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A GRADED-GAP X-RAY DETECTOR WITH CHARGE AVALANCHE MULTIPLICATION

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Current response of graded-gap $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ X-ray detector is experimentally investigated. An increase in sensitivity of the detectors is achieved using a charge avalanche multiplication effect in a narrow region of a p-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ / n-GaAs heterojunction. The graded-gap $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ X-ray detector with charge avalanche multiplication has been developed. The sensitivity of this new type detector at a bias voltage $U = 1.5$ V reaches 2.5 A/W. That is fifty times higher in comparison with the sensitivity of the detector without charge multiplication ($U = 0$).

Keywords: X-ray detectors, graded-gap $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ structures

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1. Introduction

The important advantage of X-ray detectors based on graded-gap p-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ / n-GaAs heterostructures is charge collection without application of any bias voltage [1, 2]. A charge generated by X-ray radiation in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer is collected by a graded-gap field at the p–n-junction region. In order to increase a current response of the graded-gap $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ X-ray detector, the charge avalanche multiplication effect in a narrow region of p-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ / n-GaAs heterojunction was proposed in [2]. When an external bias voltage is applied in a reverse direction, the voltage is concentrated not in a bulk of the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer, but in the p^+–n^--junction region. At a sufficiently large reverse voltage, the charge collected at the p^+–n^--junction is multiplied due to impact ionization in a high electric field. The effect of charge avalanche multiplication in a detector current response was observed in [2]. However, due to heating of the p–n-junction by the current, the long-duration effects of reverse current relaxation were observed. These effects do not allow to use the device for X-ray radiation detection.

In this paper, the possibilities to exclude a part of current response to the X-ray irradiation from the long-duration effects of reverse current changes are considered.

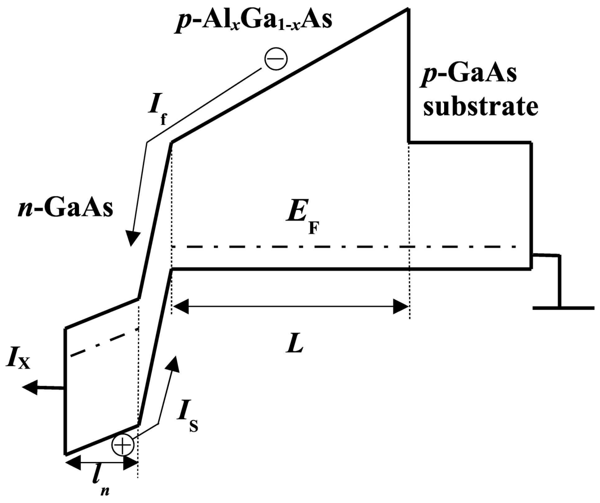

Fig. 1. Schematic band diagram of a n^--GaAs / p^+-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterostructure grown on a p-GaAs substrate with an applied reverse voltage. I_f denotes the electron flow in a graded-gap field, I_S indicates the p–n-junction reverse current.

The following structure was investigated. A high-doped ($p^+ = 10^{18}$ cm^{-3}) graded-gap p^+-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer of thickness $L = 20$ μm on the p^+-GaAs substrate was grown by a liquid-phase epitaxy. The Al_x concentration was changed from $x = 0.4$ at the substrate to $x = 0$ at the narrow-gap side. On the top of the structure, a thin ($l_n < 10^{-4}$ cm) low-doped ($n = 10^{16}$ cm^{-3}) n-GaAs layer was grown. The plane area of the detector was $S = 1\times2$ mm^2. Figure 1 shows the schematic band diagram of the heterostructure under study.

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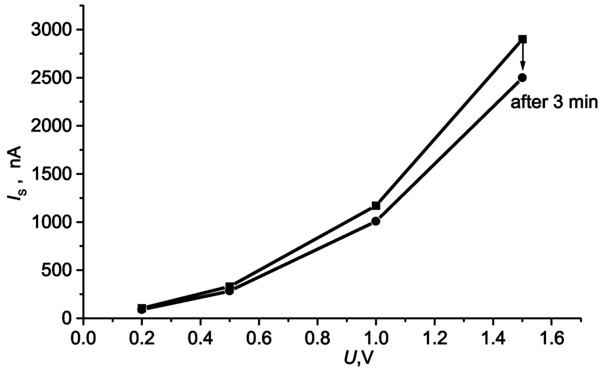

Fig. 2. Reverse current I_S through the p^+-Al$_x$Ga$_{1-x}$As / n^--GaAs heterojunction as a function of voltage U. A time interval between the I_S measurements at a given U is 3 min.

