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Large scale 2D material - active silicon photonics

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14. ABSTRACT
Accomplishment Details:
A. Hybrid integration scheme of 2D materials and high-speed characterization: With minimized interface dangling bonds, we demonstrated electro-static doping in graphene from foundry manufactured substrates. We modeled RC constant limitation and carrier transient limitation of the hybrid device and compared to experimental data.
B. Metasurface based advanced multimode interference device on silicon photonic platform: We demonstrated the first low loss metasurface structure on silicon photonic platform, which revolu-tionize the photonic integrated circuits wired by single mode waveguides. We demonstrated ultra-compact mode converter, convolver and deep learning based on the diffractive optic elements based photonic integrated processors.
C. Foundry manufacturing: We accomplish one passive and one active TAPEOUT to AIM photonics, with the low loss photonic design picked from the first passive TAPEOUT. The deep UV lithog-raphy generated photonic crystal device exhibit the lowest loss among all the published results. Given the fabrication quality, we are exploring new photonic crystal based PDK components, and designed ultralow loss metalens-photonic crystal cavity-metalens microsystems with 3dB total loss.
D. Space test of silicon photonic devices: We accomplished radiation exposure of passive and active silicon photonic devices on near earth orbit for 6,700 orbits. We characterized the nonlinear re-sponse of microring resonators and high-speed optoelectronic response of MZI modulators before and after exposure.
E. Sponsored by the grant, Gu’s group at University of Delaware published 47 peer reviewed conference and journal papers, including 2 publications on Nature Communication and 1 publication on npj 2D materials and applications. Gu delivered 23 invited seminars in the YIP period. The involved students and PI received numerous awards during the period (section B.3). Those works on international space station test; high speed graphene optoelectronics and integrated meta-systems are reported by multiple media.

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Outline:

A. Accomplishments
   A.1 Research Objectives
   A.2 Accomplishment Details
B. Impacts
   B.1 Impacts on Science and Engineering
   B.2 New Infrastructures Developed in PI's Lab
      B.2.1 MIMO Testing Setup for PIC
      B.2.2 High Speed Optoelectronic Testing of PIC
   B.3 Awards Received by the Involved Students and Postdocs
   B.4 Honors and Awards received by PI
   B.5 Service to the Science and Engineering Society
C. Changes
D. Technical Updates
   D.1 Nonlinear Materials for Integrated Photonics
   D.2 New Device and System Architectures for Silicon Photonics
      D.2.1 Ultra-low Loss Photonic Crystal Devices from AIM photonics
      D.2.2 Metasurface on Integrated Photonics: Mode Converters, Convolver and Accelerators
   D.3 Cosmic Radiation Evaluation of Large-scale PIC
   D.4 Publications
   D.5 Invited Talks
   D.6 Media Reports

A. Accomplishments

A.1 Research Objectives

During the four years efforts for YIP, we expanded capabilities towards large-scale integrated photonic systems: understanding the carrier transportation on the interface in the hybrid silicon photonic device, characterization of high-speed optoelectronics, implementation of metasurface based advanced multimode interference device on silicon photonic platform, foundry manufacturing and space test of integrated photonic devices.

A.2 Accomplishment Details

Hybrid integration scheme of 2D materials and high-speed characterization: With minimized interface dangling bonds, we demonstrated electro-static doing in graphene from foundry manufactured substrate. We modeled RC constant limitation and carrier transient limitation of the hybrid device and compared to experimental data.

Metasurface based advanced multimode interference device on silicon photonic platform: We demonstrated the first low loss metasurface structure on silicon photonic platform, which revolutionize the photonic integrated circuits wired by single mode waveguides. We demonstrated ultra-compact mode converter, convolver and deep learning based on the diffractive optic elements based photonic integrated processors.

Foundry manufacturing: We accomplish one passive and one active TAPEOUT to AIM photonics, with the low loss photonic design picked from the first passive TAPEOUT. The deep UV lithography generated photonic crystal device exhibit the lowest loss among all the published results. Given the fabrication quality, we are exploring new photonic crystal based PDK components, and designed ultralow loss metalens-photonic crystal cavity-metalens microsystems with 3dB total loss.

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Sponsored by the grant, Gu's group at University of Delaware published **47 peer reviewed conference and journal papers**, including 2 publications on *Nature Communication* and 1 publication on *npj 2D materials and applications*. Gu delivered **23 invited seminars** in the YIP period. The involved students and PI received numerous awards during the period (section B.3). Those works on international space station test; high speed graphene optoelectronics and integrated metasystems are reported by multiple media.

B. Impacts

B.1 Impacts on Science and Engineering

The impacts of the four-year efforts cover multiple aspects of photonic integrated circuits (PIC) technology. (1) Optical materials development. We expand the optical material libraries for high-speed low power optoelectronics on large-scale silicon photonic platform. (2) Expand PIC foundry library. To match the high standard and specifications for nanophotonic foundry processing, we develop metasurface based designs, and experimentally demonstrated functions from mode converter, mathematical calculation to deep learning. (3) Technology development. With device manufactured from AIM photonics, we performed radiation evaluation test on international space station. The accumulation radiation dosage test is the first step of PIC towards outer space communication applications. The sponsored efforts received attentions from media (section D.6).

