Investigation of the Internal Electric Field distribution under in-situ x-ray irradiation and under low temperature conditions by the means of the Pockel effect.

G. Prekas, P.J. Sellin, P. Veeramani, A.W. Davies, A. Lohstroh, M.E. Özsan, M.C. Veale,

Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, UK

Abstract

The internal electric field distribution in cadmium zinc telluride (CdZnTe) X-ray and γ -ray detectors strongly affects their performance in terms of charge transport and charge collection properties. In CdZnTe detectors the electric field distribution is sensitively dependant on not only the nature of the metal contacts but also on the working conditions of the devices such as the temperature and the rate of external irradiation. Here we present direct measurements of the electric field profiles in CdZnTe detectors obtained using the Pockel electro-optic effect whilst under in-situ X-ray irradiation. These data are also compared with alpha particle induced current pulses obtained by the transient current technique (TCT), and we discuss the influence of both low temperature and X-ray irradiation on the electric field evolution. Results from these studies reveal strong distortion of the electric field consistent with the build-up of space charge at temperatures below 250K, even in the absence of external irradiation. Also, in the presence of X-ray irradiation levels a significant distortion in the electric field is observed even at room temperature which matches well the predicted theoretical model.

1. Introduction

Recently, there has been a growing interest in the use of cadmium zinc telluride (CdZnTe) as a room temperature X-ray and γ -ray detector due to the combination of a large band-gap, and high atomic number. This allows CdZnTe radiation detectors to operate at, or close, to room temperature, and with good sensitivity for X-ray and γ -ray spectroscopy.¹⁻³

Furthermore, recent improvements in growth techniques have improved the CdZnTe material quality and charge transport properties, resulting in detectors with improved energy resolution. This has opened a wide field of potential applications of CdZnTe detectors for medical, space, industrial and security imaging and tomography. However there continues to be a lack of quantitative understanding of uncontrolled native defects and impurities in CdZnTe material, and their influence on drift mobility and carrier lifetime.⁴

In particular, operation of CdZnTe detectors in high flux medical X-ray beams can cause detector instabilities at very high photon flux rates⁵. There is increasing evidence that these instability phenomena are associated with the presence of deep energy levels and the build-up of trapped charges, or space charge, within the active volume of the device.⁶⁻⁷ At high incident fluxes the build-up of space charge inside the device produces an internal electric field that acts to oppose the externally-applied voltage. Eventually the net effective field across the device is significantly reduced, leading ultimately to a collapse of the electric field in the detector⁸. Such polarisation phenomena can cause a significant reduction in signal amplitude which can lead to greater long-term instability in the detector. The exact nature of the internal electric field is determined by the dynamic equilibrium between the rate of charge injection from the incident beam, and the thermally-activated charge emission rate from the deep levels in the material. Consequently, polarisation phenomena in CdZnTe detectors are critically sensitive on the intensity and energy of the incident photon irradiation, and the temperature of the detector. Indeed, evidence of electric field distortion has been reported even with low intensity X-ray spectroscopy measurements when the CdZnTe has been cooled to temperatures below 180K.⁹⁻¹⁰

In this work we present Pockels electro-optical measurements of electric field profiles in CdZnTe which are measured as a function of both temperature and external irradiation of the detector in an X-ray beam. In this way we study the influence of reducing the temperature to below 200K on the operation of the CdZnTe detectors, and the possible influence of non-uniform electric field distributions on the spectroscopic performance of the devices. Also, Pockel imaging is carried out in real-time with the detector irradiated by a variable flux of X-rays, so that variations of the internal field distribution can be assessed as a function of flux rate. Such studies are of particular interest for applications of CdZnTe

detectors in high flux X-ray scanning equipment, such as medical or security inspection systems.

2. Experimental system

2.1 Pockel's experiment.

Two similar devices (Sample A and Sample B) were used in the present study; these were fabricated from spectroscopic quality <111> oriented CdZnTe crystals fabricated by Yinnel Tech Inc, which was grown by a modified vertical Bridgman technique. The contacts are thermally evaporated Au in a planar configuration and each detector was six-sided polished to achieve optimum image quality for the electric field distribution imaging. Both sample A and sample B had the same dimensions 6mm x 6mm x 2.4mm.

