Charge Collecting Properties of Proton Irradiated CdTe Detectors

Beatrice Fraboni, Anna Cavallini, and Antonio Castaldini

***Abstract*—We have investigated the effects of proton irradiation on the charge collecting properties of planar CdTe detectors. The spatial distribution of the charge collection and of the electric field inside the material has been studied by photocurrent spectroscopy and surface potential analyses. The results indicate that a localized damaged layer is formed under the irradiated electrode due to the presence of a high concentration of electron traps. The induced p^+-type region affects the distribution of the electric field: after irradiation the field is no longer uniform inside the detector but it rapidly decreases to zero towards the damaged layer.**

***Index Terms*—Charge carrier transport, electric field distribution, proton irradiation effects, room temperature detectors.**

I. Introduction

THE interest in CdTe-based detectors arises from their promising and unique properties as room-temperature X- and gamma-ray detectors, often employed in a radiation hostile environment. Radiation damage strongly affects the performance of the detectors as a consequence of lost charge collection efficiency. The origin of this effect is linked to the generation of electrically active defects in the detector material that intervene in the charge carrier trapping properties. The determination of the charge collecting properties, that are strongly linked to the electric field distribution inside the detectors, is therefore needed to achieve a better control of the spectroscopic performance of the detector before and after exposure to ionizing field. Intense proton fluences of various energies are expected in applications such as astronomy satellites and nuclear reactor detector and the effects of high proton fluences on the performance of CdTe detectors are still under study.

Previous studies on proton irradiation effects have been carried out with high energy protons (up to 200 MeV) [1]–[4] and very limited information is available on their effects at a microscopic level [5]. It has been suggested that high energy proton irradiation (200 MeV) affects the depletion properties of the detector, possibly via the formation of a damaged layer [3].

We have investigated the effects of irradiating the cathode with low energy protons (700 keV) in order to induce a localized damaged region and to evaluate the effects of proton irradiation on the transport properties of the detectors. The spatial distribution of the charge collection properties has been evaluated by spatially resolved photocurrent (PC) spectroscopy [6], [7] and by surface potential (SP) analyses that allow to directly evaluate the electric field profile within the detector [8].

We have recently reported on the microscopic effects of 700 keV protons on CdTe:Cl studied by gamma spectroscopy, $\mu\tau$-product measurements and PICTS analyses and the results obtained [9] indicate that the detectors loose their spectroscopic capabilities after an irradiation fluence of $2.0 \times 10^{12}\ \mathrm{p/cm^2}$. The degradation of the performance is correlated to a large decrease of the $\mu\tau$-product for electrons and to the increase in concentration of deep levels associated to electron traps [9].

The results obtained in this work directly identify a localized damaged region induced by proton irradiation, of which we characterized the electrical activity. If we correlate the reported enhancement of the electron traps induced by protons [9] to the results here presented, we can interpret the effects of protons as a local modification of the effective electron density associated to the formation of a p^+-layer that affects both the charge collecting properties and the electric field distribution inside the detector.

II. Experimental

We investigated p-type CdTe:Cl detectors grown by EURORAD by the Traveling Heater Method (THM). The detectors were 2 mm $\times$ 5 mm in dimensions and 1 mm thick. On each planar detector two platinum ohmic electrodes, 50–80 nm thick, had been deposited by electroless technique. A batch of 6 detectors has been exposed through the cathode to 700 keV protons at a fluence of $1.2 \times 10^{12}\ \mathrm{p/cm^2}$. Proton irradiation was carried out the CNR-IMM Institute (Bologna, Italy) with protons produced by a 1.7 MV Tandetron accelerator. The induced damage is peaked at approximately 8 $\mu\mathrm{m}$ from the surface. The dose rate was kept constant for all the experiments to fix a common parameter among the different radiation fields. The set of irradiated detectors was chosen on the basis of similar properties, such as mobility-lifetime ($\mu\tau$) products, charge collection efficiency and energy resolution, as assessed by gamma spectroscopy and current-voltage analyses [9].

