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Comparison of Single and Two-Photon Absorption for Laser Characterization of Single-Event Upsets in SOI SRAMs

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Abstract

Laser pulse energy thresholds for SEU are compared for SOI SRAMs measured using single and two-photon absorption. The effect of the back substrate on two-photon absorption threshold measurements is also explored.

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I. Introduction

Pulsed laser techniques offer numerous advantages for single-event effects (SEE) testing compared to conventional heavy-ion testing [1,2]. The two most widely used techniques for laser SEE testing involve single-photon absorption (SPA) and two-photon absorption (TPA). Both of these techniques have advantages and disadvantages compared to each other [2]. Recent work using SOI diodes qualitatively compared the amount of charge collection between SPA and TPA from the backside for through wafer excitation [3]. This work also suggested that displacement currents caused by charge generation in the back silicon substrate could impact the amount of collected charge in TPA measurements. If displacement currents do affect charge collection, their impact on TPA SEE characterizations of integrated circuits (ICs) is unknown.

In this work, we explore differences in SEU results for ICs taken using TPA, SPA, and heavy ions. SPA and TPA laser measurements were taken on Sandia 1-Mbit SRAMs. These SRAMs were designed with different feedback resistors in different blocks within the SRAM, resulting in different threshold LETs for each block of the SRAM. TPA measurements were taken on SRAMs with and without the back substrate removed and SPA measurements were taken on SRAMs with the back substrate removed. SRAMs with the back substrate removed were also characterized with heavy ions. These data are correlated to investigate the effects of the back substrate on TPA laser measurements and differences in laser pulse energy thresholds in SPA and TPA measurements. Measurements of Sandia dual-port SRAMs (DPSRAMs) and IBM 45-nm SRAMs were also taken and compared.

II. Experimental Details

ICs were characterized using both SPA and TPA [1,4]. The wavelength of the TPA subbandgap laser pulses was approximately 1.26 μm and the pulse width was 120 fs. The optical pulses were focused onto the backsides of the SRAMs with a 100x microscope objective, resulting in a near-Gaussian profile with a full-width-at-half maximum diameter of 1.45 ± 0.05 μm at focus. For the TPA measurements, to center the laser pulse in the z-direction, a sensitive location was first found at a high laser pulse energy. The laser pulse energy and z-direction was then adjusted to find the z-direction that produced upsets at the lowest laser pulse energy as the laser pulse energy was reduced. For all tests, several areas were scanned. The wavelength of the SPA laser pulses was 590 nm and the pulse width was 1 ps. The SPA optical pulses were also focused onto the backsides of the SRAMs with a microscope objective resulting in a near-Gaussian FWHM diameter of approximately 1.1 μm. For both the TPA and SPA measurements, the laser energy was progressively decreased until no errors were detected.

The primary test vehicle was a 1-Mbit SRAM fabricated in Sandia's 0.35-μm partially-depleted SOI technology. This technology uses a 200-nm thick buried oxide with approximately a 200-nm thick top silicon active layer. This SRAM was designed to have regions of differing SEU sensitivity. It is split into 16 blocks (64 Kbits each) with different sizes of feedback resistors. Eight of the 64-Kbit blocks have resistors with varying size (including a block with no feedback resistors). The back substrates of some of the SRAMs were removed by etching in XeF_2 using techniques similar to previously published techniques [3,5]. These SRAMs have been previously characterized from the front side using heavy ions at Texas A&M's heavy-ion cyclotron and Brookhaven National Laboratory's Tandem van de Graaff [6]. For this work, they were also characterized with heavy ions from the backside with the back substrates removed. Laser tests were also performed on 36-Mbit 45-nm SOI SRAMs fabricated at IBM in their partially-depleted SOI technology and a DPSRAM fabricated at Sandia in the same 0.35-μm partially-depleted SOI technology as the 1-Mbit SRAMs. All SRAMs were tested in a dynamic mode where a checkerboard pattern was first written into the memory array. During laser exposure, the memory was continually read. When an error was detected, the memory pattern was rewritten to the SRAM and the read cycle was then continued. The 1-Mbit SRAMs, DPSRAMs, and 45-nm SRAMs were tested at bias voltages of V_{DD} = 3.0 V, 2.9 V, and 1.0 V, respectively.

