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Simulation and measurements of EBIC images of photoconductive elements based on HgCdTe

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The EBIC investigations of HgCdTe based photoconductive elements have been carried out. Simulation of two-dimensional distribution of EBIC signal is carried out by numerical solution of drift-diffusion ambipolar equation. It is shown that fitting the measured EBIC profiles by simulated ones allows to obtain the effective diffusion length in the element and the surface recombination velocity on its lateral sides. The regions with enhanced recombination rate are reveled in the elements degraded by prolonged annealing at 60°C. The lateral resolution in the EBIC measurements on photoconductive elements is estimated.

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1. Introduction

The parameters of photoconductive elements such as the carrier mobility, excess carrier lifetime and diffusion length are mainly determined by defects arising under material growth and/or element formation. This stimulates a development of characterization techniques for a study of excess carrier effective recombination rate and its spatial distribution for revealing these defects and understanding the reasons for the degradation of photoconductive element parameters. The Electron Beam Induced Current (EBIC) in the scanning electron microscope is one of such techniques, in which the excess carriers are generated by the focused electron beam [1,2]. This technique is widely used for the characterization of barrier structures such as $p-n$-junctions and the Schottky barriers and allows to determine the diffusion length and to reveal extended defects locally increasing the excess carrier recombination rate. For diffusion length measurements in barrier structures different approaches were developed [1,2], which were mainly based on the measurements of collected current dependence on the distance between the generation point and a depletion region playing a role of collector. In the photoconductive elements a collector is absent and some other approach should be used. Nevertheless, as shown in [3,4], the EBIC application for the characterization of one-dimensional arrays of small size resistive photosensitive elements could be rather effective. It was shown that a comparison of measured EBIC signal distribution with simulated one allowed to estimate the effective diffusion length in the element under study and the surface recombination velocity at its sidewalls. It could be desirable to estimate the spatial resolution in the EBIC characterization of photoconductive elements and a possibility to reveal structure defects in such elements by this method.

In the present paper the EBIC investigations of HgCdTe based photoconductive elements have been carried out. The precision of diffusion length measurements on photoconductive elements from fitting the EBIC profiles and the lateral resolution are estimated. It is shown that the resolution achieved allows to reveal the local regions with enhanced recombination rate in the degraded elements.

2. Experimentals

The one-dimensional arrays of photoconductive detectors made on the base of n-$\mathrm{Cd}_x\mathrm{Hg}_{1-x}\mathrm{Te}$ ($x \approx 0.22$) have been studied. Elements have a lateral dimensions of about $50 \times 50\,\mu$m and a thickness of active layer about $5-7\,\mu$m. The elements were protected by a multilayer dielectric film with CdTe as a first layer and a total thickness of about $1.5\,\mu$m. The experimental investigations were carried out in the scanning electron microscope JSM 840A (Jeol) at 90 K, electron beam energy $E_b = 35$ keV and beam current of about 10^{-10} A. Rather large beam energy was necessary to permeate the thick dielectric film and to create electron–hole pairs inside the active HgCdTe layer. As our estimations shown, at $E_b = 35$ keV about 30% of beam energy is absorbed inside the active layer. A bias (in the most cases ± 50 mV) was applied to the element under study and the EBIC (a change of currrent due to e-beam excitation) was measured as a function of beam position. It should be noted that the EBIC dependence on applied bias was practically linear in the range from 5 to 100 mV.

As a result, the two-dimensional distribution of detector response was obtained, which characterized the distribution of element sensitivity. An integration of this distribution could give the element response under homogeneous excitation. Under excitation conditions used the EBIC value did not exceed 10% of background current value. As shown in [3,4], in these conditions the relation of excess carrier concentration Δp to the equilibrium concentration

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$n_0\Delta p/n_0 \leq 1$ even in the excitation point, where it has the maximum value. This allows us to use for a simulation of excess carrier distribution the drift–diffusion ambipolar equation with coefficients independent of excitation conditions [5].

