PHOTONICS AT SANDIA NATIONAL LABORATORIES:
APPLYING DEVICE TECHNOLOGY TO COMMUNICATION SYSTEMS

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ABSTRACT

Photonic device activities at Sandia National Laboratories are founded on an extensive materials research program that has expanded to include device development, and an applications focus that heavily emphasizes communications and interconnects. The resulting program spans a full range of photonics research, development, and applications projects, from materials synthesis and device fabrication to packaging, test, and subsystem development. The heart of this effort is the Compound Semiconductor Research Laboratory which was established in 1988 to bring together device and materials research and development to support Sandia's role in weapons technologies. This paper presents an overview of Sandia's photonics program and its directions, using three communications-based applications as examples.

1. INTRODUCTION

Research and development at Sandia National Laboratories has traditionally been driven by national defense, intelligence, and environmental needs. While pioneering the use of lattice-mismatched (strained-layer) quantum well heterostructures for band structure engineering [1] in the early 1980s, Sandia developed a comprehensive approach to in-house realization of radiation hardened optoelectronics components and subsystems for special applications [2-4]. More recently, activities in optoelectronic components and subsystems have responded to requirements for high-throughput communications and interconnect systems.

Sandia's applications-driven optoelectronics programs are founded on an extensive in-house materials effort and an on-site Compound Semiconductor Research Laboratory (CSRL) for device prototyping. Both Metal-Organic Chemical Vapor Deposition (MOCVD) and Molecular Beam Epitaxy (MBE) capabilities have grown with the program and are supported by a major effort in pre-process material characterization and real-time in-situ process monitoring. The CSRL is a 5000-square-foot class 100 clean room for device prototyping in the areas of electronic and microwave devices and circuits, photonic and optoelectronic devices and circuits, and nanostructures. Subsystem packaging and measurement capabilities support applications. Thus, the optoelectronics program encompasses a full range of complementary activities including physics research, materials growth, device design and fabrication, device packaging and test, and finally, subsystem packaging and development.

This paper first describes three applications: high data rate externally-modulated fiber-optic communications based on GaAs/AlGaAs Photonic Integrated Circuits (PICs); a free-space photonic interconnect system (Z-Axis Photonic Interconnects) for stacked multi-chip-modules (MCMs), and a surface-normal transmission or reflectance lightwave modulator for free-space communications to and from the weapon. These descriptions are followed by a discussion of optoelectronic and microelectronic devices being developed in support of these applications.

2. APPLICATION EXAMPLES

2.1 High-speed fiber-optic links for parallel computing and sensor fusion

Weapons applications of the twenty-first century will require large amounts of
computing power and connectivity for a variety of applications ranging from advanced simulation to sensor fusion in a data-intensive environment. In the design phase, workstation clusters will transmit and receive data to and from complex simulators modeling compounded environmental tests such as radiation, thermal excursions, and mechanical shock.

Stockpiled self-aware weapons in a sensor-rich environment will exchange large amounts of data about their state of health (including self-tests of their internal systems, safety data, and information on their immediate environment). Much of this data will be carried on optical fiber networks at tens of gigabit per second data rates and possibly using Wavelength Division Multiplexing (WDM), making PICs an important enabling technology for optical modulation and switching. Both wavelength-selective and wavelength-independent devices are needed in active and passive form.

2.2 Z-Axis Photonic Interconnects for Stacked MCMs

Within the self-aware weapons and workstations described above, the use of highly parallel arrays of processor ICs for in-situ computing will push the number of interconnects per MCM to counts ranging in the thousands at speeds in the hundreds of MHz. Figure 1 illustrates the concept behind a photonic interconnect for stacked MCMs which addresses the inevitable problems associated with high densities of interconnects at high speeds: crosstalk, separability, and physical room on the MCM. Figure 2 shows a cross-section of an intermediate demonstration which employs 980 nm Vertical Cavity Surface Emitting Lasers (VCSELs), connected to integrated photoreceivers. The VCSELs were chosen for this demonstration because of their relatively efficient electrical-to-optical power conversion, low-divergence beam properties, and ability to be modulated at high data rates. The low-divergence VCSEL beam, wavelength stability, and device substrate transparency also allows for the use of techniques such as focusing binary optics. PIN diode detectors are integrated with InGaAs/InP Heterojunction Bipolar Transistors (HBTs) to build photoreceivers on InP [5]. These photoreceivers feature very low power consumption and integrated micro-optics. Our studies indicate that, for a stacked MCM system, the use of VCSELs is preferable to an implementation based on Light Emitting Diodes (LEDs). This is particularly true for the high-efficiency VCSEL devices that have resulted from Sandia’s device research and development programs, as described below. Though the VCSELs in Figure 2 do not operate at wavelengths that are transparent to silicon, laser-drilled holes can be used to allow communication between MCM layers.
2.3 Remote Data Communications using a Transmission Modulator

