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**GeSn Based Near and Mid Infrared Heterostructure Detectors**

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**Final Report**

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**“GeSn Based Near and Mid Infrared Heterostructure Detectors”**

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**Abstract**

This final report presents results obtained during the period of June 27<sup>th</sup>, 2016 to December 26, 2018 for the basic research project intended to advance the science and technology of Si photonics based on SiGeSn material system with focus on near and mid infrared GeSn detectors and focal plane arrays that operate from 1.5 to around 2.0  $\mu\text{m}$  wavelength range. During this period, we have strengthened our existing collaborations with Prof. Cheng’ group at National Taiwan University, Dr. Hendrickson at Air Force Research Laboratories, and Prof. Yu’s group at University of Arkansas. We have made innovative contributions to the material development and device development that directly impact the areas of group IV photonics for mid-infrared applications. Results were published in prestigious journals. This report will highlight a few significant contributions.

## **I. Introduction**

Si photonics has been a hot topic in semiconductor optoelectronics for a few decades owing to its promise for creating silicon-based optical devices that can exploit the benefits of silicon wafers while also being fully compatible with Si electronics. Early development of the Si photonics widely known as group IV photonics describes optoelectronics devices made from silicon (Si) and germanium (Ge). There is a catch, however, i.e. Si, Ge and their alloys are all indirect bandgap semiconductors are not materials of choice for photonic devices. In the recent decade, the group-IV material system has been expanded to include yet another group-IV element Sn. The advantage of incorporating Sn is that with enough Sn content, the group-IV alloy SiGeSn turns into a direct bandgap. While the direct bandgap allows for efficient LEDs and lasers to be developed, even before turning direct with a small amount of Sn, the material system can be benefited for photo-detecting applications. In the past decade or so, NTU-UMB collaboration has been actively pursuing development of SiGeSn-based photonic devices including emitters, detectors and focal plane arrays. This collaboration has been more recently expanded to include AFRL that has allowed for acceleration of progress in all fronts that range from design, simulation, material, device, to characterization. We shall summarize the progress we have made in this report.

## **II. Approaches and Results**

Approaches that we took in collaboration with our partners include material and structure improvement, property characterization, and device development.

### **II.1 Material and property**

We conducted an investigation on the absorption mechanism of a GeSn photodetector with 2.4% Sn composition in the active region [1]. Responsivity is measured and absorption coefficient is calculated. Square root of absorption coefficient linearly depends on photon energy indicating an indirect transition. However, the absorption coefficient is found to be at least one order of magnitude higher than that of most other indirect materials, suggesting that the indirect optical absorption transition cannot be assisted only by phonon. Our analysis of absorption measurements by other groups on the same material system showed the values of absorption coefficient on the same order of magnitude. Our study reveals that the strong enhancement of absorption for the indirect optical transition is the result of alloy disorder from the incorporation of the much larger Sn atoms into the Ge lattice that are randomly distributed.

The absorption coefficient and refractive index of Ge<sub>1-x</sub>Sn<sub>x</sub> alloys (x from 0 to 10 %) grown on Si were characterized in the near- and shortwave-infrared (IR) wavelength regions by spectroscopic ellipsometry at room temperature [2]. Using the data obtained from the Johs-Herzinger model, the Sn compositional- and strain-dependent absorption coefficient and refractive index were extracted by a data fitting process, leading to the proposed practical formulae, based on which guidance for the design of optoelectronics devices, i.e., photo detectors and emitters is

attained. These devices associated with an IR operating range have great potential applications in Si photonics.

