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Emulating Interaction of Charged-Particle Radiation with Semiconductor Devices Using Non-Linear Optical Processes

DR. ADRIAN IIDEFONSO, PH.D

Photophysics and Radiation Effects Section
Electronics Science and Technology Division

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This report describes the research conducted conducted by Dr. Adrian Ildefonso (Code 6816) during his Jerome and Isabella Karle Distinguished Scholar Fellowship from Oct 2020 to Oct 2022. This research effort aims to utilize non-linear optical processes to emulate the interaction of charged-particle radiation with semiconductor devices. The results from this work have made significant contributions to the understanding of the charge generation process via non-linear optical processes and the subsequent charge collection that occurs in semiconductor devices. This improved understanding is a necessary step toward developing predictive laser-based approaches to characterize the susceptibility of microelectronics to ionizing radiation in space. These new tools will contribute to the rapid development and deployment of robust electronic systems for space assets.

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

This report describes the research conducted by Dr. Adrian Ildefonso (Code 6816) during his Jerome and Isabella Karle Distinguished Scholar Fellowship from Oct 2020 to Oct 2022. This research effort aims to utilize non-linear optical processes to emulate the interaction of charged-particle radiation with semiconductor devices.

The abundance of charged-particle or ionizing radiation in space poses a threat for the reliable operation of electronic systems in spacecraft. Satellite surveillance and communication systems are essential assets for the DoD. Ensuring the robust operation of these systems in such an extreme operating environment is a key interest that can be partly accomplished by assessing resilience of electronic components when operating in the presence of charged-particle radiation. This process is accomplished on the ground via expensive characterization at particle accelerators that can produce high levels of charged-particle radiation for accelerated testing. An attractive alternative is to use optical processes to emulate the effects produced by these charged particles when they traverse certain regions of semiconductor devices used to build electronic systems for space. The goal of this research program was to understanding charge generation and collection processes initiated by optical sources in order to tailor them to accurately emulate and predict the effects produced by charged particles.

This report covers various results of experiments performed to study the charge deposition and collection processes in semiconductor devices and circuits using pulsed lasers to generate charge via non-linear optical processes. Some of the data acquired using a pulsed laser are compared to data acquired at a particle accelerator, and the sources of discrepancy are discussed. A brief description of the improvements to the dosimetry of the laser facility is included in the report, which were necessary to complete the present work.

The results from this work have made significant contributions to the understanding of the charge generation events induced via non-linear optical processes and the subsequent charge collection that occurs in semiconductor devices. This improved understanding is a necessary step toward developing predictive laser-based approaches to characterize the susceptibility of microelectronics to ionizing radiation in space. These new tools will contribute to the rapid development and deployment of robust electronic systems for space assets.

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EMULATING INTERACTION OF CHARGED-PARTICLE RADIATION WITH SEMICONDUCTOR DEVICES USING NON-LINEAR OPTICAL PROCESSES

1. INTRODUCTION

Satellite surveillance and communication systems are essential assets for the DoD, and ensuring the resiliency of these electronic systems is a key interest. However, outer space is considered an “extreme environment” for electronics, partly due to the particle radiation to which they are exposed during the course of a mission. Exposure to radiation can lead to two main categories of issues in electronic systems. The first is a result of cumulative exposure to radiation, where the performance of a given electronic system can degrade over time, potentially resulting in loss of operation. The second category is known as single-event effects (SEEs), which is an umbrella term for events resulting from a single particle strike that traverses electronic components, depositing energy along its path. This event can lead to current and voltage “glitches” that can propagate through the electronic system and result in undesirable effects for spacecraft operation, including catastrophic or destructive failure. The current research program is concerned with addressing the latter.

One way to ensure that electronic systems survive radiation in space is by thoroughly characterizing their SEE response using specialized facilities on the ground, typically a particle accelerator, to emulate the space radiation environment. The increasing demand for these efforts, partly propelled by the rise of the commercial space sector, has generated a bottleneck on the path to producing state-of-the-art, robust space systems in a timely manner. To alleviate this bottleneck, the use of optical sources as a means to emulate the effects of ionizing radiation has been proposed.

Optical charge generation approaches that utilize lasers to emulate the effects of cosmic radiation possess a number of benefits that could help alleviate this bottleneck: well-defined spatial and temporal interrogation, high throughput testing, and accessibility. The spatial selectivity of laser-based SEE techniques has enabled various applications including: 1) the identification and mapping of areas sensitive to radiation in a microelectronic device, 2) the verification of strategies to mitigate SEEs, 3) the study of basic mechanisms for charge generation and collection, and 4) the evaluation of complex circuit architectures with rare error signatures [1]. Importantly, accessibility to laser-based approaches has increased significantly over the past decade as more facilities have come online and commercial systems have been developed.

However, the results from laser-based approaches to date have been largely qualitative in nature. To support Navy and DoD qualification needs for space and strategic missions, laser-based approaches must evolve to become predictive of the SEE signatures induced by cosmic radiation. The critical barrier for this next step is that the SEE response of semiconductor devices and circuits is strongly dependent on the optical parameters that affect the charge generation profile. Identifying the optimal set of parameters that can best emulate cosmic radiation is a highly complicated problem because of 1) the intrinsic differences between the charge generation profiles for the two approaches, 2) the projection of these charge distributions on the wide range of possible semiconductor device structures (which differ for various applications), and 3) the unique responses of the various device types to the lateral and longitudinal aspects of the deposited charge.

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Thus, before laser-based approaches can be utilized to support the development of robust spacecraft for DoD applications, a fundamental understanding of how to optimize charge-generation parameters to predict the effects of charged-particle radiation in semiconductor devices is required.

This work proposed to improve the current understanding of charge deposition and collection resulting from non-linear optical processes with the goal of emulating the interaction of charged particle radiation with semiconductor devices used to build electronics systems for space. For this purpose, several areas need to be addressed including accurate laser pulse characterization and dosimetry, quantitative understanding of the charge deposition process from pulsed lasers, improved understanding of the effects of the pulsed characteristics (e.g., shape, energy, wavelength) on charge collection mechanisms, and understanding differences between charge collection at the device and circuit level.

This report includes results from this research effort and is organized as follows: Section 2 includes a high level overview of a laser-based SEE test setup, with experimental results provided in Section 3, followed by a brief summary. The various appendices include a comprehensive list of awards, publications and presentations produced during the period of performance of this effort.

The results from this work have made significant contributions to the understanding of the charge generation process via non-linear optical processes and the subsequent charge collection that occurs in semiconductor devices. This improved understanding is a necessary step in the path toward developing predictive laser-based SEE approaches that will contribute to the rapid development and deployment of robust electronic systems for space assets.

