SAND2011-0956C

Characterization of the Two-Photon Absorption Carrier Generation Region in Bulk Silicon Diodes

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ABSTRACT:

Charge collection due to two-photon absorption (TPA) as a function of focal plane position in large area bulk-Si diodes is reported. Implications for single event effects TPA laser test methods are discussed.

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Session Preference: Dosimetry

Presentation Preference: Oral

This work was sponsored in part by the Defense Threat Reduction Agency Basic Research Program, NASA Electronic Parts and Packaging, and by the Defense Threat Reduction Agency under IACRO 10-4962I, the U. S. Department of Energy. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

I. INTRODUCTION

Laser testing has become increasingly important for interrogating single-event effects (SEE) in microelectronics [1]. While much of this testing uses pulsed picosecond lasers at energies above the bandgap, for which single photon absorption (SPA) processes dominate carrier generation, two-photon absorption (TPA) has become an important tool for understanding the mechanisms of SEE [2]. This method relies on the use of high peak-power femtosecond pulses at subbandgap optical wavelengths. For wavelengths below the bandgap of the semiconducting material, few carriers are generated at low light intensities. However, in the region near the focal plane, where the intensity of the incident light is greatest, the material can absorb two photons simultaneously and generate a single electron-hole pair [3],[4]. Using this technique, it is possible to generate carriers at any depth in the semiconducting material [2].

While the TPA method is now commonly used for SEE studies, [5]-[10] very little experimental work has been reported that describes the physical structure of the charge cloud centered on the focal plane where TPA carrier generation is likely to occur (the "TPA region"). A detailed study of the carrier distribution produced by the TPA region is important for several areas of SEE laser testing, including TPA-induced latchup studies [12],[8] and studies that use TPA as a method to investigate charge sharing between adjacent devices [9].

This work reports measurements of the spatial extent of the TPA region in the direction of beam propagation in bulk-Si devices. This was accomplished through a combination of charge collection measurements on large area diode structures and device level technology computer aided design (TCAD) simulations. Experimental results show that the longitudinal length of the TPA region is qualitatively consistent with expected values from knowledge of the TPA process and the charge collection volumes of the tested diodes. The results also indicate that high recombination near the focal plane of the incident laser beam may lead to peak charge collection occurring when the center of the TPA region is outside of the device's sensitive volume, a phenomenon that could have implications for TPA SEE testing.

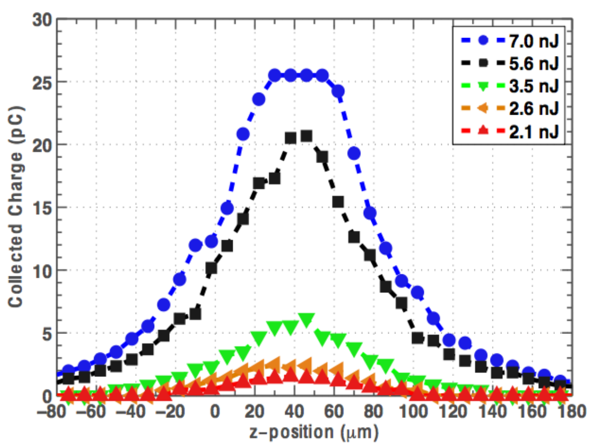

Fig. 1 Collected charge as a function of z-position for the 45 nm bulk-Si diodes. Here, positive x-axis values indicate moving the focal plane of the laser into the device, while negative values correspond to moving the focal plane away from the active region of the diode, which is at 0 μm on the x-axis.

II. EXPERIMENTAL

A. Devices Tested

To investigate the spatial characteristics of the TPA region, charge collection measurements were made on two bulk-Si diode structures. The first is a vertical n+/p bulk silicon diode fabricated in a 45 nm foundry process. Its geometry and doping concentrations were analyzed by destructive physical analysis. It is approximately 160 μm wide by 790 μm long. It features an n+ diffusion 0.5 μm deep over a lightly doped (~10^{15} cm^{-3}) p-substrate. To avoid shadowing effects from metal in the diode's overlayers, it was exposed from the backside, through the silicon substrate, which was polished.