B.2 New Infrastructures Developed in PI's lab

B.2.1 MIMO Testing Setup for PIC

MIMO systems are widely used in remote sensing and free-space RF and optical communications. As a miniaturized system, the number of MIMO ports for PIC system is limited by (1) large footprint grating couplers (2) no available setup for testing. The DMD programs multiple (hundreds) of inputs coupled onto PIC.

B.2.2 High Speed Optoelectronic Testing of PIC

Ultrafast optoelectronic responses (>40GHz) in directed contacted graphene-silicon junction on foundry manufactured integrated photonic platform; Established high-speed optoelectronic testing infrastructure in lab with 65 GHz analogue bandwidth and 20 Gb/s digital bandwidth.

B. 3 Awards Received by the Involved Students and Postdocs

April 2022	Graduate student Zi Wang received UD Nanoelectronics and Photonics award
May 2021	Graduate student Lorry Chang received AFRL ATR center summer internship
May 2021	Supervised K-12 and undergraduate students received ARO summer apprenticeship
Dec. 2020	Graduate student Anishkumar Soman received 2020 *IEEE Photonics Society Award*
Jun. 2020	Graduate student Zi Wang completed a summer intern at *Nokia Bell Lab* on fiber optical communication (Holmdel, NJ)
Jun. 2020	High school student Darren Wu's presentation on his summer intern work in our lab receives the 1st place in IEEE Integrated STEM conference
April 2020	Graduate student Hwaseob Lee receives *OSA Incubic/Milton Chang Travel Fund*
April 2020	Graduate student Yahui Xiao received *UD Charles lh Fellowship*
April 2020	Undergraduate Alec receives NASA Delaware space grant summer research scholarship on developing high temperature platform for in-situ testing of optoelectronic devices
Jun. 2019	Graduate student Dun Mao completed a summer intern at Nokia Bell Lab on design and test the high-speed silicon photonic transceivers (Holmdel, NJ)
Apr. 2019	Graduate student Anishkumar Soman received *Udel Summer Doctoral Fellowship Award*
Apr. 2019	Alec Scallo and Lorry Chang are selected for the University of Delaware's Undergraduate Research Program for their summer intern in lab
Apr. 2018	Graduate student Anishkumar Soman received *Udel Summer Doctoral Fellowship Award* for 2D material collaborative work at Army Research Lab at Adelphi
Mar. 2018	Graduate student Hwaseob Lee received *UD Bendett Fellowship*
Mar. 2018	Graduate student Zi Wang received *UD Charles lh Fellowship*
Mar. 2018	Graduate student Dun Mao received *UD Bendett Fellowship*
Mar. 2018	Graduate student Anishkumar Soman received *UD Charles lh Fellowship*
Sep. 2018	Graduate student Anishkumar Soman received *UD Professional Development Award*

B.4 Honors and Awards Received by PI

2022 Promotion to be a senior member of IEEE
2021 DARPA Young Faculty Award
2019 ARO Young Investigator Program Award
2018 NASA Early Faculty Career Award

B.5 Service to the Science and Engineering Society

Reviewer for: Nature, Science Advances, Nano Letters, Advanced Materials, Advanced Optical Materials, ACS Applied Electronic Materials, ACS Photonics, Applied Physics Letters, Optical Express, Optical Letters, Optical Materials Express, etc.
Conference Council for IEEE Photonics Society (2022-)
Committee member for the IEEE EDS Optoelectronic Devices (2021-)
Subcommittee chair for the IEEE Photonics Conference: Optical Interconnects (2021)
Vice subcommittee chair for the IEEE Photonics Conference: Optical Interconnects (2020)
Subcommittee member for the Frontier in Optics 4B Subcommittee: Photonic Integrated Devices for Computing, Sensing and other Applications (2019, 2020, 2021)
Subcommittee member for the Conference on Lasers and Electro-Optics Science & Innovation 6 Subcommittee: Optical Materials, Fabrication, and Characterization (2019, 2020, 2021)
Subcommittee member for the The Glass and Optical Materials Division Annual Meeting (2018)
Subcommittee member for PhotonIcs & Electromagnetics Research Symposium Subcommittee: SC3: 2D Materials Photonics and Optics, Part 1 & 2 (2019)

C. Changes

PI received one year no cost extension during the period of Pandemics.

D. Technical Updates

D.1 Nonlinear Materials for Integrated Photonics

The integrated photonic devices bridge the fundamental material science and device applications. The 'integrated photonic spectroscopies' provide a great supplementary to free space optical spectroscopies, as it offers cm/mm long light-mater interaction in waveguides and localized and elongated light-mater interactions via resonators. Compared to conventional spectroscopy techniques, integrated photonic platform offers superior sensitivity in probing the transience (via ultrafast spectroscopies) and permanent refractive index perturbation in materials (10^{-3}). To separate the tangled complex nonlinearities in resonators, coupled mode theory interprets the results and extract the parameters from the optical readouts. The anisotroic response can be manifested if the substrate confined photon polarization aligns with the anisotropic response in material. There are tremendous efforts on exploring alternative material platforms (e.g. lithium niobate, diamond, III-V, rare earth doped glass, chalcogenides) with research efforts on developing the correspondent fabrication techniques, as the benefits of enhanced light-mater interaction is accompanied by the device's high sensitivity to scattering and defect absorption.
We took an alternative approach with hybrid integrations: introduce new photonic materials on low loss silicon photonic platform. Hybrid integration can circumvent this fundamental limit but

brings other challenges on transferring and interface engineering. The success of hybrid integrated photonic devices can be built on three pillars: (1) comprehensive understanding of material physics in atomic, electronic and optical levels; (2) clean integration of high purity materials on low loss substrates and (3) contact engineering for highly efficient carrier transportations. My group's efforts on pushing the loss limits of nanophotonic components, explore the hybrid integration techniques and locate the best role of the hybrid device among the integrated photonic component libraries.

