Sandia's Radiation-Tolerant Silicon and InP Photonics Platforms with Multi-Project Wafer Runs

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Abstract—**Radiation-tolerant photonic integrated circuits have the potential to revolutionize communication, sensing, and computing for space and terrestrial systems, offering improvements in isolation, size, weight, power and performance, as well as entirely new functionalities. Sandia's National Security Photonics Center has developed integrated photonics platforms in silicon, GaAs, InP, and antimonide superlattices (detectors). These platforms integrate lasers, amplifiers, modulators, detectors, switches, filters, multiplexers, waveguides, and other passives. We create compact microsystems with complex photonic functions both monolithically and through heterogeneous integration of silicon and III-V photonics, CMOS, and other electro-optic materials. We have characterized these photonics platforms in radiation environments with both high-energy microbeams (as narrow as 1 micron) at Sandia's Ion Beam Laboratory and flood sources. Leveraging these capabilities, we interrogate with radiation individual elements of operating integrated photonics circuits and smaller substructures of those components and have developed new understanding of radiation effects in our photonics microsystems. Consequently, our modeling, design, and testing capability, informed by our radiation characterization results, allows us to substantially shorten the development cycle for radiation tolerant photonics. In addition, Sandia runs collaborative multi-project wafers in Silicon Photonics, InP Photonics and Silicon Read-out Integrated circuits (ROICs) that incorporate this learning. We will also describe Sandia's custom photonic solutions for other harsh environments.**

Keywords—photonics; radiation; multi-project wafer

I. Introduction

Photonics has the potential to enable new architectures and increased capabilities in military sensing, communication, and computing [1,2]. Integrated photonics offers benefits of high-bandwidth, scalability, and agility while improving size, weight and power over systems built using discrete components. Sandia's National Security Photonics Center [3] and its 60+ staff leverage the Microsystem & Engineering Science (MESA) fabrication facility to develop and deliver leading-edge integrated photonics solutions for national security.

Sandia operates the MESA semiconductor fabrication facility, a co-located silicon fab and compound semiconductor fab with a dual mission: product delivery and cutting-edge R&D. The MESA fab enables development, prototyping and small volume manufacturing of optoelectronics spanning TRL1-6+. Portions of the MESA fab activity are compliant to NNSA QMS/QC-1/10 requirements, and a subset of this is DMEA certified as Trusted.

Sandia offers both ASIC and silicon photonics MPW runs from the silicon fab. The compound semiconductor fab has foundational materials capabilities in virtually all III-V semiconductors enabling optoelectronic devices such as VCSELs, focal plane arrays, GaN-based photonics, and InP/GaAs photonic integrated circuits (PICs).

II. Radiation Testing- Capabilities and Photonics Characterization

A. *Sandia's Radiation Testing Facilities*

Sandia operates multiple radiation testing facilities including the Annular Core Research Reactor (ACRR), Z-Machine, the High-Energy Radiation Megavolt Electron Source (Hermes, a gamma simulator), the Gamma Irridation Facility (GIF), Saturn (X-rays), multiple Cobalt-60 sources, and the Ion Beam Laboratory (IBL). The IBL employs accelerators, implanters, in-situ TEM, electron beam systems, and other specialized equipment that enable its users to simulate various types of radiation exposure with targeted and precise beam placement[4]. The experiments at the IBL are then calibrated to global exposure of circuits, in this case, photonic circuits, at one of Sandia's captive radiation exposure facilities for neutron and gamma radiation, or an external facility's source.

B. *Compound Semiconductor Photonics*

Our team has broad expertise with radiation effects in arsenides, phosphides, antimonides and nitrides for devices that include lasers, photodetectors, and VCSELs through all the Sandia facilities mentioned above. InP-based photonic integrated circuits are comprised of lasers, amplifiers, modulators, and detectors. We can interrogate each of these elements individually using our Ion Beam Laboratory facility. We report InP photonic integrated circuits operated and monitored under irradiation in a Pelletron accelerator with He ions and in a Tandem accelerator with Si (heavy) ions. Experiments were performed with the ion beam scanned over the entire PIC, over individual devices, and over sub-sections of devices.

