Silicon-Based Electronic-Photonic Integrated Circuits: Resiliency in the Space Environment

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Abstract—**This work highlights recent research in the field of radiation effects in silicon-based integrated electronic-photonic circuits (ePICs). This technology involves adding additional steps to a Si CMOS or SiGe BiCMOS fabrication process to create monolithically integrated photonic components on die, right alongside conventional electronics. ePIC technology facilitates size, weight, power, and cost scaling in communication and sensing systems which have relevance for space applications. Initial studies indicate some photonic components exhibit resiliency in the inherently harsh space radiation environment. Two recent works are summarized. The first outlines an approach for predicting the response of an integrated silicon optical waveguide to a heavy ion strike. The second is on the total ionizing dose response of Ge-on-Si waveguide-integrated photodiodes.**

Keywords—**silicon photonics, integrated photonics, radiation effects, photodiodes, total ionizing dose, heavy ion strike, photonic waveguides**

I. INTRODUCTION

Breakthroughs in silicon-based (Si) optical and photonic devices over the last 15 years have enabled the integration of optical systems into standard Si wafers using conventional microprocessor fabrication techniques [1], [2]. This new field of Si-based integrated photonic circuits (PICs) is enabling the scaling of size, weight, power, (SWaP) and cost of optical communication and sensing systems in much the same way that the invention of the electronic integrated circuit enabled scaling of electronics, from systems of discrete components, to having billions of devices on die today. While Si photonics is being driven largely by terrestrial data center and telecommunications operations, space applications (where SWaP savings are more valuable still) stand to benefit greatly from this rapid technological development.

Even before the recent wave of PIC technology development, the economics of space-based laser communication systems has already been transformed by the advancement of ground-based fiber optic communication [3]. This has been due to the widespread availability of mass produced, durable, and low cost discrete optical components (namely lasers, modulators, optical amplifiers, and others) that have been developed for these terrestrial systems. To highlight a recent example, the fastest RF-based data link to the moon to date is 100 Mbps and flies on-board the Lunar Reconnaissance Orbiter launched (LRO) in 2009. In 2013 NASA demonstrated, for the first time, a duplex optical communication link to a lunar orbiter with error-free downlink rates up to 622 Mbps as part of the Lunar Laser Communication Demonstration (LLCD) [4]. Although the LLCD included no PICs, instead leveraging discrete commercial-off-the-shelf (COTs) components designed for ground-based telecommunications, it was half the mass of the LRO's RF-based system and used 25% less power. These reductions in SWaP costs are expected to improve substantially as future systems begin to replace clusters of discrete optical components with PICs. The ability to include electronic circuits and sub-systems on die alongside the photonics (ePICs) has the potential to drive SWaP costs down further still. NASA's Laser Communications Relay Demonstration (LCRD), the spiritual successor to the LLCD, is slated for launch in mid-2019 and does include a PIC within the heart of its modem module [3].

This recent progress in space-based optical communications has not come too soon. As human activity in space increases, our aging RF-based deep space communications infrastructure has become a bottleneck for mission operations [3]. The fastest data link to Mars established to date is 6 Mbps and is achieved by the state-of-the-art X-band RF system on-board the Mars Reconnaissance Orbiter (MRO). However, recent NASA studies indicate that a $\sim$250 Mbps link is required to support a crewed mission to Mars [5]. Furthermore, a wide array of other applications for PICs in space have been identified, including intra-satellite optical fiber-based communications, laser-ranging and altimetry, chemical and biological sensing, and spectrometry [6]. Most commercial PIC technology platforms are built around the silicon material system ([7]–[9] and others), however indium phosphide (InP) based PICs have also been proposed for space-based optical communications [10].

Before the progress of Si photonics can be brought to bear on space systems, the effects of space radiation on this technology must be mapped out. The importance of identifying any vulnerabilities before flight is obvious, as is the strategic

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value of discovering cases where devices may be relatively insensitive to an otherwise harsh environment.

