

# STRAINED-LAYER SEMICONDUCTOR RESEARCH AND DEVELOPMENT AT SANDIA

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Sandia National Laboratories pioneered work in strained-layer superlattice systems for electronics and optoelectronics. Based on that work, it now conducts research and development in compound semiconductor and optoelectronics physics, materials science, and device technology. Although Sandia's research relies heavily on theoretical and experimental solid state physics, this paper will emphasize applications that exploit the properties of strained-layer systems. This research allows the microelectronics and photonics community to use the special properties of strained-layer systems in an engineering, rather than an empirical, manner. The number of electronic and optoelectronic devices that depend on strained-layer systems for their highest performance with device applications indicates their importance. Selected strained-layer structures and devices developed at Sandia will be discussed.

## Introduction

Strained-layer structures are an exciting recent advance in semiconductor materials that are providing a new field of semiconductor research as well as new solid state electronic and photonic devices. They are formed by combining two or more materials with different equilibrium lattice constants in a thin-layered epitaxial structure. The complexity of such artificially structured materials may range from a single strained layer at the surface, or a single strained layer sandwiched between two layers of the substrate material [strained quantum well (SQW)], to an arbitrarily thick structure composed of thin layers that alternate in tension and compression [i.e., strained-layer superlattice (SLS)].

Superlattices composed of adjacent layers of different materials were first proposed by Esaki and Tsu in 1970.<sup>1</sup> They predicted that new electronic effects would occur when layer thicknesses in the superlattices were comparable to the electron mean free path.

**Panel 1. Acronyms in This Paper**

AFP — asymmetric Fabry-Perot cavity  
CMOS — complementary metal oxide semiconductor  
LWIR — long wavelength infrared  
SARGIC — self-aligned refractory gate integrated circuit (AT&T)  
SEED — self-electro-optic effect device  
SLS — strained-layer superlattice  
SQW — strained quantum well  
SQWFET — strained quantum well field-effect transistor  
VCSEL — vertical cavity surface emitting laser

50 However, early attempts to observe such quantum mechanical effects were unsuccessful because of dislocations at the interfaces of the thicker layers. These dislocations exceeded the critical layer thickness for these widely mismatched materials. Because the strain energy is proportional to the thickness of the layer for non-lattice-matched materials, the requirements for lattice matching limited studies of thick layer heterojunctions to aluminum arsenide (AlAs) and gallium arsenide (GaAs) compounds, including alloys of (Ga,Al)As, where the lattice mismatch is < 0.2 percent throughout the composition.

Several years earlier, Frank and Van der Merwe<sup>2</sup> had studied accommodation of lattice mismatch between crystals. Their calculations suggested that, under certain conditions, the lattice mismatch could be accommodated entirely by elastic strain without generating misfit dislocations. In 1981, Gordon Osbourn of Sandia National Laboratories performed the first theoretical calculations of the electronic band structure for selected SLS systems as a function of lattice mismatch and layer thickness.<sup>3</sup> Shortly thereafter, a high quality gallium arsenide phosphide/gallium phosphide (GaAsP/GaP) SLS system was grown at Sandia by Bob Biefeld,<sup>4</sup> and Osbourn's theoretical predictions were confirmed by measurements of the optical properties.<sup>5</sup> These studies confirmed that

high quality compound semiconductors with interesting electronic properties could be grown from lattice-mismatched semiconductors.

This pioneering work of Osbourn and his colleagues led to a large-scale effort in materials science, physics, and device research in strained-layer semiconductor systems. The widespread study and application of strained-layer semiconductor systems continues to grow rapidly. Today's highest performance, high-speed field effect transistors, and highest performance semiconductor lasers, exploit strained-layer semiconductor materials.

