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Development of Near Infrared Array Production Method

CNF Project # 509-94
Principal Investigator: Mark D. Morgan

Abstract:

The development of simple, robust, and inexpensive band-pass filter is being pursued. Electron beam lithography and masked ion beam lithography (MIBL) techniques were employed to fabricate optical filters as a critical component of an energy conversion concept utilizing semiconductor photovoltaics (PV). The conversion concept, thermophotovoltaics (TPV), when coupled with MIBL-produced band-pass filters, is capable of converting heat to electrical power with 25% conversion efficiency [1]. We are being supported by contracts sponsored by the US Army and the National Aeronautics and Space Administration.

The goal of the Army program is to demonstrate a diesel fueled TPV power supply via the fabrication of three prototype systems to be tested by Army personnel. The NASA project is a development program aimed at mating a NASA General Purpose Heat Source (GPHS) and a TPV converter to produce a power supply for deep space applications.

The patented EDTEK TPV filter is based on a high-density array of slotted antenna elements etched into a thin gold film. Typically, the cross-shaped mesh elements have line-widths of 80 nm and line lengths of 450 nm. A resonance condition occurs if the dimensions of the elements are comparable to the wavelength of the interacting electromagnetic field. Resonance wavelength, peak transmission and band-pass shape are adjusted by varying element dimensions and geometry.

Summary:

Our work over the past year has continued the prior years’ effort by producing silicon membrane stencil masks used to transfer patterns by MIBL. Fabrication of the stencil masks consisted of patterning silicon membranes (~ 0.65 µm thick) and silicon nitride membranes (~0.4 µm thick) using the CNF VB6 e-beam lithography tool. The work last year was centered on producing silicon masks and silicon nitride masks for use in both our MIBL and aperture array lithography (AAL) system [2,3]. EDTEK and the University of Houston are developing AAL for future mask production aimed at specific applications.

The fabrication of daughter stencil masks allows the printing of one square centimeter of nano-scaled features on a single substrate in less than 20 second exposure time. Using a 4 mm²-printed-area silicon stencil mask, patterned at CNF, we employed MIBL to print a larger nano-scale area onto another silicon or silicon nitride membrane thereby producing a 2nd generation mask used to print areas of 100 cm² per substrate. The substrates were processed to produce IR band-pass mesh filters for application in the TPV power generator. To date, our group has fabricated 1st generation stencil masks at CNF of 2 mm x 2 mm. From these master masks, 2nd generation masks have been fabricated with dimensions 10 mm x 16 mm. The EDTEK MIBL system has employed daughter masks and master masks to print a total of 30,000 cm² of nano-scaled features.

References:
Development of Near Infrared Array Production Method

CNF Project # 509-94
Principal Investigator: Mark D. Morgan
Users: Mark D. Morgan, Vasan Sundaram

Affiliation: EDTEK, Inc.
Primary Funding: U.S. Army, NASA
Contact: m.morgan@edtekinc.com, v.sundaram@edtekinc.com

- Prototype electric generator design requires an IR band-pass filter with 1800 cm$^2$ of nano-scaled features.
- The IR band-pass filter was fabricated using masked ion beam lithography (MIBL) - 80 nm linewidth.
- MIBL allowed exposure of entire required area ($4.4 \times 10^{11}$ elements) in 20 hours.

Figure 1: Photomicrograph of 2nd generation silicon nitride stencil mask fabricated using masked ion beam lithography.
Waveguide Fabrication and Optimization in Potassium Titanyl Phosphate

CNF Project # 764-99
Principal Investigator: Gregg Switzer

Abstract:
AdvR’s work involves the fabrication and characterization of optical waveguides in potassium titanyl phosphate (KTP) coupled to semiconductor lasers. These waveguides allow second harmonic generation (SHG) to frequency double the output of a narrow bandwidth semiconductor laser. The accuracy of the final waveguide is influenced by each step of the photolithographic process. The focus during 2005-2006 has been to explore the viability of depositing silicon dioxide as a mask for the pattern to allow in-process interrogation and optimization of the optical transmission of the waveguides. Future efforts will include refining the process of silicon dioxide depositions as well as an exploration of using other non-metallic dielectrics.

Summary:
Periodic waveguides embedded in KTP wafers provide a novel approach to high efficiency QPM of laser light. A mask containing the periodic pattern is transferred onto the surface of the KTP wafer using 5x photolithography at CNF. Although the single layer pattern transfer seems straightforward, wafer-to-wafer variations in both property and geometry require non-standard deviations from the traditional photolithography process. Once the wafer is patterned, the wafers return to AdvR for dicing, polishing and dipping onto a hot bath of rubidium nitrate salts. The rubidium ions that pass through the holes in the pattern exchange with potassium ions within the wafer causing a slight increase in the index of refraction of that region. This gives rise to total internal refraction of light as it travels down the pattern-defined optical waveguide. If a segmented waveguide is patterned with an appropriate pitch, type 1 quasi-phase matching (QPM) is possible through domain reversal in the exchanged regions allowing for highly efficient frequency doubling of laser light. The systematic errors introduced throughout the process from reticle manufacture to final lithography on to the KTP wafer critically impact the desired properties of the waveguide.

AdvR has recently designed segmented waveguides for type 1 QPM for frequency doubling 1060 nm light to 530 nm. Patterns with several distinct periods, duty cycles, and widths of waveguides were designed to compensate for variations in modal confinement (and thus the modal index) of the waveguide that can arise from substrate differences and exchange depth. Wafers have patterned with aluminum in the past, but this time it was decided to pattern the wafers with SiO₂ instead.

The ability to use SiO₂ instead of our traditional aluminum coating is advantageous because it allows us to characterize the properties of the waveguide without removal of the transparent pattern. The chip can therefore undergo repeated ion-exchanges in order to tune its optical behavior, thereby greatly improving yields. SiO₂ also acts as an electrical insulator and optical buffer between the waveguides and micro-electrodes used for electro-optic (EO) control of the index of the waveguide. EO control enables active control of the waveguide properties, opening the door for new innovative laser-based applications.

In July 2005, AdvR utilized the CVC 4500 Evaporator to deposit ~ 700A silicon dioxide (SiO₂) on KTP wafers at CNF for the first time. Our first attempt at SiO₂ deposition yielded only moderate resolution of the elements due to chipping that occurred during the lift off process. Although the waveguides were not ideal, some did produce successful frequency double output at 530 nm from a 1060 nm source and could be characterized with the SiO₂ pattern still in place as proof of concept. Future trips to CNF are expected in order to improve the SiO₂ deposition and liftoff process.

