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Report Title

Materials and Devices Research and Educational Infrastructure Enhancement Program

ABSTRACT

The aim of the program is the enhancement in the education and research infrastructure for materials and devices research and development. We have thoroughly worked with the vendors to get equipment that is very flexible and capable of performing a variety of fabrication and characterization procedures and we have been able to maximize the features on the equipment and minimize the price. The equipment has been ordered and will arrive by the middle of September, 2005. The research programs that this equipment aims to support are progressing well with Dr. Crouse, Dr. Tamargo and Dr. Arend doing cutting-edge theoretical and experimental work on semiconductor quantum dots and quantum wires and surface plasmon enhanced optoelectronic devices. We have formed several collaborations within CCNY and CUNY and outside of CUNY to research materials and devices and maximize use of the equipment. We have also organized additional K-12 education and outreach programs, targeted to underrepresented minority-serving high schools in the Harlem Community. In the future, once the equipment arrives and is operational, it will be immediately used for research and educational programs. Technology transfer programs are targeted to use the equipment as well.

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)

[1] David Crouse, Michael Crouse" Design and numerical modeling of normal oriented quantum wire infrared photodetector array " Infrared Physics and Technology, Available online 28 February 2006.

[2] David Crouse, "Phonon Modes and Electron-Phonon Interactions in Cylindrical Quantum Wires: Macroscopic and Microscopic Analyses and Device Applications", J. Appl. Phys. (in press).

[3] D. Crouse, “Numerical Modeling and Electromagnetic Resonant Modes in Complex Grating Structures and Optoelectronic Device Applications,” IEEE Trans. Electron Devices 52, 2365-2373 (2005).

[4] D. Crouse and Ravina Solomon, “Numerical modeling of surface plasmon enhanced silicon on insulator avalanche photodiodes,” Solid-State Electron. 491697-1701 (2005).

[5] D. Crouse and P. Keshavareddy, "Electromagnetic resonance enhanced silicon-on-insulator metal-semiconductor-metal photodetectors," J. Opt. A: Pure Appl. Opt. 8175-181 (2006).

[6] David Crouse, Mark Arend, Jianping Zou, and Pavan Keshavareddy, “Numerical modeling of electromagnetic resonance enhanced silicon metal-semiconductor-metal photodetectors” Optics Express 14(6), pp. 2047-2061 (2006).

[7] David Crouse, Pavan Keshavareddy, “Role of optical and surface plasmon modes in enhanced transmission and applications”, Optics Express 13(20), pp. 7760-7771 (2005).

Number of Papers published in peer-reviewed journals: 7.00

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

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Number of Inventions:

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NAME PERCENT_SUPPORTED

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FTE Equivalent:
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Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Personnel receiving masters degrees

NAME

Total Number:

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1. Foreword

The aim of the program is the enhancement in the education and research infrastructure for materials and devices research and development. We have thoroughly worked with the vendors to get equipment that is very flexible and capable of performing a variety of fabrication and characterization procedures and we have been able to maximize the features on the equipment and minimize the price. The equipment has been received and set up in Dr. Crouse's Optoelectronic Device Research Laboratory at CCNY. The research programs that this equipment aims to support are progressing well with Dr. Crouse, Dr. Tamargo and Dr. Arend doing cutting-edge theoretical and experimental work on semiconductor quantum dots and quantum wires and surface plasmon enhanced optoelectronic devices. We have formed several collaborations within CCNY and CUNY and outside of CUNY to research materials and devices and maximize use of the equipment. We have also organized additional K-12 education and outreach programs, targeted to underrepresented minority-serving high schools in the Harlem Community. The equipment is currently being used for research and educational programs. Technology transfer programs are targeted to use the equipment as well defense and civilian applications of the devices researched using the equipment.