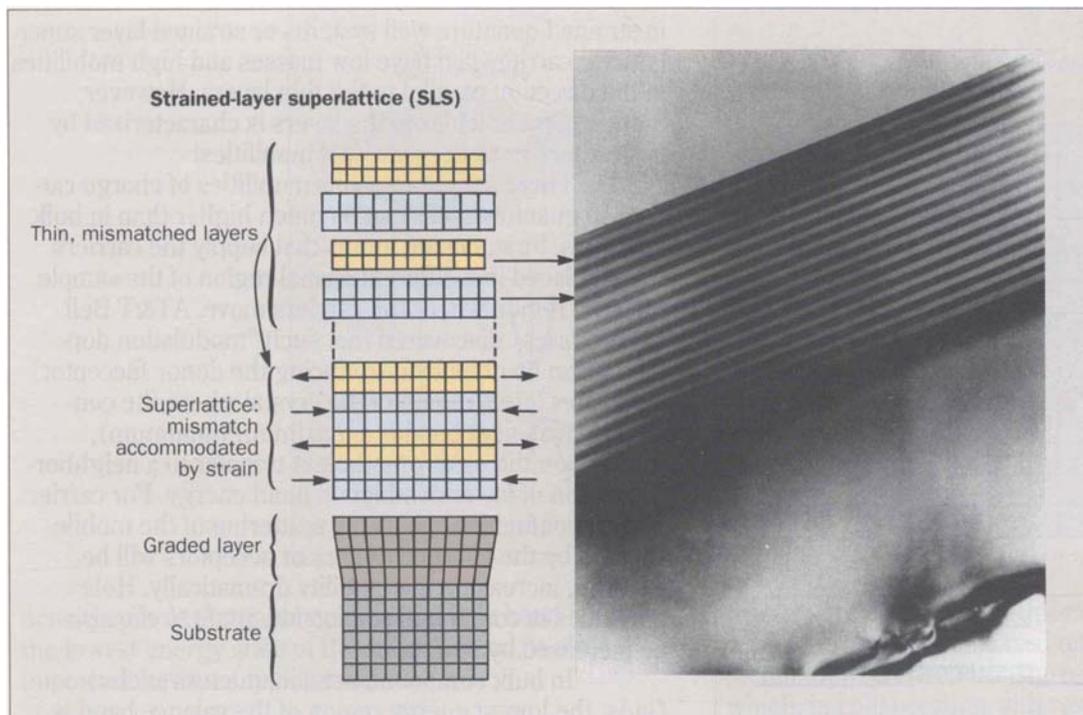
**Heteroepitaxy of Strained-Layer Semiconductors**

In strained-layer heteroepitaxy, the constituent semiconductor lattices have different lattice equilibrium lattice constants (see Figure 1). For thin enough layers, the lattice mismatch is accommodated by strain without generating misfit dislocations at the interface. The strained layer assumes the in-plane lattice constant of the substrate with a concomitant tetragonal distortion. The structure can be designed for the strained layer to be in either tension or compression, depending on the desired effect. In SLS systems, layers in tension and compression alternate to yield a structure with no net forces.

**The Importance of Strained-Layer Structures**

A fundamental property of semiconductors is the energy band gap between the valence and conduction bands.<sup>6</sup> The band gap determines the energy (or wavelength) at which the material absorbs or emits light. Furthermore, materials with a direct band gap, i.e., in which photons directly induce transitions from the valence band to the conduction band, absorb or emit light more efficiently than those with indirect band gaps. Materials with indirect band gaps require electrons to change the momentum by creating or annihilating a lattice vibration (phonon), as well as energy, to make the transition. Thus, direct band gap materials are important for optical and optoelectronic applications.

An important feature of SLSs is that they provide



**Figure 1. Schematic of a strained layer superlattice (SLS) illustrating the individual layers with their equilibrium lattice constants as well as their lattice constants in the SLS, the graded buffer layer, and the substrate.**

structures with band gaps throughout the visible and much of the infrared spectral regions [ $< 0.5\mu\text{m}$  for GaP to  $> 15\mu\text{m}$  for the indium (arsenide, antimony) [In(As,Sb)] SLS system]. Given electronic energy levels that can be altered by both strains and quantum confinement effects in sufficiently thin layers, SLSs offer unprecedented freedom to tailor materials for electronic and optoelectronic applications.