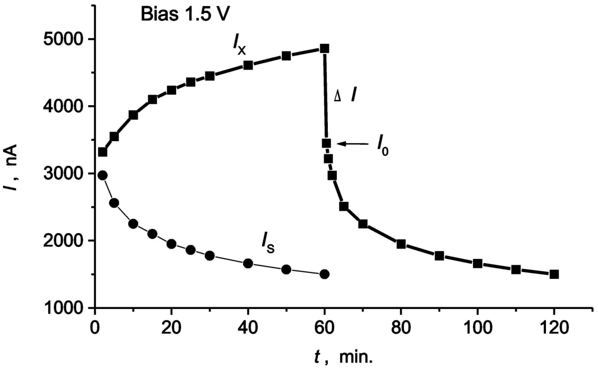

Fig. 3. Long-duration relaxation of the detector reverse current I. I_S is the reverse current in the absence of X-ray radiation, I_X is the reverse current with X-ray radiation, and I_0 is the reverse current when X-ray radiation was turned off. The X-ray power density at the detector surface was $3.7{\cdot}10^{-5}$ W/cm^2.

2. Long-duration relaxation of reverse current

The dependence of the reverse current I_S through the structure on a voltage U is shown in Fig. 2. The reverse current increases due to avalanche ionization of electron–hole pairs in high p–n-junction field. At a voltage of 1.5 V, the current increases tens of times.

At the same time, with an increase of the reverse current I_S, the long-duration process of current change in time is observed. The decrease of I_S after 3 min following the observation is shown in Fig. 2.

Figure 3 shows that a slow decrease to a new equilibrium state goes on for a few tens of minutes. We associate such a slow relaxation of the reverse current with a local heating of the p–n-junction region, mainly in the n^--GaAs layer with a thickness smaller than the hole diffusion length. In the heated thin n^--GaAs layer, slow changes of many parameters in time, such as diffusion coefficient, electron–hole recombination time, surface recombination rate, and others are responsible for the long-duration current decrease. Note that for the current through the thin n^--GaAs layer, the minority carrier (hole) current is responsible.

Upon turning on the X-ray radiation, the current through the structure increases sharply due to injection and multiplication of carriers generated by ionizing radiation and those collected from the graded-gap crystal part, and then slowly increases in time (Fig. 3). As it is seen, the injection of non-equilibrium additional majority carriers into the n-GaAs part from the graded-gap part leads to a change of character of current relaxation from the decrease in the absence of X-rays to the increase under X-ray radiation.

A total current through the graded-gap structure p^+-Al$_x$Ga$_{1-x}$As / n^--GaAs under X-ray radiation and at an applied bias, sufficient for impact ionization, is equal to

$$I_\mathrm{X} = I_\mathrm{f} + I_\mathrm{Sf}\,, \tag{1}$$

where I_f is the current of avalanche-multiplied collected charge generated by ionizing radiation in the p^+-Al$_x$Ga$_{1-x}$As layer, and I_Sf is the avalanche reverse current when I_f exists. The current I_f is the current response to X-ray radiation, i. e. that useful signal which we wish to exclude from the long-duration relaxation of total current I_X.

At turning off the X-ray radiation, the current through the structure decreases sharply by a value I_f and then decays slowly in the same way as it was in the absence of X-ray radiation (Fig. 3).

It is essential that I_f – the value of the current change at turning-off the X-ray radiation – does not depend on the time moment of turning-off. That is, independently of a long-duration and intricate relaxation of saturated total current, the difference between time-dependent currents,

$$\Delta I = I_\mathrm{X}(t) - I_\mathrm{S}(t) = I_\mathrm{f}\,, \tag{2}$$

does not depend on time. ΔI is the current response I_f to X-ray radiation.

