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| 12-10-2015   Final Report   1-Aug-2014 - 31-Jul-2015     4. TITLE AND SUBITLE   Sa. CONTRACT NUMBER     Final Report: Electrical and Optical Characterization System for   Sa. CONTRACT NUMBER     W911NF-14-1-0446   Sb. GRANT NUMBER     Sc. CANTRACT NUMBER   Sc. CONTRACT NUMBER     Yong-Hang Zhang   Sc. FNOGRAM ELEMENT NUMBER     6. AUTHORS   Sc. FNOGRAM ELEMENT NUMBER     Yong-Hang Zhang   Sc. TASK NUMBER     7. PERFORMING ORGANIZATION NAMES AND ADDRESSES   Sc. FREFORMING ORGANIZATION REPORT     Arizona State University   NUMBER     9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS   Sc. PERFORMING ORGANIZATION REPORT     VORSPA   P.O. Box 576011   10. SPONSOR/MONITOR'S ACRONYM(S)     9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS   10. SPONSOR/MONITOR'S ACRONYM(S)     (ES)   VS. Army Research Office   11. SPONSOR/MONITOR'S ACRONYM(S)     V.S. Army Research Office   11. SPONSOR/MONITOR'S ACRONYM(S) </td <td colspan="7">The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions,<br/>searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments<br/>regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington<br/>Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302.<br/>Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection<br/>of information if it does not display a currently valid OMB control number.<br/>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</td> | The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions,<br>searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments<br>regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington<br>Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302.<br>Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection<br>of information if it does not display a currently valid OMB control number.<br>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS. |  |                 |          |                                 |                  |   |   |  |
| 4. TITLE AND SUBTITLE   5a. CONTRACT NUMBER     Final Report: Electrical and Optical Characterization System for<br>IR Photodetectors   5a. CONTRACT NUMBER     W11NF-141-0446   5b. GRANT NUMBER     6. AUTHORS   5c. PROGRAM ELEMENT NUMBER     9 yong-Hang Zhang   5c. TASK NUMBER     7. PERFORMING ORGANIZATION NAMES AND ADDRESSES   5c. WORK UNIT NUMBER     7. PERFORMING ORGANIZATION NAMES AND ADDRESSES   8. PERFORMING ORGANIZATION REPORT     Arizona State University<br>ORSPA   52.2827 -6011     9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS   10. SPONSOR/MONITOR'S ACRONYM(S)<br>ARO     11. SPONSOR/MONITOR'S ACRONYM(S)   11. SPONSOR/MONITOR'S ACRONYM(S)<br>ARO     12. DISTRIBUTION AVAILIBILITY STATEMENT   APOPLEMENTARY MORTES     Approved for Public Release; Distribution Unlimited   13. SUPPLEMENTARY MORTES     13. SUPPLEMENTARY NOTES   14. ANSTRACT     This DURP project focuses on developing a measurement setup for the study of the carrier dynamics in Ga-free<br>In AsiThASE by type-11 superiattices (T251) based infrared photodetectors     14. ABSTRACT   10. SUBPLEMENTARY NOTES     15. SUBJECT TERMS   20.30 ARO MURT program to study the defects and their mitigation in<br>antinomy-based T251.3, and by a joint program from AFOSR and ARO to demonstrate novel optically-addressed<br>undicident detacted advantages for MWIR and LWIR kinfrared photodetectors  | 1. REPORT DAT  | 1. REPORT DATE (DD-MM-YYYY) 2. REPORT TYPE           |                 |          |                                 |                  | 3. DATES COVERED (From - To)                |   |  |
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| 6. AUTHORS     Yong-Hang Zhang     5c. AUTHORS     Yong-Hang Zhang     5c. TASK NUMBER     5c. TASK NUMBER     5c. TASK NUMBER     5c. TASK NUMBER     7. PERFORMING ORGANIZATION NAMES AND ADDRESSES     Arizona State University     ORSPA     P.O. Box 876011     Tempe, AZ     8. S287 -6011     9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS     (ES)     U.S. Army Research Office     P.O. Box 876011     Research Triangle Park, NC 27709-2211     12. DISTRIBUTION AVAILIBILITY 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     This DURIP project focuses on developing a measurement setup for the study of the carrier dynamics in Ga-free InAs/InAsSb T2SLs offer great advantages for MWIR and LWIR laser and detector applications due to their broad bandgap tunability and material uniformity. We have been supported by a recent ARO MURI program to study the defects and their mitigation in antimony-based T2SLs, and by a joint program from AFOSR and ARO to demonstrate novel opticalaly-addressed disu  |  |  |                 |          | 5b. GF                          | 5b. GRANT NUMBER |   |   |  |
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# **Report Title**

Final Report: Electrical and Optical Characterization System for IR Photodetectors

# ABSTRACT

This DURIP project focuses on developing a measurement setup for the study of the carrier dynamics in Ga-free InAs/InAsSb type-II superlattices (T2SL) based infrared photodetectors. Ga-free InAs/InAsSb T2SLs offer great advantages for MWIR and LWIR laser and detector applications due to their broad bandgap tunability and material uniformity. We have been supported by a recent ARO MURI program to study the defects and their mitigation in antimony-based T2SLs, and by a joint program from AFOSR and ARO to demonstrate novel optically-addressed multicolor photodetectors and focal plane arrays.

# Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

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

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

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

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

# (c) Presentations

1. Title: Carrier localization in InAs/InAsSb type-II superlattices authors: Zhi-Yuan Lin, Shi Liu and Yong-Hang Zhang conference name: SPIE DSS 2015 date: April 21th, 2015

2. Title: A real-time baseline correction method for time-resolved photoluminescence authors: Zhi-Yuan Lin and Yong-Hang Zhang conference name: SPIE optics + photonics 2015 data: August 12th, 2015

|                | Non Peer-Reviewed Conference Proceeding publications (other than abstracts): |
|----------------|--|
| Received       | Paper  |
| TOTAL:         |  |
| Number of Non  | Peer-Reviewed Conference Proceeding publications (other than abstracts):     |
|                | Peer-Reviewed Conference Proceeding publications (other than abstracts):     |
| Received       | Paper  |
| TOTAL:         |  |
| Number of Peer | r-Reviewed Conference Proceeding publications (other than abstracts):        |
|                | (d) Manuscripts  |
| Received       | <u>Paper</u>   |
| TOTAL:         |  |
| Number of Man  | uscripts:  |
|                | Books  |
| Received       | Book   |
| TOTAL:         |  |

Received Book Chapter

## TOTAL:

## **Patents Submitted**

Provisional patent: <u>name: real-time baseline correction method for time-resolved photoluminescence</u> fill date: March 24th 2015

**Patents Awarded** 

### Awards

**Graduate Students** 

NAME

PERCENT\_SUPPORTED

FTE Equivalent: Total Number:

Names of Post Doctorates

NAME

PERCENT\_SUPPORTED

FTE Equivalent:

Total Number:

Names of Faculty Supported

NAME

PERCENT\_SUPPORTED

FTE Equivalent: Total Number:

## Names of Under Graduate students supported

NAME

PERCENT\_SUPPORTED

FTE Equivalent: Total Number:

| <b>Student Metrics</b><br>This section only applies to graduating undergraduates supported by this agreement in this reporting period  |
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| The number of undergraduates funded by this agreement who graduated during this period: 0.00<br>The number of undergraduates funded by this agreement who graduated during this period with a degree in<br>science, mathematics, engineering, or technology fields: 0.00 |
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|  |

# Names of Personnel receiving masters degrees

NAME

**Total Number:** 

## Names of personnel receiving PHDs

<u>NAME</u>

**Total Number:** 

# Names of other research staff

NAME

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FTE Equivalent: Total Number:

## Sub Contractors (DD882)

**Inventions (DD882)** 

**Scientific Progress** 

See attachment

**Technology Transfer** 

| REPORT DOCUMENTATION PAGE  |   |   |   |  | Form Approved<br>OMB No. 0704-0188   |  |  |
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#### The Final Report for the ARO DURIP Program

### **Electrical and Optical Characterization System for IR Photodetectors**

Grant No.: W911NF-14-1-0446

## Period 01/08/2014 to 31/07/2015

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Director, Center for Photonics Innovation

&

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#### I. Project objective

This DURIP project focuses on developing a measurement setup for the study of the carrier dynamics in Ga-free InAs/InAsSb type-II superlattices (T2SL) based infrared photodetectors.

Ga-free InAs/InAsSb T2SLs offer great advantages for MWIR and LWIR laser and detector applications due to their broad bandgap tunability and material uniformity. We have been supported by a recent ARO MURI program to study the defects and their mitigation in antimony-based T2SLs, and by a joint program from AFOSR and ARO to demonstrate novel optically-addressed multicolor photodetectors and focal plane arrays.

#### II. Experimental systems upgrade

The transient signals from the T2SL samples, including optical signals and electrical signals, provide useful information for the understanding of the materials and devices. Time-resolved photoluminescence (TRPL) is a relatively traditional way to characterize the carrier lifetime in bulk material. We have developed a method that can significantly suppress the noise in our TRPL setup so as to make the measurement much more efficient. Furthermore, the transient electrical signal decays such as open circuit voltage decay and photocurrent decay in the photodetectors can offer more information about the carrier dynamics under the working conditions of the photodetectors. Experimental systems that can carry out the measurement for such transient electrical signals are also developed. In this DURIP program, four experimental systems are compiled or upgraded for the characterization of InAs/InAsSb T2SL materials and photodetector devices.

