($\sim 15 \mu\text{m}$). We showed that the use of different lenses with constant pulse energy and duration yields different results in sensitivity assessment. Conclusions were made as about the limitations in the application of precision irradiation methods to semiconductor structure.

Keywords

laser irradiation, radiation effects, radiation hardness, semiconductor detectors, focused radiation

1. Introduction

The choice of semiconductor device irradiation methods is primarily dictated by the specific tasks and conditions researchers deal with. However, the approach to experiments, which seems to be the most obvious from the physical viewpoint, can prove to be far not the optimum one in practical implementation.

Indeed, when it comes to evaluating sensitivity to a specific radiation type, whether heavy ions, gamma or X-ray quanta, the simplest way from the viewpoint of experimental results treatment is to use the required radiation type. This is primarily due to the fact that, for the abovementioned problem statement, irradiation with particles of the required type allows reproducing the desired principle of radiation impact on device structure materials.

The above-described approach to experiments, however logical it seems, has a restriction: exposure to the type of radiation allowing one to completely reproduce a specific mechanism of radiation impact is far not always the optimum solution from the viewpoint of time and labor consumption. This limitation, apart from scientific interest, determines, in the first approximation, the tendency to develop the simulation methods and supplementary analytical absorption models of different radiation types in materials for the practical implementation of the above methods.

Currently, a great number of works are carried out dealing with simulation methods of studying the sensitivity of semiconductor devices to ionizing exposure [1–4]. Furthermore, there are a large number of industry-specific documents regulating the application of simulation testing [5, 6].

Table 1 summarizes advantages and drawbacks of simulation methods for the example of focused laser irradiation of devices.

Thus, in the light of the above-listed advantages and drawbacks, which will be dwelt upon below, e.g. difference between non-equilibrium charge generation profiles, the aim of this work was stated as follows: to study the effect of laser beam profile on scanning exposure results for semiconductor structures the design rules of which are close to the size of the scanning beam (units or tens of microns).

2. Theoretical basis of experiments

If the irradiation of test specimens is carried out using methods differing from the required ones, a number of factors emerge which should be taken into account in order for the irradiation results to be equivalent.

Focused laser beam irradiation is often used as a faster and cheaper alternative to irradiation with heavy ions in studies of device sensitivity to space radiation. We consider in a greater detail the specific aspects of using the above type of irradiation. Laser irradiation generates non-equilibrium carriers due to the absorption of photons with energies exceeding the band gap of the irradiated device structure material for single-photon absorption mechanism, or due to simultaneous absorption of two or more photons, provided that the radiation intensity is high; in that latter case, the two-photon or multiple-photon absorption mechanisms take place [7]. For irradiation with heavy ions, energy transfer (and, subsequently, generation of non-equilibrium carriers) occurs due to Coulomb's interaction with electrons of device structure material host atoms. The possibility of using simulation methods is provided by the fact that the triggering of ionization effects is often associated with the generation of a specific quantity of non-equilibrium charge (the threshold charge concept if one deals with the generation of single event effects, or the equivalent charge model if exposure to different types of ionizing radiation is the case [8–10]).

Table 1. Advantages and drawbacks of simulation methods

Advantages	Drawbacks
Cheapness, streamlined access to information, high repeatability of results	Necessity to remove chip packaging (decapsulation)
Possibility of scanning the entire crystal area with mapping of the most sensitive areas	Optical losses due to uncontrolled light absorption by metallization components in multilayered microchips, absorption by poly-silicon and heavily doped silicon layers, light interference and diffraction
Absence of dose effects	Difficulty of theoretical (or experimental) linking of laser pulse energy parameters with space radiation parameters

Another factor to be taken into account when applying simulation methods is the difference in the nature of radiation propagation in materials. The track size of a heavy ion depends largely on the properties of the irradiated material, i.e., atomic weights of target atoms, structure density, lattice type, and many other parameters. By way of example, Fig. 1 shows images of tracks for a single heavy ion (Xe 167 MeV) in different electronics materials [11]. One can see that the track sizes vary depending on the target material, but all of them are within units of nanometers.

The radial size of non-equilibrium carrier generation profiles for heavy ions can reach hundreds of microns [12, 13]. The greatest contribution to this figure comes from delta electrons generated by ions propagating through the device structure material. The actual radial size of the non-equilibrium carrier generation profile depends on several main factors:

- velocity of incident ions: the higher the velocity as per the model reported in an earlier work [13], the higher the energy transferred to the delta electrons;
- diffusion length of electrons and holes in the structure material: delta electrons diffuse by the ambipolar mechanism (limited by the minority carrier mobility).

