Space Qualifying Silicon Photonic Modulators and Circuits

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Abstract: Here we performed the first space experiments of photonic integrated circuits, revealing the critical roles of energetic charged particles. The year-long cosmic radiation does not change carrier mobility but reduces free carrier lifetime, resulting in unchanged electro-optic modulation efficiency and well-expanded optoelectronic bandwidth.

1. Introduction

Optical communication with terabit capacity is demanded by key applications ranging from near earth to deep space communications, and from human-space exploration to astrophysics experi-mentss. Photonic integrated circuits (PICs) with extreme energy efficiency, bandwidth, and system-on-chip capacities have emerged as promising candidates for space-borne optical communication instruments and adaptive signal processors. Silicon (Si) PICs are foundry manufacturable, and the information exchange and broadcasting are carried out by optical wave-guides (WGs), which drastically expands the throughputs compared to copper interconnect, and naturally less sensitive to electromagnetic interferences, charge-related total ionizing dose (TID) and transient single-event effects. The displacement damage (DDD) of the particle radiation-induced defects is the primary concern for bulk optoelectronic components. Understanding the PIC's response to high-energy particle radiation not only facilitates this nanophotonic technology to be infused into future flight missions involving electronic circuits and fiber-based technologies [1, 2]. Such knowledge also provides scientific insights toward the explorations of nanoscale photonic modulation of energetic particle beams, particle-photon entanglement, and particle quantum optics [3, 4].

Cosmic radiation covers a wide set of radiation sources with a broad range of energy spectra. Space radiation is composed of two primary groups: cosmic rays of electromagnetic wave packets, and radiation particles (protons, electrons, and heavy ions) reaching extremely high kinetic energy. Ground radiation tests of Si PICs have been focusing on single frequency gamma and X-ray exposure of passive devices, with dosage equivalent to 1000 years of exposure on LEO. The high dosage of such electromagnetic radiation results in primary TIDs in silicon-on-insulator (SOI) and reduces the tuning efficiency. Particle radiation (especially protons and heavy ions) is considered the primary cause of degradation for bulk optoelectronics in space, but no study has been found on the particle radiation impacts on the nanoscale-doped photonic circuits. Brasch et al. combine four proton sources for reproducing the particle radiation energy spectra close to LEO and exposed passive SiNx PICs [5], but the high energy portion of the cosmic radiation particles is still missing. We know also the exposed material is undoped SiNx PICs, rather than the doped Si that we study here. Such high-energy proton exposure can lead to cluster defects and cannot be shielded even with a 10mm Aluminum (Al) sheet.

When the high-speed cosmic particles incident on the device's top surface, their kinetic energy attenuates with their penetration depth. Cascaded atomic structural damage is expected along its trajectory as the energetic particle collides with adjacent and secondary atoms. Monte Carlo simulations capture that such nuclei displacements scale with the particle mass but are inversely correlated with the particle velocity. In bulk optoelectronic components, the speed-attenuated orbital protons create nuclei vacancies and displaced atoms in the active layer embedded at least a few µm below the top surface, leading to device degradation. In optical fibers, increased insertion loss and change in refractive index were observed after cosmic radiation exposure. However, the high energy proton radiation impacts on nanoscale optoelectronic circuits are fundamentally different. Minimal nuclei displacement is expected given orbital protons' high kinetic energy and limited attenuations when they reach the top device layer of SOI, but little is known about the optoelectronic device response to the charged particle interactions with the bounded electrons. Especially, the charged particles' inelastic scattering with bounded electrons takes place at much higher kinetic energy (upto 100MeV) compared to nuclei (k-MeV) Fig.1A.

