REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
23-12-2008	Final Report	1-Jun-2005 - 31-Jul-2008

4. TITLE AND SUBTITLE
Semiconductor Quantum Dot Structures for Integrated Optic Switches - Final Report

5a. CONTRACT NUMBER
W911NF-05-1-0223

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
48411-EL.1

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Quantum dot structures have been produced by etching pillars in GaAs/AlGaAs multiple quantum well structures. The pillars as tall as 1?m and with diameter as small as 40nm were defined using direct write electron beam lithography in combination with inductively coupled plasma reactive ion etching. Waveguide structures containing quantum dot regions integrated with disordered MQW sections have been fabricated. These integrated waveguides have been tested in our laboratory and have shown evidence of good waveguiding characteristics. We are currently assessing their electro-optic and nonlinear properties.

15. SUBJECT TERMS
Semiconductor Optoelectronic Devices; All-Optical Waveguide Switches, Ultrafast Optical Devices

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR		Patrick LiKamWa
					19b. TELEPHONE NUMBER
					407-823-6816

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Semiconductor Quantum Dot Structures for Integrated Optic Switches - Final Report

ABSTRACT

Quantum dot structures have been produced by etching pillars in GaAs/AlGaAs multiple quantum well structures. The pillars as tall as 1?m and with diameter as small as 40nm were defined using direct write electron beam lithography in combination with inductively coupled plasma reactive ion etching. Waveguide structures containing quantum dot regions integrated with disordered MQW sections have been fabricated. These integrated waveguides have been tested in our laboratory and have shown evidence of good waveguiding characteristics. We are currently assessing their electro-optic and nonlinear properties.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

D. A. May-Arrioja, N. Bickel, P LiKamWa, Robust 2x2multimode interference optical switch, Optical and Quantum Electronics, 38, pp557-566, 2006

Nathan Bickel and Patrick LiKamWa, Etched quantum dots for all-optical and electro-optical switches, Microelectronics Journal, 39(3-4), pp362-364, 2008

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Daniel A. May-Arrioja, Nathan Bickel, and Patrick LiKamWa, Integrated 1x4 Photonic Switch, Abstract, Frontiers of Optics (OSA Annual Meeting), 2005.

Nathan Bickel and Patrick LiKamWa, 2 x 2 quantum dot based multimode interference switching device, Nanoflorida, 2008.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

D. A. May-Arrioja, N. Bickel, and P. LiKamWa, A 1x3 Optical Switch by Carrier Induced Beam-Steering on InP, SPIE Proceedings 6572, 65720O (2007).

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 1

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Nathan Bickel	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Patrick LiKamWa	0.10	No
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Jeeun Cho	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The objective of this research is to investigate the possibility of creating semiconductor quantum dot structures that have a much tighter tolerance in the variance in physical sizes. The prevalent method of manufacturing semiconductor quantum dots is by the self-assembly process in which nano-sized islands of a semiconductor spontaneously nucleate while being grown either by molecular beam epitaxy or metalorganic chemical vapor deposition on a lattice mismatched substrate. While these quantum dots surprisingly are of very high quality and the radiative efficiency is essentially similar to their multiple quantum well counterpart. However the additional dimensional confinement leads of improved optical gain and laser properties. One of the underlying characteristics of the self-assembled dots is the large distribution of dot sizes that inevitably arises from the random crystallization of the nano-islands. While this is not a concern for laser diodes, semiconductor optical amplifiers and intersubband infrared photodetectors, other nonlinear and electro-optic devices that would benefit from the quantum confinement of the electrons require a better localization of the energy levels. Consequently for these applications, we envision that the quantum dots formed by etching cross-hatched grooves into multiple quantum layers would produce quantum dots that are of a uniform size with a very small variance. However, we note that it is to be expected that the radiative recombination efficiency would be severely deteriorated due to the presence of a high density of defect centers. As it happens an increase in non-radiative recombination rate is not necessarily a disadvantage for nonlinear and/or electro-optic devices. In fact it can be considered to be beneficial as it could lead to a faster recovery time for the devices.