The other tested device was an n+/p diode fabricated by Sandia National Laboratories (SNL). The diode is 600 μm long and 300 μm wide with an n+ layer on a lightly doped (~10^{16} cm^{-3}) p-type epitaxial layer over a p+ substrate. A 1.2 μm layer of p-glass and a 3.9 μm layer of SiO_2 cover the active region of the diode. Because the backside of this diode was not polished, it was exposed to laser light from the topside through the p-glass and SiO_2 overlayers.

We estimated the sensitive volume thickness of the SNL bulk-Si diode by irradiating it with heavy ions under reverse bias at Lawrence Berkeley National Laboratory. The charge collected at the device terminals due to the ion irradiation was measured and the sensitive volume thickness was calculated by using the known LET of the ion. The sensitive volume thickness was estimated to be 2.1 μm, which corresponds approximately to the thickness of the p-epitaxial layer.

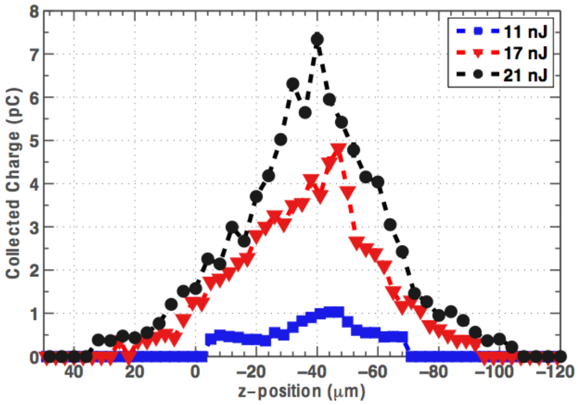

Fig. 2 Collected charge as a function of z-position for the SNL bulk-Si diodes. Negative values along the x-axis indicate stepping the focal plane of the laser into the device, while positive values indicate moving the focal plane of the laser away from the device.

A. Laser Specifics and Pulse Height Analysis

Laser tests were performed using a Ti:Sapphire pumped OPA laser operating at a subbandgap wavelength of 1.26 μm. This setup is identical to the one discussed previously in [2] and [7]. The laser spot was focused approximately in the center of the active area of each device through a 20× microscope objective, resulting in a near-Gaussian beam diameter of approximately 8 μm at the focus. The laser pulse rate was held at 1 kHz for all measurements.

Charge collection measurements were performed using a single-channel pulse height analysis (PHA) system [11]. For all measurements, each diode was reverse-biased at 5 V.

B. Experimental Procedure

To carry out the charge collection measurements, the laser spot was first focused on the surface of the device under test (DUT). This point was defined as a "zero point" in the normal direction. For the SNL diode, this corresponds to a silicon/SiO_2 interface. For the 45 nm diode, this corresponds to the bottom of the silicon substrate. In Figs. 1 and 2, the 0 μm value shown along the x-axis is this zero point. Next, a large range (150-250 μm) was defined above and below the zero point and the focal plane of the laser was moved in two micrometer steps through this range by translating the device on a Newport GTS30V High-Precision Vertical Linear Stage. At each step through the range (referred to as the "z-position" from hereon), a charge collection measurement was made. The motion of the stage was verified with a dial gauge. The on-axis accuracy of the stage was found to be within the manufacturer's specification of ± 0.75 μm.

C. Results and Discussion

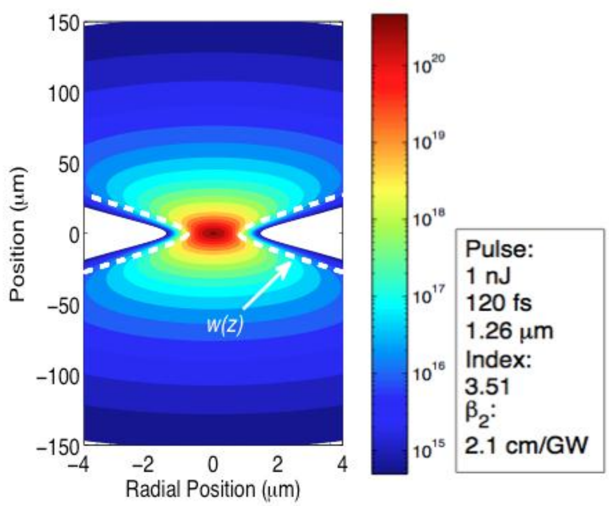

Fig. 3 Electron-hole density plot for the two-photon excitation process in silicon as a function of depth (z). Plotted in electron-hole pairs per cm^3. *W(z)* is the longitudinal dependence of the beam waist.