In an example measurement of an InP distributed Bragg reflector (DBR) laser, He ions were accelerated to create a damage plume in only the laser active region. The laser L-I curve was recorded by sweeping the gain section of the laser and monitoring the photocurrent in an on-chip integrated photodiode (Fig.1). The resulting increase in threshold current and reduction in differential efficiency of the laser L-I characteristic were similar to a laser subjected to neutron irradiation. Using

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this technique, users can strategically target various components and subcomponents of opto-electronic devices to realize a deep understanding of radiation effects and then design in techniques to improve the radiation response. Figure 2 shows the performance of an integrated electro-absorption modulator subjected to He ion bombardment. Using this technique, we were able to witness (and measure) resilient modulator performance isolated from the effects of the other photonic circuit components (DBR laser and photodiode).

C. *Silicon Photonics*

CMOS-compatible silicon photonics offers low-cost, low-power, and high-bandwidth solutions for communication, RF signal processing, beam-steering, precise timing and control and many other government applications [5]. Responses to gamma radiation of silicon photonics devices, including passive waveguides, resonant disk modulators with PN junctions, and integrated Germanium PIN photodiodes, were investigated at Sandia. These devices were irradiated using a cobalt 60 source with 130 rad/s dose rates, reaching a total dose up to 1Mrad. Gamma-radiation experiment results indicate that while degradation in performance may be possible in some cases in terms of optical loss and bandwidth, these devices are capable of operating in harsh environments required by many mission applications. Details of these results are presented in other papers at this conference [6,7]. Effort are on-going to further understand radiation effects, not only from gamma rays but also neutrons and heavy ions.

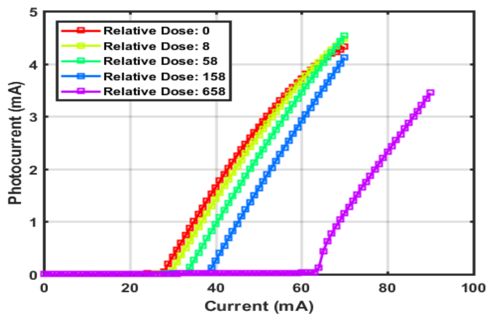


FIGURE 1. Light output of a DBR laser as a function of gain section drive current. The light was collected using an on-chip integrated photodiode. Performance degradation of the laser was due to irradiation damage from He ion bombardment.

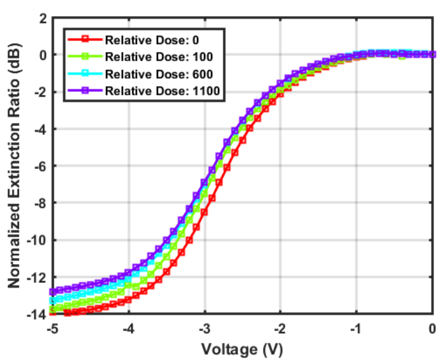


FIGURE 2. Normalized extinction ratio as a function of applied modulator voltage. The light was collected using an on-chip integrated photodiode. Performance degradation of the modulator was due to irradiation damage from He ion bombardment.

III. MULTI-PROJECT WAFERS

Sandia National Laboratories currently runs silicon photonics multi-project wafers (MPWs), silicon read-out integrated circuits on MPWs, and we are preparing to offer InP MPWs. Sandia's integrated photonics are fabricated in a trusted, ITAR-Controlled, limited access (classified) facility in Albuquerque, New Mexico.

A. *Silicon Photonics*

Over nearly a decade, Sandia has engineered a mature silicon photonics process (Fig.3). This electro-optical silicon photonics integrated circuit platform is built on silicon-on-insulator (SOI) wafer, which includes two waveguide interconnect layers (in silicon and silicon nitride), dopant implants to provide active p-n junctions and low resistance contacts, and metal interconnect with optical cladding layers (Fig.4). Examples of state-of-the-art devices that have been recently demonstrated by Sandia using this process include passive and active devices such as avalanche photodiodes [8], QKD transceivers [9], high-speed ultra-broadband amplitude modulators [10], arrayed waveguide grating based RF channelizers [11], micro-disk modulators for cryogenic temperature operation [12], and optical phased arrays for chip-scale beam steering [13].