III. Results

Before comparing SPA and TPA measurements, it is imperative to show that removing the substrate does not impact the SEU characteristics. Removing the substrate will change the electric field in the buried oxide, parasitic capacitance, and other electrical parameters, possibly affecting the SEU characteristics. Figure 1 is a plot of the heavy-ion SEU cross section for Sandia 1-Mbit SRAMs for SRAMs irradiated from the front side with the substrate in place (standard SEU characterization) and for SRAMs

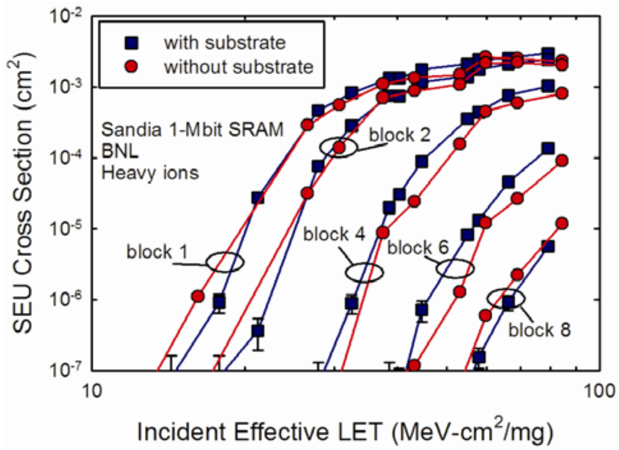

Figure 1: Heavy-ion SEU cross section versus LET for Sandia 1-Mbit SRAMs irradiated from the front side with the substrate in place and from the backside with the substrate removed with V_{DD} = 3 V.

irradiated from the backside with the substrate removed. The SEU data for the front side irradiations are taken from [6]. The same ions and energies were used for the front and backside irradiations. All irradiations were performed at Brookhaven National Laboratory at relatively low ion energies (2.5 to 6.6 MeV/u) where secondary ion effects are minimized [6]. The LET values in Figure 1 take into account the different overlayers in the beam for front side versus backside irradiation. For clarity, data are plotted for only five of the eight blocks of the SRAM with different threshold LETs. There is a reasonable correlation between both the SEU cross sections and threshold LETs. Hence, these data suggest that removing the back substrate does not significantly affect the SEU characteristics and there are no inherent reasons that TPA and SPA laser measurements from the backside cannot be used to SEU characterize devices.

Figure 2 is a comparison of TPA SEU measurements on the 1-Mbit SRAMs with and without the back substrate removed. This is the first detailed demonstration of the effect of the back silicon substrate on TPA laser measurements of ICs. Plotted are the heavy-ion threshold LETs versus the square of the laser pulse energy threshold for all eight of the 64K blocks with different feedback resistors that make up the 1-Mbit Sandia SRAM. The laser pulse energy threshold is defined as the minimum laser pulse energy where upsets were measured. The square of laser pulse energy threshold is plotted because of the "two-photon" nature of these tests. The heavy-ion threshold LETs were estimated from [6] from front side measurements at an SEU cross section of 10^{-7} cm^2. As shown in the figure, the square of laser pulse energy threshold varies linearly with the heavy-ion induced threshold LET. The line through the data points is the best fit to the data. (The fit was forced through the point $E = 0$ at $LET = 0$.) For these SRAMs, laser pulse energy threshold, E, and heavy-ion threshold LET are related by $E^2 = 0.26 \times LET$ for SRAMs with the substrate and $E^2 = 0.028 \times LET$ for SRAMs without the substrate. E is in units of nJ and LET is in units of MeV-cm^2/mg. Although laser pulse energy threshold squared varies linearly with ion threshold LET for SRAMs with and without the substrate, considerably higher laser pulse energies are required to generate upsets in SRAMs with substrates than SRAMs without substrates. These differences cannot be explained by differences in reflections at the back interfaces [3,5].

For TPA measurements both with and without a substrate, the z-direction (normal to the surface) was varied to focus the laser beam in the silicon active layer. If one assumes that the same amount of generated charge in the silicon active layer would be required to induce upsets, these data suggest that the charge generation and/or collection mechanisms are different with and without the silicon substrate. This is consistent with recent charge collection measurements performed on large area SOI diodes, which suggested that displacement currents induced by charge generation in the substrate can lead to large differences in the amounts of charge collection for SOI diodes with and without the back substrate removed [3]. These displacement currents may also be impacting charge collection in SRAMs without the substrate removed. In

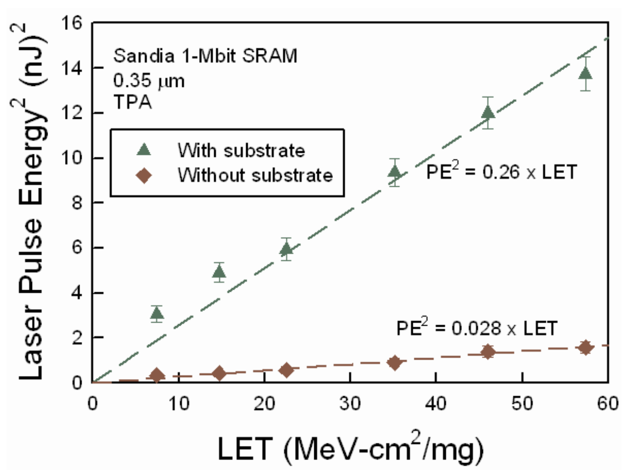

Figure 2: TPA laser measurements of the square of the laser pulse energy versus heavy-ion threshold LET for Sandia 1-Mbit SRAMs with and without the back substrate removed with V_{DD} = 3.0 V.