This work summarizes two recent studies in field of radiation effects in Si photonics. The first paper proposes a method for predicting the result of a heavy ion strike to the center of a Si photonic waveguide [11]. The method is applied to a typical Si waveguide geometry and a set of sample heavy ions and energies, and the resulting predictions are discussed. The method can be applied to arbitrary photonic structures; simple waveguides are used to illustrate the method as they are the fundamental building blocks of PICs. The second work presents the results of recent total ionizing dose (TID) experiments on pure germanium (Ge-on-Si) waveguide-integrated photodiodes [12]. These PDs have become the prevailing device for optical-to-electrical conversion in Si-based PICs, and therefore their radiation response is of great importance to the radiation sensitivity of Si photonics as a whole. These two works, together with other recent work on radiation effects in Si photonics [13], [14], are beginning to suggest a theme of possible resiliency in the space environment, which may be taken as welcomed news for the future of PICs in space. However, much work remains to be done. Future directions for radiation effects research on PICs are also discussed.

II. PREDICTING HEAVY ION EFFECTS IN SILICON PHOTONIC WAVEGUIDES

In the first paper summarized here, classical Drude theory was used to develop a framework for understanding the perturbation to the optical material properties of Si under extremely high levels of excitation, namely, electron-hole-pair (ehp) densities above $10^{20}\,\mathrm{cm}^{-3}$ [11]. This is necessary since ehp densities in the core of a heavy track in Si are believed to reach as high as $10^{22}\,\mathrm{cm}^{-3}$ [15]. The resulting relationship between ehp density, refractive index, and absorption coefficient is shown in Fig. 1. Once the theoretical framework is established, it is used to assign unique values of the complex dielectric constant to each vertex a 3-D finite-difference time-domain (FDTD) simulation mesh, according to the expected ehp distribution for each sample heavy ion strike. The simulation geometry is shown in Fig. 2. The resulting set of FDTD simulation results, slices of which are shown in Figs. 3 and 4, suggest an exponential relationship between the optical signal power loss and the linear energy transfer (LET) from the heavy ion, as shown in Fig. 5. The 3-D FDTD data is well fit by a curve of the form $y = a(e^{bx} - 1)$ where $a = 0.0119$, $b = 0.0530$, and $R^2 = 0.9994$. The data points in Fig. 5 represent one minus the optical power transmission through the excited waveguide (i.e. the sum of the fractions of the input power which are absorbed, scattered, or reflected). These losses, which are comprised of mostly free-carrier absorption losses, are transient in nature and the waveguide can be expected to recover on the timescale of the free-carrier lifetime in the material, typically 100's of picoseconds to nanoseconds in an Si waveguide. Since LETs less than 40 MeV-cm^2/mg result in less than 10% loss, these simulation results indicate many heavy ion strikes may not be problematic in a typical optical communication systems, and are likely to even go unnoticed in many cases. Extrapolation of the best fit curve out to higher LET, shown in the inset of Fig. 5, indicates 3 dB signal loss and total signal loss at LETs of 71.0 and 83.8 MeV-cm^2/mg, respectively. The signal integrity of data transmitted during the ~1 ns period (roughly the length of time it takes for most of the ehps to recombine) immediately following such a high LET strike is liable to be jeopardized. However, such high LET strikes are relatively uncommon in many space environments of interest, and even when they occur the resulting small number of bit errors per strike (possibly ~1-3 for a 1 Gbps uncoded link) can likely be handled by modest forward error correction coding. A secondary aim of [11] is to aid in the planning of experiments which seek to observe heavy ion effects in photonic waveguides experimentally.

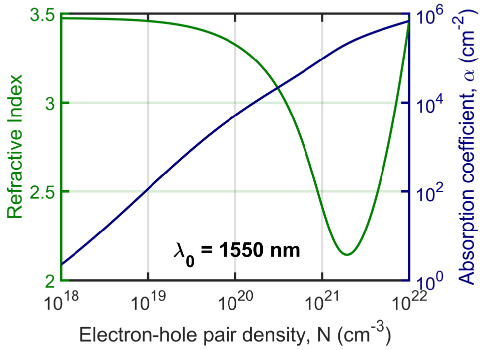

Fig. 1. The refractive index and the absorption coefficient in highly excited Si at 1550 nm from Drude theory under the assumptions outlined in [11].

