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From Direct Optical to Field-Induced Modulation of Photonic Modes Enabled by Novel 2D Materials

Sorger, Volker
THE GEORGE WASHINGTON UNIVERSITY
2121 I ST NW STE 601
WASHINGTON, DC,
US

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14. ABSTRACT
The researchers discovered a new way to engineer optoelectronic devices by stretching a two-dimensional material on top of a silicon photonic platform. Using this method, coined strainoptronics by a team led by George Washington University Professor Volker J. Sorger, the researchers demonstrated for the first time that a 2D material wrapped around a nanoscale silicon photonic waveguide creates a novel photodetector that can operate with high efficiency at the technologycritical wavelength of 1550 nanometers. Such new photodetection can advance future communications and computer systems, especially in emerging areas such as machine learning and artificial neural networks for the Air Force and DOD where SWAP-enhanced systems are critical.

Highlights: • Papers: published 7 journal papers, • Patents: filed 3 patents • Honors: o Sorger: 2019 PECASE - Presidential Early Career Award for Scientists and Engineers o Sorger: Fellow Distinction OPTICA (former OSA) o Sorger: Fellow Distinction SPIE • Training/Outreach o Held Cleanroom Hands-on training class at GW (Fall 2017/18/19). This year we are developing Si and SiN photonic structures and plasmonic devices. Students learn and operate all cleanroom tools, and characterize their fabricated devices using electronic and opto-electronic probe stations. Successfully recruited 4 MS students using this path into PhD-tracks over last 12 months at GW alone. Supported female US-citizen graduate student and recruited female Hispanic US-citizen master student at UCR. o Hispanic UCR graduate student completed journeyman ship at ARL transferring expertise in TMD growth. o 3T: PI served on outreach events such as at the student leadership workshop of SPIE O&P o PI: served at SPIE Scholarship Committee • Community Engagement o Connected with DOD-labs staff towards exploring transitioning paths for our technology such as with Dr. Gregory Garrett (ARL) on joint R&D developments on modulators and photodetectors, and continued collaboration with Dr. Madan Dubey and his group at ARL on MoS2 GaN integration similar to the MoS2 SiN integration of this project (see image below) o Established NDAs with… Northrop Grumman Aerospace Systems: NEXT R&D Division BAE Information and Electronics Systems Integration Inc. NIST Gaithersburg: Dr. Albert Davydov, Dr. Kartik A. Srinivasan Mayo Clinic, Special Purpose Processor Development Group Singapore University for Technology and Design o PI served as the Editor-in-Chief of Nanophotonics. Raised impact factor of the journal to a competitive IF = 8.5 over last 12 months. PI became OPTICA Associate Editor. o PI is DC photonics student chapter advisor for OSA & SPIE. o Spin-off: Sorger establishes a SME company: Optelligence LLC

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Year-3 Final Report

From Direct Optical to Field-Induced Modulation of Photonic Modes

PI: Volker J. Sorger

Co-PI: Ludwig Bartels

for

Dr. Gernot Pomrenke (AFOSR)

Reporting Period: 8/1/2017 to 9/29/2020

EXECUTIVE SUMMARY

- **Papers:** published 7 journal papers,
- **Patents:** filed 3 patents
- **Honors:**
  - *Sorger*: 2019 PECASE - Presidential Early Career Award for Scientists and Engineers
  - *Sorger*: Fellow Distinction OPTICA (former OSA)
  - *Sorger*: Fellow Distinction SPIE
- **Training/Outreach**
  - Held Cleanroom Hands-on training class at GW (Fall 2017/18/19). This year we are developing Si and SiN photonic structures and plasmonic devices. Students learn and operate all cleanroom tools, and characterize their fabricated devices using electronic and opto-electronic probe stations. Successfully recruited 4 MS students using this path into PhD-tracks over last 12 months at GW alone. Supported female US-citizen graduate student and recruited female Hispanic US-citizen master student at UCR.
  - Hispanic UCR graduate student completed journeyman ship at ARL transferring expertise in TMD growth.
  - 3T: PI served on outreach events such as at the student leadership workshop of SPIE O&P
  - PI: served at SPIE Scholarship Committee
- **Community Engagement**
  - Connected with DOD-labs staff *towards exploring transitioning paths* for our technology such as with Dr. Gregory Garrett (ARL) on joint R&D developments on modulators and photodetectors, and continued collaboration with Dr. Madan Dubey and his group at ARL on MoS2 GaN integration similar to the MoS2 SiN integration of this project (see image below)
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  - PI is DC photonics student chapter advisor for OSA & SPIE.
  - Spin-off: Sorger establishes a SME company: Optelligence LLC

Highlight – *Strainoptronics: 2D Materials with a Twist*

SUMMARY

Researchers discovered a new way to engineer optoelectronic devices by stretching a two-dimensional material on top of a silicon photonic platform. Using this method, coined *strainoptronics* by a team led by George Washington University Professor Volker J. Sorger, the researchers demonstrated for the first time that a 2D material wrapped around a nanoscale silicon photonic waveguide creates a novel photodetector that can operate with high efficiency at the technology-critical wavelength of 1550 nanometers. Such new photodetection can advance future communications and computer systems, especially in emerging areas such as machine learning and artificial neural networks for the Air Force and DOD where SWAP-enhanced systems are critical.