In order to measure the electric field distribution, we used the Pockels electro-optic effect¹¹⁻¹⁵. This technique is extensively used to measure the average internal electric field distribution between the anode and the cathode of a device and it relies on a voltage-induced birefringence phenomena. The system used is described in detail in figure 1. To measure the electric field profiles as a function of light intensity distribution, a pair of crossed analysing polarisers is used, together with a light source which uniformly illuminates the crystal with near-infrared light parallel to the contacts and perpendicular to the applied electric field lines. Finally the light intensity images were recorded by a CCD digital camera and saved to a computer for offline analysis. The light is generated by a tungsten white light source and filtered by a 980nm narrow band pass filter with 3.7nm bandwidth. Then Plane-polarised light is incident on the side of the sample after passing through the first analysing polariser oriented at 45 degrees with respect to the direction of the electric field. After passing through the crystal the light goes through the second polariser whose polarisation vector is perpendicular to the first polariser. The transmitted beam is then collected by an objective lens coupled to the CCD camera.

Under these conditions the intensity of the transmitted light $I(x,y)$ is given by equation (1),

$$I(x, y) = I_0(x, y) \sin^2 \left[\frac{\sqrt{3} \pi n_0^3 r_{41} d}{2 \lambda_0} E(x, y) \right] \quad (1)$$

where $I_0(x,y)$ is the maximum intensity transmitted through the unbiased detector with the polarisers parallel; n_0 is the field free refractive index in CdZnTe; r_{41} is the linear electro-optic coefficient, $d=6\text{mm}$ is the optical path length through the crystal; $E(x,y)$ is the mean electric field intensity along the optical path; and λ is the wavelength of the incident light.

A calibration was initially carried out to optimise the light intensity level using an optical power meter to verify the incident light intensity on the sample. The light intensity was kept to a minimum not exceeding a value of 900 uW/cm^2 , to prevent distortion of the electric field due to the photo-generated carriers.

The sample was mounted inside a customised optical cryostat which contained two optical sapphire windows to allow transmission of the near infrared light through the sample, and vacuum shields to allow measurements at low temperatures down to 100K. In addition, the top lid of the cryostat contained a 2mm thick aluminium window to allow X-ray irradiation of the device during Pockel measurements. X-ray irradiation was performed using an Ag 500 μA X-ray tube, with the CdZnTe sample arranged so that the X-rays irradiated the top cathode electrode.

2.2 Transient current Technique experiment.

In order to verify the measured electric field profiles, and to perform an independent calibration of the electric field magnitude, we positioned an alpha particle source inside the cryostat to allow simultaneous alpha particle induced transient current technique (TCT) measurements (Fig.2). For this measurement an ^{241}Am alpha particle source was used, which also irradiated the top cathode of the device. Positive bias voltage was applied to the rear anode contact, using a bias-T configuration. The detector output was fed into a high bandwidth current preamplifier with variable gain to buffer the signal, which was then passed through a timing filter amplifier (TFA) to improve the signal to noise ratio and the final voltage output pulses were recorded before digitising using a TDS-3034B oscilloscope. The TFA output was also passed to a constant fraction discriminator which produced a low noise trigger signal for the oscilloscope. The gain of the current preamplifier used for these measurements from 10^5 V/A , with a bandwidth of 14 MHz.

3. Results

3.1 Room temperature electric field distribution.

Initial measurements of electric field distribution at room temperature were carried out using voltages up to 700V, which is a typical operating voltage for a planar CdZnTe device of thickness 0.24cm. In figure 3, we report the images of the light intensity distribution profiles of the biased detector from 0V up to 700V in steps of 100V. The lighter portions of the profile are clearly associated with high levels of light transmission. Since, according to our initial calibration, the illumination of the crystal is rather uniform over an area of 10mm x 10mm, the light intensity profiles are directly indicative of the electric field distribution profiles. The features appearing at the pictures are simply surface scratches due to insufficient side polishing and they are not associated with the crystal or image quality.