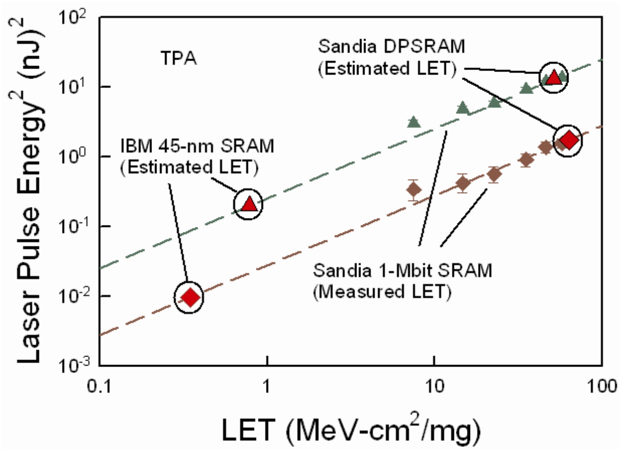

Figure 3: TPA laser measurements of the square of the laser pulse energy versus heavy-ion threshold LET for Sandia 1-Mbit SRAMs with and without the back substrate removed and estimates of the threshold LETs for Sandia DPSRAMs and IBM 45-nm SRAMs based on TPA measurements.

supporting evidence, as will be shown in the full paper, the differences in charge collection between SRAMs and diodes with and without substrates are quantitatively similar. In any case, regardless of the mechanism for the large difference in laser pulse energy required to induce upsets, the fact that laser pulse energy threshold can still be correlated to heavy-ion threshold LET with a linear dependence, suggests that this mechanism does not qualitatively affect TPA SEU measurements (at least for these SRAMs).

This is further supported by estimations of heavy-ion threshold LETs for other SRAMs. In Figure 3, the 1-Mbit SRAM data of Figure 2 are replotted on a logarithmic scale. The dashed lines are the fits based on the 1-Mbit SRAMs. From laser pulse energy threshold measurements and the fits for the 1-Mbit SRAMs, we can estimate the heavy-ion threshold LETs for the Sandia DPSRAM and for the IBM 45-nm SRAM. These estimated heavy-ion threshold LETs are also given in Figure 3. The laser pulse energy thresholds for these SRAMs were measured using TPA for SRAMs with and without the back substrate removed. Based on heavy-ion measurements, the threshold LET of the DPSRAMs is ~65 MeV-cm^2/mg [7] and based on proton measurements, the threshold LET of the IBM SRAM is ~0.19 MeV-cm^2/mg [8]. The estimated threshold LETs for TPA laser measurements with and without the back substrate show the same general trends. For the DPSRAM, the estimated threshold LETs are close to the values determined by heavy-ion measurements. Thus, for these SRAMs, TPA measurements on the 1-Mbit SRAMs and DPSRAMs both with and without the back substrate removed successfully estimate the correct threshold LET. However, for the 45-nm IBM SRAMs, the estimated threshold LETs for TPA laser measurements with and without the back substrate removed both overestimate the threshold LETs as determined by proton irradiations. One possible cause for this may be the large laser spot size relative to the physical dimensions of the SRAM cells [7]. Recall that the laser spot size is ~1.45 μm, which can overlap multiple transistors in the struck cell and in adjacent cells [7]. As a consequence, even though displacement currents may be affecting the amount of charge collection for TPA measurements on SRAMs with substrates, they still yield the same general conclusions as TPA measurements on SRAMs with the back substrate removed.

SPA measurements were also performed on the same devices as the TPA measurements. Because the backside silicon substrate will completely attenuate the SPA laser beam, all SPA measurements were performed with the back substrate removed. Figure 4 is a plot of the heavy-ion threshold LET versus SPA laser pulse energy threshold for the 64K blocks that make up the 1-Mbit Sandia SRAM. Similar to the TPA 1-Mbit SRAM measurements, the laser pulse energy threshold varies linearly with ion threshold LET. Estimated threshold LETs for the Sandia DPSRAM and for the IBM 45-nm SRAM are also given in Figure 4 determined using the relationship between laser pulse energy threshold and ion threshold LET ($E = 0.068 \times LET$). The SPA