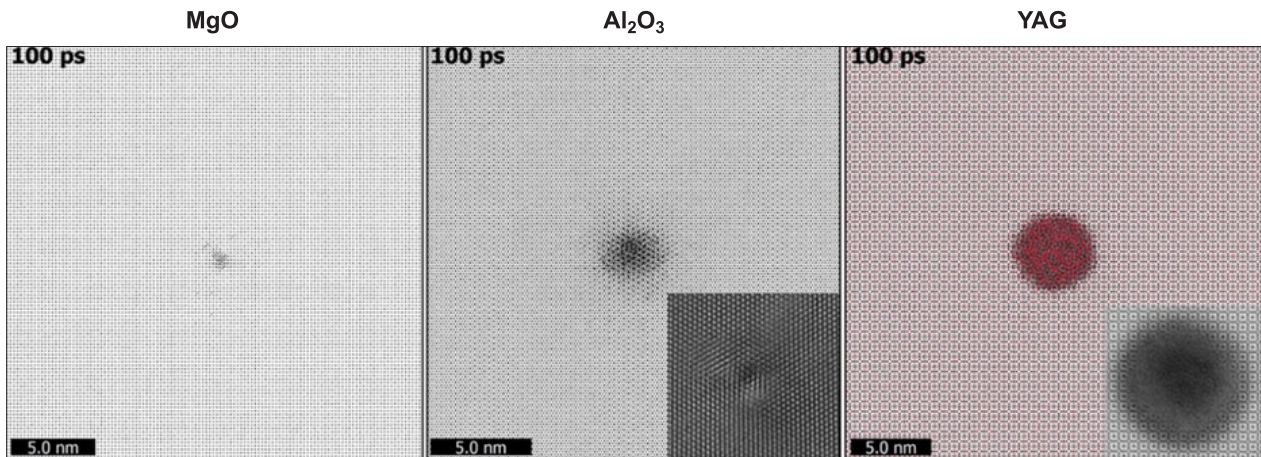


Figure 1. Track sizes of heavy ions penetrating in different electronics materials [11]

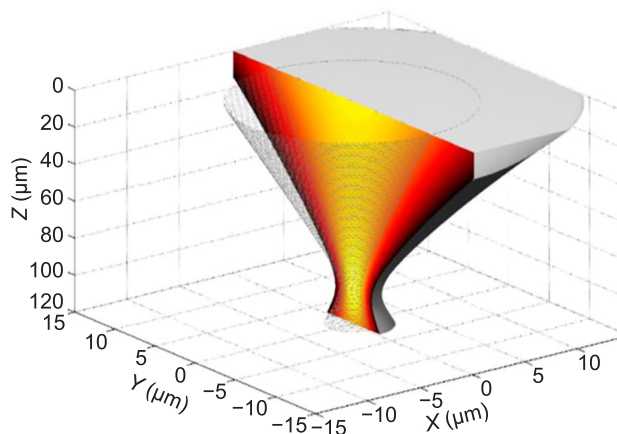


Figure 2. Propagation profile of focused laser beam [1]

The beam size of focused laser radiation (even for extremely large lens magnifications and small apertures of optical systems) is restricted by the diffraction limit, which is close to the radiation wavelength [14, 15]. Thus, the minimum admissible radiation spot size at the beam waist for infrared lasers is about 1 mm. It should be also noted that for majority of optical systems, the beam profile can be as shown in Fig. 2 [1], i.e., the minimum size is only achieved at the lens focus, whereas in the other points the beam is significantly wider. Regarding the application of simulation methods, it should be noted that optical systems have been developed allowing one to obtain almost perfectly collimated beams. These developments are aimed at achieving a more accurate imitation of non-equilibrium carrier generation profiles for heavy ions, and again, in those cases the non-equilibrium carrier generation profile size should not be smaller than the diffraction limit [12].

With a permanent downscaling of design rules of technological processes in the device industry, it becomes an increasingly important task to take into account track

sizes for incident radiation (in fact, here one deals with the non-equilibrium carrier generation profiles). Multiple failures caused by single ions were first observed in the 1990s when the design rule approached a size of several dozens of nanometers [16, 17]. A natural consequence of that fact was researchers' concern about the risk of triggering multiple failures in case of exposure to focused laser beams [18].

Sensitivity estimations based on the results of laser irradiation experiments should also take into account the effects of diffraction and inner reflections from interlayer metallization [19–21], which greatly complicate the development of evaluation models aimed at finding a correlation between the energy parameters of laser radiation and space radiation. Figure 3 shows examples of interlayer metallization arrangement in microchips fabricated using an advanced technology [22, 23].

Most advanced device structures allow reproduce requiring ionization effects, even for large amounts of surface metallization, using various techniques of decapsulation and irradiation of opposite crystal side.

Despite the above challenges, the development and implementation of simulation methods is a promising trend for research and testing centers.

3. Test bed

Position-sensitive pixel detector structures were irradiated on a PULSYS-RAD focused laser system (PULSCAN, France) which can be used for studying semiconductor device sensitivity to single event effects caused by ionisation. Figure 4 shows a photo of the focused laser system workstation.

The system has 2 laser sources. The PULSUS-PICO source generates picosecond 1064 nm laser pulses providing for silicon device operation in single-photon