We have also studied the optical transitions in SiGeSn quantum well structure using optical pumping at different wavelengths [3]. A SiGeSn/GeSn/SiGeSn single quantum well structure featuring type-I band alignment was grown and comprehensively characterized. Three pump lasers with different penetration depths and photon energies were used to pinpoint the optical transition characteristics of the sample. The carrier generation, re-distribution and recombination under each pumping condition were analyzed in details. By comparing the temperature-dependent photoluminescence spectra of the GeSn quantum well with that of SiGeSn and GeSn thin film samples possessing similar Si and Sn compositions, the clear optical transition mechanism was identified. In a related study, SiGeSn/GeSn/SiGeSn single quantum well structure was grown using an industry standard chemical vapor deposition reactor with low-cost commercially available precursors [4]. The material characterization revealed the precisely controlled material growth process. Based on the temperature-dependent photoluminescence spectra and correlative band structure calculation, the contour plots for bandgap energy separation and barrier heights were systematically studied, according to which the direct bandgap Type-I band alignment quantum well in SiGeSn material system can be achieved by using current developed chemical vapor deposition technique.

Optical properties of germanium tin ( $\text{Ge}_{1-x}\text{Sn}_x$ ) alloys have been comprehensively studied with Sn compositions from 0 to 12 % [5]. The room temperature photoluminescence (PL) spectra show gradual shift of emission peaks towards longer wavelength as Sn composition increases. Temperature dependent PL shows the PL intensity variation along with the temperature change, which reveals the indirectness or directness of the bandgap of the material. As temperature decreases, the PL intensity decreases with Sn composition less than 8 %, indicating the indirect bandgap  $\text{Ge}_{1-x}\text{Sn}_x$ ; while the PL intensity increases with Sn composition higher than 10 %, implying the direct bandgap  $\text{Ge}_{1-x}\text{Sn}_x$ . Moreover, the PL study of n-type doped samples shows bandgap narrowing compared to the unintentionally doped thin film with the similar Sn compositions due to the doping.

## II.2 Light Emitting Devices

We have demonstrated room-temperature 2- $\mu\text{m}$  GeSn p-i-n homojunction light-emitting diode for in-plane coupling to group-IV waveguides [6]. We studied electroluminescence of a planar p-i-n diode based on an undoped GeSn layer where the p- and n-type electrodes are fabricated by using the CMOS process of ion implantation. As shown schematically in Fig. 1(a), unlike the prior-art Ge/GeSn/Ge heterojunction PIN diodes that emit mainly vertically into free space, this LED is deliberately constructed to have the following features: (1) ease of manufacture in a foundry via a simple epitaxial structure, (2) end-fire coupling into on-chip transparent Ge or Si waveguides in close proximity, (3) emission in the new 2- $\mu\text{m}$  communications band where new low-loss fibers operate, (4) ion implanted P and N doping, (5) ease of making source arrays, (6)

monolithic construction for the “all-group-IV” photonics scenario, and (7) compatibility with photonic and optoelectronic circuits. The results suggest that this LED, when directly internally modulated, can serve as a laser-diode “surrogate” in several situations. Measurements at 300K showed a strong and broad electroluminescence (EL) peak at 2  $\mu\text{m}$  at the low forward-bias current density of 0.4 A/cm<sup>2</sup> associated with the indirect band-to-band optical transition illustrated by the temperature-dependent measurement as shown in Fig. 1(b). Growth, structure, fabrication process, and characterization details of the planar diode are presented in [6]. The measurement shows a broad spectrum at a peak energy located below the bulk bandgap of Ge associated with indirect optical transition analyzed by taking into account composition- and strain-dependent modeling. This work provides an alternative approach to the fabrication of GeSn-based p-i-n light-emitting diodes as well as moving towards the integration with waveguided on-chip group IV photonic devices.

