



Silicon based mid infrared SiGeSn heterostructure emitters and detectors

**Greg Sun
UNIVERSITY OF MASSACHUSETTS**

**05/16/2016
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) 16-05-2016		2. REPORT TYPE Final		3. DATES COVERED (From - To) 17 Jun 2014 to 16 Dec 2015	
4. TITLE AND SUBTITLE Silicon based mid infrared SiGeSn heterostructure emitters and detectors				5a. CONTRACT NUMBER FA2386-14-1-4073	
				5b. GRANT NUMBER Grant 14IOA070_144073	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Greg Sun				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF MASSACHUSETTS 285 OLD WEEPOT RD NOTH DARTMOUTH, MA 27472356 US				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
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(AOARD)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) 14IOA070_144073	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Code A: Approved for public release, distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT We have investigated the surface plasmon enhancement of the GeSn p-i-n photodiode using gold metal nanostructures. We have conducted numerical simulation of the plasmonic structure of 2D nano-hole array to tune the surface plasmon resonance into the absorption range of the GeSn active layer. Such a structure is fabricated using FIB on a previously made photodiode for feasibility demonstration. The result indicates that the photocurrent of the diode can indeed be enhanced with the plasmonic structure on top. Within the time span of this project, we have completed one iteration of the process that includes design, fabrication, and characterization. There is room to improve and future optimization of the design and fabrication should yield more improvement.					
15. SUBJECT TERMS electronic materials, heterostructure semiconductors, light emitting devices					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 21	19a. NAME OF RESPONSIBLE PERSON CASTER, KENNETH
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 81-42-511-2000

Final Report for AOARD Grant FA2386-14-1-4073 (AOARD-14-4073)

“Silicon Based Mid Infrared SiGeSn Heterostructure Emitters and Detectors”

February 10, 2016

Principal Investigator:

Greg Sun

Engineering Department

The University of Massachusetts at Boston

Boston, MA 02125, USA

greg.sun@umb.edu

Tel: 617-287-6432

Fax: 617-287-6053

Period of Performance: June 17th, 2014 to December 15, 2015

Abstract

This Final Report presents results obtained on an eighteen-month basic research project intended to advance the science and technology of Si photonics based on SiGeSn material system with focus on plasmon-enhanced GeSn photodetectors that operate around 2.0 micron wavelength range. Approaches taken on this project include invention, numerical modeling, simulation, device design, device fabrication and characterization. Original, leading-edge contributions were made in the areas of group IV photonics for mid-infrared applications. Experimental implementation of our device design demonstrates the feasibility of detectivity enhancement of GeSn photodetectors by metal nanostructures. Such a photodetector design can be conveniently implemented in focal plane arrays in which each detector pixel operates under back illumination and the metal nanostructure sitting on top serves as the contact to readout circuits. To this end, performance of back illuminated device is studied. In addition to the collaboration with Prof. Cheng at NTU specifically funded with this grant, collaborations with other scientists in Taiwan and in U.S. have led to many interesting and important basic research advances in areas that are closely related to this project during the same period.

Introduction

The main goal of this 18-month basic research project was to advance the science and technology of silicon-based photonic devices using SiGeSn heterostructures. Such devices work in mid IR spectral range and form the foundation for mid IR photonics that enable on-chip systems for applications ranging from vibrational spectroscopy, chem/bio sensing, medical/health uses, to environmental monitoring. The collaboration between UMB and NTU has demonstrated GeSn LEDs with a direct bandgap [1] and more recently a study of strain dependence of GeSn Raman shift [2]. The effort of this project is mostly directed toward the improvement of GeSn detectors with the use of surface plasmons induced by carefully designed metal nanostructures. The goal is to replace the current mid IR detectors that are usually photo-diodes made from narrow bandgap III-V or II-VI semiconductor compounds such as InGaAs, InSb, HgCdTe (MCT) or type-II InGaAs/InGaSb superlattice. These photo-diodes are incompatible with the CMOS process and therefore cannot be easily integrated with Si electronics. The GeSn mid IR detectors developed in this project, on the other hand, are fully compatible with the CMOS process.

