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SiGeSn Heterostructure Photonics Technology for Ultrafast Communications in the 2 micron Infrared Region

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The accomplishments that have been made since the last report submission are described in great detail in a series of peer-reviewed papers that have been published in prestigious international journals.

15. SUBJECT TERMS
Silicon-Germanium-Tin, SiGeSn, photonic heterostructures

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FINAL REPORT--REVISED

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SiGeSn Heterostructure Photonics Technology for Ultrafast Communications in the 2 micron Infrared Region

1 July 2014 through 30 June 2017

Richard Soref and Greg Sun, Principal Investigators

Submitted to the Air Force Office of Scientific Research

(Dr. Gernot Pomrenke, Program Manager)

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1. The Research Topic

The work on this grant focusses on "group IV photonics" in the SiGeSn materials system. This group IV photonics—which is integrated upon a silicon wafer-- is an expanded version of silicon photonics. The new group IV heterostructures investigated in this grant offer, in many cases, a direct bandgap that enables the invention of efficient, active-photonic devices that support promising dual-use applications in optical communications, computing, sensing, and night vision, albeit at wavelengths longer than 1.55 microns. Here, the 2-micron wavelength is propitious for communications over novel fiber links that use the emerging low-loss hollow-core photonic-crystal optical fibers.

2. The General Goal

The general objective of the research is to invent silicon-based foundry-compatible GeSn/SiGeSn laser diodes, LEDs, infrared amplifiers, photodetectors, electro-optical modulators-and-switches, and nonlinear optical components—all of which shall enable ultrafast mid-infrared communications.

3. The PIs and Their Approach

The Principal Investigators on this project, Professor R. A. Soref and Professor G. Sun, performed basic physics-and-photonics research on topics that are closely related to the title thrust of this AFOSR program. For the most part, their work comprised new science insights and theoretical modeling-and-simulation with an eye towards Technology Transitions. In some cases, the PIs consulted on experimental materials science work and on experimental photonics work that was performed outside of the University of Massachusetts: for example, collaboration with the University of Arkansas on some of the first GeSn lasers in the world.

4. The Scientific Collaborations

Collaborations were provided at no cost to the Air Force. The talented scientists who worked with the PIs were mainly University Professors and AFRL scientists, including Joshua Hendrickson and Justin Cleary at AFRL, Fisher Yu at the University of

Arkansas, Jacob Khurgin at Johns Hopkins, Haibo Liang at McMaster, Mo Soltani at Raytheon, Volker Sorger at George Washington, Jose Capmany at Valencia, Goran Mashanovich, Milos Nedeljkovic and Graham Reed at Southampton, Francesco De Leonardis and Vittorio Passaro at Polytecnico di Barii, Dan Buca at Forshungs Zentrum Julich, and Henry Cheng and Din-Ping Tsai at National Taiwan University.

5. Publications and Conference Presentations

Over this three year period, as a result of the synergistic interactions-and-investigations just described, the PIs authored, or co-authored 121 innovative path-finding, peer-reviewed publications in prestigious journals and presentations at top-level conferences, mostly invited papers. The complete specifics of all these journal articles and conference papers are given in the several pages at the end of this Report. It is probably fair to say that this AFOSR-sponsored work has had impact upon the science community judging from the many references that scientists in the community have made to the aforementioned publications—as specified in this link: https://scholar.google.com/citations?user=IoPkLrYAAAAJ&hl=en. In particular, the 2-μm thrust set forth by Dr. Soref in his Nature Photonics article is being adopted by the community.

6. Honors and Activities during the Grant

On April 14, 2016, Professor Soref was elected Fellow of the National Academy of Inventors. The January 2016 group-IV Review Article by Drs. Soref, Buca and Yu was printed by the Optical Society in their Optics and Photonics News magazine, and 18,000 copies were mailed to members. An Editor of APL Photonics invited Prof. Soref to write a lengthy Tutorial on integrated photonic switching, which has thus far received 2100 downloads. Professor Soref served on the Program Committee of the 2017 IEEE Summer Topicals and the 2016 Optical Interconnects Conference at Photonics West. and he was a session organizer at PIERS Shanghai 2016. Dr. Soref was Guest Editor of the 2014 Special Issue on Nanoplasmonics for SPIE Nanophotonics.