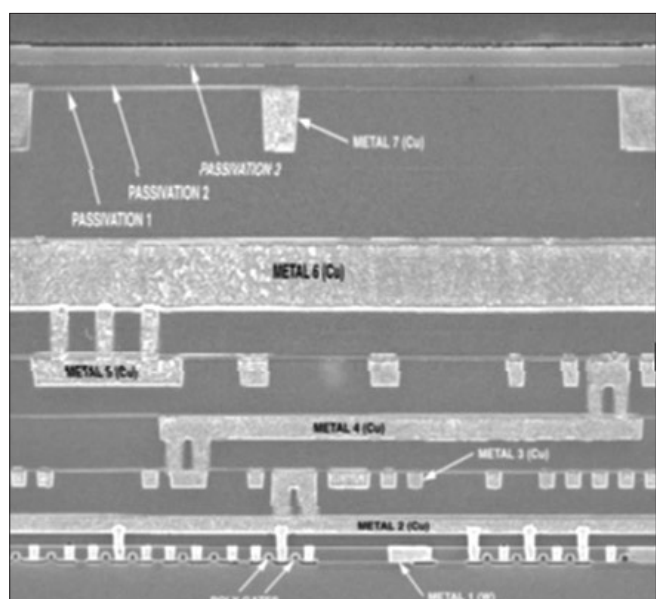
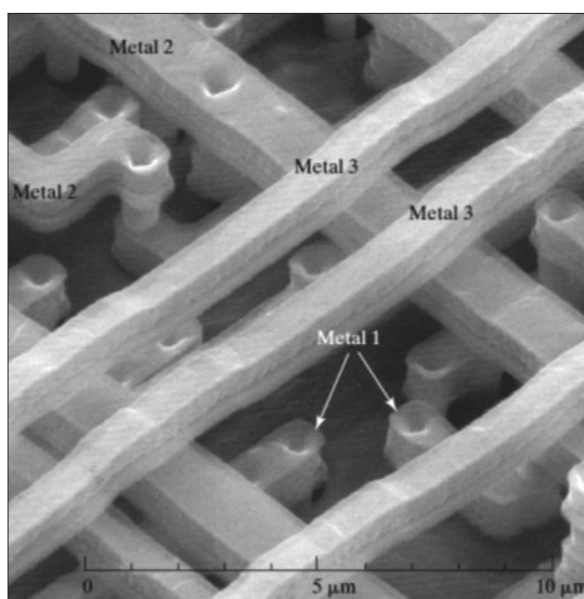


Figure 3. Examples of interconnections with multilayered bulk metallization [22, 23]



Figure 4. PULSYS-RAD focused laser testing system workstation

absorption mode at low ($\sim 10\text{--}100\text{ cm}^{-1}$) absorption coefficients [24, 25]. The latter is important for achieving a homogeneous pulse energy absorption depth profile in the device structure, which can be critical for irradiation of opposite crystal side. The second source, PULSYS-2P, generates femtosecond 1550 nm laser pulses providing for silicon device operation in two-photon absorption mode, which is attractive due to the possibility of localizing the impact in the depth of the structure by means of focusing [7]. Calculated density distributions of generated non-equilibrium carriers for different radiation sources of the system and a $100\times$ lens are illustrated in Fig. 5.

The system has 3 lenses with different magnifications of 5, 20 and 100.

The laser beam divergence parameters for the three lenses were measured using the Foucault knife-edge test [26] for different device structures (based on different semiconductor materials) used as detectors. The results are presented in Fig. 6 [27].

During focused laser beam propagation, the radiation spot size w as a function of depth z is approximated by an expression of the following type:

$$w(z) = w_0 \left[1 + \left(\frac{z}{z_R} \right)^2 \right]^{1/2}, \quad (1)$$

where w_0 is the spot radius at the beam waist, and z_R is the confocal parameter, or the Rayleigh length describing the area in which the beam radius is within $\sqrt{2}w_0$.

For the $5\times$ and $20\times$ lenses, results were only obtained for the 1064 nm radiation, since the magnification of these lenses is insufficient for producing a beam intensity that can trigger the two-photon absorption mechanism while working with PULSYS-2P source. For the $100\times$ lens, measurements were carried out for both laser sources of the system. The results are shown in Table 2.

Table 2. Beam divergence data [28]

Lens magnification	Laser spot radius at waist (μm)	Rayleigh length (μm)
$5\times$	11	300
$20\times$	3.6	20.5
$100\times$	1.4	2.52

