



Defense Threat Reduction Agency
8725 John J. Kingman Road, MS
6201 Fort Belvoir, VA 22060-6201



DTRA-TR-21-34

TECHNICAL REPORT

Correlation of Laser- and Ion-Induced Effects on Emerging Technologies

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May 2021

HDTRA1-16-1-0007

Prepared by: Robert
Reed

Vanderbilt University
Nashville, TN 37203

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 03/31/2020		2. REPORT TYPE Final			3. DATES COVERED (From - To) 7/1/17 to 12/31/2020	
4. TITLE AND SUBTITLE Correlation of Laser- and Ion-Induced Effects on Emerging Technologies				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER HDTRA1-16-1-0007		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Robert Reed				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) VANDERBILT UNIVERSITY, THE DONALD CLINTON BROWN 110 21ST AVENUE S STE 937 NASHVILLE TN 37203-2416					8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Threat Reduction Agency 8725 John J. Kingman Road Fort Belvoir, VA 22060-6201					10. SPONSOR/MONITOR'S ACRONYM(S) DTRA	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) DTRA-TR-21-34	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The objective of this work is to understand the charge generation and collection by pulsed-laser irradiation in advanced electronic devices with sufficient clarity that advanced device response is predictable from first principles physics and design information. No a priori limits on the materials, their arrangements, or the parameters of the laser light are to be established. Rather, computations will proceed from first principles, and the effects of varying band gaps, dielectric functions, materials, and materials placement will be studied. Experimental methods using proven electro-optical measurement techniques with sub-picosecond resolution will be used to capture laser-induced charge collection signatures.						
15. SUBJECT TERMS Single Event Effects, Two photon absorption, TPA, laser ion correlation,						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Reed	
U	U	U	Unlimited	53	19b. TELEPHONE NUMBER (Include area code) 615-473-3462	

DTRA Basic Research Final Report

Grant/Award #: HDTRA1-16-1-0007

PI Name: Robert Reed

Organization/Institution: Vanderbilt University

Project Title: Correlation of Laser- and Ion-Induced Effects on Emerging Technologies

What are the major goals of the project?

List the major goals of the project as stated in the approved application or as approved by the agency. If the application lists milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion. Generally, the goals will not change from one reporting period to the next. However, if the awarding agency approved changes to the goals during the reporting period, list the revised goals and objectives. Also explain any significant changes in approach or methods from the agency approved application or plan.

Over two decades ago, researchers demonstrated the ability of femtosecond pulsed lasers to produce single-event upsets (SEUs) in electronic circuits. In the decades that followed, there were significant advances in the experimental methods associated with laser testing of single transistors and complex circuits. Only limited research has been performed to quantify the relationship between ion-induced charge collection mechanisms and laser-induced mechanisms. A quantitative correlation between pulsed laser single event testing, ion testing, and modeling/theory requires research on the experimental methods for characterizing the response to an ionizing event and development of modeling and simulation techniques for laser interaction with complex semiconductor devices and circuits.

The objective of this work is to understand the charge generation and collection by pulsed-laser irradiation in advanced electronic devices with sufficient clarity that advanced device response is predictable from first principles physics and design information. No a priori limits on the materials, their arrangements, or the parameters of the laser light are to be established. Rather, computations will proceed from first principles, and the effects of varying band gaps, dielectric functions, materials, and materials placement will be studied. The work has and will continue to borrow heavily from recent advances in the basic physics of the interaction of light and nano-structures. Theory and simulations are being augmented by a robust and tightly coupled experimental program. Experimental methods using proven electro-optical measurement techniques with sub-picosecond resolution will be used to capture laser-induced charge collection signatures. imec (Interuniversity MicroElectronics Center) and others will provide advanced electronic devices. The goal is to understand the underlying mechanisms of laser interactions with electronic materials and devices at a level that enables computations with accuracy similar to that of our ion-computations. Together they will establish the basis for a new testing paradigm for advanced devices, as outlined below.

Lasers conveniently induce charge in microelectronic devices and they are increasingly important for qualitative testing, particularly for identifying sensitive regions. However, the absence of a comprehensive theoretical and computational foundation severely limits quantitative comparisons to ion effects, as well as use of lasers to generate charge predictably in specific regions of devices fabricated in complex material systems. The spatial and temporal profiles of the charge generation

process are both significantly different for ions and lasers. Ions are generally unaffected by materials interfaces, and secondary particles, including electrons and nuclear reaction products, move across the device with relative impunity. Moreover, it is difficult to determine to what extent laser-based SEE results actually mimic ion effects in any given situation.

The status prior to begin this research on laser testing of microelectronics can be summed up graphically as in the left-hand panel of Fig. 1. On any given device, laser and ion measurements can be made, and an empirical relationship between quantities of generated charge can be established. However, to a very significant extent the relationship is *ad hoc* and not generalizable even when relatively minor modifications to the composition and structures of devices are made.

Two key ideas formed the cornerstone of our work in ion-induced SEE. The first was that the work should be based on a mathematical foundation of sufficient power that experimental results could be predicted in advance and used to understand experimental results when key structural and compositional information about a device was available. The second was that all of the relevant physics – both radiation and device physics – should be treated with the same uniformly high standard of detail and completeness. The computational system that has emerged from the confluence of these ideas has been remarkably effective for understanding single event effects. The right-hand panel of Fig. 1 illustrates this tight coupling of ion computations and measurements with the quadrant entitled “Ion Computations” and the shaded arrow.

The key objective of this proposed research, as illustrated by the “Laser Computations” quadrant and shaded arrow in the right-hand panel of Fig. 1 is to establish the same tight coupling between laser computations and laser measurements that we have achieved for ions. These laser computations will be grounded in the same basic principles that were outlined in the previous paragraph. When this has been achieved, when it is possible to compute laser and ion interactions in the same structure and in so doing to predict with reasonable surety the resulting charge distributions, the quantitative groundwork will have been laid to predict ion effects with laser measurements according to the paradigm in the figure, not as a direct empirical connection between measured quantities (left), but indirectly through a detailed microscopic understanding of the interaction of the various forms of radiation with the structure (right). Then, and only then, can laser measurements be viewed as a plausible predictor of ion-induced single event effects.

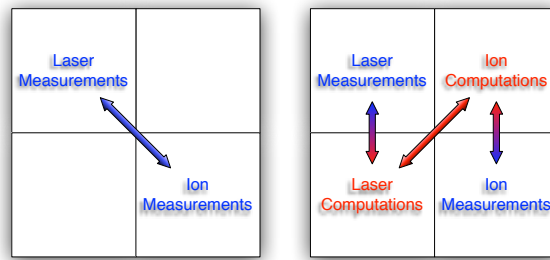


Fig. 1. A schematic illustrating the empirical relationship between laser and ion-based measurements of single event effects that exists presently (left), and the quantitative relationship envisioned in this proposal that is established by relating robust, first principles computations of laser- and ion-materials interactions (right).

What was accomplished under these goals?

For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive and negative); and 4) key outcomes or other achievements. Include a discussion of stated goals not met. As the project progresses, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

Introduction:

Below is a bullet list of the major activities for the entire performance period of the grant, we will discuss each in more detail in the section that follow.

- Development of laser test bench at Vanderbilt
- Measuring TPA Coefficients in Semiconductor Materials
- Sub-Picosecond Electro-Optical Sampling Techniques
- Laser and Ion Testing of Simple Device Structures
- Laser and Ion Testing of Advanced Device Structures

Development of laser test bench at Vanderbilt

Abstract:

A tunable pulsed-laser test bench capable of creating spatially and temporally localized carrier densities of controlled magnitude within electronic devices and components is described. The system can be used for identifying and characterizing areas that are sensitive to radiation-generated charge. The methods employed to control, quantify and record the exposure conditions (irradiance) used to create the free carriers during testing are described in detail. A sample of experimental results that can be obtained with the test bench is presented.

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Section 1. Purpose of the Laser Test Bench

Pulsed lasers have long been used as a way of simulating the effects of transient ionizing radiation in semiconductors [1]. Despite significant differences in the distributions of excess carriers generated by a charged particle and a laser, [2-13] laser pulses have been shown to be an important diagnostic tool in the study of single-event effects.

Heavy ion strikes generated by particle accelerators are spatially and temporally non-deterministic. This makes it difficult to map sensitive areas or to synchronize ion strike events with circuit operation, e.g., during a clock transition. Pulsed lasers, on the other hand, can be synchronized with circuit operations and thus can generate charge in a device at a specific location with precise timing.

Photons with energies greater than the bandgap of a semiconductor can generate excess carriers through direct ionization. However, they are rapidly attenuated and only penetrate a short distance into the semiconductor. For example, at 532 nm, photons have a 1/e depth in silicon of 1.3 μm . Sub-bandgap photons have a much longer penetration depth since they are not directly absorbed, for example a 1064-nm laser has a 1/e depth of 900 μm . If the laser intensity is high enough, however, multi-photon absorption may generate an electron-hole pair. A tightly focused beam, therefore, can be used to generate charge at a precise 3-dimensional location within a circuit or device [14].

The test bench described here was developed to enable quantitative laser testing of a wide range of circuits and devices that incorporate various semiconductor materials. The photon energy required to generate electron-hole pairs (ehps) depends on the semiconductor bandgap. Thus, the laser testbench should be tunable over a large range to cover single and multiple photon absorption. A careful calibration of the test bench and accurate characterization of the laser parameters and techniques used is required in order to produce repeatable results and accurate simulations of the energy deposited by the laser pulses. The details of this setup, the laser parameters, and the techniques used are described here.

Section 2. Laser Test Bench Description

2.1 Test Bench Layout

The laser source for the test bench is a titanium-sapphire chirped pulse amplifier (Titan, Quantonix Inc.) pumping an optical parametric generator (OPG; TOPAS from Light Conversions, Inc.) that provides output pulses with 100-300 fs duration at a 1 kHz repetition rate. The center wavelength of output pulses is tunable from the UV to the mid-IR with pulse energies from 10-100 $\mu\text{J}/\text{pulse}$, depending on the wavelength. The test bench can be quickly configured for operation in the visible, near-IR, or mid-IR wavelength ranges by swapping out a short list of components, as listed in table 1.

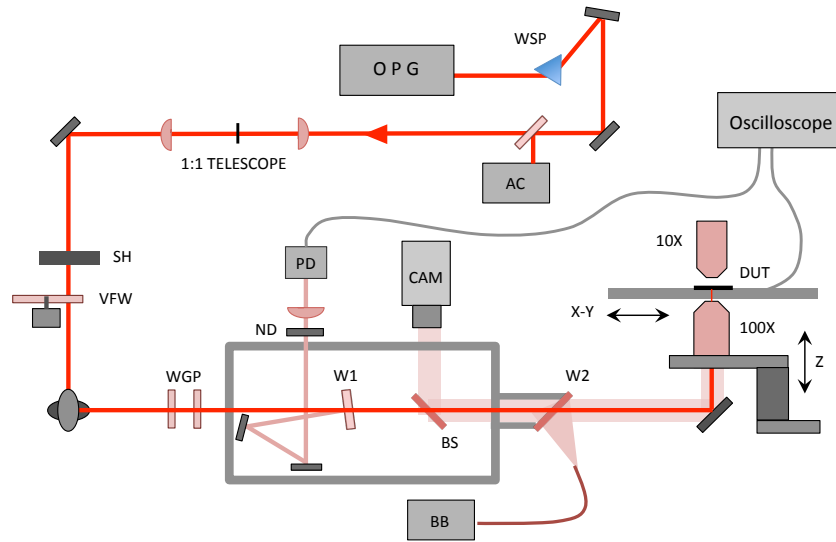


Figure 1: Schematic of the laser test-bench; pulses from the laser (OPG) are wavelength-separated by a prism (WSP), blocked by a shutter (SH), modulated by a motorized variable ND filter wheel (VFW), and attenuated by wire-grid polarizers (WGP). The pulse duration can be measured with an autocorrelator (AC) in front of the 1:1 telescope. A window (W1) reflects a small percentage toward a photodiode (PD) and a 50% beamsplitter (BS) reflects an image of the device under test (DUT) toward a camera. An exit window (W2) brings broadband light (BB) onto the beam path for imaging. The microscope objective is mounted to a precision z-stage and the DUT is fixed to a precision x-y stage. Another objective (10X) can be used to view the topside of the device for gross positioning.

Wavelengths from the OPG are separated by a prism and directed toward the test bench (see figure 1) using silver mirrors, which have good reflectivity from the visible through the IR. The spot-size and beam divergence from the laser is wavelength-dependent; a 1:1 telescope with a movable 2nd lens is used to optimize the beam diameter at the input aperture of the microscope objective. The objectives used (with either 100X or 50X magnification) have a 3 mm entrance aperture, which is normally overfilled to provide a focused spot size at the device under test (DUT) that is near the theoretical (diffraction) limit. At 1260 nm, the incident spot size is adjusted to give a transmission through the 100X objective of roughly 50% [15]. The size and position of the laser spot at the back aperture of the objective strongly affects the transmission of the setup and the energy at the DUT position. Before every experiment, the movable lens in the telescope is set to the correct position for that wavelength and the beam is centered at the input aperture by maximizing the energy measured after the microscope objective. Spatial filtering of the laser's intensity profile can be accomplished by placing an appropriately sized (high-damage threshold) pinhole at the focal point of the telescope.

A large shutter is used to block the laser; a second, (small-aperture) fast shutter can be placed inside the telescope to deliver a pre-determined number of pulses (down to a single pulse). A motorized continuously-variable neutral density (ND) filter wheel ($OD_{max} \sim 2$) in the beam path can be used to provide automated pulse energy modulation for experiments studying the energy dependence of device

response. A pair of wire-grid ultra-broadband polarizers is used to set the average pulse energy (or the maximum energy used during modulation), while maintaining constant polarization.

Attenuated laser pulses enter a light-tight box containing a window and two beamsplitters. The first beamsplitter is an uncoated CaF_2 pick-off window that reflects a small portion ($\sim 7\%$) of the laser pulse toward a photodiode, for real-time energy measurements during the experiment. The window is mounted at near-normal incidence, so the fraction of energy reflected is nearly independent of the incident polarization, which varies with the wavelength from the laser system. Because signal wavelengths are p-polarized and idler wavelengths are s-polarized as they enter the light-tight box, a 45° angle of incidence would give a very small reflection of signal wavelengths (near Brewster's angle) and a much higher reflection for the idler wavelengths. Next, a 50% broadband beamsplitter is used to reflect the image formed by the microscope objective toward a camera. Finally, laser pulses exit the light-tight box through a window which is used to reflect broadband light from a fiber-coupled tungsten-halogen lamp onto the laser beam axis.

The broadband light and laser pulses are directed upward by a silver mirror into the microscope objective. Typically, a $100\times$ Mitutoyo Plan Apo objective with a long working distance is mounted to the precision vertical stage (GTS30V, Newport, Inc.), providing axial (z) positioning of the focal plane with sub- μm precision. The broadband light illuminates the DUT over the roughly $100\ \mu\text{m}$ field of view of the microscope objective. A $50\times$ objective is available for situations where it is advantageous to have a larger field of view. Some of the light hitting the DUT is scattered back through the objective and reflected from the 50% beamsplitter in the light-tight box, providing a magnified image of the device and the laser spot to the camera. When near- or mid-infrared laser wavelengths are used for testing, a silicon window on the light-tight box prevents visible light from entering the IR-camera. This allows visualization of the device and the point where charge generation is expected to occur deep within the silicon layers of the DUT. For testing with visible wavelengths, the silicon window is replaced with a coated-glass beamsplitter and a CCD camera is used for viewing the device.

Wavelength (nm)	400-1100	900-1700	1500-2300
Photodetector	Silicon	InGaAs	PbSe
Camera	CCD	IR vidicon	IR vidicon
Image beamsplitter	50% vis coated glass	50% nIR coated glass	50% nIR coated glass
Exit window	50% vis coated glass	Polished silicon	Polished silicon

Table 1) Components of the test bench with wavelength specificity; when testing in different regions of the spectrum, these components can be quickly interchanged to prepare the test bench.

The DUT is mounted to the precision x-y stage and moved laterally over the objective to position the focused laser spot at the point of interest. Computer control and synchronization of the precision motorized stages with the laser repetition rate enables automated positioning and scanning of the DUT in all three dimensions over the focused laser spot while collecting and recording device responses and photodiode traces on the oscilloscope for each position. Additionally, a 10× objective with manual focusing is mounted above the device for top-side viewing and gross positioning of the device.

2.2 Optical Components- Non-Linear Effects

The overall transmission of the test-bench apparatus and the transmission of each individual optical component in the setup was measured over a range of incident pulse energies to rule out the possibility of any intensity-dependent (non-linear) absorption. A pyro-electric energy probe (J-10MB-LE, Coherent, Inc.) was centered on the collimated laser beam (with diameter around 5-7 mm) just in front of and just behind each optical element to measure its transmission. Incident and transmitted pulse energies were measured by averaging thousands of pulses over the available range of incident pulse energies (from about 0.5 μJ to at least 20 μJ at 1260 nm). For each of the optical components in the test bench, the transmission was found to be near the expected value and independent of the incident intensity over this range. The typical transmission of the test bench, using the 100× objective (measured from in front of the light-tight box to the DUT position), at a center wavelength of 1260 nm is about 5% for pulse energies in both the nanojoule and microjoule ranges.