AdvR greatly appreciates the extra effort the CNF staff made in response to our specific needs.
Waveguide Fabrication and Optimization in Potassium Titanyl Phosphate

CNF Project # 764-99
Principal Investigator: Gregg Switzer
Users: Philip Battle, Tim Fry, Gregg Switzer, Will Suckow
Primary Funding: SBIR
Contact: battle@advr-inc.com, fry@advr-inc.com, switzer@advr-inc.com, suckow@advr-inc.com
Web Site: www.advr-inc.com

Figure 1: Contrast of a well defined SiO\(_2\) patterned waveguide vs. a poorly defined pattern. A majority of the waveguides from this initial test resulted in poor quality, prompting a future return to CNF to improve the photolithography process.

Figure 2: Frequency tunable 1064 nm input was coupled into a newly patterned QPM waveguide and frequency doubled for scanning an iodine absorption line at 532 nm.
Tunnel Coupled Quantum Well-Quantum Dots Active Medium for High-Frequency Semiconductor Lasers

CNF Project # 780-99
Principal Investigator: Serge Oktyabrsky

Abstract:
The project is focused primarily on materials, technologies and components for the III-V optoelectronic devices integrated with a silicon platform. The goal is to provide design and technology for light emitters and photodetectors with high thermal stability and high bandwidth suitable for hybrid microintegration on Si electronics into massively parallel arrays [1]. The major focus is on the microcavity optoelectronic devices, such as vertical cavity surface-emitting lasers (VCSELs), microcavity light-emitting diodes, and resonant cavity photodetectors, which are anticipated to play the major role in the future chip-level optical interconnect technology. In 2005/06, structures of tunnel coupled pairs consisting of InGaAs quantum wells grown on top of self-assembled InAs quantum dots (QW-on-QDs) were employed to improve the gain medium in thermally stable semiconductor QD laser diodes. We have developed a tunnel QW-on-QDs structure with a QD resonance transition which is red-shifted ~ 35 meV relative to the QW ground state (GS). Edge-emitting lasers utilizing this active medium were developed and characterized. All-epitaxial vertical cavity surface emitting lasers with triple-pair tunnel QW-on-QDs medium demonstrated continuous wave mode lasing with 5.7 mA minimum threshold current at QD ground state emission wavelength, 1131 nm [2].

Summary:
QD-on-QW active medium was developed and characterized in edge-emitted lasers. Our approach is to use multiple pairs of tunnel coupled QWs grown on QDs structures (QW-on-QDs) as opposed to multiple QD layers for a single QW [2]. Optimized energy separation between ground energy states of QW and QDs within a pair was found to be ~ 35 meV, which is close to the energy of LO phonon. This transition with narrow linewidth, 21.6 meV at T = 77K, indicates an efficient LO-phonon assisted tunneling of carriers from QW into QD ensemble states. The highest gain ( > 50 cm⁻¹ in waveguide lasers) was achieved with a QW-on-QDs active medium with GS relative separation of c 35-40 meV. VCSELs with 3 x (QW-on-QDs) active medium were designed, grown, and processed. The design was based on AlGaAs/GaAs all-epitaxial distributed Bragg reflectors (22 and 34 pairs in the top and bottom reflectors, respectively) intracavity p-contact, and single selectively oxidized current aperture. The devices demonstrated relatively high operating voltage ( > 5V), likely because of high resistance of intracavity contact. Nevertheless, CW lasing mode of first QD-based VCSEL with tunnel-coupled medium was demonstrated with oxide aperture sizes from 5 to 17 µm at room temperature. Best measured differential efficiency of ~ 6.2% was observed in small-aperture lasers [3].

References:
Tunnel Coupled Quantum Well-Quantum Dots Active Medium for High-Frequency Semiconductor Lasers

CNF Project # 780-99
Principal Investigator: Serge Oktyabrsky
Users: Jobert van Eisden, Rama Kambhampati

Affiliation: College of Nanoscale Science and Engineering, University at Albany-SUNY
Primary Funding: MARCO/DARPA
Contact: soktyabr@uamail.albany.edu, jvaneisden@uamail.albany.edu, RKambhampati@uamail.albany.edu
Web Site: www.albany.edu/~soktyabr

• Active medium consisting of InGaAs Quantum Wells grown on top of self-assembled InAs Quantum Dots (QW-on-QD) coupled by tunneling was developed.

• Damping-limited bandwidth of QW-on-QD active medium is estimated at 30 Ghz.

• VCSELs with tunnel-coupled QW-on-QD were fabricated.

• Threshold current density of ~ 4kA/cm² at 1130 nm was measured.

Figure 1, top left: Schematic band diagram of tunnel coupled Quantum Well-Quantum Dot medium.

Figure 2, bottom left: TEM (200) dark field cross-section of QD-on-QW medium.

Figure 3, above: Light-current characteristic of all-epitaxial tunnel coupled QD-on-QW VCSEL.
Preparation of Silicon Based Photonic Materials

CNF Project # 810-99
Principal Investigator: Philippe Fauchet

Abstract:
By forming a lattice of macroscopic dielectric media, an optical analogy of a crystal can be fabricated, called a photonic crystal. This investigation seeks to use silicon fabrication techniques to construct photonic bandgap structures with the capability of manipulating light for potential all-optical silicon based optoelectronic circuits. The optical properties of silicon photonic structures are also used to build biosensors. To achieve these goals, various thin-film deposition, etching, annealing, and photolithographic processes were performed at CNF. Equipment used in this project includes the MOS dry oxide and nitride LPCVD furnace, the Applied Materials RIEX etcher, JEOL 9300 e-beam writer, Plasmatherm 770 chlorine silicon etcher, HTG System III-HR Contact Aligner, Zeiss SEMs, Oxford PlasmaLab 80+ RIE, GaSonics Aura 1000 Asher, Heidelberg DWL 66 Laser Pattern Generator, PlasmaTherm 720 aluminum etcher, GSI PECVD nitride deposition, CAD tools, and the GCA PG3600F optical pattern generator.

