Naval Research Laboratory
Washington, DC 20375-5320

NRL/5650/MR—2023/4

Long-Wave Infrared Integrated Photonics: Closeout Report

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December 18, 2023

REPORT DOCUMENTATION PAGE

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1. REPORT DATE 18-12-2023	**2. REPORT TYPE** NRL Memorandum Report	**3. DATES COVERED** **START DATE** 01/10/2019	 **END DATE** 09/30/2023

4. TITLE AND SUBTITLE

Long-Wave Infrared Integrated Photonics: Closeout Report

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER** 0601153N
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER** 1P84

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION / AFFILIATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory 4555 Overlook Ave SW Washington, DC 20375-5320	**8. PERFORMING ORGANIZATION REPORT NUMBER** NRL/5650/MR—2023/4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 N Randolph Street Arlington, VA 22217-1995	**10. SPONSOR / MONITOR'S ACRONYM(S) NUMBER** ONR	**11. SPONSOR / MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTAL NOTES

14. ABSTRACT

This final report provides information regarding NRL Base program Long-Wave Infrared (LWIR) Integrated Photonics, including technical objectives, technical progress, and archival publications and presentations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	SAR	7

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EXECUTIVE SUMMARY

This final report provides information regarding NRL Base program Long-Wave Infrared (LWIR) Integrated Photonics, including technical objectives, technical progress, and archival publications and presentations.

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LONG-WAVE INFRARED INTEGRATED PHOTONICS: CLOSEOUT REPORT

1. TECHNICAL OBJECTIVE AND PAYOFF

1.1 Technical Objective

We intend to demonstrate that the electromagnetic interactions in semiconductor waveguides in the long-wave infrared (LWIR) are fundamentally different from those of bulk materials. We will accomplish this by quantifying the influence of multi-phonon absorption, free-carrier absorption, and surface effects on passive waveguide loss in the LWIR. This understanding will lead to the development of new sources of LWIR waveguide radiation based on second-order nonlinearities and to the development of efficient waveguide microcantilever bolometry.

Photonic integration describes the co-fabrication of multiple photonic components onto a single semiconductor wafer using standard processing techniques. Most of this work has been done in the near-infrared, resulting in compact, chip-scale scale systems with the functionality of much-larger bulk-optics based systems. However, the materials typically used in state-of-the-art photonic integrated circuits include silicon nitride and silicon dioxide, which are opaque to radiation in the long-wave infrared.

Entirely new material platforms, sources, and detection approaches must be developed to extend photonic integration to the long-wave infrared. The first step in this process is to understand the long-wave infrared electromagnetic interactions in CMOS-compatible waveguide materials, such as germanium-on-silicon, and gallium arsenide on fluoride. This knowledge can then be used to design low-loss waveguide components such as gratings, couplers, and splitters, followed by the design of efficient sources and detectors on-chip. Then, by combining an increasingly sophisticated range of components into single long-wave infrared photonic integrated circuits, chip-scale systems such as chemical detectors or hyperspectral imagers may eventually replace their bulky, expensive predecessors.

1.2 Payoff

Long-wave infrared radiation (approximately 7-14 μm) has a number of important defense applications, ranging from hyperspectral imaging, to infrared seeking and countermeasures, to chemical sensing. To date, these systems use traditional bulk optics (mirrors, lenses, gratings, etc.) which limit their deployment to large-scale (benchtop or vehicle-based) operational scenarios. A reduction in the size, weight, and power of these systems would dramatically expand the usage scenarios to include handheld and micro-UAVs, while reducing the cost and power consumption.

2. TECHNICAL APPROACH

To extend photonic integration to the long-wave infrared, we intend to model, fabricate, and optically characterize germanium-on-silicon and gallium-arsenide-on-fluoride waveguides. We have experience with

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Manuscript approved December 15, 2023.

numerical modeling of waveguides (Comsol Multiphysics, RSoft, and PhoeniX Optodesigner), as well as design and layout. The new waveguide materials required for the long-wave infrared will be purchased from suppliers with proven experience in epitaxy and wafer-bonding. We will then perform waveguide fabrication at NRL using standard patterning (photolithography) and etching (ICP-RIE plasma etching) techniques. In addition, our experience in the near-infrared with micro-cavity ringdown techniques and cutback techniques will allow us to make high-precision loss measurements in the long-wave IR. Comparisons between our measured loss spectra and theoretical predictions, as a function of waveguide width and polarization, will enable us to understand what the dominant sources of loss are, and how they differ from bulk values. We will work with Jacob Khurgin, a well-known expert in semiconductor optics, to establish a new theoretical framework for the multi-phonon polariton to explain waveguide lattice absorption.