2. EXPERIMENTAL SETUP

2.1 Laser Setup Description

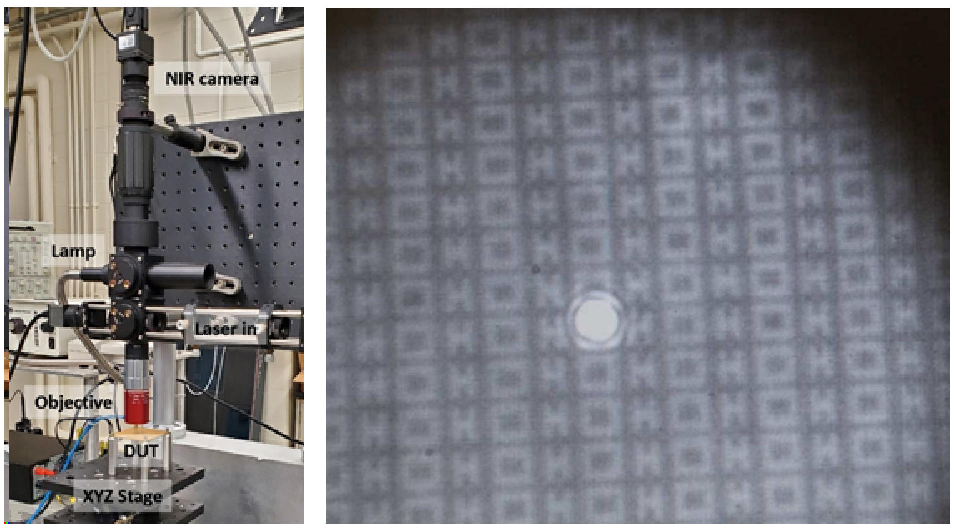
The Ultra-fast Laser Laboratory (Code 6816) at the U.S. Naval Research Laboratory (NRL) has the capabilities to perform SEE testing using a pulsed laser (PL) setup. In PL SEE testing, charge can be induced in a semiconductor via single-photon absorption (SPA) or two-photon absorption (TPA), depending on the type of material and the laser wavelength [1]. The lab has different experimental setups to support both mechanisms of charge generation. This description focuses specifically on the setup designed for TPA experiments in silicon. Other capabilities in this lab have been described elsewhere [2].

The laser system outputs pulses centered at a wavelength of 1260 nm. Each pulse has a duration of 150 fs (measured as full-width at half-maximum, FWHM) with a fixed repetition rate of 1 kHz. The laser pulse energy is tunable from 1 pJ to 20 nJ. Several microscope objectives with various levels of magnification are available for testing. The focused spot size of the beam incident on the device under test (DUT) will depend on the objective used. Typically, a 100x objective is used for testing as it provides the smallest focused spot size. Table 1 includes a complete list of available objectives.

The beam delivery arm, shown in Fig. 1 allows for imaging the DUT while simultaneously delivering and focusing the laser beam at a given position in the DUT. This configuration allows the user to co-locate the focused beam (bright spot in Fig. 1b) with a specific position of the DUT in real time.

Table 1—List of Available Microscope Objectives

Magnification	Working Distance (mm)	Typical Focused Spot Size (μm FWHM)
100x	12	1.1
50x	17	1.5
20x	20	4.4
10x	30.5	8.7
5x	37.5	17.5



(a) (b)

Fig. 1—(a) Current physical setup for imaging the DUT and delivering the pulsed laser at NRL. (b) Photograph of a 1-Mbit Sandia SOI SRAM taken by PL-SEE microscope. The bright white circle is the laser spot as it shows in the camera.

2.2 Improvements to Dosimetry and Experimental Capabilities

The first requirement for understanding charge deposition processes from pulsed-laser testing is accurate and repeatable characterization methods for the various laser pulse characteristics. The main parameters responsible for the charge distribution profile generated in a semiconductor are the wavelength, laser pulse energy, pulse duration, and focused spot size. These are routinely characterized and a detailed description of the dosimetry procedures implemented for this system have been described elsewhere [3, 4]. Several improvements in characterization and dosimetry techniques have been made in recent years. During this program, the laser beam line was re-designed to both improve the day-to-day beam stability and to streamline laser pulse characterization. This new beam line also allows for additional components, such as a variable beam expander, which will allow for custom tailoring of the beam focusing. A Grenouille pulse measurement unit from Swamp Optics was also integrated into the beam line to obtain pulse width measurements.

In addition to the physical improvements to the setup, custom software was developed to automatically measure the spatial profile of the focused laser beam used for PL SEE testing. The software characterizes the spatial profile of the beam by measuring the intensity of the laser reflected from an optical mirror with a sensitive camera. Various pictures of the beam are taken to obtain intensity profiles in the axial and radial dimension. An example of the measured beam profiles for several objectives are shown in Fig. 2. This software significantly reduced the time required to measure the focused spot size from 30-45 min to 5-10 min, all while saving additional useful data not previously available. This development is a significant improvement because the focused spot size is a critical parameter for quantitative experiments and accurate numerical simulations. These improvements now allow for more careful pulsed-laser characterization, which were necessary for all the experiments related to the present work.

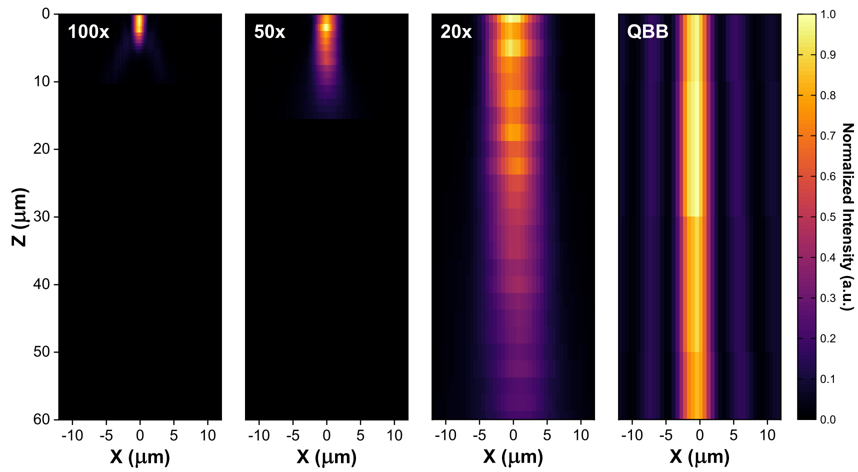


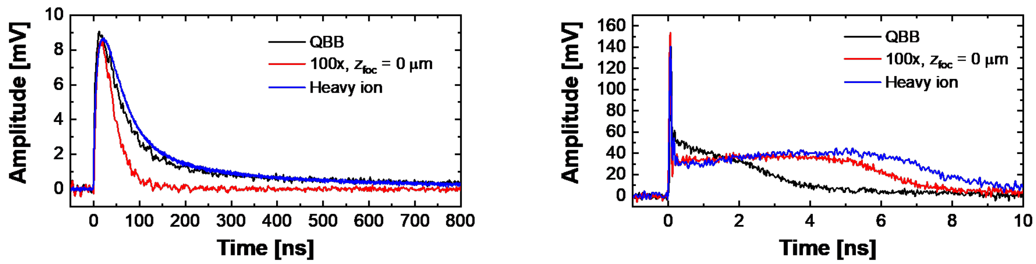
Fig. 2—Comparison of the measured normalized intensity profiles generated by four different focusing geometries.