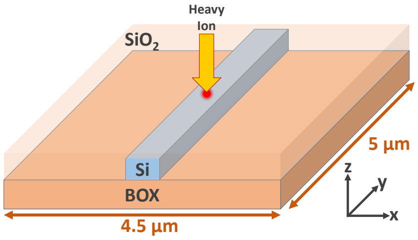

Fig. 2. The 3-D silicon waveguide geometry used in the FDTD simulations. A normally incident heavy ion strike directly to the center of the waveguide is considered.

III. TOTAL IONIZING DOSE EFFECTS IN WAVEGUIDE INTEGRATED PHOTODIODES

Conventional normal-incidence PDs have been studied by the radiation effects community for at least the last four decades. However, the waveguide-integrated PD, particularly the Ge-on-Si versions that are ubiquitous in Si-based PICs, represent a relatively new class of PD, with some of the first practical devices demonstrated in the research environment in 2006 [16]. In a recent study, Ge-on-Si waveguide-integrated PD building blocks from a commercial ePIC platform were exposed to 10-keV X-rays to emulate space ionizing radiation [12]. The typical physical geometry of these devices

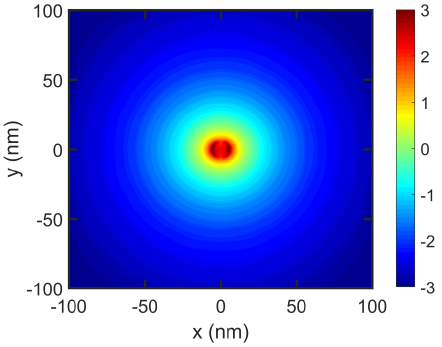

Fig. 3. A 2-D slice of the normalized absorbed power per μm^3 taken from 3-D FDTD simulations results. The slice is taken in the xy plane in the center of a Si photonic waveguide which has been excited by a normally incident heavy ion strike (see Fig. 2 for geometry reference). In this example, the heavy ion is ^{78}Kr with an energy and LET of 3117 MeV and 13.92 MeV-cm^2/mg, respectively. The color bar is on a $\log_{10}$ scale.

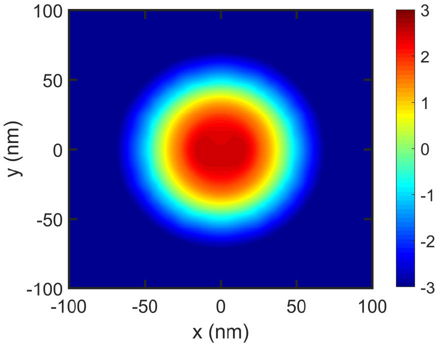

Fig. 4. A 2-D slice of the normalized absorbed power per μm^3 taken from 3-D FDTD simulations results. The slice is taken in the xy plane in the center of a Si photonic waveguide which has been excited by a normally incident heavy ion strike (see Fig. 2 for geometry reference). In this example, the heavy ion is ^{84}Kr with an energy and LET of 316 MeV and 40.00 MeV-cm^2/mg, respectively. The color bar is on a $\log_{10}$ scale.

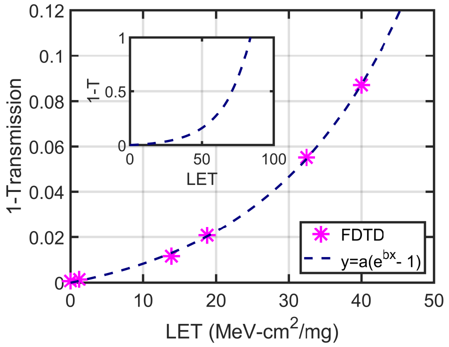

Fig. 5. The total transmission loss of an optical signal centered at 1550 nm traveling through a Si photonic waveguide excited by a heavy ion strike is plotted against LET. Data points are shown with the best fit exponential of the form $y = a(e^{bx} - 1)$ where $a = 0.0119$, $b = 0.0530$, and $R^2 = 0.9994$. This fit is extrapolated out to higher LETs in the inset.