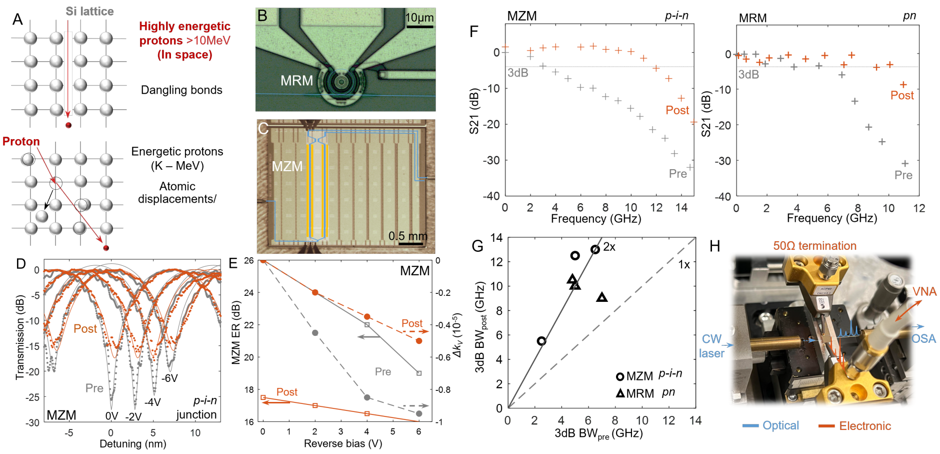

Fig. 1. Atomic origin and impacts on silicon photonic device level responses.(A) The atomistic picture of highly energetic protons in space triggered ionization of bounded electrons and thus the mid-gap defects, and low energy proton-induced atomic displacement, creating carrier scatter centers and reduce carrier mobility. (B) Microscope image of the MRM (size of 10µm) and (C) MZM with sub-centimeter feature size. Blue lines: optical WG path.(D) Voltage-dependent transmission spectra of the same MRR and (E) MZM pre- and post-flight. Dots are measured data points and the curves are the theoretical fitting. (F) Measured electro-optic modulation response S21 of an MZM pre- (grey) and post-flight (or-ange), and S21 comparison for MRM. (G) 3dB optoelectronic bandwidth of post-flight devices versus pre-flight devices for the MZMs (circles) and MRMs (triangles). (H) Setup for characterizing the high-speed response of MZM.

2. Results

Leveraging the manufacturing capability of Si photonic foundries, we performed the first space test of subwavelength photonic devices by exposing arrays of Si PIC devices and circuits on LEO for nearly 11 months [6]. The PICs from different foundries were mounted on the Materials International Space Station Experiment-Flight Facility (MISSE-FF) located near the exterior of the International Space Station (ISS). The radiation dosage is expected to approach the amount received by the optical instruments in CubeSat missions. Si photonic modulators with µm and sub-cm size (Fig.1 B-C) were prepared to compare their direct current, continuous wave response, high-speed optoelectronic, and nonlinear optic responses before and after LEO exposure. Limited charge scattering centers are created, given the unchanged carrier mobility, series resistance, and electro-optic tuning efficiency. The significantly reduced free carrier lifetime, reflected as the expanded optoelectronic bandwidth and reduced thermal nonlinearities, is attributed to the high energy protons created dangling bonds in the top Si layer on SOI. Through characterizing arrays of doped waveguides with different lengths, we observe the evidence of the heavy ion degradation and damaging trajectories along SOI.

The LEO-exposed MPW dies include arrays of the carrier depletion-based Si photonic modulators, including 10 µm radius MRMs (Fig.1 B-C) and MZMs with the active arm length of sub-cm. The bias and RF electronic signals are sent to the chip through high-speed GSG probes. The Si single-mode WGs define the optical paths for making the interferometric circuits (marked as blue lines in (Fig.1 B-C)). Different from most of the ground test reports, our experiments show that the electro-optic tuning efficiency remains invariant after radiation exposure for both MRMs and MZMs (Fig.1 D-E). The extinction ratio (ER) drops from near 24 dB to 14 dB for MRMs drops from 26 dB to 17.5 dB for MZMs (Fig.1 D). By fitting the model to the transmission spectra, the intrinsic quality factor for the MRM is extracted for pre- and post-flight devices (drops from 36k to 25k at zero bias), indicating 30 percent in-crease in propagation loss . Reduced sensitivity of ER and extinction coefficient to reverse bias is observed in both MZMs and MRMs (Fig.1 E).