3. Simulation of sensitivity distribution

To calculate the two-dimensional distribution of photoconductive element sensitivity the linear two-dimensional equation of photoconductivity [5]

$$\frac{\partial^2 \Delta p(x,y,x_0,y_0)}{\partial x^2} + \frac{\partial^2 \Delta p(x,y,x_0,y_0)}{\partial y^2} - \frac{e\mu_a E(x)}{D_a}\,\frac{\partial \Delta p(x,y,x_0,y_0)}{\partial x} - \frac{\Delta p(x,y,x_0,y_0)}{L^2} = -\frac{\delta(x-x_0,y-y_0)}{D_a},$$

where $\mu_a = \frac{n_0}{(n_0+\Delta p)/\mu_h + \Delta p/\mu_e}$ and $D_a = \frac{n_0 + 2\Delta p}{(n_0+\Delta p)/D_h + \Delta p/D_e}$ are the ambipolar mobility and diffusivity, respectively; D_e and μ_e are the electron diffusivity and mobility, respectively; D_h and μ_h are the hole diffusivity and mobility, respectively; x is the coordinate along the applied electric field, $E(x)$ is the electric field, $L = (D_a\tau)^{0.5}$ is the excess carrier diffusion length, τ is their lifetime and (x_0, y_0) is the beam coordinate, was solved numerically. The carrier recombination on the lateral sides of element was described by a finite surface recombination velocity S independent of x. The effect of $n^+{-}n$ contacts on the excess carrier distribution was approximated by assuming the finite surface recombination velocity (in a common case different from S) on these contacts [6]. The lateral distribution of electron–hole pair generation was calculated using the Monte-Carlo method. In the experimental conditions used $\Delta p/n_0 \leq 1$, thus, taking into account that in HgCdTe at 80 K $\mu_e \gg \mu_h$, D_a and μ_a can be approximated as $D_a \approx D_h$ and $\mu_a \approx \mu_h$.

The distribution of excess carriers obtained by the described procedure was used to calculate a change of element resistance under the electron beam excitation and then a current increase (EBIC). It should be noted that the surface recombination velocity on the top and bottom active HgCdTe layer interfaces under simulation was assumed to be small because, as shown in [7], the surface recombination velocity on CdTe/HgCdTe interface is smaller than that on the free HgCdTe surface. Therefore, the obtained effective diffusion length values could include the recombination on these interfaces and for this reason could be smaller than real ones. In more details the simulation procedure was described elsewhere [3].

4. Results and discussion

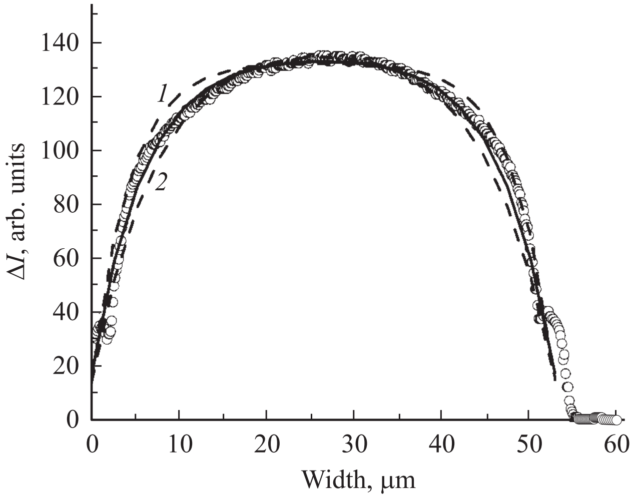

Figure 1. EBIC profile measured across the photoconductive element at a half of its length. The simulated profile are calculated with $L = 6.5$ (solid line), 9 (*1*) and 4.5 μm (*2*).

