# Epitaxial Growth and Processing of Compound Semiconductors

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### Introduction
The emphasis of this research program is the epitaxial growth and processing of III-V compound semiconductors. The epitaxial growth of the heterostructures is performed in the chemical beam epitaxy laboratory. The laboratory consists of two gaseous source epitaxy reactors interconnected to several smaller chambers, which are used for sample introduction and *in-situ* surface analysis. Such a multichamber epitaxy system allows heterostructures to be fabricated within a continuous ultrahigh vacuum environment.

In the following sections, the status of the various III-V-based projects will be discussed. The III-V gas source molecular beam epitaxy (GSMBE) system is utilized for the development of (In,Ga)(As,P)-based optical devices for all-optical communication networks and the fabrication of GaAs-based devices implementing one- and two-dimensional photonic bandgap crystals within their structure.

## 1. Development of Components for Ultrafast All-Optical Communication Networks

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The need for ultrafast (100 Gbits/sec) all-optical communication networks is intensifying as the amount of data-containing communication traffic continues to grow at an exorbitant rate. Although wavelength division multiplexed (WDM) systems are being implemented, aggregate data rates may be limited by electronic signal processing speeds at the originating and terminating ends of the fiber optic networks. The ability to move away from electronic processing and towards all-optical processing of the network-level data is attractive for the realization of high speed communication networks due to simplicity of integration and possible elimination of optoelectronic conversion.

In order to eliminate electronic processing on the network level, all-optical processing components must transfer, store, and rate-convert all data to and from the data rate of the source (i.e. a computer) to the network data transmission rate. One such required component is the semiconductor optical amplifier (SOA). Advantages of SOAs versus silica fiber amplifiers, include their smaller size, larger bandwidth, and ease with which SOAs can be incorporated into optoelectronic integrated circuits. SOAs have a wide range of uses in communication systems such as optical amplification, all-optical switching, optical demultiplexing, wavelength conversion, clock recovery, and dispersion compensation.

One of the main advantages of a heterostructure design for a SOA is that the thickness of the active layer can be dramatically reduced. A small active region thickness allows the amplifier to exhibit substantial gain even at very low injected current densities. The band structure is designed to confine carriers to the active region, which is much shorter than the carriers' diffusion length. In addition, the active layer is designed to have a larger index of refraction than that of the cladding layers, causing the confinement of light to an active region with a thickness smaller than the wavelength of light. Thus, the active region essentially represents an optical waveguide. To operate a SOA as a broadband single-pass device, its facets must be coated with an antireflective coating to avoid the creation of resonator modes.

This project aims to develop, fabricate, and characterize an InGaAsP/InP SOA structure. The chosen material system, (In,Ga)(As,P), offers a range of bandgap energies compatible with all-optical fiber networks and can be grown by gas source molecular beam epitaxy (GSMBE) on InP substrates. The structure has been grown by GSMBE and optically characterized using photoluminescence. The active layer has been shown to have a bandgap that corresponds to a wavelength $\lambda$=1.57 μm, catering to a $\lambda$=1.55 μm lightwave communication system. Currently, the SOAs are under fabrication within the Technology Research Laboratory and the Exploratory Materials Laboratory.

## 2. Photonic Crystals in III-V Materials

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This project represents the combined efforts of the research groups led by Professors John D. Joannopoulos, Leslie A. Kolodziejski, Erich P. Ippen, and Henry I. Smith. Prof. Joannopoulos' research group designs the structures and theoretically calculates the optical properties. Prof. Kolodziejski's group fabricates the various devices with embedded one- and two-dimensional photonic bandgap crystals using III-V compound semiconductor technologies. Prof. Smith's group provides the expertise in nanoscale fabrication. Finally, Prof. Ippen's research group optically characterizes the devices. The complexity of the design, fabrication and characterization of these structures necessitates a strong interaction between the various research groups.

### A Two-Dimensional Photonic Bandgap Light-Emitting Diode

Enhanced light extraction is observed from a light-emitting diode (LED) structure containing a two-dimensional (2D) photonic crystal. In semiconductor LED structures, the extraction efficiency is reduced by the capture of emitted light into planar waveguide modes. The photonic crystal is used to enhance the extraction efficiency by (i) creating a photonic bandgap (PBG) that eliminates the unwanted waveguide modes at the emission wavelength, or (ii) Bragg scattering the planar waveguide modes into radiation modes. To create the photonic crystal, a 2D array of holes is etched into the top cladding layer of an asymmetric InGaP/InGaAs quantum well (QW) structure that emits light with wavelengths around 980 nm. The 50 x 50 μm, 2D photonic crystal LED mesa consists of an active region, a low refractive index spacer layer of oxidized AlGaAs, and an oxidized AlAs/GaAs distributed Bragg reflector (DBR). To investigate the effect of the photonic crystal on light extraction, the lattice constant and hole diameter of the photonic crystal is varied. To minimize carrier recombination, the holes do not penetrate the InGaAs QW; however, the hole depth is still sufficient to cause strong Bragg scattering. The DBR reflects the QW emission and the oxide spacer layer minimizes the coupling to the lateral guided modes in the high dielectric layers of the DBR. Photoluminescence (PL) images were recorded from both uniformly pumped LED mesas and selectively pumped regions on the LED mesas. Light extraction enhancements as high as 100x were measured from photonic crystal LEDs at a particular wavelength as compared to LEDs without a photonic crystal. The enhancement is attributed to the strong Bragg scattering of the quantum well emission into vertical radiation modes. Bragg scattering of the PL pump light into guided modes is also used for efficient optical pumping of the quantum well.