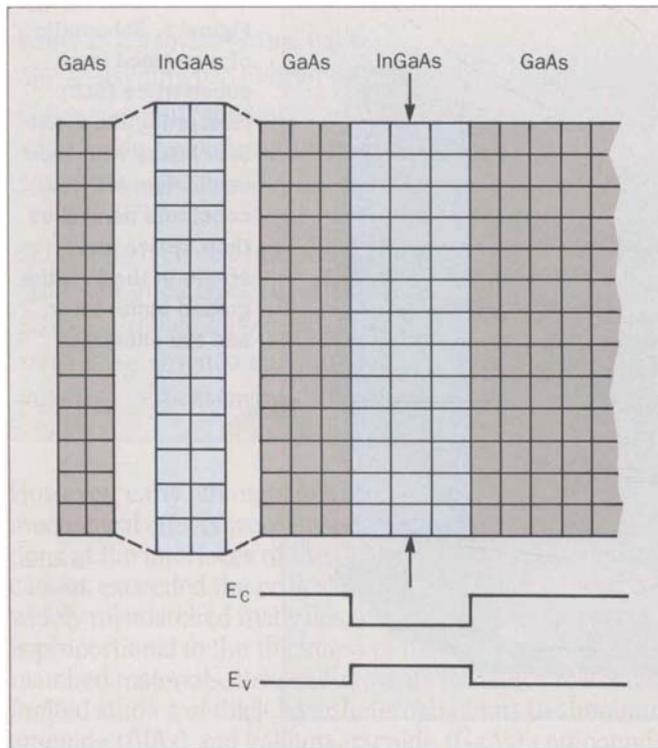
#### **Electrical and Optical Properties**

The energy band gap can be measured directly by optical absorption, luminescence, or photocurrent spectroscopy. Such measurements have verified theoretical predictions of the effects of strain and layer width (quantum size effects) in SLSS, and showed the ability to tailor the band gap at a given composition (lattice

constant). For example, the band gap for GaAsP can be varied continuously between 1.4 and 2.1 electronic volts (eV)—wavelengths from 0.89  $\mu\text{m}$  to 0.59  $\mu\text{m}$ —at a lattice constant of 5.55 angstroms ( $\text{\AA}$ ).

Work at Sandia in the InGaAs/GaAs and InGaAs/AlGaAs systems first showed the potential for integrating small band gap materials, such as GaInAs, with GaAs or AlGaAs. Heterostructures from this combination of materials yield larger band offsets, shown schematically in Figure 2, than were previously available. The larger band offsets dramatically improve the performance of various electronic and optoelectronic devices that will be discussed later.

For electronic device applications, transport properties are paramount. The electronic properties of the semiconductor can be controlled in local regions by



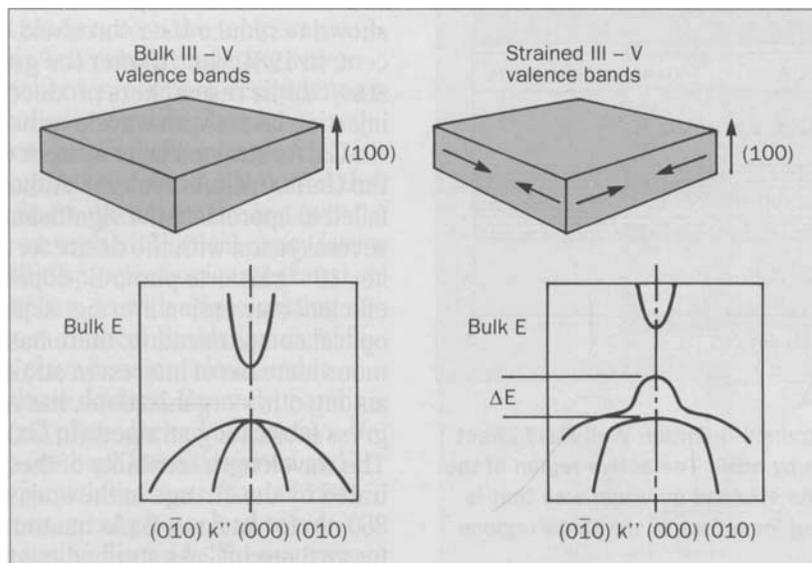
**Figure 2. Schematic illustration of the band offsets at a heterojunction between a strained quantum well and the substrate material. The ability to use strained materials greatly increases the materials systems, and resulting band offsets available for band gap engineering.**

incorporating dopants that provide mobile electrons to the conduction band, or holes to the valence bands. An essential property of semiconductors for electronic device applications is carrier mobility, i.e., the ratio of the electron or hole velocity to the imposed electric field. Mobilities are controlled by two parameters: *carrier scattering* and *effective mass*. They are decreased by scattering from impurities and lattice vibrations, or by increases in effective mass of the charge carrier. Mobilities are anisotropic

in strained-quantum well systems or strained-layer superlattices; carriers can have low masses and high mobilities in the direction parallel to the thin layers. However, motion perpendicular to the layers is characterized by large effective masses and low mobilities.