Photocurrent analyses have been carried out at room temperature in planar ohmic contacts configuration. A monochromatic photon beam of approximately 20 $\mu\mathrm{m}$ in diameter, obtained from a QTH lamp focused into a monochromator, has been focused onto the sample and has been scanned across the cross-sectional surface between the two ohmic contacts. The photogenerated carriers are swept out by the electric field due to the external applied bias and the obtained photocurrent profile mirrors the local charge carrier recombination activity. The photon flux ranges between 10^{12} and 10^{14} photons/cm^{2}s to work in low injection conditions and to avoid plasma effects. PC profiles have been collected both with below- and above-band gap

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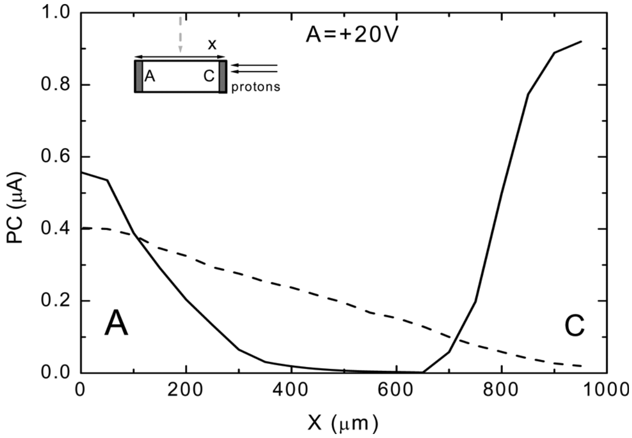

Fig. 1. PC profiles of CdTe detectors obtained in cross-section before (dashed line) and after (solid line) proton irradiation, for $\lambda = 840$ nm. The anode and cathode sides are marked as A and C, respectively. An external bias $\mathrm{Vb} = 20$ V is applied to the anode. The inset shows the sample layout during the measurements.

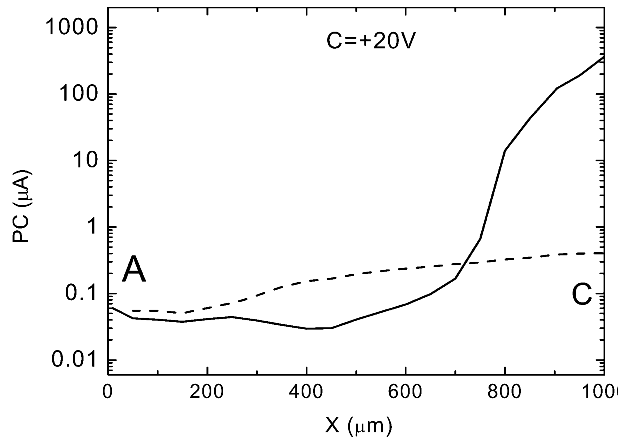

Fig. 2. PC profiles of CdTe detectors obtained in cross-section before (dashed line) and after (solid line) proton irradiation, for $\lambda = 840$ nm. The anode and cathode sides are marked as A and C, respectively. An external bias $\mathrm{Vb} = 20$ V is applied to the cathode.

light ($\lambda = 840$ nm and 630 nm, respectively), to assess the bulk properties of the material. The photocurrent signal has been collected by a lock-in amplifier, the chopping frequency being <10 Hz.

Surface potential profiles have been obtained by connecting a tungsten tip to a high impedance electrometer (Keithley 6517). The tip has been positioned at regular intervals (20 μm) on the cross-sectional surface of the detector, between the two ohmic contacts, thus enabling the collection of the potential signal versus distance from one ohmic contact to the other [8]. It has been shown [10] that this experimental procedure allows to obtain information on the voltage variations within the bulk of the detector. All measurements have been carried out in air.

III. Results and Discussion

The charge collecting properties of planar CdTe detectors have been investigated by spatially resolved PC spectroscopy analyses and by SP measurements in the configuration sketched in the inset of Fig. 1.