3. EXPERIMENTAL RESULTS

3.1 Tailoring Optical Charge Deposition to Emulate Single-Event Transients Generated by Charged Particles

Recently, a new technique was developed at NRL for SEE testing that better emulates the charge deposited by heavy ions, a category of charged particles that are present in space. This technique uses a focusing lens with a conical surface instead of a traditional spherical surface. The resulting focused beam is known as a quasi-Bessel beam (QBB) that, when compared with the traditional Gaussian beam, features a larger axial-to-radial aspect ratio. A comparison of traditional techniques (i.e., 100x, 50x, 20x) with the new QBB approach is shown in Fig. 2. As shown, the intensity of the QBB is relatively long in the axial direction, while remaining radially confined, which results in a charge distribution profile that more closely resembles that produced by heavy ions [5]. This technique was successfully shown to yield excellent quantitative agreement between the single-event transients (SETs) measured using pulsed lasers and ionizing particles in a large-area silicon photodiode, as shown in Fig. 3a. This technique was also shown to accurately and quantitatively reproduce the SETs induced via ionizing particles in an operational amplifier [6].

When this new technique was applied to a silicon-germanium (SiGe) heterojunction bipolar transistor (HBT), however, the resulting SETs had different time-domain characteristics when compared to particle-induced SETs. As shown in Fig. 3b, the results from using the traditional focusing geometry (100x) were more similar to the ionizing particle when compared to those produced by the novel focusing geometry. The origin of this result is unclear, and several hypotheses were explored during the present research effort.



(a) (b)

Fig. 3—Comparison of SETs induced by the traditional optical focusing geometry (100x), the novel QBB focusing geometry, and an ionizing particle for (a) a large-area photodiode and (b) a SiGe HBT.

3.2 Impact of Carbon Doping on SEEs in SiGe HBTs

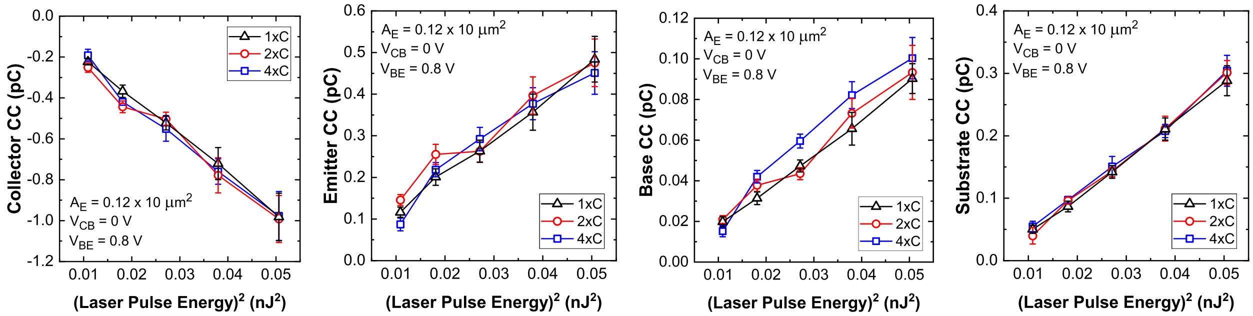
One potential source for the observed discrepancy is the effect of bulk traps on the optical charge generation processes. For modern SiGe HBTs, carbon doping is introduced into the p-type base to improve fabrication processing margins [7]. Carbon atoms are known to introduce bulk traps in the semiconductor material, which can affect optical absorption processes. Therefore, the effect of carbon on the charge generation and collection processes must be evaluated.

For this experiment, commercial-grade SiGe HBTs were fabricated by GlobalFoundries using a 130-nm SiGe BiCMOS process with varying levels of carbon doping in the SiGe base. Different wafers were fabricated with 1, 2, and 4 times the amount of carbon introduced during the SiGe base growth step in the process of record. Accordingly, these samples are labeled as 1xC, 2xC, and 4xC, referring to the relative carbon dose in each sample.

PL-SEE testing using the setup described in Section 2 was performed to evaluate any differences in the measured SET response of these carbon-doped samples. First, the laser focus was placed in the most sensitive region of the DUT (i.e., the one that produced the largest SET). Then, the laser pulse energy was swept and transient current waveforms were collected at each value. These current transients were then integrated to obtain the total charge collected at each terminal of the device, as shown in Fig. 4. For each terminal, the data for all samples lie within the measured standard deviation, indicating no significant difference from the addition of carbon.

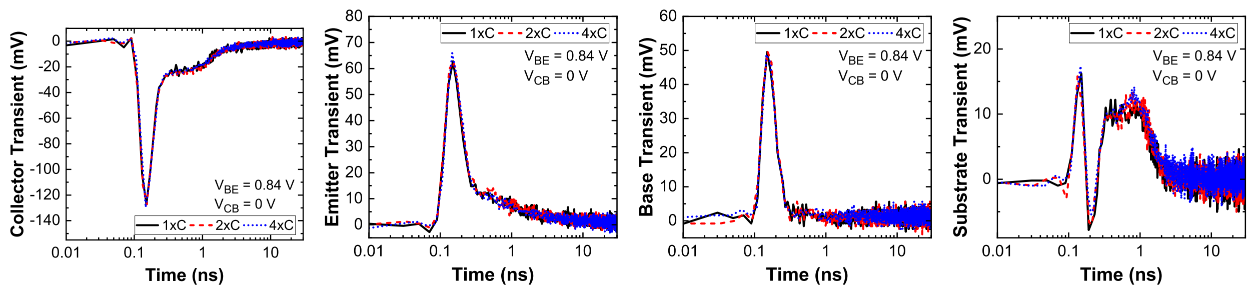
As secondary confirmation of this result, the transient waveforms for each terminal across all samples are shown in Fig. 5 for a forward active bias configuration of the HBTs. For each terminal, the transients for all samples are virtually identical, showing no measurable effect from the additional carbon.

Additional confirmation was obtained via physics-based technology computer-aided design (TCAD) simulations, which showed that the amount of carbon required to observe changes in the SET response would significantly impair the electrical performance of the device. The results of this work show that practical amounts of carbon have no measurable impact on the SET response of SiGe HBTs. A detailed description of the experiment, results, and physics-based simulations can be found in [7].



(a) (b) (c) (d)

Fig. 4—Collected charge measured on the (a) collector, (b) emitter, (c) base, and (d) substrate terminals as a function of the laser pulse energy squared for V_{BE} = 0.84 V and V_{CB} = 0 V. Each curve corresponds to a device with 1x, 2x, and 4x the amount of carbon compared to the process of record. The error bars correspond to the standard deviation of the collected charge values extracted from 15 individual transients. For each terminal of the SiGe HBT the data for each sample lie within the measured standard deviation, indicating no significant difference.