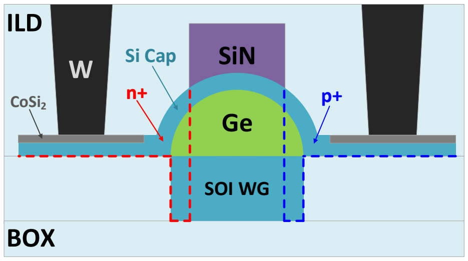

Fig. 6. A cross-sectional diagram of Ge p-i-n PD integrated with a Si photonic waveguide. The development of Ge-on-Si waveguide integrated PDs represents one of the key milestones enabling the advancement of Si photonics.

differs significantly from normal-incidence PDs, and is shown roughly to scale (the waveguide height is 220 nm) in Fig. 6. The performance of the PDs was carefully measured immediately before and after radiation exposure. The devices were characterized in terms of DC photocurrent response, capacitance, dark current, and optical-electrical conversion frequency response (O/E FR). Fig. 7 shows the PD dark current just before, during, and after X-ray irradiation. The small changes observed here were determined to be primarily temperature driven, rather than a radiation effect. None of the samples, which were irradiated up to 5 Mrad(SiO_2), exhibited measurable radiation-induced dark current enhancement (the measurement uncertainty was limited to ±0.4 nA). The ~2 nA abrupt changes at beam switching are attributed to, at least in part, an X-ray induced photocurrent. Fig. 8 shows the spectral response of the PD, including its input grating coupler, for fixed optical input power (0 dBm). The inverted parabolic shape matches the expected transfer characteristic of the grating coupler, the loss of which is 4-5 dB at the peak. Here the sample irradiated to 5 Mrad(SiO_2) performs similarly to a nominally identical control sample (which was not irradiated) both before and after irradiation. The inset shows how the small uncertainty in loss between the laser and the PD translates to a small uncertainty in the internal responsivity, with the dashed line at the top representing the theoretical limit at 100% quantum efficiency. Three representative O/E FR measurement results are shown in Figs. 9, 10, and 11. The data shows the device performance was not significantly impacted by as much as 5 Mrad(SiO_2) of TID, a large dose relative to many space environments. The small changes observed are within the experimental uncertainty and show no correlation with TID. These results indicate the tested Ge-on-Si waveguide integrated PDs are suitable for use in ionizing radiation environments, even without hardening. As the design of specific Ge-on-Si waveguide-integrated PDs varies only modestly across the device class, it would seem reasonable to speculate that these results apply broadly to the class, provided the design does not differ greatly from those studied in [12]. For additional details, including a discussion on what physical mechanisms may underlie the absence of a TID response, the reader is referred to [12].

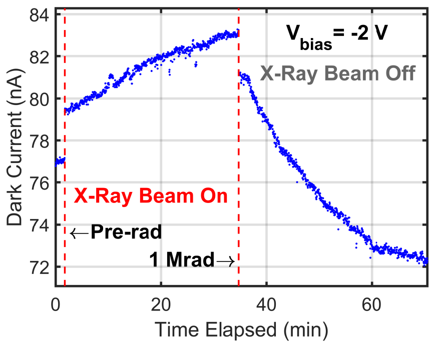

Fig. 7. The PD dark current measured in-situ during X-ray irradiation. Upon further investigation, the small changes observed here were determined to be temperature driven, and were not attributed to a radiation effect.

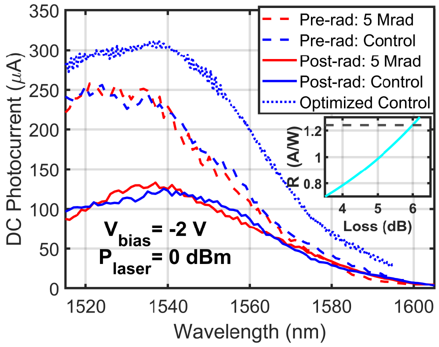

Fig. 8. The DC photocurrent response of the PD is compared against a non-irradiated control sample both before and after irradiation. The input optical power is fixed to 0 dBm and wavelength is swept. A measurement of the control sample in which the fiber-to-chip coupling efficiency was optimized allows for an estimate of the responsivity in the inset.

