Abstract—We review Sandia’s silicon photonics platform for government applications. Silicon photonics offers the potential for extensive size, weight, power, and cost (SWaP-c) reductions compared to existing III-V or purely electronics circuits. The Sandia fabrication facility is certified as a trusted foundry and can therefore produce devices and circuits intended for military applications. We will describe a variety of silicon photonics devices and subsystems, including both monolithic and heterogeneous integration of silicon photonics with electronics, that can enable future complex functionality in aerospace systems, principally focusing on communications technology in optical interconnects and optical networking.

1. INTRODUCTION

Optical interconnects have been proposed for more than 25 years as the solution to the limitations of electrical interconnects [1]. They have moved from being the solution only for long distance networks to being the dominant interconnect within local area networks in large enterprises and for rack-to-rack interconnections in data centers and high performance computers. Today, almost all subsystems consist of high value electrical chips with electrical IO connected to optical transceivers surrounding it to provide longer distance communications than is practical with only electrical connections. However, in the long run, both the bandwidth density and power limitations of having to traverse the connections between electronic ICs and the optical transceivers will place a serious limit on the IO bandwidth and power consumption.

In addition to optical interconnects, which are largely digital in nature, there is a burgeoning interest in using photonics to assist in very high radio frequency systems, known as RF photonics [2,3]. In electronic warfare systems if we can detect radar signals and send back a false reflection, we can fool the adversary into thinking we are at a different location, or even an array of targets (e.g. aircraft), versus a single one or visa-versa. To do that, we need to coherently detect the incoming radar signal, synthesize the desired reflection signal, and transmit that back to the sender. Importantly, but an issue beyond the scope here, is that our object must have low natural reflection compared to the signal we generate. The upward trend in radar frequencies beyond 100 GHz requires our detection and modulation to be agile over a full decade in RF frequencies from 10 GHz to greater than 100 GHz. Because this range is about 0.1% of the carrier bandwidth in optical systems, photonics holds promise for being able to assist in being able to make these systems with lower size, weight, power, and cost (SWaP-C) compared to their purely RF counterparts [3].

While there are important differences in the requirements of digital communication and RF systems, an intimately integrated platform consisting of electronics and photonics can achieve the ultimate in compactness, bandwidth, and when desired low power systems [4]. Two factors principally contribute to the overwhelming superiority of the approach. First, by locating the optical modulators close to (within a few micrometers) to the signal sources, we eliminate the power dissipation and signal degradation of long electrical transmission lines connecting the electronics chips to the optical transceivers [4]. Second, by using dense wavelength division multiplexing (DWDM), we can transmit signals from different sources on the chip on the same optical path (waveguide on the backplane and fiber from the backplane), increasing the bandwidth density by the number of wavelengths, which may be some day up to 100 wavelengths. Thus for communications applications, at 10 Gbps per connection, we can have 1 Tbps per waveguide or fiber, completely eliminating the bandwidth constrictions of the electrical IO of the high value IC. Importantly it doesn’t need to be a monolithically integrated platform if there can be many connections with high yield and low capacitance. Indeed flip-chip bonding and 3D chip stacking can be a more appealing solution as it does not require compromises in either the electronic or photonics technologies to accommodate the integration. It also allows for more efficient area utilization by using the third dimension.

Within the last 10 years, there has been important technology maturation in silicon photonics [5-11]. Silicon photonics offers the key critical components required to realize this integrated platform: small low capacitance optical modulators [5-7] and detectors [8-9], DWDM multiplexers [10-11], and a waveguide routing platform to bring the light onto the chip where it can be coupled to optical fibers. Silicon also has the important advantage of being the same material as the electronic ICs, eliminating potential problems arising from differing coefficients of expansion in thermally varying environments.