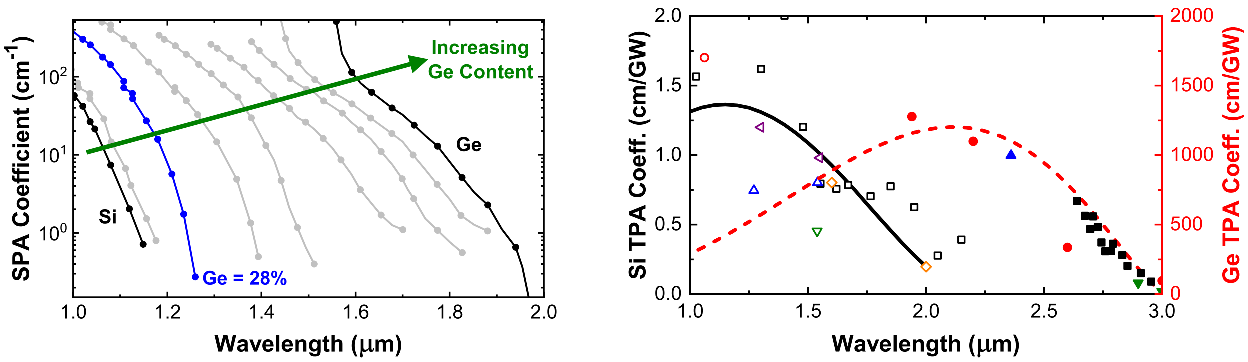
(a) (b) (c) (d)

Fig. 5—Comparison of the (a) collector, (b) emitter, (c) base, and (d) substrate transients recorded for V_{BE} = 0.84 V and V_{CB} = 0 V using a laser pulse energy of 225 pJ (laser-equivalent LET ≈ 7.8 MeV-cm^2/mg) for all three samples. Each curve corresponds to a device with 1x, 2x, and 4x the amount of carbon compared to the process of record. For each terminal, the transient waveforms for all samples are virtually identical.

3.3 Wavelength Dependence of SEEs in SiGe HBTs

Another potential hypothesis for this discrepancy is that the amount of Ge present in the base of this bipolar transistor is affecting the charge generation mechanisms. The Ge in these devices is placed around the boron-doped base of the transistor, and the amount and distribution are typically tailored to improve DC and AC performance. For these particular samples, the Ge is estimated to be around 25%, based on the published literature [8]. Given the large differences in the optical properties of Si and Ge, the current hypothesis is that the localized SiGe film is affecting the ability of both the Gaussian and the QBB techniques to adequately emulate the results obtained from heavy ion testing. The work discussed in this section was presented at the 2022 IEEE Nuclear and Space Radiation Effects Conference (NSREC) [9].

A comparison of important optical properties for Si and Ge are shown in Fig. 6. Fig. 6a shows the SPA coefficient as a function of wavelength for pure Si, pure Ge, and various compositions of SiGe alloys. Highlighted in blue is the absorption coefficient for a SiGe film with 28% Ge content, an amount similar to that present in the SiGe HBTs. At 1260 nm, the wavelength used for all laser measurements in Fig. 3b, the absorption coefficient for 28% Ge is orders of magnitude larger than that of pure Si. In addition, Fig. 6b shows the TPA coefficient as a function of wavelength for pure Si and pure Ge. The peak TPA coefficient for Ge is orders of magnitude larger than that of Si even at 1260 nm. Because these two absorption coefficients are larger for Ge than Si, it is likely that an increased amount of charge is being locally deposited in the SiGe film, which is located within the emitter-base-collector stack.



(a) (b)

Fig. 6—(a) SPA coefficient as a function of wavelength for different Ge concentrations. The absorption coefficient for 28% Ge (highlighted in blue), is orders of magnitude larger than for pure Si. (b) TPA coefficient for pure Si (solid line, open symbol) and pure Ge (dashed line, closed symbol) as a function of wavelength. The lines show simulated coefficients, while the symbols show experimental values found in the literature. Note that the Ge TPA coefficient is three orders of magnitude larger than that of Si. Both coefficients point towards an increased amount of charge in SiGe compared to Si.

To verify this hypothesis, PL-SEE measurements were performed on the 8HP SiGe HBT at 1260 nm, 1550 nm, and 1700 nm using a similar setup described in Section 2. The measurements were performed with all terminals on the device tied to 0 V. This condition was chosen because it is favorable for modeling and simulations. The measured time-domain waveforms were processed and their peak amplitude and collected charge were extracted. To focus on the charge generation in SiGe compared to Si, the resulting transient peak amplitude for each terminal was then plotted against the collected charge in the substrate. Because the substrate is made of doped silicon (i.e., no Ge), this allows to compare the resulting transient amplitudes for equal amounts of charge generated in the substrate.

To compare the PL-SEE results with heavy-ion results, transients were measured at the Lawrence Berkeley National Laboratory using their 10 MeV/amu ion cocktail. The same GF 8HP SiGe HBT was utilized, and transients were recorded for a variety of ion linear energy transfer (LET) values with all device terminals grounded.

The results of the PL-SEE experiments are shown and compared to heavy ion data in Fig. 7. There are several noteworthy results in these curves. First, there is a strong wavelength dependence observed for the collector, base, and emitter terminals. For the base and emitter in particular, this dependence is not monotonic, and the transient amplitudes are larger for 1260 nm and 1700 nm compared to 1550 nm. This result follows the trends of numerical simulation, which are not shown in this report as they are part of a forthcoming publication. Second, there is a difference in the functional shape in the emitter data for 1260 nm, compared to the other two wavelengths. These functional forms suggest a different charge generation mechanism responsible for the increased peak amplitude response (e.g., enhanced SPA for 1260 nm vs. enhanced TPA for 1700 nm). Finally, the 1550 nm data are closest to heavy-ion results, but they are still not well correlated.

Additional optimization of the focused spot size may be required, similar to previous work [10]. These efforts are in progress and the results will be submitted to a journal publication.