The ND filters used for diagnostics and calibration routines were tested for non-linear absorption effects by measuring the filter transmission of the collimated 1260nm laser beam at both high pulse energies ($\sim 50 \mu\text{J}$) and low pulse energies (a few nJ), using different sensors. The transmission of several OD1 filters was found to be almost identical with the two sensors at these very different incident intensities. Since we could find no evidence of non-linear absorption in these filters (or in any of the test bench components) at these extremes of incident intensity, the transmission factor of each component can be taken as a constant for any pulse energy within this range.

2.3 Characterization of Large-Area Photodiodes

The photodetectors used for energy measurements during device testing were characterized using the Fresnel-reflection set-up shown in figure (2). This setup was used to measure the wavelength, spot-size, and energy dependence of the response of each photodiode to pulses from our laser.

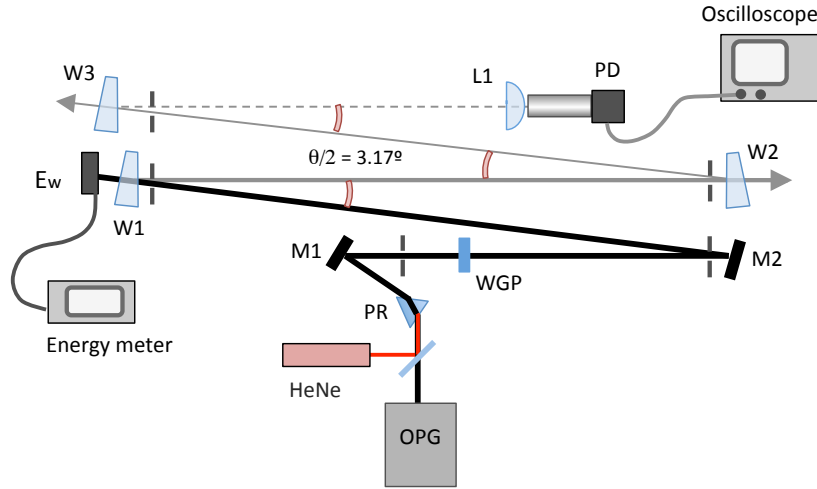


Figure 2: Fresnel reflection setup used to produce accurately known picojoule and nanojoule level pulse energies for characterization of photodiodes. A series of first surface reflections after the prism (PR) produces a known fixed attenuation of laser pulses. Variable attenuation is provided by a wire-grid polarizer (PZ). Incident pulse energies are measured with an energy probe (EP) placed behind the first window (W1). The reflected energy is focused by lens (L1) onto the photodiode (PD).

The Fresnel-reflection set-up uses first-surface reflections from uncoated wedged windows placed at precisely measured angles to the incident laser pulses in order to produce known (fixed) attenuation of incident laser pulses. The percentage of the pulse energy reflected from each window is calculated using the Fresnel equations for the wavelength, glass type, and angle of incidence used. Because a small angle of incidence was used (3.17°), the reflectivity is nearly insensitive to the polarization of the incident light. A wire-grid ultra-broadband polarizer was used to variably attenuate the laser pulse energies as needed to cover the useful range of the detector response. A calibrated pyroelectric energy probe with a 10 mm absorber (J-10MB-LE, Coherent, Inc) was used to measure the pulse energy behind the first wedged window. The reflection from the final window is concentrated on the detector surface using a CaF_2 lens ($f = 10 \text{ cm}$). A light shield between the lens and the detector prevents stray light from affecting the photodiode response.

Since the energy of the pulses from the OPG fluctuates from pulse-to-pulse, the energy meter was used in statistics mode, and the average of $\sim 10,000$ pulses was recorded, along with the averaged peak amplitude of the photodiode response for each setting of the wire grid polarizer. The standard deviation in pulse energy was typically less than 5%. The energy measured behind the first window (E_w) is the incident energy minus the energy reflected by the two glass-to-air interfaces: $E_w = E_i - E_i R_1 - E_i (1 - R_1) R_1 = E_i (1 - R_1)^2$, where R_1 is the reflectivity of the glass surface given by the Fresnel equations. The small amount of energy resulting from multiple reflections is ignored. The energy from the first glass surface reflection is ($E_i R_1$) and the energy that finally reaches the photodiode is: $E_p = E_i * R_1 * R_2 * R_3 * (1 - R_{\text{lens}})$. At a

wavelength of 1260 nm, the total attenuation of the setup is 7.77×10^{-5} or (1/12,900), so that a 1 μ J pulse is accurately attenuated to 77.5 pJ.

Three different types of large area photodetectors (silicon ET-2040, InGaAs ET-3020, and PbSe ET-6000, from Electro-Optics Technology), designed to work at different wavelengths (see Table 1), were characterized in the Fresnel reflection setup. Each detector has an active area of at least 3 mm in diameter. Our results indicate that while the silicon and PbSe detectors exhibit a linear response to a wide range of femtosecond laser pulse energies, the InGaAs detectors exhibit strongly non-linear behavior. Plots of the energy incident on the photodiode versus the peak response from the InGaAs photodiodes (figure 3a) show a gradually decreasing slope, and a nearly saturated response above ~ 1 nJ/pulse. The region of linear response can be increased by integrating the area under the response curve. In addition, the slope of the initial response and the saturation level was found to be dependent on the spot-size of the incident laser energy; smaller spots gave a higher peak response but saturated at lower pulse energy. Figure (3b) shows the measured InGaAs detector peak response as a function of the estimated spot-size incident on the absorber, at fixed (150pJ) incident pulse energy.

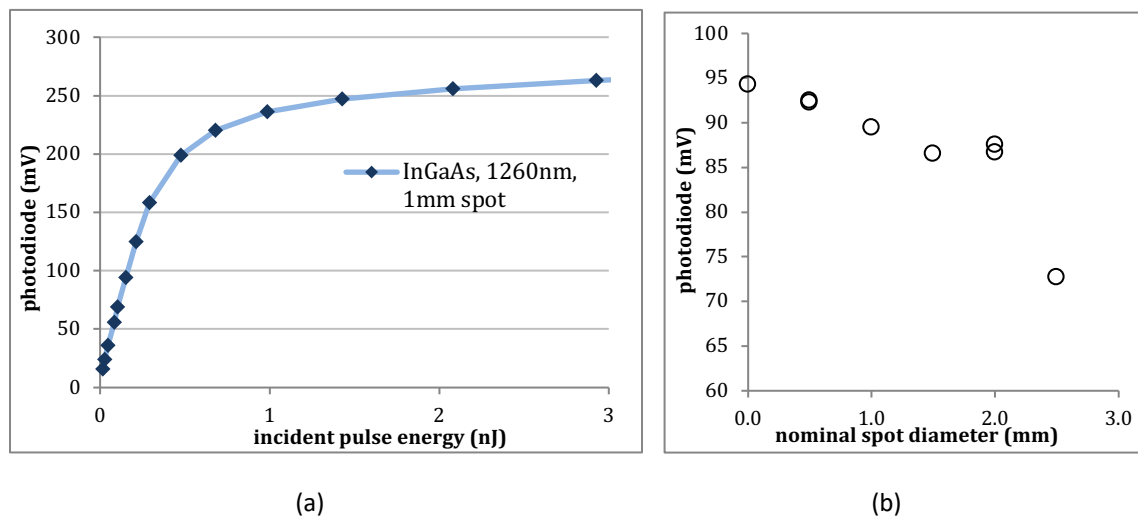


Figure 3. a) InGaAs detector peak (mV) response to laser pulses at 1260nm as a function of increasing incident pulse energy (nJ), b) the same detector response to pulses with fixed (150pJ) energy but decreasing (1/e) spot diameter. The detector's active area is 3mm in diameter.

The InGaAs detector response changes when the edges of the active area are illuminated with even small amounts of laser energy; the resulting electrical output pulse has two peaks and reaches a higher amplitude than when the exposure is entirely contained within the active area of the detector. This is evident in the plot of detector peak response versus spot-size (figure 3b), near the 2 mm spot diameter position. For larger spot sizes, more light is lost outside the active area, giving a reduced response. Incandescent room lights also affect the detector response, making it necessary to shield the detectors from ambient light.

Each photodiode was characterized over a wide range of incident energies at several wavelengths in the useful range of each detector type. Plots of the measured slope of the linear-response region of each detector versus laser wavelength indicated that the wavelength-dependence of the response to femtosecond pulses is similar to the continuous-wave responsivity curves published by the manufacturer. Our observations of the detector response within the Fresnel calibration setup indicate the need to carefully control photodiode exposure conditions in order to obtain a reproducible and predictable response from the detectors.

2.4 A High-Speed Oscilloscope for Data Acquisition

Device transients and photodiode response curves are captured with an 8-channel Teledyne LeCroy Labmaster 36zi oscilloscope. The 36zi has a 36 GHz analog bandwidth and a sampling rate of 80 GS/s. It is able to achieve the maximum sampling rate simultaneously on all 8 channels. Each channel has a 64 MB record length. This is important because it allows simultaneous capture of both very short transients and the much longer photodiode response from every laser pulse.

It is often advantageous to collect many data points at a single location on the device to account for changes in the pulse energy, either from variations in the laser output or from intentional modulation of the incident energy. The oscilloscope is able to capture data in “sequence mode” which allows capturing hundreds or thousands of points as a single set of measurements. It is capable of triggering on every laser pulse and capturing multiple channels at the laser’s repetition rate of 1 kHz.

The collected data must be saved to disk or transferred to a computer after each set of measurements. In situations where the device response is very short (10’s of picoseconds), but the photodiode response is much longer (100’s of ns for the PbSe detector), it is inefficient to save all of those data. Instead, the oscilloscope offers a method to transfer a subset of the recorded points. For short transients we might only transfer the first N points, whereas for longer transients at high sampling rates we might transfer every Nth point, effectively reducing the sampling rate on a specific channel. By parsing the data in this manner, we save time in the transfer to the host computer, speed up the scanning rate, reduce storage space, and save post-processing and analysis time.

2.5 A Calibrated Pico-joule Energy Meter

A factory-calibrated, 9 mm active area InGaAs photodiode sensor (PD10-IR-pJ, Ophir Inc.) with readout (Juno with Scope Adapter, Ophir Inc.) is used to make rapid measurements of laser pulse energies (nominally 10 pJ to 20 nJ) of wavelengths in the 900 – 1700 nm range at the DUT location (figure 1). The manufacturer guarantees the energy calibration for nanosecond pulses but has not tested the calibration with femtosecond pulses (which have intensities $\sim 10^4$ times higher at equal pulse energies). To verify the sensor calibration, we tested it in the Fresnel reflection setup (figure 2) with attenuated femtosecond pulses at 1260 nm from our laser. The manufacturer recommended using a large spot size and less than 10 nJ/pulse to avoid damaging the sensor. We found that the sensor response remained linear with pulse energies from ~ 20 pJ up to ~ 8 nJ, but the reported energy varied with the spot size of the laser pulse (figure 4). Laser pulses with spot sizes greater than or equal to about 5 mm in diameter gave a response very close to that predicted in our setup by the reflection-attenuated readings from the

pyroelectric sensor. Using smaller spot sizes caused the PD10 sensor to report higher than expected pulse energies ($\sim 130\%$ of expected energy with ~ 2 mm diameter spots). Even with a large spot diameter (6 mm), we found the response of this sensor to femtosecond pulses became non-linear and showed signs of saturation with pulse energies above 8 nJ/pulse.

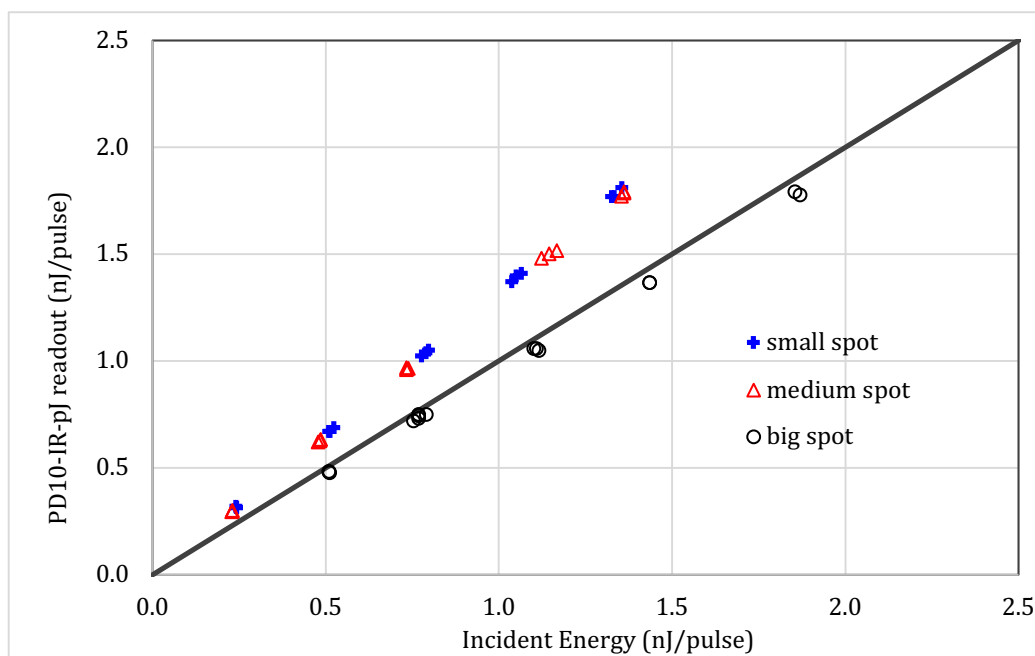


Figure 4) Pulse energies reported by the PD10-IR-pJ sensor (points) versus pulse energies measured in the Fresnel reflection setup (solid line) Reported versus expected pulse energies from the PD10-IR-pJ sensor as measured in the Fresnel reflection setup, for several incident spot sizes (small spot, 1-2mm, medium spot, 2-3mm, and big spot, ~ 6 mm diameter) on the sensor.

Section 3. Real-Time Pulse Energy Measurements

Quantitative and repeatable characterization of a device response to laser pulses requires that accurate pulse energy measurements be made during testing. Pulse energies may fluctuate due to instabilities within the laser or may be intentionally modulated during testing; in either case, a measurement of the energy of every pulse is necessary. In our test bench, the photodiode response is correlated with a pulse energy measurement at the DUT position over the range of pulse energies likely to be used during testing. Since photodiode responses and optical component reflectivities are wavelength dependent, a calibration must be performed for each wavelength used. Calibrations must include information about what telescope position was used, what ND filter was in the photodiode path, and which objective was installed.

During component testing, the reflected energy from the window in the light-tight box is attenuated with a neutral density filter (OD1 or OD2) to avoid saturating the photodiode and is then focused to a 1 mm spot diameter in the center of the active area of the photodiode. By using the photodiode output pulse as a trigger for the oscilloscope, the experimenter can ignore any laser pulses below the level

corresponding to the set trigger threshold. Alternatively, a sync-output pulse from the Ti/S laser can be used as an external trigger, so that every laser pulse is recorded, even those that might be too low to be detected with the photodiode. External triggering allows continuous modulation of the pulse energy with the motorized variable filter wheel. During testing, the oscilloscope records both the photodiode pulse and the corresponding device transient for every laser pulse used. Together with a photodiode calibration curve, this provides a record of the pulse energy that was used to generate every recorded transient.

Attempts to use a pair of InGaAs photodiodes for calibration routines proved unreliable, due to non-linear behavior of the detectors and their dependence on incident spot size. For example, we found that the response of InGaAs detectors placed at the output of 100 $\times$ objectives is strongly dependent on the distance from the objective lens. Energy readings from the calibrated pyro-electric energy probe, however, show no significant dependence on the distance from the objective, and readings from the Ophir picojoule sensor are independent of spot size when the spot is greater than ~ 5 mm in diameter.

3.1 Calibrations using Direct Energy Measurement

For near-IR wavelengths, the Ophir sensor can be used to directly measure pulse energies at the output of the objective, since it is sensitive to laser pulses of the same magnitude used during most experiments. The Juno readout with scope adapter provides a DC voltage proportional to the pulse energy at the sensor for every pulse. The sensor is placed at the DUT position and the spot size is adjusted to >5 mm diameter with the objective z-stage. The maximum pulse energy is set with the polarizer and the motorized filter wheel is used to modulate the energy from near zero to the maximum while the oscilloscope records the voltage from the scope adapter (on one channel) and the photodiode responses (on another channel) for every laser pulse. This setup allows correlation of photodiode response with pulse energy at the DUT (see figure 5) within a few seconds; the procedure can be done immediately before device testing.