As shown in [3,4], the simulation rather well described the sensitivity distribution in resistive elements, especially the profiles in the direction y perpendicular to the direction of applied electric field. Fitting such profiles allowed to estimate the effective diffusion length L and the surface recombination velocity S on the lateral sides of elements, which were exposed to ion etching under element formation. In the present work the precision of L estimation from such measurements is evaluated. The measured EBIC profile $\Delta I(y)$ together with simulated curves are presented in Fig. 1. The results of best fitting achieved with $L = 6.5\,\mu$m and $S = 4.5 \cdot 10^4$ cm/s are shown by a solid line. The curves shown by dashed lines are calculated with L equals to 4.5 and 9 μm. It is seen that such change in L leads to a pronounced disagreement between the calculated and experimental profiles. Moreover, some qualitative difference between the measured and calculated curves arises. An increase of L under simulation leads to an increase of width of regions with the reduced signal adjacent to the lateral sides as compared with the experimental one while its decrease leads to a decrease of this width. Thus, it is seen that the precision of L estimations in the photoconductive elements studied is not worse than 20–30% and the lateral resolution should essentially depend on L. As mentioned above the obtained effective diffusion length value could be partly determined by the recombination on the top and bottom interfaces. For this reason the effective diffusion length could be smaller that the real one. But in should be stressed that just this value should be used for the characterization of technology process quality and for the prediction of element parameters independent of detail mechanism determining its value. For more detail analysis of these mechanisms a comparison with the diffusion length or lifetime values measured on as-grown material could be used.

Other question arising under the EBIC characterization of resistive photosensitive elements is associated with a possibility to reveal electrically active extended defects. To

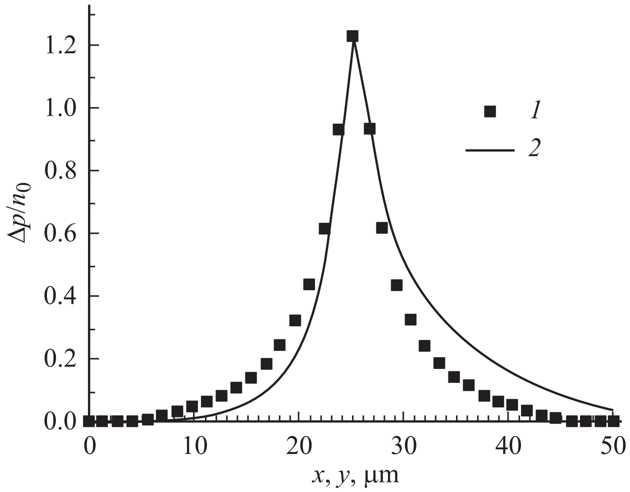

Figure 2. Excess carrier distribution across (*1*) and along the photoconductive element (*2*) calculated for e-beam located in the middle of element with $L = 6.5\,\mu$m.

evaluate the spatial resolution the excess carrier distribution is calculated for e-beam located in the middle of photoconductive element (Fig. 2). It is seen that the full width at half maximum of excess carrier concentration profile is close to the diffusion length value. The width of regions with the reduced signal adjacent to the lateral sides, as shown above, is also comparable with the diffusion length, i. e. is of about $5-10\,\mu$m. Therefore, it could be assumed that the lateral resolution of about $5-10\,\mu$m could be achieved in the EBIC study of such photoconductive elements.

To check these estimations the recombination defects are introduced in the HgCdTe photoconductive elements by their prolonged annealing at 60°C. The EBIC images of one of such element before and after annealing are presented in Fig. 3. Before annealing the image of element is typical for homogeneous photoconductive element [3,4] with a signal increasing near the contact with positive bias and decreasing near the lateral sides. The element with the small defect region (marked with arrow) is chosen for a