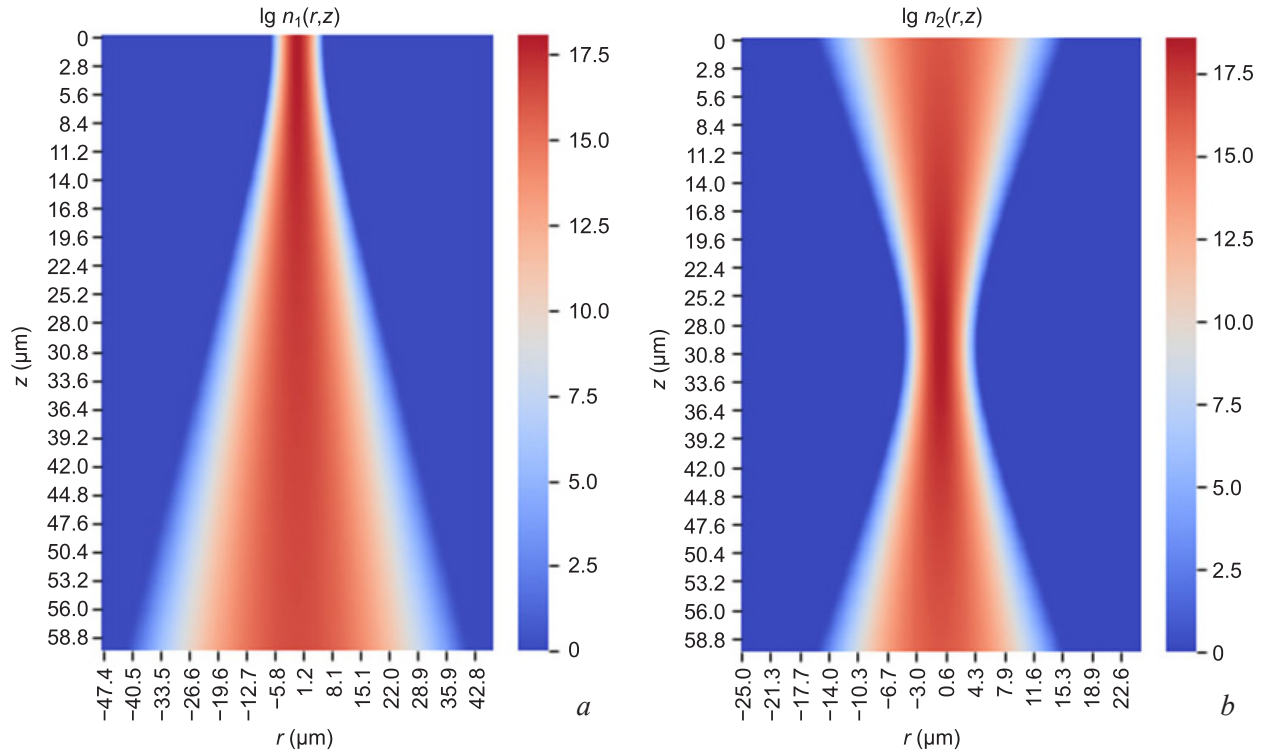


Figure 5. Density distributions of generated non-equilibrium carriers for different absorption mechanisms upon irradiation with wavelengths (a) $\lambda = 1064\text{ nm}$ and (b) $\lambda = 1550\text{ nm}$

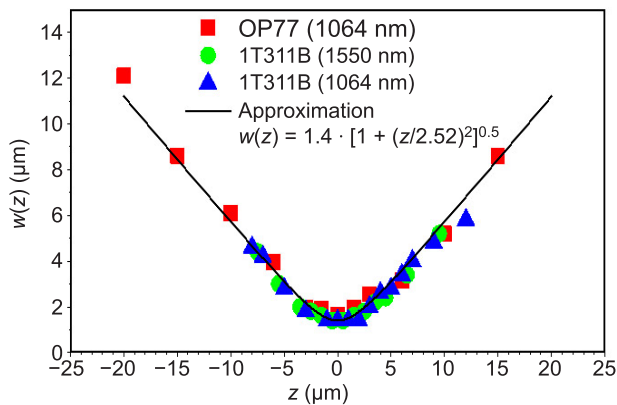


Figure 6. Laser beam size as a function of focal position

Parameters of PULSYS-RAD system radiation sources are summarized in Table 3.

4. Test specimens

The test specimens were monolithic pixel detectors. The specimens were in the form of device structures allowing the detection of impact on discrete pixels, provided by a sensitive detector section and a detector signal processing section. The detector contained 64×64 pixels. Figure 7 shows an image of the crystal and its operation diagram. The monolithic pixel detector crystal size was 3700×3700 mm.

After detector specimen preparation (installing on the test bed), the switch-on procedure was as follows:

- connection of a 40–600 kOhm external resistor to outputs 5 (Fig. 7) for detector activation threshold setting; the lower the setting, the higher the detector sensitivity;
- +5 V positive biasing of outputs 4;

Table 3. Pulse parameters for different sources of PULSYS-RAD system

Parameter	Laser source type	
	PICO	2P
Laser wavelength	1064 nm	1550 nm
Pulse duration	30 ps	450 fs
Minimum pulse energy* (nJ)	0.0076	0.0067
Maximum pulse energy* (nJ)	28.55	5.90

Note: *Actual certified testing equipment parameters.

- connection of outputs 6 to the ground of the respective power inputs;
- +5.5 to +6 V positive biasing of chip substrate, “ground” being connected to the GND output;
- the output signal can be read from outputs 3: the detector row address signal is read from outputs OUT1–OUT12, and the detector column address signal, from outputs OUT13–OUT24. Low output voltage indicates illumination of the respective pixel.

Each pixel in the detector contains 2 photodiodes showing the row and column coordinates. The typical size of the pixel cell is 15×15 mm. Cell diagram is shown in Fig. 8.

The detector output signal generation principle was as follows. Ionizing radiation impact on a detector pixel generates current, which is amplified by the pixel’s amplifier circuit and sent to the row/column decoder for the generation of digital signal (code) showing the irradiated pixel coordinate. Without irradiation, the current is determined by the photodiode dark current value, the detector