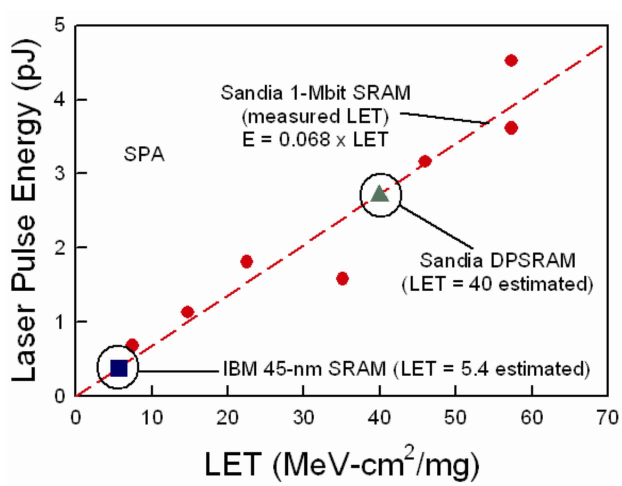

Figure 4: SPA laser measurements of laser pulse energy versus heavy-ion threshold LET for Sandia 1-Mbit SRAMs with the back substrate removed and estimates of the threshold LETs for Sandia DPSRAMs and IBM 45-nm SRAMs based on SPA measurements.

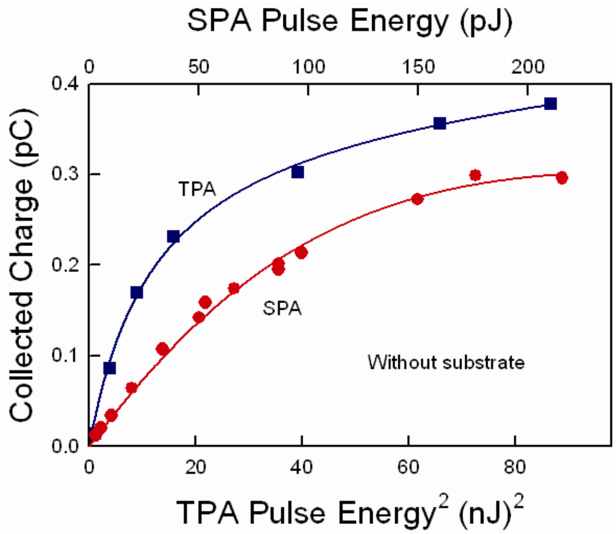

Figure 5: Collected charge versus pulse energy for TPA and SPA measurements.

measurements significantly overestimate the threshold LET for the IBM 45-nm SRAMs. As mentioned above, this could be due to the large laser spot size compared to the small dimensions of the IBM SRAMs. (The laser spot size is roughly twice as large as a single cell [7].) The SPA measurements appear to underestimate the threshold LET of the Sandia DPSRAM, but the estimated heavy-ion threshold LET is much closer to the measured heavy-ion threshold LET than for the IBM SRAM and possibly within experimental uncertainty.

Combining the laser 1-Mbit SRAM measurements performed here and diode charge collection measurements performed previously [3], it is now possible to directly compare TPA laser pulse energy (squared) to SPA laser pulse energy at threshold. Figure 5 is a plot of TPA laser pulse energy threshold squared and SPA laser pulse energy threshold versus collected charge for devices with the backside silicon substrate removed. These curves are essentially plots of the laser induced collected charge versus ion threshold LET for SPA and TPA laser measurements for Sandia 1-Mbit SRAMs. These plots were determined as follows. From the diode measurements [3], the relationship between laser pulse energy and collected charge were determined. Similarly, in this work, the relationships between laser pulse energy and ion threshold LET were determined for TPA and SPA measurements. Equating the laser pulse energies for the diode and SRAM measurements, collected charge can be then be related to ion threshold LET. In Figure 5, collected charge is plotted versus laser energy (or laser energy squared) but at the same LET for both TPA and SPA measurements. For example, a TPA pulse energy squared of 80 (nJ)^2 occurs at approximately the same LET as an SPA pulse energy of 200 pJ. A quantitative comparison between TPA and SPA depends on numerous test parameters. For example, for SPA, the laser wavelength and spot size could affect the correlation. For TPA, the laser wavelength, spot size, pulse width, and possibly the phase characteristics of the pulse could affect the correlation. Considering these differences, there is reasonable quantitative agreement between the charge required to induce upsets by TPA and SPA with the back substrate removed.

IV. Summary

TPA and SPA laser measurements have been performed on the backside of SOI SRAMs with and without the back substrate removed. Considerably larger values of TPA laser pulse energy are required to induce upsets in SRAMs with the back substrate not removed than for SRAMs with the back substrate removed. One possible cause of this is the generation of displacement currents caused by charge generation in the back substrate by TPA. However, whatever the mechanism, it does not appear to affect the qualitative nature of TPA SEU characteristics. With the back substrates removed, there is reasonable quantitative agreement in the charge collection from TPA and SPA for equivalent deduced heavy-ion LET. These results suggest that both TPA and SPA laser measurements with the back substrate removed can be used to qualitatively assess single event effects in SOI SRAMs.

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