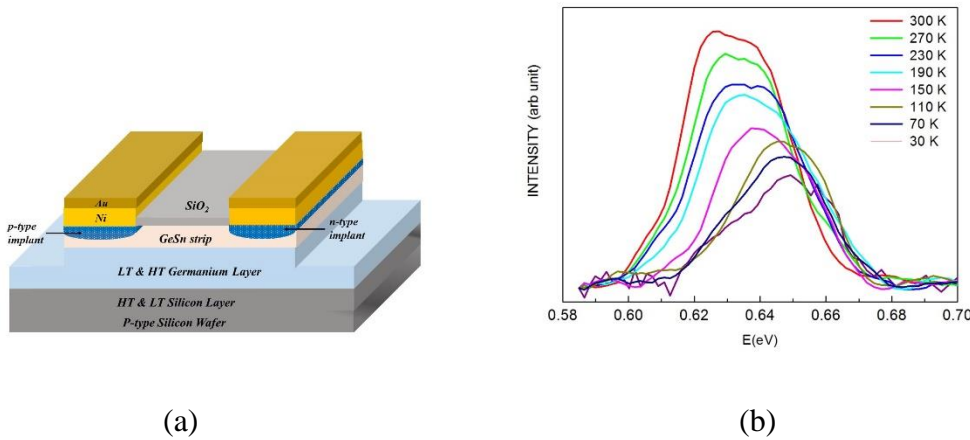


Figure 1. (a) Schematic plot of the finished mesa diode and (b) temperature-dependent electroluminescence spectrum of the sample.

In another study on GeSn LEDs, we have systematically studied their temperature-dependent characteristics with Sn composition up to 9.2% [7]. Such diodes were based on Ge/GeSn/Ge double heterostructures (DHS). Both photoluminescence and electroluminescence spectra have been characterized at temperatures from 300 to 77K. Based on our theoretical calculation, all GeSn alloys in this study are indirect bandgap materials. However, due to the small energy separation between direct and indirect bandgap, and the fact that radiative recombination rate greater than non-radiative, the emissions are mainly from the direct C-valley to valence band transitions. The electroluminescence emissions under current injection levels from 102 to 357 A/cm<sup>2</sup> were investigated at 300 K. The monotonic increase of the integrated electroluminescence intensity was observed for each sample. Moreover, the electronic band structures of the DHS were discussed. Despite the indirect GeSn bandgap owing to the compressive strain, type-I band alignment was achieved with the barrier heights ranging from 11 to 47 meV.

The most challenging of them all has been the demonstration of group-IV lasers. To this end we have achieved an optically pumped edge-emitting 2.5- $\mu\text{m}$  GeSn laser on the Si substrate that operated up to 110 K [8]. The whole device structures were grown by an industry standard chemical vapor deposition reactor using low cost commercially available precursors  $\text{SnCl}_4$  and  $\text{GeH}_4$  in a single run epitaxy process. The lasing characteristic of a 600  $\mu\text{m}$ -long edge-emitting device is clearly shown in Fig. 2(a) by the light-light (L-L) curves at 10 and 90 K. The thresholds were measured as 68 and 166  $\text{kW}/\text{cm}^2$ , respectively. The SEM image of the ridge waveguide device is also shown in inset along with its lasing spectra at 90 K in comparison with the PL spectra at 10, 100, and 300 K. Temperature-dependent characteristics of laser-output versus pumping-laser-input showed lasing operation up to 110 K as shown in Fig. 2(b) for the 1100  $\mu\text{m}$ -long edge-emitting device. Each curve shows threshold characteristic. The temperature-dependent thresholds were extracted from 87 to 396  $\text{kW}/\text{cm}^2$ , based on which the  $T_0$  was extracted as 65 K. Laser threshold versus temperature for the purpose of fitting  $T_0$  is shown in inset. The work lays the foundation for the ultimate goal of achieving an electrically pumped GeSn laser.