Approaches and Results

Building upon the previous success from the UMB-NTU collaboration on GeSn-based p-i-n photodiodes with an active GeSn layer that is almost fully strained [3], we have set forth to improve the responsivity of GeSn detectors in this project. The employed strategy is to use the surface plasmon effect to enhance the optical field in the GeSn active region which leads to increased absorption of incident photons and in turn creates electron-hole pairs that contribute to the electric current that can be detected. Specifically, we considered the use of a gold metal film perforated with a two-dimensional subwavelength hole array as the plasmonic structure to be deposited on top of the GeSn p-i-n photodetector. Such structures are capable of producing enhanced optical fields under the illumination of some wavelengths residing in its surface plasmon resonance range [4-7]. They have been used to improve the performance of quantum dot infrared photodetectors (QDIPs) [8,9]. Increased photocurrent [8] and detection wavelength selection [9] have been demonstrated.

The device structure of the GeSn p-i-n photodetector that we worked on to improve its performance is shown in Fig.1(a). There are a set of three samples all of p-i-n photodiodes that were previously produced [1]. Their measured dark I-V characteristics, measured and simulated spectral response are shown in Fig. 1(b-d).

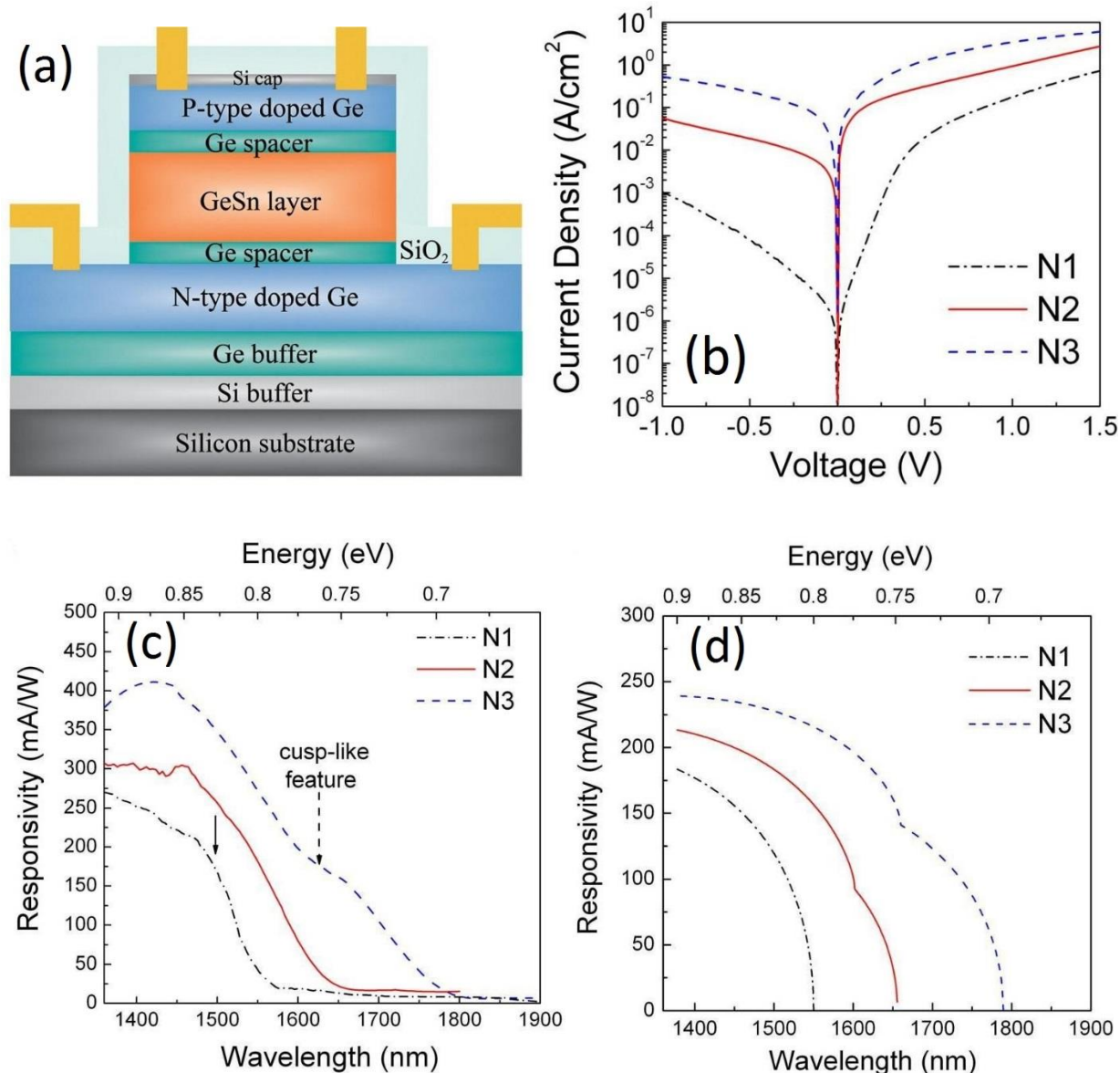


Figure 1. (a) A cross-sectional schematic of the GeSn p-i-n photodiode. (b) Dark I-V characteristics of the three samples. (c) Spectral response of the samples measured at zero bias. (d) Calculated responsivity of the samples.

Three samples were grown on an n-type Si (001) wafer using solid source molecular beam epitaxy with a low temperature growth [9, 13]. The structure consists of: (a) a 100 nm-thick high temperature (HT) Si layer, (b) a 100 nm-thick low temperature (LT) Si layer, (c) a 60 nm-thick Ge layer grown at LT, (d) a strain-relieved 60 