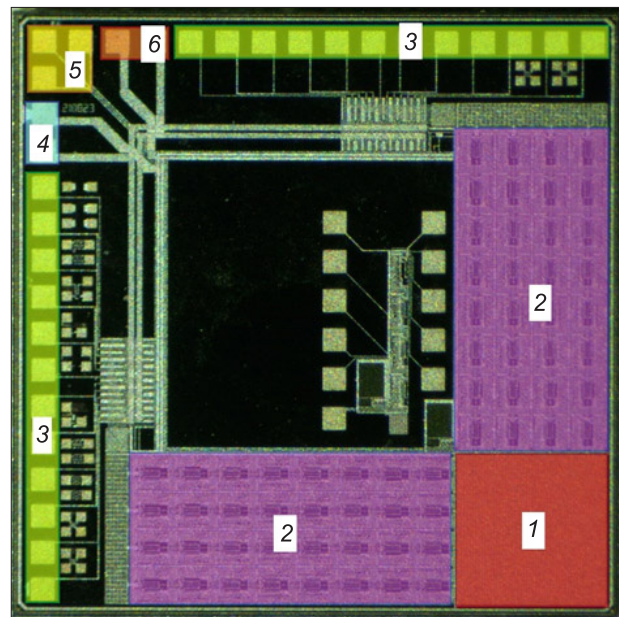
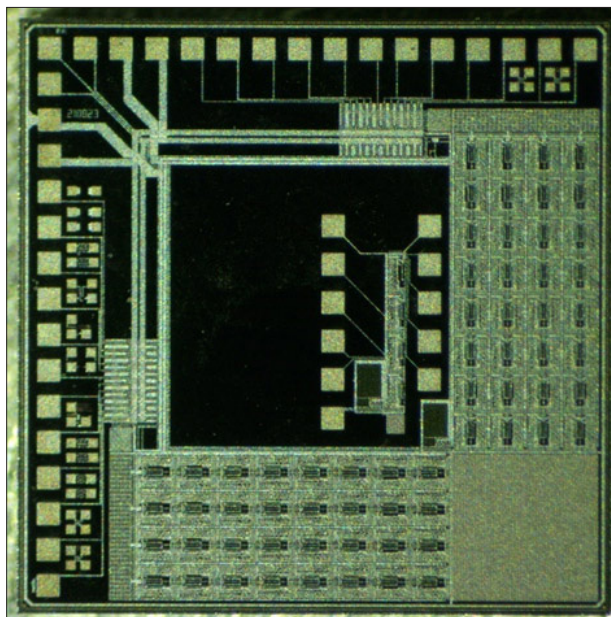


Figure 7. Structure of monolithic pixel detector crystal: (1) photodiode detector, (2) signal processing system (amplifiers and row and column decoders), (3) signal outputs, (4) power outputs, (5) external resistance setting outputs, (6) “ground”

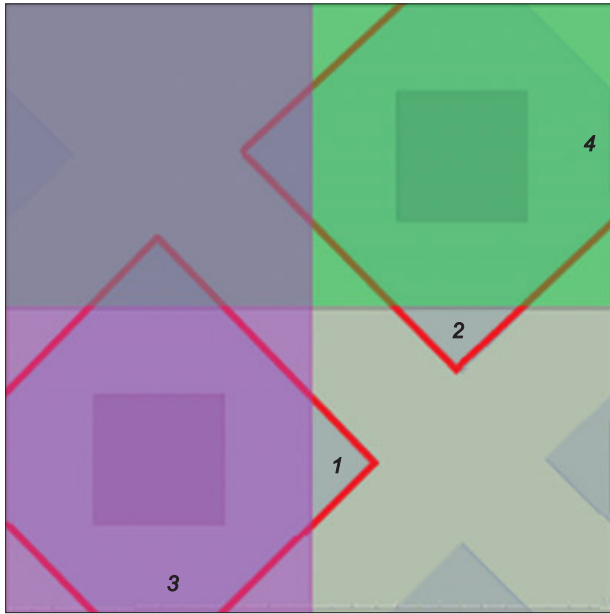


Figure 8. Test specimen pixel schematic: (1) metallization-stripped column sensitive element (diode) area; (2) metallization-stripped row sensitive element (diode) area; (3) column conductor metallization; (4) row conductor metallization. The area limited by metallization 3 and 4 but not pertaining to detector photodiodes was also stripped of metallization and hence was potentially sensitive to ionizing laser exposure

output being set to logical 1 (one). With an increase in the photocell current due to irradiation, the respective row/column outputs are set to logical 0 (zero). The magnitude of radiation impact (the energy or flux of the incident radiation quanta) can be evaluated, although indirectly, by measuring the shift of the logical 0 and 1 levels resulting from variation of the detector's external circuit resistivity, or by analyzing the duration of the digital response signal received.

5. Experimental method

The enclosure of the PULSYS-RAD pulsed laser testing system provides the possibility of complete specimen shadowing. The electrical parameters were set with a PXI-E module (National Instruments (NI), US). The measuring device was a DSOS204A digital oscilloscope (Keysight, US). Figure 9 shows connection diagram of test workstation components.

One should bear in mind the following: since the detector outputs are digital, impact level evaluation from output signal amplitude is impossible, since the output signal is always ~5 V if the detector is activated.

The experiment showed that, where necessary, the irradiation impact level can be characterized based on