To confirm this fact, the simultaneously measured currents I_X, with X-ray radiation, and the reverse current I_0 without it, as functions of X-ray radiation absorbed in the structure, P_abs, are shown in Fig. 4. The measurements repeated after 3 min intervals are also shown. One can see that in spite of remarkable changes of current values registered with radiation and without it after a 3 min time interval, the values of difference $\Delta I = I_\mathrm{X} - I_0$ between these currents do not depend on time and can be defined as a value corresponding to X-ray radiation power.

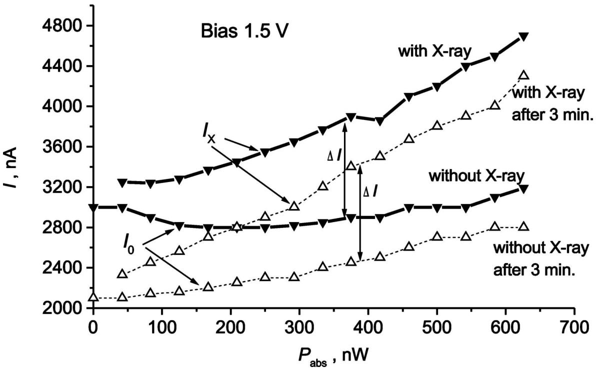

Fig. 4. Simultaneously measured currents: I_X at X-ray radiation and I_0, when the radiation was turned off for a short time, as functions of X-ray absorbed power, P_{abs} (full triangles). The measurements repeated after 3 min are shown by empty triangles. The bias voltage was 1.5 V.

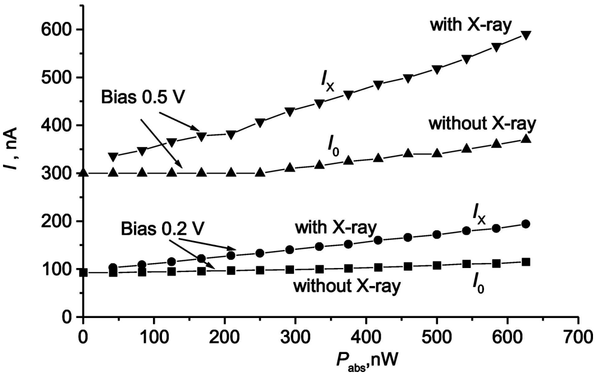

Fig. 5. Simultaneously measured currents: I_X at X-ray radiation and I_0, when the radiation was turned off for a short time, as functions of X-ray absorbed power, P_{abs}, at bias voltages of 0.2 and 0.5 V.

Figure 5 shows the analogical measurements at bias voltages of 0.2 and 0.5 V. The current change without X-ray radiation on a radiation power scale is caused by a time change in the measurement process.

Thus, it is shown that, in spite of an intricate character of long-duration relaxation processes taking place in the X-ray detector with charge avalanche multiplication, the current response to X-ray radiation does not depend on time and can be separated as a difference between the total current at X-ray radiation and the current without the radiation at any moment of time.

3. Sensitivity of the detector with charge avalanche multiplication

To measure the sensitivity of the detector, an X-ray tube with a Cu anode has been used as an X-ray radiation source with characteristic radiation of 8 keV. The anode voltage was $U_A = 30$ kV. The output X-ray radiation power was controlled by varying the anode current I_A from 1 to 30 mA. The density of X-ray radiation on the detector surface was $3.7{\cdot}10^{-5}$ W/cm^2 at $U_A = 30$ kV and $I_A = 20$ mA.

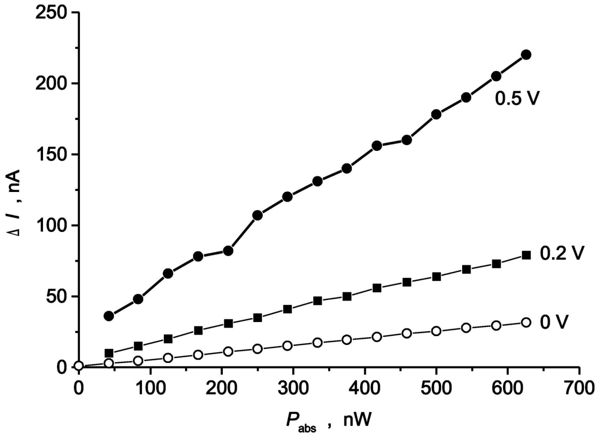

Fig. 6. Current response ΔI of the detector as a function of X-ray absorbed power P_{abs} at different bias voltages.