THE SITUATION

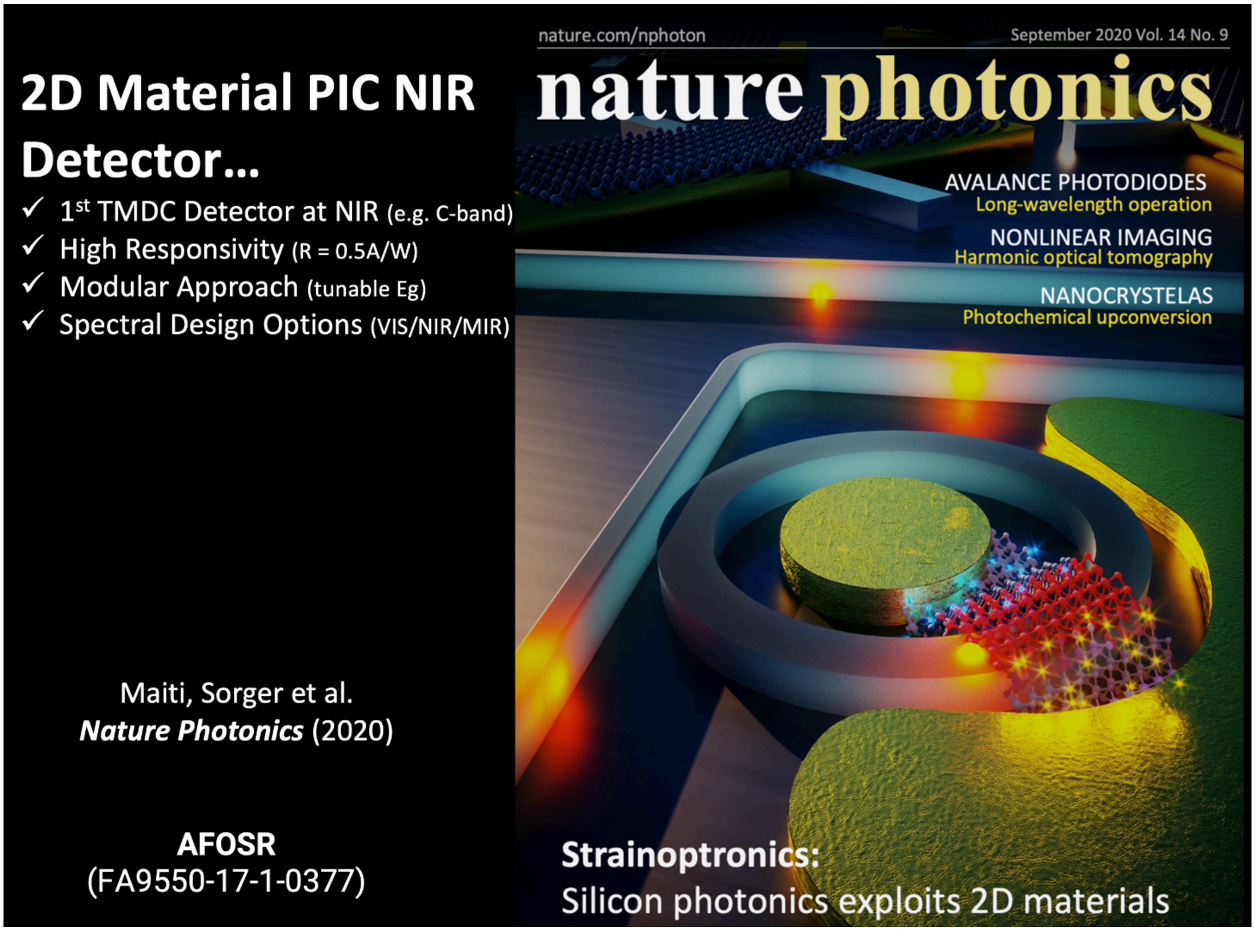
The ever-increasing data demand in DOD's network-centric warfare along with the looming AI-warfare and general modern societies requires a more efficient conversion of data signals in the optical domain, from fiber optic internet to network-edge devices such as RF-receivers or 5+G smartphones. This conversion process from optical to electrical signals is performed by a photodetector, a critical building block in optical networks. 2D materials have scientific and technologically relevant properties for photodetectors; because of their strong optical absorption, designing a 2D material-based photodetector would enable an improved photo-conversion, and hence more efficient data transmission and tensor-operation such as for synaptic weighting in neural networks. However, 2D semiconducting materials, such as those from the family of transition metal dichalcogenides, have, so far, been unable to operate efficiently at telecommunication wavelengths because of their large optical bandgap and low absorption.

THE SOLUTION

Strainoptronics provides a solution to this shortcoming and adds an engineering tool for researchers to modify the electrical and optical properties of 2D materials, and thus the pioneered 2D material-based photodetectors.
Realizing the potential of strainoptronics, the researchers stretched an ultrathin layer of molybdenum telluride, a 2D material semiconductor, on top of a silicon photonic waveguide to assemble a novel photodetector. They then used their newly created strainoptronics "control knob" to alter its physical properties to shrink the electronic bandgap, allowing the device to operate at near infrared wavelengths, namely at the telecommunication (C-band) relevant wavelength around 1550 nm.

The researchers noted one interesting aspect of their discovery: the amount of strain these semiconductor 2D materials can bear is significantly higher when compared to bulk materials for a given amount of strain. Indeed, these novel 2D material-based photodetectors are 1,000 times more sensitive compared to other photodetectors using graphene. Photodetectors capable of such extreme sensitivity are useful not only for data communication applications but also for medical sensing and possibly even quantum information systems – all paving a way for Information dominance for the Air Force and DOD ecosystem.

