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Characterisation of irradiated and non-irradiated silicon sensors with a table-top two photon absorption TCT system

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Abstract: A tabletop Two Photon Absorption-Transient Current Technique (TPA-TCT) set-up built at CERN was used to investigate a non-irradiated PIN diode, an irradiated PIN diode, and a non-irradiated 5×5-multipad HPK LGAD. The intrinsic three dimensional spatial resolution of this method is demonstrated under normal incidence of the laser probe. A charge collection versus depth profile of the non-irradiated PIN diode is presented, where reflection on the rear silicon-air interface was observed. It is found that the time-over-threshold versus depth profile is particularly suitable to determine the boundaries of the DUT's active volume. A depth scan of the irradiated PIN diode is discussed and a method to omit the single photon absorption background is presented. Finally, a charge collection measurement in the inter-pad region of the 5×5-multipad HPK LGAD is presented and it is demonstrated that TPA-TCT can be used to image the implantation and the electric field of segmented silicon devices in a three dimensional manner.

Keywords: Radiation damage evaluation methods; Solid state detectors; Lasers; Radiation damage to detector materials (solid state)

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1 Introduction

Two Photon Absorption-Transient Current Technique (TPA-TCT) is a tool to characterise silicon sensors with three dimensional resolution by generating charge at the focal point of a femtosecond laser [1, 2]. Lasers with photon energies well below the band gap energy and pulses in the fs-regime are used to minimize Single Photon Absorption (SPA) and to only enable absorption due to Two Photon Absorption (TPA). TPA depends quadratically on the intensity of the light source, wherefore highly focussing optics are used to increase the signal to noise ratio and they as well increase the spatial resolution. Excess charge carriers are usually only generated in a volume of 20 µm along the beam propagation axis and 1 µm lateral around the focal point in TPA-TCT.

TPA-TCT is a new measurement technique and its application and its methodology is currently investigated. This work gives a brief overview of the recent studies at the TPA-TCT set-up at CERN. Three different TPA-TCT measurements are presented: a depth scan of a non-irradiated PIN diode, a depth scan of an irradiated PIN diode, and a two-dimensional scan across the inter pad region of a 5×5-multipad HPK LGAD.

2 Set-up and samples

A detailed description of the TPA-TCT set-up at CERN can be found in [2]. In general, there are two main components in the set-up: the laser system and the focussing objective. The laser was developed in collaboration with FYLA [3] and it was optimised to fulfil the requirements of TPA-TCT. It provides a central wavelength of $\lambda = 1.55$ µm, which is well beyond the regime of linear absorption in silicon, and pulses of $\Delta\tau = 430$ fs length. The pulse energies can be adjusted from 100 pJ to 10 nJ via a neutral density filter and the pulse frequency can be varied from single pulse up to 8 MHz via an acousto-optic modulator. The pulse frequency used in this work is 200 Hz. The focussing objective has a numerical aperture of NA = 0.5 and confines the volume of main charge carrier generation to $\approx$1 µm $\times$ 1 µm $\times$ 20 µm. Details of the diodes used are given in table 1. The sensor PIN120 was irradiated with neutrons at the JSI in Ljubljana.

Table 1. Details of the sensors used. Further details for PIN7859 are given in [4] and for PIN120 in [5].

Name	Producer	Bulk type	Active thickness [µm]	Physical thickness [µm]	Φ_{eq} [10^{15}cm^{-2}]
PIN7859	CNM	p-type	285	285	0
PIN120	HPK	n-type	120	320	6.25
LGAD5x5	HPK	p-type	50	200	0