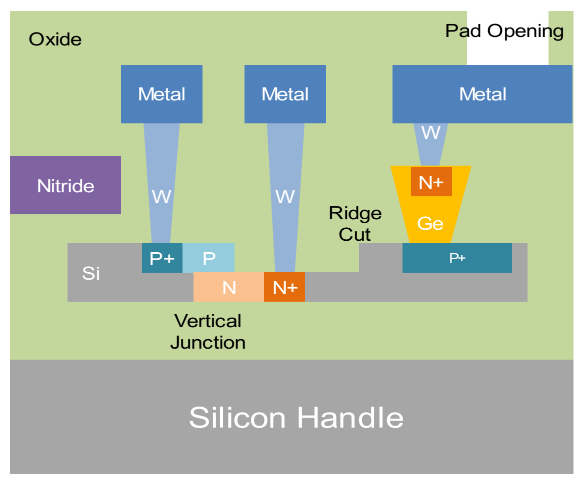


FIGURE 3. Silicon Photonics platform device schematic.

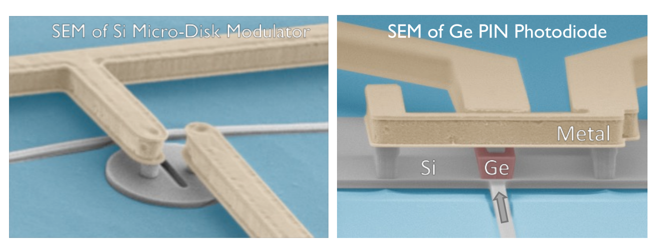


FIGURE 4. SEM photos of a silicon photonic micro-disk modulator and a Germanium PIN photodiode

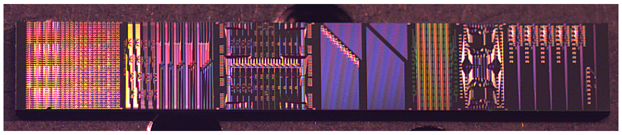


FIGURE 5. A set of devices from a Silicon Photonics multi-project wafer run.

To facilitate designers to develop prototypes and products, Sandia's Silicon Photonics device library contains 20 active components and 22 passive components, supported by 37 issued patents. The PDK, developed with Synopsys OptoDesigner software (previously PhoeniX), allows for collaborative design. Future multi-project wafer offerings will run on a 200 mm SOI platform. We offer three types of deliverables: passive (Si + SiN), Passive + Active, and Passive + Active + Germanium, the later using selective area germanium epitaxy. Our typical block is 4 mm x 26 mm. Fig. 5 shows a completed MPW deliverable with 5 riders.

Efforts are on-going to advance the current silicon photonic platform with the integration of electro-optic materials to enable nonlinear optical applications and high-power handling. In one implementation, a die of unpatterned thin-film lithium niobate (LN) is bonded to a silicon photonic die. Guided light propagating in the silicon layer is coupled into the thin-film lithium niobate (LN) layer via appropriate waveguide designs[14]. Demonstrated optical circuits include an electro-optic Mach Zehnder modulator (MZM) with greater than 100-GHz electrical modulation bandwidth [15]. This heterogeneous integration approach does not require etching fine features in the LN film and may be extended to wafer scale processing.

Heterogenerous integration also offers the opportunity to integrate amplifers and lasers into the silicon photonic platform [16]. III-V epitaxial layers may be transferred onto a silicon photonic SOI substrate and then patterned to create hybrid structures with optical gain. This capability is currently being implemented at MESA's co-located silicon fab and semiconductor fab at Sandia to support applications requiring compact form-factor and high-power.

