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14. ABSTRACT

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Proposal Number: 68501ELRIP **Agreement Number: W911NF-16-1-0354**

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STEM Degrees: **STEM Participants:**

Major Goals: The Defense University Research Instrumentation Program (DURIP) is designed to improve the capabilities of U.S. Universities to conduct research and to educate scientists and engineers in selected technical areas of importance to national defense. DURIP funding provides for the acquisition of research equipment and instrumentation for this purpose.

This proposal is for the purchase of a rapid thermal annealer/processor.

The P.I., Professor Yong-Hang Zhang, of the Arizona State University will use the equipment to augment and enhance research capabilities in the area of type II superlattice photodetectors as well as III-V transistors and emerging non-volatile memories, HEMTs, MEMS based sensors, and optoelectronic devices such as LEDs, solar cells, and lasers.

Accomplishments: Nanofabrication equipment was purchased under this DURIP program. The AS-One 150 Rapid Thermal Processing (RTP), greatly improved the material and device processing capability in many DoD areas of research as well as ongoing student training and education. The RTP tool benefits a large number of users at Arizona State University, where the research ranges from post-Si nanoelectronic devices like III-V transistors and emerging non-volatile memory, HEMTs, MEMS based sensors, and optoelectronic devices such as LEDs, solar cells, and lasers. This tool allows the development innovative fabrication methods, novel device structures, and sustainable research concepts beneficial to many DoD applications.

Training Opportunities: In terms of education, the new tool has enhanced the learning and training of researchers and students by augmenting hands-on experience to better prepare them for future work and research relevant to DoD needs. In addition to hands on training of growth and process equipment training of students and junior researchers, ASU offers several hands on courses in the area of material processing and device fabrication. Including, special topic graduate courses in the area of optoelectronics, including III-V and II-VI materials and devices for defense and homeland security, EEE 435 Fundamentals of CMOS & MEMS, and EEE 439 Semiconductor Facilities/Cleanroom Practices. These courses and other training procedures exposes students to the newly purchased RTP system among the other tools in the cleanroom.
The students going through these courses have a decent understanding of the basic theory, along with practical knowledge of material growth and characterization as well as device fabrication. These types of courses receive very positive feedback from students and fellow faculty members.

Results Dissemination: This tool benefits a large number of groups at various levels, where the research ranges from post-Si nanoelectronic devices such as III-V transistors and emerging non-volatile memories, HEMTs, MEMS based sensors, as well as optoelectronic devices such as LEDs, solar cells, photodetectors, and lasers. The tool is supporting the development of new fabrication methods and new concepts that are of great interest to DoD applications on advanced electronic and communication systems.

Some of the investigators are also working on AlGaN-based ultraviolet LED fabrication as well as logic and memory devices beyond the Si CMOS using ferroelectricity in doped HfO2. Both of which will be positively impacted by the proposed acquisition of cleanroom equipment. Other work positively impacted, is the recent and ongoing work in the area of bismuth containing III-V semiconductor systems with narrow bandgaps for mid- and long-wavelength infrared device applications. In particular, InAs/InAsBi and GaSb/InAsBi superlattices strain balanced/lattice matched at the GaSb lattice constant, offer the prospect of alloying technologically important 6.1 Å semiconductors with semiconducting InAsBi (Bi mole fractions < 7.3%) and semimetallic InAsBi (Bi mole fractions > 7.3%). Unlike bulk ternary materials, these systems have the advantage that arbitrarily thick, coherently strained layers can be grown at the readily accessible GaSb lattice constant without misfit dislocations.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: The investigators are currently collaborating with the Army Research Laboratory (ARL) and Night Vision Lab to study novel substrates for HgCdTe and HgCdSe grown on InSb, GaSb and InAs for IR photodetector and FPA applications. They have demonstrated the state-of-the-art CdTe virtual substrates grown on lattice matched InSb substrates with world record long minority carry lifetime. Many are excited about the use of these new materials with high quality and relatively low cost for HgCdTe. HgCdSe alloys have some very similar material properties to HgCdTe. Their energy bandgaps cover a very broad wavelength range from near infrared to far infrared. Due to the availability of large-size substrates (GaSb and InAs), this material system could be an excellent alternative to HgCdTe materials for low-cost and large-area IR FPAs. They can also be integrated with many lattice-matched II/VI wide bandgap materials to cover the green-UV spectral range, enabling novel ultrahigh efficiency multi-junction solar cells and multicolor FPAs. That could revolutionize next-generation tandem solar cells for space applications and UV-IR adaptive staring cameras for imaging and sensing applications.