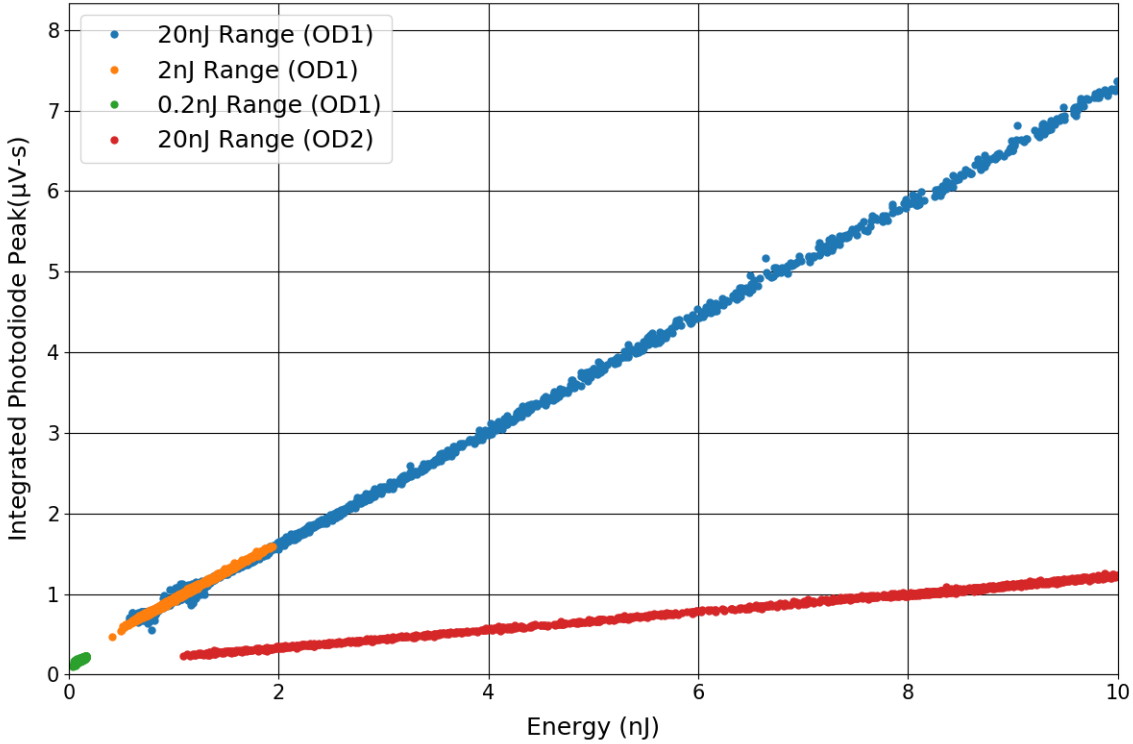


Figure 5: InGaAs photodiode calibration curves showing the correlation of photodiode response curves to energy measured at the DUT using the Ophir pJ sensor and Juno with scope adapter. The curves were taken with either an OD1 or an OD2 ND filter before the photodiode. At pulse energies exceeding 10 nJ, the Ophir sensor response becomes non-linear as the sensor begins to saturate.

3.2 Calibrations using ND Filters

Another calibration method is required for wavelengths outside the useable range of the Ophir sensor. The Coherent pyroelectric sensor is accurate for the entire range of wavelengths from the laser, but it requires μJ -level pulse energies, much higher than what is typically used for device testing. However, since we have shown that the optical components in the test bench do not exhibit non-linear (intensity-dependent) absorption, calibrations done at higher (μJ level) pulse energies should be valid. To bring the pulse energies at the photodiodes down to the linear response range, we used an extra pair of OD1 ND filters in the path of the reflection from the pick-off window. Since the transmission of the ND filters was accurately measured and shown to be independent of incident pulse energy, we know that the filters would attenuate the energy at the DUT by the same factor, if they had been placed in the path of the full incident beam (before the pick-off window). Therefore, we can apply the same attenuation factor to the μJ -level energies measured at the DUT (with the pyroelectric sensor) to obtain the pulse energy that *would have* been present at the DUT if the *total beam energy* had been attenuated. This allows the photodiode readings to be correlated with the much higher pulse energies that are being measured at the DUT with the pyroelectric sensor.

To verify the accuracy of the ND filter + pyroelectric sensor calibration technique, we performed calibrations using both sensor types at a wavelength of 1260 nm and compared the results. As can be

seen in figure 6, the measured ratio of photodiode response (mV) to measured pulse energy (nJ) at the DUT is indistinguishable between the two methods. This shows that the technique is valid and justifies use of the pyroelectric sensor and ND filters to perform calibrations at any wavelength in our test bench.

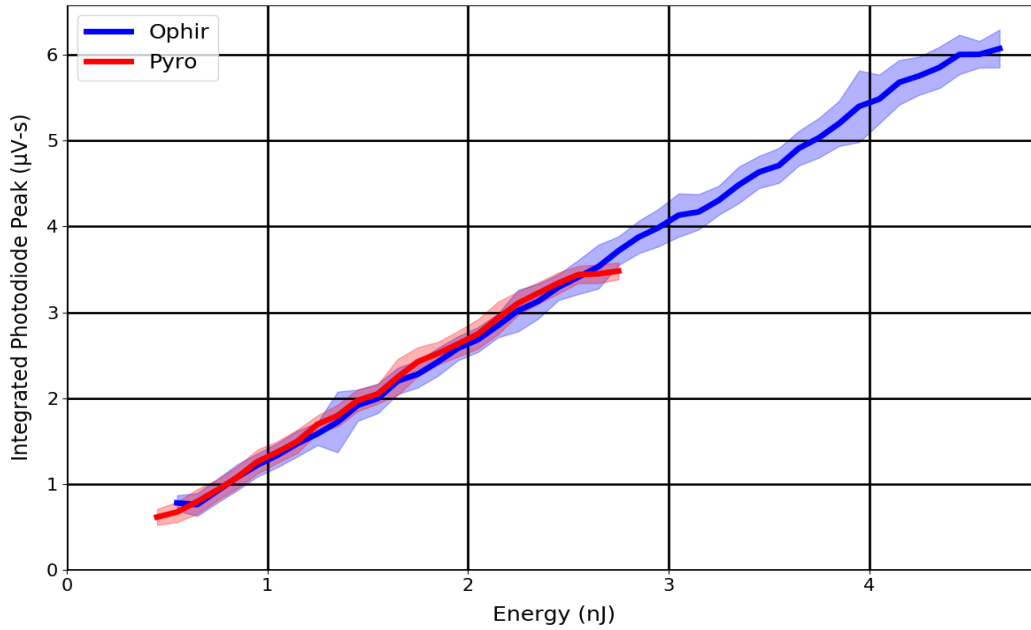


Figure 6: A comparison of the two techniques for calibrating photodiodes at 1260nm in the test bench. The area under the photodiode response curve and the pulse energy measured at the DUT for both methods is shown. The pyroelectric sensor reading, multiplied by the attenuation factor of the two OD1 filters, is shown in red and the Ophir picojoule sensor reading is shown in blue. The solid lines represent the average value binned over 100 pJ, while the bands indicate 2 standard deviations.

3.3 Calibrations with and without an Aperture

Test bench calibration curves occasionally showed a high variance in the photodiode response to a given pulse energy measured at the DUT position. This was caused by clipping of the beam at the entrance aperture of the objective, which passes only the central portion of the beam, while a sample of energy from the entire beam profile was concentrated on the photodiode. Fluctuations in the spatial distribution of intensity can therefore result in a varying fraction of the energy appearing at the DUT. SHG conversion of 1260 nm pulses to visible light confirmed that the beam profile from the OPG can vary from pulse to pulse in the absence of spatial filtering. We found that by centering a 3 mm aperture on the portion of the beam reflected from the pick-off window, the variance is significantly reduced. The aperture matches the fraction of the beam reaching the photodiode and the DUT, which increases the precision of the calibration curve. The aperture has become a permanent addition to the test bench.

Section 4. Laser Spot Size Measurements

The laser spot size was estimated at the entrance to the diagnostics box and again at the back aperture of the objectives by centering an iris diaphragm on the beam and closing the iris down until 67% of the total pulse energy was transmitted through the iris. The iris was then removed, and its open diameter

was measured using calipers. This technique quickly provides a rough measure of the $1/e$ diameter of the beam. The procedure was repeated for several positions of the second lens in the telescope to determine the degree to which the back aperture of the objective is filled as a function of the lens position. The beam telescope must be readjusted when the laser wavelength is changed; for example, the spot-size and beam divergence at 2200 nm is much larger, and a different telescope position is needed to set the beam size at the back aperture.

The laser spot size at the DUT position was measured using the knife-edge technique. A razor blade was clamped to the precision x-y stage and an energy probe was fixed in position above the stage just over the razor blade. The fraction of light passing by the razor's edge was measured as the razor blade was moved through the focused beam along the x- (or y-) axis. Visible light from the broadband source was used to verify that all light from the objective was captured by the energy probe. The razor's edge is not perfectly straight on a micron scale, so the camera image was used to find a location on the blade's edge with a nearly straight profile. The average pulse energy was recorded as a function of the stage/razor edge position using a 100 nm step-size. This was repeated for a range of axial (z)-positions of the objective/focus position to fully characterize the focused beam profile; the results are shown for 1260 nm in figure 7. Assuming a Gaussian profile for the beam, we fit an error function to the transmitted energy as a function of the scan distance. This proved to be a reasonable assumption from the degree of fit to the raw data. This curve was analytically differentiated to determine the beam profile, as opposed to fitting a Gaussian to numerically differentiated data with noise. The result of the curve fit gives a focused spot radius ($1/e^2$) of $1.6\ \mu\text{m}$ and a Rayleigh range of $\sim 8\ \mu\text{m}$.

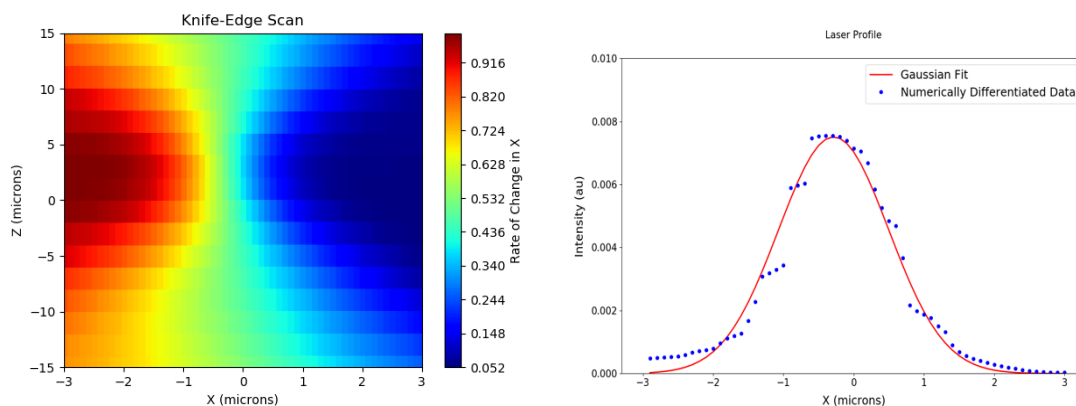


Figure 7: Results of the knife-edge scanning technique performed at the DUT position for 1260 nm are shown; a) intensity plot showing the rate of change in laser energy measured at the sensor as the razor edge is scanned laterally across the focused beam, as a function of the axial distance (z) from the focus position, b) shows the laser intensity profile measured at the focus position (z = 0).

Section 5. Pulse Duration Measurements

Autocorrelation measurements are performed just in front of the test bench using a 50% broadband beamsplitter to produce crossed-beams in a thin BBO crystal. The SHG signal produced by the overlapping pulses is measured with a large-area photodiode as a function of the position of a retro-mirror on a motorized stage in one arm of the autocorrelator. The acquisition is computer-controlled

and takes just a few seconds to perform. An example autocorrelation trace is shown in figure 8. Repeated measurements of the pulse duration have given very consistent results over time. The average FWHM of autocorrelation traces taken at 1260 nm in front of the test bench is 350 fs; assuming laser pulses have a hyperbolic secant pulse shape, the corresponding pulse width is 230 fs. While the laser pulses are significantly shorter just outside the laser, the output beam contains higher harmonics and sum frequencies that are collinear with the desired wavelength. Complete separation of the undesired wavelengths is accomplished with a prism (WSP in figure 1), at the cost of added spatial and temporal dispersion (chirp).

Autocorrelation at the DUT is more complicated due to the strong focusing and the high numerical aperture of the microscope objective. However, since the objective (and all other optical components in the test bench) use materials that exhibit low dispersion in the visible and near-IR, they should not introduce significant stretching (chirp) to the laser pulse. For simulations and dosage calculations, we assume the pulse width at the DUT position is nearly equal to that measured in front of the test bench.

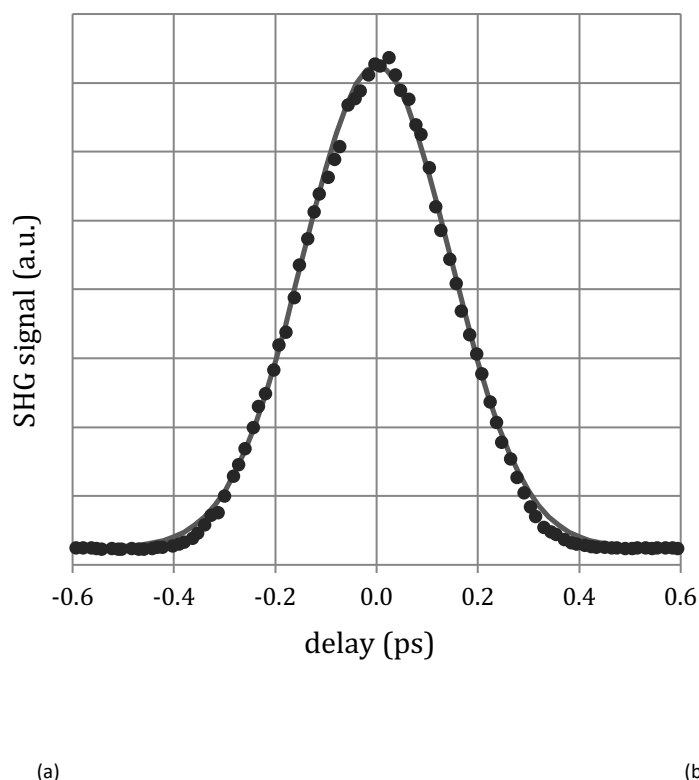


Figure 8: Autocorrelation of laser pulses at 1260nm taken before the test bench with crossed beams. The FWHM is 350fs, indicating a pulse width of 234fs.

Section 6: Experimental Results from the Laser Test Bench

Single Event Latchup (SEL) is a potentially destructive event where the charge from a heavy ion can turn on a parasitic thyristor PNPN structure inherent in many CMOS circuits. The technique of using a pulsed laser to create localized free-carriers via two-photon absorption TPA pulsed laser is useful for screening parts for potential SEL and generating threshold maps for sensitive regions.

When SEL occurs, the part enters a persistent high-current state until the latchup path is turned off – usually by removing power. We have built a programmable circuit that can be used to monitor circuits for SEL and automatically remove and then reapply power, resetting the circuit and turning off the latchup path (figure 9). One of the key characteristics of the latchup-reset circuit is the ability to respond fast enough that the circuit can be reset in less than 1 ms after the event occurs. Since our laser operates at a 1 kHz repetition rate, this means that each laser pulse can potentially cause a latchup. If the device were slower to respond, then some laser pulses would occur during the reset phase, which would greatly complicate data analysis and interpretation. A monitor signal is applied to an oscilloscope input to record when a latchup event occurs.



Figure 9: Latchup detection and reset circuit.

The graded neutral density filter continually modulates the pulse energy during the test. At a fixed location, the laser will include energies that cause SEL and those that do not. Thus, at each location a threshold laser energy may be determined for causing SEL. With the neutral density wheel rotating at approximately 3 times per second, the entire energy range is covered with around 350 points. It is common to take data from 1000 points (1 second) at each location to achieve better statistics.

Due to random fluctuations in the laser profile there may be an overlap in pulses that do and do not cause SEL. That is, pulses with recorded energies above the threshold may not show SEL, while pulses below the threshold may cause SEL. Logistic regression is used to determine the threshold from measured data. Figure 10 shows an example with multiple points at one location. The threshold is defined as the point where the logistic function is 0.5, corresponding to a 50% probability that latch-up will occur.

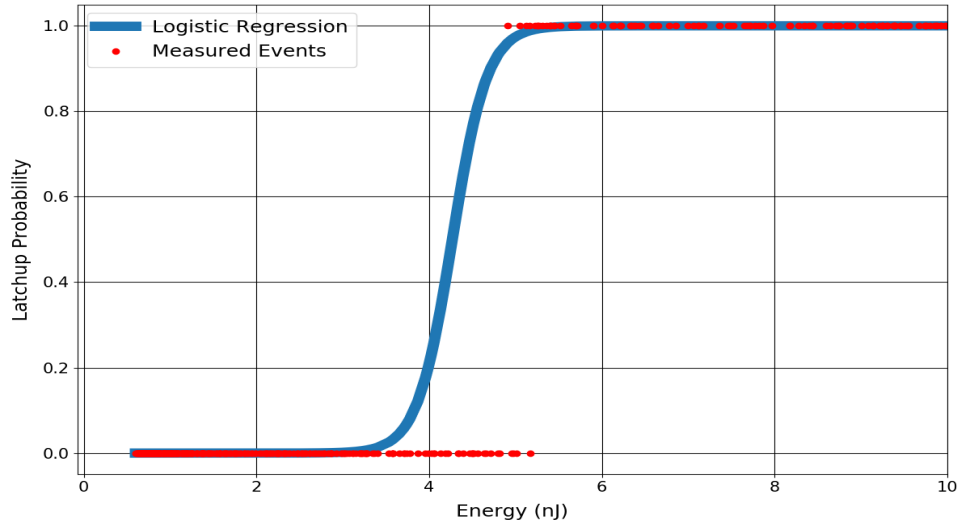


Figure 10- Logistic fit to upset data as a function of laser pulse energy.