B. InP Photonics

Sandia National Laboratories has a state-of-art InP/GaAs PIC design and fabrication capability supported by 15 years of development experience and > 21 issued patents [17,18,19,20]. Our platform's foundation is state-of-the-art III-V semiconductor crystal growth using metal-organic chemical vapor deposition (MOCVD) with post-growth quantum-well band-gap modification using quantum-well intermixing (QWI) methods. We operate two arsenide-phosphide MOCVD reactors with tailored in-situ monitoring capability.

Sandia's InP device library includes active devices such as tunable diode lasers, modulators, amplifiers, detectors, and passive devices such as multi-mode interference devices, turning mirrors, and interconnection optical waveguides. In addition, we also commonly include electrical passive components such as co-planar waveguides, microstrips, capacitors, and resistors. Figure 6 shows a cross-section of the device layers while Fig. 7 shows example photonic integrated circuits designed and fabricated in the Sandia InP line.

Lasers/Amplifiers

Sandia can integrate single-mode (>40 dB SMRS) tunable lasers with other active and passive components to provide an on-chip source of coherent light. We have also demonstrated monolithically integrated injection locked lasers.

Semiconductor optical amplifiers (SOAs) can be used throughout PICs to boost input and output powers where needed. It is important to carefully design and characterize SOAs as they have the potential to require large amounts of electrical power and add noise to the signal. The key parameters in designing the SOAs are the signal gain, amplified spontaneous emission (ASE) and saturation power. When using an SOA for amplification of information carrying signals it is imperative to operate the SOA in the linear regime to avoid pattern dependent effects and distortion. Sandia has developed a process for realizing a two-stage amplifier where the first stage features high gain and the second stage features high output saturation power.

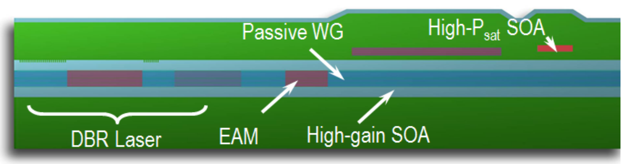
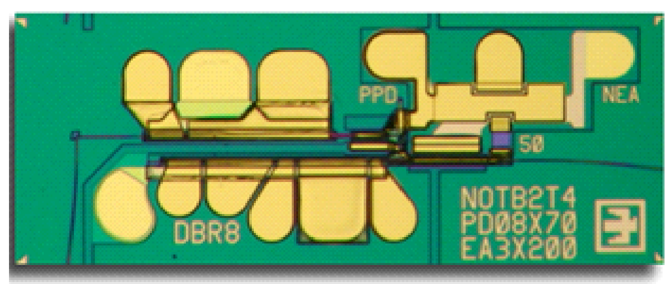
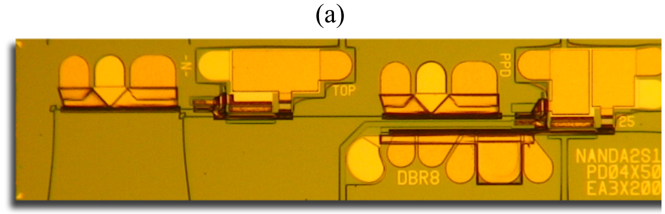


FIGURE 6. Depiction of the cross-section of an example photonic integrated circuit which shows the various regions tailored for specific functions of a particular device.



(a)



(b)

FIGURE 7. Example monolithic intergrated InP photonic integrated circuits. (a) A 40 Gbps NOT all-optical logic chip and (b) a NAND all-optical logic

Photodiodes

Photodiodes are commonly characterized by their responsivity and bandwidth. However, for analog type circuits the input saturation power is also of interest. Sandia has patented a method to improve the power handling capability of PDs by using evanescent coupling. The space between the waveguide and absorber, the collector, is designed for evanescent coupling, which distributes the optical absorption along the length of the device. This prevents a buildup of photogenerated carriers at the front end of the device, which mitigates field screening and allows the device to handle higher optical powers.

Modulators

Sandia has developed a full range of optical modulators including, electro-absorption modulators (EAM), Mach-Zehnder modulators (MZM), as well as phase modulators. These devices are characterized by the insertion loss, modulation efficiency, and bandwidth. For the cases of amplitude modulators, they are also characterized by the extinction ratio. Specifications can be found in Table 1.