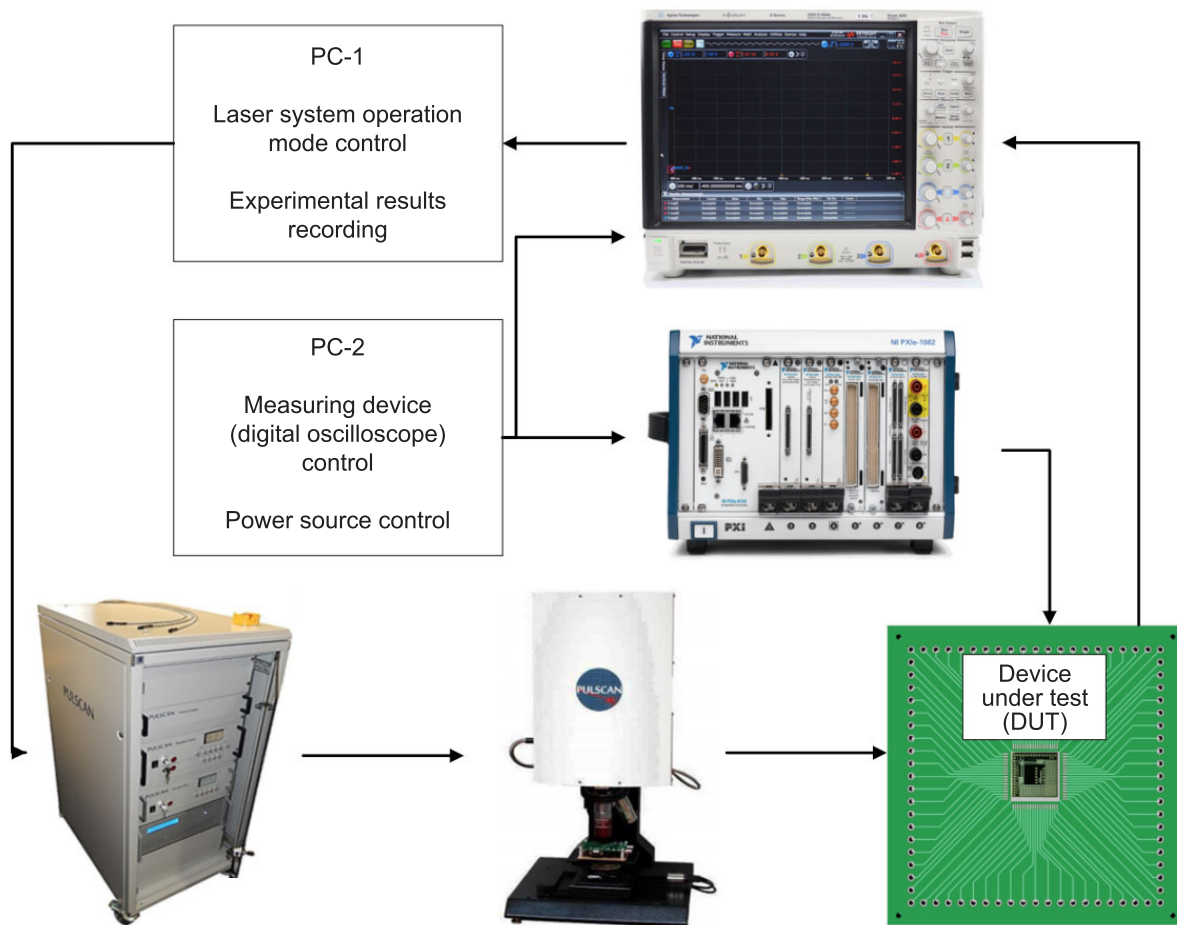


Figure 9. Diagram of component location for monolithic pixel detector sensitivity testing