Professor Sun, on this grant, has made important contributions to fundamental plasmonic science and Si-based photonics in collaboration with scientists in United States and Taiwan. He has also published large number of papers, one of which appeared on Nature Photonics, and delivered many talks at conferences, some of which are invited. He helped organize three high profile conferences, namely MRS symposium, 9th International Conference on Nanophotonics, and 8th International Conference on Surface Plasmon Photonics. He served as guest editor for Optics Express and ACS Photonics.

7. Summary of the Accomplishments

The accomplishments are published in theory papers and in experimental papers. Those numerous results can be grouped into six categories (1) new materials-science results in the SiGeSn system and new SiGeSn/GeSn heterolayered devices (including quantum wells), mainly in the form of infrared detectors and optically pumped lasers , (2) new microwave photonic chips in the silicon- on-insulator platform, chips that feature programmable reconfigurable filters and meshes, (3) an extensive series of new results in the field of nonlinear optics with work that includes Brillouin lasing in Ge, third-order SiGeSn susceptibilities, electric-field-induced second-order effects, supercontinuum generation and third-harmonics in Ge-on-Si, all-optical switching in SiC, GeSn Raman shifting, and biphoton generation in AlGaN, (4) the field of plasmonic-photonics, and here some fundamental and important contributions were made on the topics of metasurfaces, Spasers-and-Speds, split-ring resonators and 2 x 2 EO switching in a 3-waveguide coupler with charge accumulation under an ITO-embedded plasmonic central waveguide, (4) advances in phase-change-material photonics both in free space and waveguided structures, (5) new free-carrier physics in the Ge an AlGaN systems, (6) advances in waveguided standing-wave resonator spatial routing switches using electro-optical 1D PhC structures in the Si-based group IV photonics platforms.

8. Highlights of the Grant Results

We proposed waveguided nanobeam resonators embedded in the arms of a Mach Zehnder interferometer (MZI) and our analysis indicates that this structure is an advance in the art of integrated 2 x 2 electro optical switching. Figure 1 shows a top view of the device in the Ge-on-Si_3N_4 platform, operative at wavelengths from 1.9 to 5.4 microns. The orange and green shadings indicate P and N doping of the lateral Ge PIN diode within the rib-waveguided 1D photonic crystal regions. We predicted low

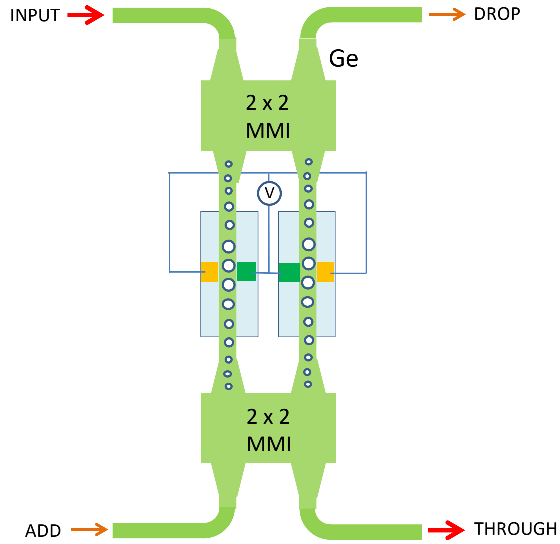

Figure 1. Chip-integrated 2 x 2 EO switch using identical 1D PhC tapered resonators in each MZI arm.

low crosstalk and low insertion loss. Simulations indicate EO switching at 500 attojoules-per-bit which puts these results into relevance and overlap with AFOSR's initiatives on attojoules photonics. We wrote a series of papers on the 2 x 2s showing their application to SOI, GOS and GON platforms and revealing their impact upon N x N matrix switching, electro-optical logic, and wavelength-division multiplexing.

We made a fundamental contribution to the free-carrier physics of crystalline germanium. This work is a sophisticated extension of Dr. Soref's 1987 paper on free-carrier response in silicon, work that has received 2300 citations in the literature. Figure 2 shows a portion of our theory results for Ge when a concentration ΔNe of electrons is injected into this semiconductor. The two graphs here show the carrier-induced increase in real index Δn as well as the simultaneous induced change in infrared absorption coefficient Δα.