The impact of the LEO exposure on micro-electronic properties is characterized across tens of p-i-n junctions in MZM and p-n junctions in MRM. No significant change in capacitance or series resistance of the junctions was observed, where series resistance is inversely related to carrier mobility. Increased ideality factor (average value from 1.37 to 1.43) and reduced reverse saturation current are identified by fitting the IV curves of p-n and p-i-n junctions. The high-speed optoelectronic spectra of that carrier depletion-based Si photonic MZMs and MRMs were carried out using identical experimental apparatus (same power level of optical carrier, and RF signal) for pre- and post-flight samples (Fig.1 F). Within ¿30 measurement datasets per device for 12 devices (3 pairs of MZMs and 3 pairs of MRMs), it is conclusive that S21 spectra show well-expanded 3dB optoelectronic bandwidths across multiple modulators with different device footprints(Fig.1 G-H). The faster modulator response, along with the increased ideality factor and reverse saturation current, indicates the reduced recombination lifetime. Note that the photon lifetime in MRM is around 5ps.

3. Conclusion and Discussions

Despite numerous proposals of system-on-chip integration of optical modules for avionics, limited literature is found on space radiation impacts on nanoscale devices, which are critical in propelling nanotechnology for space instrumentation. In addition to the unknown radiation spectra, the device-to-device variations are another challenge blurring the underlying physical mechanism. In this work, we advance the understanding of these issues by sending foundry-manufactured dies with hundreds of passive and active devices beyond 2,000 km altitude. Those nanoscale optoelectronic devices and circuits are characterized by the electronic, optical, high-speed optoelectronic, and nonlinear optics aspects. Studies in bulk semiconductor components indicate the charged energetic particles recombine or migrate and form stable defects in the Si lattice structure, resulting in reduced carrier mobility and optoelectronic efficiency [43-44]. No study has been found on the effects of particle radiation on doped PICs. Interestingly, the reduced free carrier lifetime in the Si device layer leads to optoelectronic bandwidth improvement of MZMs and MRMs. In contrast, the sub-cm long active long arm with p-n junctions shows a few dB excess loss, which results in reduced ER in both MZMs and MRMs. Nevertheless, after long-term exposure, the ER stays beyond 10 dB, providing sufficient modulator amplitude. Remarkably, the tuning efficiency of both types of modulators remains unchanged, unlike many ground radiation exposure results on PIC. Also, we observed that four adjacent long WGs with p-i-n junctions suffered from very high insertion loss after LEO exposure, likely attributed to the accidental deposition of heavy ions and formation of nanoscale cluster defects. The behavior of heavy ions (mostly coming from galactic cosmic rays) aligns with the characteristic of low possibility but disruptive damage to the Si nanowire, including low flux 4 particles cm-2s-1, high atomic number, and high energy. The deposition and reflection of a single heavy ion on Si WG arrays lead to the disconnection of multiple cm-long active WGs on the same row.

The small form factor and space radiation hard on-chip active nanophotonic instruments may provide a miniaturized system-on-chip platform for future astrophysics study, earth science observations, and space optical communications. Our research combines the specialties of astronomy and nanoscale optoelectronics, specifying the major impacts on Si photonics from the high-energy or-bital particle radiation from the complex space environment. The ground tests with high-density (k-M rad) X-ray or -ray exposure on Si, a-Si, SiC, and SiNx PICs result in totally different types of radiation damage of TID associated with surface oxidation. In contrast, the LEO cosmic radiation dosage is much lower but carries extremely high energy particle radia-tion including protons, alpha particles, and heavy ions. The lightweight charged particles alter the electronic bonds and mid-gap defects without reducing carrier mobility. After carefully evaluating nine aspects of the nanophotonic device responses over 100 devices, we conclude that the orbital radiation does not create carrier scattering centers but introduces carrier recombination centers, which result in unchanged driving voltage and reduced bit-error rates for PIC transceivers, respectively. By avoiding large footprint modulators, those radiation-hard active nanopho-tonic components can build fully integrated systems with minimal shielding requirements for year-long orbital operation [6, 7].

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