PC and SP analyses provide complementary information since PC describes the charge collection properties of minority carriers while SP determines the spatial distribution of the electric field. The electric field E distribution could be, in principle, determined from photocurrent profiles, since the collected current depends on E. However, some necessary optical parameters such as reflectivity of the sample surface, absorption coefficient before and after irradiation (related to the defective states inside the material) are not available for the samples here investigated, thus preventing the straightforward extraction of the distribution and intensity of E(x). For this reason we determined the spatial distribution of the electric field by SP analyses. While photocurrent measurements allow for the determination in non-contact mode of the spatial charge collection across the device, SP measurements provide direct information on the electrical behaviour of each contact. In fact, SP measurements are carried out in common-mode voltage, i.e. when one of the contacts is connected to the electrometer low electrode, the traveling tip probes the other contact. Good agreement has been reported on PC and SP analyses of depletion layers carried out on Si and GaAs irradiated detectors [7], [8].

Typical PC profiles for not-irradiated detectors are reported as dashed lines in Figs. 1 and 2. The side of the anode and of the cathode are marked. In Fig. 1 the external bias, $\mathrm{Vb} = +20$ V, is applied to the anode while in Fig. 2 it is applied to the cathode. The increasing trend observed in the PC signal at the biased contact is expected according to the mechanism of charge generation, drift and diffusion with a planar configuration due to the electric field distribution induced by the external applied bias [11]–[13]. The symmetry of the PC profile with respect to the contact where the bias is applied indicates that the material is homogeneous and that so are its charge collecting properties, despite the small difference observed between the non-irradiated profiles in Fig. 1 and 2 due to the non perfectly symmetric ohmic contacts.

The observed damage depth, larger than the proton penetration depth predicted by SRIM simulation [9] is the result of three factors: the tail of the damage itself, the shape of the beam generation volume within the material [14] and its dependence on the charge carrier diffusion length.

After irradiation through the cathode, we have carried out the same analyses on the same detectors and we have obtained the profiles reported as solid lines in Figs. 1 and 2 with the bias applied to the anode and cathode, respectively. Fig. 1 (Vb applied to the anode) shows an enhancement of the collected current intensity under both the cathode and the anode, the variation in the PC signal under the cathode being particularly relevant if compared to the signal present in the not-irradiated material. If we apply the external bias at the cathode, as shown in Fig. 2, the PC profile shows a marked asymmetry: the signal under the anode is comparable with the one collected in the not-irradiated detector while the current collected under the cathode increases of three orders of magnitude. This behaviour indicates that the charge collecting properties have been drastically modified by proton irradiation and that the changes mostly affect the region localized under the cathode. In fact, the anomalously high photocurrent measured under the cathode when a positive

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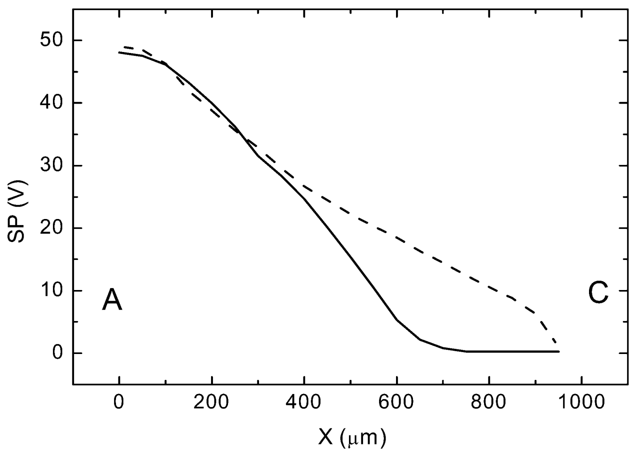

Fig. 3. SP profiles of CdTe detectors obtained in cross-section before (dashed line) and after (solid line) proton irradiation. The anode and cathode sides are marked as A and C, respectively. An external bias $\mathrm{Vb} = 20\ \mathrm{V}$ is applied to the anode.