Reference: Maiti, Sorger et al. "Strain-Engineered High Responsivity $MoTe_2$ Photodetector for Silicon Photonic Integrated Circuits ***Nature Photonics***, doi.org/10.1038/s41566-020-0647-4 (2020).



Caption: Strainoptronics – 2D Materials with a twist. Bending or straining 2D materials enables to change their bandgap. Here, researchers lowered the bandgap of $MoTe_2$ such that it can absorb light of telecommunication frequencies. That way, researchers demonstrated the first efficient 2D photodetector integrated onto silicon photonics chips operating in the C-band. Ref: Maiti, Sorger, et al. ***Nature Photonics*** (2020).

A. MAJOR GOALS & DELIVERABLES

We progressed in respect to experimentally fabricating, testing, and demonstrating a number of functional opto-electronic devices to include a) electro-optic modulators, and b) photodetectors using a variety of 2D materials and photonic structures. The latter included i) Silicon photonics structures, ii) SiN photonics that we developed in year-2 partially using cleanroom resources of the Molecular Foundry at LBNL, iii) foundry-tapeout devices towards creating a bond and link with industry, iv) straight waveguides and optical ring-resonator cavities.

With respect to the goals, we completed (or partially completed) the following statements-of-work (SOW) from the proposed grant: In **year 1&2,** i.e. the 2018/19 reports these included: 1,2,3,(4),(5),6,7,8,(9),(10). Brackets denote work-in-progress. In **year 3**, we focused on high-speed measurements of the various photodetectors and modulator devices, and focus on all-optical device as well. We did start with all-optical devices already, demonstrating two-photon absorption nonlinearity in passive Gold optical nanoantenna arrays, where we integrated epsilon-near-zero (ENZ) materials, which was not part of this project however. We also initiated a collaboration with Prof. Kinsey (VCU) towards modeling the all-optical nonlinearity of free-carrier-based material systems such given by contributions from both inter- and intraband carriers as well as mobility and pump power. We further discussed our results of the MoTe2 EAM with Prof. Reed (Stanford) to understand a) the observed hysteresis, as well as the physical underlying effect of the OE modulation. From the 6 possible effects electro-optic modulation effects (phase change, Pockels, free-carrier, exciton, Franz-Keldysh, and QCSE) we can rule out 4 at this time, and are considering now both the exciton dissociation effects as well as free-carrier dispersion. The hysteresis is most likely due to charge-state trapping in the $MoTe_2$-oxide interfaces (e.g. similar to a FLASH memory floating gate). Using these results as a foundation, we now proceed to integrating 2D materials into these array's to tailor their response. Note, for task 8-10, we do have initial results actually, such as two exciton based photodetectors and one EA modulator, yet they are not published yet. Detailed accomplishments are discussed in the next section, and this pdf report. For the remaining year, we will continue to focus on measuring and experimentally testing these devices and drive them towards publication and possible transition paths with the DOD labs. In fact, we spoke with several DOD lab researchers at the recent summer conferences already, such as at IEEE RAPID.

SOWs from Project Grant

1. Growth a pre-selected number of TMD materials directly on SOI/SiN platform. Explore substrate compatibility.
2. Demonstrate TMD growth patterning techniques for selective spatial localization towards ease in device integration.
3. Characterize TMD defects with respect to growth/substrate/post-growth-treatment/device operation. Use of FIB, Raman, PL, Lifetime, TEM, atom-field-probe.
4. Modeling of optical parameters relevant for electro-optic modulators (EOM), and all-optical switches (AOS) to include optical overlap factors, material index change (upon modulation), modal group index, optical cavity (Purcell effect), device scaling.
5. Modeling of electrical and optical performance impact on EOM and AOS to include optical power penalty, electrical power dissipation, RC delays and resistance effects, and cavity lifetime considerations.
6. Modeling of all-optical switches based on 2nd order nonlinear susceptibility leading to cavity bistability including cavity-to-waveguide coupling, and $\chi^{(2)}$ nonlinearity threshold power by applying the Wigner quasi probability to analyze the characteristics of the 2nd harmonic cavity mode with stochastic processes to obtain the time dependent power distributions, threshold power, and temporal response of the AOS.
7. Derive an energy-per-bit model for AOS and EOM based on pertinent parameters. Model and analyze cavity impact on switching performance towards atto-Joule/bit device performance.

8. Study (theoretically/experimentally) material and switching mechanisms to include exciton, free-carrier (Drude), and phase-change effects.
9. Fabricate, demonstrate and verify cavity-based AOS and EOM switching devices deploying 2D materials as the active switching material in a Silicon-SiN photonic platform.
10. Demonstrate the first AOS or EOM based using a TMD switching mechanism towards 100's of aJ/bit modulation performance.

B. MAJOR ACCOMPLISHMENTS/SIGNIFICANT RESULTS

1) 2D Material Fundamentals & Test-capability Developments:

- Strong evidence of collective polaritonic mode in multi-layer WS_2 layers coupled to plasmonic lattice
- Developed new equations of motion approach to explain the effect of exciton-exciton interactions on the formation of the collective polaritonic mode.
- Used the collective modes to fabricate an electrically tunable polaritonic waveguide.
- Developed semi-analytical method to determine optical index of micrometer small 2D material flakes using integrated photonic ring-resonators
- Developed method for preparing devices (ring-based) into critical coupling condition via tuning the ring's resonance using 2D materials.
- Performed micrometer small ellipsometry on 2D material flakes (with Accurion Inc). This allows to obtain the optical indices (dispersion) of the actual flake used in the device.
- Achieved CVD integration of MoS2 into waveguides avoiding non-scalable material transfer.
- Developed transition-metal-trichalcogenide-based wires for scalable contacts.