Summary:
In the first approach we define a variety of photonic crystal resonators/waveguides on SOI wafers by e-beam lithography and fabricated by RIE. The structures are integrated with tapered ridge waveguides for light coupling. All coupling facets are polished after fabrication. To enable for electric field tuning, electrodes are integrated with photonic crystal resonators, and liquid crystals are infiltrated throughout the photonic structures [1-4]. In Figure 1, a 1-D photonic crystal cavity, with a “defect” lattice in the matrix and a photonic crystal waveguide, is integrated with a vertical contact. We have also fabricated resonators of other geometries, like ring resonator, [5,6] and the preliminary measurement shows their discrete resonance peaks with quality factors as high as 30,000.

Fabricated photonic crystals can also be used in biosensing applications. Their optical properties are highly sensitive to environmental variations (e.g. ambient refractive index changing, biological molecules binding etc.). Photonic crystals therefore are an attractive platform for label-free biosensing applications. Binding of the target biological molecules is monitored by observing a red shift of the transmission resonance.

References:
Preparation of Silicon Based Photonic Materials

CNF Project # 810-99
Principal Investigator: Philippe Fauchet
Users: Mikhail Haurylau, Wei Sun, Jidong Zhang, Mindy Lee

Affiliation: Electrical and Computer Engineering, University of Rochester
Primary Funding: Intel Corporation and Air Force Office of Scientific Research
Contact: fauchet@ece.rochester.edu, haurylau@ece.rochester.edu, wesun@ece.rochester.edu, jidong@ece.rochester.edu, mindylee@optics.rochester.edu

Figure 1, top left: 1-D photonic crystal cavity, with a “defect” lattice in the matrix and a photonic crystal waveguide, with an integrated vertical contact.

Figure 2, bottom left: 2-D PBG microcavity integrated on SOI wafer for biosensing.

Figure 3, above: Normalized transmission spectra of the photonic crystal microcavity. Curve (a) indicates the initial status, curve (b) is measured after glutaraldehyde is applied and curve (c) is obtained by infiltrating BSA (Bovine Serum Albumin) molecules.
Etched Facet Technology for Blue-Violet Lasers

CNF Project # 924-01
Principal Investigator: Alex Behfar

Abstract:

A blue-violet (405 nm) emitting laser was fabricated using a new etched facet technology for GaN-based material. The technology can allow the fabrication of short-cavity lasers with higher yield than possible in cleaved facet lasers.

Summary:

Nichia Chemical first demonstrated GaN-based blue lasers on sapphire substrates in 1995 and has subsequently been able to produce commercially available CW lasers [1]. Nichia uses cleaving to form the facets of its blue lasers, but prices of such lasers have remained very high. There is tremendous interest in fabricating inexpensive 405 nm-emitting GaN based lasers for the next generation of DVD applications.

Cleaving to form mirror facets is the standard process for making edge-emitting lasers. An alternative to cleaving is to etch the laser facets. Etched facets with high quality were formed in GaAs through a process based on chemically assisted ion beam etching (CAIBE) at Cornell University [2]. These laser devices are characterized by precisely located mirror facets with quality and reflectivity equivalent to those obtained by cleaving.

The EFT allows lasers to be fabricated on the wafer in much the same way that integrated circuit chips are fabricated on silicon. Etched facet lasers are monolithically integratable with other photonic devices on a single chip [3] and can be tested inexpensively at wafer-level [4]. Facet reflectivity modification (FRM) can be used to modify the reflectivity of the etched facets through deposition of dielectric coatings with the wafer intact.

A key to obtaining high quality etched facets is high selectivity between the etch mask and the semiconductor material in the etching process. The etch facets formed in GaN were formed with a selectivity of better than 10:1 and the etch rate was higher than 0.25 μm/min.

Formation of a cavity in the GaN system through cleaving does not easily allow a cavity length below 500 μm. Since the material system has very high defect density (presently around 1E5 defects/cm² for the best available material), assuming a ridge width of 2 μm, a cavity of such length will on average contain at least 1 defect. As such, the GaN system provides additional incentive for using etched facets since much shorter cavities can be formed with relative ease. Assuming a cavity length of 50 μm with the same ridge width of 2 μm, the probability of a cavity with a defect is a factor of 10 lower. This leads to significantly increased yield.

Acknowledgements:

Alfred Schremer, Malcolm Green, Alan Morrow and the rest of the BinOptics technical team contributed to this work.

References:

Etched Facet Technology for Blue-Violet Lasers

CNF Project # 924-01
Principal Investigator: Alex Behfar
Users: Cristian Stagarescu, Vinu Vainateya, Jeonghyun Hwang, Mahesh Pitchumani, Fareen Khaja

Affiliation: BinOptics Corporation
Primary Funding: BinOptics Corporation
Contact: behfar@binoptics.com, stagarescu@binoptics.com, vainateya@binoptics.com, hwang@binoptics.com, pitchumani@binoptics.com, fareen.khaja@binoptics.com
Web Site: http://www.binoptics.com

- Low-cost blue-violet emitting lasers for next generation DVD players.
- High defect density in GaN material severely impacts laser diode yield.
- Improved yield with short cavity etch facet lasers.

Figure 1: SEM image of an etched GaN facet.

Figure 2: Spectral characteristics of a blue-violet laser.
Sub-Wavelength Confinement in Integrated Metal Slot Waveguide on Silicon

CNF Project # 980-01
Principal Investigator: Michal Lipson

Abstract:
There is a growing research interest in optical circuits at the nanometer scale for future integration of optical, optoelectronic and electronic devices on-chip. For this goal, however, the typical dimensions of conventional dielectric waveguides are dictated by diffraction, therefore limiting dense on-chip integration. Plasmonic waveguides such as nanoparticle chains [1], nanorods [2], in contrast, guide light through the interaction of photon and electron oscillation around the metal surface, and are potential candidates for nanoscale optical elements with sizes much smaller than the diffraction limit. The tradeoff between the confinement level and propagation loss, however, is a fundamental limitation of such waveguides. Therefore, structures offering both high confinement and relatively low loss are desired. To overcome the traditional limitations of plasmonic waveguides, we use the inverted metal slot waveguide with a dielectric core sandwiched between metal cladding [3]. As is general for surface plasmon, the electric field polarized perpendicular to the metal-dielectric interface is bound around the interfaces due to the high dielectric discontinuity between metal and dielectric. For narrow slot, the plasmonic waves around the two interfaces interact and result in a symmetrical mode where the light is almost completely confined in the dielectric slot, enabling extreme sub-wavelength confinement across the slot far beyond the diffraction limit. The effective index of the slot increases due to the coupled plasmonic waves. Therefore, for three-dimensional realistic structures the light is vertically confined via the index confinement mechanism. Using the metal slot with silicon, we show experimentally a low loss plasmonic waveguide on silicon substrate with very high confinement, and we also show high coupling efficiency between these waveguides and dielectric silicon waveguides using very compact tapers.