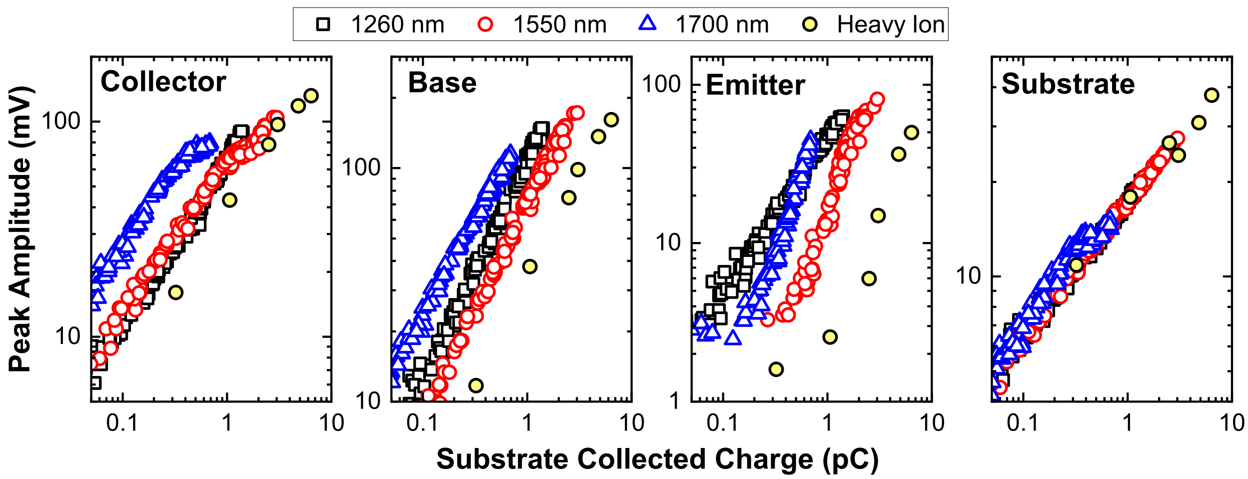


Fig. 7—Peak amplitude at the collector, base, emitter, and substrate terminals of the GF 8HP SiGe HBT as a function of the collected charge in the substrate terminal. Laser data were taken at various wavelengths with a focused spot size of approximately 2 μm when all terminals of the device were grounded. The data for various wavelengths are compared to heavy-ion data. While not optimal, better agreement is obtained for a wavelength of 1550 nm.

The results of these wavelength-dependent experiments and the numerical simulations (not shown) strongly suggest that the reason for the poor correlation shown in Fig. 3b for both the Gaussian and QBB approaches is a result of enhanced SPA at 1260 nm due to the Ge content in these SiGe HBTs. While not shown for brevity, these findings are supported by 2-D, physics-based TCAD simulations. In these simulations an increased amount of charge was deposited in the vicinity of the SiGe layer compared with the rest of the Si device to emulate enhanced SPA. The experimental trends observed in the peak amplitudes versus collected charge were reproduced by these simulations. However, the data and numerical simulations also suggest that alternative wavelengths could be used to significantly improve this correlation. Additional studies that utilize both the Gaussian and QBB approaches at different wavelengths are still in progress.

3.4 Characterization and Mitigation of Circuit-Level SETs in RF Systems

As a first step in understanding differences in charge collection between individual devices and complex systems, the SEE response of a radio-frequency (RF) receiver was investigated using the pulsed laser at NRL. RF receivers are ubiquitous in space systems, and they are one of the critical system-level blocks in any communications link between a ground station and a spacecraft.

Testing this particular system required the design of a high-frequency setup for SET measurements, for which signal integrity and timing were critical. After successfully developing this setup, clear eye diagrams were measured, indicating proper operation of the test bench and the circuit. As shown in Fig. 8, the pulsed laser introduced SETs that resulted in data corruption, which is evidenced by the apparent “closing” of the “eye” in the diagram. When the eye is closed, it represents a corruption in the digital data (i.e., flipping a logic one to a logic zero, or vice-versa).

Once the SEE sensitivity of a system is determined, the next step is typically to apply mitigation techniques. This work applied machine-learning techniques, for the first time, to detect and mitigate single-event upsets in this RF system while it is carrying modulated data. As shown in Fig. 9, this novel mitigation approach reduced SEUs by 30%.

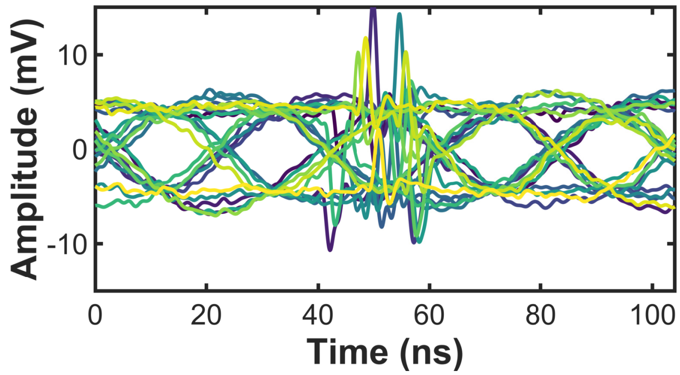


Fig. 8—Eye diagram measured at the output of the RF receiver. The laser-induced SETs are shown. The "closing" of the "eye" indicates that the data bits were corrupted.

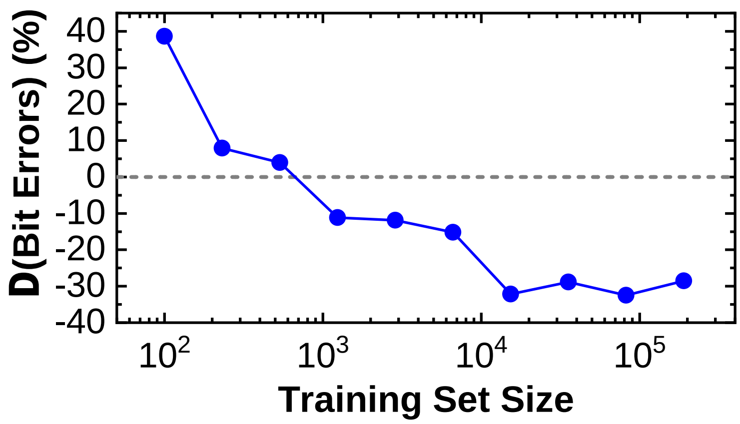


Fig. 9—Percent change in symbol errors when a machine-learning-based mitigation approach is applied as a function of the size of the training data used. A positive value means more errors were introduced when attempting to correct the data. A minimum training set size on the order of 1000 SETs is required for any improvements to be made by this technique.

This work resulted in a peer-reviewed journal publication [11] and was awarded the Meritorious Paper Award at the 2021 Nuclear and Space Radiation Effects Conference.

4. SUMMARY

During this effort, significant advances have been made towards understanding the use of non-linear optical processes to emulate the interaction of charged particle radiation with semiconductor devices. These advances necessitated improvements in the dosimetry and characterization procedure of the PL SEE system, which were developed under this effort. Pulsed-laser data have been collected at the device and circuit level for a variety of conditions, and compared with results obtained at particle accelerators. One important finding of this work is that for Si/SiGe devices, utilizing the optimal range of wavelengths might be required for these optical processes to properly emulate the effects of charged particles.

This effort has resulted in an improved understanding of the nuances in charge deposition from non-linear optical processes that will inform new approaches to better emulate the effects of charged particles on semiconductor devices. This result will, in turn, enable a wider range of PL-SEE experiments and test campaigns that would alleviate the strain imposed by the limited availability of particle accelerators on the development of robust electronics for space environments. Increased access to alternative testing techniques will result in a shorter timeline from development to deployment of critical space assets.