Table I: YIP efforts on exploring hybrid silicon photonic devices with material-led device functionality

Material	Device integration	Function
Graphene	PhC waveguide with *p-i-n* junction for ultrafast optoelectronics	Field accelerated carrier transportation and thermionic emission enhanced near infrared absorption in directly contact graphene-silicon p/n junction [*npj 2D Mater. and Applications* 2018] [*ACS Appl. Electron. Mater.* 2019] [*APL* 2020] [*IEEE JSTQE* 2020]
Monolayer MoS_2	Field effect transistors (FET)	Observation of 2H-T' phase transition mechanism in monolayer MoS2 with hydrogen plasma exposure; quantified the Fermi-level shift by plasma exposure by Schottky barrier and contact resistance. [*ACS Appl. Mater. and Interfaces* 2020]
Perovskite, Tellurium	Solution integration on MRR	Low threshold absorption saturation in waveguide; nonlinearity suppressed loss in MRR [*Adv. Opt. Mat.* 2021] [*CLEO* 2022]

We combined nonlinear coupled mode theory and experiments to reveal new light-matter interaction processes in a variety of interesting material systems (Table I), including third order nonlinearities in 2D materials, photorefractive responses in perovskite and polymorphic phase transitions in layered chalcogenide materials. The small footprint nonlinear nanophotonic component are highly desired in activation functions for large-scale photonic computing processors.

Optical nonlinearities are often closely tightened with the free-carrier dispersion and absorption dynamics. Understanding and manipulation of carrier generation and transportation is critical in pursuing efficient and high-speed optical interconnect devices. In the past, I studied three material systems (Table I): monolayer MoS_2 transistor, and graphene-silicon *p-i-n* junction. Micro-photocurrent mapping reviewed insights on the lateral photo-carrier transportation, and bright insights on the development of advanced 2D material photodetectors powered by the silicon photonic substrates.

D.2 New Device and System Architectures for Silicon Photonics

D.2.1 Ultra-low Loss Photonic Crystal Devices from AIM photonics

Photonic crystal platforms (PhC) are widely adopted in quantum optic systems, for single mode cavity manifested light-matter interactions. Also, the suspended PhC are one of the basic components for MEMS based switches and oscillators. The bottleneck for those technologies is limited by their high insertion loss (~20 dB) and limited scalability. In the past few years, we have been pursuing ultralow loss and scalable integrated photonic components through foundry run. We start with the PhC platform, where the slow light and cavity enhancement are widely used in active components. We demonstrated the first low loss photonic crystal waveguides through AIM photonics multi-project-wafer run (Fig. 3). For sub-millimeter-long photonic crystal waveguides, 2 dB total component loss and 40 dB extinction ratio are observed across dies. A three-dimensional coupler between the channel and photonic crystal waveguides reduces the insertion loss to less than 1 dB per port. The high extinction ratio is attributed to the excellent geometric homogeneity of the nano-manufactured nanophotonic structures.

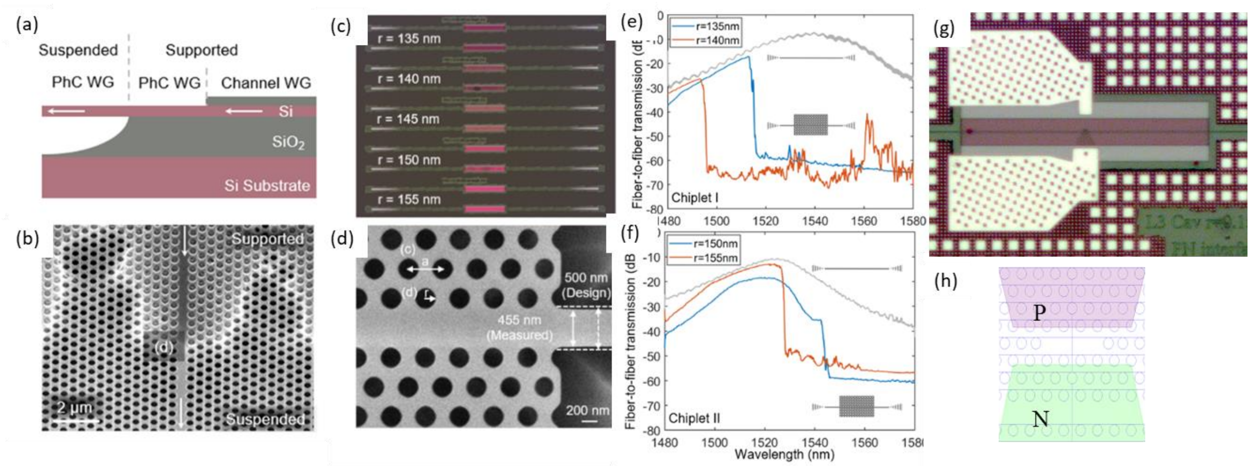

Figure 3. 2dB component loss in photonic crystal structures by foundry manufacturing. (a-b) Low loss three-dimensional coupler between a channel WG and a PhC WG. (c-d) Optical microscope and SEM view of the fabricated PhC devices. (e-f) Measured transmission of grating couplers (grey) and PhC devices from two chiplets. (g-h) The active PhC switch device on AIM photonics active run.