nm-thick Ge layer grown at HT, (e) an n-type doped Ge layer with thicknesses of 280 nm, (f) un-doped intrinsic layers of Ge/Ge_{1-x}Sn_x/Ge with thicknesses of 15/300/15 nm, (g) an unstrained p-type doped Ge layer with thicknesses of 100 nm, and (h) a thin Si cap layer of 1 nm. Layers (a) to (d) serve as a virtual substrate for the subsequent growth of the p-i-n DH diode. This structure gives a smaller lattice mismatch than

that occurring between GeSn and a Si substrate. The Ge layers (e) and (g) serve as contact electrodes. Both layers are moderately doped at a nominal concentration of $5 \times 10^{18} \text{ cm}^{-3}$. Three samples were grown. On the first sample (N1), the intrinsic layer (f) consists of only Ge, which serves as a reference for the other two samples (N2, N3) whose Sn compositions in the GeSn layer were determined to be 1.78% (N2) and 3.85% (N3), respectively. The I-V characteristics of the samples measured in a dark environment in Fig. 2(b) exhibits rectifying behavior, which is a diode characteristic. The observed dark currents found in these samples are lower than those reported previously for similar structures. The fact that the dark current of the GeSn diode increases with the increasing Sn content can be attributed to the reduction of the GeSn bandgap, and the increase of defect density of the film.

In order to improve the performance, we have first performed the simulation of plasmonic nanostructures consisting of thin gold films perforated with a two-dimensional subwavelength hole array on top of the p-i-n diode as shown schematically in Fig. 2. The device will be illuminated from the back side of sample and surface plasmons can be created at the interface between the gold thin film and the dielectric layers below. As a result, the optical field gets enhanced in the GeSn active layer.

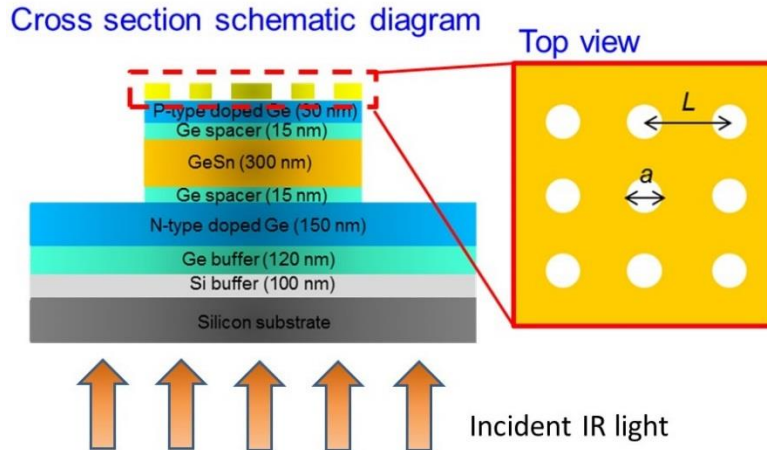


Figure 2. Schematic view of the plasmonic enhanced GeSn p-i-n photodiode with a thin gold film perforated with 2D hole array.