Summary:
We fabricate the metal slot waveguide on an SOI wafer. The pattern is defined using electron beam lithography and etched by RIE. Then a photolithography step is used to define the window for metal evaporation and a bilayer resist structure is used for successful liftoff of 300 nm Au. Experimentally we show a low loss plasmonic waveguide on silicon with high confinement. The measured loss is about one order of magnitude lower than previously demonstrated structures with a similar level of lateral confinement. We also show for the first time experimentally high coupling efficiency between these waveguides and dielectric silicon waveguides using very compact tapers. The realization of deep sub-wavelength confinement and efficient coupling with standard dielectric silicon waveguides has attractive applications in nanoscale circuits and on-chip integration of optical, optoelectronic and electronic devices.

References:
**Sub-Wavelength Confinement in Integrated Metal Slot Waveguide on Silicon**

**CNF Project # 980-01**

**Principal Investigator: Michal Lipson**

**User: Long Chen**

**Affiliation:** Electrical and Computer Engineering, Cornell University

**Primary Funding:** Air Force Office of Scientific Research (AFOSR)

**Contact:** mlipson@ece.cornell.edu, lc286@cornell.edu

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**Figure 1**

Top left: Schematics of (a) cross section of the metal slot with silicon (b) integration of the metal slot waveguide with silicon wire waveguides.

**Figure 2**

Bottom left: Microscope image of the metal slot integrated with a dielectric silicon wire waveguides.

**Figure 3**

Above: Propagation loss of the metal slot waveguide with different slot width.
Evolutionary Photonics

CNF Project # 980-01
Principal Investigator: Michal Lipson

Abstract:

We simulate an evolutionary process in the lab for designing a novel high confinement photonic structure, starting with a set of completely random patterns, with no insight on the initial geometrical pattern. We show a spontaneous emergence of periodical patterns as well as previously unseen high confinement sub-wavelength bowtie regions. The evolved structure has a Q of 300 and an ultra small modal volume of \(0.112\left(\frac{\lambda}{2n}\right)^3\). The emergence of the periodic patterns in the structure indicates that periodicity is a principal condition for effective control of the distribution of light.

Summary:

We demonstrate and fabricate the design of a sub-diffraction limit mode volume optical resonator. The device is in a single layer slab, with a center bow tie cavity and surrounded by distributed Bragg layers. The bow tie creates a small modal volume cavity. The Bragg layers act to confine light in the bowtie cavity and increase Q of the structure.

The device geometry was generated with an evolutionary algorithm from random. There was no initial seeding for the device geometry. The merit function for device design was the field intensity in the structure center. Repeated runs of the algorithm generated the same basic geometry. Structure was limited to 250 nm thick silicon substrate, 4 by 5 \(\mu\)m, and surrounded by either oxide or air lower index material.

The device was analyzed and found to have sub-diffraction limited mode volume of \(0.112\left(\frac{\lambda}{2n}\right)^3\). Excitation was provided by 1.5 \(\mu\)m wavelength continuous wave. Device simulation was run until a steady state was achieved. The unusual shape of the resonator has not been previously reported in the literature and opens a potential for future optical structure design. The small mode volume could be used to offset low Q values and increase bandwidth of resonators which need high bandwidth and high nonlinear effects.

The algorithm demonstrates a completely different approach for ground up structure design. It could be used to explore photonic devices with unusual properties, which are difficult or impossible to design efficiently “by hand”.

The CNF nanocluster was used for evolutionary simulations for device design. Devices were fabricated with JEOL e-beam lithography on SOI wafers.

References:

Evolutionary Photonics

CNF Project # 980-01
Principal Investigator: Michal Lipson
Users: Alexander Gondarenko, Stefan Preble, Jacob Robinson, Long Chen
Affiliations: Electrical & Computer Engineering; Applied & Engineering Physics; Cornell University
Primary Funding: NSF
Contact: ML292@cornell.edu, AAG42@cornell.edu

• An evolutionary algorithm on a distributed computing platform at CNF nanocluster was used to design a new class of optical resonators.

• The new resonators show a sub diffraction limit optical mode volume $0.112(\lambda/2n)^3$.

• We attempted to design structures by hand, similar to the ones produced by the algorithm, but in simulations, our devices performed poorer.

• We fabricated hand and computer evolved devices to show fabrication feasibility.

• The devices shows a narrow central slot (10s of nanometers), surrounded by distributed Bragg layers.

Figure 1: Device “hand designed” from results of evolutionary algorithm. 1.5 µm excitation field. Designed for sub diffraction optical mode volume.

Figure 2: Device designed by evolutionary algorithm, theoretically out-performs hand designed device. 1.5 µm excitation field. Designed for sub diffraction optical mode volume.
Ultra-High Resolution Imaging of Highly Confined Optical Modes in Sub-Micron Scale SOI Waveguides

CNF Project # 980-01
Principal Investigator: Michal Lipson

Abstract:
Highly confined optical modes, made possible by the large index contrast in silicon on insulator (SOI) or semiconductor air-bridge platforms, has allowed for the development of a variety of compact and efficient photonic devices. Recent SOI photonic devices include optical switches and modulators in microring resonators [1] and photonic crystal cavities [2]. Optical buffers based on the large group index in photonic crystals [3] and electromagnetically induced transparency (EIT) [4] have been shown experimentally. Raman gain [5] and lasing [6] as well as efficient wavelength conversion [7] have also been recently demonstrated. The efficiency of these processes relies on the high concentration of optical intensity in the submicron-sized silicon core.

With this recent success of highly integrated sub-micron-scale photonic structures, comes the need for improved measurement and characterization techniques to better understand and design future devices. Of particular interest is the measurement of local near field properties of these devices. Here the highly confined nature of these devices makes local field measurements particularly challenging. Because light is confined to non-radiating guided modes and mode features are often smaller than the free space diffraction limit, conventional far field microscopy can not resolve the local characteristics of guided modes. Therefore much interest has been shown in the use of near field scanning optical microscopy (NSOM) to observe the local nature of guided modes in photonic devices. NSOM measures the optical near field by scanning a sub-wavelength-sized probe in the vicinity of an evanescent field near the sample’s surface.