2. Program Objective

The objectives of the project included research and educational objectives:

1. Enhance the educational infrastructure in materials and device fabrication and increase the number of students studying materials and devices at the undergraduate and graduate level.
2. Enhance the research infrastructure in materials and device fabrication and perform innovative and high quality research.
3. Enhance K-12 recruitment and outreach programs to underrepresented communities in the New York metropolitan area.

To meet these objectives, the following equipment was requested:

1. Rapid Thermal Annealer: The RTA will be used to anneal the electrical contacts to produce a good electrical contact and to anneal materials after crystal growth or ion implantation procedures.
2. Wire Bonder: The wire bonder will be used after the contacts have been fabricated and annealed in order to wire the device to an electronic package for either high-speed characterization or final device packaging and implementation into a larger optoelectronic system.
3. RF Network Analyzer: Perform broad bandwidth (up to 40 GHz) electrical characterization of devices after the devices have been wired into a package with the wire bonder. High frequency transmission line effects will need to be mitigated along the path from the contacts of the optoelectronic materials through the wire bond and out along a PC board microstrip trace to an RF connector.

After thoroughly investigating what vendors which vendors would be able to provide maximum capability, flexibility and low costs, purchase orders were submitted in late June 2005 for these three pieces of equipment. The vendors and equipment that were purchased were:

1. Surface Science Integration – Solaris 150 Rapid Thermal Processor for $64,270. This system was chosen because of its flexibility, impressive capabilities and unmatched price.
2. West Bond – Wedge Wire Bonder for $24,640.85. This system was chosen because of its wedge and wire bonding capability.
3. Agilent Technologies – N5230A–PNA–L network analyzer for $101,089.60 with many features that will allow for flexible high speed electrical characterization

There were a variety of research programs and projects at The City College of New York and The City University of New York. The past and future impact on two of these projects will be described in this report. These projects are:

1. Semiconductor quantum wire intersubband photodetectors
2. Surface plasmons: Optoelectronic Devices and Thermophotovoltaic materials

3. Results

3.1 Impact of Equipment on Quantum Wire Research

The requested equipment will have significant impact on capabilities of CCNY and CUNY researchers to perform cutting-edge research and development on infrared photodetectors that use intersubband transitions in III-V and II-VI semiconductor heterostructures as the photon detecting mechanism. These quantized intersubband levels are produced in nanoscale structures, such as quantum wells, wires and dots where the conduction band and valence band subbands are "quantized", or in other terms, the energy difference between subband levels becomes comparable to the energy of IR radiation (Fig. 1). The state of the art with intersubband detectors includes recently developed quantum well infrared photodetectors (QWIPs) that use GaAs/AlGaAs/GaAs quantum wells and a variety of other materials. However, QWIPs have several significant drawbacks that have limited their implementation in practical and widespread sensor systems. One major drawback is their inability to detect normal incident light as a result of the well known selection rules for photon absorption in these structures. This characteristic of QWIPs requires the use of grating couplers or other techniques to produce off-normal incidence. The second issue with QWIPs is that phonon scattering is not inhibited to the same degree as occurs in quantum wires (QR) and quantum dots (QD), disallowing the possibility of higher temperature operation.

