



AFRL-AFOSR-JP-TR-2017-0049

Direct Bandgap group IV Materials

**Hung Hsiang Cheng
NATIONAL TAIWAN UNIVERSITY**

**01/21/2016
Final Report**

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services, Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</p>					
1. REPORT DATE (DD-MM-YYYY) 22-06-2017		2. REPORT TYPE Final		3. DATES COVERED (From - To) 25 Jun 2014 to 24 Jun 2015	
4. TITLE AND SUBTITLE Direct Bandgap group IV Materials				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER FA2386-14-1-4057	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Hung Hsiang Cheng				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NATIONAL TAIWAN UNIVERSITY 1 ROOSEVELT RD. SEC. 4 TAIPEI CITY, 10617 TW				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-JP-TR-2017-0049	
12. DISTRIBUTION/AVAILABILITY STATEMENT A DISTRIBUTION UNLIMITED: PB Public Release					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Direct bandgap group IV materials have been long sought for in both academia and industry for the implementation of photonic devices. This proposal works on the fundamental issues and planar photonic devices that are suitable for the integration with the group IV based electronic devices. In this project, we have accomplished (a) direct bandgap group IV materials of GeSn, (b) GeSn-based planar light-emitting diode operated at near infrared with direct emission, and (c) the first planar photodetector (Appl. Phys. Lett. 105, 231109 (2014) and references within) This move a step forward toward the monolithic integration of optic and electronic devices in a single chip (all group IV materials). Still, there are two other components (waveguide channel and modulator) that is needed for the all group IV materials optoelectronic and this will be the main targets for next project.					
15. SUBJECT TERMS lasers, group IV					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON CASTER, KENNETH
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 315-229-3326

Final Report for AOARD Grant AOARD-144057

“Direct Bandgap group IV Materials -- from basic research to application in photonic devices of planar light emitting diode, detector and laser ”

6/12/2015

PI and Co-PI information:

- Name of Principal Investigators: Prof. H. H. Cheng
- e-mail address : hhcheng@ntu.edu.tw
- Institution : Center for Condensed Matter Sciences and Graduate Institute of Electronics Engineering, National Taiwan University
- Mailing Address : No 1 Roosevelt Road, Section 4, National Taiwan University, Taipei, Taiwan, R. O. C
- Phone : 886-2-33665255
- Fax : 886-2-23655404
- Name of Co-PI: Prof. G. Sun, Dr. R. A. Soref
- Institution: Department of Physics, University of Massachusetts Boston, Massachusetts 02125, USA

Period of Performance: June/25/2014 – June/24/2015

Abstract:

Direct bandgap group IV materials have been long sought for in both academia and industry for the implementation of photonic devices. This proposal works on the fundamental issues and planar photonic devices that are suitable for the integration with the group IV based electronic devices. In this project, we have accomplished (a) direct bandgap group IV materials of GeSn, (b) GeSn-based planar light-emitting diode operated at near infrared with direct emission, and (c) the first planar photodetector (Appl. Phys. Lett. 105, 231109 (2014) and references within) This move a step forward toward the monolithic integration of optic and electronic devices in a single chip (all group IV materials). Still, there are two other components (waveguide channel and modulator) that is needed for the all group IV materials optoelectronic and this will be the main targets for next project.

Introduction:

The energy band of group IV element of Si and Ge are indirect. This means, in the optical process of emission, electrons at the conduction band minimum needs to

give up a finite momentum to recombine with holes at valence band minimum. As a consequence, only a fraction of electron can find the hole yielding a low emission efficiency. Similar observation also occurs in the absorption process. Therefore, these materials are not suitable for use as optical devices (optical emitter and photodetector). In the last couple of years, another group IV element-Sn is employed in the growth of group IV materials. The incorporation of Sn modulates the bandgap of the host IV-IV compounds, and, above a certain Sn composition, the energy band of the IV-IV compounds changes from an indirect to a direct bandgap as that of III-V compounds which are suitable for optical devices. This leads to the demonstration of GeSn-based light-emitting diodes (LEDs) and photodetectors (PDs). In these works, the LEDs (PDs) emit (collect) light from the surface of the sample (perpendicular to the wafer surface). However, for the integration with Si-based electronics, the devices need to emit (collect) light parallel to the wafer surface. In this project, we focus on planar GeSn-based photonic devices and the results on LEDs and PDs is demonstrated. Next stage, we propose to move to another horizon of the integration of optical emitter and detector which is the building block for optoelectronic.

This report is divided into the following three sections:

- (a) Planar GeSn-based photonic devices – light-emitting diode and photodetector
- (b) Related Publications

- (a) Planar GeSn-based photonic devices – light emitting diode and photodetector

Sn-based direct bandgap group IV materials have been established in our laboratory and these results have been reported in several journals (see the report last year). In our previous work, the first GeSn-based planar LEDs is proposed and demonstrated. The LEDs is built upon a diode, which consists of an undoped layer. The sample is fabricated into a mesa strip, and electrical contacts are placed at two ends of the strip by ion implantation. The p-i-n structure lies in the plane of the Ge wafer. By applying external voltage across the electrical contact, the light emits from the side of the strip.