The gold nano-hole array is characterized the period L and nano-hole diameter a , both of which can be tuned to alter the properties of the surface plasmons. Using FDTD simulation software, we have systematically varied both L and a to investigate the change of surface plasmon resonance with the intention to tune it to absorption wavelength of the GeSn active layer. The simulation results are shown in Fig. 3. By changing the period L while keeping $a = 100 \text{ nm}$, we are able to tune the SP resonance shown as the dips in the transmission spectra in Fig.3(a). By fixing $L = 300 \text{ nm}$ and changing the hole diameter a , we are able to tune the transmission intensity as shown in Fig. 3(b).

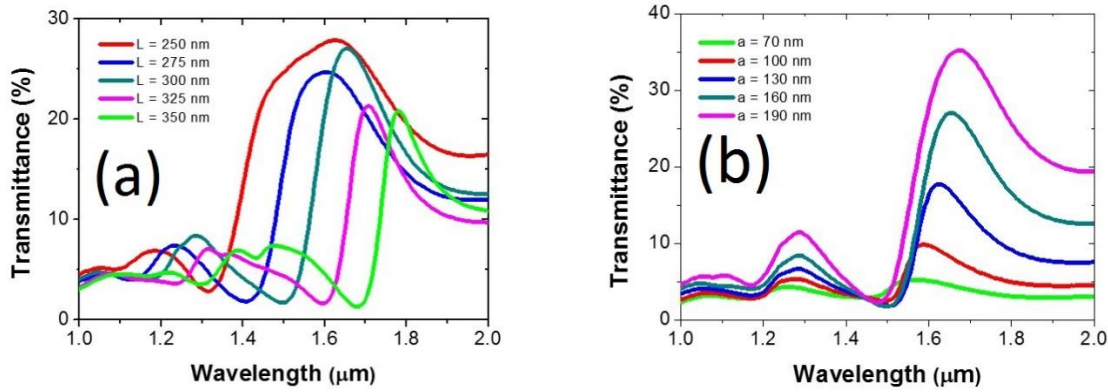


Figure 3. (a) Tuning of the surface plasmon resonance with the hole period with constant $a = 100\text{nm}$. (b) Tuning of the transmission peak with the hole diameter a while fixing $L = 300\text{nm}$.