Our approach is very straightforward; the semiconductor wafer is first covered with PECVD grown silicon dioxide to a thickness of 200nm. A layer of PMMA is spin-coated on top of the film and then exposed to the electron beam that writes an array of 30nm diameter discs. A Leica EBPG 5000+ was used for the electron beam lithography. After developing the resist, a layer of 30nm thick chromium metal is deposited by e-beam evaporation and “lift-off” process is used to leave 30nm diameter metal discs on top of the SiO_2 film. The Cr metal serves as the protective mask for etching off the unwanted SiO_2 film using a reactive ion etching process leaving an array of etched SiO_2 pillars that act as the mask during the etching of the semiconductor. The sample is then loaded in an inductive coupled plasma reactive ion etcher (ICP-RIE) and the GaAs multiple quantum well (MQW) material is etched using BCl_3 reagent gas. Although the concept is extremely simple and we had very little trouble to obtaining our first batch of samples that were test structures using GaAs substrates, in the end we were plagued with endless problems with our ICP-RIE which was a critical component for this

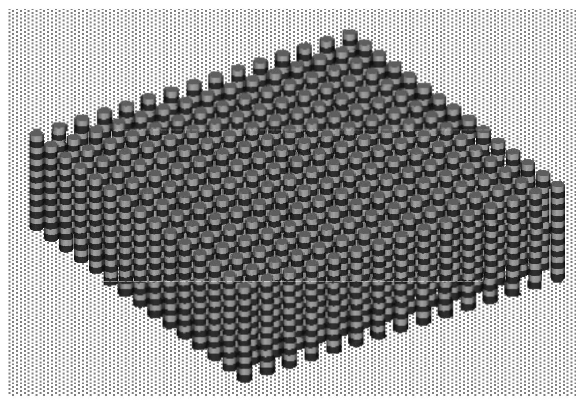

Fig. 1 Schematic drawing of etched QD stacks.

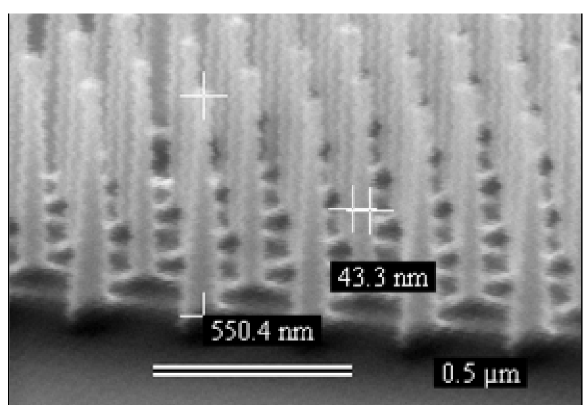

Fig. 2 Scanning electron micrograph of etched GaAs pillars.

project. Figure 2 shows a photograph of an array of etched MQW pillars, obtained using a scanning electron microscope (SEM). We spent over a year trying out a variety of possible fixes to repair the dry etcher and finally in the last month we trace the problem back to a relatively large vacuum leak that resulted from the manufacturer technician's failure to tighten a couple of screws that hold two sections of the vacuum chamber together. Recently after the tool has been repaired we have been able to successfully prepare some etched quantum dot stacks starting from GaAs/AlGaAs MQW structures. Figure 3 shows an SEM picture of the resulting pillars. As expected, these nanostructures are extremely fragile and therefore need to be handled with care. We then proceeded to fabricate a waveguide device that contains the quantum dots. The device consists of a mode launching waveguide and an output waveguide and a center region that overlaps with the etched quantum dots. In order to sample the quantum dots with a guided optical beam, we needed to make sure that the photons are not absorbed in the MQW sections of the device by selectively disordering these regions. The device shown schematically in figure 4, was fabricated using the following steps. First the thoroughly cleaned MQW sample was coated with a 200nm thick layer of silicon oxide using a plasma enhanced chemical vapor deposition process. A photolithographic step was undertaken to delineate a window on top of the SiO_2 film which was subsequently opened by reactive ion etching. The sample was then subjected to a rapid thermal annealing of 850ºC for 20s under a flow of ultrahigh purity nitrogen gas. This step caused the MQW immediately underneath the SiO_2 film to undergo partial intermixing between the wells and barriers so that the absorption edge was shifted to significantly higher energies (>50meV). Next the quantum dot regions were defined in the un-intermixed section of the MQW sample using electron beam lithography to delineate regularly spaced holes in a thin PMMA resist layer. 30nm of chromium is then evaporated on the sample and after a "lift-off" process, an array of chromium disks remains on the surface of the sample. The sample is then placed in an inductively coupled plasma - reactive ion etching (ICP-RIE) process chamber and the chromium disks act as masks during the etching process to produce and array of etched pillars containing quantum boxes. These pillars are extremely fragile at this stage and are set in place by placing a drop of BCB and spinning off the excess. After the BCB has been cured, the top surface is cleaned off of the BCB using reactive ion etching. Another photolithographic stage is performed to delineate the ridge waveguide by wet chemical etching. The substrate is then lapped and polished to a device thickness of 125μm and the device is cleaved to a total length of about 5mm. The device was mounted and tested in our end-fire coupling setup and it was found to guide a