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Person Months Worked: 1.00 **Funding Support:**
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International Collaboration:
International Travel:
National Academy Member: Y
Other Collaborators:

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Participant: Shane Richard Johnson

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Nanofabrication equipment was purchased under this DURIP program. The AS-One 150 Rapid Thermal Processing (RTP), greatly improved the material and device processing capability in many DoD areas of research as well as ongoing student training and education. The RTP tool benefits a large number of users at Arizona State University, where the research ranges from post-Si nanoelectronic devices like III-V transistors and emerging non-volatile memory, HEMTs, MEMS based sensors, and optoelectronic devices such as LEDs, solar cells, and lasers. This tool allows the development innovative fabrication methods, novel device structures, and sustainable research concepts beneficial to many DoD applications.

15. SUBJECT TERMS
Rapid thermal processing; RTP; nanoelectronic devices

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Final Report

Acquisition of cleanroom research equipment to support ongoing DoD programs at ASU

(Sponsor award number: W911NF-16-1-0354)

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Abstract

This report summaries the installation and startup of the nanofabrication equipment purchased under this DURIP program. This tool, the AS-One 150 Rapid Thermal Processing (RTP), has greatly improved our material and device processing capability in many DoD areas of research as well as ongoing student training and education. The AS-One 150 RTP tool benefits a large number of users at Arizona State University, where the research ranges from post-Si nanoelectronic devices such as III-V transistors and emerging non-volatile memory, HEMTs, MEMS based sensors, as well as optoelectronic devices such as LEDs, solar cells, and lasers. This tool is assisting in the development innovative fabrication methods, novel device structures, and sustainable research concepts that are of great interest to many DoD applications in the area of advanced electronic and communication systems.

Introduction

In order to properly and thoroughly study material and device properties made of various semiconductors, such as type-II superlattices (T2SLs) for defense applications, one needs state of the art processing and fabrication equipment in addition to excellent material growth and optical and electrical characterization labs. The necessary fabrication and processing must take place in a cleanroom environment using metal and dielectric deposition, annealing, photolithography, and etching.

Arizona State University (ASU) is well equipped with both materials growth and device processing. The ASU NanoFab facility within the Center for Solid State Electronics Research (CSSER) consists of 3700 ft^2 of cleanroom space and hosts a complete set of processing tools for various kinds of device fabrication. The ASU NanoFab is a flexible processing facility that supports the southwest regional infrastructure for nanotechnology discovery and innovation. The ASU NanoFab is one of the 16 sites in the new NSF National Nanotechnology Coordinated Infrastructure (NNCI) – with funding at $4 million over 5 years. The facility was also a member of the previous national consortia of the National Nanotechnology Infrastructure Network (NNIN). NNCI sites provide researchers from academia, small and large companies and government labs with access to the user facilities to enable leading-edge fabrication, characterization, and expertise within all disciplines of nanoscale science, engineering and technology. These facilities support many research programs funded by DoD as well as many other federal, state, and private funding agencies and sponsors.

Rapid Thermal Processor

The cleanroom facility originally established in the mid-1980s is regularly upgraded. This DURIP provided an equipment upgrade for Rapid Thermal Processing (RTP) through the purchase of the AS-One 150 RTP from AnnealSys. This replaced an old ambient system with a contemporary a tool that can be operated at atmospheric pressures, partial pressures, and under vacuum. As a result contaminates, such as oxygen previously not completely removed during operation using the old chamber, have been greatly reduced using the new RTP system equipped with a vacuum chamber. The maximum temperature and duration of the temperature peak has also been greatly improved. The new RTP has enabled the annealing of materials/devices at extremely high temperature with precise gas (or mixed gas) flow.