There are two reasons mobilities of charge carriers in quantum wells can be much higher than in bulk materials. First, dopant atoms that supply the carriers can be placed in a different spatial region of the sample than the region where the carriers move. AT&T Bell Laboratories<sup>7</sup> discovered that such “modulation doping” can be done by introducing the donor (acceptor) impurities into a region of the crystal where the conduction (valence) band is a maximum (minimum), whereupon the electrons (holes) transfer to a neighboring region of lower conduction band energy. For carrier motion confined to the plane, scattering of the mobile carriers by the charged donors or acceptors will be reduced, increasing the mobility dramatically. Hole mobilities in compound semiconductor SLSS can also be increased by strain.

In bulk compound semiconductors such as GaAs, the lowest energy region of the valence band is doubly degenerate, containing both light and heavy holes. Electrical transport is dominated by the heavy holes because of their high state density. Figure 3 shows how strain can be used to remove this degeneracy. For quantum wells in biaxial compression the lowest energy valence band will consist of light holes<sup>8</sup> with measured in-plane effective mass as small as  $0.1m_0$  compared to  $\approx 0.5m_0$  for bulk GaAs.<sup>9</sup> Transport parallel to the layers dominated by light holes yield hole mobilities comparable to the electron mobility.<sup>10</sup> The extremely high electron mobilities offer the potential for very high-speed devices. And the ability to develop strained-layer compound semiconductor structures, where electrons and holes have comparable mobilities, offers the possibility for complementary logic analogous to the complementary metal oxide semiconductor (CMOS) technology that is critical to silicon (Si) technology. The reduced



**Figure 3. Valence band structure of a bulk III-V compound compared to the valence band structure under biaxial compression illustrating strain-induced removal of the degeneracy between the light and heavy holes at  $k=0$ .**

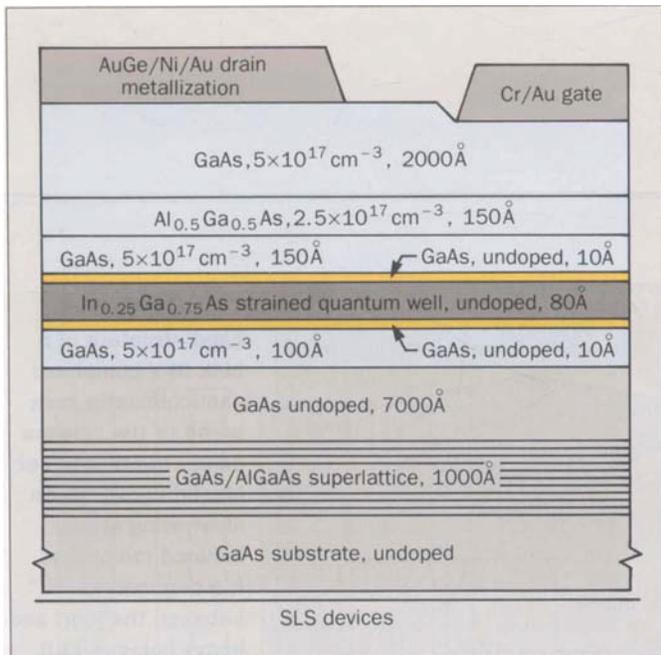
density of hole states, when the light hole band is made the lowest energy state of the valence band, is also important for laser applications.

### Electronic Devices

Much of the current research in compound semiconductor electronic devices is driven by the need for devices that have higher speeds but require less power. It is well known that InGaAs has a higher electron mobility than GaAs. This feature was exploited by Sandia<sup>11</sup> to create strained quantum well field-effect transistors (SQWFETs) based on strained quantum wells of InGaAs in GaAs. Figure 4 shows a typical SQWFET structure. SQWFETs showed excellent performance, including high intrinsic transconductance and low noise, and were free of the persistent photoconductivity effects that plague AlGaAs/GaAs devices at the high Al content required for high performance devices. The promise displayed by early SQW (so-called *pseudomorphic*) devices led to their transfer to various companies for fabrication with short gate length for high frequency operation.