Figure 3 illustrates the cross-section of a packaged electro-optical modulator for remote data communications [6]. Here, an asymmetric Fabry-Perot transmission modulator is combined with a miniature optical corner reflector element to enable remote modulation of electrical data onto an external light beam coming from an optical fiber or free-space laser. The corner reflector assures the return of the data to the location of the source light beam from any direction within its 30 degree solid-angle acceptance cone. The modulator device is made from epitaxially-grown InGaAs-InAlAs Bragg-mirror stacks combined with a strained InGaAs-AlGaAs superlattice region to form a reverse-biased PIN diode on GaAs. Depending on size and structure, this device has the capability of modulation in the hundreds of MHz. The mirror stack and active material region can be tuned for operation at various wavelengths. Modulators of this type have been built for operation at 1060 nm and at 1300 nm [7],[8]. Modulation depths in the range of 30%-60% (depending on mode and wavelength of operation) have been demonstrated.

Figure 3. Packaged transmission modulator for remote laser communication.

3. PHOTONIC DEVICE RESEARCH AND DEVELOPMENT

3.1 Vertical Cavity Surface Emitting Lasers (VCSELs)

Sandia's program in VCSELs for communication and interconnect has two major thrusts: developing reliable, highly efficient, individually addressable, electrically pumped VCSELs at 980 nm and at visible wavelengths [9],[10]. The 980 nm VCSELs are being developed in the (In,Ga)As materials system. Sandia also demonstrated and is developing visible VCSELs (red) in the (Ga,In)P/(Al,Ga,In)P material system. Figure 4 illustrates the cross-section of a high-efficiency 980 nm VCSEL, along with a light-current curve showing its performance. The inset shows a cross-section the device. Due to the selective oxidation layers (shown in the device cross-section), this VCSEL operates with the high efficiency and low threshold current shown [11]. This is an important extension of Sandia's previous work on material doping and mirror profiling to achieve minimum series resistance in the device. The addition of the oxidized layers has resulted in the record -50% wall-plug efficiency (at <2 mW of output power) indicated in Figure 4.

Figure 4. Characteristics and cross-section of a 980 nm high-efficiency oxidized-layer VCSEL.

3.2 Photonic Integrated Circuits (PICs) and GaAs/AlGaAs Phase Modulators

Figure 5 illustrates the basic structure of the high electrooptic Figure of Merit (FOM) modulators that Sandia is building to realize photonic integrated circuits. Here, the GaAs and GaAlAs layers provide vertical confinement in the waveguide, while the rib effects horizontal confinement.
Etched Rib Waveguide

a. Etched rib waveguide structure.

Figure 5. High-FOM GaAs/AlGaAs Rib-Waveguide Structure.

The structure is a reverse-biased p-n junction, where the diode depletion region overlaps the central GaAs waveguide region. Because of the combined effects of high electric field and carrier sweep-out, the structure provides the high FOM (optical phase shift at a given voltage and length) described above. A wide-bandwidth version of the phase modulator has also been demonstrated. This device features a distributed electrode design that matches the optical and electrical wave velocities to achieve high-frequency, broadband modulation capability [12]. Other designs are being optimized for coupling to optical fibers, and special package arrangements are being developed to overcome the intrinsic mode mismatch between the device of Figure 5 and optical fibers [13].

A GaAs/AlGaAs rib-waveguide combiner/splitter is illustrated in Figure 6. This and other designs for splitters and combiners are used to create Mach-Zehnder intensity modulators and frequency-shifters from the high-FOM phase modulators described above. They take advantage of advanced etch monitoring [14].

b. GaAs/AlGaAs waveguide cross-section.

Figure 6. A rib-waveguide splitter/combiner for GaAs/AlGaAs PICs.

3.3 Reflectance Modulators

Experience with VCSELs provides a technology base for the development of surface-normal reflection/transmission optical modulators. This electro-optical modulator device is an adaptation of the classical Asymmetric Fabry-Perot (AFP) Reflectance Modulator and relies on the red-shift of the absorption edge through the quantum-confined Stark effect to attenuate reflected light in an unbalanced, vertical Fabry-Perot cavity. The design has been extended to include a second coupled cavity which recycles the transmitted light discarded by the original device for wider-wavelength operation over a greater temperature range [15]. As discussed, applications for these devices include both free-space and fiber-based bidirectional optical communications and control.

4. CONCLUSION

This paper presents a review of the Sandia Labs photonic programs that support communications and interconnect. The related activities range from materials research to device development and subsystem prototyping. Three applications are discussed: wide bandwidth fiber communications using guided-wave PICs, a
highly parallel free-space z-axis photonic interconnect for stacked MCMs, and remote communications based on a surface-normal transmission modulator. The device research supporting these projects was also described as it applies to the systems, thus demonstrating Sandia's comprehensive device-based approach to photonic communications and interconnects.

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6. REFERENCES


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