2) Modulator Demonstrations:

- Demonstrated 1st photonic ITO-based MZI modulator with in Silicon photonics (VpL=0.52Vmm)
- Demonstrated 1sthybrid plasmon ITO-based MZI modulator (VpL=0.09Vmm)
- Demonstrated 1st plasmonic ITO-based MZI modulator with lateral biasing (VpL=0.06Vmm)
- Demonstrated 1st dual-ITO-gated photonic modulator synergistically using KK-relations (ER/V = 0.75dB/V)
- Demonstrated 1st TMD material integrated phase-change material based modulator in Si-Photonics.
- Demonstrated 1st TMD material electro-absorption modulator in Silicon Photonics.

3) Photodetector Demonstrations:

- Demonstrated 1st Graphene plasmon slot detector in Si-Photonics (R=0.7A/W, R = responsivity).
- Demonstrated 1st TMD material microring resonator (Si-Photonics) detector using strain engineering. (R=0.5A/W, NEP = 90 pW/Hz$^{0.5}$, f_{3dB} = 35 MHz)
- Demonstrated 1st near-exciton TMD detector in Si-Photonics (R~0.5-1A/W)
- Demonstrated 1st ON-exciton plasmon slot TMD detector in Si-Photonics with record-high responsivity (R=1.36A/W)

Below for more details including figures, paper citations, and summaries.

C. SCHOLARLY WORK/OUTPUT SUMMARIES

PART A = Published and Submitted Work

(Journal Paper 1) Microring Resonators Coupling Tunability by Heterogeneous 2D Material Integration (Fig. 1) Note, this paper was mentioned in the 2018 report, but was not published at that time, now it is.

Abstract: Layered two-dimensional (2D) materials provide a wide range of unique properties as compared to their bulk counterpart, making them ideal for heterogeneous integration for on-chip interconnects. Hence, a detailed understanding of the loss and index change on Si integrated platform is a prerequisite for advances in opto-electronic devices impacting optical communication technology, signal processing, and possibly photonic-based computing. Here, we present an experimental guide to characterize transition metal dichalcogenides (TMDCs), once monolithically integrated into the silicon photonic platform at 1.55 µm wavelength. We describe the passive tunable coupling effect of the resonator in terms of loss induced as a function of 2D material layer coverage length and thickness. Further, we demonstrate a TMDC-ring based hybrid platform where resonance shift has been mapped out as a function of flake thickness, which correlates well with our simulated data. These experimental findings on passive TMDC-Si hybrid platform open up a new dimension by controlling the effective change in loss and index, which may lead to the potential application of 2D material based active on chip photonics.

Reference: R. Maiti, C. Patil, R. Hemnani, M. Miscuglio, R. Amin, Z. Ma, R. Chaudhary, C. Johnson, L. Bartels, R. Agarwal, V. J. Sorger, "Loss and Coupling Tuning via Heterogeneous Integration of MoS_2 Layers in Silicon Photonics", **Optics Materials Express**, 9, 2. (2018)

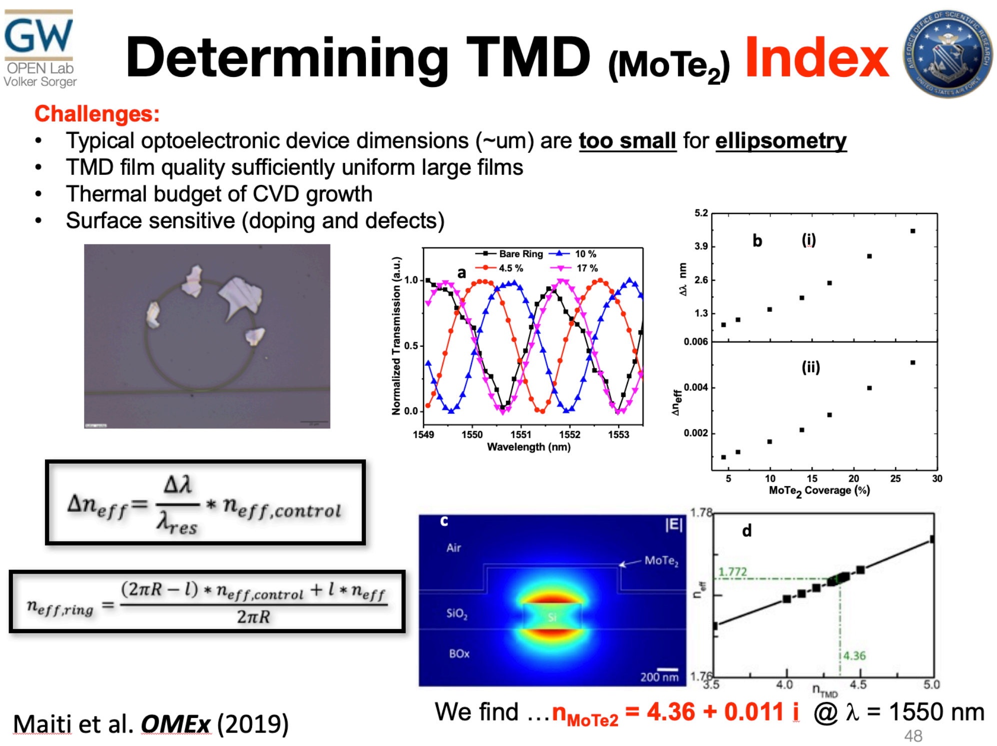


Figure 1. Here we then use the 2D printer and demonstrate passive (placement) tuning of microring cavities. We demonstrate precise control from under- over critical, to overcoupling regimes when placing 2D materials on top of the ring with high accuracy and coverage length. Note this paper was mentioned in the 2018 report, but was not published at that time, now it is.