The AS-One 150 RTP also has a stainless steel water-cooled chamber. The cold wall chamber technology and reactor design offer a number of advantages:

- High process reproducibility
- Low memory effect (Process chamber remains at the same temperature)
- Higher cooling rates
- Accurate pyrometer temperature measurement (no signal from the lamps)
- Low temperature pyrometer control (down to 150°C or less)
- Ultra clean and contamination-free environment
- No metallic and no cross contamination
- Atmospheric and vacuum capability
- Minimum volume, reduced surface for high vacuum performance
- Uniform gas distribution over the sample
- Easy chamber cleaning

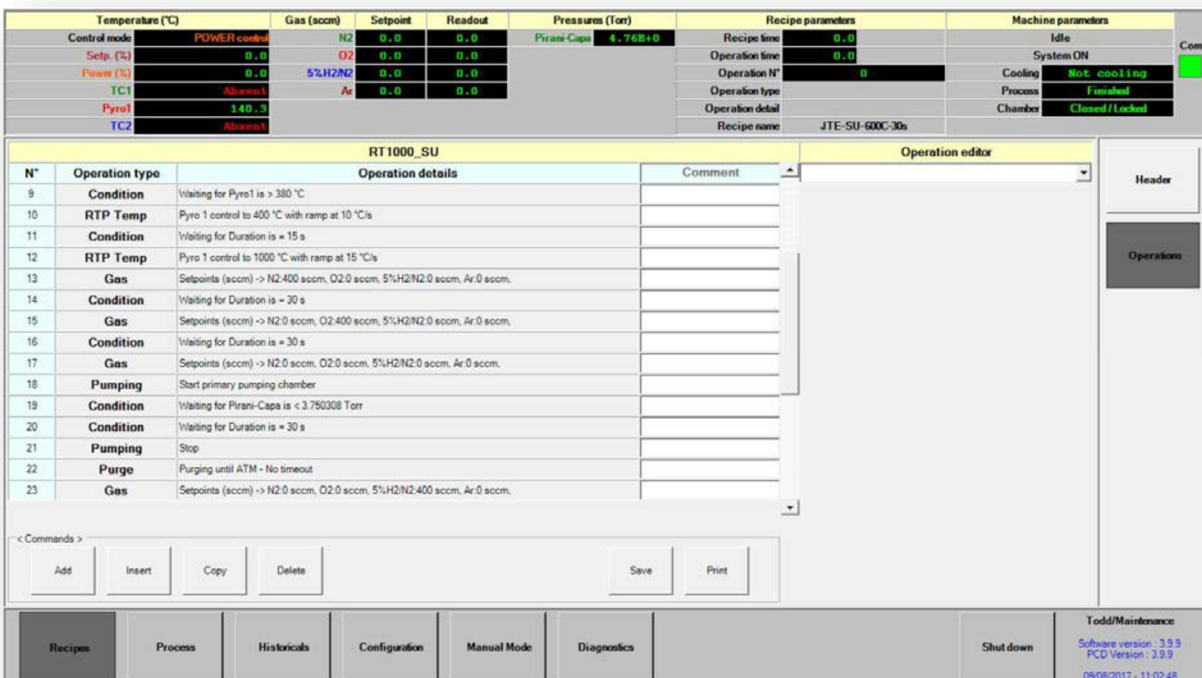
At the AS-One 150 has been plumbed with four process gases (Shown below). All of these gases can be used under sub-atmospheric conditions to provide anneal conditions under partial gas pressures.

Gas line	Gas nature	MFC range
1	N_2	2,000 sccm
2	O_2	2,000 sccm
3	$3\%H_2/N_2$	2,000 sccm
4	Ar	2,000 sccm

AS-One 150 RTP Uncrating and Installation

Typical RTP Run

Typical RTP Recipe



AS-One 150 RTP Standard Operating Procedure (SOP)

Listed below is the procedure for operating the RTP.

