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SAND-94-02-C
CONF-940142--29

Sandia's Photonic Program and Its Changing National Role

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ABSTRACT

Photonics activities at Sandia National Laboratories are founded on an extensive materials research program. In 1988, the Compound Semiconductor Research Laboratory (CSRL) was established at Sandia to bring together device and materials research and development, in support of Sandia's role in weapons technologies. Recently, industrial competitiveness has been added as a major mission for the national laboratories. As a result, present photonics programs are not only directed towards internal applications-driven projects, but are increasingly tied to the Department Of Energy's (DOE's) Technology Transfer Initiatives (TTIs), Cooperative Research and Development Agreements (CRADAs), and participation in partnerships and consortia. This evolution yields a full range of photonics programs, ranging from materials synthesis and device fabrication to packaging, test, and subsystem development. This paper presents an overview of Sandia's photonics-program directions, using three applications as examples.

1. INTRODUCTION

Sandia National Laboratories has traditionally been driven by defense, intelligence, and environmental program 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 [2-5]. Recently, research and development activities in optoelectronic components and subsystems have responded to both internal requirements for high-throughput communications systems and a new external mission that focuses on involvement in industrial competitiveness through TTIs, CRADAs, and participation in partnerships and consortia. This changing role is a result of the US Congress charging the DOE National Laboratories with a major mission of assisting domestic industry to enhance international competitiveness. Sandia has responded by finalizing 110 CRADAs for approximately \$250 M in microelectronics and photonics.

Applications-driven optoelectronic 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, Optoelectronic Integrated Circuits (OEICs), and nanostructures. Subsystem packaging and measurement capabilities support applications. Thus, the optoelectronic 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: a Coherent Optical Monolithic Phased-Array Steering System (COMPASS) based on GaAs/AlGaAs Photonic Integrated Circuits (PICs); a

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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 communications. A brief overview of materials and processing capabilities is then followed by a delineation of the optoelectronic and microelectronic devices being developed in support of these applications.

2. APPLICATION EXAMPLES

2.1 COMPASS

Figure 1 represents a functional perspective of COMPASS [6]. It employs a PIC, based on the GaAs/AlGaAs materials system. The PIC performs microwave single sideband modulation of light, followed by the beam steering (phase shifting) function. Finally, it distributes phase information and signal power via one optical fiber to each of the antenna transmit/receive modules. This allows the antenna to be located remotely from the photonic control circuitry. Each fiber element emanating from the PIC contains both the original continuous wave (CW) reference laser signal and a second laser signal which has been single-sideband modulated (frequency shifted) by the radio frequency (RF) radar signal. For beam steering, the modulated signal also contains the phase information needed by each antenna element. These phase shifts are generated optically, but translate into the RF at the antenna elements, due to the frequency translation function in the front end of the PIC. The PIC itself is based on GaAs/AlGaAs p-n junction optical waveguide modulator structures that are designed to obtain

Figure 1. COMPASS block diagram

figures of merit (FOM)s of approximately 80 degrees per volt-mm. These high FOMs allow for large phase changes over relatively small waveguide lengths. This will reduce the size and cost of the PIC, and improve the frequency response of the modulators. As an example, a FOM of 60 degrees per volt-mm yields a 0.16 cm long optical frequency translator (OFT). In contrast, the 4.5 degrees per volt-mm FOM obtainable from other modulator technologies results in a 2.1

cm OFT length. Thus, it will be possible to produce many PIC chips per wafer on a high-FOM GaAs/AlGaAs wafer, leading to smaller chip size and lower system cost.

2.2 Z-Axis Photonic Interconnects for Stacked MCMs

According to the Semiconductor Industry Association (SIA) road map [7], the number of interconnects per MCM will approach counts ranging in the thousands at speeds in the hundreds of MHz. Figure 2 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 3 shows a cross-section of an intermediate solution which employs 980 nm Vertical Cavity Surface Emitting Lasers (VCSELs). 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 and wavelength stability also allows for the use of techniques such as focusing binary optics. PIN diode detectors will be

Figure 2. A stacked MCM with photonic interconnects.

integrated with heterojunction bipolar transistors to build photoreceivers. Our studies indicate that, for a stacked MCM system, the use of VCSELs is preferable to an implementation based on Light Emitting Diodes (LEDs). As we have shown in our present prototype system, the LEDs will consume more overall power due to low quantum efficiencies and high beam divergence. In addition, the LEDs are more difficult to modulate and the high beam divergence will tend to increase cross-talk between data channels. Figure 4 is a partially assembled (LED-based) prototype in which a detector array chip is mounted on a silicon MCM substrate sample. This sample illustrates advanced micro-alignment techniques such as double-sided v-groove etching in self-aligning spacers.