D.2.2 Metasurface on Integrated Photonics: Mode Converters, Convolver and Accelerators

The metasystem implements high-throughput vector-by-matrix multiplications within miniaturized footprint. The strong computing capability incorporates the fabrication variation related uncertainties, and thus the pre-trained metasystem can perform machine learning tasks without post-tuning. We demonstrated three functional metasystems: a 15-pixel spatial pattern classifier reaches near 90% accuracy with femtosecond inputs, a three-channel wavelength demultiplexer and a compressed sensing based hyperspectral image classifier. The diffractive optical network may revolutionize photonic integrated circuits architecture with densely integrated phase shifters, spatially multiplexed throughput, and data processing capabilities. For the next few years, I am planning to combine the specialties in section A for reprogrammable diffractive optical processors, including the electronic optic controlling device, circuits, and control algorithms.

Here listed my group's past achievements.

- First demonstration of in-plane dielectric metasurface for ultra-low loss compact mode convertor, mathematic operation, and Fourier optic systems [*Nature Commun.*2019];

- First experimental demonstration of metasurface based machine learning device at telecommunication wavelength [*Nature Commun.* Revision submitted];
- Focusing and defocusing switching of metalens with new optical phase change materials [*Opt. Lett.* 2021].

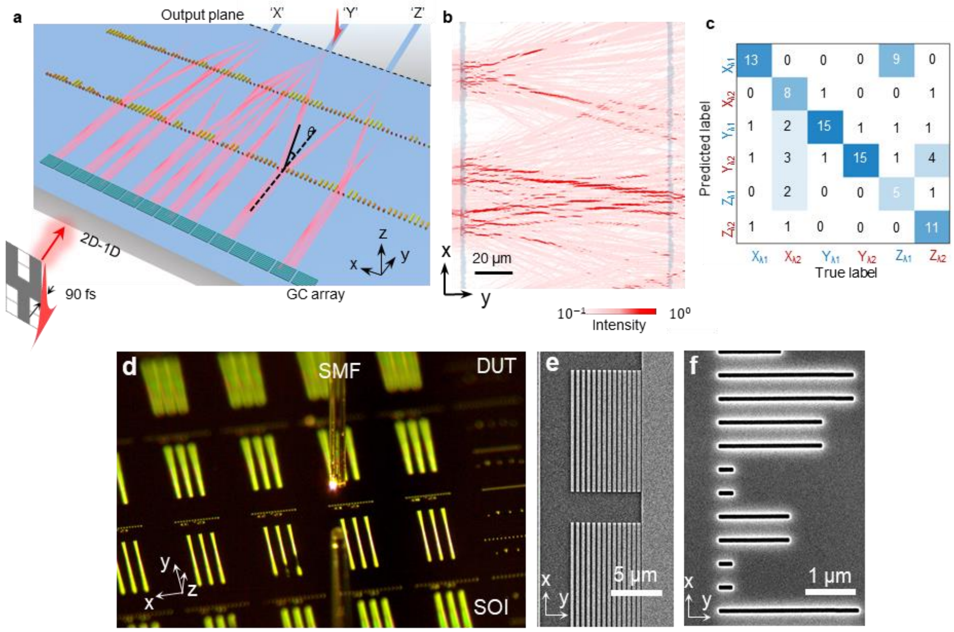

Figure 4. Integrated photonic system for hyperspectral image classifier. (a) Schematics of the system architecture. (b) Subwavelength structure manifested diffraction between metasurface layers. The numerically simulated light intensity is superimposed onto the optical microscope image of a fabricated metasystem. (c) The confusion matrix for the spectral-spatial pattern classification metasystem. (d) The device under test (DUT) includes arrays of metasystems fabricated on a silicon-on-insulator (SOI) substrate. (e) SEM images show the nanostructure of the input grating coupler array and (f) metasurface structures.

D.3 Cosmic Radiation Evaluation of Large-scale PIC

PIC brings attentions as a lightweight, scalable, and miniaturized alternative to the bulk/fiber based optical instruments, from biosensing to communications. By compensating the cost of nanomanufacturing with payload, PIC and nanophotonic components might exhibit significant advantage over the traditional instruments. However, how those nanophotonic devices respond in space environments should be the first step along the way for technical transfer. The result is reported by AIM photonics website.

As the first step, we performed six-month exposure of active silicon photonic devices on international space station (ionic radiation and atomic oxygen), where the most commercial activities take place. We compared nonlinear optic responses and high-speed optoelectronic efficiency between pre- and post-flight foundry devices. It is the first step to understand the impact of these radiation effects and verify the operation robustness and reliability of silicon Photonics Integrated Circuits (PIC) in order to develop proper risks mitigation strategies for incorporating them in future spaceborne instruments.