The laser is scanned along the device to detect sensitive regions. 1000 laser pulses are measured at each x-y location to cover the complete range of energies provided by the attenuator wheel. Post-processing of the scan data yields a sensitivity map that can be used for additional analysis, such as measurements of a sensitive cross-section. Figures 11 a) and 11 b) are sample sensitivity maps which plot the threshold energy as determined by the logistic regression at each point.

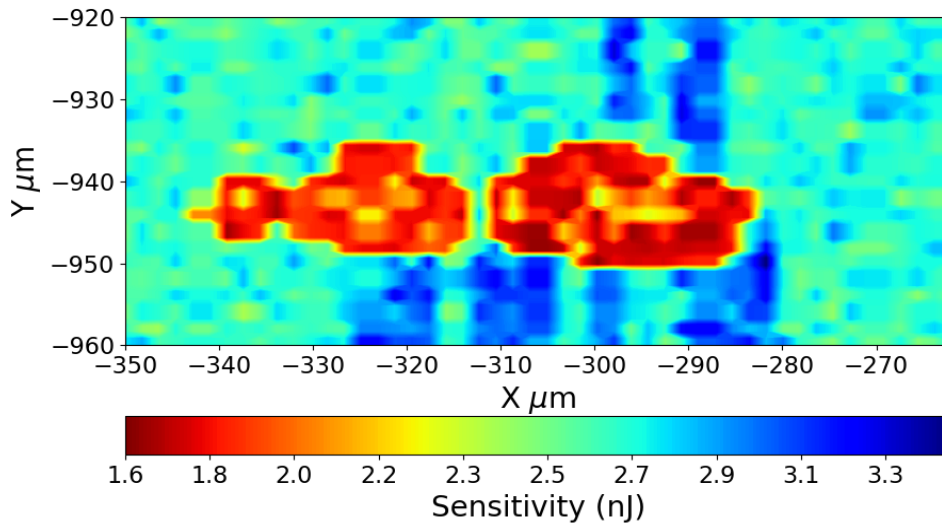


Figure 11: Sensitivity maps showing the pulse energy required to induce a latch-up event with 50% probability over a selected area of the sample.

Section 7: Discussion

The laser testing facility at Vanderbilt University is described here in detail. The test bench enables 3-dimensional localization of charge generation through the absorption of laser pulses and allows capture

of SETs synchronized to each laser pulse with high temporal resolution. The setup can be quickly adapted for testing at any wavelength from the near-UV to the mid-IR, allowing testing to be performed on several semiconductor types, using single or multi-photon absorption mechanisms. Average pulse energies can be adjusted from a few pJ to tens of μJ at most wavelengths and can be continuously varied at each device location during automated area or volume scans. Device transients are monitored and recorded for every laser pulse used during testing, along with a photodiode response curve that is carefully calibrated to the energy incident at the surface of the DUT. Autocorrelation measurements of the pulse duration can be performed quickly at any time; repeated measurements have shown the pulse width at a given wavelength to be stable over the long-term. The spot size at the DUT position has been measured for frequently-used wavelengths and was found to be near the diffraction-limit for the microscope objective. This testing system together with the diagnostic and calibration procedures described here provides an accurate measure of the irradiance used to stimulate SETs, which is necessary for repeatable characterization of a given device and improves the predictive power of computer simulations of radiation-induced effects.

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Measuring TPA Coefficients in Semiconductor Materials

Problems with previously published results for TPA coefficients

Many of the previously published studies of non-linear optical properties of silicon were motivated by the emerging field of silicon photonics. The samples used in these studies may have different material properties from those of interest to our work (doping levels and/or resistivity are frequently not specified). The wavelengths used in these studies are often either telecom standards (usually near 1550nm) or those available from common solid-state pulsed lasers (i.e., 1064nm). For telecom applications, non-linear absorption is to be avoided; the purpose of most existing studies is to define the intensity range that excludes non-linear effects. Therefore, relatively low intensities (often less than 10GW/cm²) are used, and the maximum absorption is usually just a few percent of the incident light.

However, in testing components for radiation effects, a high yield of TPA is needed to produce measureable device effects, so much higher incident intensities (>100GW/cm²) are frequently used. Material properties measured at low intensities may be altered by the higher intensities used in radiation effects testing. In addition, when high levels of TPA are induced, the resulting high density of generated free-carriers may absorb a significant fraction of the incident light pulse.

The experimental method used in most published work is the z-scan technique, where the sample under test is translated through the focus of a lens (the z-axis) in order to vary the laser fluence, while the transmitted light is measured as a function of the (z) position. InGaAs photodiodes are typically used to measure the transmitted fraction of the incident light. The laser spot size is normally measured at just one position- the focus of the lens. The laser beam is then assumed to have a Gaussian spatial and temporal shape, so that the intensity as a function of z-position can be calculated from Gaussian beam optics, based on the spot-size measured at the focus. This approach assumes perfect Gaussian behavior

of the optics and the laser beam. Sample reflectivity is assumed to be constant and equal to the low intensity value. Two-photon absorption is assumed to be linear with incident intensity, and the resulting transmission plot (as a function of z-position) is fitted to a theoretical equation for the transmitted power, with the TPA coefficient (β) as the fit parameter.

Reported values for the TPA coefficient as measured with the z-scan technique vary widely (from 0.5 to 10 cm/GW for wavelengths near 1260nm). The inconsistency in measured results could be due to differences in the properties of the sample materials used, or to several uncertainties inherent to the technique. First, the actual laser pulse width and spatial beam profile are often not specified. The laser parameters often do not match those of a perfect Gaussian beam, which would cause differences between actual and calculated intensities. While a linear dependence on intensity is assumed and the linear coefficient (β) is used to fit data to the resulting equation, few papers experimentally verify the linearity of the response. If free-carrier absorption or other non-linear effects such as refractive index changes are significant, the transmission may not change linearly with intensity. This could lead to a 'best-fit' value for β that does not represent pure TPA. The assumption of constant sample reflectivity (equal to low-intensity value) is suspect, since it is known that the refractive index of silicon changes with incident intensity (Kerr-effect). The z-scan technique does not easily allow measurement of the beam reflected from a moving sample; however, it is reasonable to expect intensity-dependent changes in the reflectivity of the surface, which changes the fraction of light that penetrates into the sample.

Finally, InGaAs photodiodes exhibit highly non-linear behavior; their response varies strongly with incident wavelength, spot-size, background illumination, and even with the divergence of the incident laser beam. These detectors are often used because pulse energies available from most tunable mid-IR lasers are typically low (a few hundred nanojoules) and calibrated probes are not available for such low pulse energies. Unless these photodiodes are operated with exposure conditions within the linear portion of their response, errors in the measurements of transmitted laser pulses can result.

Motivation for in-house measurements

Most of the published measurements of non-linear properties of semi-conductor materials use relatively low laser intensities on samples that were undoped or lightly doped. The reported values for β in those materials vary over a wide range, possibly due to assumptions made in the z-scan technique, or perhaps to real differences in material properties. Accurate TPA coefficients are critical input parameters to computer simulations of laser-induced charge generation. In order to accurately simulate TPA-induced device effects, we need an accurate characterization of the non-linear response of the materials under test in our lab when exposed to pulses from our laser. To determine the high-intensity non-linear properties, not just for intrinsic silicon, but for silicon with the various doping levels that are commonly used in modern devices, we have undertaken experiments to measure the TPA coefficients in our lab, using our laser source, tuned to the wavelengths we use for radiation testing.

Experimental technique used at the VUFEL

The laser used for radiation effects testing at the VUFEL is a 1kHz repetition-rate, Ti/S-pumped optical parametric generator (OPG) that produces tunable wavelengths from the UV to the mid-IR with pulse durations around 100-200fs and pulse energies as high as 100 μ J. These pulse energies are much higher

than what is available from the more typical OPO or OPA, and are high enough to allow the use of a calibration-certified pyro-electric energy sensor to directly measure the energy of each laser pulse, down to a minimum of roughly 200nJ.

Our experiments have focused on measurements of the two-photon and free-carrier absorption of silicon when exposed to laser pulses with a center wavelength of 1260nm. The temporal width of laser pulses was measured using autocorrelation after a wavelength-separating prism; the FWHM pulse width at 1260nm is consistently found to be 300fs. Instead of moving the sample through the focus of a lens, we use a pair of wire-grid polarizers to vary the incident laser pulse energy while the sample is at a fixed z-position with known laser spot-size. At this wavelength, over 60μJ/pulse is available from the laser; the calibrated sensor can measure as little as 200nJ, allowing us to vary the incident pulse energy (and intensity) over two orders of magnitude at a single z-position. The spot-size at the sample is measured in both x and y directions using the knife-edge technique; a Gaussian fit to the resulting profiles gives a measure of the beam diameter ($d = 2 \cdot 1/e^2$), which is used to calculate the average incident laser intensity, $I = E_{(inc)}/(FWHM \cdot d)$.

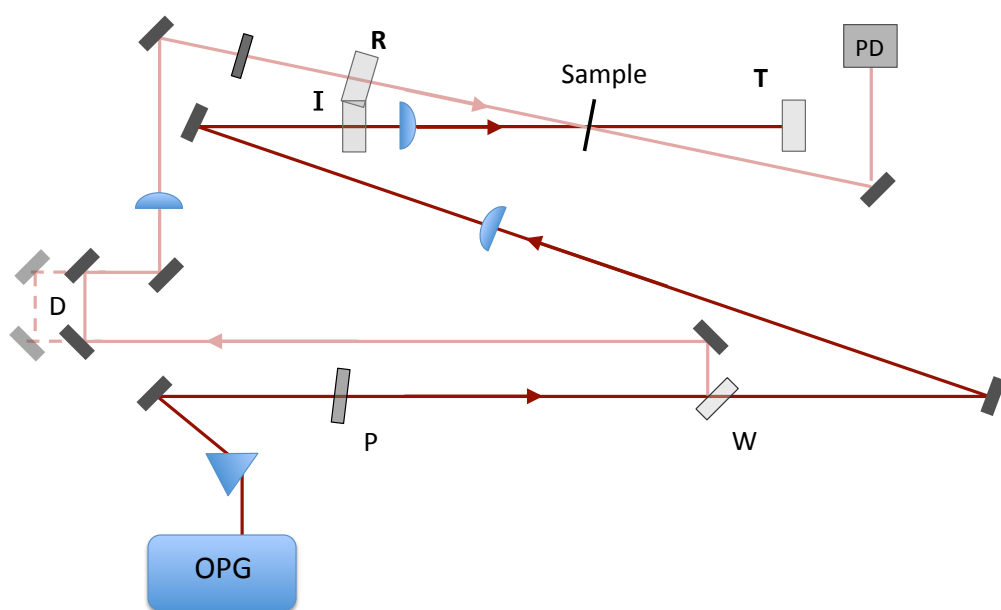


Figure 1: Set-up for TPA measurements; laser wavelengths from the OPG are separated with a prism and attenuated with a polarizer (P) before being focused and directed to the sample. A calibrated energy sensor can be placed at positions labeled I, R, and T, to measure the incident, reflected, and transmitted beams. A small portion of the pump beam is reflected from the window (W), to serve as a probe beam for time resolved pump-probe measurements. It is variably delayed, focused, and attenuated before reaching the sample. The transmitted probe beam is measured at a photodiode (PD).

The sample is placed at an angle of about 10° to the incident beam, to separate the reflected light from the incident light. For each incident pulse energy used, the calibrated energy sensor is first placed at the

incident position (I), where the energy of thousands of laser pulses is averaged and recorded. The probe is then moved to the transmitted energy position (T) and then to the reflected energy position (R), averaging thousands of pulses at each position. A visible alignment laser is used to determine the optimum probe location for R, T, and I measurements, and identical mounts are located at each position to ensure the beam is centered on the probe. The alignment laser is used to change the R and T positions when a different z-position is used.

Results for highly-doped silicon:

The measured absorption and reflection of a highly doped (p-type, 10^{18}cm^{-3}) silicon wafer (500 μm thick, polished on both sides) is shown below as a function of the incident light intensity. This material has significant linear absorption due to its high free-carrier density. Assuming low scattering losses from the polished front and back surfaces, the energy absorbed by the sample E_{abs} is calculated as the incident pulse energy E_{inc} minus the reflected E_{refl} and transmitted E_{tran} pulse energy.

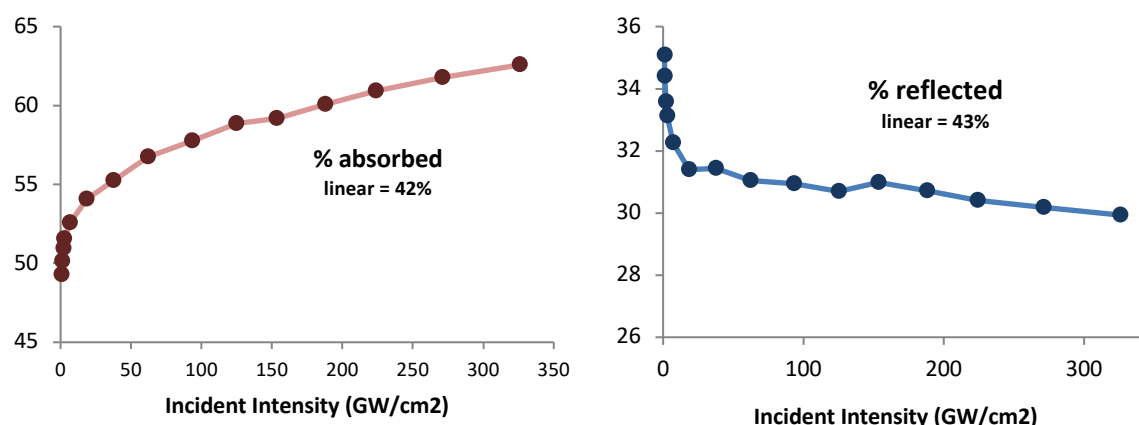


Figure 2: Measurements of the percent of 1260nm incident light absorbed and reflected from a highly doped silicon wafer are shown as a function of the intensity of incident femtosecond laser pulses. High intensity results were obtained using a small spot-size at the sample; low I results required using several larger spot sizes at the sample surface. Pulse energies were measured using a calibrated sensor and each spot-size used was measured using the knife-edge technique.

Characterization of this sample in a UV-vis-IR spectrophotometer with an integrating sphere determined that the linear, low-intensity transmission near 1260nm is $\sim 15\%$ and the total surface reflection is $\sim 43\%$, giving a linear absorption of 42% of low-intensity light incident on the sample. Our results show that the sample reflectivity changes dramatically with increasing incident intensity, and the change is most rapid at the lower intensities ($<10\text{GW}/\text{cm}^2$). This is due in part to the increasing internal absorption, which reduces the magnitude of the reflection from the second surface. However, the second reflection is small compared to the first-surface reflection, and this cannot explain the large change observed. It is likely that an intensity dependent refractive index change occurs, which invalidates the assumption of a constant, linear reflectivity often made in published measurements of silicon. Nonlinear reflectivity and absorption was observed with this sample for very low laser pulse intensities ($\sim 0.1\text{GW}/\text{cm}^2$). Obviously, the rate at which absorption increases with incident intensity is not constant over the range of

intensities measured here. We are currently performing computer simulations to determine the extent to which the sample thickness affects the shape of this curve. It is likely that linear absorption by pre-existing free-carriers affects the rate at which TPA generates free-carriers with increasing incident intensity.

Results for intrinsic (undoped) silicon:

The same experiments were performed with a polished “undoped” (intrinsic) silicon wafer with 280 μm thickness. The linear reflectivity and transmission of intrinsic silicon at 1260nm is 48% and 52%, respectively, with 0% of the incident light being absorbed. Results from several experiments measuring the fraction of the incident light that is transmitted, reflected, and absorbed as a function of incident intensity are shown in Figure 3 below. At low laser intensities, the measured values for reflectivity and transmission were within $\sim 2\%$ of the low-intensity values. The reflectivity does change with intensity, but the change is less rapid than was found for highly doped silicon. Slight drifts in the average power from the laser while the measurements are performed and noise in the sensor reading at low energies produces some scatter in the results.