1. Overview

1.1. This document covers the procedure that should be followed for normal operation of the ANNEALSYS AS-ONE 150.

1.2. Tool Capabilities

1.2.1. Substrates and materials. Check with ASU NanoFab for restrictions. Not all materials are allowed.

1.2.2. Sample sizes.

1.2.2.1. Susceptor that hold small pieces up to a 100mm wafer

1.2.2.2. 6” wafer

1.2.3. Vacuum Pump - The pump is used to evacuate the atmosphere from the chamber.

1.2.4. Process Gas Options.

1.2.4.1. Argon 0-2000sccm

1.2.4.2. Forming gas - (N_2 / H_2) 0-2000sccm

1.2.4.3. Nitrogen 0-2000sccm

1.2.4.4. Oxygen 0-2000sccm

1.2.5. Temperature range is from 300°C to 1200°C.

1.2.5.1. Susceptor ramp rate = 20°C/second maximum

1.2.5.2. Silicon wafer ramp rate = 40°C/second maximum

1.2.6. Anneal Time

1.2.6.1. 300°C to 800°C = 1 hour

1.2.6.2. 800°C to 1000°C = 5 minutes

1.2.6.3. >1000° contact ASU NanoFab staff.

2. Safety

2.1. DO NOT leave the clean room, while the tool is running.

2.2. Burn Hazard

2.2.1. Substrate, susceptor and quartz window may be at high temperature. Wait for sufficient cool down of the substrate for unloading.

2.3. Possible eye damage

2.3.1. The lamp furnace emits strong visible and infrared light during operations.

3. Set Up Procedures

3.1. Enter your “Login” and “Password” than select “OK”.

3.2. Annealsys software pages

3.2.1. Recipes - no operator access

3.2.2. Process - contains all the functions to operate the tool.

3.2.3. Historical - all previous runs are archived here

3.2.4. Configuration - no operator access

3.2.5. Manual Mode - used for troubleshooting

3.2.6. Diagnostics - used for troubleshooting

3.3. Create new recipe - under construction

4. *Operation Procedures*

4.1. Load Sample

4.1.1. Ensure that the process page is selected.

4.1.2. Select “Purge until ATM”. The Pirani-Cap value will increase to approximately 760Torr

4.1.3. Select “Unlock”. If the chamber is at atmosphere, a solenoid will release the chamber lid.

4.1.4. Carefully open the chamber up by the handle. Lift it until it goes all the way up.

4.1.5. Ensure that the susceptor is cooled off.

4.1.6. Remove susceptor lid and place it on the landing pad. (use the tweezers provided)

4.1.7. Place sample on the susceptor using non-metal tweezers.

4.1.8. Replace the susceptor lid. (use the tweezers provided)

4.1.9. Carefully close chamber using the handle.

4.2. Process Sample

4.2.1. Select recipe “Name”.

4.2.2. Select “Download” and wait for a “Downloading was successful” message.

4.2.3. Check the “Last Downloaded Recipe” and ensure that is the recipe that is desired.

4.2.4. Select “Start process”.

4.2.5. A historical page will open displaying pertinent information. The file can be renamed to reflect the user, temperature and hold time.

4.2.6. Select Start

4.2.7. Graph displays (temperature, gas and pressure)

4.2.8. A “Finished” message will be displayed when the recipe is completed. Select “OK”.

4.2.9. The historical file will be available for review. The file will be stored for future review as well.

4.3. Unload Sample

4.3.1. Ensure that the process page is selected.

4.3.2. Select “Purge until ATM”. The Pirani-Cap value will increase to approximately 760Torr

4.3.3. Select “Unlock”. If the chamber is at atmosphere, a solenoid will release the chamber lid.

4.3.4. Carefully open the chamber up by the handle. Lift it until it goes all the way up.

4.3.5. Ensure that the susceptor is cooled off.

4.3.6. Remove susceptor lid and place it on the landing pad. (use the tweezers provided)

4.3.7. Remove the sample on the susceptor using non-metal tweezers.

4.3.8. Replace the susceptor lid. (use the tweezers provide)

4.3.9. Carefully close chamber using the handle.

4.4. Shutdown

4.4.1. Run the “Idle” recipe.

4.4.2. Select “Shutdown”. No other action needed.

Integration with existing facilities

The new RTP in combination with existing cleanroom tools has significantly expand the research capabilities of the ASU CSSER cleanroom. The RTP has enabled the capability of annealing materials/devices at extreme high temperature with precise gas (or mixed gases) flow.