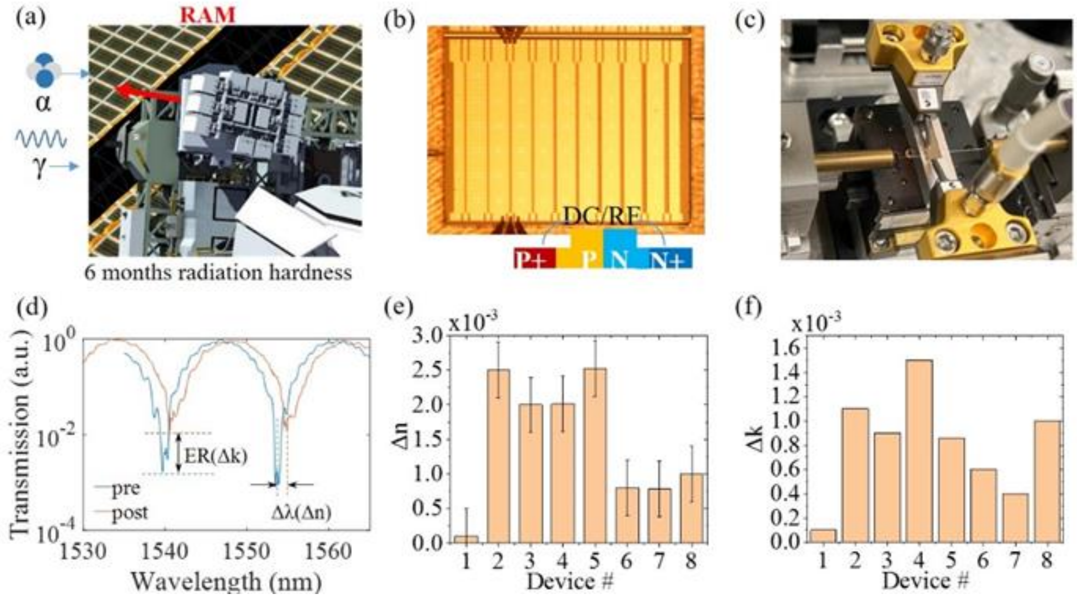

Figure 5. Cosmic radiation and atomic oxygen exposure of silicon photonic Mach-Zehnder Modulator. (a) Radiation environment. (b) Device image and (c) setup of the MZM modulator. (d) Representative transmission spectra for pre and post flight devices. (e) Extracted real part and (f) imaginary part of effective index changes of 8 MZMs post flight.

D.4 Publications (sponsored)

1. [Invited review] Z. Wang†, Y. Xiao†, K. Liao†, T. Li,† H. Song, B. Yuan, H. Chen, S. Z. Uddin, D. Mao, F. Wang, Z. Zhou, W. Jiang, N. K. Fontaine, A. Willner, X. Hu and T. Gu, Metasurface systems for advanced optical communication, *Nanophotonics* (submitted)
2. T. Kananen, M. Wiggins, Z. Wang, F. Wang, A. Soman, K. Booksh, A. Alu and T. Gu, Quasi-BIC enhanced graphene absorption in mid-infrared plasmonic-photonic system (in submission)
3. Lee, F. Wang, A. Kecebas, S. K. Ozdemir, T. Gu, Embedded meta-atoms defined non-Hermitian states in integrated photonics (in submission)
4. Y. Xiao, F. Wang, D. Mao, T. Kananen, T. Li, H. Lee, Z. Wang and T. Gu, Scalable photonic crystal waveguides with 2 dB component loss, *Photonic Technology Letters*, in press (2022)
5. Z. Wang, L. Chang, F. Wang, T. Li and T. Gu, Integrated photonic metasystem for image classifications at telecommunication wavelength, *Nature Communications*, 13, 2131 (2022)
6. Y. Wang, J. Liu, K. Gu, A. Soman, T. Gu, C. Arnold, R. Register, Y.-L. Loo, R. Priestley, Epitaxially Crystallized Polyethylene Exhibiting Near-Equilibrium Melting Temperatures, *Polymer Engineering and Science*, 1-7 (2022)
7. Wang, Z. Wang, T. Li, B. Sun, L. Zhou, T. Gu, Focusing and defocusing switching of silicon photonic metalens by indium selenide, *Optics Letters* 46, 4088-4091 (2021)
8. Wang, L. Zhao, H. Lee, Y. Xiao, T. Li, Y. Wang, A. Soman, T. Kananen, X. Hu, B. P. Rand and T. Gu, Controlling Microring Resonator Extinction Ratio via Metal-Halide Perovskite Nonlinearity, *Advanced Optical Materials* 2100783 (2021)