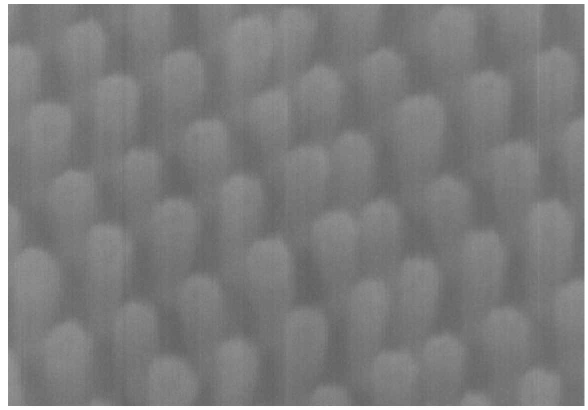

Fig. 3 SEM photograph of etched pillars in a GaAs/AlGaAs MQW sample. The center to center spacing is 200nm.

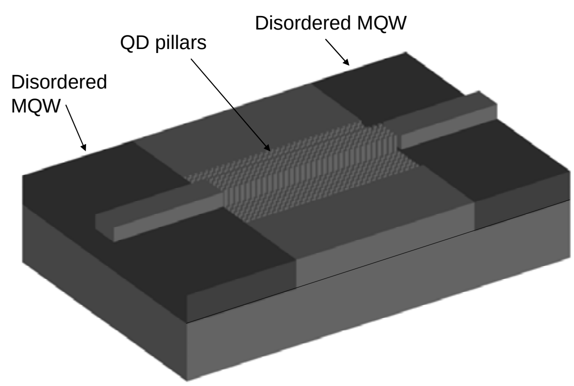

Fig. 4 Schematic drawing of a quantum dot waveguide device.

laser beam set at 880nm. Unfortunately as of the time of this report no other characterization experiments have been conducted yet. These measurements are currently underway and will be reported at a later date.

However, while the ICP-RIE was under repairs, experiments were performed on devices that were fabricated using a self-assembled InAs quantum dot structure. The wafer that was purchased from NanoSemiconductor (now Innolume) consists of 10 layers of InAs quantum dots embedded in InGaAs wetting layers with GaAs as the barrier material. The quantum dots layers are bounded on the top and bottom by $Al_{0.35}Ga_{0.65}As$ p-doped and n-doped waveguide cladding layers respectively and the whole structure was grown on a n-doped GaAs substrate. The peak of the photoluminescence spectrum was located at 1270nm at room temperature which makes the structure ideal for electro-optic modulation at or near the 1300nm wavelength range. A multi-mode interference (MMI) switch based on this structure was designed with the help of "Beamprop" which is a simulation software from R-soft. The schematic drawing of the device is shown in figure 5 and consists of two input and two output single mode waveguide and a central interfering region. Two electrodes placed in the middle region serve to inject electrical currents in the quantum dots immediately below the electrodes. The device operates essentially as directional coupler that passes the optical signals launched into one of the input ports to the output port that is crossed with the input port when no current is injected. With the application on an electrical signal into one of the electrodes, electrons are injected into the quantum dots and the refractive index in that region is altered such that the interference of the modes is disturbed significantly at which point the input optical signal is rerouted to the output port that is inline with the input port thereby resulting in optical switching. In order to discriminate the injection of the electrons in the specific region where the optical field is highest, the electrodes need to be isolated from each other and from the surrounding areas. This was accomplished by etching a 2µm wide groove all around the electrodes. The depth of the groove was carefully designed so that it would not interfere with the mode interference. The device simulations indicated that a groove depth of 2.4µm would result in an additional loss of 12dB while a groove depth of 1.45µm only resulted in an additional loss of 0.25dB. In the fabricated device, the isolation groove around each electrode was carefully etched to a depth of 1.45µm. Figure 6 shows photographs of the output facet of the device with and without applied bias and figure 7 shows the normalized intensities of the two complementary output as a function of injected current. The preliminary results shows that the splitting ratio between the two output