We develop and implement a new type of NSOM: Transmission NSOM (TraNSOM) which has higher resolution than aperture NSOM techniques [8] and higher collection efficiency than existing apertureless techniques [9]. We implement this new technique on a commercial AFM by measuring small changes in transmission as the waveguide is scanned by a metallic AFM probe. With this technique we measure optical decay lengths as small as 85 nm in highly confined SOI waveguides.

Summary:
We perform ultra-high resolution imaging of the optical near field of sub-micron-scale silicon on insulator (SOI) waveguides using a transmission near field scanning optical microscopy (TraNSOM) technique we developed and implemented on a commercial AFM. We report resolution 18 times smaller than the free space wavelength ( ~ 85 nm) limited only by the size of the AFM probe. We implement this technique by measuring small changes in transmission through the waveguide as we scan it with PtIr coated AFM probe. The change in transmission at each point is related to the local intensity of the optical near field. We fabricate these waveguides to operate at a wavelength near 1.55 µm using electron bean lithography and ICP etching. The Si waveguides are approximately 500 nm wide and 250 nm tall on a 3 µm buried oxide. The waveguides are covered with about 160 nm of thermal oxide which we use as a hard mask for etching. Measured optical mode profiles agree well with theory.

References:
Ultra-High Resolution Imaging of Highly Confined Optical Modes in Sub-Micron Scale SOI Waveguides

CNF Project # 980-01  
Principal Investigator: Michal Lipson  
User: Jacob Robinson

Affiliation: Electrical and Computer Engineering, Cornell University
Primary Funding: Air Force Office of Scientific Research (AFOSR)
Contact: mlipson@ece.cornell.edu, jtr26@cornell.edu

- Optical mode imaged by measuring changes in optical transmission as a sub-micron scale SOI waveguide is scanned by a metallic AFM probe.

Figure 1, top left: Topographical AFM image of silicon on insulator (SOI) waveguide.

Figure 2, bottom left: Simultaneously recorded TraNSOM image of the optical mode (free space wavelength of 1.532 µm) confined to the waveguide shown in Figure 1. Optical standing wave pattern is a result of reflections at the input and output interfaces.

Figure 3, above: Solid line: Cross section of the mode profile measured along the line from point P to point Q in Figure 2. Dotted markers: Mode profile simulated with finite element mode solver. Dashed line: Simultaneously recorded topography measured from point P to Q.
Tunable Optical Delay with On-Chip Analogue to EIT

CNF Project # 980-01
Principal Investigator: Michal Lipson

Abstract:

Recent theoretical analysis of coupled micro resonators has revealed that coherence effects in coupled resonator systems are remarkably similar to those in atoms. Similar to the atomic systems, where electromagnetically induced transparency (EIT) occurs due to quantum interference effects induced by coherently driving the atom with an external laser [1], induced transparency can also occur in a photonic resonator system where coherent interference between two coupled resonators is instead enforced by the geometry of a nanophotonic structure. In particular, for particular configurations of waveguides side-coupled to resonators, there exists an all-optical dark state that can be asymptotically decoupled from the waveguide for proper tuning of the resonator frequencies. The existence of such an all-optical dark state, which gives rise to an EIT-like transmission spectrum, is critical for on-chip coherent manipulation of light at room temperatures, including the capabilities of stopping, storing and time-reversing of an incident pulse [2]. We provide the first experimental observation of structural tuning of the EIT-like spectrum in integrated silicon optical resonator systems. Our results demonstrate that the resonant interference required for coherent manipulation of light can indeed be achieved on-chip without the use of atomic resonance. Consequently, many of the basic limitations on bandwidth and decoherence that result from the fragility of the electronic coherence may be fundamentally overcome.

Summary:

The device is fabricated on SOI substrate using e-beam lithography and plasma dry etching. The device consists of two serially coupled ring resonators. The diameters of the two rings are 10 µm. The center-to-center distance between the two rings is 15.69 µm. Both the waveguide coupled to the rings and the one forming the rings have a width of 450 nm and a height of 250 nm. A slight difference in perimeter between the two rings (8 nm) is introduced to detune the ring resonances.

The transmission spectrum for the quasi-TM mode shows two dips at from the low-Q resonances of the two ring resonators (Q = 770). Due to the coherent coupling between these low-Q resonances, a narrow transmission peak appears with a quality factor Q = 11,900. Like the transparency peak in EIT spectrum, this high-Q transmission peak corresponds to a large group delay of 17.9 ps which corresponds to an effective group index of 207, considering the physical length of the device. Both the transmission spectrum and the group delay spectrum can fit very well with a theoretic model.

This delay is determined by the detuning between the two ring resonances. If the cavity is lossless, the delay will approach infinite when the detuning approaches zero. In the fabricated device, the maximal delay is limited by the scattering loss in the ring resonators. In the experiment, the detuning is controlled by tuning the resonance of each resonator thermally, and peak group delays between 7.8 ps to 25.0 ps are measured, corresponding to variable group index from 90 to 290. Higher group delay results in higher scattering loss, and therefore lower peak transmission.

References:
Tunable Optical Delay with On-Chip Analogue to EIT

CNF Project # 980-01
Principal Investigator: Michal Lipson
Users: Qianfan Xu, Jagat Shakya

Affiliation: Electrical and Computer Engineering, Cornell University

Primary Funding: Semiconductor Research Corporation;
National Science Foundation’s CAREER award

Contact: mlipson@ece.cornell.edu, qx23@cornell.edu, jbs68@cornell.edu

Figure 1: Top view microscopic picture of the serially coupled silicon micro-ring resonators as an on-chip all-optical analogue to the electromagnetically induced transparency. Arrows show the direction of light in the cavity.

Figure 2: Measured optical delay in the device (squares) at different wavelengths, which matches well with theory (solid line). A peak delay of 17.9 ps observed at the center of the EIT-like transmission peak (dashed line, right y-axis).
Terahertz & Infrared Photonic Crystal Structure

CNF Project # 1183-03
Principal Investigator: Yujie J. Ding

Abstract:

Photonic crystal structure is a promising candidate for manipulating light. Previous works are most focused on infrared photonic crystal. For the Terahertz (1 THz = 10^{12} Hz) far infrared range, which is of great interest to people for its application in bio-sensing, imaging etc., only a few results has been obtained [1]. In this project, we are working on designing and fabricating 1 D (Bragg reflector) and 2 D photonic crystal structures for THz frequency range. Apart from THz photonic crystal structures, we are also interested in fabricating 2 D photonic crystal slab structures for 1.55 µm infrared range. This structure is designed to demonstrate a low loss sharp bending waveguide to be applied for optical interconnect on single Si chip.