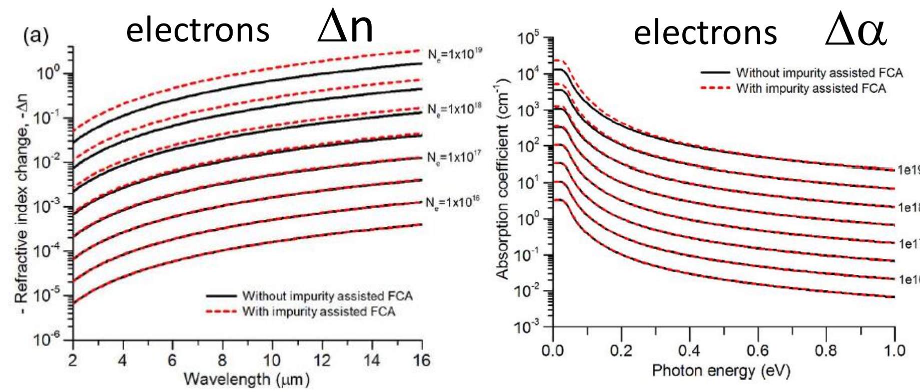

Figure 2. Predicted change in (a) real index of Ge vs wavelength, (b) extinction of Ge vs photon energy, using the electron concentration as a free parameter.

We consulted with the University of Arkansas on many of their GeSn experimental devices, and Figure 3 shows representative results for their infrared photodetectors. After those results were published, further increases in D* were made, making the diodes competitive with III-V devices. We also worked on developing optically pumped GeSn lasers and

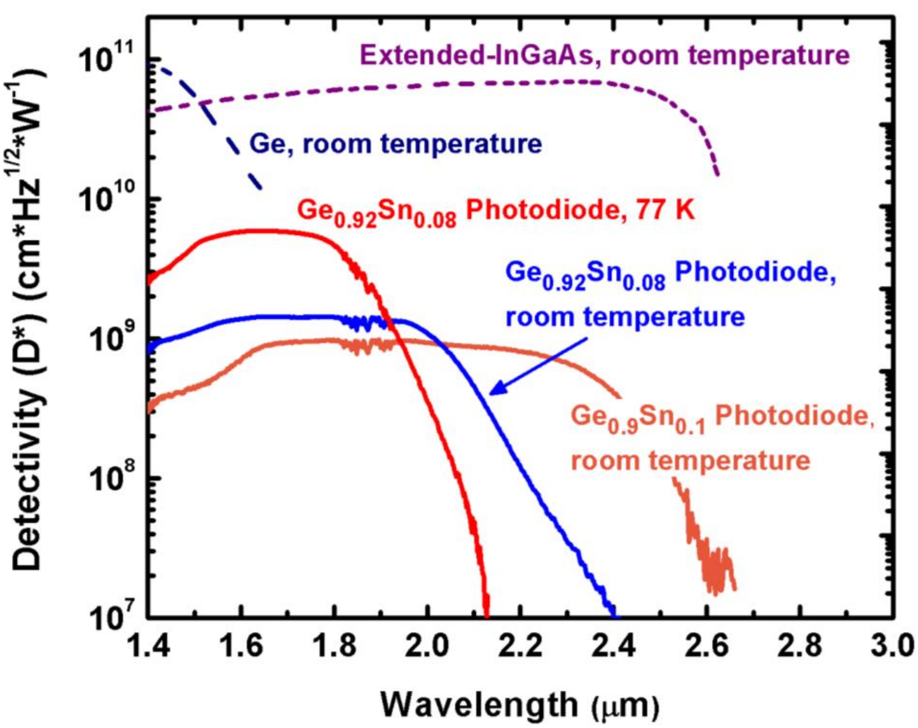

Figure 3. Measured detectivity of infrared photodiodes made by Fisher Yu's group.