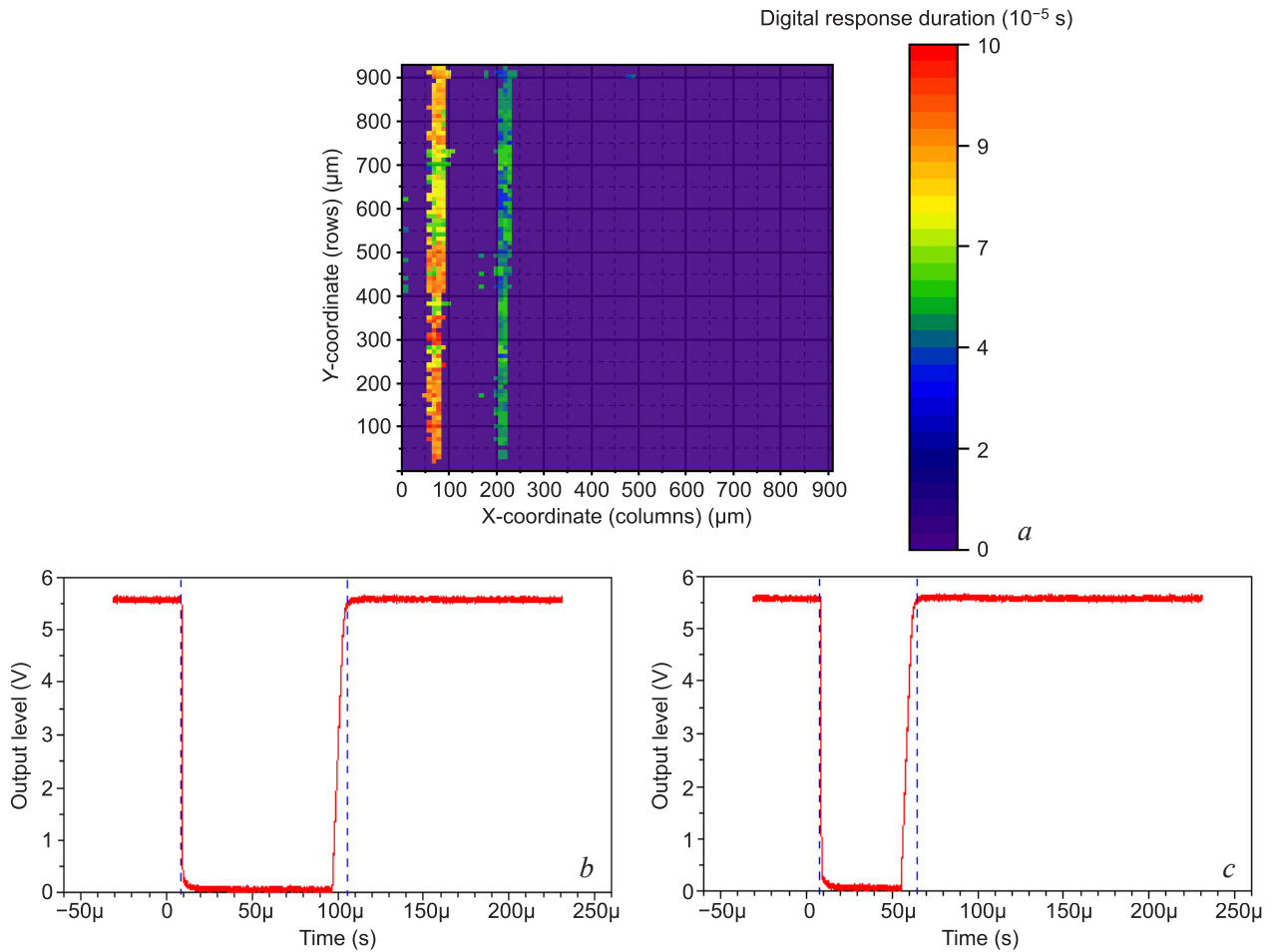


Figure 10. Response time diagrams of monolithic pixel detectors for scanning mode irradiation

digital response duration (Fig. 10), because the energy absorbed by the detector pixels is spent for the generation of electron/hole pairs, the number of which, in turn, characterizes the ionization current. The digital section of the detector is activated, depending on the external resistivity setting, at different ionization current levels (the test structures were designed for an average activation threshold of ~ 70 nA). Preliminary testing data showed that the threshold level of the external resistivity at which noise is filtered out is ~ 200 kOhm.

It is well-known that excess non-equilibrium carriers in semiconductors recombine in an exponential manner with a time constant, referred to as the non-equilibrium carrier lifetime. This statement, obviously, describes generalized physical processes, whereas, in fact, there are a number of factors controlling recombination rate. However, in the authors' opinion, this simplification would be appropriate to justify the choice of radiation impact level characterization criterion. The above statement, again with some degree of simplification, can also be applied to pixel detector photodiodes in the following verbal form: ionization current generated as a result of pulse radiation impact relaxes in an exponential manner with a time constant, referred to as the ionization reaction relaxation time.

Thus, if the detector digital section activation threshold is X_{th} (mA) and E_{th} (pJ), then irradiation with laser pulses having the energies E_1 and E_2 , such that $E_1 > E_2 > E_{th}$, will generate currents with the amplitudes $X_1 > X_2 > X_{th}$. Taking into account the above, during pulsed irradiation with the energy E_1 the current X_1 will decay to the threshold level X_{th} in a longer time than for pulsed irradiation with the energy E_2 , and this is described by the digital response duration.

6. Discussion

We consider the test results for the monolithic pixel detector with the following variable parameters: lens magnification, scanning grid step, and detector external resistivity setting. The output energy of the system's optical source was set constant. Figure 11 shows scanning results in the form of response signal maps.

To analyze the effect of the variable parameters, one should calculate the ratio between the number of pulses which triggered the detector and the total number of pulses during one irradiation session. Experimental data and calculation results are summarized in Table 4.