Today the highest performance compound semiconductor FETs are all based on SQW technology. This technology has been transferred to Alpha Industries, which, in collaboration with researchers at Sandia, has produced 0.25 $\mu\text{m}$  gate length n-channel InGaAs/GaAs SQWFETs with record transconductances. InGaAs/GaAs SQWFETs are used in high frequency [60 gigahertz (GHz)] high-power microwave systems. Indeed, because of their high frequency and low noise characteristics, n-channel InGaAs/GaAs SQWFETs fabricated by General Electric are used in the very large array astronomical telescope at Socorro, New Mexico. This strained quantum well technology was also made compatible with AT&T's self-aligned refractory gate, integrated circuit (SARGIC) process and inserted into the AT&T pilot line.<sup>12</sup>

Even more significant than the electron transport in SQWFETs is the strain-induced modification of the valence band structure (see Figure 4). Sandia researchers showed that by exploiting strain-induced light holes, p-channel SQWFETs with exceptional performance could be fabricated.<sup>13</sup> These were the first high performance



**Figure 4. Structure of a Strained Quantum Well Field Effect Transistor (SQWFET) grown by MBE. The active region of the device is the  $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$  strained quantum well that is modulation-doped by adding impurities in the GaAs regions on either side of the SQW.**

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p-channel FETs in any compound semiconductor system. This technology was transferred to Rockwell and Honeywell, where similar results were obtained. Current research at Sandia is concentrating on combining the high performance p-channel SQWFET with n-channel devices to form complementary logic in III-V compound semiconductors similar to Si-based CMOS.

#### Optoelectronic Devices

The strain-induced effects important for electronic devices can also be exploited to greatly enhance performance in optical devices. For lasers, the most obvious advantage of SQWs is the wide wavelength range offered by strain- and quantum-confinement-induced changes in the band gap. Other important advantages include reduced threshold current, increased efficiency, and higher modulation frequencies. These latter advantages result from the reduced density of states at the valence band edge associated with the strain-induced low mass holes. Although lasers that exploit this effect are still in early stages of development, the effect has been

shown to reduce laser threshold currents up to 50 percent. In 1984, shortly after the growth of high quality SLSS, Sandia researchers produced continuous wave (cw) injection lasers with wavelengths out to  $1.06\mu\text{m}$ <sup>14</sup> in the (In,Ga)As strained-layer system (compared to  $0.86\mu\text{m}$  in the GaAs/AlGaAs system). Although the community failed to appreciate the significance of this work for several years, with the desire for a 980 nanometer (nm, i.e.,  $10^{-9}$ ) laser to pump Er-doped fiber amplifiers for efficient conversion into signal photons at 1530 nm for optical communication, there has recently been an enormous increase of interest in strained-layer lasers. Sandia, among other organizations, has made significant progress fabricating strained (In,Ga)As quantum well lasers. The wavelength tunability of these SQW lasers is illustrated by the change in the emission wavelength from 860 nm for an 8 nm GaAs quantum well and to 900 nm for an 8 nm InGaAs strained quantum well.<sup>15</sup>

Another exciting area of research is vertical cavity surface emitting lasers (VCSELs). In these devices, the mirrors are made by epitaxial growth of multilayer structures with alternating high and low refractive indices of appropriate thickness. Such epitaxial semiconductor mirrors were first grown by researchers at AT&T Bell Laboratories,<sup>16</sup> and Sandia researchers pioneered their use for a variety of optical and optoelectronic applications, including all-epitaxial VCSELs.<sup>17</sup>

The short optical cavity length for the structure shown of only  $2.5\mu\text{m}$ , and the active quantum well thickness of ~15 nm, results in singular behavior for such lasers.<sup>18</sup> For example, positioning the active quantum wells in regions of high optical field within the cavity gives preferentially high gain along the axis of the cavity to yield extremely high differential efficiency. With this configuration, active regions of < 5 nm are needed. For such short active regions, the band gap is renormalized by electron-electron interactions resulting from the high local electron density in the quantum wells. These interactions change the lasing frequency from the band gap frequency, and the short cavity length can only

