Radiation induced control of electric field in Au/CdTe/In structures

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In this contribution we demonstrate both experimentally and theoretically the possibility to control the profile of internal electric field by compensation of the space charge formed by carriers trapped at deep levels Q_T with space charge present due to band bending at the metal/CdTe interface Q_M . The demonstrated mechanism represents a promising way to decrease the problems associated with charge collection efficiency in CdTe x-ray detectors operated at high fluxes of x-ray photons.
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Accumulation of space charge at deep levels resulting in deformation of internal electric field represents one of the main factors affecting the charge collection efficiency in CdTe and CdZnTe x-ray and gamma ray semiconductor detectors. The effect of time dependent change in charge collection efficiency, known as polarization, has been studied for a long time.^{1–6} This effect is a result of screening of the electric field by space charge formed due to band bending at contacts with Schottky barriers and takes place even without any radiation. Bale and Szeles⁷ have shown, that deformation of the internal electric field profile can be observed at high radiation fluxes even in samples with Ohmic contacts. This type of polarization represents a significant problem in development of semiconductor radiation sensors for applications in computed tomography, where fluxes of x-ray photons up to $10^8 \text{ mm}^{-2} \text{ s}^{-1}$ are required.

The electrons and holes are trapped during drift to the electrodes and form negative space charge below the anode and positive space charge below the cathode. The electric field profile has a minimum, called the pinch point,⁷ which can evolve into a dead layer at very high fluxes, or in the presence of deep levels with a high concentration.⁸ Weakening of the electric field in certain parts of the detector inevitably results in an increase in the collection time of the carriers. If the collection time becomes comparable or longer than the trapping times at dominant deep levels, the charge collection efficiency will decrease. It is therefore desirable to operate the detector with constant electric field or with such a profile where the electric field deformation is weak, so that the trapping time remains longer than collection time throughout the detector.

In this contribution we demonstrate both experimentally and theoretically the possibility to control the profile of the internal electric field by compensation of the space charge formed by carriers trapped at deep levels Q_T with space charge present due to band bending at the metal/CdTe interface Q_M .

The samples used in this study were fabricated from semi-insulating CdTe:In grown by the Vertical Gradient freeze method in the Institute of Physics, Charles University in Prague. The resistivity of the samples was $3\text{--}5 \times 10^9 \text{ } \Omega \text{ cm}$. The crystal exhibits relatively good charge collection efficiency of electrons with a mobility-lifetime prod-

uct $\mu\tau_e \sim 10^{-3} \text{ cm}^2/\text{V}$. Room temperature thermoelectric effect measurements have shown that the sample is slightly n-type. Indium and gold were deposited on opposite surfaces of the samples with dimensions $5 \times 5 \times 2.5 \text{ mm}^3$ by evaporation. The sides of the samples were optically polished with final $0.05 \text{ } \mu\text{m}$ grit and chemically etched in 1% Br-methanol solution for 1 min. Studies of the distribution of the electric field in the volume of the devices frequently employed the Pockels electro-optic effect.^{1–4} The sample is illuminated with low intensity IR light which has passed through a narrow band-pass 980 nm filter. A pair of 90° orthogonally orientated polarizing filters are arranged either side of the cryostat, with the transmitted light imaged by an IR-enhanced digital charge coupled device camera. All presented measurements were performed at room temperature. An x-ray tube with an Ag anode was used as the source of x-ray radiation. The Au electrode of the CdTe sample, acting as the cathode, was simultaneously irradiated with x-ray photons.

The results of measurement of steady-state electric field profiles for applied external voltage 500 V (average internal $E=2000 \text{ V/cm}$) are shown in Fig. 1. The steady-state without flux was achieved in 1 min after applying the voltage, when most of charge redistribution happened within the first 10 s. Then the electric field profile remained unchanged

FIG. 1. (Color online) The results of electric field profiles through sample acquired by Pockel's effect measurement. An external voltage 500 V was applied. The electric field decreases from cathode forming a dead layer below the anode when no x-ray flux was applied. The electric field profile approaches a constant value with an increasing x-ray flux. Further increase in radiation flux results in formation of dead layer below the cathode. X-ray tube with a silver target, operated at 30 kV was used.