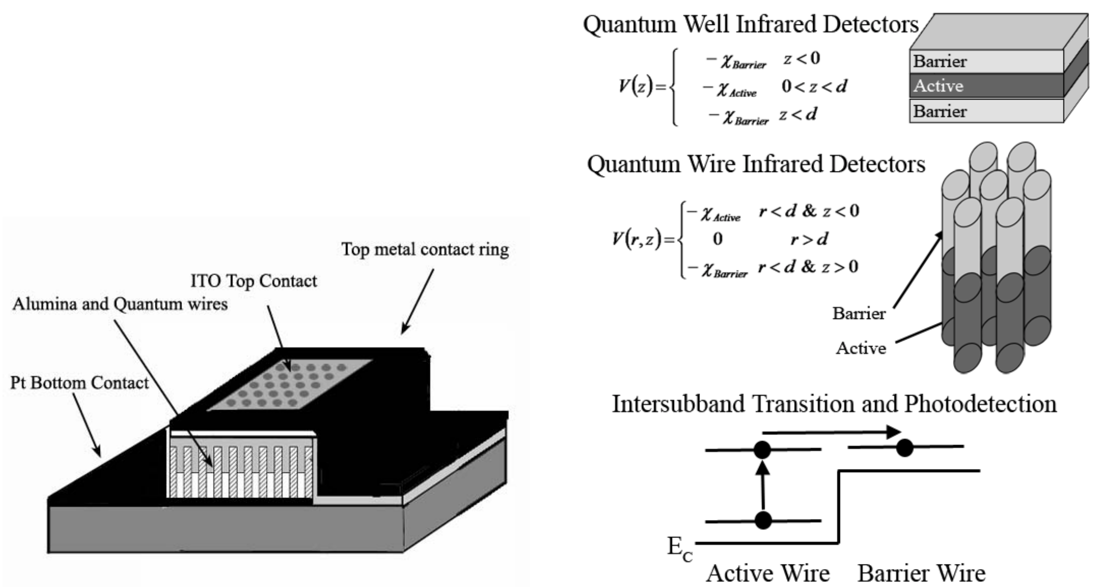

Figure 1: Left: The structures of a QWIP and QRIP. Right: If normal incident light falls on the detectors only the QRIP will produce an appreciable current because of the photon absorption selection rules.

These two issues are either solved or mitigated by using QRs and intersubband transitions QR heterostructures. First, the photon absorption rules can be avoided by structures that restrict electron or hole motion in directions parallel to the surface of the device, as is accomplished in QRs. Second, the one dimensionality of the QRs produces a strong optical-phonon (OP) scattering around the OP energy Δ that, if the QR is fabricated accordingly, can produce electron confinement to electron states below Δ. This then should allow for IR photodetectors that are capable of operating at higher temperatures compared to state of the art QWIPs and the more conventional bulk HgCdTe-based IR photodetectors.

In this project, we have been modeling normal-oriented II-VI semiconductor quantum wire heterostructures and evaluating their use as QRIPs. These QRs use a solvent-based DC electrochemical growth of II-VI semiconductors quantum wires in an anodized aluminum (i.e., alumina) template. As shown in Fig. 2, the II-VI semiconductor QRs in the alumina structure are composed of a hexagonal array of normal oriented wires (i.e., normal with respect to the substrate surface). Each wire is composed of two parts, one part being the active wire where photons are absorbed and another part that serves as a barrier region where ideally, only photo-excited electrons are capable of traversing. In the proposed project, we investigated whether an alumina-based template would be feasible to fabricate the QRs and subsequently the FPA with the associated read-out integrated circuitry (ROIC).

This project on QRIPs required a collaborative and concerted effort by several groups of researchers including groups responsible for theoretical analysis, optical device development and ROIC design. The equipment in this program will be used to support the efforts of the optical device development and ROIC design groups. What follows is a brief description of the progress of the theoretical and optical device development groups and how it relates to use of the equipment purchased in this program.

Use of Equipment in QRIP Project

The use of the rapid thermal annealer (RTA) and the wire bonder will play a crucial role in the continued research and development of these structures and devices. The RTA will be used to perform critical thermal processes to improve II-VI crystalline quality and modify the interface between the active and barrier portions of the QR. When the wires are initially grown, there are a lot of defects that can be eliminated by annealing, including interstitial group VI atoms. The wire bonder will be used later for electrical characterization and packaging. The wire bonder will allow for direct connection to sensitive electrical characterization equipment without the need for a probe station.