3 TPA-TCT measurements

The following measurements are performed with laser illumination from the top side and the current induced at the DUT's top side electrode is read out. In normal incidence TPA-TCT reflection occur when the reflective indices at the rear interface between the active volume and the non-active volume do not match, e.g. when no support wafer is below the active volume. To study reflections at the silicon air interface, sensor PIN7859 is used, because it has no support wafer below the active volume. The DUT is biased to 200 V, which is well above the device's depletion voltage. It is temperature stabilised at 20 °C and the DUT's ambient is continuously flushed with dry air. The result of a depth scan is shown in figure 1(a). The upper plot shows the charge collected in 25 ns against the focus position in silicon (z_{Si}) and the lower plot shows the time-over-threshold (ToT) for 20% maximum signal height as well against z_{Si}. The ToT is defined as the time the current transient is above a certain threshold after illumination. Electrons are collected at the top side electrode of the DUT and holes are collected at the DUT's back side electrode. Therefore, holes (electrons) dominate the current transient when charge is generated at the top (back) side, because the other charge carrier is almost immediately collected at the corresponding electrode. Holes have a lower mobility inside silicon compared to electrons [6], which leads to a higher ToT value. At $\frac{2}{3}$ depth inside the detector ($z_{\mathrm{Si}} = 0.19$ mm) the hole and electron drift time is the same and the ToT profile reaches its minimum value. The regions where holes and electrons dominate the current transients can be discriminated in the ToT plot by the two maxima (marked by h^{+}-drift and e^{-}-drift). The two black lines are aligned along the z_{Si} values of the ToT maxima and enclose the active volume of the DUT. The found thickness of the active volume (≈285 µm) is in good agreement with the thickness given in reference [4]. Signal beyond the sensor boundaries is associated to reflection at the silicon air interface. The reflection is clearly visible in both plots: in the collected charge profile it occurs as a tail ($0.285 \leqslant z_{\mathrm{Si}} < 0.6$) and in the ToT profile it occurs as a mirrored version of the ToT profile of the active volume. It can be seen that the boundaries of the active volume can be easily discriminated in the ToT profile, due to the characteristic peaks of the hole and electron drift.

Radiation damage in silicon leads to additional energy levels inside the band gap. The intermediate levels trap carriers and make them available for SPA. SPA does not depend on the position of the focal point and therefore appears as a constant background in a TPA-TCT depth scan. A measurement of sensor PIN120 at different bias voltages is shown in figure 1(b), where the constant SPA background is clearly visible. The measurement is performed at −20 °C. Figure 1(c) shows the same measurement data after the contribution of SPA is removed. Following the methods described in [2, 7], a waveform recorded at $z_{\mathrm{Si}} < -0.2$ µm is subtracted from all other waveforms

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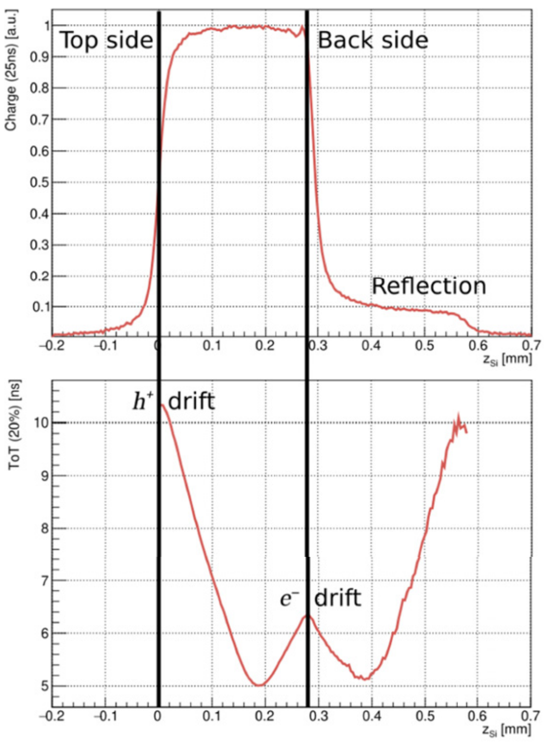
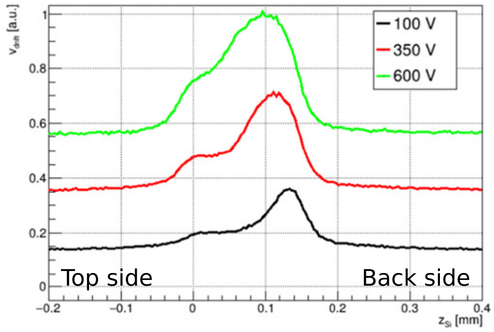
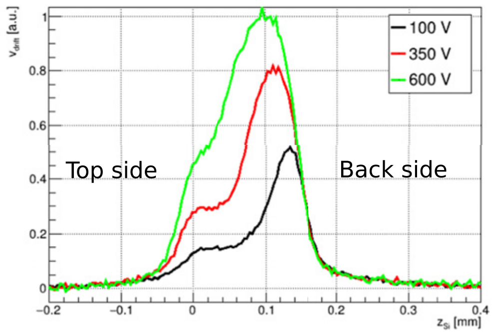