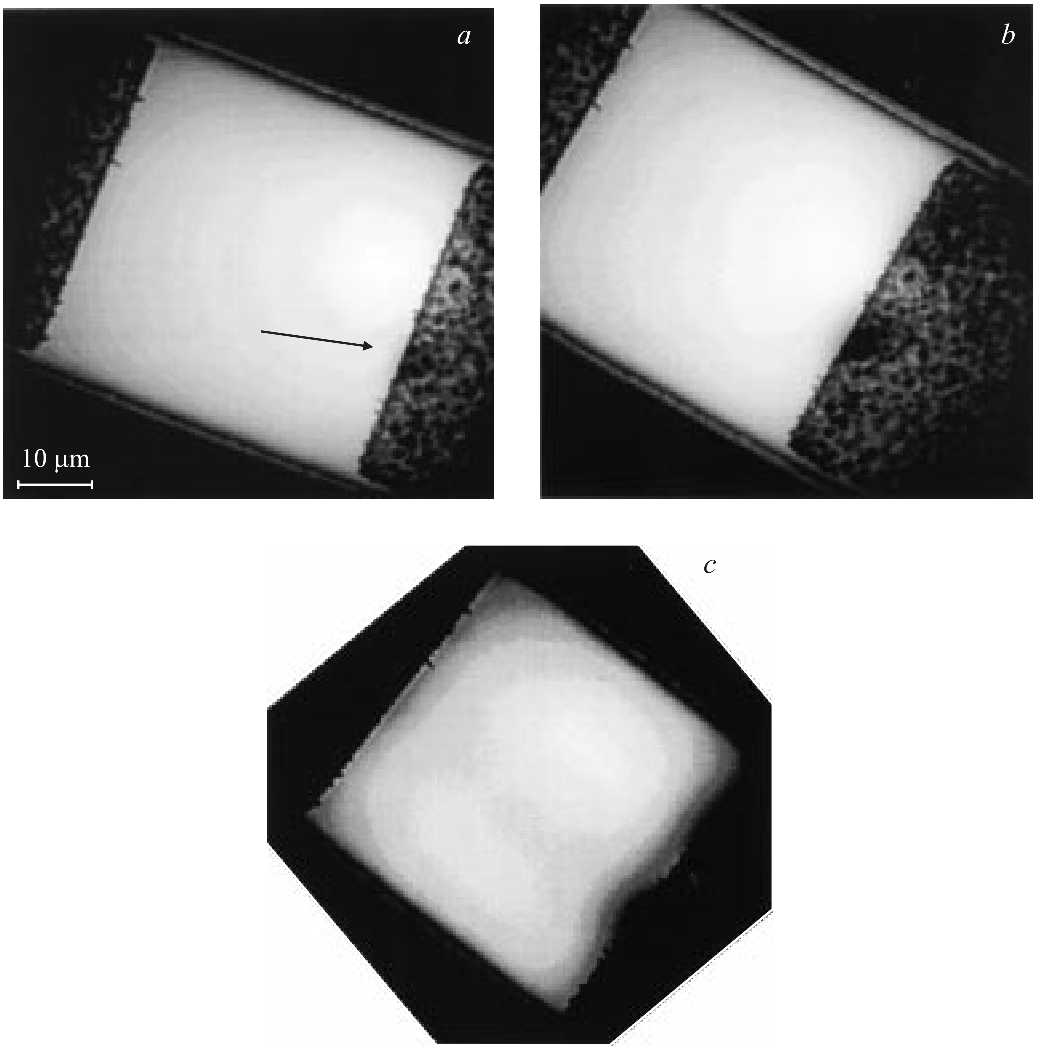

Figure 3. EBIC images of HgCdTe photoconductive element before (*a*) and after annealing at 60°C for 32 (*b*) and 90 h (*c*).

study, because other elements are found to be more stable to such annealing. It should be noted that before annealing the defect region revealed practically does not affect the element photoresponse. Annealing leads to an increase of dark contrast in this defect region and additionally a dark line appears in the image, which crossed the elements. The full width at half maximum for these defects is of about $10\,\mu$m that well correlate with the above estimation. These results demonstrate that the EBIC investigations allow to reveal the regions with enhanced recombination rate with a lateral resolution comparable with effective diffusion length. Moreover, it is shown that such resolution allows to study degradation processes and to reveal the regions, in which the recombination rate increases under degradation. Thus, such investigations could be used for the study of degradation processes in HgCdTe photoconductive elements for clarifying their reason.

5. Conclusion

Thus, it is shown that fitting the measured distribution of EBIC signal on HgCdTe photoconductive elements allows to obtain the effective diffusion length with a precision of about 20−30%. The lateral resolution, which can be achieved in such measurements is comparable with the diffusion length and allows to reveal the defect region arising due to ion etching damage or element degradation under prolonged annealing. The EBIC investigations have been shown to be promising for the estimation of material parameters in photoconductive elements and for studying the degradation processes in such elements.

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