Summary:

In the previous year, we worked on optimizing both the design and fabrication of our photonic crystal structures. For our THz 2 D photonic crystal structures, we selected high resistivity Si wafer with a thickness of around 300 µm, which is thinner than the wafer we used before. We also selected new patterns for the 2 D photonic crystal. Besides etching circular air holes to form either the square lattice or hexagonal lattice which we tried before, we tried some new structures with square shaped air holes arrayed in square lattice and hexagonal shaped air holes arrayed in hexagonal lattice. We also optimized the parameter of the hole diameter and the lattice constant to achieve a broader photonic bandgap. The fabrication process of our THz photonic crystal remains almost the same; the major steps are thermal oxidation to grow SiO₂ mask layer, HTG photo lithography, PT72 SiO₂ etching, and Unaxis 770 Si through wafer deep etching.

For the 1.55 µm infrared photonic crystal slab waveguide, we selected silicon on insulator (SOI) wafers with a thicker SiO₂ insulating layer. This will help to reduce the leakage loss of the SOI slab waveguide. In fabrication, we used PECVD to deposit the SiO₂ mask layer. Unlike the thermal oxidation method, deposition will not change the top Si device layer thickness. Since the feature size of this structure is sub-micron (around 500 nm), electron-beam lithography was selected to write the patterns on the wafer. For SiO₂ mask etching, we used the PT72 and for top Si layer etching the PT770 is selected.

From our experimental characterization, we have identified the photonic bandgap for both of our 2 D THz photonic crystal and infrared photonic crystal structures. Further measurement and optimization of structures are still expected.

Reference:

Terahertz & Infrared Photonic Crystal Structure

CNF Project # 1183-03
Principal Investigator: Yujie J. Ding
Users: Hongqian Sun, Wei Shi

Affiliation: Electrical & Computer Engineering Dept., Lehigh University
Primary Funding: State of Pennsylvania
Contact: yud2@lehigh.edu, hos4@lehigh.edu, wes4@lehigh.edu
Near IR Quantum Dot Lasers for Ultrashort Pulse Generation

CNF Project # 1190-04
Principal Investigator: Prof. Farhan Rana

Abstract:
In recent years quantum dot (QD) lasers have become an active field of research. They offer a number of advantages over their quantum well laser counterparts, exhibiting lower threshold currents and improved temperature stability. Furthermore, a gain medium which comprises of self assembled quantum dots grown by MBE exhibits a broader gain spectrum along with a lower line-width enhancement factor compared to a quantum well based gain medium. These two factors make the prospects for producing pulses with widths approaching 100 fs via mode-locking quite lucrative.

Summary:
Our group is actively investigating QD lasers for generating ultra-short pulses via mode-locking. Recently, passively mode-locked quantum dot lasers have successfully produced pulses with pulse widths approaching 400 fs and peak powers of 500 mW [1,2].

A monolithic passively mode-locked semiconductor laser is comprised of a ridge waveguide etched into the semiconductor. On this ridge, two sections are defined of which the longer one is forward biased and acts as the gain section. Electrically isolated from the gain section is the saturable absorber section whose length is usually kept much shorter than the gain section. This segment is reverse biased, and for a suitable reverse bias voltage and forward bias current, the laser begins to emit a train of pulses at a repetition rate which depends on the length of the ridge waveguide. Feedback in the laser is provided by the cleaved facets which can be coated with various dielectric films to increase or decrease reflectivity.

One of the most promising samples consisted of three stacks of self-assembled InAs QDs sandwiched between AlGaAs cladding layers grown on a GaAs substrate. Waveguides with widths ranging from 2.5 µm were patterned using standard lithography techniques. Etching of the waveguides was performed on the newly installed III-V PlasmaTherm-770 ICP etcher. A combination of BCl<sub>3</sub>/Ar with the right RF parameters was able to provide a smooth, vertical waveguide profile. The waveguides were then planarized using a thermally curable polyimide before the top metal contact was evaporated. The samples were then thinned to 110 µm and after evaporating the back contact, the laser bars were cleaved with lengths varying between 250 µm and 3 mm. Unfortunately only laser bars whose lengths were below 1 mm demonstrated lasing at wavelengths just below 1200 nm. Several tens of mW of power was collected from one side of the device. The shorter waveguide lasers exhibited threshold currents around 100 mA. So far we have been unable to confirm mode-locking in these devices. Their short lengths would lead to repetition rates exceeding 50 GHz and would be a step forward towards high repetition rate devices. Facet coating by evaporating dielectric layers resulted in the reduction of the threshold currents as well as more output power.

References:
Near IR Quantum Dot Lasers for Ultrashort Pulse Generation

CNF Project # 1190-04
Principal Investigator: Prof. Farhan Rana
User: Faisal R. Ahmad

Affiliation: School of Electrical and Computer Engineering, Cornell University
Primary Funding: NSF
Contact: fr37@cornell.edu, fra3@cornell.edu
Web Site: http://people.ece.cornell.edu/rana/

Figure 1, top left: A schematic representation of a modelocked semiconductor laser. The waveguide is surrounded by low index polyimide. The gain and the saturable absorber section are electrically isolated. Light is extracted from one of the facets.

Figure 2, bottom left: A SEM showing the cleaved facet of a fabricated laser diode.

Figure 3, above: Coating one of the facets with a high reflector leads to an increase in the output power as well as reduction in the threshold current.
High Sensitivity Uncooled Microcantilever Infrared Imaging Arrays

CNF Project # I202-04
Principal Investigator: Gregory Simelgor

Abstract:
Multispectral Imaging is developing an infrared imaging detector based on an advanced bimorph microcantilever design. The bimorph design utilizes a combination of metallic and dielectric materials to create a temperature-sensitive structure that serves as the moving element in a variable-plate capacitor. The microcantilevers are integrated directly onto a CMOS integrated circuit, and all microcantilever materials are compatible with standard silicon IC foundry processing. Sensitivity modeling and measurements indicate an order-of-magnitude improvement over the current industry standard, vanadium oxide microbolometers.

Summary:
Uncooled vanadium oxide (VO$_x$) and amorphous silicon (a-Si) microbolometers are presently the technologies of choice for thermally sensing and imaging long wave infrared radiation. However, the performance of these devices has not improved significantly in recent years and studies indicate that these technologies may be reaching their performance limits [1,2].