(Journal Paper 2) Microring Resonators Coupling Tunability by Heterogeneous 2D Material Integration (Fig. 2) Note, this paper was mentioned in the 2018 report, but was not published at that time.

Abstract: Atomically thin 2D materials such as transition metal dichalcogenides (TMDs) provide a wide range of basic building blocks with unique properties, making them ideal for heterogeneous integration with a mature chip platform for advances in optical communication technology. The control and understanding of the precise value of the optical index of these materials, however, is challenging, as the standard metrology techniques such as the millimeter-large ellipsometry is often not usable due the small lateral 2D material flake dimension. Here, we demonstrate an approach of passive tunable coupling by integrating few layers of MoTe2 onto a microring resonator connected to a waveguide bus. We find the TMD-to-ring circumference coverage length ratio required to precisely place the ring into a critical coupling condition to be about 10% as determined from the variation of spectral resonance visibility and loss as a function of TMD coverage. Using this TMD-ring heterostructure, we further demonstrate a semiempirical method to determine the index of a 2D material (nMoTe2 of 4.36 + 0.011i) near telecommunication-relevant wavelength. The placement, control, and optical property understanding of 2D materials with integrated photonics pave the way for further studies of active 2D material-based optoelectronics and circuits.

Reference: R. Maiti, R. A. Hemnani, R. Amin, Z. Ma, M. H. Tahersima, T. A. Empante, H. Dalir, R. Agarwal, L. Bartels and V. J. Sorger, "A semi-empirical integrated microring cavity approach for 2D material optical index identification at 1.55 µm", **Nanophotonics**, 8(3) (2019).

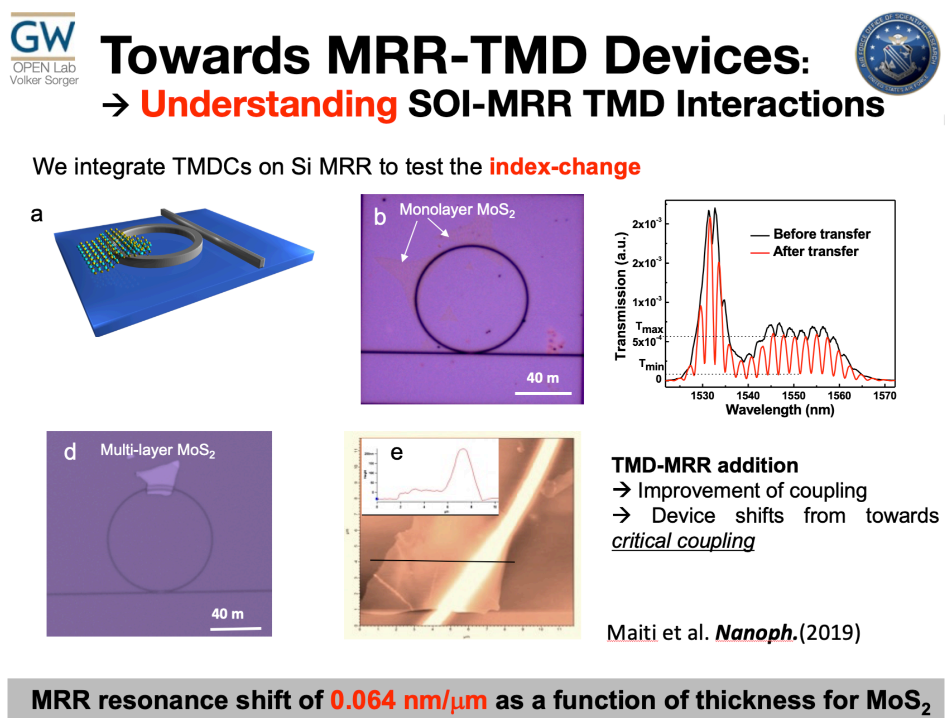


Figure 2. Here we then use the 2D printer and demonstrate passive (placement) tuning of microring cavities. We demonstrate precise control from under- over critical, to overcoupling regimes when placing 2D materials on top of the ring with high accuracy and coverage length. Note, this paper was mentioned in the 2018 report, but was not published at that time, now it is.

(Journal Paper 3) 0.52 V·mm ITO-based Mach-Zehnder Modulator in Silicon Photonics (Fig. 3) Note, this paper was mentioned in the 2018 report, but was not published at that time, now it is.