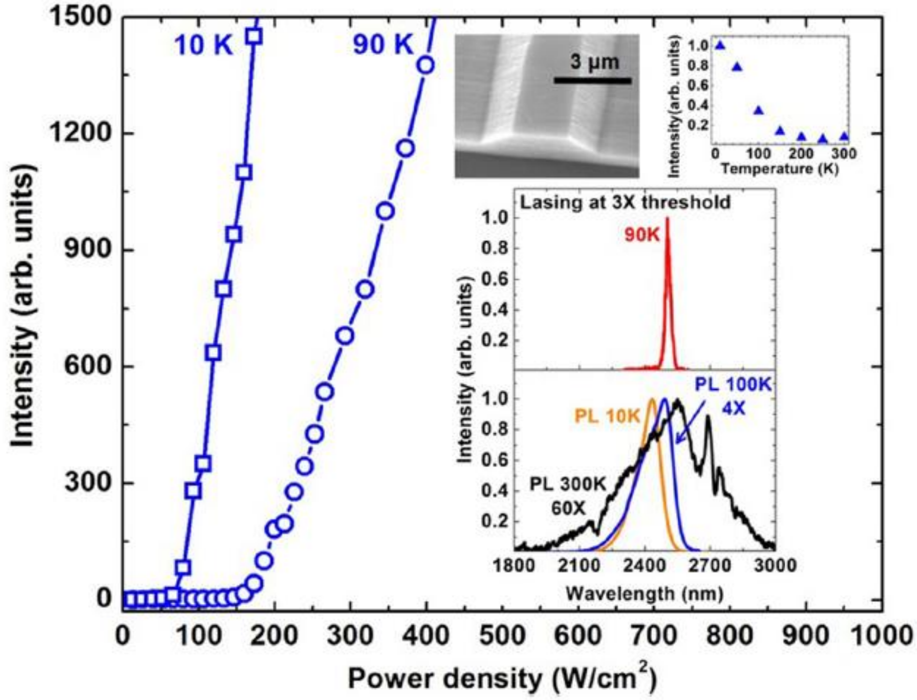

Figure 4. Measured characteristics of 2500-nm GeSn laser on Si that is operating at 110K

some highlights are indicated here in Figure 4 which shows the experiments made on our edge-emitting devices. After this work was published in APL, additional improvements were made.

Using energy-band theory and nonlinear optical physics, we calculated the third-order nonlinear susceptibility Chi-3 of SiGeSn alloys. Figure 5 presents results of the Chi-3 magnitude for representative alloys as a function of a wide infrared wavelength range. These published results are—to the best of our knowledge-- the first report in the literature for these ternary semiconductors.

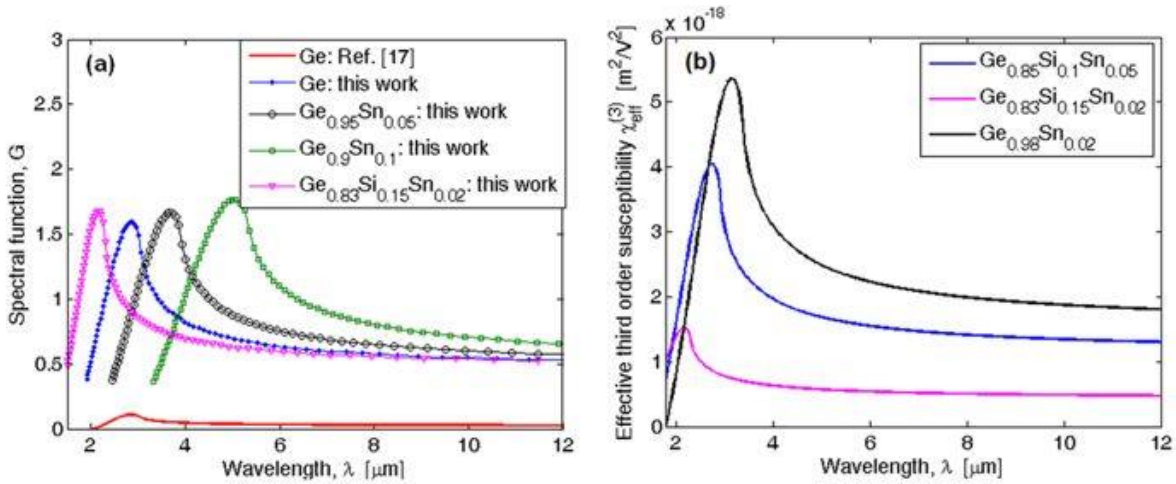

Figure 5. Predicted dispersion function and Chi-3 of selected SiGeSn alloys as a function of wavelength over 2 to 12 microns.