Our proposed technique makes use of MEMS structures that respond mechanically to the absorption of infrared radiation. These structures were invented at the Oak Ridge National Laboratory (ORNL) [3] in the mid-1990s. Multispectral Imaging has licensed the ORNL technology [4-6] and is pursuing its commercialization using the resources at CNF.

Each pixel of our sensing array comprises the following components: an anchor, which elevates the sensing element above the substrate; a thermally isolating dielectric element of the paddle support arm; a thermally sensitive bimorph element of the paddle support arm; and the paddle itself. The gap between the paddle and the substrate serves as a resonant cavity for infrared radiation, and enhances the absorption of energy by the paddle. Heat flows from the paddle to the relatively cooler substrate through the thermally sensitive part of the support arm, causing the support arm to bend and the paddle to change its height relative to the substrate. The temperature-sensitive paddle height is measured capacitively by the underlying CMOS integrated circuit.

Although the process of integrating the MEMS structures on top of the CMOS circuit has not been completed, extensive modeling and measurements of both the CMOS and the MEMS structures separately indicate an order-of-magnitude improvement over microbolometer performance.

References:
High Sensitivity Uncooled Microcantilever Infrared Imaging Arrays

CNF Project # I202-04
Principal Investigator: Gregory Simelgor
User: Lijun Jiang

Affiliation: Multispectral Imaging, Inc.
Primary Funding: Venture capital
Contact: gsimelgor@multispectral.net, ljiang@multispectral.net
Web Site: http://www.multispectral.net

Table: FUNDAMENTAL NOISE LIMITS and NEDT (mK)

<table>
<thead>
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<th>Source</th>
<th>Value</th>
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</thead>
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<tr>
<td>Temperature Fluctuation Noise</td>
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<tr>
<td>Thermomechanical Noise (Sense Mode)</td>
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<td>Thermomechanical Noise (Reset Mode)</td>
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<tr>
<td>1/f + White Noise</td>
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<tr>
<td>kT/C Noise</td>
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<tr>
<td>Total NEDT (Sense Mode)</td>
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</tbody>
</table>

Figure 1, top left: Schematic diagram showing the operating principle of the bimorph microcantilever IR sensor.

Figure 2, bottom left: SEM images of single pixel. Cantilever bending response to changes in the tensile and compressive stresses in the thin film layers used to fabricate the microcantilever sensor structure.

Figure 3, above: SEM images of pixels from small arrays. To date, we have fabricated test structures with single pixels and small arrays of up to 64 x 64 pixels.
Integration of Nanophotonic Devices Based on Silicon & Polymer Waveguides

CNF Project # 1227-04
Principal Investigator: Roberto Panepucci

Abstract:

We are developing integrated photonic devices based on silicon and polymer materials. Micro-electro-opto-mechanical-systems (MEOMS) fabricated on a silicon-on-insulator technology are integrated with wavelength selective filters to develop complex sensor arrays and switches. Polymer materials have been investigated as a platform for incorporating passive as well as active functions in integrated photonic devices. CNF’s capabilities serve to complement FIU’s Motorola Nanofabrication Facility inaugurated in 2005.

Summary:

We are investigating the fabrication of suspended silicon waveguides, or micro-electro-opto-mechanical systems (MEOMS), that can be used to detect displacement in fully integrated fiber-optic devices. As part of the development of this device we have also investigated the fabrication of ultra-small silicon ring resonators. These ring resonators act as filters for on-chip wavelength division multiplexing (WDM) and demultiplexing. The ability to perform on-chip WDM is critical for querying the large arrays of integrated sensors we are developing.

Silicon waveguides are fabricated using silicon-on-insulator wafers with a Si device layer of 200-400 nm thickness over a 3 µm buried oxide layer. The devices are patterned using HSQ resist at 100 kV using the Leica VB6. Waveguide lengths vary from 5-10 mm and incorporate a previously developed nanotaper coupling structure that allows efficient coupling of > 90% of light from a tapered fiber. The waveguides are etched in the PT770 using Cl₂:BCl₃:Ar ICP-RIE. Typically devices are clad in SiO₂ using the GSI PECVD, diced and polished for testing. We are developing release methods to allow a suspended section of the device to interact with the environment. Electrostatic actuation of the device is implemented with on-chip electrodes. Figure 1(a) shows an SEM of the gap between cantilever waveguide and receiving waveguide in such a device. Figure 1(b) shows an optical micrograph of a 2 µm radius ring resonator used to multiplex the optical signal between different parts of the photonic circuits. This device has a free-spectral-range (FSR) of 47 nm, the largest for single ring resonator reported to date.

Polymer devices are of interest due to the ease of integration with nanocrystals, chromophore molecules and other dopants. We are investigating the use of 1D and 2D photonic crystal structures integrated with polymer waveguides. We are using PMMA/DR1 mixtures which have allowed us to directly pattern the waveguide layer in a single electro-beam lithography step using grayscale to achieve 3D structures. Lithography is carried out with the Leica VB6 at 100 kV using thin Au overlayer for charge dissipation. The polymer is deposited over a 30 nm Si₃N₄ capped 4 µm SiO₂ lower cladding. A wet etching step is used to release the structure. Figure 2(a) shows a SEM of cross section of the resulting 2D photonic crystal layer. Figure 2(b) shows a SEM top view of the 1D cavities inserted in a ridge waveguide.

Simulation of these structures is performed with a commercial package from RSOFT. The characterization of these devices is carried out in our labs through a fiber-optic test setup which includes piezoelectric nanopositioners and infrared imaging.

References:

Integration of Nanophotonic Devices Based on Silicon & Polymer Waveguides

CNF Project # 1227-04
Principal Investigator: Roberto Panepucci
Users: Xuan Wang, Roberto Panepucci

Affiliation: Electrical and Engineering Department, Florida International University
Primary Funding: NSF, AFOSR
Contact: roberto.panepucci@fiu.edu

Figure 1(a): SEM of the gap between cantilever waveguide and receiving waveguide in a released device.

Figure 1(b): Optical micrograph of a 2 µm radius ring resonator with a free-spectral-range (FSR) of 47 nm, the largest for single ring resonator reported to date.

Figure 2(a): SEM of cross section of the PMMA/DR1 2D photonic crystal layer.