#### 1. TRPL system

A previously used TRPL system was upgraded with new equipment and a Real-time Baseline Correction (RBC) method is developed, which make the measurement more efficient. As shown in Figure 1, the newly purchased equipment is in the blue dashed boxes, and the equipment used for the RBC modification of the experiment is marked using the red circles. The newly purchased equipment includes a fast HgCdTe (MCT) detector and a 1064 nm pulse laser. The new fast MCT detector has an effective area of 0.5 mm  $\times$  0.5 mm, 24 times larger than the old one. The larger effective area collects more photoluminescence (PL) and the signal intensity is enhanced. The new 1064 nm laser has a short pulse width of less than 1 ns, and a high pulse energy of 7  $\mu$ J, which enables the system to resolve the short lifetime of the samples with weak PL signals. The RBC method implants a chopper and a lock-in amplifier into the system and suppresses the noise by 2 orders of magnitude. The upgraded TRPL system can perform experiments with a higher cutoff frequency and a larger signal-to-noise ratio.

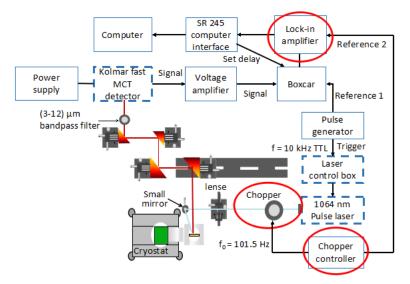


Figure 1. The block diagram of the upgraded TRPL system. The detector and laser are newly purchased. The chopper and lock-in amplifier are implanted to suppress the noise. After the upgrade, the system has a higher cutoff frequency and a larger signal-to-noise ratio.

#### 2. Cryostat-based time-resolved electrical signal measurement system

In this system, the detector samples are wire-bonded and the electrical signals are extracted using copper wires, providing a cut-off frequency of 1 MHz. The samples in the cryostat can be cooled down to 8 K with a thermal shield and down to 12 K without the thermal shield for optical injection. Multiple lasers have been purchased and integrated into this system. With multiple lasers at different wavelengths, the system is capable of testing the behaviors of the device at different light absorbing conditions, providing useful information for the understanding of the device physics. This system can be used for both transient open circuit voltage measurements and transient photocurrent measurements.

Figure 2 shows the experimental setup using the 1064 nm pulse laser. The same RBC method is applied here to suppress the noise. Figure 3 shows the experimental setup using the 785 nm CW laser, which can be modulated electrically, generating a square wave of light. The decay tails of the rising edges and falling edges are as short as 5  $\mu$ s. Figure 4 shows the experimental setup using the 3390 nm CW laser. This laser cannot be modulated electrically and therefore it has to be modulated by a chopper. Due to the finite size of the chopped laser beam, the rising time and falling time of the incident light intensity is on the order of 100  $\mu$ s under a 100 Hz operation.

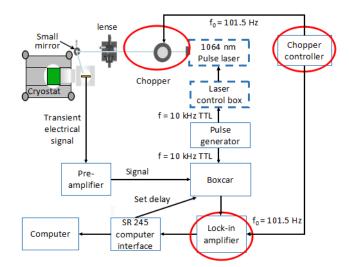


Figure 2. The cryostat-based optically pumped transient electrical signal measurement system using a 1064 nm pulse laser as the excitation source. The dashed blue boxes mark the newly purchased equipment. The signal-to-noise ratio of the measurement is enhanced by the RBC method.

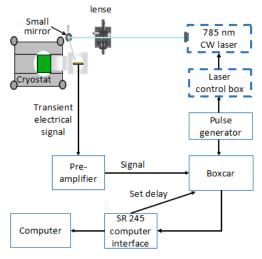


Figure 3. The cryostat-based optically pumped transient electrical signal measurement system using a 785 nm modulated CW laser as the excitation source. The dashed blue boxes mark the newly purchased equipment.

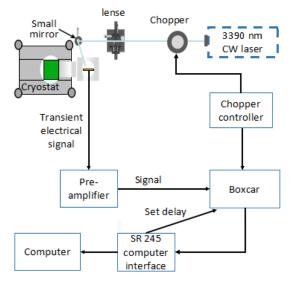


Figure 4. The cryostat-based optically pumped transient electrical signal measurement system uses a 3390 nm CW laser as the excitation source. This laser cannot be modulated electrically so its light beam is modulated by a chopper mechanically. The dashed blue box marks the newly purchased equipment.