2. SILICON PHOTONICS INTRODUCTION

Silicon photonics uses etched silicon waveguides surrounded by silicon dioxide (or oxide as it is often called) as shown pictorially in figure 1a. The silicon and silicon
dioxide have a high difference in refractive index that allows the silicon to guide light around relatively sharp bends, facilitating devices with dimensions in the few micrometer range. We can build an optical filtering function in silicon by coupling the light into a microresonator as shown in figure 1b. If you consider light of varying wavelength, light that is resonant with the wavelength of the resonator will couple into the resonator and then to the ‘drop port’. All other wavelengths of light will not couple to the resonator. This creates a dip in the transmission spectrum from input to output for the light that can resonantly couple. An example is given by the red curve in figure 1d.

If we implant n-type and p-type dopants into the waveguide in the ring (or disk), we make a p-n diode structure (1c). The diode’s charge varies according to the voltage applied across the diode. The index of refraction of the waveguide also changes as a function of the charge in the waveguide; hence we can modulate the voltage on the diode to change the index of refraction and thus the position of the resonant frequency. This is shown in Figure 1d for 2 voltages, in this case 0V and 3.5V reverse bias. Remember, this is a modulator, so we need to bring in continuous wave (CW) light from off chip. After passing through the modulator, it becomes modulated with the data. So, if the light has an optical frequency at the green dashed line, the intersection of that line with the two curves shows that a logic one on the optical output occurs when the voltage is at 0V and a logic zero occurs when the voltage is at 3.5V reverse bias. So the shift in resonance as a result of the change in index of refraction is converted to a digital amplitude modulation.

Because the modulator is resonant, we can bring in a number of CW light sources and modulate each one with a different resonant modulator, without the need for a separate optical multiplexer as shown in Figure 2. Each modulator converts the electronic signal applied to the modulator to an optically modulated signal by modulating a different CW light source. For the receiver side of the link, we can use an optical demultiplexer consisting of cascaded passive microring resonators to demultiplex the optical signals onto detectors, grown in the silicon photonics process.

Many transceivers today use Mach-Zehnder modulators (MZMs), based on a phase-modulated interferometer, for their EO conversion at the transmitter because the environmental and fabrication sensitivities of the MZMs are much less stringent than those of resonant modulators. MZMs are more fabrication tolerant, can handle more power, and are generally more linear and suitable for RF analog applications.

3. PROCESS DESCRIPTION

Sandia’s silicon photonics process consists of a thin silicon layer with a thick buried oxide layer to prevent absorption of the optical wave in the substrate. A silicon nitride layer is deposited above the silicon layer to aid in coupling to fibers and provide a crossover layer for optical signal routing. Active devices are made in the silicon layer by selective p-type and n-type doping. Our devices use vertical PN junctions, which gives a stronger carrier concentration change with applied voltage; thus our devices tend to operate at lower voltage compared to most devices in the research community at large.

Germanium detectors are made using selective area growth on top of a silicon waveguide; the optical signal couples into the germanium region from the silicon waveguide below. A single layer of routing metal is generally used, although we
have processed one run with as many as five layers; that
same run included the monolithic integration of radiation-
hardened CMOS electronics with a silicon photonic
modulator [12]. We have also developed a design manual
that has enabled external collaborators to submit photonics
designs. This CMOS-compatible silicon photonics process
is implemented in Sandia’s Microsystems & Engineering
Sciences Applications (MESA) Complex, which was
certified as a Trusted Foundry by the DoD in 2011.

4. SILICON PHOTONICS DEVICES

Resonant Modulators
We have demonstrated among the lowest energy resonant
modulators to date with switching energies below 1
femtojoule per bit at 10 Gbps [13]. A photograph of a
similar device is shown in Figure 1c. When driven
differentially, we can make use of the optimal charge
transfer when biased slightly in forward bias while
maintaining the speed of a reverse biased device and
maintain compatibility with future low voltage CMOS
drivers with power supply voltages below 0.5V. Using these
differential techniques, the energy consumed by the
modulator itself was from 1 to 3 fJ/bit depending on the
desired extinction ratio from 3 to 5. It’s worth noting that a
similar modulator with somewhat higher doping in the n-
type and p-type regions achieved sub-femtojoule energies
per bit at data rates above 25 Gb/s [14].