Abstract: Electro-optic modulators transform electronic signals into the optical domain and are critical components in modern telecommunication networks, RF photonics, and emerging applications in quantum photonics, neuromorphic photonics, and beam steering. All these applications require integrated and voltage-efficient modulator solutions with compact form factors that are seamlessly integrable with Silicon photonics platforms and feature near-CMOS material processing synergies. However, existing integrated modulators are challenged to meet these requirements. Conversely, emerging electro-optic materials heterogeneously and monolithically integrated with Si photonics open up a new avenue for device engineering. Indium tin oxide (ITO) is one such compelling material for heterogeneous integration in Si exhibiting formidable electro-optic effect characterized by unity-order index change at telecommunication frequencies. Here we overcome these limitations and demonstrate a monolithically integrated ITO electro-optic modulator based on a Mach Zehnder interferometer (MZI) featuring a high-performance half-wave voltage and active device length product of $V_{\pi}L$ = 0.52 V·mm. We show, that the unity-strong index change enables a 30 micrometer-short π-phase shifter operating ITO in the index-dominated region away from the epsilon-bear-zero ENZ point for reduced losses. This device experimentally confirms electrical phase shifting in ITO enabling its use in applications such as dense on-chip communication networks, nonlinearity for activation functions in photonic neural networks, and phased array applications for LiDAR.

Reference: R. Amin, R. Maiti, C. Carfano, Z. Ma, M. H. Tahersima, Y. Lilach, D. Ratnayake, H. Dalir, H. Dalir, V. J. Sorger, "0.52 V-mm ITO-based Mach-Zehnder Modulator in Silicon Photonics", ***APL Photonics* 3**, 126104 (2018).

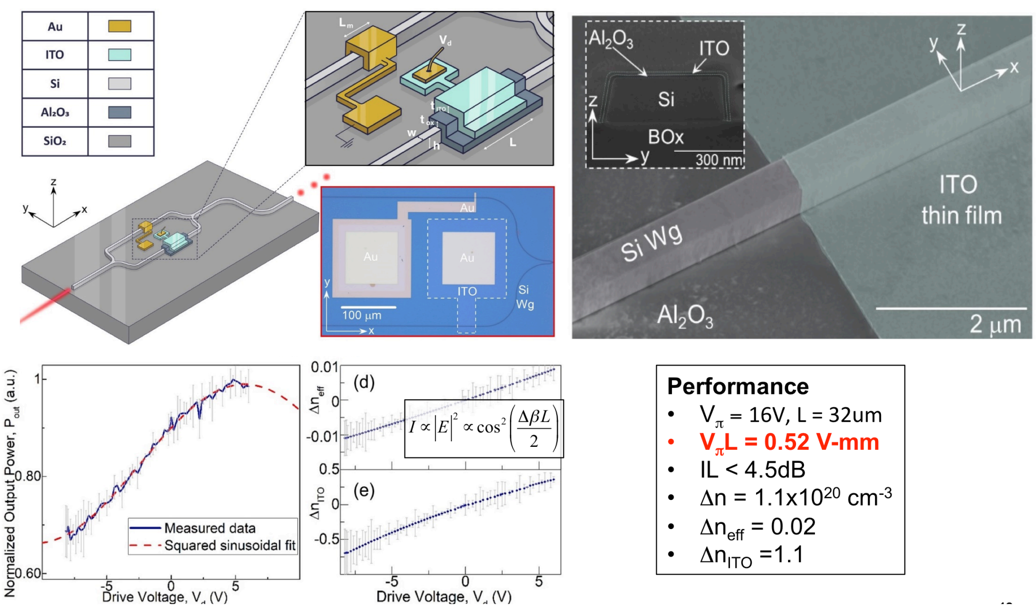


Figure 11. First demonstration of an ITO-based Silicon MZI modulator. Paper to be accepted at APL Photonics. The device shows a high performance of VπL = 0.52V-mm. Note, this is not an ENZ device, since ENZ bears too much loss. In a phase shifter we want to stay away from ENZ to maximize the dn/dκ, as realized here. Note, this paper was mentioned in the 2018 report, but was not published at that time, now it is.

(Journal Paper 4) Coupling-enhanced dual ITO layer electro-absorption modulator in silicon photonics (Fig. 4)

Abstract: Electro-optic signal modulation provides a key functionality in modern technology and information networks. Photonic integration has not only enabled miniaturizing photonic components, but also provided performance improvements due to co-design addressing both electrical and optical device rules. The millimeter to centimeter footprint of many foundry-ready electro-optic modulators, however, limits density scaling of on-chip photonic systems. To address these limitations, here we experimentally demonstrate a coupling-enhanced electro-absorption modulator by heterogeneously integrating a novel dual-gated indium-tin-oxide phase-shifting tunable absorber placed at a silicon directional coupler region. This concept allows utilizing the normally parasitic Kramers-Kronig relations here in an synergistic way resulting in a strong modulation depth to insertion loss ratio of about 1. Our experimental modulator shows a 2 dB extinction ratio for a just 4 µm short device at 4 V bias. Since no optical resonances are deployed, this device shows spectrally broadband operation as demonstrated here across the entire C-band. In conclusion, we demonstrate a modulator utilizing strong index change from both real and imaginary parts of active material enabling compact and high-performing modulators using semiconductor near-foundry materials.

Reference: M. H. Tahersima, Z. Ma, Y. Gui, S. Sun, R. Amin, H. Dalir, R. Chen, M. Miscuglio, V. J. Sorger, "Coupling-enhanced Dual ITO Layer Electro-absorption Modulator in Silicon Photonics", ***Nanophotonics***, pre-print, doi:10.1515/nanoph-2019-0153 (2019).