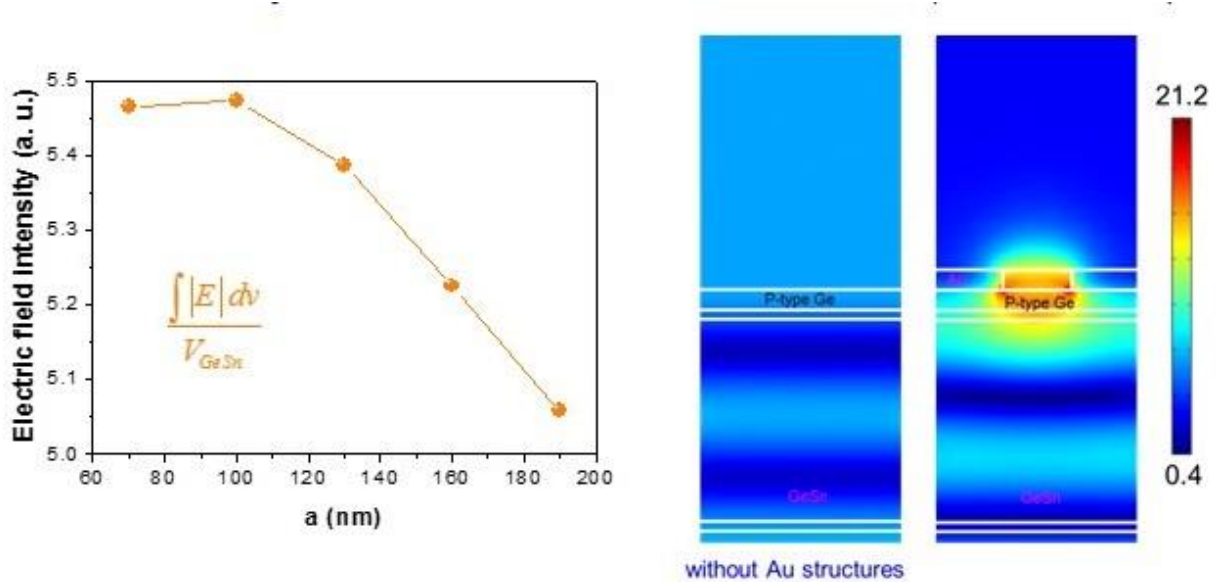


Fig. 4 Field enhancement factor as a function of the hole diameter with fixed hole period and surface plasmon profile at $a = 100\text{nm}$.

We have chosen the gold structure with $L = 300\text{nm}$ for plasmonic enhancement and calculated its electric field enhancement as function of the hole diameter which shows that maximum field enhancement is achieved at $a = 100\text{nm}$ as shown in Fig. 4 along with its surface plasmon mode profile. Such profile is compared to the same dielectric layers without the gold film on top. Significant field enhancement is obtained. In addition, the surface plasmon mode profile suggests that the mode extends into the GeSn active region where absorption takes place.

We subsequently implemented this structure on a GeSn p-i-n photodiode. Following the deposition of a gold thin film, the nanoholes are milled using a focused-ion beam (FIB) system

(FEI Helios 600 NanoLab) through a collaboration with Prof. D. P. Tsai at Academia Sinica. The beam currents and accelerating voltages are 40 pA and 30 keV, respectively. The target diameter and period of nanoholes are 100 nm and 300 nm, respectively. The fabricated gold film with holes is shown in Fig.5(a). Four such patches, each of $50 \times 50 \mu\text{m}^2$, are made inside the top ring contact of the photodiode with the attempt to fill in as much of the detector area as possible. Three sets of samples are made for comparison. One as is (control sample) without any metal on top, another with gold film but no pattern, the third with the gold film with 2D nanohole array of $L = 300\text{nm}$ and $a = 100\text{nm}$. We have measured their photocurrents under the same illumination condition for comparison. The result is shown in Fig. 5(b). Among the three samples, relative to the control sample, the sample with gold film on top but without hole pattern showed deteriorating performance, the sample with the patterned gold thin film demonstrated better performance as expected.

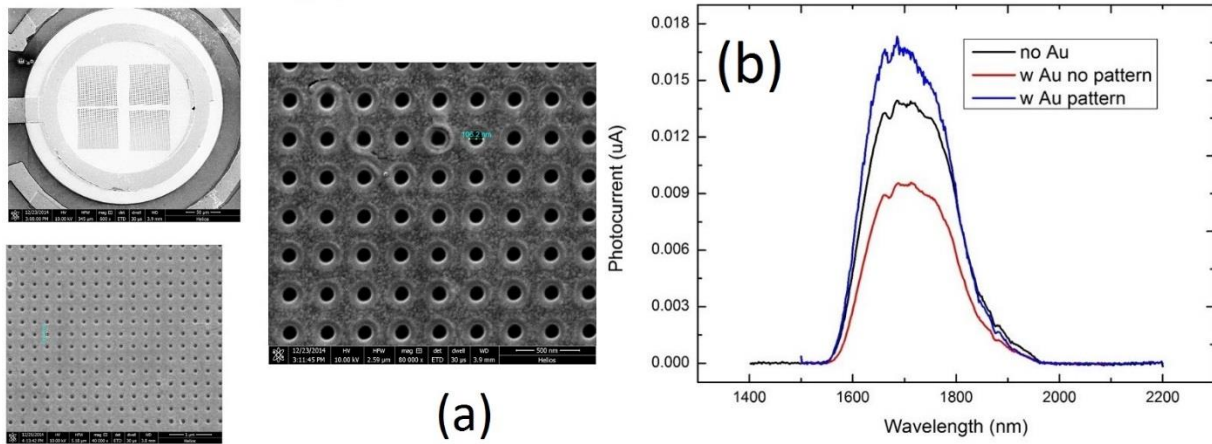


Figure 5. (a) Image of patterned gold thin film fabricated with the FIB on top of the GeSn photodiode. (a) Photocurrent of three samples: one as is without gold film on top, another with un-patterned gold film, the third with patterned gold film.