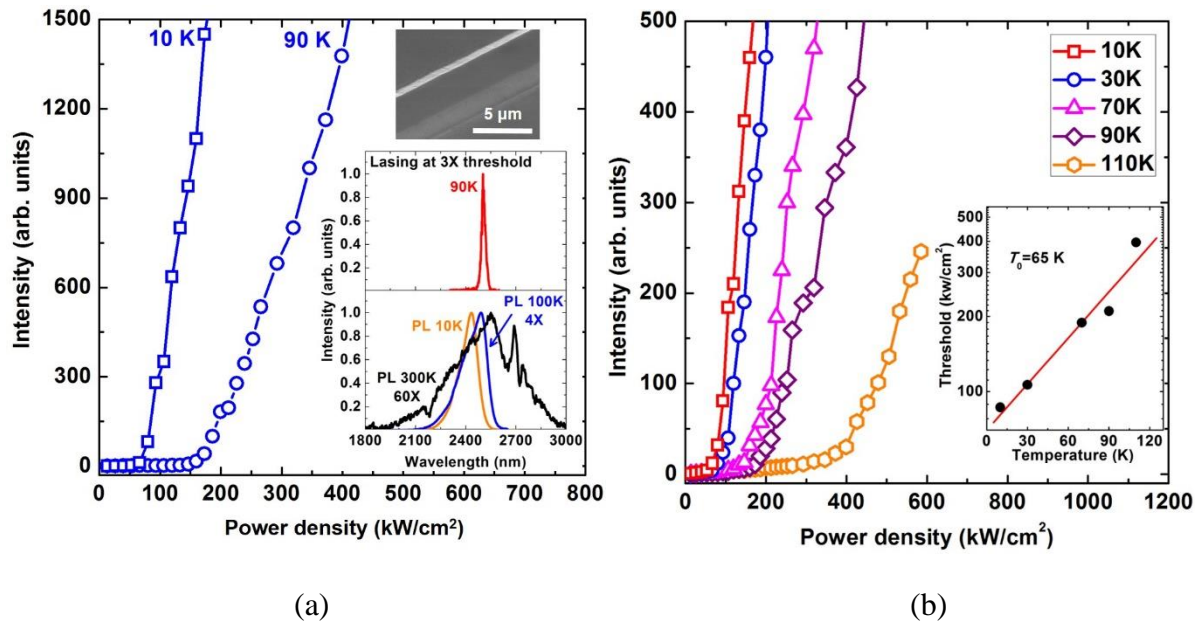


Figure 2. L-L curves of the 600  $\mu\text{m}$ -long edge-emitting device at 10 and 90 K and (b) L-L curves of the 1100  $\mu\text{m}$ -long edge-emitting device taken at the temperatures from 10 to 110 K.

### II.3 Photodiodes

We have completed the work on a GeSn-based p-i-n photodetector grown on a Ge wafer that collects light signal from the back of the wafer and the result was published [9]. Temperature dependent absorption measurements performed over a wide temperature range (300 K down to 25 K) show that (a) absorption starts at the direct bandgap of the active GeSn layer and continues up to the direct bandgap of the Ge wafer, and (b) the peak responsivity increases rapidly at first

with decreasing temperature, then increases more slowly, followed by a decrease at the lower temperatures. The maximum responsivity happens at 125K, which can easily be achieved with the use of liquid nitrogen. The temperature dependence of the photocurrent is analyzed by taking into consideration of the temperature dependence of the electron and hole mobility in the active layer, and the analysis result is in reasonable agreement with the data in the temperature regime where the rapid increase occurs. This investigation demonstrates the feasibility of a GeSn-based photodiode that can be operated with back-side illumination for applications in image sensing systems.

We have also systematically studied Si-based GeSn photodiodes with 2.6  $\mu\text{m}$  detector cutoff for short-wave infrared detection [10]. Normal-incidence  $\text{Ge}_{1-x}\text{Sn}_x$  photodiode detectors with Sn compositions of 7 and 10 % have been demonstrated. Such detectors were based on  $\text{Ge}/\text{Ge}_{1-x}\text{Sn}_x/\text{Ge}$  double heterostructures grown directly on a Si substrate via a chemical vapor deposition system. A temperature-dependence study of these detectors was conducted using both electrical and optical characterizations from 300 to 77 K. Spectral response up to 2.6  $\mu\text{m}$  was achieved for a 10 % Sn device at room temperature. The peak responsivity and specific detectivity ( $D^*$ ) were measured as 0.3 A/W and  $4 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$  at 1.55  $\mu\text{m}$ , respectively. The spectral  $D^*$  of a 7 % Sn device at 77 K was only one order-of-magnitude lower than that of an extended-InGaAs photodiode operating in the same wavelength range, which indicates the promising future of GeSn-based photodetectors.