Fig. 1 shows collected charge as a function of beam waist position in the z-direction (normal to the active region of the diode) for the 45-nm foundry diodes. For the figure, values to the right of 0 μm on the x-axis represent moving the focal plane deeper into the device, while values to the left of 0 μm correspond to moving the focal plane away from the surface of the device and into the air. To quantify the total spatial extent in the z-direction of the TPA region, the FWHM of each curve was calculated and an average FWHM was found. This value is 77.31 ± 2.87 μm for the 45-nm technology diode. Fig. 2 shows data collected in a manner identical to that of Fig. 1 for the SNL diode. The averaged FWHM for the curves of Fig. 2 is 37.75 ± 3.43 μm. The ratio of the FWHM for the 45-nm technology diode to the FWHM of the SNL diode is approximately 2:1. Since the 45-nm technology diode is just an n+ diffusion over a lightly doped p-substrate, it has a much thicker sensitive volume than the SNL diode. This would allow the carriers generated by the laser pulse to

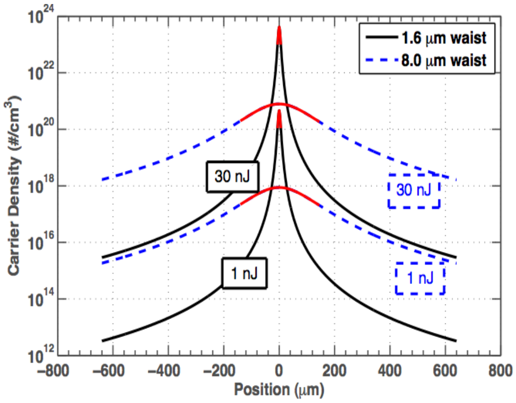

Fig. 4 Carrier density along a longitudinal cutline through the center of Fig. 3. Red regions denote the confocal parameter for each beam waist size.

be collected over a much larger range, leading to the higher values for collected charge (and the greater FWHMs) that are shown for the 45 nm diode.

Figs. 3 and 4 represent carrier densities based on the equations that describe the TPA process ([2]-[4], [14]). These equations represent a zero order model of TPA in semiconductors. As a result, only carrier generation is considered while higher order optical effects that could be contributing to the results shown in Figs. 1 and 2 are not considered. The zero order model does provide valuable *qualitative* insight into TPA. Fig. 3 is a contour plot of carrier generation in silicon due to TPA processes for a beam diameter at the waist of 1.6 µm. The white regions outside of *w(z)* represent a generated carrier density below 10^{15} cm^{-3}. The values chosen for the laser pulse energy, pulse width, and wavelength are shown in the figure. The value for β_2 (the two-photon absorption coefficient) comes from [13]. Fig. 4 shows carrier concentration as a function of position along a vertical cut line centered at 0 µm on the x-axis of the contour plot shown in Fig. 3. Therefore, the x-axis of Fig. 4 represents the same quantity as the y-axis of Fig. 3, that is, the longitudinal position along the TPA region. Fig. 4 plots the carrier density for two laser pulse energies and two different beam waist diameters. The red regions of Fig. 4 represent the portion of the cutline that is well collimated around the focal plane (the confocal parameter of the beam) for each waist diameter. Complete details of the calculations that produced Figs. 3 and 4 will be provided in the final paper. The data in Figs. 1 and 2 show a charge collection profile of approximately 150-250 µm, which is qualitatively consistent with what one would expect from the calculations in Fig 4. This will be explored further in the final paper via TCAD simulations.