In summary, we have investigated the surface plasmon enhancement of the GeSn p-i-n photodiode using gold metal nanostructures. We have conducted numerical simulation of the plasmonic structure of 2D nano-hole array to tune the surface plasmon resonance into the absorption range of the GeSn active layer. Such a structure is fabricated using FIB on a previously made photodiode for feasibility demonstration. The result indicates that the photocurrent of the diode can indeed be enhanced with the plasmonic structure on top. Within the time span of this project, we have completed one iteration of the process that includes design, fabrication, and characterization. There is room to improve and future optimization of the design and fabrication should yield more improvement.

References

1. H. H. Tseng, K. Y. Wu, H. Li, V. Mashanov, H. H. Cheng, **G. Sun**, and R. A. Soref, “Mid-infrared electroluminescence from a Ge/Ge_{0.922}Sn_{0.078}/Ge double heterostructure p-i-n diode on a Si substrate,” *Appl. Phys. Lett.* **102**, 182106 (2013)
2. C. Chang, H. Li, T. P. Chen, W. K. Tseng, H. H. Cheng, C. T. Ko, C. Y. Hsieh, M. J. Chen, and G. Sun, “The strain dependence of Ge_{0.917}Sn_{0.083} Raman shift,” *Thin Solid Films* **593**, 40–43 (2015)
3. H. H. Tseng, H. Li, V. Mashanov, Y. J. Yang, H. H. Cheng, G.-E. Chang, R. A. Soref, and G. Sun, “GeSn-based p-i-n photodiodes with strained active layer on a Si wafer,” *Appl. Phys. Lett.* **103**, 231907 (2013)
4. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, “Extraordinary optical transmission through sub-wavelength hole arrays,” *Nature*, **391**, 667-669 (1998)
5. T. Matsui, A. Agrawal, A. Nahata, and Z. Valy Vardeny, “Transmission resonances through aperiodic arrays of subwavelength apertures,” *Nature*, **446**, 517-521 (2007)
6. M. I. Stockman, “Nanoscience: Dark-hot resonances,” *Nature* **467**, 541–542 (2010)
7. L. Salomon, F. Grillot, A. V. Zayats, and F. de Fornel, “Near-Field Distribution of Optical Transmission of Periodic Subwavelength Holes in a Metal Film,” *Phys. Rev. Lett.* **86**, 1110 (2001)
8. C.-C. Chang, Y. D. Sharma, Y.-S. Kim, J. A. Bur, R. V. Shenoi, S. Krishna, D. Huang, and S.-Y. Lin, “A Surface Plasmon Enhanced Infrared Photodetector Based on InAs Quantum Dots,” *Nano Lett.* **10**, 1704–1709 (2010)
9. C.-Y. Chang, H.-Y. Chang, C.-Y. Chen, M.-W. Tsai, Y.-T. Chang, S.-C. Lee, and S.-F. Tang, “Wavelength selective quantum dot infrared photodetector with periodic metal hole arrays,” *Appl. Phys. Lett.* **91**, 163107 (2007)

Project Metrics

A. List of Publications

1. H. Tran, W. Du, S. A. Ghetmiri, A. Mosleh, G. Sun, R. A. Soref, J. Margetis, J. Tolle, B. Li, H. A. Naseem, and S.-Q. Yu “Absorption coefficient and refractive index studies of Ge_{1-x}Sn_x alloys towards Si photonics device applications,” submitted to *Journal of Applied Physics* (October 2015)
2. C. Chang, H. Li, T. P. Chen, W. K. Tseng, H. H. Cheng, C. T. Ko, C. Y. Hsieh, M. J. Chen, and G. Sun, “The strain dependence of Ge_{0.917}Sn_{0.083} Raman shift,” accepted to *Thin Solid Films*
3. Y.-W. Huang, W. T. Chen, W.-Y. Tsai, P. C. Wu, C.-M. Wang, G. Sun, and D. P. Tsai, “Aluminum plasmonic multi-color meta-hologram,” *Nano Letters* **15**, 3122–3127 (2015)
4. A. Mosleh, M. Alher, W. Du, L. C. Cousar, S. A. Ghetmiri, S. Al-Kabi, W. Dou, B. R. Conley, G. Sun, R. A. Soref, B. Li, H. A. Naseem, S.-Q. Yu, “Direct growth of Ge_{1-x}Sn_x