9. [Invited] Y. Xiao, Z. Wang, F. Wang, H. Lee, T. Kananen, T. Gu, Engineering the light coupling between metalens and photonic crystal cavity for robust on-chip microsystem, *Journal of Optical Microsystems* (2021)
10. Wang, X. Niu, X. Hu, T. Gu, X. Wang, J. Yang, H. Yang, T. Ao, S. Wang and Q. Gong, All-Optical Mode-selective Router Based on Broken Anti-PT Symmetry, *Physical Review Applied* 14 (4), 044050 (2020)
11. [invited] D. Mao†, C. Cheng†, F. Wang, Y. Xiao, T. Li, A. Soman, T. Kanenen, X. Zhang, M. Krainak, P. Dong and T. Gu, Device architectures for low voltage and ultrafast graphene integrated phase modulators, *IEEE Photonics Society Journal of Selected Topics in Quantum Electronics* 27 (2), 1-9 (2020)
12. Mao, M. Chen, X. Ma, A. Soman, H. Xing, T. Kananen, N. Augenbraun, C. Cheng, M. Doty and T. Gu, Sub-bandgap laser patterning of planar chalcogenide photonics, *Optical Material Express* 10 (9), 2126-2134 (2020)
13. Soman†, R. A. Burke†, Q. Li†, M. D. Valentin, T. Li, D. Mao, M. Dubey, and T. Gu, Hydrogen plasma exposure of monolayer MoS_2 FET and protection by monolayer graphene, *ACS Applied Materials & Interfaces* 12 (33), 37305-37312 (2020)
14. Y. Wang, K. Gu, A. Soman, T. Gu, R. A. Register, Y.-L. Loo and R. D. Priestley, Circumventing Macroscopic Phase Separation in Immiscible Polymer Mixtures by Bottom-Up Deposition, *Macromolecules* 53, 5740–5746 (2020)
15. Q. Li, Y. Wang, T. Li, W. Li, F. Wang, A. Janotti, S. Law and T. Gu, Localized strain measurement in molecular beam epitaxially grown chalcogenide thin films by micro-Raman spectroscopy, *ACS Omega* 5, 8090-8096 (2020)
16. Wang, Z. Wang, D. Mao, M. Chen, T. Kananen, A. Soman, X. Hu, C. Arnold and T. Gu, Light emission from self-assembled and laser-crystallized chalcogenide metasurface, *Advanced Optical Materials* 1901236 (2020)
17. Z. Wang, T. Li, A. Soman, D. Mao, T. Kananen and T. Gu, On-chip wavefront shaping with dielectric metasurface, *Nature Communication* 10, 3547 (2019)
18. Soman, U. J Nsofor; U. Das, T. Gu and S. Hegedus, Correlation between in situ diagnostics of the hydrogen plasma and the interface passivation quality of hydrogen plasma post-treated a-Si: H in Silicon Heterojunction Solar Cells, *ACS Applied Materials & Interfaces* 11, 16181 (2019)
19. Lee, T. Kananen, A. Soman and T. Gu, Influence of surface roughness on microring based phase shifters, *Photonic Technology Letters* 11, 813-816 (2019)
20. Mao, T. Kananen, J. Sinsky, N. W. Petrone, J. Hone, P. Dong and T. Gu, Bandwidth limitation of directly contacted graphene-silicon optoelectronics, *ACS Applied Electronic Materials* 1, 172 (2019)
21. T. Li, D. Mao, N. Petrone, R. Grassi, H. Hu, Y. Ding, Z. Huang, M. Yu, G. Lo, D.-L. Kwong, J. C. Hone, T. Low, C. W. Wong and T. Gu, Spatially controlled electrostatic doping in graphene p-i-n junction for hybrid silicon photodiode, *npj 2D Materials and Applications* 2, 36 (2018)

Peer reviewed conference publications:

22. (Invited) T. Gu, Suppression of radiative and electronic loss channels in graphene plasmonics,