After image processing the average electric field profiles between the cathode and anode, illustrated in figure 4, were calculated. These profiles clearly demonstrate that the electric field is uniformly distributed between the cathode and the anode, consistent with a low concentration of space charge which is typical of a semi-insulating CdZnTe detector under equilibrium, room temperature conditions. To obtain the value of the charge density and potential distribution, we used the Poisson equation which simply calculates the differential and integral of the electric field as a function of thickness (equation 2,3) respectively. An estimate of the charge density distribution with this analysis gave a value of approximately (10^{13}cm^{-3}). As the applied voltage on the detector is increased the mean electric field strength increases at a constant rate, with the field profiles.

$$E = -\nabla\varphi \quad (2)$$

$$\nabla^2\varphi = -\frac{\rho}{\epsilon\epsilon_0} \quad (3)$$

Where $\nabla^2 \varphi = (\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2})\varphi(x, y, z)$, $\mathbf{E}$ is the electric field strength, φ is the potential distribution, ρ is the charge density distribution and ϵ_0 and ϵ are the permittivity of the free space and medium respectively.

3.2 Low temperature electric field distribution.

To investigate the low temperature field distribution the sample was cooled to 240K, and Pockel's imaging was carried out with the sample at a fixed voltage of 400 V. The resulting Pockel's images and intensity profiles were acquired at 20 K temperature steps up to room temperature. Figure 5 shows the resulting light intensity distribution profiles. As previously shown, at room temperature the light intensity is uniform throughout the thickness of the device, however as the temperature decreases a high intensity part of the image, corresponding to enhanced field strength, appears towards the cathode side of the device. At very low temperatures (<250K) this high field region is localised under the cathode side. There is no further significant change in the shape or brightness of the light intensity below 240K where the profiles saturate. Figure 6 shows the calculated electric field profiles as a function of temperature, which clearly illustrates a significant distortion to the linear electric field distribution at temperatures lower than 260K. Below this temperature the field distribution rapidly separates into a low-field region, covering the majority of the detector thickness, and a high-field region close to the device cathode. In the high-field region the electric field strength rapidly increases to a limiting value of $\sim 3000 \text{ Vcm}^{-1}$ whereas in the low-field region of the device the electric field strength approaches a minimum value of $\sim 600 \text{ Vcm}^{-1}$. As reported later the significant increase and localisation of the electric field close to the cathode will influence the drift times of the charge carriers, for example resulting in faster collection of charge carriers which are created in the near-cathode region.

The observed distortion of the electric field at low temperatures is mainly attributed to the accumulation of positive space charge arising from deep traps in the material. Using the same form of the Poisson equation (equation 2, 3) we were able to obtain an estimate of the charge density and potential distribution across the device at

various low temperatures. From that analysis of the field profiles an estimate the internal charge density (fig 7), was obtained which can reach values up to $3 \times 10^{15} \text{ cm}^{-3}$. The build-up of space charge tends to produce an internal field inside the device which acts against the applied field, and reduces the effective internal voltage and hence the effective field strength which acts on the charge carriers (fig 8). At temperatures between 250K and 300K the concentration of the space charge is distributed throughout the device thickness, which confirms that the trapping arises throughout the bulk and not from the surface. These data show a very large internal potential building up inside the device at low temperature, as much as 300V at 200K. As a result a device biased with 400V and operated at 200K will function as if it were biased at only 100V, leading to a shift of the peaks to lower channel numbers and loss of spectroscopic information.

To confirm the significant distortion of the electric field profile at low temperature we recorded alpha particle induced current pulses using a ^{241}Am alpha particle source. This transient current technique (TCT) provides information on the drift field in a semiconductor detector by analysis of the width and shape of the current pulses.¹⁶ In this configuration the width of the current pulse is a measure of the electron drift time across the device, and hence a probe of the electric field distribution. Figure 9 shows the resulting alpha particle current pulses, acquired at 400V bias and at various temperatures. The data show a significant decrease in the Full Width Half Maximum (FWHM) of the pulses, from 160 ns FWHM at $T = 300 \text{ K}$ to 41 ns FWHM at $T = 220 \text{ K}$. The shorter pulse width at low temperatures corresponds to fast electron drift across the narrow high field region (eg. ~0.2 mm at 220K) compared to the slower drift of electrons at higher temperature (eg. at 300 K) where the field is more uniform but with a significantly lower average value. At low temperature the shape of the current pulse matches the observed field profile - with initial large amplitude due to high drift velocity, indicating the portion of the electric field where total electron collection takes place, followed by a long low-amplitude part of the pulse corresponding to low drift velocity.