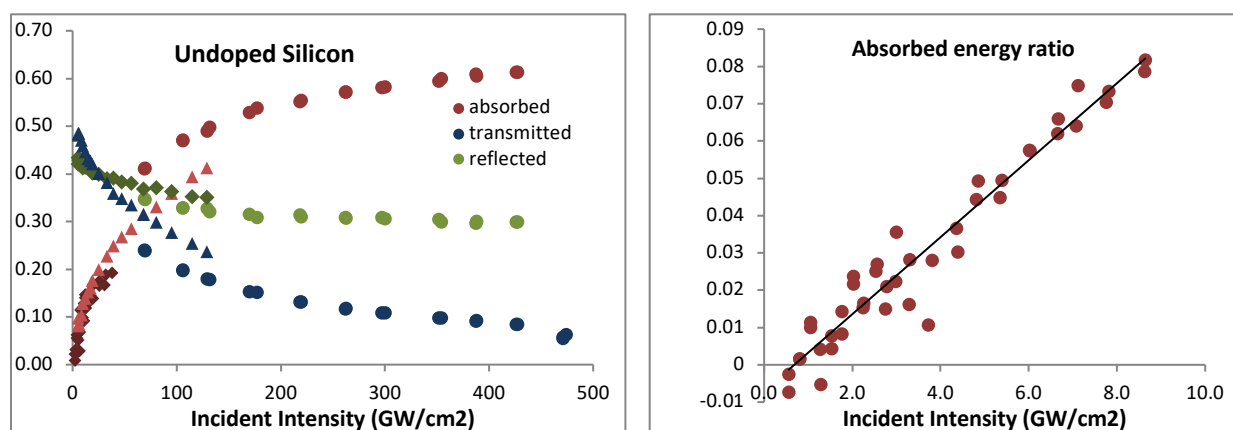


Figure 3: Left panel: Results of several experiments measuring the transmitted, reflected, and absorbed fractions of laser pulse energies incident on a sample of undoped silicon are shown. Experiments using different spot sizes are indicated with triangles, circles, and diamonds. Right panel: The absorption of relatively low intensity laser pulses by an undoped silicon sample is shown, along with a linear fit to the data.

Several different spot-sizes at the sample surface were used, corresponding in the figure to triangles, circles, and diamonds. Had our measurement of the intensity at each position been accurate, these plots would overlap in regions of equal incident intensity- since they do not, we conclude that the beam spatial profile likely deviates from that of a perfect Gaussian beam, and may not have been consistent from one experiment to the next.

To address these problems, several improvements to the experimental setup were made. A 2:1 telescope was installed to allow a wider range of spot sizes and to provide control over the beam divergence. Spatial filtering to remove higher order transverse modes was accomplished with an iris placed near the focus the telescope. The iris was optimized using an IR camera to produce a more

uniform and consistent intensity profile. Measurements were repeated using several different spot sizes and a wide range of incident energies at 1260nm. A comparison of absorption data at the same calculated intensity (with different spot sizes) serves as a cross-check on our calculated intensities. To reduce the scatter in our measurements, a second detector is being used to monitor and record the incident energy during measurements of reflected and transmitted energies, allowing compensation for any drift in the average incident laser pulse energy.

When the total absorption is low and dominated by TPA, the slope of a linear fit to the absorbed energy ratio $(E_{\text{inc}} - E_{\text{ref}} - E_{\text{tra}})/(E_{\text{inc}} - E_{\text{ref}})$ versus the intensity just inside the sample $E_{\text{inc}} - E_{\text{ref}}$ gives the TPA coefficient for that sample. Taking the average of several measurements made at less than 5% absorption on undoped silicon wafers gives a two-photon absorption coefficient of $1.4 \pm 0.1 \text{ cm/GW}$. This value is close to that found in more recent studies using wavelengths near 1260nm, including one which used a similar technique instead of the usual z-scan. Our result is nearly identical to that found recently in a collaborator's lab. The sample was damaged upon exposure to an approximate pulse intensity of 400 GW/cm^2 .

TPA in other semiconductor materials:

Similar measurements done with highly-doped P-type silicon at 1260nm gave an apparent non-linear absorption coefficient that is about 1/3 that of undoped silicon. Because of the potential interaction of free-carrier absorption and TPA-induced generation, we are not yet confident in the measurement of TPA in this material. Further experiments and computer simulations are needed to give a quantitative description of the interacting mechanisms involved in intensity dependent absorption in heavily doped P-type silicon.

In contrast, measurements made on N-type silicon lightly doped with phosphorus ($\sim 10^{15} \text{ cm}^{-3}$) showed no significant linear (low-intensity) absorption at 1260nm, but when exposed to high intensity laser pulses, revealed very strong non-linear absorption. The average non-linear absorption coefficient measured for this material was 4 - 5 cm/GW (about 3X higher than that of undoped silicon). It is believed that strong free-carrier generation and subsequent absorption by those carriers contributes to the non-linear response of N-type material. Further investigation is needed. Disentangling the competing mechanisms involved in non-linear absorption of laser pulses is complicated by the limited range of doping levels commonly available. For example, we would like to compare N-type and P-type with both light doping and high doping, but were unable to obtain these materials.

Absorption measurements were also made on samples of intrinsic germanium using laser pulses centered at 2200nm, where linear absorption is nearly zero. Assuming TPA is the dominant non-linear absorption mechanism and using very low pulse intensities (to keep the total absorption below 10%), we measured a TPA coefficient of $100 \pm 20 \text{ (cm/GW)}$, which is 66X higher than that of silicon. Further measurements are needed to improve the uncertainty in this value.

Pump-probe measurements:

To estimate the fraction of light-induced absorption due to TPA-generated free carriers, pump-probe experiments were done. These experiments reveal the time-dependence of the onset and decay of non-linear absorption in a sample. A small portion of the 1260nm pulse (the probe) is split off, variably

delayed with a retro-mirror on a motorized stage, and then passed through the sample at the same spot as the pump beam (Figure 1). The probe beam energy is monitored with a photodiode as a function of the delay between pump and probe pulses. By scanning the delay, a measure of the sample absorbance is obtained as a function of time with sub-picosecond resolution. Sample absorption that is found only after passage of the pump pulse is due to free-carriers generated by the pump pulse, and can be significant for high intensity pulses such as those used in transient generation. Measurement of the sample absorption just after passage of a pump pulse, together with knowledge of the absorbance of free-carriers and the sample thickness provides a direct measure of the density of TPA-generated carriers.

An example of time-dependent transmission of a probe beam is shown in Figure 4. for a pump beam intensity of 270GW/cm^2 incident on a sample of highly-doped P- type silicon. The transmission of the pump beam was about 9% under these conditions. Absorbance changes that exist during the pump laser pulse (near $t = 0$) are due to laser-induced changes to the material's dielectric properties (assumed to be TPA), while absorbance that exists long after the passage of the strong pulse is due to the free carriers generated by the laser pulse. Our measurement indicates roughly 1.5% of the probe beam was absorbed by free-carriers after passage of the pump beam. However, an accurate quantitative measure of the local free-carrier density requires that the probe spot-size be significantly smaller than the pump spot-size at the sample, and that the photodiode respond linearly to incident pulse energies. With refinements to this experiment, it should be possible to map out the free-carrier density created by the pump pulse.

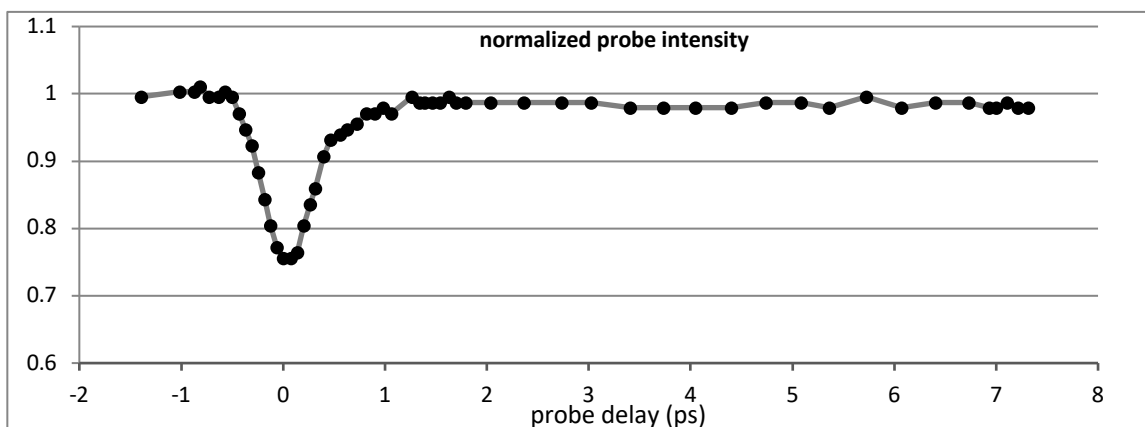


Figure 4: The relative transmission of a weak probe beam through a sample of highly doped silicon is shown as a function of its time of arrival relative to the strong pump beam. The two beams arrive at the same spot on the sample at time $t=0$.

To determine the extent to which absorption is due to free carriers generated during the laser pulse, pump-probe measurements of undoped silicon were made (Figure 5, left panel). The probe beam for these experiments had $\sim 1/100^{\text{th}}$ of the pump pulse energy and a slightly smaller spot size at the sample

surface. Knowledge of the absorbance of free-carriers at this wavelength and the sample thickness provides a measure of the density of TPA-generated carriers in the sample volume being probed.

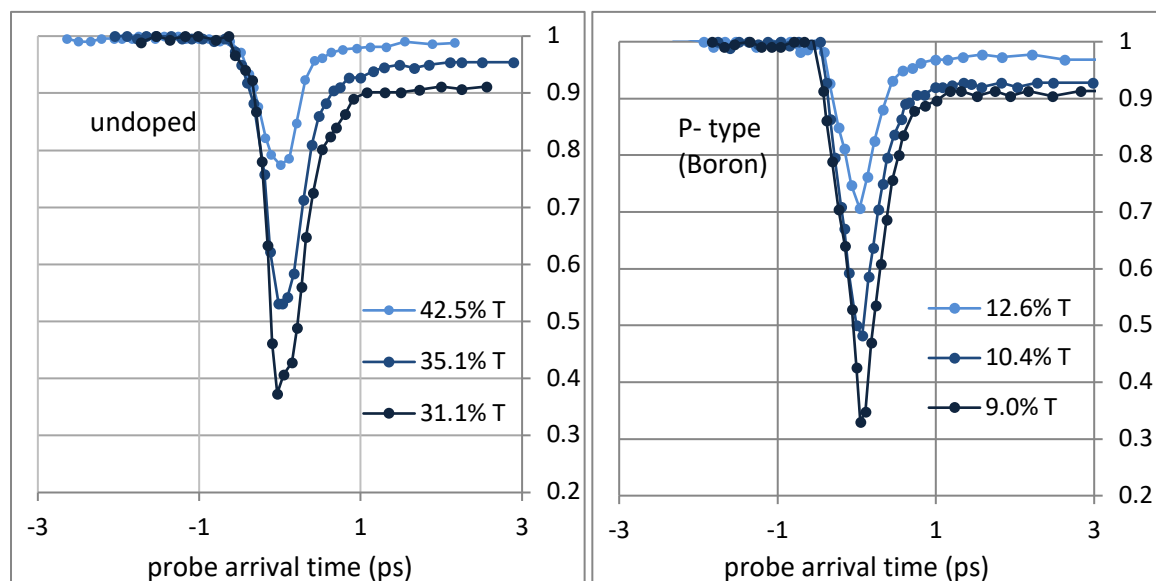


Figure 5: Relative transmittance of a probe pulse at times relative to the arrival of a pump pulse ($t=0$) through undoped silicon and P-type doped silicon. Transmittance is normalized to the value found before arrival of the pump pulse, and is shown for pump pulses with increasing intensity (decreasing transmission). Pump intensities used on P-doped samples were about 3X higher than those used on the undoped sample.

Pump-probe measurements were also made at 1260nm for heavily doped (P-type) silicon (Figure 5 right panel). In this material, linear absorption is strong ($\sim 75\%$ for a $300\mu\text{m}$ thick sample). This attenuates the laser pulse as it travels through the sample, reducing the intensity available for TPA. It is likely that strong free-carrier absorption is the cause of the change in the shape of the transient absorption. Both pre-existing and generated carriers absorb photons from the pump pulse during its passage, producing a feedback mechanism that complicates the determination of TPA coefficients. The overall effect is an apparent reduction in the efficiency of non-linear absorption; the non-linear absorption coefficient for this material measured in our lab is about $1/3$ that of undoped silicon. Further experiments and computer simulations are needed to give a quantitative description of the interacting mechanisms involved in laser-induced free carrier generation in heavily doped P-type silicon.

Pump-probe measurements were also made on intrinsic germanium wafers at a wavelength of 2200nm, where linear (low intensity) absorption is nearly zero. Pump-probe measurements made on a germanium wafer with a thickness of $330\mu\text{m}$ indicated no significant free carrier absorption immediately after exposure to high-intensity laser pulses. Pump pulses that produced 45% absorption of the probe pulse returned to zero absorption immediately after the passage of the pump pulse. This result indicates that either no free-carriers are created by TPA or that recombination is extremely fast.

Summary of work done and work left to do

Non-linear absorption properties were measured for several semiconductor materials, including undoped, lightly doped, and heavily doped silicon, and intrinsic germanium. Non-linear absorption coefficients (assumed to be TPA) were extracted from the low-intensity data for each of these materials, and varied from 1.4 cm/GW for undoped silicon to 100 cm/GW for germanium. Our results clearly show that for high intensity laser pulses, linear absorption and generated free-carrier absorption can both play a role in the response of these materials to strong laser pulses.

In order to fully understand the dynamics of intensity-dependent absorption in semiconductor materials, we need more experiments and computer simulations. The model we develop will help determine the appropriateness of using a simple linear coefficient in our simulations of laser-induced radiation effects testing, and may lead to changes in the technique used in our lab to measure non-linear properties of semiconductor materials. Disentangling the competing mechanisms involved in non-linear absorption of laser pulses is complicated by the limited range of doping levels commonly available.

Pump-probe measurements made of the time-dependent linear absorption resulting from intense laser pulses will aid our understanding of the role played by TPA generated free-carriers in the absorption of light by semiconductor materials with different types of dopants, over a range of doping levels. Using the pump-probe technique to measure non-linear absorption has great potential; by scanning a small weak probe beam across the region recently affected by a strong pump beam, one can quantitatively map out the free-carrier density as a function of both time and space. With a large probe spot-size and an IR camera, it should be possible to image the 2-D distribution of generated free-carriers with a single laser pulse.

Sub-Picosecond Electro-Optical Sampling Techniques

Introduction

The electro-optic (EO or Pockels) effect has been used for decades to manipulate the polarization of light. The term refers to the birefringence that is induced in certain crystalline materials (those which lack inversion symmetry) under the influence of an applied electric field.

When the polarization of light traveling through such a crystal is oriented correctly relative to the crystal axis and the applied electric field, one component of the polarization vector will travel at a different speed than the other component. The resulting phase delay between the two components accumulates as the wave propagates through the crystal in proportion to the strength of the applied electric field. When the light emerges from the crystal, these polarization components are out of phase, resulting in a polarization vector with a changed direction. In electro-optic sampling, the applied electric field is the signal of interest, and the measured quantity is the degree to which the polarization has been rotated by the electric field of the signal.

A polarization analyzer is commonly used to measure very small changes in the direction of polarization of a beam of light. The analyzer typically consists of a quarter wave-plate that is adjusted to convert the linearly polarized light into circularly polarized light ($E_x = E_y$), followed by a prism-polarizer that splits the

light into two beams with orthogonal polarization directions. A pair of balanced photodiodes is used to measure the power in these two beams (see Figure 7). With zero electric field applied to the electro-optic crystal, the power of the light beam is equally divided between the two detectors, and each produces exactly the same output. The photodiodes are connected to a differential amplifier, whose output is zero volts when no field is applied to the crystal. When a change in the polarization is induced by an electric field in the sampling crystal, the rotated linear polarization becomes elliptically polarized after the quarter wave-plate, and an imbalance is created in the two detectors. The differential amplifier then outputs a signal that is proportional to the field in the crystal, and any common-mode noise is rejected. By modulating the amplitude of the light beam used to sample the field in the crystal, a lock-in amplifier can be used to further isolate the signal from noise, allowing detection of very small signals.

Using very small crystals of commonly available materials like lithium tantalate and high quality components in the polarization analyzer, experimenters have routinely demonstrated detection of sub-millivolt electric field strengths, which makes it possible to use an electro-optic probe to sample the fringe fields in close proximity to an electric circuit, without actually contacting the circuit components.

However, the real advantage of this technique is that lasers with very short pulse-durations can be used as the light source for sampling electric fields in an electro-optic crystal. With today's ultrafast lasers, pulse widths of 100 fs and high repetition rates are common. Using a short pulse of light as the probe beam, the sampling takes place in the time required for the pulse to travel through the region of the crystal that is affected by the electric field. Since the region of the crystal exposed to the fringe field of a small electric signal is usually just a few microns, sampling times can be significantly less than a picosecond. Using a single light pulse split into two paths, one path can be used to trigger an electrical signal in a test circuit and the other can be delayed with a variable path-length and used to probe the signal. This allows jitter-free sampling of fast-changing electric fields. The time-dependence of the evolving signal can be 'mapped-out' with sub-picosecond resolution by iterative sampling at different delay times between the trigger and the probe pulse. The temporal resolution of such measurements is intrinsically limited only by the frequency response of the electro-optic crystal. Using this technique with probe crystals of lithium tantalate, a temporal resolution of 300 fs has been demonstrated.

The temporal resolution of an electro-optic probe can be directly measured using photoconductive (PC) switches that are integrated into the device under test. These PC switches have been shown to create current pulses with rise times that are equal to the laser pulse duration, so any longer rise time resulting from the EO probe measurement reveals the temporal resolution of the probe.