films on Si using a cold-wall ultra-high-vacuum chemical-vapor-deposition system,” **invited paper**, *Frontiers in Materials* **2**, 1-7 (2015)

5. W.-L. Hsu, P. C. Wu, J.-W. Chen, T.-Y. Chen, B. H. Cheng, W. T. Chen, Y.-W. Huang, C. Y. Liao, G. Sun, and D. P. Tsai, “Vertical split-ring resonator based anomalous beam steering with high extinction ratio,” *Scientific Reports* **5**, 11226 (2015)
6. T.N. Pham, W. Du, B.R. Conley, J. Margetis, G. Sun, R.A. Soref, J. Tolle, B. Li, S.-Q. Yu, “Si-based $\text{Ge}_{0.9}\text{Sn}_{0.1}$ photodetector with peak responsivity of 2.85 A/W and longwave cutoff at 2.4 μm ” *Electronics Letters* **51**, 854 – 856 (2015)
7. B. R. Conley, J. Margetis, W. Du, H. Tran, A. Mosleh, S. A. Ghetmiri, J. Tolle, G. Sun, R. Soref, B. Li, H. A. Naseem, and S.-Q. Yu, “Si based GeSn photoconductors with a 1.63 A/W peak responsivity and a 2.4 μm long-wavelength cutoff,” *Applied Physics Letters* **105**, 221117 (2014)
8. S. A. Ghetmiri, W. Du, B. R. Conley, A. Mosleh, A. Nazzal, G. Sun, R. A. Soref, J. Margetis, J. Tolle, H. A. Naseem, and S.-Q. Yu, “Shortwave-infrared photoluminescence from $\text{Ge}_{1-x}\text{Sn}_x$ thin films on silicon,” *Journal of Vacuum Science & Technology B* **32**, 060601 (2014)
9. S. A. Ghetmiri, W. Du, J. Margetis, A. Mosleh, L. Cousar, B. R. Conley, L. Domulevicz, A. Nazzal, G. Sun, R. A. Soref, J. Tolle, B. Li, H. A. Naseem, and S.-Q. Yu, “Direct-bandgap GeSn grown on Silicon with 2230 nm photoluminescence,” *Applied Physics Letters* **105**, 151109 (2014)

B. List of Conference Presentations

1. T. Pham, W. Du, J. Margetis, S. A. Ghetmiri, A. Mosleh, G. Sun, R. A. Soref, J. Tolle, H. A. Naseem, B. Li, and S.-Q. Yu, “Temperature dependent study of Si based GeSn photoconductor,” to be presented at *SPIE Optics + Photonics* (San Diego, August, 2015)
2. S.-Q. Yu, S. A. Ghetmiri, W. Du, J. Margetis, Y. Zhou, A. Mosleh, A. Nazzal, G. Sun, R. A. Soref, J. Tolle, B. Li, H. A. Naseem, “Si based GeSn light emitter: mid-infrared device in Si photonics,” to be presented at *SPIE Optics + Photonics* (San Diego, August, 2015)
3. T. Pham, B. Conley, J. Margetis, H. Tran, S. A. Ghetmiri, A. Mosleh, W. Du, G. Sun, R. A. Soref, J. Tolle, H. Naseem, B. Li, and S.-Q. Yu, “Enhanced responsivity up to 2.85 A/W of Si-based $\text{Ge}_{0.9}\text{Sn}_{0.1}$ photoconductors by integration of interdigitated electrodes,” *Proceeding of the Conference on Lasers and Electrooptics (CLEO)*, (San Jose, May, 2015)
4. S. A. Ghetmiri, W. Du, Y. Zhou, J. Margetis, T. Pham, A. Mosleh, B. Conley, A. Nazzal, G. Sun, R. A. Soref, J. Tolle, H. Naseem, B. Li, and S.-Q. Yu, “Temperature-dependent characterization of $\text{G}_{0.94}\text{Sn}_{0.06}$ light-emitting diode grown on Si via CVD,” *Proceeding of the Conference on Lasers and Electrooptics (CLEO)*, (San Jose, May, 2015)
5. D. P. Tsai, P. C. Wu, W. L. Hsu, W. T. Chen, Y. W. Huang, C. Y. Liao, W. Y. Tsai, A. Q. Liu, N. Zheludev, and G. Sun, “Vertical split-ring resonators for plasmon coupling, sensing and metasurface,” **invited talk**, in Resonant Dielectric, Semiconductor and Metallic Nanostructures, 4th Photonics Global Conference (Singapore, June-July 2015)