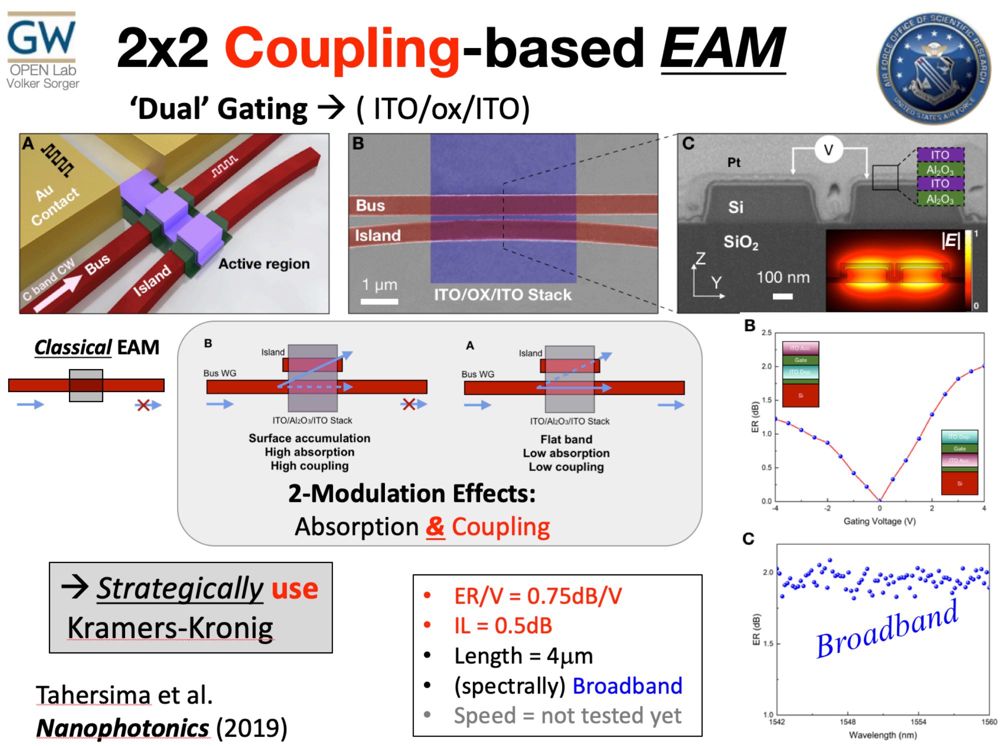
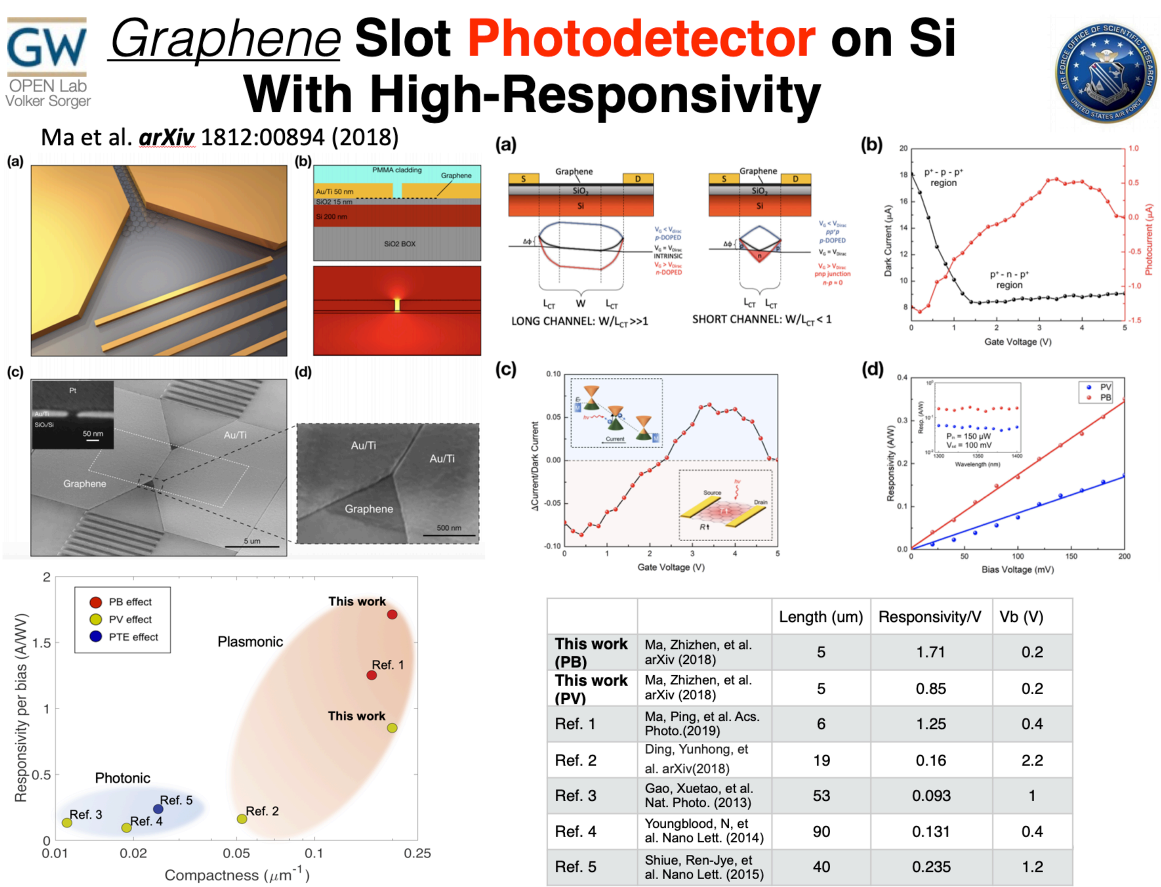