Impact on research-related education

In terms of education, the new tool has enhanced the learning and training of researchers and students by augmenting hands-on experience to better prepare them for future work and research relevant to DoD needs. In addition to hands on training of growth and process equipment training of students and junior researchers, ASU offers several hands on courses in the area of material processing and device fabrication. Including, special topic graduate courses in the area of optoelectronics, including III-V and II-VI materials and devices for defense and homeland security, EEE 435 Fundamentals of CMOS & MEMS, and EEE 439 Semiconductor Facilities/Cleanroom Practices. These courses and other training procedures exposes students to the newly purchased RTP system among the other tools in the cleanroom.

The students going through these courses have a decent understanding of the basic theory, along with practical knowledge of material growth and characterization as well as device fabrication. These types of courses receive very positive feedback from students and fellow faculty members.

Impact on on-going research programs

This tool benefits a large number of groups at various levels, where the research ranges from post-Si nanoelectronic devices such as III-V transistors and emerging non-volatile memories, HEMTs, MEMS based sensors, as well as optoelectronic devices such as LEDs, solar cells, photodetectors, and lasers. The tool is supporting the development of new fabrication methods and new concepts that are of great interest to DoD applications on advanced electronic and communication systems.

Some of the investigators are also working on AlGaN-based ultraviolet LED fabrication as well as logic and memory devices beyond the Si CMOS using ferroelectricity in doped HfO2. Both of which will be positively impacted by the proposed acquisition of cleanroom equipment. Other work positively impacted, is the recent and ongoing work in the area of bismuth containing III-V semiconductor systems with narrow bandgaps for mid- and long-wavelength infrared device applications. In particular, InAs/InAsBi and GaSb/InAsBi superlattices strain balanced/lattice matched at the GaSb lattice constant, offer the prospect of alloying technologically important 6.1 Å semiconductors with semiconducting InAsBi (Bi mole fractions $< 7.3\%$) and semimetallic InAsBi (Bi mole fractions $> 7.3\%$). Unlike bulk ternary materials, these systems have the advantage that arbitrarily thick, coherently strained layers can be grown at the readily accessible GaSb lattice constant without misfit dislocations.

In addition, the investigators are currently collaborating with the Army Research Laboratory (ARL) and Night Vision Lab to study novel substrates for HgCdTe and HgCdSe grown on InSb, GaSb and InAs for IR photodetector and FPA applications. They have demonstrated the state-of-the-art CdTe virtual substrates grown on lattice matched InSb substrates with world record long minority carry lifetime. Many are excited about the use of these new materials with high quality and relatively low cost for HgCdTe. HgCdSe alloys have some very similar material properties to HgCdTe. Their energy bandgaps cover a very broad wavelength range from near infrared to far infrared. Due to the availability of large-size substrates (GaSb and InAs), this material system could be an excellent alternative to HgCdTe materials for low-cost and large-area IR FPAs. They can also be integrated with many lattice-matched II/VI wide bandgap materials to cover the green-UV spectral range, enabling novel ultrahigh efficiency multi-junction solar cells and multicolor FPAs. That could revolutionize next-generation tandem solar cells for space applications and UV-IR adaptive staring cameras for imaging and sensing applications.

Conclusions

The newly purchased RTP equipment has greatly improved our material and device processing capability in many DoD areas of research, as well as ongoing student training and education. Including many experiments that benefit DoD funded research, such as AFOSR funded "Modulation-Doped Heterovalent Structures for High-Speed Electronic Device Applications". Furthermore, this tool benefits a large number of users at Arizona State University, where the research ranges from post-Si nanoelectronic devices such as III-V transistors and emerging non-volatile memory, HEMTs, MEMS based sensors, as well as optoelectronic devices such as LEDs, solar cells, and lasers.