IEEE RAPID (2022)
23. (Invited) Z. Wang, L. Chang and T. Gu, Integrated Metasystem for Fourier Optics and Machine Learning, PIERS (2022)
24. Mao, L. Chang, H. Lee, T. Li, F. Wang, Y. Xiao, Z. Wang, P. Dong, A. W. Yu, M. A. Krainak and T. Gu, Cosmic radiation effect on silicon photonic Mach-Zehnder Modulator, CLEO (2022)
25. L. Chang, D. Mao, H. Lee, A. W. Yu, M. A. Krainak, T. Gu, Cosmic radiation enhanced photothermal dispersion in critically coupled silicon microring resonators, CLEO (2022)
26. Y. Xiao, D. Mao, Y. Wang and T. Gu, photo-refractive switching of mcro-ring resonators via few-layer Tellurium, CLEO (2022)
27. Z. Wang, L. Chang, F. Wang, T. Li, W. Yang, B. Yuan, T. Gu, Hyperspectral image classification via integrated metasystem, CLEO (2022)
28. H. Lee, A. Soman, T. Li, T. Kananen, D. Mao, S. K. Ozdemir, T. Gu, Electro-optic tuning of non-Hermiticity in a silicon microring resonator, CLEO (2021)
29. Wang, L. Zhao, H. Lee, Y. Xiao, T. Li, Y. Wang, A. Soman, T. Kananen, X. Hu, B. P. Rand, and T. Gu, Controlling the extinction ratio of microring resonators by perovskite nonlinearity, CLEO (2021)
30. Y. Xiao, Z. Wang, F. Wang, H. Lee, T. Gu, Optimization of the light coupling between metalens and photonic crystal resonators for robust on-chip microsystems, CLEO (2021)
31. (Invited) T. Gu, Y Xiao, Z Wang, D Mao, F Wang, T Li, H Lee, Foundry integrated nanophotonic devices and metasystems, *Frontiers in Optics* FW1B. 1 (2020)
32. H. Lee, T. Li, C. Cheng, S. K. Ozdemir, T Gu, Active tuning of silicon photonic microring resonator towards a chiral exceptional point, *Frontier in Optics* FW4D.4 (2020)
33. Y. Xiao, Z. Wang, F. Wang, H. Lee, T. Kananen, T. Gu, Robust Light Coupling to Photonic Crystal Waveguide Using Integrated Metalens, *CLEO: Science and Innovations*, JTh2B. 20 (2020)
34. H. Lee, F. Wang, T. Li, A. Scallo, Z. Wang and T. Gu, Topological compensation of Rayleigh scattering induced reflection in a single mode waveguide, *CLEO: QELS_Fundamental Science*, FTu4A. 1 (2020)
35. Wang, Y. Xiao, T. Kananen, T. Li, Z. Wang, H. Lee, X. Hu and T. Gu, Low-loss photonic crystal platform by foundry processing, *CLEO: QELS_Fundamental Science,* JTu2D. 28 (2020)
36. Z. Wang, L. Chang, F. Wang, T. Li and T. Gu, Machine Learning with integrated metasystem, *CLEO: Science and Innovations*, SF2O. 8 (2020)
37. [Invited] Z. Wang, T. Li, L. Chang, F. Wang, Y. Xiao, D. Mao, T. Kananen, T. Gu, On-chip wavefront shaping with dielectric metasurface, *Proc. SPIE 11290, High Contrast Metastructures* IX, 112900I (2020)
38. [Postdeadline] Z. Wang, T. Li, A. Soman, T. Gu, On-chip wavefront shaping with dielectric metasurface, *Frontier in Optics* FTu6B.3 (2019)
39. T. Gu, D. Mao, T. Li, T. Kananen, High Detectivity in CMOS Substrate Powered Graphene p-i-n Junction, *IEEE Research and Applications of Photonics in Defense Conference* (2019)
40. T. Gu, Graphene Modified Plasmonic Sensors, *National Aerospace & Electronics Conference* (2019)

41. Z. Wang, T. Li, A. Soman, T. Gu, On-chip Wavefront Shaping with High Contrast Dielectric Metalens, *CLEO: Science and Innovations*, SM1J. 2 (2019)
42. Mao, M. Chen, N. Augenbraun, A. Soman, X. Ma, T. Kananen, M. Doty and T. Gu, Micromachining of Chalcogenide Waveguides by Picosecond Laser, *CLEO: Science and Innovations*, SF3O. 5 (2019)
43. T. Kananen, A. Soman, A. Malkani, Z. Wang, B. Xu, T. Gu, Graphene Modified Plasmonic Guided Mode for CO_2 Detection, *CLEO: QELS_Fundamental Science*, FTh4C. 4 (2019)
44. Lee, T. Li, Z. Wang, A. Soman, A. Scallo, T. Gu, Spatially locked mode in defected microring resonators, *CLEO: QELS_Fundamental Science*, FTu4B. 7 (2019)
45. Soman, R. Burke, Q. Li, M. Valentin, E. Zakar, U. Nsofor, S. Hegedus, U. Das, J. Shi, Y. Zhang, T. Gu, Hydrogen plasma treatment of MoS_2, *CLEO: Science and Innovations*, JTu2A. 118 (2019)
46. H Lee, T Kananen, C Santori, JS Pelc, R Bose, R. G. Beausoleil, T. Gu, Microring resonator based compact on-chip phase tuner, *CLEO: QELS_Fundamental Science*, JW2A. 36 (2018)
47. D Mao, T Kananen, J Sinsky, N Petrone, J Hone, P Dong, T. Gu, Small-signal model for heterogeneous integrated graphene-silicon photonics, *CLEO: Science and Innovations*, SM2B. 4 (2018)

D.5 Invited Talks

1. Build low loss integrated photonics with meta-atoms: from nonreciprocity to deep learning, CUNY (2022)
2. Suppression of radiative and electronic loss channels in graphene plasmonics, IEEE Research and Applications of Photonics in Defense Conference (2022)
3. Integrated metasystem for Fourier optics, machine learning and imaging, Department Seminar, Peking University, Beijing, China (2021)
4. Integrated Metasystem for Fourier Optics and Machine Learning, Photonics Empowered by Artificial Intelligence, PhotonIcs & Electromagnetics Research Symposium (PIERS) (2021)
5. Integrated photonic metasystem for analogue signal processing: from Fourier optics to machine learning, IEEE Summer Topicals Meeting (2021)
6. Space test of photonic integrated circuits, IEEE Research and Applications of Photonics in Defense Conference (2021)
7. Nanophotonic device for space communication, 15^{th} Delaware Space Grant Symposium, Newark, DE (2021)
8. Foundry integrated nanophotonic devices and metasystems, Frontier in Optics, DC (2020)
9. Integrated metasurface systems for signal processing, IEEE Research and Applications of Photonics in Defense Conference (2020)
10. Research update report, NASA Glenn Research Center, Cleveland, OH (2020)
11. Van der Waals integrated 2D materials on active silicon photonic platform, Lawrence Symposium on Epitaxy, Scottsdale, AZ (2020)
12. Photonic integrated metasystems, OSA Engineer Week Celebration (2020)
13. On-chip wavefront shaping with dielectric metasurface, SPIE Photonics West, section High Contrast Metastructures IX, San Francisco, CA (2020)