Figure 3. Cross section of an MCM photonic interconnect prototype based on 980 nm VCSELs.

Figure 4. Partially assembled LED-based initial prototype (CMOS-compatible photodiode array shown).

2.3 Remote Data Communications using a Transmission Modulator

Figure 5 illustrates the cross-section of a packaged electro-optical modulator for remote data communications [8]. 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 angle. The modulator device is made from an epitaxially-grown InGaAs-InAlAs mirror stack 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 a 1060 nm wavelength range, and at 1300 nm [9],[10]. Modulation depths in the range of 30%-60% (depending on mode and wavelength of operation) have been demonstrated.

Figure 5. Packaged transmission modulator for remote laser communication.

3. MATERIALS AND PROCESSING RESEARCH AND DEVELOPMENT

3.1 Materials Research and Development

Sandia's materials program operates six MBE growth chambers and three MOCVD systems. The program spans a range of activities; from novel devices and heterostructures, to fundamental growth science and technology, to development of novel materials. Our efforts to achieve reproducible epitaxial growth have led to the development of a number of new real-time monitoring technologies. These include Reflection Mass Spectroscopy for monitoring reflected fluxes during MBE, absorption spectroscopy, and optical reflectance spectroscopy for on-line control of MOCVD and MBE growth [11]. Current materials growth projects involve AlGaInP, InGaAsSb and InGaAsP alloys, in addition to the now-common strained-layer (In,Ga)As/(Al,Ga)As/GaAs and (In,Ga)As/Al(Ga)As/InP systems. An exploratory effort in the growth of CdTe and related II-VI compounds supplements the III-V materials program. This diversity of material expertise enables Sandia to tailor optoelectronic devices for a wide range of applications.

Sandia is partnered with Hewlett-Packard through one materials-based CRADA and with Motorola through two other materials-based CRADAs. One of the CRADAs with Motorola will explore aluminum nitride materials and various combinations of gallium antimonide and

indium arsenide. A second CRADA with Motorola will address metal-organic vapor-phase epitaxial (MOVPE) for high-performance integrated circuits.

3.2 Processing Research and Development

Processing and fabrication capabilities in the CSRL are extensive. Electron beam lithography capable of sub-20 nm features is available, in addition to standard optical contact lithography. Etch techniques include reactive ion beam etching (RIBE) of metals, dielectrics, and compound semiconductors, electron cyclotron resonance (ECR) ion etching, and standard wet etching. Deposition capabilities include plasma-enhanced chemical vapor deposition (PECVD), electron beam evaporation of metal films, sputter deposition of refractory metal films and dielectrics, and electroplating. In addition, the CSRL contains facilities for ion implantation and rapid thermal annealing. Figure 6 shows four scanning electron micrographs (SEMs) that represent various aspects of these capabilities. Figure 6a is a binary optic lens [12]. These lenses are employed for focusing beams for either free space interconnects or efficient fiber coupling. For high efficiency, they may need submicron features that require electron beam lithography. Implementation in semiconductor materials may imply the use of RIBE. Figure 6b is a self-aligned sputtered-tungsten-gate field effect transistor structure employed in our complementary digital GaAs program [13]. Figure 6c is a Vertical Cavity Surface Emitting Laser (VCSEL) structure that has been patterned by e-beam lithography and etched by RIBE [14]. Finally, Figure 6d is an example of a grating that is used in a program to improve coupling of light between optical fibers and GaAs rib waveguide devices [12]. This grating again uses advanced capabilities such as e-beam lithography and

a. Binary-optic lens outer rings.

b. Self-aligned W-gate FET.

c. Patterned and RIBE-etched VCSEL.

d. Grating fabricated with e-beam lithography and RIBE.