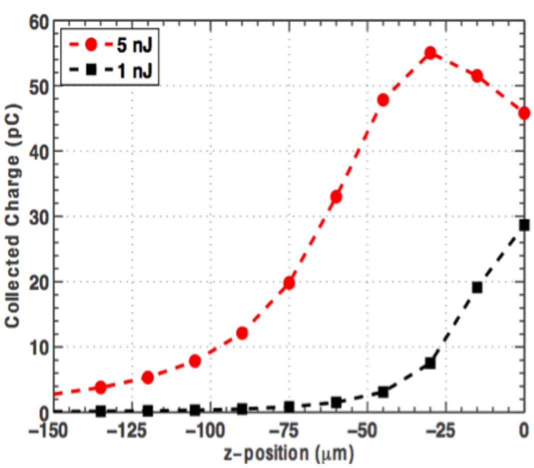

Fig. 5 The results of 2D simulations of TPA in the SNL diode for two different laser energies at a 1.6 µm beam waist. Here, 0 µm corresponds to the top of the n+ layer.

III. Peak Collected Charge Shifts due to Carrier Recombination

To facilitate a qualitative comparison between the TPA measurements and the equations governing carrier generation due to TPA processes in silicon devices discussed earlier, two-dimensional device level simulations were carried out for the SNL epi-based diode using Synopsys TCAD tools and the runtime library discussed in [14]. The simulations were procedurally identically to the experimental measurements. The resulting current transients were integrated over time to find the total collected charge at each z-position step. A result for two laser pulse energies for a beam waist of 1.6 µm is shown in Fig. 5. For this figure, the 0 µm value on the x-axis corresponds to the center of the TPA region being at the top of the n+ layer of the SNL diode.

For the 1 nJ laser pulse, the peak value of collected charge occurs when the laser is focused at the surface of the n+ layer (at 0 µm). This means that peak charge collection occurs when the high carrier density center of the TPA region is contained roughly within the diode's 2.1 µm epi-layer. However, for the 5 nJ pulse, the peak collected charge occurs when the center of the TPA region is approximately 30 µm into the diode's p+-substrate. These trends are consistent with the experimental results, which show a peak in the collected charge when the TPA region is centered well within the p-substrates of both diode types.

Simulation results (details to be presented in the full paper), also indicate that, for higher laser pulse energies, when the center of the TPA region is within the sensitive volume of the diode, significant carrier recombination takes place prior to the field driven charge collection process. However, when the simulator's recombination models are turned off, the peak charge collection occurs at 0 μm for all simulated laser pulse energies and the dip shown for the 5 nJ pulse in Fig. 5 is no longer seen. These simulation results suggest that at higher laser pulse energies, enough carriers are generated that a significant amount of those carriers recombine before they have a chance to be collected. The carriers that remain after the initial, short-term injection and recombination processes are quickly collected by the diode via drift. This phenomenon would be more apparent for the 1.6 μm waist due to the carrier density being much higher in a smaller region around the focal plane than for the 8.0 μm waist size (Fig. 4). This suggests that greater charge collection occurs when the lower carrier density portions of the TPA region (i.e., the green and blue regions of Fig. 3) are within the sensitive volume of the diode. While the carrier density falls off quickly away from the center of the TPA region, a smaller fraction of the generated carriers will recombine, allowing a larger amount of carriers to be collected than when the center of the TPA region is centered on the top of the n+ layer. This also corresponds to observing a peak collected charge at a larger spot size than would be indicated by the beam diameter at the waist alone. This could become an issue for many SEE studies that rely on TPA. For example, in many of these studies, the focal point of the beam is moved in the z-direction over a suspected sensitive region until the peak charge collection is seen. It is usually assumed that the peak charge collection occurs at the narrowest point of the beam waist. However, if recombination causes the peak collected charge to be observed when the lower carrier density portions of the TPA region are within the device's sensitive volume, the size of the laser spot when peak collected charge is seen would be larger than expected (due to the beam radius's dependence in the z-direction). SEE studies that rely on TPA to map out sensitive regions of devices or circuits should quantify the sensitivity to this issue.

IV. Conclusion

Experimental results show that the region of carrier generation for TPA exposures is consistent with knowledge of the charge collection volume of the tested diodes. Simulation results show that significant carrier recombination causes the peak collected charge to be observed when lower carrier density portions of the TPA region are within a device's sensitive volume. Further work is required to truly understand the significance of these results for future TPA SEE studies. The role of carrier recombination in determining the peak collected charge due to TPA will be discussed in detail in the final paper.

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