Mach-Zehnder Modulators
We have demonstrated MZMs in the same process as the
resonant modulators with 3 dB bandwidths of 24 GHz [15].
The device bandwidth is constrained by the optical losses in
the silicon and RF losses in the aluminum metallization, but
further improvement in bandwidth is possible.

Integrated Germanium Detectors
On the receiver side, we have demonstrated Germanium
detectors with a 3 dB bandwidth of 45 GHz [9]. Typical
dark currents are ~ 10nA.

Tunable Filters and Modulators
We have also demonstrated integrated heater-modulators
with closed loop control sub-systems to stabilize the
modulator wavelength to the incoming laser [11,17]. These
will be described the next section.

2 x 2 Switching Elements
We have also designed electrically controlled optical 2 x 2
switching elements shown in Figure 5 for constructing
optical networks. We have developed broadband MZM
switches [15,18] and wavelength selective switches (WSS)
[7,11] either making use of thermal properties for
compactness and broadly tunable devices and carrier effects
for high-speed devices. The optimal choice of switch to use
depends critically on the application.

Figure 5: Mach-Zehnder (MZ) and Micro-resonator (MR)
switching elements [clockwise: 15, 7, 10, 18]

5. SUB-SYSTEMS

Transmitters
A silicon photonics modulator has a nice feature that it can
be driven very simply with a differential voltage [13]. The
device is driven with a positive and negative voltage, but the
positive voltage is always less than the sweep out voltage of
the device, so that it remains in slight reverse bias where the
carriers are swept out quickly. The differential drive enables
the maximum charge differential for a reverse biased device,
hence lowering the applied voltage compared to a
completely reverse biased device. Also, the voltage that
must be supplied by the CMOS circuit is only half of that
which must be applied by a reverse bias only circuit,
avoiding increased energy and potential reliability issues
that accompany a Cascode amplifier that is typically used to
double the CMOS voltage for high-voltage output drivers.
We have demonstrated the integration of CMOS differential drivers flip-chip bonded to these low voltage modulators as shown in Figure 6 [19]. The devices had 14 µm flip-chip pads on 50 µm centers. The electronic circuit was implemented using an IBM 45 nm CMOS process. Our first demonstration achieved 5 Gb/s operation at 80 fJ/bit, but relatively large series resistance in the bond pads was responsible for the limited speed of operation and the relatively high energy. That energy consumption included all the leakage paths in over 50 additional transceivers as well.

**Resonant Wavelength Control**

As the effective index of refraction of silicon is temperature and fabrication sensitive, small changes in either cause the device resonant wavelength to shift from its desired operating point. We have developed several methods to frequency lock a modulator and a filter to the incoming laser wavelength. The first used a sensor and with a thermal heater [20]. The device achieved lock over 55°C, but the limitation of the approach was that the sensor did not give a simple indication of the temperature of the ring. A second method relied on measuring bit errors on the drop port of a modulator [21]. That method has the advantage of optimizing the modulator for exactly the quantity that you care about, but has a disadvantage in that it requires a high-speed receiver at the transmitter. Lastly, we demonstrated both filter and modulator stabilization using a balanced homodyne detection method in Figure 7 [22]. Other techniques have been demonstrated by researchers using power measurements [23-25], dither signals, [26] and using Pound-Drever-Hall stabilization methods [27, 28].

![Figure 7: Balanced Homodyne detection locking of a filter to the incoming wavelength showing the (a) the photonic circuit, (b) the transfer function and (c) the experimental results with the filter locked to an oscillating laser [22].](image)

**6. SUMMARY**

We have described our silicon photonics process, devices, and sub-systems. These include ultra-low power high-speed modulators, thermo-optic wavelength control, integrated germanium detectors, optical wavelength selective and broadband switches, and flip-chip bonded heterogeneous integration of modulator drivers with silicon photonics. These devices, circuits and sub-systems will enable new functionalities and reduced size, weight, power, and cost compared with existing photonic technologies and traditional electrical solutions. This is expected to impact both commercial and government applications.

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**8. REFERENCES**

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