Figure 6. SEMs showing various CSRL processing capabilities.

RIBE. In particular, the RIBE allows the grating to be etched in an angled or surface normal configuration.

4. DEVICE RESEARCH AND DEVELOPMENT

4.1 Vertical Cavity Surface Emitting Lasers (VCSELs)

Sandia's program in VCSELs has two major thrusts: developing reliable, highly efficient, individually addressable, electrically pumped VCSELs, and understanding coupled emission from 2-D arrays of VCSELs for scaling to higher output. Both 980 nm and visible VCSELs have been developed as part of Sandia's program [15],[16]. The 980 nm VCSELs are being developed in the (In,Ga)As materials system. Sandia also recently demonstrated visible VCSELs (red) in the (Ga,In)P/(Al,Ga,In)P material system. Figure 7 illustrates the cross-section of a 980 nm VCSEL, along with a light-current curve showing its performance. The inset shows an SEM of an array of the devices as fabricated. Due to the implantation layers (shown in the device cross-section), this VCSEL operates with high efficiency and exhibits a low threshold current.

Figure 7. Characteristics, cross-section, and SEM of a 970 nm high-efficiency VCSEL.

Figure 8a is a SEM of a phase-corrected 2-D phase-locked surface-emitting array. Every second element in the array contains an epitaxially-grown phase correcting layer. Figure 8b shows the far field pattern of the optically-pumped array output. Here, the central (on-axis)

lobe contains 50% of the emitted light. Without the phase correcting layers, most of the power in the far-field pattern would be in the four off-axis lobes [17].

a. SEM of a phase-locked VCSEL array.

b. Optically-pumped far-field.

Figure 8. Structure and output from a phase-locked VCSEL array.

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

A GaAs/AlGaAs rib-waveguide combiner/splitter is illustrated in Figure 9 [18]. This combiner/splitter is used to create Mach-Zehnder amplitude modulators and frequency-shifters from the high-FOM phase modulators described above. Figure 10 illustrate the basic

Figure 9. A rib-waveguide splitter/combiner for GaAs/AlGaAs PICs.

structure of this type of modulator. Here, the GaAs and GaAlAs layers provide vertical confinement in the waveguide, while the rib effects horizontal confinement. 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 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 [19]. Combiners and splitters are currently being optimized, along with the high-frequency modulators, and will be incorporated into a high-frequency four-arm Mach-Zehnder, which is the primary element of the SSB modulator in the COMPASS PIC described above.

a. Etched rib waveguide structure.

b. GaAs/AlGaAs waveguide cross-section.

Figure 10. High-FOM GaAs/AlGaAs Rib-Waveguide Structure.

4.3 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 [20]. As discussed, applications for these devices include both free-space and fiber-based bi-directional optical communications and control.

4.4 Supporting Electronic Devices

Effective use of photonic devices requires supporting electronic devices for driver circuits, logic, and interface functions. For our applications-driven projects, there are three electronic device programs. The first is based on a CRADA with Alpha Industries for 60 GHz power. Devices developed under this agreement will be based on GaAs strained-layer quantum well materials, will employ 0.15 micron T-gates, and will result in devices capable of driving broad-band photonic circuits. Triquint Semiconductors Inc. and Sandia are in the final stages of establishing a CRADA for 10 Gbit/s digital GaAs circuits. Chips resulting from this CRADA are targeted to address needs for high-speed logic functions for such applications as ATM/SONET switches. Finally, recent work at Sandia has yielded a GaAs Complementary Heterostructure

Field Effect Transistor (CHFET) logic inverter [13]. This technology will be advantageous for low-power, high-speed circuits used in MUX, DEMUX, and driver applications because it will reduce the overall power required for photonic interconnects.

5. CONCLUSION

This paper has presented a top-level review of Sandia's photonic programs, spanning activities from materials research, to device development and subsystem prototyping. Three applications were discussed: the COMPASS approach to phased array radar steering, a free-space z-axis photonic interconnect for stacked MCMs; and remote communications based on a transmission modulator. The materials and device processing technologies supporting these projects were described and examples were given which illustrate increasing work with industry through CRADAs.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000

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