#### II.4 Focal Plane Array

Building upon the success of the demonstration of the  $\text{Ge}/\text{Ge}_{0.975}\text{Sn}_{0.025}/\text{Ge}$  p-i-n photodetector operated with back-side illumination [9], we have moved on to the next step - experimental fabrication and testing of a GeSn-based image sensor focal-plane array operating at  $-15^\circ\text{C}$  in the 1.6 to 1.9  $\mu\text{m}$  spectral range [11]. An array of 320 by 256 pixels with a period of 30  $\mu\text{m}$  was fabricated using the same processing steps and “recipes” used for the fabrication of a single diode. After the processing, indium pillars were deposited onto the mesa surface of the diodes. An optical microscope image of part of the array is shown in Fig. 3(a) and a schematic plot of the mesa and “platform” electrical contacts is plotted in Fig. 3(b). For image readout, the 2D pixel array of  $\text{Ge}/\text{GeSn}/\text{Ge}$  PIN hetero photodiodes was flip-chip bonded to a customized silicon CMOS readout integrated circuit. To enhance the detection sensitivity, the Ge wafer was thinned to  $\sim 200 \mu\text{m}$  and the imager chip is cooled to  $-15^\circ\text{C}$  by a thermal electric cooler. After these processes, an incandescent light bulb was imaged by placing it in front of the back-side of the sample, with a focusing lens placed between the bulb and the diode array. The light bulb had 250W emission (model E27). It contained three W filaments in the center and the inner surface of the light bulb is alumina coated. Before imaging, the light bulb was turned on for a few minutes. The recorded grey-scale contrast infrared image, together with a visible-light image taken by a cell phone camera for comparison, is shown in Fig. 4. The IR contrast image shows characteristics different from the cell-phone camera image, because the diodes are sensing 1600- to-1900 nm signals. Several bright areas are observed, as marked by the arrow lines. The

filaments inside the light bulb are clearly resolved, as indicated by the solid arrow line. In addition, several bright regions are resolved at the inner surface of the light bulb, as indicated by the dashed arrow lines; this is attributed to local heating caused by the filaments.

The Ge wafer used in the present imaging array will be replaced in future tests by a Germanium on Silicon wafer offering thin film Ge upon Si or on SiO<sub>2</sub>/Si. This is expected to increase the infrared responsivity obtained in back-side illumination, and it will allow manufacture of the imager in a Si-based foundry. Our experiments are a significant step towards realization of group-IV near-mid infrared imaging systems, such as those for night vision.

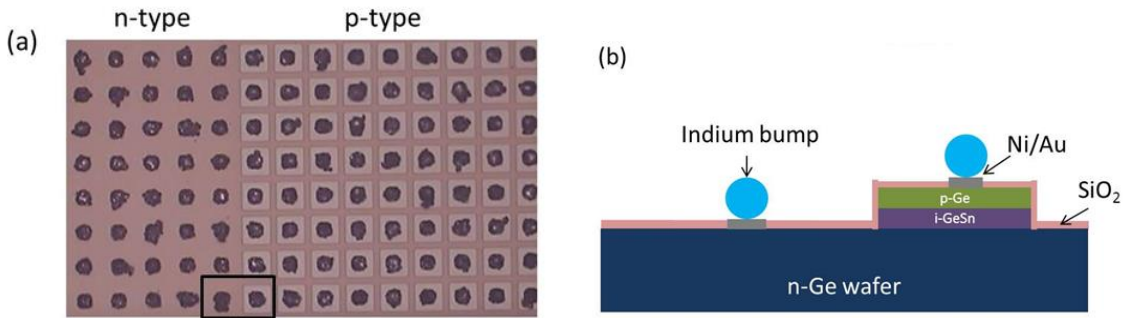


Figure 3. (a) Optical microscope image of part of the array. (b) Schematic plot of the mesa and electrical contact.