#### 3. Probe-station-based ultrafast transient electrical signal measurement system.

A high-speed system with a 1 GHz cut-off frequency was developed based on a low temperature probe station. This probe-station-based system can be used for both the transient open circuit voltage measurement and the transient photocurrent measurement. The probe station uses liquid nitrogen as the coolant and therefore the sample can be cooled down to 77 K. The 1064 nm pulse laser with a short pulse width of less than 1 ns is coupled into the probe station. The transient voltage of the photodetectors is amplified by a preamplifier before it feeds into the high speed boxcar averager. The old slow cable in the probe station with a cut-off frequency of 50 MHz was replaced with a fast cable with a cut-off frequency of 40 GHz. The old pre-amplifier with a cut-off frequency of 1 MHz was replaced with faster pre-amplifiers whose cut-off frequencies are 1 GHz. Overall, this system can achieve a time resolution as short as 1 ns, allowing the measurements of fast transient electrical signals down to 10 ns.

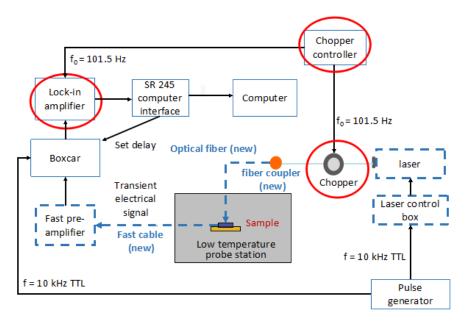


Figure 5. The probe-station-based system for ultra-fast transient electrical signal measurements. The newly purchased equipment is shown in blue dashed boxes. This system can be used for both transient open circuit voltage measurement and transient photocurrent measurement with a time resolution of 1 ns.

The details of the systems for the fast transient optical and electrical signal measurements are summarized in Table 1.

Table 1. Summary of the time resolutions and lowest operation temperatures of the systemsfor the high-speed transient optical and electrical signal measurements.

| No | Measurement | Cooling       | Laser type          | Time       | Lowest          |
|----|-------------|---------------|---------------------|------------|-----------------|
|    | type        | system        |                     | resolution | temperature (K) |
| 1  | optical     | cryostat      | 1064 nm pulsed      | 30 ns      | 12              |
| 2  | electrical  | cryostat      | 1064 nm pulsed      | 1 µs       | 12              |
| 3  | electrical  | cryostat      | 785 nm modulated CW | 5 µs       | 12              |
| 4  | electrical  | cryostat      | 3390 nm CW          | 100 µs     | 12              |
| 5  | electrical  | Probe station | 1064 nm pulsed      | 1 ns       | 77              |

#### 4. Visible-to-NIR PL system

In addition, a new PL system covering a wavelength range from visible to near infrared (NIR) was built. The new PL system has the capability of characterizing the optical properties of the CdTe materials, which is used for the AFOSR multi-color detector project.

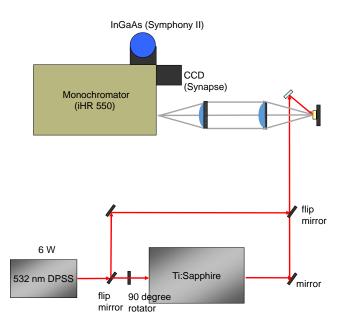


Figure 6. Visible-to-NIR PL system

The new Horiba PL system has the capability of characterizing materials with PL in the wavelength range of 300 nm ~ 1700 nm. The system consists of an iHR550 monochromator, a CCD detector and an InGaAs array detector. The iHR550 monochromator with a focal length of 550 mm enables high resolution spectra measurement. Its unique asymmetric Czerny-Turner design allows for extremely low stray light. With the 3 grating turret, the measurements can be done with the optimal grating within each spectra range. The CCD array detector is thermoelectrically cooled, back illuminated and deep depleted, providing high quantum efficiency in the 300 nm to 1050 nm wavelength range. The InGaAs array detector is liquid nitrogen cooled and has high responsivity and low noise level in the near IR region (from 800 nm to 1700 nm). Combined with the advanced iHR550 monochromator, the system is available for fast PL measurements while maintaining high responsivity and high spectral resolution (0.1 nm for CCD and 0.2 nm for InGaAs detector).

Two lasers are currently used in this system: a 6 W 532 nm Diode Pumped Solid State (DPSS) laser, and a Ti:Sapphire laser. The output power of the Ti:Sapphire laser is determined by the pumping power of the DPSS laser, and typically 0.5 W of power at 800 nm can be achieved with 5 W pumping power. The wavelength of the Ti:Sapphire laser can be continuously tuned from 750 nm to 950 nm.

#### **III.** Summary

In order to study the carrier dynamics in InAs/InAsSb T2SL materials and devices, a few experimental systems have been developed. These experimental systems include a time-resolved photoluminescence (TRPL) system, a cryostat-based transient electrical signal measurement system with three available lasers at different wavelengths, and a probe-station-based transient electrical signal measurement system. Additionally, a steady state visible-NIR PL system was built to study the CdTe material for multi-color detector applications.