3.2 Impact of Equipment on Surface Plasmon Optoelectronic Device Research

A significant research program on surface plasmons (SP) has been initiated at CCNY and CUNY by Dr. David Crouse and Dr. James Hammonds. Dr. Crouse has been researching ultrafast Si-based photodetectors that use SPs and other electromagnetic resonance modes to channel and localize light. The equipment that was purchased in this Instrumentation Grant will be crucial to the continued research and development of these ultrafast Si-detectors. The wire bonder will allow direct connection to the RF vector network analyzer and allow for accurate high speed electrical characterization of these devices. Three types of these detectors are:

1. Si metal-semiconductor-metal photodetectors (MSM): These detectors are typical Si MSM detectors where we have taken a close look at the design of the metal contacts to channel the optical signal around the contacts and into the Si and localize the light near the contact/Si interface.
2. Si avalanche photodiodes (APD): We have redesigned an APD device to use electromagnetic resonance modes in order to decrease timing jitter and noise and increase gain.
3. Silicon-on-insulator MSMs: The entire structure, including the design of the metal contacts, the thicknesses of the top Si film and the oxide are designed to achieve unprecedented bandwidth and responsivity. The structure uses a variety of electromagnetic resonance modes.

These devices are currently being fabricated and will soon be ready to be characterized using the RF vector network analyzer and the wire bonder.

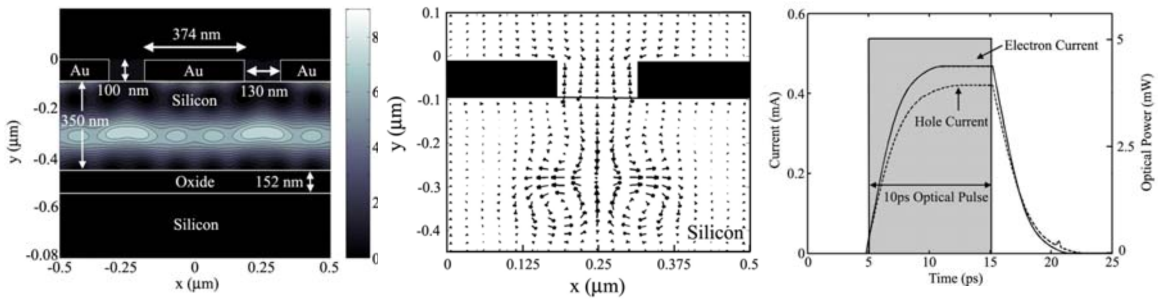

Fig. 2 **Left:** The electromagnetic energy density profile for a SOI MSM-PD with Au contacts and a 350nm thick Si top layer. Practically all of the energy is absorbed in the top Si layer producing both high responsivity and a high bandwidth. **Center:** The Poynting vector of the 850nm, TM polarized, normal incident beam. It is seen that the ER modes channel the light around the contacts and localize it in the top Si thin film layer of the SOI structure. Vortices of the Poynting vectors are evident. Only the top Si layer is shown because the fields in the rest of the structure are small. **Right:** The induced photocurrent for a 5ps, 50% duty cycle 5mW input pulse of light. These results indicate that both high responsivity (0.17A/W) and bandwidth (50GHz) can be achieved.

Conclusion of Technical Progress

All of the technical objectives of the program are progressing very well with the equipment purchased in this program having a significant impact on the research on a variety of projects at CCNY and CUNY including the quantum wire project and surface plasmon project mention in this report. Dr. Crouse, Dr. Tamargo and Dr. Arend are also getting collaborations within CCNY and CUNY with other researchers to fully utilize the equipment.

Education and Outreach Programs

Dr. Crouse, Dr. Arend and Dr. Tamargo have extensive education and outreach programs in their labs and will use the equipment purchased in this program to further these programs. Among their research groups, they have ten graduate students performing a variety of research projects; a substantial percentage of these will make use of the equipment. Also, they have participated in summer K-12 outreach programs where high school students from surrounding Harlem schools perform research projects over the summer. The equipment that was purchased will allow them and other CCNY faculty members to offer a wider range of research projects to these K-12 students.