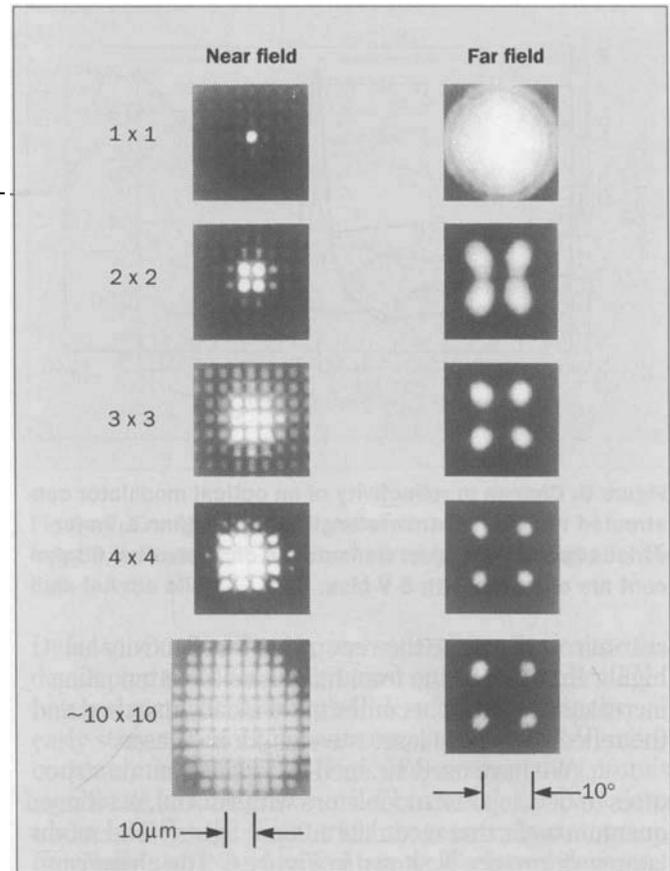
support one longitudinal mode across the temperature range from 77 K to 400 K. As a result, the lasing wavelength exhibits much smaller temperature dependence than that of a conventional edge-emitting laser.

Because of advantages, including single frequency, simple processing and circular mode output that can be easily coupled to fibers, VCSELs in the last two years have been widely researched. Vertical cavity lasers are also ideal for monolithic optoelectronic integrated circuits and optical logic devices. As with edge-emitting lasers, Sandia's extensive numerical simulation capabilities for lasers and arrays plays a major role in understanding and designing these devices. Recently, Sandia researchers have produced phase-locked SEL arrays.<sup>19</sup> Various array configurations have been designed and constructed. Array designs with the wave fronts from adjacent pixels 180 degrees out of phase, lead to a 4-lobed far-field pattern shown in Figure 5. These arrays exhibit an almost ideal 4-lobed Fraunhofer diffraction pattern, consistent with theoretical predictions.<sup>20</sup> As larger arrays are pumped (or excited), the width of the beam decreases, and the pattern is observed to remain unchanged for up to array sizes of 20 by 20.

**Optical Modulators.** Optical modulators impress signals on laser beams for information transfer. In contrast to communication systems where information is applied by modulating the laser directly, systems based on optical modulators are independent of the laser that generates the beam to carry the information. The types of optical modulators under development at Sandia include:

- *Reflection modulators*, in which the beam is sent back to the source after information is impressed by amplitude modulation of the beam
- *Transmission modulators*, in which the amplitude of the transmitted beam is modulated electrically or optically
- *Phase modulators*, in which the phase of the beam is modulated.