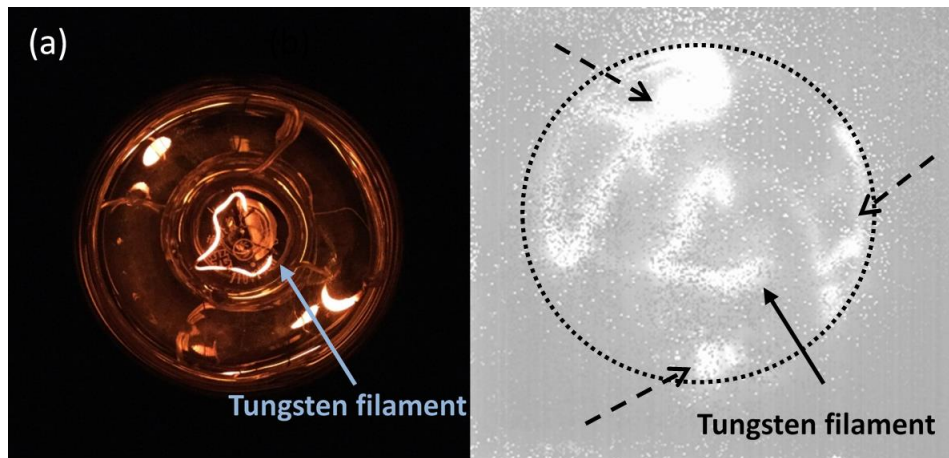


Figure 4. (a) Light bulb image operated at a low power of 20 W taken by cell phone. The image show the shape of the tungsten filament located at the center. (b) Light bulb image taken by our GeSn-based diode array (320 by 256 diodes). The image shows the capability of imaging and “displaying” the thermal profile of the object.

### III. Collaboration

Dr. Sun at UMB and Dr. Cheng at NTU visited Dr. Hendrickson and others at Wright Patterson AFB in summer, 2016 at the beginning of the project and developed a strategy to work

collaboratively on the project. During the visit, Dr. Hendrickson hosted a seminar presented jointly by Sun and Cheng to attendees of AFRL personnel and colleagues from Dayton University. Since then GeSn samples have been delivered to AFRL for analysis. Specifically, detector samples have been provided to Dr. Hendrickson for device testing and raw samples to Dr. Bruce "Chip" Claflin for material evaluation at AFRL. As a joint effort on enhancing performance of GeSn photodetectors, designs of plasmonic structures from Dr. Sun's group have been recently forwarded to Dr. Hendrickson's group for implementation on the detector samples provided by Dr. Cheng. This grant support has also enabled collaboration between Dr. Sun and Dr. Yu at University of Arkansas on SiGeSn related material and device effort which is funded by Dr. Gernot Pomrenke at AFOSR. In addition, Dr. Sun has also continued his collaboration with Prof. Tsai's group at National Taiwan University on optical metasurfaces [12,13].

#### IV. Summary

In summary, we have made significant progress in several areas of the group-IV photonics including material quality and device development. Better quality material with improved material properties have been demonstrated. As a result, LEDs of higher Sn contents for higher efficiency and optically-pumped laser device have been achieved. In addition, photodiodes with detectivity and responsivity in mid IR approaching the performance of their commercial counterpart have been fabricated. Finally, a GeSn-based 320 x 256 image sensor focal-plane array operating in near and mid IR is demonstrated. These advances have been reported in 11 papers in prestigious journals and are listed in below in the order in which they are referenced in this report.

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Publications resulted from the support of this grant are listed below, which also serve as the references for this report.

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