(a) Non-irradiated



(b) Irradiated



(c) Irradiated (SPA corrected)

Figure 1. TPA-TCT measurement of a non-irradiated 285 µm thick PIN diode (a) and an irradiated 120 µm thick PIN diode ((b) and (c)). Figure (a) shows the collected charge profile against z_{Si} in the upper plot and the time-over-threshold against z_{Si} in the lower plot for sensor PIN7859. Figure (b) shows the drift velocity against z_{Si} measured in sensor PIN120 and figure (c) shows the same measurement data after correction of the single photon absorption background.

to eliminate the contribution of SPA. The focal point is for those z_{Si} values well outside the active volume and the amount of TPA is negligible, wherefore only SPA contributes to those waveforms. It should be noted that depending on the entrance window size of the DUT the waveform should not be taken with the focal point to far above the DUT to omit the risk of laser beam clipping at the entrance window. To reliably correct the SPA background the amount of laser light entering the entrance window has to be constant over the whole measurement. The drift velocity profiles are extracted from the current transients using the prompt current method [8]. The drift velocity is proportional to the electric field, wherefore it can be used to get the qualitative electric field profile inside the DUT. The calculated drift velocity profiles show that the diode depletes from the back towards the front side and that the electric field is the highest at the back side. The observation is linked to the effect of space charge sign inversion [9].

The three dimensional spatial resolution of TPA-TCT is used to image the charge collection in the inter-pad region of a 5×5-multipad HPK LGAD (sensor LGAD5x5) in depth. The measurement is performed at room temperature with the DUT biased to 80 V, which is well above the depletion voltage. One pad is read out and other pads are left floating. The result is shown in figure 2, where the upper figure shows a schematic of the DUT's structure and the lower figure shows the result of the two dimensional scan. It can be seen that TPA-TCT resolves three different implant regions, which were associated to the p-stop, the JTE, and the pad region. It is found that inside the p-stop region and the JTE region significantly less charge is collected compared to the pad region. Moreover, the JTE caused bending of the electric field in the pad region is resolved.

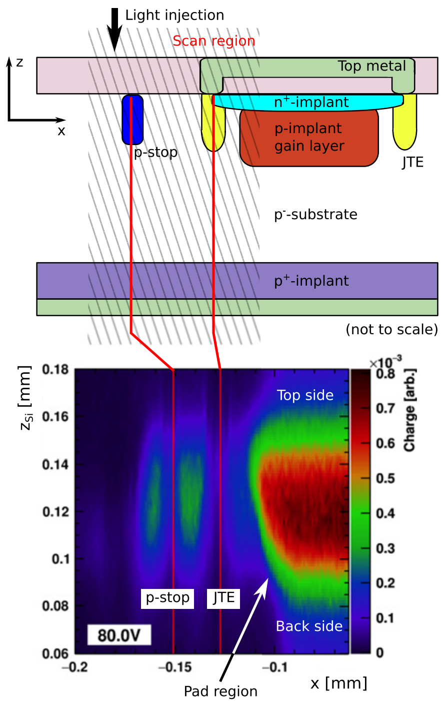


Figure 2. Top: schematic implantation of a multipad LGAD (after [10]). Bottom: charge collection in the inter-pad region of a 5×5-multipad LGAD.

4 Conclusion

TPA-TCT under top illumination was employed to study non-irradiated and irradiated silicon diodes. It was demonstrated that the ToT profile can be used to determine the DUT's boundaries and a method to remove the SPA contribution for irradiated devices was presented. Finally, it was demonstrated that TPA-TCT can be used to 3D image the implantation and the electric field of structured silicon devices.

Acknowledgments

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