Our past success demonstrating form-birefringent-based difference frequency generation in the mid-infrared will be applied to gallium arsenide on fluoride waveguides for new long-wave IR sources. In addition, we will fabricate heaters adjacent to our germanium waveguides, and measure the long-wave thermal radiation emitted from the waveguide facet. Finally, we have years of experience working with micromachined semiconductor waveguides coupled to microbridges and microcantilevers. This modeling, fabrication, and analysis expertise will be extended to long-wave infrared microcantilever bolometry.

3. TECHNICAL PROGRESS

3.1 Germanium-on-Silicon Waveguides

We have completed finite-element modeling of the waveguides, including modal dispersion, substrate leakage, bend loss and coupling strength. The MBE Ge-on-Si material has been procured. We created a new MJB4 mask for waveguide measurements to include Fabry-Perot cutback loss measurements using paperclips and microring measurements. We used the mask to fabricate waveguides (termed sample GOS-02), which were then etched and diced into individual die using a wafer scribing and cleaving tool. We built a laboratory measurement apparatus to couple light from a tunable long-wave infrared laser into the waveguide facets, and then collect the emitted light through a spatial filter into a liquid-nitrogen cooled MCT detector. This apparatus has been used to successfully measure propagation loss and coupling loss from the waveguides. Propagation losses are in the 5-15 dB/cm range, spanning 6.85 μm to 11.25 μm, and have been made for both the TE_{00} and TM_{00} modes. Coupling losses were measured to be approximately 12 dB/facet and agreed well with finite-element simulations. Microrings were measured using thermal tuning and showed losses that agreed with propagation losses and coupling that agreed with theory.

We demonstrated the reddest waveguide microring resonator ever measured (wavelengths of 10 μm and above) and some of the highest Q-factors reported in the LWIR. These results were presented at CLEO (2021) and published in Optics Express. Comparisons of our measured losses with those reported by other groups and simulations suggest that our loss is dominated by background p-doping in the deposited germanium and/or the silicon substrate.

We then purchased new material from the MBE supplier grown with a slight background n-doping to counteract the possible presence of p-doping and decrease free-carrier-based propagation loss. We also designed a new waveguide mask for photolithographic definition of the waveguides to enable cleaner separation of bend loss from propagation loss, lower insertion (coupling) loss, and waveguides for chemical sensing. This new mask has been used with the new germanium-on-silicon material to fabricate new GOS waveguide samples, termed GOS-03. The fabrication involved patterning photoresist on the surface of the sample via the MA-6 contact aligner in the NSI. The samples were then etched using the general fluorine ICP-RIE in the NSI. Unfortunately, this tool has been producing poor etches for years (since about 2020) and high-quality etches (smooth, vertical sidewalls with etch rates consistent with the manufacturer's specifications) have not been achieved, despite considerable processing effort. Our understanding is that the NSI has been unable to procure the needed replacement parts for this etch tool to achieve acceptable results.

Despite these shortcomings, the fabricated waveguide samples were laser-scribed and cleaved into 4.8-mm long dice. The samples were then measured using the same setup as that used to measure the previous GOS-02 samples. The waveguide loss measurements confirmed that the propagation losses are significantly higher in GOS-03 than in GOS-02. These higher losses are likely due to increased sidewall roughness, which increases scattering losses. This is consistent with observations from the scanning electron microscope which showed very rough curved waveguide sidewalls. The waveguides also came out narrower than nominal widths and narrower than GOS-02, increasing substrate leakage loss and bend loss. These high losses prevent any conclusions about the source of the material loss in the germanium.

3.2 Nonlinear Optics

Nonlinear optics with wafer-bonded GaAs-on-BaF2. We have completed the finite-element modeling of the GaAs-on-BaF2 waveguides to optimize the GaAs thickness for birefringent phase-matching. We have procured the epitaxial GaAs material to include a layer of GaAs grown above an InGaP sacrificial layer/etch stop. And we have been focusing on wafer-bonding the GaAs to BaF2 with Onyx Optics. So far, they have demonstrated successful low-temperature Van der waals bonding (optical contacting) beween 19-mm square pieces of bulk GaAs and BaF2. They are in the process of side-polishing the material and further strengthening the bond via bond edge removal and surface-normal pressure.

Onyx has shipped wafer-bonded material in a specially-designed jig that allows processing of the material for removal of the GaAs substrate to reveal only the epitaxial material for waveguide processing and lithography. We are in the process of testing the substrate removal and the bond strength during this processing.

4. PUBLICATIONS AND PATENTS

Dmitry A. Kozak, Nathan F. Tyndall, Marcel W. Pruessner, William S. Rabinovich and Todd H. Stievater, "Germanium-on-silicon waveguides for long-wave integrated photonics: ring resonance and thermo-optics," *Optics Express* **29** 15443 (2021).

Dmitry A. Kozak, Nathan F. Tyndall, Marcel W. Pruessner, William S. Rabinovich, and Todd. H. Stievater, "Long-Wave-Infrared Integrated Photonics with Germanium-on-Silicon Waveguides," *Conference on Lasers and Electro-Optics*, San Jose, CA, (virtual) (2021) (oral presentation).