Many different experimental geometries of electro-optic sampling have been demonstrated; some are optimized for maximum temporal resolution, others for the best voltage sensitivity. We propose to begin using the simplest geometry to obtain our initial results, and to gradually increase the complexity and capability of our apparatus as needed to address the project's goals. The simplest experimental design (see Figure 1) would employ a thin plate of lithium tantalate with an optical polish on both sides and a high-reflection coating on one of the polished sides. The plate would be large enough to cover the region of interest and could be placed directly on top of the device. The ultrafast laser beam would be focused to around 5-10 μ m in diameter and would enter the crystal from the top side, be reflected from

the bottom side (which is in contact with the circuit) and would then be sent to the polarization analyzer. The beam position could be moved around the area of interest while scanning the time delay of the probe pulse at each position. The resulting map of the electric field as a function of position and time constitutes a time-resolved image of the field on the surface of the circuit. While this simple technique is not entirely non-invasive, the effect of the dielectric lithium tantalate crystal in contact with the circuit should be a small perturbation on the impedance characteristics of the device.

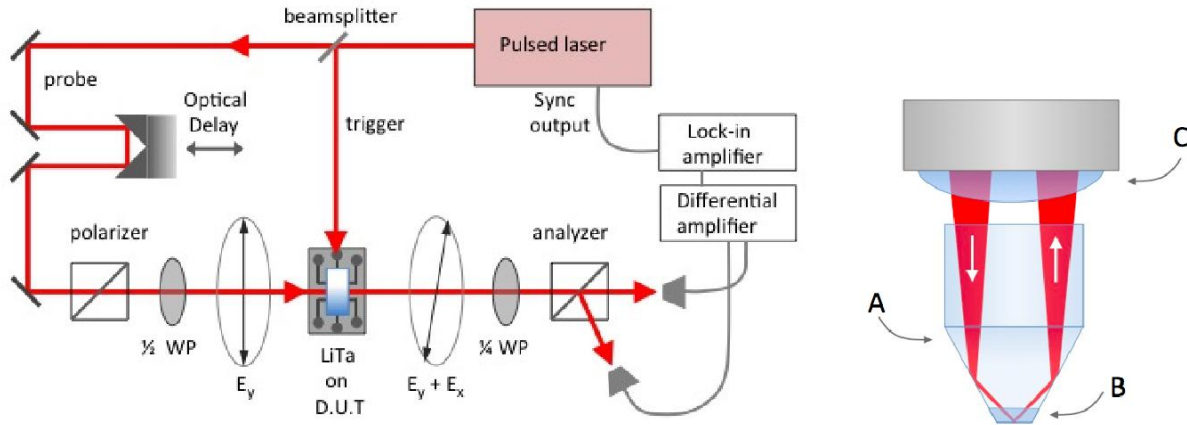


Figure 1: (Left panel) Basic layout of an electro-optic sampling experiment. (Right panel) Non-contacting electro-optic probe design using total internal reflection. A: Glass cylinder with prism tip, B: Lithium tantalite crystal, C: Microscope objective.

A more complex but powerful technique that has been used by several groups employs small, optically polished probe tips ($\sim 40 \mu\text{m}$ square). These probes have been shown to have high sensitivity to electric fringe fields without making physical contact with the device under test. An example of one of these probe designs is shown in Figure 1 (right side panel); it employs total internal reflection inside a glass prism to direct the probe beam down to the tip of the crystal and then reflect it back out to the analyzer. This probe design allows quasi-point sampling of the electric fields without contacting the device; the only disturbance to the test circuit is the small capacitive coupling between the DUT and the probe crystal.

Experimental setup

We have acquired the necessary optics (polarizers, beamsplitters, detectors, a microscope objective, and a LiTa crystal with a suitable reflective coating), and have built an experimental setup (see Figure 2)

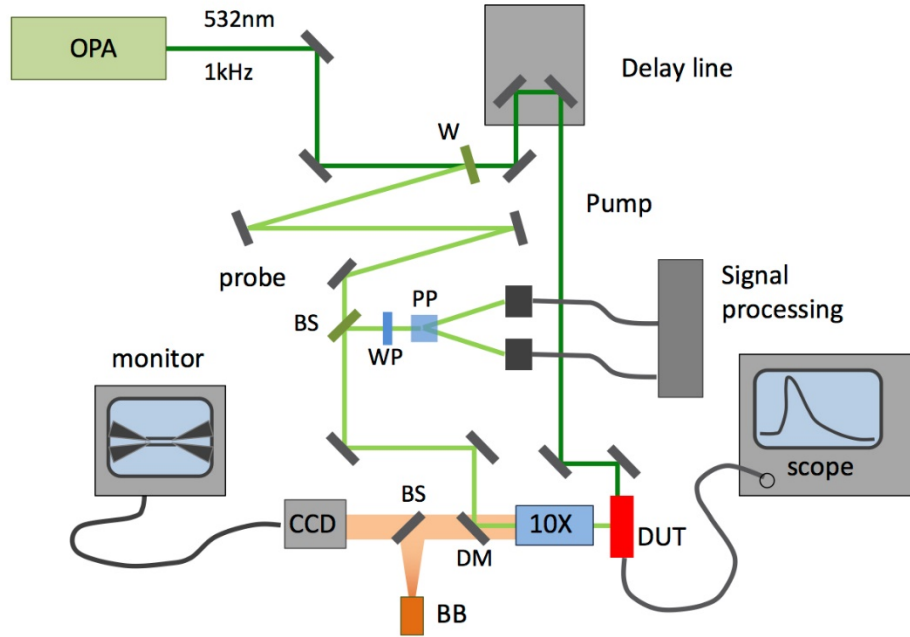


Figure 2: The layout of our electro-optic sampling experiment built at Vanderbilt. In the figure, W: window, BS: beamsplitter, WP: waveplate, PP: polarizing prism, CCD: camera, BB: broadband light source, DM: dichroic mirror, 10X: microscope objective

that includes a 10X microscope objective coupled to a CCD camera for focusing the probe pulse and simultaneous viewing and positioning of the device under test. A custom crystal mount fabricated at Vanderbilt has been incorporated into a kinematic mount that allows precise (6-axis) positioning of the EO crystal in front of the DUT.

Initial experiments

We have designed and fabricated a custom test circuit (Figure 3) with a coplanar micro-strip-line where electric fields are concentrated by the close proximity of the conducting strip-lines. The test board is capable of producing both DC and pulsed electrical potentials synchronized with the femtosecond laser pulse. The amplitude of the DC fields across the strip line can be continuously adjusted from zero to a few hundred volts/mm. This will allow us to begin with very high amplitude fields, which should give a strong electro-optic signal. We can then gradually reduce the applied field amplitude while re-optimizing parameters affecting the EO signal amplitude (such as probe input polarization direction, crystal orientation and proximity, lock-in amplifier settings, etc.). The goal is to determine the minimum field amplitude we can detect above noise, since the sensitivity of the EO probe technique will determine its applicability to the measurement of weak transients in complex devices. The test board

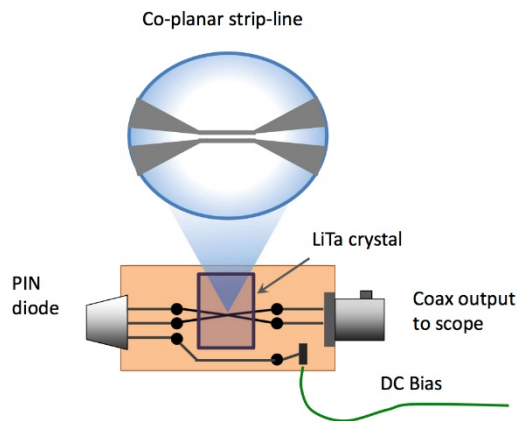


Figure 3: The layout of the test board built for initial EO measurements, showing a simulated magnified image of the coplanar strip-line where electric fields will be measured.

can also generate a pulsed signal from an onboard photodiode. By directing a portion of the laser pulse to the photodiode, a fast electrical pulse passes through the strip-line with amplitude proportional to the laser pulse energy. The photodiode signal can be monitored on an oscilloscope during the experiment. Another portion of the same pulse is sent through the variable delay line and used as the probe beam for time-resolved EO sampling of the pulse from the photodiode.

Current Status

We have begun experiments using the test circuit to determine the sensitivity and threshold (above noise) of EO measurements with our setup. Because of the simple geometry of the test board, these initial experiments should allow us to correlate the EO signal obtained with the known field strength on the device, giving a quantitative measure of the sensitivity of the technique.

Our colleague at Rochester (Dr. Bill Donaldson) has provided us with an electro-optic crystal coated for 532nm and has begun preparing crystals optimized for our experimental setup (matching the crystal design to our pulse width, preferred probe wavelength, and technique). Once the measurement technique has been optimized, our colleague will design and fabricate an electro-optic probe tip, which will be integrated into the microscope test bench, allowing measurement of transients in tight spaces on complex devices.

We have worked with IMEC to design specialized test structures to accommodate the probe. These early test devices will involve a highly scaled III-V transistor, possibly a nanowire.

Laser and Ion Effects in Simple Device Structures

Analysis of TPA Pulsed-Laser-Induced Single-Event Latchup Sensitive-Area

Two-photon absorption (TPA) pulsed-laser testing is used to analyze the TPA-induced single-event latchup sensitive area of a specially designed test structure. This method takes into account the existence of an onset region in which the probability of triggering latchup transits between 0 and 1 as the laser pulse energy increases. This variability is attributed to a combination of laser pulse-to-pulse variability and variations in local carrier density and temperature. For each spatial position, the latchup probability associated with a given energy is calculated. Calculation of latchup cross section at lower laser energies, relative to onset, is improved significantly by taking into account the full probability distribution. The transition from low probability of latchup to high probability is more abrupt near the source contacts than for surrounding areas.

TPA pulsed-laser testing was used to analyze the onset region for laser-induced SEL and provide insight into the SEL cross section. The latchup data versus laser energy data are fitted to a Weibull distribution, in which two key parameters, the mean threshold and shape parameter, are used to analyze latchup as a function of location. The p+ and n+ regions have higher latchup threshold than the surrounding areas. The width of the onset region varies with the location of the laser strike. The p+ and n+ areas have narrow onset regions, but otherwise, there is not much correlation between location and the width of the onset region. For each pixel, the effective cross section is calculated by multiplying the pixel area by the latchup probability. This pulsed-laser TPA-induced SEL test method and analysis helps to provide understanding of the variation of SEL sensitivity with area and to provide an improved estimate of latchup cross section through the onset region.

P. Wang, A. L. Sternberg, J. A. Kozub, E. Zhang, N. A. Dodds, S. L. Jordan, D. M. Fleetwood, R. A. Reed, and R. D. Schrimpf, "Analysis of TPA Pulsed-Laser-Induced Single-Event Latchup Sensitive-Area," IEEE Trans. on Nucl. Sci., vol. 65, no 1, Jan., pp. 502-509, 2018.

Understanding the Average Electron–Hole Pair-Creation Energy in Silicon and Germanium Based on Full-Band Monte Carlo Simulations

The thermalization process of sub-10-eV charge carriers is examined with treating carrier transport with fullband Monte Carlo simulations. The average energy loss (3.69 eV in Si and 2.62 eV in Ge) required to create a thermalized electron–hole pair, obtained from the simulations, is very close to the experimentally measured radiation–ionization energies of Si and Ge irradiated with high-energy particles. These results suggest that only interactions that occur after the radiation-generated charge carriers decay to energies of ~10 eV or less determine the fundamental property of the radiation–ionization energies. In addition to an energy loss equal to the band gap energy via impact ionization, acoustic-phonon emission, which has been omitted in prior work, contributes 30% of the remaining carrier energy loss, while optical-phonon emission contributes the other 70%.

The radiation–ionization energies of 3.69 eV in silicon devices and 2.62 eV in germanium devices are examined through full-band Monte Carlo simulations based on the detailed electronic band structures

and carrier scattering models. This paper extends previous understanding by showing that both acoustic-phonon emission and optical-phonon emission contribute significantly to energy loss. These are in addition to the energy loss associated with the band gap energy via impact ionization.

Another finding of this paper is that the radiation-ionization energy can be completely accounted for by carrier transport in the lowest energy bands, as indicated by the agreement between the calculated and experimental pair-creation energies. Charge carriers resulting from interactions of high-energy particles with the target material lose energy by various processes following the initial scattering events, but the average energy required to create a thermalized EHP is determined only by interactions that occur after the carriers have energies of ~ 10 eV or less.

J. T. Fang, M. Reaz, S. L. Weeden-Wright, R. D. Schrimpf, R. A. Reed, R. A. Weller, M. V. Fischetti and S. T. Pantelides, "Understanding the average electron-hole pair-creation energy in silicon and germanium based on full-band monte carlo simulations", IEEE Trans. on Nucl. Sci., vol.66, no.1, pp. 444-451, Jan 2019.

Polarization Dependence of Pulsed Laser-Induced SEEs in SOI FinFETs

Pulsed, laser-induced, single-event current measurements on silicon-on-insulator (SOI) FinFETs at subbandgap wavelength (1260 nm) are affected by the polarization of the laser light used in the experimental testing setup. Such polarization dependence is not observed during pulsed laser, single-event effects testing on large-area silicon diodes, suggesting that polarization dependence arises due to the presence of the nanoscale fin. Plasmonic enhancement is proposed as a likely mechanism for the polarization effects due to the metal/dielectric interfaces in the fin region. The observed polarization dependence has ramifications for collection and interpretation of data acquired by pulsed laser testing. Device orientation of FinFETs and other nanoscale devices during pulsed laser testing should be considered in order to ensure consistent testing conditions and reproducible measurement results across multiple measurement campaigns.

Pulsed, laser-induced current transients in an SOI FinFET were measured as a function of device orientation relative to the optical polarization of the laser. Dependency on the device response is experimentally observed, demonstrating that device orientation impacts pulsed laser testing measurements. A systematic effect resulting from the measurement setup was ruled out, and the geometry and feature size of the device preclude a subwavelength grating-based optical response. Similar polarization measurements conducted on a large-area Si diode show no polarization dependence, confirming the role of the small feature size and radial asymmetries of a FinFET in the polarization dependence. Optical simulations were conducted to further examine the impact of incident laser polarization on the optical field distribution within a single fin. A plausible mechanism for the polarization-dependent transient current response is proposed based on the polarization dependence of SPPs, which affects the energy density available for charge generation in the fin region.

Based on this article, it can be predicted that this polarization dependence could be observed in nanoscale devices with metal/dielectric/metal interfaces near the active region of the device, such as in multigate transistors. Planar devices, due to lack of the metal/dielectric/metal interface and

asymmetries, would not be expected to exhibit polarization dependence. Indeed, optical simulations employing bulk materials to model planar devices have shown agreement with experiments [9], confirming that nanoscale optical processes are not dominating charge generation in planar devices. During pulsed laser testing of devices that could exhibit polarization dependence, the device orientation must be considered and documented to ensure robust and repeatable testing of devices that are not rotationally symmetric. Any adjustments of a given device or package between measurements, such as storage for multiday testing, or different orientations of similar devices to be compared, may result in testing under a different polarization configuration and a different measured device response. Due to the fundamental difference between energy deposition from light-matter interaction and heavy-ion collisions, such care with device orientation in the measurement setup is not necessary for heavy-ion testing. A device that exhibits such polarization dependence in pulsed laser testing will exhibit that dependence for any configuration of pulsed laser testing using wavelengths larger than the critical feature size of the device.

L. D. Ryder, R. D. Schrimpf, S. M. Weiss, R. A. Reed, K. L. Ryder, A. L. Sternberg, J. A. Kozub, H. Q. Gong, E. X. Zhang, D. Linten, J. Mitard and R. A. Weller, "Polarization dependence of pulsed laser-induced sees in soi finfets", IEEE Trans. on Nucl. Sci., vol.67, no.1, pp. 38-43, Jan 2020.

Comparison of Sensitive Volumes Associated With Ion- and Laser-Induced Charge Collection in an Epitaxial Silicon Diode

A sensitive volume is developed using pulsed laser induced collected charge for two bias conditions in an epitaxial silicon diode. These sensitive volumes show good agreement with the experimental two-photon absorption laser-induced collected charge at a variety of focal positions and pulse energies. When compared to ion-induced collected charge, the laser-based sensitive volume overpredicts the experimental collected charge at low bias and agrees at high bias. A sensitive volume based on ion-induced collected charge adequately describes the ion experimental results at both biases. Differences in the amount of potential modulation explain the differences between the ion and laser-based sensitive volumes at the lower bias. Truncation of potential modulation by the highly doped substrate, at the higher bias, results in similar sensitive volumes.

Ion- and pulsed laser-induced collected charge experiments were used to define sensitive volumes for an epilayer silicon diode at two bias conditions. The single laser-based sensitive volume describes the collected charge results from the laser experiments at multiple pulse energies and focal positions, whereas the laser-based sensitive volume agrees with ion experimental results only at biases when the device is fully depleted. When the device is not fully depleted, differences in potential modulation between the ion- and laser-induced charge cause the respective sensitive volumes to differ.

The differences in the sensitive volumes describing the ion- and laser-induced collected charges have implications for error rate calculations, one of the main uses for sensitive volumes. The ion- and laser-based sensitive volumes from -5 V were input to CRÈME96, and the laser-based sensitive volume results in an error rate that is over twice as large as the ion-based sensitive volume. By using the laser-based sensitive volume to predict ion-induced SEEs at -5 V results in an overprediction of collected charge and error rate, while at -90 V, the predictions agree with the experimental results.