### Guiding Light Through Sharp Bends using 2-Dimensional Photonic Crystals

Optical signal processing requires guiding an optical signal around sharp bends with a radius of curvature on the order of a wavelength. Conventional waveguiding is the result of total internal reflection at the interface between the high-refractive index guiding layer and its low-index surroundings. However, sharp bends in the conventional index-contrast waveguides may cause large optical losses depending on the wavelength of the light being guided and on the radius of curvature. Using a two-dimensional (2D) photonic crystal can minimize optical losses due to radiation. Efficient, sharp-bend waveguides are created by introducing a line defect of smaller radius dielectric cylinders into a photonic crystal composed of an array of cylindrical dielectric rods. The periodic arrangement of dielectric rods, which surrounds the line defect, creates a photonic band gap (PBG) or a range of frequencies in which light can not propagate. Thus, an optical signal with a frequency inside the PBG has its energy confined inside the line defect. However, the diamenter of the cylinders in the line defect remains large enough to provide index guiding in the third dimension (normal to the plane of periodicity of the photonic crystal). Localization of the defect mode inside the line defect allows guiding around sharp corners including a 90° bend with low loss.

The cylindrical rods of the photonic crystal consist of a high-index 860 nm thick GaAs layer sandwiched between a 100 nm thick $SiO_2$ cap layer and a 640 nm thick low-index $Al_xO_y$ layer. An additional 860 nm thick $Al_xO_y$ layer resides below the cylindrical rods in order to decouple the GaAs guiding layer from the GaAs substrate. The heterostructure is grown using gas source molecular beam epitaxy on a (100) GaAs substrate. The $Al_xO_y$ is initially grown epitaxially as AlGaAs. The fabrication process commences by evaporating 100 nm of $SiO_2$ on to the sample. Next, the waveguides and photonic crystal are defined by using direct write electron beam lithography and a nickel liftoff process. The pattern is transferred to the $SiO_2$ by reactive-ion etching (RIE) using a $CHF_3$ plasma, after which, the nickel mask is removed. Using the $SiO_2$ mask, the cylindrical rods are created by etching the GaAs and the AlGaAs to a total depth of 1.5 μm using a $BCl_3$ plasma. Next, the AlGaAs is transformed to $Al_xO_y$ using a wet thermal oxidation process. Finally, each sample is lapped and cleaved in order to create a smooth input facet to promote the efficient coupling of a test signal. Transmission through the various structures is measured as a function of frequency and compared to theoretical simulations. Photonic crystal and line defects with rods of various dimensions are being fabricated to further optimize the waveguide design.

### GaAs Nanoelectromechanical Optical Switch

As part of ongoing research efforts towards the fruition of all-optical signal processing, the possibility of a tunable wavelength filter using a photonic crystal is currently being explored. The examination, critical analysis and development of a nanoelectromechanical optical switch will serve as a prelude to the successful development of a novel wavelength tunable microcavity photonic crystal in a III-V material system. Although not necessarily the ultimate ends in itself, this device can be catalogued as an extremely useful component. There are several notable attributes of this particular optical switch. Firstly, the optical switch will employ nanoelectromechanical systems (NEMS) technology. NEMS, evolving from a flourishing, yet still developing, microelectromechanical systems (MEMS) technology, incorporates some of the same founding physics principles of MEMS while offering a reduction in size. Secondly, the opto-electromechanical device will be fabricated in a material system not commonly used for electromechanical operation. Once developed, new fabrication sequences could lead to more complex nanoelectromechanical designs in a similar system. Lastly, since the optical switch will be fabricated in a material system commonly used for optical devices, it can be easily integrated into an optical network.

The optical switch's topology consists of two self-aligned GaAs strip waveguides separated by a small (~100 nm) gap. The first (input) waveguide will be a multimode waveguide gradually tapered to a single mode waveguide. The second (output) waveguide will be a single mode waveguide tapering to a multimode waveguide at the output. The output waveguide and the multimode portion of the input waveguide will rest on a supportive aluminum oxide layer, while the single mode portion of the input waveguide will be suspended in air forming a cantilever. An electrostatic force, applied between the single mode cantilever and the substrate, creates a misalignment between the two waveguides. The aligned state has high transmission from the input to the output waveguide, while the deflected state has low transmission.

## Publications

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Erchak, A. A., D. J. Ripin, S. Fan, P. Rakich, G. S. Petrich, L. A. Kolodziejski, E. P. Ippen, and J. D. Joannopoulos, "Enhanced Emission from a Light-Emitting Diode Modified by a Photonic Crystal." *Mat. Res. Soc. Symp. Proc*. Pittsburgh, PA, USA, 637, Forthcoming.