IV. FUTURE DIRECTIONS

Setting aside the promise of these initial studies, much work remains to prepare for broader deployment of integrated photonics in space. The remaining work includes, in no particular order, (i) experimental observation of transient heavy ion effects on photonic waveguides described above and in [11], (ii) investigations on the effects of non-ionizing radiation (i.e. displacement damage) on integrated photonic devices, (iii) circuit and sub-system level testing to examine aggregate level effects of many integrated photonic and electronic devices connected together (e.g. a Mach-Zehnder modulator with integrated electronic drivers), (iv) single event effects in waveguide-integrated PDs, and (v) radiation studies on InP-based PICs are also needed, especially since InP-based lasers on Si via hybrid integration remains the leading candidate for on-die optical sources in Si photonics [17].

CONCLUSIONS

Integrated photonics provides a technological development path for SWaP and cost scaling of optical systems, particularly in systems relevant for space applications where SWaP savings are exponentially more valuable. These savings have the potential to be enhanced even further by monolithic integration of electronic circuits and sub-systems on die, a capability which is already being commercialized [7], [8]. However, the effects of space radiation on PICs has not yet been fully explored. Early studies, including the two summarized here [11], [12], and others [13], [14], are beginning to suggest a picture of resiliency for Si-based PICs under the harsh space radiation environment. These findings, taken together with recent progress in laser-based communications in space, and with

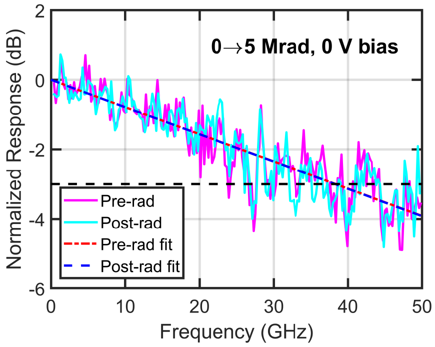

Fig. 9. The normalized O/E conversion frequency response of a Ge-on-Si waveguide-integrated PD at zero volts bias before and after receiving 5 Mrad(SiO_2) of X-ray irradiation.

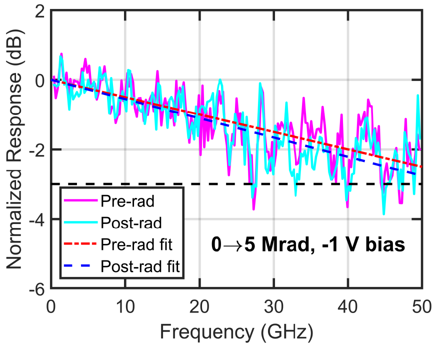

Fig. 10. The normalized O/E conversion frequency response of a Ge-on-Si waveguide-integrated PD at -1 V bias before and after receiving 5 Mrad(SiO_2) of X-ray irradiation.

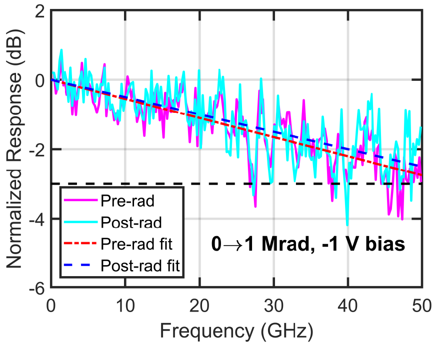

Fig. 11. The normalized O/E conversion frequency response of a Ge-on-Si waveguide-integrated PD at -1 V bias before and after receiving 1 Mrad(SiO_2) of X-ray irradiation.

the increasing prevalence of U-class spacecraft (CubeSats), and with the continued rapid advancement of PIC technology driven by terrestrial data and telecommunications applications, all point toward the coming of a new generation of ultra-low SWaP, radiation tolerant, optics-based communications and sensor technology for space applications.

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