6. G. Sun, "Plasmonic enhancement of optical absorption, electroluminescence, fluorescence, and Raman scattering by metal nanoparticles: limits and comparison," **Symposium Keynote** in About Nanoparticles, Metallic Nanostructures and Their Optical Properties XII, *SPIE Optics + Photonics* (San Diego, August, 2014)
7. D. P. Tsai, P. C. Wu, W. T. Chen, K.-Y. Yang, C.-M. Wang, Y.-W. Huang, G. Sun, S. Sun, L. Zhou, A. Q. Liu, "Polarization controlled colorful images reconstructed by reflective metahologram," **invited talk** in Imaging and Cloaking, *SPIE Optics + Photonics* (San Diego, August, 2014)
8. P. C. Wu, W. T. Chen, K.-Y. Yang, C.-M. Wang, Y.-W. Huang, G. Sun, S. Sun, L. Zhou, A. Q. Liu, D. P. Tsai, "Reflected metasurface for polarization-controlled hologram application," in Fabrication, *SPIE Optics + Photonics* (San Diego, August, 2014)
9. W. Du, S. A. Ghetmiri, A. Mosleh, B. R. Conley, L. Huang, A. Nazzal, R. A Soref, G. Sun, J. Tolle, H. A. Naseem, and S.-Q. Yu, "Investigation of Photoluminescence from Ge_{1-x}Sn_x: A CMOS-Compatible Material Grown on Si via CVD," *Proceeding of the Conference on Lasers and Electrooptics (CLEO)*, No. JW2A.57 (San Jose, California, June, 2014)
10. B. R. Conley, L. Huang, S. A. Ghetmiri, A. Mosleh, W. Du, G. Sun, R. Soref, J. Tolle, H. A. Naseem, and S.-Q. Yu, "Extended Infrared Absorption to 2.2 μm with Ge_{1-x}Sn_x Photodetectors Grown on Silicon," *Proceeding of the Conference on Lasers and Electrooptics (CLEO)*, No. SM2H.5 (San Jose, California, June, 2014)
11. S. A. Ghetmiri, B. R. Conley, A. Mosleh, L. Huang, W. Du, A. Nazzal, G. Sun, R. Soref, J. Tolle, H. A. Naseem, and S.-Q. Yu, "Photoluminescence from GeSn/Ge Heterostructure Microdisks with 6% Sn Grown on Si via CVD," *Proceeding of the Conference on Lasers and Electrooptics (CLEO)*, No. AW1H.2 (San Jose, California, June, 2014)

C. Collaborations Developed with the Support of the Project

The success of this project builds upon a long history of collaboration between Dr. Greg Sun of UMass Boston and Dr. Henry Cheng of NTU in Taiwan with complementary expertise on this material system and devices dating back almost 10 years.

This funding also allowed Dr. Sun to develop a collaboration with Prof. Q.-S. Yu at University of Arkansas on Sn-based material and device development and with Prof. D. P. Tsai of National Taiwan University on nanophotonics. Both collaborations have benefitted this project on SiGeSn device development and their optical performance enhancement with surface plasmons from metal nanostructures.

Going forward, Dr. Sun has secured collaborations with Drs. Joshua Hendrickson and Justin Cleary, both Research Physicists in the Sensors Directorate (RYDH) of AFRL at Wright-Patterson AFB, for the future development of this project.