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7. A. Ildefonso, J. M. Hales, A. Khachatrian, J. W. Teng, G. N. Tzintzarov, D. Nergui, B. L. Ringel, U. Raghunathan, V. Jain, J. D. Cressler, and D. McMorrow, "The Effects of Carbon Doping on the Single-Event Transient Response of SiGe HBTs **70**(8), 1797–1804 (Aug. 2023), doi:10.1109/TNS.2023.3255169.

8. B. Jagannathan, M. Khater, F. Pagette, J. S. Rieh, D. Angell, H. Chen, J. Florkey, F. Golan, D. Greenberg, R. Groves, S. Jeng, J. Johnson, E. Mengistu, K. Schonenberg, C. Schnabel, P. Smith, A. Stricker, D. Ahlgren, G. Freeman, K. Stein, and S. Subbanna, "Self-aligned SiGe NPN transistors with 285 GHz f¡sub¿max¡/sub¿ and 207 GHz f¡sub¿T¡/sub¿ in a manufacturable technology **23**(5), 258–260 (2002), doi:10.1109/55.998869.

9. A. Ildefonso, J. M. Hales, A. Khachatrian, P. D. Cunningham, D. Nergui, G. N. Tzintzarov, A. P. Omprakash, J. D. Cressler, and D. McMorrow, "Leveraging the Wavelength Dependence of Optical Charge Generation to Correlate Ion- and Laser-Induced Transients in Modern SiGe HBTs, Number A-2 (2022 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2022.

10. A. Ildefonso, Z. E. Fleetwood, G. N. Tzintzarov, J. M. Hales, D. Nergui, M. Frounchi, A. Khachatrian, S. P. Buchner, D. Mcmorrow, J. H. Warner, J. Harms, A. Erickson, K. Voss, V. Ferlet-Cavrois, and J. D. Cressler, "Optimizing Optical Parameters to Facilitate Correlation of Laser- and Heavy-Ion-Induced Single-Event Transients in SiGe HBTs **66**(1), 359–367 (Jan 2019), ISSN 0018-9499, doi:10.1109/TNS.2018.2882821.

11. A. Ildefonso, J. P. Kimball, A. Khachatrian, Y. Mensah, J. W. Teng, G. N. Tzintzarov, S. G. Rao, A. Moradinia, J. D. Cressler, and D. McMorrow, "Using Machine Learning to Mitigate Single-Event Upsets in RF Circuits and Systems **69**(3), 381–389 (Mar. 2022).

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Appendix A

AWARDS AND ACCOMPLISHMENTS

1. **Meritorious Conference Paper Award** - 2021 IEEE Nuclear and Space Radiation Effects Conference for **A. Ildefonso** et al., "Using Machine Learning to Mitigate Single-Event Upsets in RF Circuits and Systems," IEEE Trans. Nucl. Sci., vol.69, no.3, pp.381-389, March 2022.

2. **Outstanding Student Paper Award** - 2021 IEEE Nuclear and Space Radiation Effects Conference for J. W. Teng, D. Nergui, H. Parameswaran, G. N. Tzintzarov, H. Ying, C. D. Cheon, S. G. Rao, **A. Ildefonso**, N. A. Dodds, R. N. Nowlin, M. Gorchichko, E. X. Zhang, D. M. Fleetwood, J. D. Cressler, "Response of Integrated Silicon RF pin Diodes to X-ray and Fast Neutron Irradiation," IEEE Trans. Nucl. Sci., vol.69, no.3, pp.282-289, March 2022.

3. **Outstanding Conference Paper Award and Outstanding Student Paper Award** - 2020 IEEE Nuclear and Space Radiation Effects Conference for G. N. Tzintzarov, **A. Ildefonso**, J. W. Teng, M. Frounchi, A. Djikeng, P. Iyengar, P. S. Goley, R. Bahr, A. Khachatrian, S. P. Buchner, D. McMorrow, J. D. Cressler, "Optical Single-Event Transients Induced in Silicon-Photonic Waveguides by Two-Photon Absorption," IEEE Trans. Nucl. Sci., vol.68, no.5, pp.785–792, May 2021.

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Appendix B

LIST OF PEER-REVIEWED JOURNAL PUBLICATIONS AS FIRST OR CO-AUTHOR

This appendix includes a full list of journal publications as first or co-author submitted for review or published during the course of this program.

REFERENCES

B1. M. Frounchi, G. N. Tzintzarov, **Ildefonso, A.**, and J. Cressler, "High Responsivity Ge Phototransistors in a Commercial 90-nm CMOS Si-Photonics Platform for Monolithic Optoelectronic Receivers," *IEEE Electron Device Lett.* **42**(2), 196–199 (Feb. 2021).

B2. S. J. Pearton, A. Aitkaliyeva, M. Xian, F. Ren, A. Khachatrian, **A. Ildefonso**, Z. Islam, M. A. J. Rasel, A. Haque, A. Y. Polyakov, and J. Kim, "Review–Radiation Damage in Wide and Ultra-Wide Bandgap Semiconductors," *ECS Journal of Solid State Science and Technology* **10**(5), 055008 (May 2021), doi:10.1149/2162-8777/abfc23.

B3. J. M. Hales, A. Khachatrian, S. Buchner, **A. Ildefonso**, D. M. Monahan, S. D. LaLumondiere, and D. McMorrow, "Mapping the Spatial Dependence of Charge Collection Efficiency in Devices Using Pulsed-Laser Testing," *IEEE Trans. Nucl. Sci.* **68**(5), 617–625 (May 2021), doi:10.1109/TNS.2021.3049651.

B4. J. W. Teng, **A. Ildefonso**, G. N. Tzintzarov, A. Moradinia, P. F. Wang, X. Li, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, "Variability in Total-Ionizing-Dose Response in 4th-Generation SiGe HBTs," *IEEE Trans. Nucl. Sci.* **68**(5), 949–957 (May 2021), doi:10.1109/TNS.2020.3048669.

B5. G. N. Tzintzarov, **A. Ildefonso**, J. W. Teng, M. Frounchi, A. Djikeng, P. Iyengar, P. S. Goley, R. Bahr, A. Khachatrian, S. P. Buchner, D. McMorrow, and J. D. Cressler, "Optical Single-Event Transients Induced in Silicon-Photonic Waveguides by Two-Photon Absorption," *IEEE Trans. Nucl. Sci.* **68**(5), 785–792 (May 2021), doi:10.1109/TNS.2021.3051802. Received Outstanding Student Paper Award and Outstanding Conference Paper Award at the 2020 Nuclear and Space Radiation Effects Conference.

B6. S. J. Pearton, A. Haque, A. Khachatrian, **A. Ildefonso**, L. Chernyak, and F. Ren, "Opportunities in Single Event Effects in Radiation-Exposed SiC and GaN Power Electronics," *ECS Journal of Solid State Science and Technology* **10**(7), 075004 (July 2021).