Despite the differences in the ion- and laser-based sensitive volumes found here, a path forward for using pulsed laser-induced SEEs to predict heavy ion-induced SEEs is still possible. The type of analysis presented here, based on detailed electrical and optical simulations, provides a possible path toward a definition of physically informed sensitive volumes. Using the appropriate simulation tools for each of the charge deposition methods, an understanding of the particular physics that defines the sensitive volumes can be determined. By understanding the differences between the important physics for ion- and laser-induced SEEs, the sensitive volume model for one can be adjusted appropriately to the other. This is correlating simulation spaces and then using the appropriate simulation to predict SEEs, rather than trying to directly correlate experimental ion- and laser-induced SEEs. This process would be particularly useful for highly scaled devices. Light interacts with highly scaled devices and devices with metal-dielectric interfaces much differently than ions [23], which necessitate a greater understanding of the basic physics at play for both ion- and laser-induced SEEs.

K. L. Ryder, L. D. Ryder, A. L. Sternberg, J. A. Kozub, E. X. Zhang, A. Khachatrian, S. P. Buchner, D. P. McMorro, J. M. Hales, Y. Zhao, L. Wang, C. Wang, R. A. Weller, R. D. Schrimpf, S. M. Weiss, and R. A. Reed, "Comparison of Sensitive Volumes Associated With Ion- and Laser-Induced Charge Collection in an Epitaxial Silicon Diode," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 1, pp. 57-62, Jan, 2020.

Comparison of Single-Event Transients in an Epitaxial Silicon Diode Resulting from Heavy Ion-, Focused X-Ray-, and Pulsed Laser-Induced Charge Generation

Heavy ion, focused X-ray, and pulsed laser single event transient experiments are performed on a silicon epitaxial diode. Collected charge, transient rise times, and transient fall times are calculated and compared between the different sources. The transient shape characteristics depend on the source (ion, X-ray, or laser), even when similar amounts of charge are generated. The observed differences are examined and explained in terms of basic charge collection mechanisms.

SETs from heavy ions, pulsed lasers, and focused X-rays were examined as a function of charge generated within the diode's epitaxial layer. We observed that equivalent amounts of generated charge from the different SEE sources did not result in equivalent SET shapes. Even trends in SET shape with respect to bias or generated charge were different amongst the different sources, illustrating the effect different charge generation profiles have on the carrier transport mechanisms within our test structure. It is hypothesized that the observed discrepancies in SET shape are due to differences in the spatial and temporal distributions of the charge generation profiles, resulting in differing amounts of perturbations to the internal electric field and potential modulation.

This work demonstrates that the SET shapes from different sources are not inherently the same, even if similar amounts of charge are generated. Source-dependent SET shape characteristics means that direct comparisons between different charge-generation methods is difficult, re-enforcing the understanding that developing a universal, predictive correlation between them could prove unobtainable. It could, however, provide opportunities to develop worst-case experiments for tailored SEE characterization testing. As it stands, alternative SEE testing methods show promise for basic research and ad hoc correlations to heavy ion testing.

K. Ryder, L. Ryder, A. Sternberg, J. Kozub, E. Zhang, R. Weller, R. Schrimpf, S. Weiss, R. Reed, S. LaLumondiere, A. Khachatryan, S. Buchner, D. McMorrow, J. Hales, Y. Zhao, L. Wang, C. Wang, "Comparison of Single-Event Transients in an Epitaxial Silicon Diode Resulting from Heavy Ion-, Focused X-Ray-, and Pulsed Laser-Induced Charge Deposition," IEEE Trans. Nucl. Sci., Early Access Article, 2021

Laser and Ion Effects in Advanced Structures

Persistent Laser-Induced Leakage in a 20 nm Charge-Pump Phase-Locked Loop (PLL)

A persistent loss-of-lock error was experimentally observed in a 20 nm charge-pump phase-locked loop (PLL). Through circuit modeling and simulation, the observed error was attributed to a non-recoverable off-state leakage increase resulted from two-photon absorption (TPA) laser-induced damage. The laser-induced damage is consistent with results from 28 nm bulk transistors.

Laser-induced persistent loss-of-lock error is observed in a charge-pump PLL fabricated in a TSMC 20 nm bulk technology. Through circuit analysis and simulation, the persistent loss-of-lock error is identified as laser-induced off-state leakage in transistors in the differential amplifier of the digital LUSHIFT sub-circuit module. Laser experimental results on single transistors demonstrated the existence of laser-induced transistor damage in the same incidence laser energy range. These results may provide insight into similar types of errors that occur during TPA single-event characterization of devices and circuits in advanced technologies.

Y. P. Chen, T. D. Loveless, A. L. Sternberg, E. Zhang, J. S. Kauppila, B. L. Bhuvu, W. T. Holman, M. L. Alles, R. A. Reed, D. McMorrow, R. D. Schrimpf, and L. W. Massengill, "Persistent Laser-Induced Leakage in a 20 Nm Charge-Pump Phase-Locked Loop (PLL)," IEEE Trans. on Nucl. Sci., vol. 64, no 1, Jan., pp. 512-518, 2017.

Scaling Effects on Single-Event Transients in InGaAs FinFETs

The single-event-transient response of InGaAs FinFETs with different fin widths is examined using pulsed-laser and heavy-ion irradiation. Devices with wider fins collect more charge in both environments. Quantum-well structures confine charge collection in the channel, and determine the sensitive volume. Simulations show that the charge density produced by irradiation is similar for devices with different fin widths, but more charge is collected by wider fin devices due to the larger channel volume. Charge accumulated in the buffer and substrate layers modulates the body potential, altering the degree of backgate control, leading to additional effects associated with charge accumulation in wider fin devices. Optical simulations for a model system suggest that optical phenomena in the fins should be considered for laser testing. These include optical interference, plasmonic enhancement at the metal–dielectric interfaces, and enhanced electron–hole pair recombination due to multiple reflections in multigate devices with nanoscale dimensions.

This paper describes the SET response of InGaAs FinFETs with different fin widths. For both pulsed-laser irradiation and heavy-ion irradiation, wider fin devices collect more charge. The SETs exhibit similar drain bias dependence for both types of irradiation. Larger drain bias increases the electric field on the drain side, which produces higher peak drain current and more collected charge. The SET cross section also scales with fin width, and stronger scaling effects are observed for lower drain biases. The transient

tails overlap for all devices, which is due to similar charge collection in the substrate for all device widths. The SET dependence on ion LET is also reported. Ions with higher LET generate more electron-hole pairs in the channel, and thus higher peak drain current, more collected charge, and larger SET cross section.

The 3-D TCAD simulations show that the enhanced charge collection of the wider fin devices is mainly due to larger geometric volumes. Charge accumulated underneath the fin functions as a back gate, which produces stronger channel modulation effects for wider fin devices. Lumerical simulations on a simple model system are consistent with observed trends of laser-induced charge collection with fin width, and suggest that optical phenomena including plasmonic effects and enhanced e-h pair recombination due to multiple reflections within confined, multigate structures will play an increasingly important role for pulsed-laser-induced SET tests of advanced nanoelectronic technologies. These include emerging FinFETs and gate-all-around devices, and thus is an important consideration in testing of nanoscale devices.

H. Q. Gong, K. Ni, E. X. Zhang, A. L. Sternberg, J. A. Kozub, K. L. Ryder, R. F. Keller, L. D. Ryder, S. M. Weiss, R. A. Weller, M. L. Alles, R. A. Reed, D. M. Fleetwood, R. D. Schrimpf, A. Vardi and J. A. del Alamo, "Scaling effects on single-event transients in ingaas finfets", IEEE Trans. on Nucl. Sci., vol.65, no.1, pp. 296-303, Jan 2018.

Laser-Induced Single-Event Transients in Black Phosphorus MOSFETs

Laser-induced single-event transients (SETs) are observed in black phosphorus (BP) MOSFETs. The SETs are relatively small, which is consistent with expectations for thinfilm fully depleted transistors. The position dependence and the bias-dependence of the measured SETs in BP transistors are investigated to study the charge collection mechanisms. The peak drain current is maximized when the pulsed-laser strikes at the center of the channel region. The amplitudes of the SETs are also relatively independent of the overdrive voltage. The drain-to-source SET current increases when $|V_{DS}|$ increases, due to a shunt effect.

We have evaluated the pulsed-laser radiation response of HfO₂-passivated BP transistors. SETs are observed when the laser pulse is incident on the channel. Given the geometry of the BP devices, as well as the small magnitude and short pulse duration of the transient, we expect these effects to be less severe than those observed in conventional planar MOSFETs. This results from the relatively thin channel material. The SET peak value is maximum when the laser is incident on the center of the channel. The peak of the laser-induced SETs does not significantly depend on the overdrive voltage, but it is proportional to the drain-to-source bias in both the n-type and p-type conduction regions, which can be explained by the laser-shunt effect.

With the development of BP technology, it is expected that the collected charge will decrease when the thickness of the channel material scales down (becoming closer to a true 2-D layer), but the dependence on position and bias will likely be consistent with the results discussed earlier. We expect the results of this paper to be similarly helpful in the development of future BP-based devices and integrated-circuit technologies.

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Pulsed-Laser Induced Single-Event Transients in InGaAs FinFETs on Bulk Silicon Substrates

The pulsed-laser single-event transient response of InGaAs FinFETs on bulk silicon substrates is investigated. Charge collection due to a source–drain shunt effect and drain-to-substrate junction charge collection contribute to the observed transients. The transient response of these silicon substrate devices is compared to that of InGaAs FinFETs on semiinsulating substrates. Faster transients with reduced peak currents and peak widths are observed on the silicon substrate devices. Simulations show hole collection by the silicon substrate. This reduces the amount of source-barrier lowering and bipolar-amplification relative to other III–V devices. Moreover, the reduced hole lifetime in the GaAs buffer layer also contributes to the relative reduction of the bipolar amplification in these devices.

Both channel and junction charge collections are shown to contribute to the pulsed-laser induced SET response of InGaAs FinFETs on silicon substrates. The channel current results from a transient source–drain shunt and parasitic bipolar amplification. The transient response is not controlled by the gate due to the 3-D FinFET structure. The InGaAs FinFETs on silicon substrates show lower peak current and narrower FWHM compared with InGaAs FinFETs on InP substrates. TCAD simulations show that holes are efficiently collected by the substrate contact due to lack of confinement in the channel. Furthermore, the semi-insulating GaAs buffer layer reduces the hole lifetime, thereby reducing the hole density underneath the channel. The reduced hole accumulation in the channel eliminates source barrier lowering and bipolar amplification effects typically seen in other III–V devices, further reducing SET sensitivity. This makes InGaAs FinFETs in Si substrates an attractive candidate for future high-mobility nMOSFET technologies.

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Enhanced Charge Collection in SiC Power MOSFETs Demonstrated by Pulse-Laser Two-Photon Absorption SEE Experiments

A two-photon absorption technique is used to understand the mechanisms of single-event effects (SEEs) in silicon carbide power metal–oxide–field-effect transistors (MOSFETs) and power junction barrier Schottky diodes. The MOSFETs and diodes have similar structures enabling the identification of effects associated specifically with the parasitic bipolar structure that is present in the MOSFETs, but not the diodes. The collected charge in the diodes varies only with laser depth, whereas it varies with depth and lateral position in the MOSFETs. Optical simulations demonstrate that the variations in collected charge observed are from the semiconductor device structure and not from metal/passivation-induced

reflection. The difference in the spatial dependence of collected charge between the MOSFET and diode is explained by bipolar amplification of the charge carriers in the MOSFETs. Technology computer-aided design (TCAD) device simulations extend this analysis to heavy ion- induced charge collection. In addition, there is discussion comparing this analysis with experimental results from prior works that show enhanced charge collection resulting from heavy ion irradiation.

Two-photon backside laser testing has been used to identify the source of bias-dependent charge collection amplification with localized ionization in SiC power MOSFETs and SiC power diodes. Peaks in charge collection were seen with the movement of the laser focus between power MOSFET cells at a fixed depth. These peaks are not observed in similar measurements on SiC power diodes. Comparing the different responses of the diode and MOSFET, it is observed that when the laser is focused on the neck region of a MOSFET cell, the greatest charge collection occurs. This agrees with prior simulated results. The charge collection increases as the bias voltage increases, supporting results seen in earlier work using heavy ions. We conclude that the parasitic bipolar amplification inherent in the vertical SiC power MOSFET structure is the cause of these phenomena and is an important mechanism when SEB is observed in these devices.

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Single Event Transient Response of Vertical and Lateral Waveguide-Integrated Germanium Photodiodes

Pulsed-laser induced single event current measurements on two geometries of waveguide-integrated germanium photodiodes were conducted over a range of operating voltages to examine the impact of photodiode geometry on the transient response. Vertical PIN photodiodes exhibit transients with a duration that is relatively independent of the operating voltage while the transient duration in lateral PIN photodiodes depends on operating voltage. Furthermore, the experimental measurements facilitate identification of device dimensions that impact the transient response. These results can be used to identify potential radiation mitigation strategies for photodiodes operating in a radiation environment. Understanding the implications of design choices is critical for designing integrated photonic systems that balance system performance with tolerance for radiation degradation.

In this work, the pulsed-laser induced SET response of waveguide-integrated germanium photodiodes was experimentally examined for two common geometries – vertical PIN junctions and lateral PIN junctions – under different bias and pulse energy conditions. The SETs of VPIN devices exhibited a voltage-independent temporal duration that was consistently smaller than transients collected from LPIN devices at the same pulse energies. Moreover, the SETs of LPIN devices exhibited a voltage-dependent temporal duration. As the temporal response of photodiodes is dominated by the transit of carriers across the junction, design choices that impact the transit time of carriers by either changing the distance that carriers must cross or the speed at which they can drift have a significant impact on device performance. Charge transport simulations suggest that the voltage-dependent temporal response of

the LPIN devices is associated with electric field amplitudes that directly affect carrier velocity. The impact of device geometry on the transients can be related to the impact that design parameters have on the performance metrics of a device operating under more typical terrestrial conditions. Similar to other SET susceptible devices, radiation tolerance of the device depends on the system response to the injected transient and the operating environment of the device, such as temperature. Relating the radiation response of the photodiode to its geometry is critical for evaluating the impact of a design decision not only on traditional performance metrics but also on the radiation tolerance to ensure the reliability of integrated photonic systems in radiation environments.

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Single-Event-Induced Charge Collection in Ge-Channel pMOS FinFETs

Peak transient currents due to pulsed-laser or heavy-ion irradiation of Ge pMOS FinFETs are nearly independent of gate bias. This is because the prompt photocurrent is due primarily to a transient source-drain shunt. In contrast, longer-term diffusion charge collection is strongly gate-bias dependent. This bias dependence results from hole injection from the source in response to the transient increase in electron concentration in the channel. The transients measured at the source terminal change polarity when the strike location moves from source to drain, but this effect does not occur for the transients measured at the drain terminal. Charge collection mechanisms are studied using TCAD simulations.

Single-event charge collection behavior in Ge-channel p-type FinFETs depends strongly upon gate bias, as well as on heavy ion or pulsed-laser strike location. The "fast" portion of the transient signal is due to a transient source-drain shunt effect. Hence, the peak transient current is nearly independent of gate bias. After the drift current in the channel is "quenched" by the gate, increased charge collection comes only from the slower tail of the transient. As a result, the total collected charge changes dramatically with gate bias. Unlike SiGe pFinFETs and planar Ge devices in previous studies, the change in polarity of transient current that occurs when the strike location moves from source to drain is observed only for source transients in this ultrathin quantum well device, and not for drain transients. The differences between the charge collection on the Ge pMOS FinFETs in this work and that of previous work on planar SiGe and Ge pMOS devices are due primarily to the significant improvement of gate control of Ge-FinFETs over planar devices.

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Laser Pulse to Current Transient: Simulation of Pulsed Laser-Induced Testing in Microelectronic Devices

A method to carry out a priori simulations of PL-SEE experiments is reported. Nonlinear optical simulations are conducted to model three-dimensional distributions of charge from a laser pulse. These pulsed laser-induced charge distributions are then incorporated into a charge transport solver to model the movement of charge as the device returns to a steady state. The output of the simulation

infrastructure is a current transient from which collected charge and the temporal characteristics of the transient can be determined. This complete approach to modelling, which includes full device structure information, nonlinear optical energy deposition and the subsequent movement of optically generated charge in a device, allows for direct comparison between experimental and simulated current transients. A large area silicon diode was used as the test vehicle, and good agreement was found between simulations and experiments in both total injected charge as well as temporal characteristics. Importantly, the a priori simulation approach does not require knowledge from prior heavy ion testing, making it a predictive tool with broad versatility and minimal reliance on approximations.

In this work, we report a laser pulse-to-transient simulation infrastructure (LPTSI) that makes use of first-principles nonlinear optical simulations to calculate 3-D spatial distributions of optically generated carriers that are then incorporated into a charge transport solver to simulate the transient response of a device under test. This simulation approach not only minimizes reliance on approximations, but also allows for simulation of the temporal component of the device response, which was not possible with earlier simulation techniques. A large area epitaxial silicon diode was used as a test structure for demonstrating LPTSI, with simulation results showing good agreement with experiments in a variety of testing conditions. This agreement between simulation and experimental results validates LPTSI as a predictive tool for simulating PL-SEE measurements. As the minimum feature size of semiconductor devices continues to decrease and the materials stack complexity continues to increase, continued development of versatile, quantitative simulation approaches that can incorporate arbitrary device configurations and material constituents is critical for maintaining PL-SEE testing as a valuable testing technique that augments traditional SEE testing techniques.