Reflection modulators are useful for both free-space

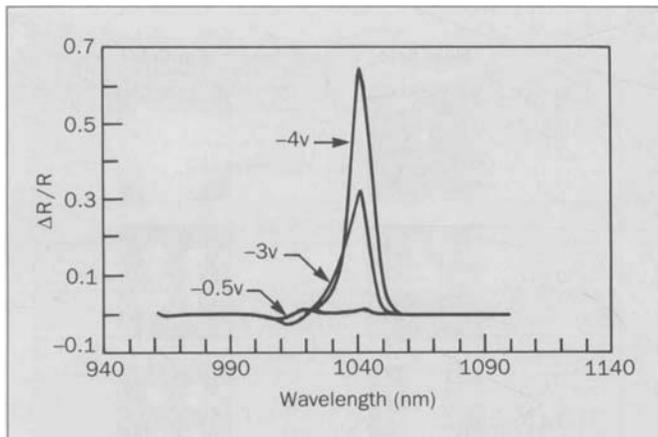


**Figure 5. Measured far field pattern for a vertical cavity surface emitting laser array. Note the 4-lobed far-field pattern expected for the out of phase array configuration.**

and fiber-based bi-directional optical communications and control. Transmission modulators are important for optical bistability and optical computing, and phase modulators are essential to coherent optical communication systems.

**Fabry-Perot Reflection Modulators.** Reflection optical modulators have structures similar to the VCSELs. They use an asymmetric Fabry-Perot (AFP) cavity formed by a high reflectivity rear mirror and a lower reflectivity front mirror.<sup>21</sup> The cavity's active region is made of strained quantum wells with material and well-widths chosen to have exciton absorption near the resonant frequency of the cavity.

Applying an electric field across the cavity produces a red-shift of the absorption edge through the quantum-confined Stark effect. The resulting increase in absorption attenuates light reflected from the cavity's



**Figure 6. Change in reflectivity of an optical modulator constructed to operate at wavelengths greater than  $1\mu\text{m}$  for various applied voltages. Reflectance changes over 65 percent are observed with 5 V bias.**

rear mirror. Because the rear mirror's reflectivity is higher than that of the front mirror, as the attenuation increases the cavity becomes more ideally matched and the reflectivity at the laser wavelength increases.

We have used strained-layer superlattice structures to develop AFP modulators with (In,Ga)As strained quantum wells that modulate  $1.06\mu\text{m}$  light.<sup>22</sup> The modulator performance is shown in Figure 6. The change in reflectance with applied voltage is plotted for a modulator operating near the  $1.06\mu\text{m}$  wavelength of a Nd:YAG laser. Applying 5V across the AFP results in a reflectance change of more than 65 percent at this widely-used laser wavelength.

In a novel variation on the AFP concept, the original AFP design was modified to include two coupled cavities in a tandem configuration.<sup>23</sup> The two cavities in the monolithic structure have the same resonant wavelength. They produce a double-dipped reflectance spectrum that can be strongly modulated by electrically tunable electro-optic effects in the superlattice cavity. This tandem AFP modulators allow wider-wavelength operation over a greater temperature range and possess reduced sensitivity to variations in material growth parameters.

**Transmission Modulators.** In contrast to quantum-confined stark effect modulators, which induce a red shift in the absorption edge under an applied bias, Wannier-Stark localization under an applied bias results in a blue shift of the absorption edge. This effect is useful for transmission optical modulators. Two dimensional NXN arrays that exhibit excellent uniformity over areas

encompassing several hundred devices have been produced. These devices can be switched electrically or optically, and form the critical element in bistable optical switches. To achieve optical bistability, researchers at AT&T Bell Laboratories connected these Wannier-Stark modulators in series with a load resistor and an external voltage source in a self-electro-optic effect device (SEED) configuration.<sup>24</sup> Arrays of these devices are being explored for building blocks for highly parallel optical computers, and for specialized applications such as optical correlation, matrix algebra, and pattern recognition. High performance optical switches, either electrical or optical, to gate optical signals are fundamental for optical computing elements. A promising approach under investigation at Sandia, in collaboration with AT&T Bell Laboratories, is the phototransistor-actuated surface-emitting microlaser.<sup>25</sup> Here, phototransistors are monolithically integrated with vertical-cavity microlasers. Absorption of light in the phototransistor switches base changes large currents [several milliAmps (mA)] for small [10 milliWatt (mW)] incident light under electrical bias to yield high optical gain (i.e., over 50). Arrays of these devices are ideally suited for image amplification, neural networks, and wavelength conversion. They also could function as optical bistable elements, optical amplifiers and optical switches with gain. These elements are promising for optical computers that will exploit massively parallel architectures to pursue higher computation and image processing speeds.