B7. **A. Ildefonso**, J. P. Kimball, A. Khachatrian, Y. Mensah, J. W. Teng, G. N. Tzintzarov, S. G. Rao, A. Moradinia, J. D. Cressler, and D. McMorrow, "Using Machine Learning to Mitigate Single-Event Upsets in RF Circuits and Systems," *IEEE Trans. Nucl. Sci.* **69**(3), 381–389 (Mar. 2022).

B8. J. W. Teng, D. Nergui, H. Parameswaran, G. N. Tzintzarov, H. Ying, C. D. Cheon, S. G. Rao, **A. Ildefonso**, N. A. Dodds, R. N. Nowlin, M. Gorchichko, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, "Response of Integrated Silicon RF *pin* Diodes to X-ray and Fast Neutron Irradiation," *IEEE Trans. Nucl. Sci.* **69**(3), 282–289 (Mar. 2022).

B9. J. M. Hales, A. Khachatrian, **A. Ildefonso**, S. Buchner, D. Adams, D. Wheeler, S. Messenger, C. Mishler, N. Budzinski, S. Jordan, R. van Art, and D. McMorrow, “Pulsed-Laser Testing to Quantitatively Evaluate Latchup Sensitivity in Mixed-Signal ASICs,” *IEEE Trans. Nucl. Sci.* **69**(3), 429–435 (Mar. 2022).

B10. D. Nergui, J. W. Teng, M. Hosseinzaadeh, Y. Mensah, K. Li, M. Gorchichko, **A. Ildefonso**, B. L. Ringel, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, “Total-Ionizing-Dose Response of SiGe HBTs at Elevated Temperatures,” *IEEE Trans. Nucl. Sci.* **69**(5), 1079–1084 (May 2022).

B11. T. Nelson, P. Pandey, D. G. Georgiev, M. R. Hontz, A. D. Koehler, K. D. Hobart, T. J. Anderson, **A. Ildefonso**, and R. Khanna, “Hybrid Edge Termination in Vertical GaN: Approximating Beveled Edge Termination Via Discrete Implantations,” *IEEE Trans. Electron Devices* **69**(12), 6940–6947 (Dec. 2022).

B12. N. E. Sepúlveda-Ramos, J. W. Teng, **A. Ildefonso**, H. P. Lee, S. G. Rao, and J. D. Cressler, “Impact of Device Layout on Thermal Parameters and RF Performance of 90-nm SiGe HBTs,” *IEEE Trans. Electron Devices* **70**(3), 850–856 (Mar. 2023).

B13. J. M. Hales, **A. Ildefonso**, A. Khachatrian, S. Buchner, and D. McMorrow, “Quantitative Prediction of Ion-Induced Single-Event Transients in an Operational Amplifier Using a Quasi-Bessel Beam Pulsed-Laser Approach,” *IEEE Trans. Nucl. Sci.* **70**(4), 354–362 (Apr. 2023), doi:10.1109/TNS.2022.3232724.

B14. T. Nelson, D. G. Georgiev, M. R. Hontz, R. Khanna, **A. Ildefonso**, A. D. Koehler, A. Khachatrian, and D. McMorrow, “Examination of Trapping Effects on Single Event Transients in GaN HEMTs,” *IEEE Trans. Nucl. Sci.* **70**(4), 328–335 (Apr. 2023), doi:10.1109/TNS.2022.3220235.

B15. **A. Ildefonso**, J. M. Hales, A. Khachatrian, J. W. Teng, G. N. Tzintzarov, D. Nergui, B. L. Ringel, U. Raghunathan, V. Jain, J. D. Cressler, and D. McMorrow, “The Effects of Carbon Doping on the Single-Event Transient Response of SiGe HBTs,” *IEEE Trans. Nucl. Sci.* **70**(8), 1797–1804 (Aug. 2023), doi:10.1109/TNS.2023.3255169.

B16. J. W. Teng, B. L. Ringel, Z. R. Brumbach, J. P. Heimerl, Y. A. Mensah, G. N. Tzintzarov, **A. Ildefonso**, A. Khachatrian, D. McMorrow, P. Oldiges, and J. D. Cressler, “The Propagation of Extended SET Tails in RF Amplifiers Using 45-nm CMOS on PDSOI,” *IEEE Trans. Nucl. Sci.* **70**(8), 1829–1837 (Aug. 2023), doi:10.1109/TNS.2022.3224356.

Appendix C

LIST OF PEER-REVIEWED CONFERENCE PAPERS WITHOUT PROCEEDINGS AS FIRST OR CO-AUTHOR

This appendix includes a full list of conference papers as first or co-author accepted for presentation during the course of this program. In the largest radiation effects research conferences it is common for these conference papers to be peer-reviewed, but there may not be official conference proceedings.

REFERENCES

C1. **A. Ildefonso**, G. N. Tzintzarov, D. Nergui, J. M. Hales, A. Khachatrian, A. Omprakash, S. P. Buchner, D. McMorrow, and J. D. Cressler, "Laser-Induced Transients in SiGe HBTs Generated via Two-Photon Absorption Using Gaussian and Quasi-Bessel Beams, Number B-5 (2020 IEEE Nuclear and Space Radiation Effects Conference), Dec. 2020.

C2. J. W. Teng, **A. Ildefonso**, G. N. Tzintzarov, A. Moradinia, P. F. Wang, X. Li, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, "Variability in Total-Ionizing-Dose Response in 4th-Generation SiGe HBTs, Number H-2 (2020 IEEE Nuclear and Space Radiation Effects Conference), Dec. 2020.

C3. G. N. Tzintzarov, **A. Ildefonso**, J. W. Teng, M. Frounchi, A. Djikeng, P. Iyengar, P. S. Goley, R. Bahr, A. Khachatrian, S. P. Buchner, D. McMorrow, and J. D. Cressler, "Optical Single-Event Transients Induced in Silicon-Photonic Waveguides by Two-Photon Absorption, Number D-3 (2020 IEEE Nuclear and Space Radiation Effects Conference), Dec. 2020.

C4. D. Nergui, **A. Ildefonso**, G. N. Tzintzarov, A. Omprakash, and J. D. Cressler, "An Investigation of SET Charge Transport Mechanisms in SiGe HBTs, Number PB-2 (2020 IEEE Nuclear and Space Radiation Effects Conference), Dec. 2020.

C5. **A. Ildefonso**, J. P. Kimball, J. D. Cressler, and D. McMorrow, "Using Machine Learning to Mitigate Single-Event Upsets in RF Circuits and Systems, Number D-3 (2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2021.

C6. J. W. Teng, D. Nergui, H. Parameswaran, G. N. Tzintzarov, H. Ying, C. D. Cheon, S. G. Rao, **A. Ildefonso**, N. A. Dodds, R. N. Nowlin, M. Gorchichko, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, "Response of Integrated Silicon RF *pin* Diodes to X-ray and Fast Neutron Irradiation, Number C-1 (2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2021.