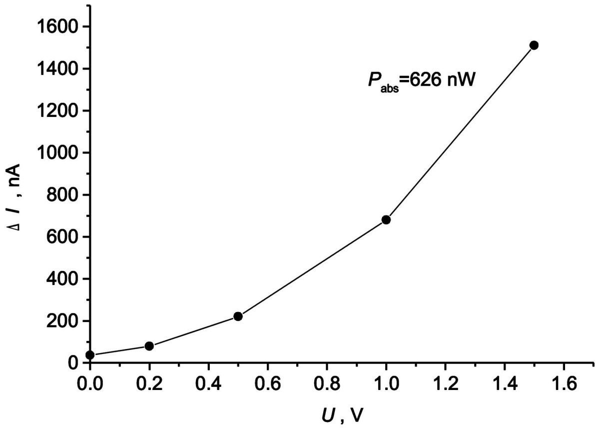

Fig. 7. Current response ΔI of the detector as a function of bias voltage U at $P_{abs} = 626$ nW.

The dependences of the current response $\Delta I = I_f$ on the absorbed X-ray radiation power at the applied voltages of 0.2 and 0.5 V, and without the bias, are shown in Fig. 6. The current multiplication effect takes place already at 0.2 V. In spite of complexity of an impact ionization process, a nearly linear dependence of the avalanche current on the absorbed power is observed at all bias voltages.

The sensitivity of the detector,

$$g = \frac{\Delta I}{\Delta P_{abs}}, \tag{3}$$

is determined by the bias voltage. At a constant absorbed X-ray power, the current response $\Delta I = I_f$ sharply increases with the applied voltage (Fig. 7). Correspondingly, the detector sensitivity increases strongly when the applied voltage increases. In the absence of the bias ($U = 0$), the sensitivity of the graded-gap detector ($g = 0.05$ A/W) coincides with the sensitivity of conventional detectors. At the bias voltage $U = 1.5$ V, due to avalanche multiplication of the collected charge, the detector sensitivity increases by a factor of 50 and reaches $g = 2.5$ A/W.

The sensitivity of conventional X-ray detectors based on different semiconductors is determined by the threshold energy required for an electron–hole pair generation and by the charge collection efficiency. The average threshold energy for different materials used in conventional X-ray detectors varies from 2.98 eV for Ge to 7.68 eV for PbJ_2 [3]. Consequently, the maximum sensitivity of conventional detectors (for 100% charge collection efficiency), evaluated in the same way as in [4], is in the range of 0.13–0.34 A/W_{abs}. So, the sensitivity of the graded-gap $Al_xGa_{1-x}As$ X-ray detectors with charge avalanche multiplication exceeds ten times the sensitivity of conventional detectors.

4. Conclusions

1. The difference between the total current, relaxing in time at X-ray radiation, and the current, when the radiation is turned off for a short time, determines the independent on time current response of the graded-gap $Al_xGa_{1-x}As$ X-ray detector with charge avalanche multiplication to the X-ray absorbed power in the graded-gap structure.
2. Because of avalanche multiplication of the collected charge, the detector sensitivity markedly exceeds the sensitivity of conventional detectors. The sensitivity reaches 2.5 A/W at bias voltage of 1.5 V.

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VARIZONINIS RENTGENO SPINDULIUOTĖS DETEKTORIUS SU GRIŪTINIU KRŪVIO DAUGINIMU

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Santrauka

Eksperimentiškai tirtas varizoninių $Al_xGa_{1-x}As$ Rentgeno spinduliuotės detektorių srovės atsakas. Siekiant padidinti detektorių jautrį, panaudotas krūvininkų griūtinio dauginimo efektas p-$Al_xGa_{1-x}As$ / n-GaAs sandūros srityje. Sukurtas varizoninis Rentgeno spinduliuotės detektorius su griūtiniu krūvio dauginimu. Naujo detektoriaus srovės atsako jautris, esant postūmio įtampai $U = 1{,}5$ V, siekia 2,5 A/W. Šis dydis yra apie 50 kartų didesnis už Rentgeno spinduliuotės detektorių, kuriuose nėra krūvio dauginimo ($U = 0$), jautrį.