14. International Space Station Flight pre-launch report, Goddard Space Flight Center, Greenbelt, MD (2019)
15. Integrated photonic circuits for space communication and sensing, NASA Glenn Research Center, Cleveland, OH (2019)
16. Invited talk, “Apollo at 50: To the Moon and Beyond” celebrating the 50th anniversary of the Apollo 11 Moon landing, Newark, DE (2019)
17. Invited talk, Nokia Bell Labs, Holmdel, NJ (2019)
18. Department seminar of material science department, University of Delaware, Newark, DE (2018)
19. Progress report, AIM photonics members meeting, Syracuse, NY (2018)
20. Low power silicon photonic nonlinear optics with graphene, State Key Laboratory for Artificial Microstructure and Microscopic Physics, Peking University, Peking, China (2018)
21. Ultrafast optoelectronic response in graphene-silicon p-i-n junctions, 7th conference on Advances in Optoelectronics and Micro/nano-optics, Xi’an, China (2018)
22. Hybrid silicon photonics for space communication and sensing, Goddard Space Flight Center, Greenbelt, MD (2018)
23. Ultrafast optoelectronic response in graphene-silicon p-i-n junctions, Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD (2017)

D.6 Media Reports

- 04/18/2022: Nature portfolio community discusses the integrated metasurface system as a new way of composing integrated photonics
https://engineeringcommunity.nature.com/posts/emergence-of-intelligence-with-complexity-in-integrated-optical-system

- 04/15/2022: AIM photonics shares our recent work on Space test of photonic integrated circuits
https://www.aimphotonics.com/news-events-courses/aim-photonic-integrated-circuits-tested-in-space

- 7/18/2020: Group’s NASA project is highlighted on a Udaily article:
https://www.udel.edu/udaily/2020/july/mars-space-exploration-astronomy-physics-rover-nasa/

- 5/5/2020: Gu receives ARO Young Investigator Award
https://www.udel.edu/udaily/2020/july/tingyi-gu-army-research-office-young-investigator-program/

- 11/14/2019: Tiantian, Zi and Dun's works are highlighted on UD EE CURRENTS
https://issuu.com/udengineering/docs/2019_ecurrents_issuu?fr=sYTVlMjUxNjc5MQ

- 10/21/2019: Our graphene and silicon photonic devices are scheduled for launch to ISS from

Wallops Flight Facility. Our work is highlighted on NASA EPSCoR ISS Stimuli.
https://www.nasa.gov/sites/default/files/atoms/files/epscor_stimuli_iss_508.pdf

- 9/26/2019: Graduate student Zi Wang's work on on-chip metasurface is reported by UDaily, IEEE spectrum, Phys.org, Newswise, ScienceDaily, nanowerk
https://www.udel.edu/udaily/2019/september/tingyi-gu-integrated-photonics-nature-communications/
https://spectrum.ieee.org/nanoclast/semiconductors/optoelectronics/microsize-lens-pushes-photonics-closer-to-an-onchip-future
https://phys.org/news/2019-09-team-photonics.html
https://www.newswise.com/articles/compute-at-the-speed-of-light
https://www.sciencedaily.com/releases/2019/09/190926122028.htm
https://www.nanowerk.com/nanotechnology-news2/newsid=53680.php

- 3/28/2019: Group's works on high-speed graphene silicon photonic devices are highlighted on UDaily, ScienceDaily, Phys.org, nano werk, rdmag, sohu
https://www.udel.edu/udaily/2019/march/tingy-gu-silicon-graphene-devices/?utm_source=UDaily+Subscribers&utm_campaign=a12a6e4f8f-UDaily_News_Email&utm_medium=email&utm_term=0_0b5034716d-a12a6e4f8f-177532417&fbclid=IwAR2E1fC4vo3OcXZsIk9Z_n3RbrziBGzhY8Er1G6rHlVBpM7NbQ-t4lS-bm8
https://www.sciencedaily.com/releases/2019/03/190329134756.htm
https://phys.org/news/2019-03-explores-graphene-silicon-devices-photonics-applications.html
https://www.nanowerk.com/nanotechnology-news2/newsid=52468.php?utm_source=feedblitz&utm_medium=FeedBlitzRss&utm_campaign=nanowerkemergingtechnologiesnews
https://www.rdmag.com/news/2019/03/research-probes-graphene-silicon-devices-photonics-applications
https://m.sohu.com/a/304579831_313834/?pvid=000115_3w_a

- 10/19/2018: Work with undergraduate students on sending integrated photonic device to space
https://www.ece.udel.edu/news/2018/rocket-launch/

- 08/15/2017: Gu receives NASA Early Career Faculty Award
https://www.udel.edu/udaily/2017/august/tingyi-gu-nasa-grant-photonic-devices/
https://www.nasa.gov/directorates/spacetech/strg/ecf17

- 11/02/2017: Gu receives AFOSR Young Investigator Award
https://www.udel.edu/udaily/2017/november/tingyi-gu-air-force-investigator-award/
https://www.wpafb.af.mil/News/Article-Display/Article/1339310/afosr-awards-grants-to-43-scientists-and-engineers-through-its-young-investigat/