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What opportunities for training and professional development has the project provided?

If the research is not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report." Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

2017:

Robert Reed, Ron Schrimpf, and Mike Alles attended the 2016 Nuclear and Space Radiation Effects Conference and Short Course. Robert was the general chair.

Robert Reed attended at 2017 GOMAC.

Robert Reed and Ron Schrimpf attended 2016 Radiation Effects on Components and Systems Conference and Short Course.

Robert Reed attended the Geant4 Space Users Workshop.

2018

Professors E. X. Zhang, R. A. Reed, R. D. Schrimpf, and student J. Trippe attended the 2017 Radiation Effects Short Course at the Nuclear and Space Radiation Effects Conference.

2019

Professors E. X. Zhang, R. A. Reed, R. D. Schrimpf, and student J. Trippe attended the 2018 Radiation Effects Short Course at the Nuclear and Space Radiation Effects Conference.

2020

Professors E. X. Zhang, R. A. Reed, R. D. Schrimpf, and student K. Ryder and L. Ryder attended the 2019 Radiation Effects Short Course at the Nuclear and Space Radiation Effects Conference.

2021

Professors E. X. Zhang, R. A. Reed, R. D. Schrimpf, and student K. Ryder and L. Ryder attended the 2019 Radiation Effects Short Course at the Nuclear and Space Radiation Effects Conference.

How have the results been disseminated to communities of interest?

If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

The entries below were either directly or indirectly support by this program.

Publications

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Manuscripts in review

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Invited Talks

- [1] R. A. Reed, "Modeling and Simulation of Single Event Effects," Presented to the National Academies of Sciences, Engineering, and Medicine Committee on Space Radiation Effects Testing Infrastructure for the U.S Space Program, Washington DC, March 29—31, 2017.
- [2] R. A. Reed, R. A. Weller, J. M. Trippe, S. L. Weeden-Wright, E. D. Funkhouser, C. N. Arutt, R. D. Schrimpf, B. D. Sierawski, K. M. Warren, L. W. Massengill, D. M. Fleetwood, M. L. Alles, E. X. Zhang, and M. Asai, "Applications of MRED (Monte Carlo Radiative Energy Deposition)," 12th GEANT4 Space Users Workshop, Guildford, UK, April 10-12, 2017.
- [3] R. A. Reed, R. A. Weller, R. D. Schrimpf, J. Fang, M. Reaz, S. T. Pantelides, Makoto Asai, S. L. Weeden-Wright, M. V. Fischetti, "Monte Carlo Transport of Low Energy Electrons," 13th GEANT4 Space Users Workshop, Houston, TX, Nov. 28-30, 2018.

Professional presentations

Presentations at IEEE Conferences on Nuclear and Space Radiation Effects, New Orleans, LA, July 17-21, 2017

- [1] R. Jiang, E. X. Zhang, S. M. Zhao, D. M. Fleetwood, R. D. Schrimpf, R. A. Reed, M. L. Alles, J. C. Shank, B. Tellekamp, and W. A. Doolittle, "Total-ionizing-dose response of Nb2O5-based MIM diodes for neuromorphic computing applications."
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- [4] P. Wang, A. L. Sternberg, J. A. Kozub, E. X. Zhang, D. M. Fleetwood, R. A. Reed, R. D. Schrimpf, N. A. Dodds, and S. L. Jordan, "Using two-photon absorption to measure the single-event-latchup sensitive-volume."
- [5] H. Gong, K. Ni, E. X. Zhang, A. L. Sternberg, J. A. Kozub, K. L. Ryder, R. F. Keller, M. L. Alles, R. A. Reed, D. M. Fleetwood, R. D. Schrimpf, A. Vardy, X. Cai, and J. A. del Alamo, "Scaling effects on single-event transients in InGaAs FinFETs."
- [6] C. N. Arutt, W. Liao, H. Gong, M. L. Alles, J. L. Davidson, E. X. Zhang, A. L. Sternberg, D. M. Fleetwood, R. A. Reed, R. D. Schrimpf, P. D. Shurva, J.-T. Lin, B. W. Alphenaar, K. M. Walsh, and S. McNamara, "Dose-rate effects on the total ionizing dose response of piezoresistive micromachined cantilevers."
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- [10] J. T. Howard, E. J. Barth, R. D. Schrimpf, R. A. Reed, L. C. Adams, D. Vibbert and A. F. Witulski, "Methodology for identifying radiation effects in robotic systems with mechanical and control performance variations."

- [11] J. D. Black, J. A. Dame, D. A. Black, P. E. Dodd, M. R. Shaneyfelt, J. Teifel, J. G. Salas, R. Steinbach, M. Davis, R. A. Reed, R. A. Weller, J. M. Trippe, K. M. Warren, A. M. Tonigan, R. D. Schrimpf and R. S. Marquez, "Using MRED to screen multiple-node charge-collection mitigated soi layouts."
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- [14] C. Liang, R. Ma, K. Li, Y. Su, H. Gong, K. L. Ryder, P. Wang, A. L. Sternberg, E. X. Zhang, M. L. Alles, R. A. Reed, S. J. Koester, D. M. Fleetwood and R. D. Schrimpf, "Laser-induced single-event transients in black phosphorus mosfets."
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- [30] M. Rony, E. Zhang, M. Reaz, K. Li, R. Reed, J. Kauppila, A. Witulski, R. Schrimpf, B. Rax, A. Daniel, P. Adell, "An Ionizing-Dose-Aware Behavioral Model of a Successive-Approximation Analog to Digital Converter,"
- [31] E. Wilcox, M. Casey, J. Pellish, M. Breeding, R. Reed, R. Schrimpf, M. Alles, "Observation of Low-Energy Proton Direct Ionization in a 72-Layer 3D NAND Flash Memory,"
- [32] M. Rony, I. Samsel, E. Zhang, A. Sternberg, M. Reaz, S. Austin, R. Reed, D. Fleetwood, M. Alles, J. Mitard, R. Schrimpf, K. Li, D. Linten, "Single-Event-Induced Charge Collection in Ge-Channel pMOS FinFETs,"
- [33] M. Casey, J. Pellish, NASA GSFC, USA, S. Stansberry, Science Systems and Applications, Inc., USA, M. Breeding, R. Reed, Vanderbilt University, USA, "E-4 Direct Ionization from Low-Energy Electrons in a Highly-Scaled CMOS Process,"
- [34] R. Austin, K. Ryder, B. Sierawski, R. Reed, R. Schrimpf, N. Mahadevan, G. Karsai, A. Witulski, "Quantification of Fault Consequences to Track and Mitigate Risk in a CubeSat Experiment Using Model-Based Systems Analysis,"

Other Contributed Talks

- [35] J. Kauppila, K. Warren, R. Weller, M. Mendenhall, R. A. Reed, R. Schrimpf, L. W. Massengill, A. L. Amort, and M. F. Cabanas-Holmen, "Analyzing Single Event Effects with Monte Carlo Radiation Transport and Electronic Design Automation Tools," Hardened Electronics And Radiation Technology Conference (HEART), Denver, CO, April 24-28, 2017. **(Outstanding Conference Paper Award)**
- [36] P. F. Wang, E. X. Zhang, K. H. Chuang, W. Liao, H. Gong, P. Wang, C. N. Arutt, K. Ni, M. W. McCurdy, I. Verbaauwhede, E. Bury, D. Linten, D. M. Fleetwood, R. D. Schrimpf, and R. A. Reed, "X-ray and proton

- radiation effects on 40 nm CMOS physically unclonable function devices," Radiation Effects on Electronic Components and Systems (RADECS) 2017, Geneva, Switzerland, Oct. 2-6, 2017.
- [37] R. A. Austin, B. D. Sierawski, J. M. Trippe, A. L. Sternberg, K. M. Warren, R. A. Reed, R. A. Weller, R. D. Schrimpf, M. L. Alles, L. W. Massengill, D. M. Fleetwood, G. W. Buxton, III, J. C. Brandenburg, W. B. Fisher, and R. Davis, "RadFxSat: A flight campaign for recording single-event effects in commercial off-the-shelf microelectronics," RADECS 2017, Geneva, Switzerland, Oct. 2-6, 2017.
 - [38] R. Reed, R. Weller, S. Weiss, J. Kozub, A. Sternberg, R. Schrimpf, L. Ryder, K. Ryder, I. Samsel, W. Donaldson, and L. Wang, "Correlation of Laser- and Ion-Induced Effects on Emerging Technologies," Government Microcircuit and Applications Conference (GOMAC), Reno, NV, March 20-23, 2017.
 - [39] B. D. Sierawski, R. A. Reed, K. M. Warren, A. L. Sternberg, R. A. Austin, J. M. Trippe, R. A. Weller, M. L. Alles, R. D. Schrimpf, L. W. Massengill, D. M. Fleetwood, G. W. Buxton, III, J. C. Brandenburg, W. B. Fisher, and R. Davis, "CubeSat: Real-time soft error measurements at low earth orbits," , IEEE Intl. Reliability Physics Sympos., Monterey, CA, April 2-6, 2017.
 - [40] A. Sternberg, R. A. Reed, R. D. Schrimpf, P. Wang, and J. Kozub "Using Pulsed Lasers as a Diagnostic Tool for Radiation-Induced Single-Event Latchup," Small Satellite Conference, Logan Utah, August 5-10, 2017.
 - [41] S. E. Zhao, R. Jiang, H. Gong, P. Wang, E. X. Zhang, N. Waldron, B. Kunert, J. Mitard, N. Collaert, S. Sioncke, D. Linten, R. D. Schrimpf, R. A. Reed, and D. M. Fleetwood, "Gate bias and length dependences of total-ionizing-dose effects in InGaAs FinFETs on bulk Si," RADECS 2018, Gothenburg, Sweden, Sept. 17-21, 2018.
 - [42] W. Liao, M. L. Alles, E. X. Zhang, D. M. Fleetwood, R. A. Reed, R. A. Weller, and R. D. Schrimpf, "Monte Carlo simulation of displacement damage in graphene," RADECS 2018, Gothenburg, Sweden, Sept. 17-21, 2018.
 - [43] R. Johnson, A. Witulski, D. Ball, K. Galloway, A. Sternberg, E. Zhang, R. Reed, R. Schrimpf, J. M. Lauenstein, A. Javanainen, "Parasitic Bipolar Action in SiC Power MOSFETs Demonstrated by Two-Photon Laser Experiment," RADECS 2018, Gothenburg, Sweden, Sept. 17-21, 2018.
 - [44] L. Adams, W. Arthur, E. Barth, R. Reed, J. Howard, R. Peters, R. Schrimpf, "Machine Learning Techniques for Mitigating Sensor Ionizing Dose Failures in Robotic Systems," RADECS 2018, Gothenburg, Sweden, Sept. 17-21, 2018.
 - [45] Rebekah Austin, Brian Sierawski, Robert Reed, James Trippe, Kevin Warren, Andrew Sternberg, Robert Weller, Arthur Witulski, "Mitigation of Single-Event Effects in CubeSat Commercial Off-the-Shelf Components," Government Microcircuit and Applications Conference (GOMAC), Miami, FL, March 12-15, 2018
 - [46] K.F. Galloway, A. F. Witulski, R. D. Schrimpf, A.L. Sternberg, D.R. Ball, A. Javanainen, R. A. Reed, B.D. Sierawski, and J-M. Lauenstein, "Failure Estimates for SiC Power MOSFETs in Space Electronics," Hardened Electronics And Radiation Technology Conference (HEART), Tucson, AZ, April 18-20, 2018.
 - [47] Brian D Sierawski, Rebekah A Austin, James M Trippe, Kevin M Warren, Andrew L Sternberg, Robert A Reed, Robert A Weller, Eric Skoog, Gerald W Buxton III, W Burns Fisher, Robert Davis, Christopher E Thompson, "The RadFxSat Mission to Study Radiation Effects on Advanced Nanoelectronics," Small Satellite Presentation, Logan, UT, Aug. 2019.
 - [48] Rebekah Austin, BD Sierawski, AF Witulski, RD Schrimpf, RA Reed, G Karsai, N Mahadevan, "Effective Small-Satellite Radiation Assurance for Non-Specialists", Small Satellite Poster, Logan, UT, Aug. 2019.
 - [49] A. Witulski, B. Sierawski, R. Austin, G. Karsai, N. Mahadevan, R. Reed, R. Schrimpf, "Model-Based Radiation Assurance for Satellites with Commercial Parts," NASA NEPP Electronics Technology Workshop, Greenbelt, MD, Jun., 2019.
 - [50] K. L. Ryder, L. D. Ryder, A. L. Sternberg, J. A. Kozuba, E. X. Zhang, B. D. Sierawski, A. Khachatryan, S. P. Buchner, D. P. McMorro, J M. Hales, Y. Zhao, L. Wang, C. Wang, R. A. Weller, S. M. Weiss, R. D. Schrimpf, and R. A. Reed, "Correlation of Sensitive Volumes

- Associated with Ion- and Laser-Induced Charge Collection in an Epitaxial Silicon Diode," Single Event Effects Symposium, La Jolla, CA, May, 2019.
- [51] J. Adams, J. Fisher, J. Nonnast, Z. Robinson, R. Reed, K. Warren, B. Sierawski, "Space Ionizing Radiation Environment and Effects (SIRE2) Model for Satellite Design," Applied Space Environments Conference, Los Angeles, CA, May, 2019.
 - [52] A. Raman, D. Howe, S. Miller, D. Falconer, I. Khazanov, G. Li, K. Warren, B. Sierawski, R. Reed, S. Fu, "Novel Software Application to Forecast Solar Events and their Effects," Applied Space Environments Conference, Los Angeles, CA, May, 2019.
 - [53] B. D. Sierawski, T. D. Haeffner, M. W. McCurdy, E. X. Zhang, R. F. Keller, M. L. Alles, R. A. Reed, "Single Event Transients in FinFETs at Low Temperature," Single Event Effects Symposium, La Jolla, CA, May, 2019.
 - [54] R. Austin, "Capturing and Modeling Radiation Hardness Assurance Throughout the Project," Single Event Effects Symposium, La Jolla, CA, May, 2019.
 - [55] S. Miller, A. Raman, D. Howe, D. Falconer, I. Khazanov, G. Li, S. Fu, K. Warren, B. Sierawski, R. Reed, M. Hindi, "Novel Software Application to Forecast Solar Events and their Effects," Space Weather Workshop, Boulder, CO, Apr. 2019.
 - [56] RA Austin, RD Schrimpf, AF Witulski, N Mahadevan, G Karsai, BD Sierawski, RA Reed, Capturing and Modeling Radiation Hardness Assurance throughout the Project Lifecycle, Microelectronics Reliability and Qualification Workshop (MRQW), Los Angeles, CA, 2019.
 - [57] R. A. Reed, R. D. Schrimpf, E. X. Zhang, D. M. Fleetwood, M. L. Alles, A. L. Sternberg, J. A. Kozub, H. Gong, K. Ni, I. K. Samsel, "Radiation-Induced Transients in Advanced Devices," MRQW, Los Angeles, CA, 2019.
 - [58] M.L. Breeding, R.A. Reed, K.M. Warren, and M.L. Alles, "Radiation Effects in 3D Integrated Systems: A Monte Carlo Analysis of Metallic Layers," Presented at the 2019 Government Microcircuit Applications & Critical Technology (GOMACTech) Conference, Albuquerque, NM, March 2019.
 - [59] M.L. Breeding, R.A. Reed, K.M. Warren, and M.L. Alles, "Exploration of the Impact of Physical Integration Schemes on Soft Errors in 3D ICs Using Monte Carlo Simulation," Presented at the International Reliability Physics Symposium (IRPS) Conference, Monterey, CA, April 2019.
 - [60] D. M. Fleetwood, E. X. Zhang, C. D. Liang, P. Wang, C. X. Zhang, R. D. Schrimpf, M. L. Alles, R. A. Reed, A. O'Hara, S. T. Pantelides, Y. Su, R. Ma, and S. Koester, "Radiation Effects on MOS Devices Based on 2D Materials," Chongqing, China on May 29-31. 2019.
 - [61] K. Li, E. Zhang, S. Bonaldo, A. Sternberg, J. Kozub, M. Reaz, L. Ryder, K. Ryder, H. Gong, S. Weiss, R. Weller, A. Vardi, J. Alamo, R. Reed, D. Fleetwood, R. Schrimpf, "Pulsed Laser-Induced Single-Event Transients in InGaAs FinFETs with Sub-10-nm Fin Widths," Radiation and Its Effects on Components and Systems (RADECS), September 16-20, 2019.
 - [62] S. Bonaldo, E. Zhang, S. Zhao, V. Putcha, B. Parvais, D. Linten, S. Gerardin, A. Paccagnella, R. Reed, R. Schrimpf, D. Fleetwood, "Total-ionizing-dose Effects in InGaAs MOSFETs with High-k Gate Dielectrics and InP Substrates," RADECS, September 16-20, 2019.

What do you plan to do during the next reporting period to accomplish the goals?

If there are no changes to the agency-approved application or plan for this effort, state "No Change." Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

Project has ended.