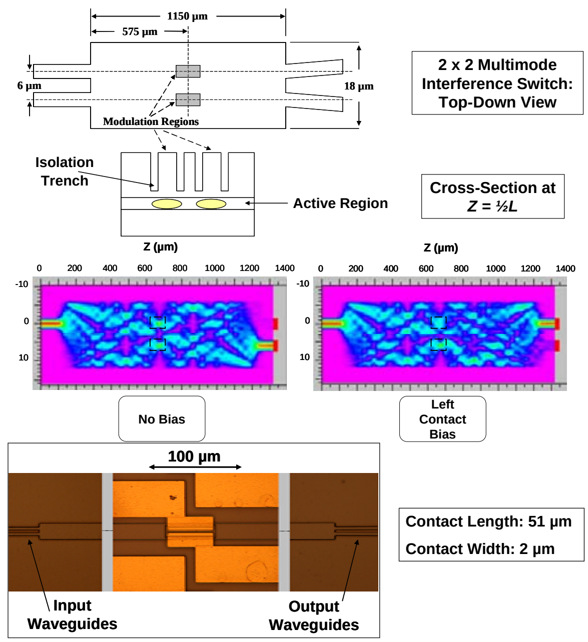

Fig. 5. Schematic drawing of MMI quantum dot switch and the BPM simulation results

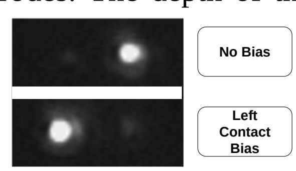

Fig. 6. Photographs of output facet.

ports can be continuously tuned from a 1:24 ratio to a 22:1 ratio with about 24mA injected into one of the electrode. A 50:50 split ratio was achieved with a 16.5mA current bias.

The future plan is to fabricate a similar device based on the etched quantum dots and compare the performances of the devices.

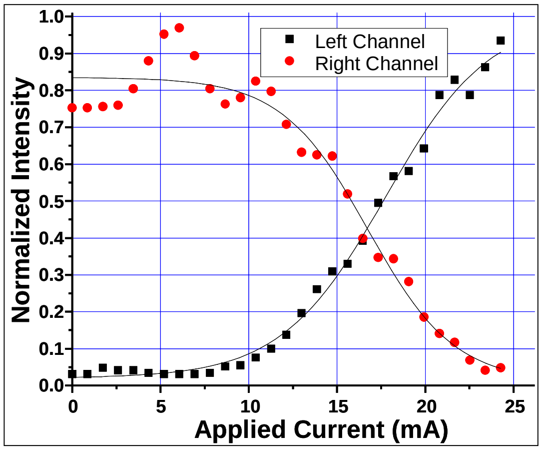

Fig. 6. Switching characteristics of the quantum dot MMI switch.

In conclusion, the project embarked upon a highly ambitious task of creating highly uniform quantum dots by employing electron beam lithography coupled with highly anisotropic etching process of ICP-RIE of multiple quantum wells. Although all the required resources were in place in our new nanofabrication cleanroom facility at CREOL, we were continuously plagued with breakdowns of our ICP-RIE tool. After many months of diagnosing and parts replacement, finally a vacuum leak detection revealed an incorrectly assembled vacuum chamber. After this defect has been repaired, the equipment is operating satisfactorily although. Unfortunately we ran out of time on the duration of this project to arrive at a definitive outcome.