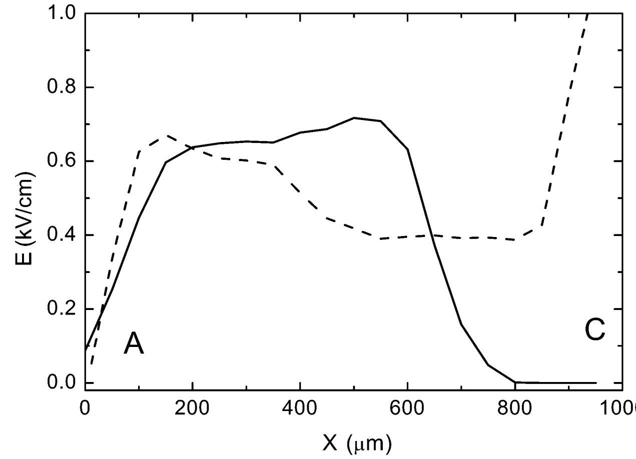

Fig. 4. Electric field distribution obtained from SP profiles (Fig. 3) of CdTe detectors before (dashed line) and after (solid line) proton irradiation. The anode and cathode sides are marked as A and C, respectively. An external bias $\mathrm{Vb} = 20\ \mathrm{V}$ is applied to the anode.

bias is applied to it (Fig. 2), can only be justified by a localized strong alteration of the material transport properties related to the defect states introduced by proton irradiation [9], [11]. The increase in the collected current at the cathode when the positive bias is applied to the anode (Fig. 1) confirms the presence of an electrically active damaged layer that enhances the collection of negative charge carriers.

Results reported on the microscopic characterization of proton irradiated p-type CdTe detectors [9] indicate two significant effect induced by the irradiation: the reduction of the mobility-lifetime for electrons coupled to an increase in deep levels that act as electron traps. If we correlate these observations with the present results, we can hypothesize the conversion into p^{+}-type material of the damaged layer under the cathode due to modifications in the material electrical compensation process [15]. The p^{+}-like layer behaves like an injecting contact if a positive bias is applied to the cathode, as can be inferred from Fig. 2, where the collected minority carrier current increases of three orders of magnitude with respect to the not irradiated sample. When a negative bias is applied to the cathode, as in Fig. 1, the layer behaves like a blocking contact and the collected current is much lower than in the previous case.

This local alteration of the charge carriers distribution and trapping should have an effect on the electric field distribution inside the material, closely linked to spatial variations in its charge collecting properties.

Fig. 3 reports the SP profile as a function of distance between the ohmic contacts, as measured in the cross-sectional configuration sketched in the inset of Fig. 1. The anode and cathode positions are indicated. The profile of the potential under the cathode is quite different before and after irradiation, suggesting that significant alterations have locally occurred in the fixed and mobile charge distribution. By differentiating the interpolated surface potential profiles we obtain the electric field distribution curves reported in Fig. 4 [8].

The electric field distribution obtained for the not-irradiated detectors closely resembles the distribution recently found by Pockels effect on planar CdTe detectors [16], where the electric field resulted uniformly distributed all over the detector thickness, slightly increasing towards the cathode when the anode is positively biased. This behaviour has been observed only for planar CdTe detectors, i.e. detectors with two ohmic contacts. After irradiation the distribution of the electric field results significantly altered under the cathode, where its intensity decreases towards zero. This marked decrease well correlates with the hypothesized local conversion of the damaged layer into a p^{+}-type region that acts as an improved injecting contact into the bulk p-type material.

IV. Conclusions

In conclusion we have investigated the effects of proton irradiation on the charge collecting properties of planar CdTe detectors. The spatial distribution of the charge collection and of the electric field inside the material has been studied by photocurrent spectroscopy and surface potential analyses, methods that allow for a direct determination of their profile across the device. The results indicate that a localized damaged layer is formed under the irradiated electrode where the charge transport mechanisms are significantly altered due to the presence of a higher concentration of electron traps that locally modify the material electrical compensation process. This results in the formation of a p^{+}-type region that affects the distribution of the electric field: after irradiation the field is no longer uniform inside the detector but it rapidly decreases to zero towards the damaged layer under the irradiated contact. These results provide both an assessment of the experimental tools available for the determination of the major transport parameters that control the spectroscopic performance of radiation detectors and a deeper understanding of the performance degradation of CdTe detectors exposed to proton irradiation.

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