Figure 2(b): Shows a SEM top view of the 1D cavities in a ridge waveguide.
Super Compact Gratings for DWDM Wavelength Mux/Demux Applications

CNF Project # I366-05
Principal Investigator: Seng-Tiong Ho

Abstract:
There are current needs for various monolithically integrated photonic devices and subsystems with dense wavelength division multiplexing (DWDM) capabilities. While making enormous progress, the current integrated DWDM Mux/Demux devices are still large in size (typically ~ 100-1,000 mm² for AWG). Meanwhile, the typical size of active devices, such as laser diodes, is < 0.5 mm², which is > 1,000x smaller. Thus the size of wavelength Mux/Demux will dominate all other active-passive components when integrated. This makes the wavelength Mux/Demux among the most expensive components to integrate.

Research Summary:
We have devised a monolithically integrated ultra-compact wavelength Mux/Demux on InP platform that can have a size of ~ 0.5-5 mm² at DWDM resolution, which will open up various opportunities that could lead to WDM-On-Chips that are substantially more compact than current technology. As the costs of integrated devices are proportional to the chip size, this will mean substantial reduction in the chip costs as well as increase in the integrated on-chip functionalities.

The ultra-compact wavelength (λ) Mux/Demux is based on a monolithically integrated curved diffraction grating on InP chip, which provides wavelength dispersion and beam focusing. Our approach results in high spatial resolution for the grating dispersion and hence high wavelength resolution at small physical size.

Summary:
In the current year, we fabricated some initial wavelength demultiplexer structures based on the super compact grating. The device fabrication process can be summarized as follows: we start with epitaxial grown InP/InGaAsP wafers. First, a layer of SiO₂ is grown by PECVD to act as InP/InGaAsP etch mask later. Then, the device pattern is written by e-beam lithography using PMMA as resist. The PMMA pattern is etched in RIE and transferred to the SiO₂ layer. The SiO₂ layer then acts as etching mask for InP/InGaAsP ICP etching, with typical etching depth of ~ 4 µm.

The initial fabrication run shows promising results. With a mm-size device, we are able to demonstrate wavelength resolution of 50 GHz. We are continuing to optimize the grating design as well as the fabrication process, and will push the device size and wavelength resolution further.

References:
Super Compact Gratings for DWDM Wavelength Mux/Demux Applications

CNF Project # 1366-05
Principal Investigator: Seng-Tiong Ho
User: Yingyan Huang
Affiliation: Department of Electrical Engineering and Computer Science, Northwestern University
Primary Funding: NSF
Contact: sth@ece.northwestern.edu, yingyan@ece.northwestern.edu

• Fabricated a novel super compact grating with minimal aberration, thus allow narrow slit size and large diffraction angle.
• Achieved 50 GHz wavelength resolution with device size < 1 mm².

Figure 1, top left: SEM picture of the fabricated wavelength demultiplexer with detector.

Figure 2, bottom left: SEM picture of the super compact grating.

Figure 3, above: Initial measurement result of the device transmission spectrum, showing 50 GHz pass band. The different height of the peak comes from the quantum well absorption at different wavelength.
Metal-Semiconductor-Metal Ultraviolet Photodetector on AlGaN

CNF Project # 1390-05
Principal Investigator: William R. Donaldson, Roman Sobolewski

Abstract:
Metal-semiconductor-metal photodiodes on AlGaN substrates are being developed to measure ultra-fast, deep-UV pulses on the OMEGA Laser System.

Summary:
This work involves the fabrication of metal-semiconductor-metal photoconductive detectors and photodiodes on aluminum gallium nitride (AlGaN). These photon detectors have finger widths and spacings between 150 to 5000 nm and are expected to have response times in the picosecond (ps) regime. At the University of Rochester, we have demonstrated that metal-semiconductor-metal (MSM) photodetectors have response times as short as 0.8 ps when fabricated on GaAs and 5.0 ps on Si. These devices have been used for the ultra-fast detection of photons not only because of their superior speed performance, but also because their planar geometry makes them suitable for use as either a discrete devices or as part of an optoelectronic integrated-circuit. AlGaN will allow us to extend this performance into the deep ultraviolet. Fundamental properties of these devices will be characterized at the University of Rochester, using an electro-optic sampling system. The devices will then be packaged for use on the OMEGA inertial confinement fusion (ICF) laser system as UV and x-ray detectors. Unlike GaN devices, which were fabricated at CNF in previous years, the AlGaN device should be blind to the OMEGA operating wavelength of 351 nm.

Two graduate students, Allen Cross and Shuia Wu, associated with the project, have been trained at CNF in the past year and have fabricated the first AlGaN devices.

The finger widths of the MSM structure ranged from 0.15 µm to 5 µm and two different active areas (25 x 25 and 50 x 50 µm square) were patterned. The smaller device have higher speed but lower sensitivity. To couple the electrical signal out of the devices, contact pads are fabricated adjacent to the interdigitated optically active region. For the ultra-fast characterization, the contact pad are rectangular regions equal to the area of the inter-digitated region. However, for applications on the OMEGA laser system, a smooth transition to a 50-Ohm transmission line is needed. In this case, an exponentially tapered pad is used to match the device to a 1-mm wide micro-strip transmission line.

The current-voltage characteristics of these two different geometries have been measured. The dark current increases by a factor of 10 between the small rectangular pads and large exponentially tapered pads. Thus the dark current is dominated by leakage between the pads, which are as much as 50 µm apart, rather than the fingers, which are 0.5 µm apart. We are exploring additional processing steps to reduce the pad leakage current.
Metal-Semiconductor-Metal Ultraviolet Photodetector on AlGaN

CNF Project # 1390-05
Principal Investigator: William R. Donaldson, Roman Sobolewski
Users: Allen Cross, Shuai Wu

Affiliation: Laboratory for Laser Energetics, University of Rochester
Contact: billd@lle.rochester.edu, acro@lle.rochester.edu, shuaiwu@pas.rochester.edu
Primary Funding: U.S. Dept of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority
Web Site: http://www.lle.rochester.edu/

Figure 1, top left: The MSM photodiodes are fabricated on AlGaN. The MSM structure size shown here is 25 x 25 µm. The finger width is 0.3 µm (a) and 1.0 µm (b).

Figure 2, bottom left: The large exponentially tapered pads used for impedance matching to a 50-Ohm transmission line.

Figure 3, above: The current-voltage characteristics of these two different geometries shown in Figures 1 and 2 have been measured. The dark current increases by a factor of 10 between the small rectangular pads and large exponentially tapered pads.