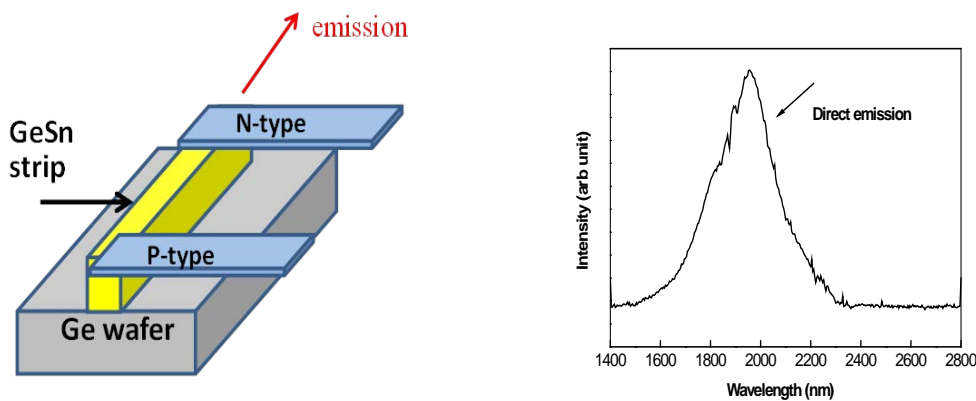


Fig. 3. (a) Left plot: Schematic plot of the proposed waveguided LED. (b) Right plot: EL spectrum

We like to point out that, the planar LED has the following advantages over the vertical LED: (a) As the length of the strip can be much greater than the thickness of the layer, the emission strength of the LED would be greater, resulting in a greater emission intensity as compared to the vertical LED. (b) The strip also functions as an optical cavity. (c) The structure can be integrated with most planar electronic devices, which is required for the integration of optoelectronic applications. With those advantages described above, in the next stage, we move to the laser structure which is desired in various applications.

Reference:

- (1) Aboozar Mosleh, Mourad Benamara, Seyed Amir Ghetmiri, Benjamin R Conley, Murtadha Abdulmueen Alher, Wei Du, Greg Sun, Richard Soref, Joe Margetis, John Tolle, Shui-Qing Yu, and Hameed A Naseem, Investigation on the Formation and Propagation of Defects in GeSn Thin Films, ECS Trans. 2014 64(6): 895-901
- (2) Mid-infrared electroluminescence from a Ge/Ge_{0.922}Sn_{0.078}/Ge double heterostructure p-i-n diode on a Si substrate, H. H. Tseng, K. Y. Wu, H. Li, V. Mashanov, H. H. Cheng, G. Sun and R. A. Soref, Appl. Phys. Lett. 102, 182106 (2013). Editor's Picks on Semiconductor Research from APL (2014)

(a) Related Publications (2014)

- (1) Reflection high energy electron diffraction studies on Si_xSn_yGe_{1-x-y} on Si(100) molecular beam epitaxial growth, A.I. Nikiforov, V.I. Mashanov, V.A. Timofeev, O.P. Pchelyakov, H. H. Cheng, Thin Solid Films, Volume 557, 30 April 2014, Pages 188-191.

- (2) Structural and optical characteristics of Ge_{1-x}Sn_x/Ge superlattices grown on Ge-buffered Si(001) wafers, Jia-Zhi Chen, H. Li, H. H. Cheng, and Guo-En Chang, *Optical Materials Express* Vol. 4, Iss. 6, pp. 1178–1185 (2014).
- (3) Electrical characteristics of Ni Ohmic contact on n-type GeSn, H. Li, H. H. Cheng, L. C. Lee, C. P. Lee, L. H. Su, and Y. W. Suen, *Appl. Phys. Lett.* **104**, 241904 (2014).
- (4) Substitutional Incorporation of Sn in Compressively Strained Thin Films of Heavily-Alloyed Ge_{1-x}Sn_x/Ge Semiconductor Probed by X-ray Absorption and Diffraction Methods, Soo, Yun-Liang; Wu, Tai-Sing; Chen, Y. C.; Shiu, Y. F.; Peng, H. J.; Tsai, Y. W.; Liao, P.Y.; Zheng, Y. Z.; Chang, Shih-Lin; Chan, Ting; Lee, Jyh; Sterbinsky, George; Li, Hui; Cheng, Henry, 2014 *Semicond. Sci. Technol.* 29, 115008 (2014). [doi:10.1088/0268-1242/29/11/115008](https://doi.org/10.1088/0268-1242/29/11/115008).
- (5) Characteristics of Sn segregation in Ge/GeSn heterostructures, H. Li, C. Zhang, T. P. Chen, and H. H. Cheng, *Appl. Phys. Lett.* 105, 151906 (2014); <http://dx.doi.org/10.1063/1.4898583> Volume 105, Issue 15, 13 October 2014.
- (6) GeSn p-i-n waveguide photodetectors on Si substrate, Yu-Hsiang Peng, H. H. Cheng, Vladimir I. Mashanov, and Guo-En Chang, *Appl. Phys. Lett.* 105, 231109 (2014).