**Long Wavelength Infrared Photodetectors.** Strain offers an additional parameter in optimizing detectors to operate at specific wavelengths. Strained-layer detectors have been demonstrated for a variety of visible and infrared (ir) wavelengths for radiation-hardened applications. An important advance is the demonstration of InAsSb SLS detectors for long wavelength ir (LWIR) applications. No bulk III-V compound semiconductor has a small enough band gap for detector operation in the militarily important spectral region from 8 to  $14\mu\text{m}$ . However, work at Sandia has shown that  $\text{InAs}_x\text{Sb}_{1-x}/\text{InSb}$  on InSb substrates or  $\text{InAs}_u\text{Sb}_v/\text{InAs}_x\text{Sb}_y$  on InAs

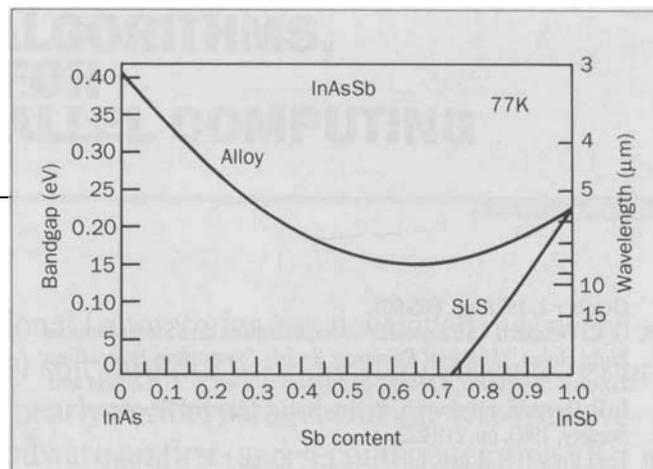
substrates can be tailored to produce high performance detectors in this important spectral region. The band structure engineering required to accomplish these LWIR detectors relies on heterojunctions between the two InAsSb compositions, strain-tailoring, and quantum confinement effects.

Infrared photoluminescence studies of high quality InAsSb SLs show that this system forms a so-called type II superlattice in which the minima in the conduction and valence band are in adjacent layers of the superlattice.<sup>26</sup> The band gap for InAs<sub>x</sub>Sb<sub>1-x</sub>/InSb SLs is compared with the band gap in the InAsSb alloy in Figure 7. The band gap of the SLS goes to zero at an As content of about 30 percent, for higher As content, the SLS is metallic.

In principle, LWIR detectors can be designed to have arbitrarily long cut-off wavelengths. In practice, growth of the appropriate structure increases in difficulty as the cut-off wavelength increases because of increasing strain and the required increase in control of layer composition and thickness. To date, detectors have been shown with spectral response out to 14 $\mu$ m in InAs<sub>0.18</sub>Sb<sub>0.82</sub>/InSb SLs. Detectors have also been demonstrated that are background limited when viewing a 300 K object, and exhibit a detectivity D\* greater than 1 $\times$ 10<sup>10</sup> cm<sup>-1</sup> Hz/W at wavelengths up to 10 $\mu$ m.<sup>27</sup>

As noted above, photodetectors have been shown that operate at wavelengths out to 14 $\mu$ m. In addition to these photovoltaic detectors that function in the absence of an applied bias, photoconductive detectors have been shown that operate throughout the 8 to 14 $\mu$ m spectral region.<sup>28</sup> Although the two types of detectors have similar basic materials structures, materials are undoped, and lateral rather than vertical geometries are used for photoconductive detectors.

A new area of research and development was opened by the realization that heterostructures in III-V materials could be used to fabricate infrared detectors that operate at much longer wavelengths than those associated with the intrinsic band gap. Based on Sandia's work, a Manufacturing Operations Development Integration Laboratory was funded by the Department of



**Figure 7. Energy band gap versus composition for InAsSb/InSb SLs at 77 K compared to the band gap for the bulk InAsSb alloy.**

Defense (DOD) at Sandia, and several companies are now developing LWIR detectors based on SLs or other III-V heterostructures. Although III-V materials are in the early stages of development compared to the II-VI mercury cadmium tellurium (HgCdTe) system, they promise significant advantages over II-VI materials for LWIR detector technology. III-V materials are more robust, more thermally stable, and have more well-behaved dopants compared to II-VI materials.

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(Manuscript received May 13, 1991)