C7. D. Nergui, J. W. Teng, **A. Ildefonso**, M. Gorchichko, E. X. Zhang, D. M. Fleetwood, and J. D. Cressler, "Total-Ionizing-Dose Response of SiGe HBTs at Elevated Temperatures, Number C-2 (2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2021.

C8. A. Khachatrian, **A. Ildefonso**, S. Buchner, J. M. Hales, G. Foster, A. Koehler, J. Mittereder, and D. McMorrow, "Investigation of Deep-Level Traps in AlGaN/GaN HEMTs Using Variable-Wavelength Laser Light, Number A-1 (2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2021.

C9. J. M. Hales, A. Khachatrian, **A. Ildefonso**, S. Buchner, D. Adams, D. Wheeler, S. Messenger, C. Mishler, N. Budzinski, S. Jordan, R. van Art, and D. McMorrow, "Pulsed-Laser Testing to Quantitatively Evaluate Latchup Sensitivity in Mixed-Signal ASICs, Number A-1 (2021 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2021.

C10. G. N. Tzintzarov, J. W. Teng, **A. Ildefonso**, and J. D. Cressler, "Analysis of the Impact of Radiation-Induced Optical Transients on Deep-Space Optical Communication Systems using PPM (Optical Fiber Communication Conference (OFC) 2021), 2021, p. F4E.5.

C11. J. M. Hales, **A. Ildefonso**, A. Khachatrian, S. Buchner, and D. McMorrow, "Towards Predicting Single-Event Transients in an Operational Amplifier Using a Quasi-Bessel Beam Pulsed-Laser Approach, Number B-2 (2022 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2022.

C12. T. Nelson, D. G. Georgiev, M. R. Hontz, R. Khanna, **Adrian Ildefonso**, A. D. Koehler, A. Khachatrian, and D. McMorrow, "Examination of Trapping Effects on Single Event Transients in GaN HEMTs, Number PA-3 (2022 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2022.

C13. **A. Ildefonso**, J. M. Hales, A. Khachatrian, P. D. Cunningham, D. Nergui, G. N. Tzintzarov, A. P. Omprakash, J. D. Cressler, and D. McMorrow, "Leveraging the Wavelength Dependence of Optical Charge Generation to Correlate Ion- and Laser-Induced Transients in Modern SiGe HBTs, Number A-2 (2022 IEEE Nuclear and Space Radiation Effects Conference (NSREC)), July 2022.

C14. **A. Ildefonso**, J. M. Hales, A. Khachatrian, J. W. Teng, G. N. Tzintzarov, D. Nergui, B. L. Ringel, U. Raghunathan, V. Jain, J. D. Cressler, and D. McMorrow, "The Effects of Carbon Doping on the Single-Event Transient Response of SiGe HBTs, Number A-2 (2022 Radiation Effects on Components and Systems (RADECS) Conference), Oct. 2022.

C15. J. W. Teng, B. L. Ringel, J. P. Heimerl, G. N. Tzintzarov, **A. Ildefonso**, A. Khachatrian, D. McMorrow, P. Oldiges, and J. D. Cressler, "The Role of Bipolar Amplification in the SET Response of Narrowband RF Amplifiers Using SOI CMOS, Number B-1 (2022 Radiation Effects on Components and Systems (RADECS) Conference), Oct. 2022.

Appendix D

LIST OF PRESENTATIONS

This appendix includes a full list of presentations delivered during the course of this program.

REFERENCES

D1. **A. Ildefonso**, G. N. Tzintzarov, D. Nergui, J. M. Hales, A. Khachatrian, A. Omprakash, S. P. Buchner, D. McMorrow, and J. D. Cressler, "Laser-Induced Transients in SiGe HBTs Generated via Two-Photon Absorption Using Gaussian and Quasi-Bessel Beams, Number B-5 (oral presentation at the *2020 IEEE Nuclear and Space Radiation Effects Conference*), Dec. 2020.

D2. **A. Ildefonso**, J. P. Kimball, J. D. Cressler, and D. McMorrow, "Using Machine Learning to Mitigate Single-Event Upsets in RF Circuits and Systems, Number D-3 (oral presentation at the *2021 IEEE Nuclear and Space Radiation Effects Conference*), July 2021.

D3. **A. Ildefonso**, J. M. Hales, A. Khachatrian, S. P. Buchner, and D. McMorrow, "Not All Pulsed-Laser SEEs Are Created Equal: The Importance of Accurate Characterization and Reporting of Pulsed-Laser Parameters, Number B-4 (oral presentation at the *2022 Single Event Effects Symposium*), May 2022.

D4. **A. Ildefonso**, J. M. Hales, A. Khachatrian, P. D. Cunningham, D. Nergui, G. N. Tzintzarov, A. P. Omprakash, J. D. Cressler, and D. McMorrow, "Leveraging the Wavelength Dependence of Optical Charge Generation to Correlate Ion- and Laser-Induced Transients in Modern SiGe HBTs, Number A-2 (oral presentation at the *2022 IEEE Nuclear and Space Radiation Effects Conference*), July 2022.

D5. **A. Ildefonso**, "Single-Event Effects Research at the U.S. Naval Research Laboratory," [INVITED] SCALE Workforce Development Program, June 2021.

D6. **A. Ildefonso**, A. Khachatrian, J. M. Hales, S. Buchner, and D. McMorrow, "Simulating the Natural Space Radiation Environment on Earth - Pulsed Lasers," [INVITED] Single-Event Effects University Symposium, Oct. 2022.

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Appendix E

LIST OF TECHNICAL REPORTS

This appendix includes a full list of technical reports written or published during the course of this program.

REFERENCES

E1. K. L. Ryder, A. M. Phan, M. J. Campola, A. Khachatrian, D. P. McMorrow, and **A. Ildefonso**, "Analog Devices AD620 Instrumentation Amplifier Laser Single-Event Effects Characterization Test Report," Technical Memorandum NASA/TM-20210026447, National Aeronautics and Space Administration (NASA), Jan. 2022. URL `https://ntrs.nasa.gov/citations/20210026447`.

E2. K. L. Ryder, A. M. Phan, M. J. Campola, A. Khachatrian, D. P. McMorrow, and **A. Ildefonso**, "Texas Instruments LM7171 Voltage Feedback Amplifier Laser Single-Event Effects Characterization Test Report," Technical Memorandum NASA/TM-20210026449, National Aeronautics and Space Administration (NASA), Jan. 2022. URL `https://ntrs.nasa.gov/citations/20210026449`.

E3. D. McMorrow, S. Buchner, J. M. Hales, **A. Ildefonso**, A. Khachatrian, G. Allen, M. Campola, and K. L. Ryder, "Pulsed-Laser Single-Event Effects (PL SEE) Testing – A Practical Desk Reference," Technical Report DTRA-TR-23-43, Defense Threat Reduction Agency, Fort Belvoir, VA, USA, May 2023. URL `https://apps.dtic.mil/sti/trecms/pdf/AD1204115.pdf`.