Using on-chip monolithic GeSn light sources and detectors, we envision that an Integrated microwave photonic (IMWP) chip could be constructed in the future for operation at 2 microns. As a near-term IMWP solution, the SOI platform is a good alternative, and we have studied this chip with the goal of defining and analyzing a reconfigurable network for processing microwave-modulated optical signals. We proposed the 2D hexagonal, programmable network illustrated in Figure 6 which shows a "mesh" comprised of broadband 2 x 2 Mach Zehnder devices operating in the cross or bar or splitting modes. This means that each arm in any hex-shape is an MZI.

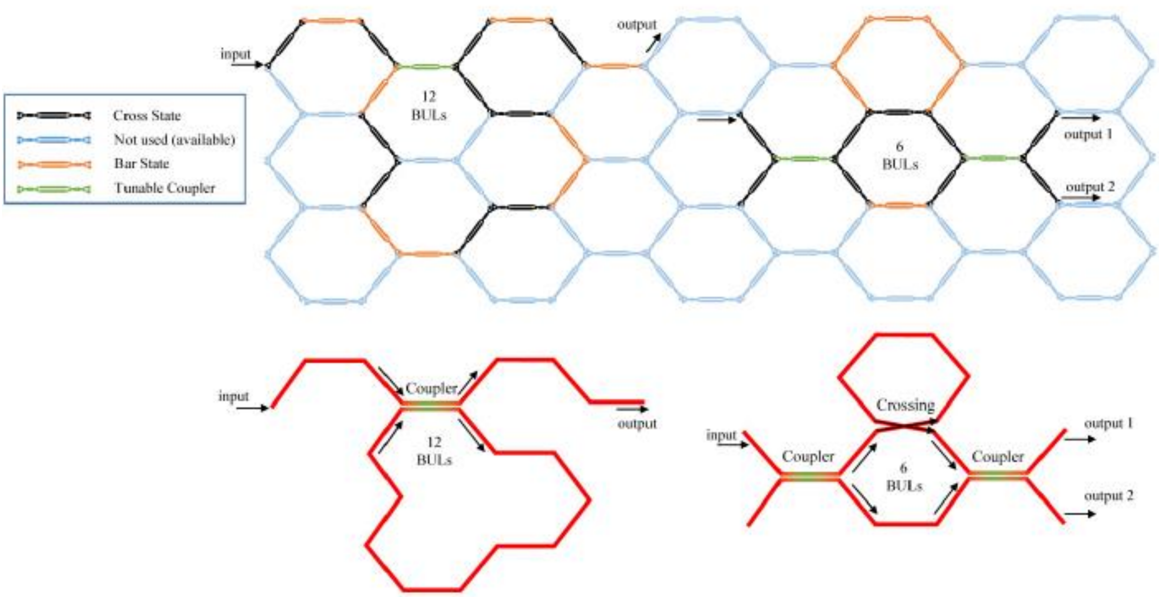

Figure 6. Plan view of waveguided optical "hexagonal-lattice mesh" that can be configured for a "ring" resonator as well as a ring-assisted interferometer.

Rather than a rectangular connection of MZIs, the six-sided approach is the most efficient topology, and in Figure 6, a variety of filters can be configured easily.

9. Potential Technology Transitions

Within the 121 published results, we can specify at least seven projects that could transition into commercial products after more development—as follows: (1) The laser papers with Fisher Yu's group are a foundation for the future electrically pumped GeSn laser that has potential for manufacture, (2) the near-infrared imager chip paper with Henry Cheng's group has potential for a manufactured GeSn infrared camera chip, although this would require considerable financial investment, (3) the reconfigurable processor papers with Jose Capmany's group could become a new silicon-photonic microwave chip with advanced features, (4) the series of papers on phase-change materials has three transition potentials—spatial-light-modulator products, fiber-optic switching products and waveguided switch- matrix chips that could be used in a data center, (5) the paper with Professor C. S. Tan's group on Ge-on-Nitride has potential for a new kind of mid-infrared wafer that would supplement the Ge-on-Si wafers currently envisioned for longwave application, (6) the prototype GeSn light emitting diodes and infrared detectors could lead to commercial emitter/sensor products made in a modified silicon-photonics foundry, (7) the papers with AFRL on the 2 x 2 electro-optical nanobeam switch could transition to a new kind of commercial, resonant switching device in both the SOI and GOS integrated-photonic foundry platforms.

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