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FIG. 2. Profile of energy bands used for the simulation.

within 24 h of testing. The steady state profiles of electric field under irradiation were achieved approximately within 2 s.

The electric field decreases from the cathode forming a dead layer below the anode, when no x-ray radiation was applied. This situation corresponds to a prevailing positive space charge accumulated in the sample. The profile of the electric field approaches a constant value with an increasing x-ray flux. Further increase in radiation flux results finally in the formation of a dead layer below the cathode. Similar results were obtained on the other two samples used in the study.

The acquired experimental data were simulated using software developed at the Institute of Physics, Charles University. It is based on the simultaneous solution of drift-diffusion and Poisson equations of a system consisting of one deep level, characterized by ionization energy, and electron and hole-capture cross sections. The standard Shockley-Read model describes recombination through the level. The boundary conditions are set by the Fermi energy pinned to the metal, which yields band bending at the surface.⁸ According to the standard model of the difference of work functions between metal and semiconductor, Au ($\Phi_{\text{Au}} \sim 5.2$ eV) can form an Ohmic, slightly blocking or slightly injecting contact on semi-insulating CdTe ($\Phi_{\text{CdTe}} \sim 5.1\text{--}5.3$) depending on the actual position of the Fermi level in CdTe and the voltage polarity. Indium having a much smaller work function ($\Phi_{\text{In}} \sim 4.1$ eV) is a clear candidate for a hole blocking contact (bands bent downwards) when used as an anode. However, surface dipoles can substantially modify the expected values as derived from the simple work function difference model.

We have used therefore the difference of work functions between both metals and CdTe as an optimizing parameter of the model, looking for agreement with the experimental profiles in both polarities of the applied voltage. The chosen band profiles for $\Phi_{\text{Au}} - \Phi_{\text{CdTe}} = 150$ meV (bands bent upwards) and $\Phi_{\text{In}} - \Phi_{\text{CdTe}} = -50$ meV (bands bent downwards) are shown in Fig. 2 (without applied voltage). The results of the simulation of the electric field for an applied voltage of 500 V are presented in Fig. 3. Apparently, the chosen model very well fits the experimental data. The parameters of the deep level used in the simulation were as follows: concentration $N_{\text{deep}} = 4 \times 10^{11} \text{ cm}^{-3}$, capture-cross section for electrons $\sigma_e = 5 \times 10^{-13} \text{ cm}^2$, and capture-cross section for holes $\sigma_h = 3 \times 10^{-14} \text{ cm}^2$. The inaccuracy of the experimental re-

FIG. 3. (Color online) The results of the simulation for $\Phi_{\text{Au}} - \Phi_{\text{CdTe}} = 150$ meV (bands bent upwards) and $\Phi_{\text{In}} - \Phi_{\text{CdTe}} = -50$ meV (bands bent downwards).

sults is mostly caused by the optical properties of the sample surface.

Without x-ray flux the sample is positively charged due to the band bending at the Au/CdTe interface (bands bent upwards) which prevails over the smaller band bending at the CdTe/In interface (bands bent downwards). The observed turn-over of the field with increasing radiation flux (Fig. 1) can be explained by the assumed compensation of this positive space charge with negative space charge due to electrons trapped at the deep level. The prevailing capture of electrons and build-up of negative space charge under illumination is a result of the higher capture-cross section of electrons compared to holes chosen in the model. The profiles of space charge (Fig. 4) for the electric field profiles (Fig. 3) clearly confirm the mechanism of space charge compensation described above. With the used polarity of the external voltage the contacts are blocking the flow of both electrons and holes. The band bending at the In/CdTe interface is much smaller than assumed from the contact potential difference probably due to the dipoles formed at the interface due to presence of thin oxide layer between In and CdTe. This conclusion is based on the above described simulations of electric field profiles.

The demonstrated mechanism represents a promising way to decrease the problems associated with electric field modification and reduced charge collection efficiency in CdTe x-ray detectors operated at high fluxes of x-ray photons.

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FIG. 4. (Color online) The calculated profiles of space charge for the electric field profiles in Fig. 3 clearly confirm the mechanism of space charge compensation.

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