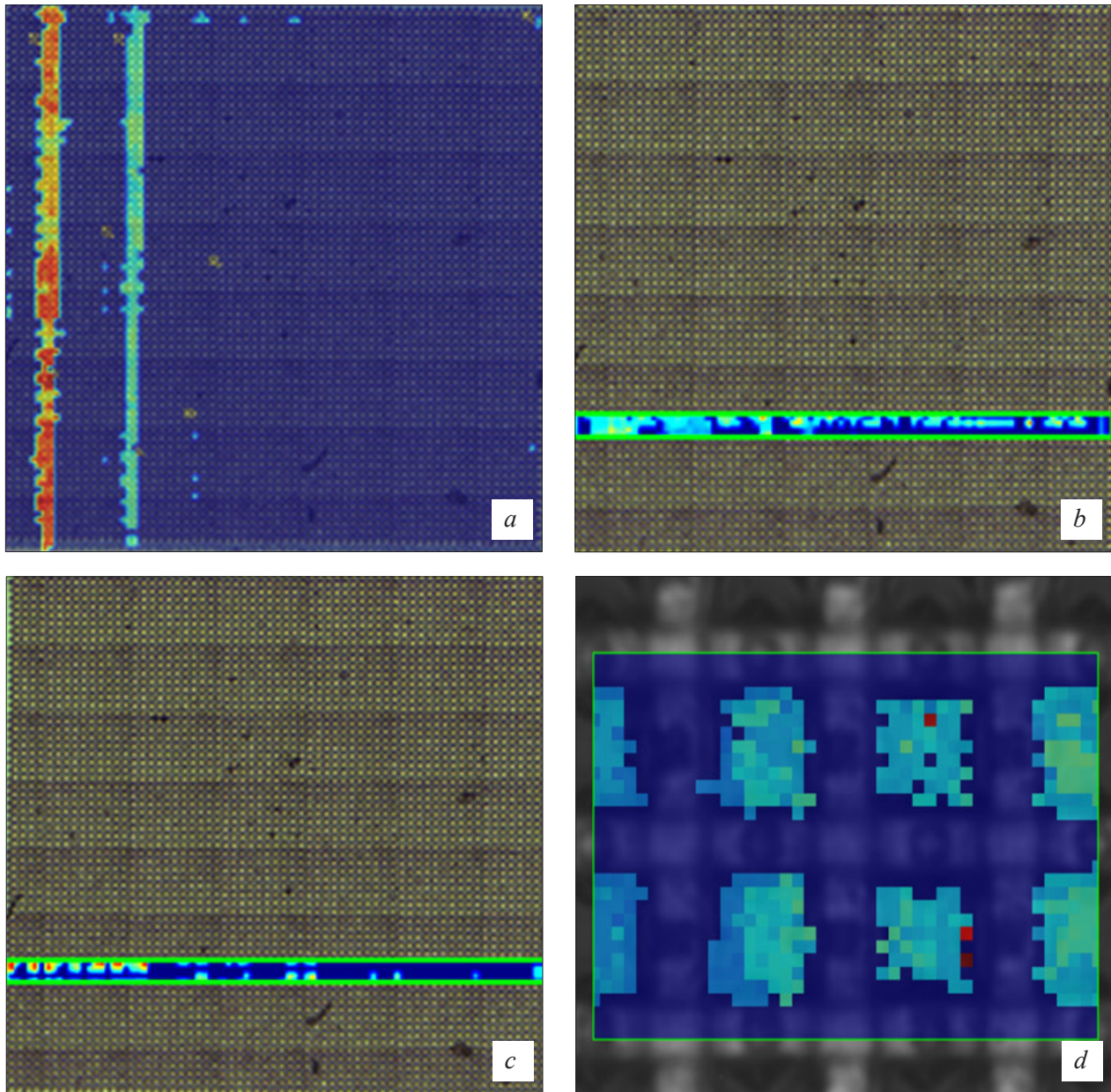


Figure 11. Comparison between scanning results for different scanning modes: (a) $R_{\text{ext}} = 508 \text{ kOhm}$, $20\times$ lens, scanning step $10 \mu\text{m}$; (b) $R_{\text{ext}} = 274 \text{ kOhm}$, $20\times$ lens, scanning step $10 \mu\text{m}$; (c) $R_{\text{ext}} = 508 \text{ kOhm}$, $100\times$ lens, scanning step $10 \mu\text{m}$; (d) $R_{\text{ext}} = 600 \text{ kOhm}$, $100\times$ lens, scanning step $1 \mu\text{m}$

Table 4. Experimental scanning results

Session	R_{ext} (kOhm)	Lens	Scanning step (μm)	Total number of laser pulses per session	Number of detector activation events	Percentage of detector activation events (%)
<i>a</i>	508	$20\times$	10	8648	551	6.3
<i>b</i>	274	$20\times$	10	364	160	43.9
<i>c</i>	508	$100\times$	10	364	91	25.0
<i>d</i>	600	$100\times$	1	1290	415	32.2

We compared the results between pairs of sessions in which only one parameter differed:

- sessions *a* and *b*: external resistivity;
- sessions *a* and *c*: lens magnification;

– sessions *c* and *d*: scanning step (these results were obtained for slightly different external resistivity levels: the detector sensitivity was lower for session *d*).

Comparison between sessions *a* and *b* confirmed the above-described detector operation feature: setting a higher external resistivity lowers the detector sensitivity.

The most interesting was to compare between sessions *a* and *c*. The external resistivity, the scanning step, and the laser energy being the same, a far greater number of detector pixels were triggered (the ratio between the respective triggering event percentages was ~4). This can indicate that the use of a lens with a greater magnification allows increasing the beam intensity, which controls the generation rate of non-equilibrium carriers and, hence, the generated current level.

We also compared the results for sessions *c* and *d*. It can be seen that, despite a lower sensitivity for session *d*, the fraction of activated pixels for session *d* was greater (32.2 vs 25.0 %). The Authors attribute this result to the fact that the 10 μm scanning step is far greater than the beam waist size formed by the 100 $\times$ lens (1.4 μm), and hence, some detector pixels were possibly not illuminated at such a large scanning step.

The maps shown in Fig. 11 also suggest that the greater the lens magnification and the smaller the scanning step, the more localized the response signals. This is, obviously, accounted for by the fact that a lens with a greater magnification forms a narrower laser beam. A more detailed analysis of the microscopic images superimposed with the scanning results, taking into account the pixel structure shown in Fig. 8, suggests that the metallization-stripped pixel area is only 30–40% of the total pixel area.

Conclusion

The scanning results for the test monolithic pixel detector suggest the following conclusions as to the desired operation modes of laser focusing systems. For obtaining the most adequate experimental results on the sensitivity of electronic devices with discrete components fabricated following small design rules (in this work, the test specimens were pixel detectors, but the same conclusions apply to other types of devices, e.g. memory cells, programmable logical ICs etc.), it is highly desirable to maximize the lens magnification for localizing the irradiation impact (obtaining the smallest possible radiation spot) and set the scanning step smaller than the design rule (technological process, distance between adjacent cells or discrete components), but not greater than the focused laser beam waist size. When doing that, one should bear in mind that there is a difference in the radiation intensities for similar energy settings but different lenses.

Another important factor significantly limiting the possibility of microchip response data recording and further analysis is the scope of information received. In this work, the limiting factors were the size and number of response signal oscillograms stored in the testing system software and limited by the control PC memory size.

The above conclusions illustrate the challenges faced when finding a correlation between sensitivity data on the basis of merely pulse energy data, without taking into account the parameters of specific laser systems used.

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