Conclusions

In conclusion, we have presented electro-optical imaging of the electric field distribution in CdZnTe detectors using the Pockel effect, as a function of device temperature and in-situ X-ray irradiation. At room temperature the electric field distribution is uniform between the electrodes, whereas the electric fields become significantly distorted at temperatures below 250K. At low temperatures the electric field collapses and splits to form separate high-field and low-field regions in the device. Similar phenomena have also been observed when the detector is irradiated with an X-ray flux at room temperature. In this case a strong field minimum develops close to the centre of the device, consistent with the accumulation of positive space charge due to the trapping of free-carrier holes created by the X-ray irradiation. These field distortion effects observed at low temperatures and under X-ray irradiation have a direct influence on the carrier drift and charge collection efficiency of the devices.

Acknowledgments

This work was supported by the RCUK/EPSRC Basic Technology grant ‘HEXITEC’.

References

- [1] R. James *et al.*, Semiconductors for Room Temperature Nuclear Detection Applications, Academic Press, New York, 1995, pp. 384. [2] T.E Schlesinger *Et al.*, 2001 Mater. Sci. Eng. **32** 103.
- [3] Cs. Szeles *et al.*, IEEE Trans. Nucl. Sci., vol. 54, no. 4, pp. 1350–1358, August 2007. [4] K. Suzuki IEEE Transactions on Nuclear Science, Vol. 49, No. 3, June 2002.
- [5] Derek S. Bale *et al.*, Applied Physics Letters **92** , 082101 (2008).
- [6] J. Franc *et al.*, IEEE Transactions on Nuclear Science, Vol. **54**, No. 4, (August 2007). [7] G.S Camarda *et al.*, IEEE Nuclear Science Symposium Conference Record (2007). [8] A. Jahnke and R. Matz, Med. Phys, **26**, 38, (1999).
- [9] B.W.Sturm *et al.*, IEEE Transactions on Nuclear Science, Vol. **52**, No. 5 (October2005).
- [10] H. Toyama *et al.*, Japanese Society of Applied Physics, Vol. **45**, No.11, 2006, pp8842 8847.
- [11] P. De Antonis *et al.*, IEEE Transactions on Nuclear Science, Vol. **43**, No. 3, June1996.

- [12] H.W. Yao *et al.*, Mater. Res. Soc. Symp. Proc. **487** (1998), pp51.
- [13] A. Cola *et al.*, Nuclear Instruments and Methods in Physics Research A 568 (2006), pp 406-411.
- [14] A. Burger *et al.*, Journal of Electronic Materials, Vol **32**, No 7, 2003.
- [15] S. Namba, Journal of American Optical Society. Vol **51**, pp76-79 (1961).
- [16] J. Fink *et al.*, Nuclear Instruments and Methods in Physics Research A 565 (2006), pp 227-223.
- [17] Derek S. Bale *et al.*, Physical Review B **77** 035205 (2008).

List of figures

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5 :

Figure 6:

Figure 7:

Figure 8:

Figure 9:

Figure 10:

Figure 11:

Figure 12:

Figure Captions

Figure.1: Experimental set up for Pockel's measurements and electric field imaging.

Figure.2: Experimental set up for Transient Current Technique and Time of Flight measurements.

Figure.3: Light intensity distribution profiles from Sample B at different voltages at room temperature. The cathode is on the top.

Figure.4: Electric field distribution profiles from Sample B at different voltages at room temperature.

Figure.5: Light intensity distribution profiles from Sample A at different temperatures at -400V. Cathode is on the bottom.

Figure.6: Electric field distribution profiles from Sample A at different temperatures at -400V.

Figure.7: Charge density distribution profiles from Sample A at different temperatures at -400V.

Figure.8: Effective voltage distribution profiles from Sample A at different temperatures at -400V.

Figure.9: Alpha particle induced current pulses from Sample A at different temperatures at -400V, irradiating the cathode.

Figure.10: Light intensity distribution profiles from Sample B at different X-ray fluxes, at -450V. Irradiating the cathode. Cathode is on the top.

Figure.11: Electric field distribution profiles from Sample B at different X-ray fluxes, at -450V.

Figure.12: Charge density distribution profiles from Sample B at different X-ray fluxes, at -450V Irradiating the cathode.