Passives

Passive circuit elements serve to route the optical signals to various parts of the PIC. Specified here are several passive circuit elements, including low loss optical waveguides, total internal reflecting (TIR) mirror, and multi-mode interference (MMI) splitters/combiners. The TIR mirror can turn the optical path 90° with essentially zero bend radius. This makes for very compact circuits. Sandia has processes for multiple types of optical waveguides and techniques for coupling between them. We also have buried heterostructure waveguides.

Sandia is preparing to provide a three-tiered collaborative MPW offering. Tier 1 employs a single regrowth process but the devices have some limited performance metrics. Tier 2 adds process complexity (two re-growths) but offers improved device performance. Tier 3 is a full custom process that allows us to engineer the highest performance levels. See table 1.

Sandia will provide PDKs for each component within a standard device library using, for example, Synopsys Optodesigner software. Second, we will provide design service from our staff at cost, but consistent with the cost of European foundries. Full custom designs would involve staff engagement in the design. The MPWs will start on a 2” InP wafer platform with four wafers per lot.

C. Silicon Read Out Integrated Circuits for detectors

Sandia has many years of experience developing end-to-end solutions for fully-custom ROICs and focal-plane arrays for a variety of national security customers. This includes fully-custom design and fabrication of ROICs in Sandia and commercial foundries, design and fabrication of custom photodetectors (silicon, III-V, P-i-N, pinned, and avalanche photodiodes), and development of the processes required to bond photodetectors to ROICs (primarily indium and direct-bond-interconnect). These fully-custom focal-plane arrays range from large-format (> 1600 mm^2) imagers to the world’s highest-speed imagers [21].

TABLE 1.
Sandia designs ROICs and other custom integrated circuits

Process		Tier 1	Tier 2	Tier 3
Description		One MOCVD regrowth	Two MOCVD regrowths	Full custom process
Lasers	Tunable (~5 nm)	YES	YES	YES
	Tunable (~40 nm)	YES	YES	YES
SOA	High Gain (dB/cm)	400	400	400
	High P_{sat}	NO	YES	YES
Detectors	R (A/W)	0.8	0.8	0.8
	P_{in} saturation (dBm)	15	15	15
	Bandwidth (GHz)	> 20	> 40	> 40
Wave-guide	Propagation Loss (dB/cm)	< 2	< 2	< 2
	Turning mirror loss (dB)	N/A	< 0.5	< 0.5
EA-Modulator	Length (µm)	125	125	125
	Efficiency (dB/V/cm)	800	800	800
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	40	40
MZ-Modulator	Electrode Length (µm)	250	250	250
	Efficiency (V_π)	2	2	2
	Loss (dB)	~1	~1	~1
	Bandwidth (GHz)	> 20	> 20	> 40
Phase Modulator	Length (µm)	200	200	200
	Efficiency (°/V)	20	20	20
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	> 20	> 40

in our silicon line (as well as most other foundries) using Sandia’s radiation-hardened CMOS7, 350 nm fabrication process. MPW runs will be on a 200 mm platform, and Sandia’s CMOS8, 180 nm MPWs will be available in the near future. MPW runs are generally offered at the beginning and middle of the calendar year. As with Sandia’s InP MPW engagement model, design in Sandia’s CMOS7 process can be performed (1) wholly outside of Sandia with Sandia’s Cadence- and Synopsys-compatible PDK, or (2) partial to full-custom analog and/or digital design through engagement with Sandia’s integrated-circuit design staff. A variety of IP is available to support core analog and digital functions.

IV. SUMMARY

Sandia National Laboratories offers access to multiple photonics MPW runs for National Security applications. These MPW platforms have been informed by Sandia’s experience with photonics in radiation and other harsh environments, allowing us to substantially shorten the development cycle. The silicon photonics MPW program has successfully produced photonic integrated circuits for a variety of customers. Sandia’s new InP MPW offering will leverage > 15 years of photonic integrated circuit development and a full library of photonic elements.

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