Figure 4. We introduce and experimentally demonstrate a novel coupling-enhanced dual-gated ITO modulator heterogeneously integrated at the coupling regime between a silicon waveguide bus and a short coupling island. We show that for our coupling-enhanced electro-absorption modulator, both the real and imaginary index modulation of this ITO/oxide/ITO stack synergistically contribute towards the modulation, thus exploiting the Kramers-Kronig relations synergistically. This way we experimentally achieve a 2 dB ER modulation while being 4 µm compact (0.5 dB/µm) with an IL of 2 dB (ER/IL=1) for 4 V of applied bias. We verify a flat spectral response across the C-band frequencies since neither optical nor material resonances are needed in this device configuration. The design features careful process control to enable an ITO material away from the ENZ point at light ON state to reduce losses while demonstrating a near-unity ITO EO index change under modulation. Taken together, the heterogeneous integration of an emerging EO material, ITO, which is commonly used in the semiconductor industry, offers positive device synergies demonstrating a compact coupling-enhanced modulator on a silicon photonic platform

(Journal Paper 5) Compact Graphene Plasmonic Slot Photodetector on Silicon-on-insulator with High Responsivity (Fig.5)

Abstract: Graphene has extraordinary electro-optic properties and is therefore a promising candidate for monolithic photonic devices such as photodetectors. However, the integration of this atom-thin layer material with bulky photonic components usually results in a weak light-graphene interaction leading to large device lengths limiting electro-optic performance. In contrast, here we demonstrate a plasmonic slot graphene photodetector on silicon-on-insulator platform with high-responsivity given the 5 μm-short device length. We observe that the maximum photocurrent, and hence the highest responsivity, scales inversely with the slot gap width. Using a dual-lithography step, we realize 15 nm narrow slots that show a 15-times higher responsivity per unit device-length compared to photonic graphene photodetectors. Furthermore, we reveal that the back-gated electrostatics is overshadowed by channel-doping contributions induced by the contacts of this ultra-short channel 2 graphene photodetector. This leads to quasi charge neutrality, which explains both the previously-unseen offset between the maximum photovoltaic-based photocurrent relative to graphene's Dirac point and the observed non-ambipolar transport. Such micrometer compact and absorption-efficient photodetectors allow for short-carrier pathways in next generation photonic components, while being an ideal testbed to study short-channel carrier physics in graphene optoelectronics.

Reference: Z. Ma, K. Kikunage, H. Wang, S. Sun, R. Amin, M. Tahersima, M. Miscuglio, H. Dalir, V. J. Sorger, "Compact Graphene Plasmonic Slot Photodetector on Silicon-on-insulator with High Responsivity", arXiv, 1812.00894 (2018).



		Length (um)	Responsivity/V	Vb (V)
This work (PB)	Ma, Zhizhen, et al. arXiv (2018)	5	1.71	0.2
This work (PV)	Ma, Zhizhen, et al. arXiv (2018)	5	0.85	0.2
Ref. 1	Ma, Ping, et al. Acs. Photo.(2019)	6	1.25	0.4
Ref. 2	Ding, Yunhong, et al. arXiv(2018)	19	0.16	2.2
Ref. 3	Gao, Xuetao, et al. Nat. Photo. (2013)	53	0.093	1
Ref. 4	Youngblood, N, et al. Nano Lett. (2014)	90	0.131	0.4
Ref. 5	Shiue, Ren-Jye, et al. Nano Lett. (2015)	40	0.235	1.2

Figure 5. Device performance. (a) Band diagram for long and short channel device. For the short-channel detector, because of the small W/L$_{ct}$, the charge transfer region has a significant influence inside the channel. (b) Measurement of photocurrent and dark current (I_{sd}) from the photodetector (V_{sd} = 0.1V), the photocurrent changes sign when the photovoltaic effect is stronger than bolometric effect (c) Change of current, two peaks are observed in different polarity for either bolometric effect and PV effect dominant regions, both with a maximum ratio of more than 7% (d) Measured responsivity vs. bias voltage, a linear fit of 1.71A/WV and 0.85A/WV for PB and PV effect is retrieved, respectively. Inset shows a broadband responsivity from 1300 to 1400 nm. The measurement is mainly limited by metallic grating coupler operating wavelength.

(Journal Paper 6) A Lateral MOS-Capacitor Enabled ITO Mach Zehnder Modulator for Beam Steering (Fig. 6)

Abstract: Here, we experimentally demonstrate an Indium Tin Oxide (ITO) Mach-Zehnder interferometer heterogeneously integrated in silicon photonics. The phase shifter section is realized in a novel lateral MOS configuration, which, due to favorable electrostatic overlap, leads to efficient modulation (VπL = 63 V. µm). This is achieved by (i) selecting a strong index changing material (ITO) and (ii) improving the field-overlap as verified by the electrostatic field lines. Furthermore, we show that this platform serves as a building block in an end-fire silicon photonics optical phased array (OPA) with a half-wavelength pitch within the waveguides with anticipated performance, including narrow main beam lobe (<3°) and >10 dB suppression of the side lobes, while electrostatically steering the emission profile up to ±80°, and if further engineered, can lead not only towards nanosecond-fast beam steering capabilities in LiDAR systems but also in holographic display, free-space optical communications, and optical switches.

Reference: R. Amin, R. Maiti, J. K. George, X. Ma, Z. Ma, H. Dalir, M. Miscuglio, V. J. Sorger, "A Lateral MOS-Capacitor Enabled ITO Mach-Zehnder Modulator for Beam Steering" arXiv:1907.11131 (2019).

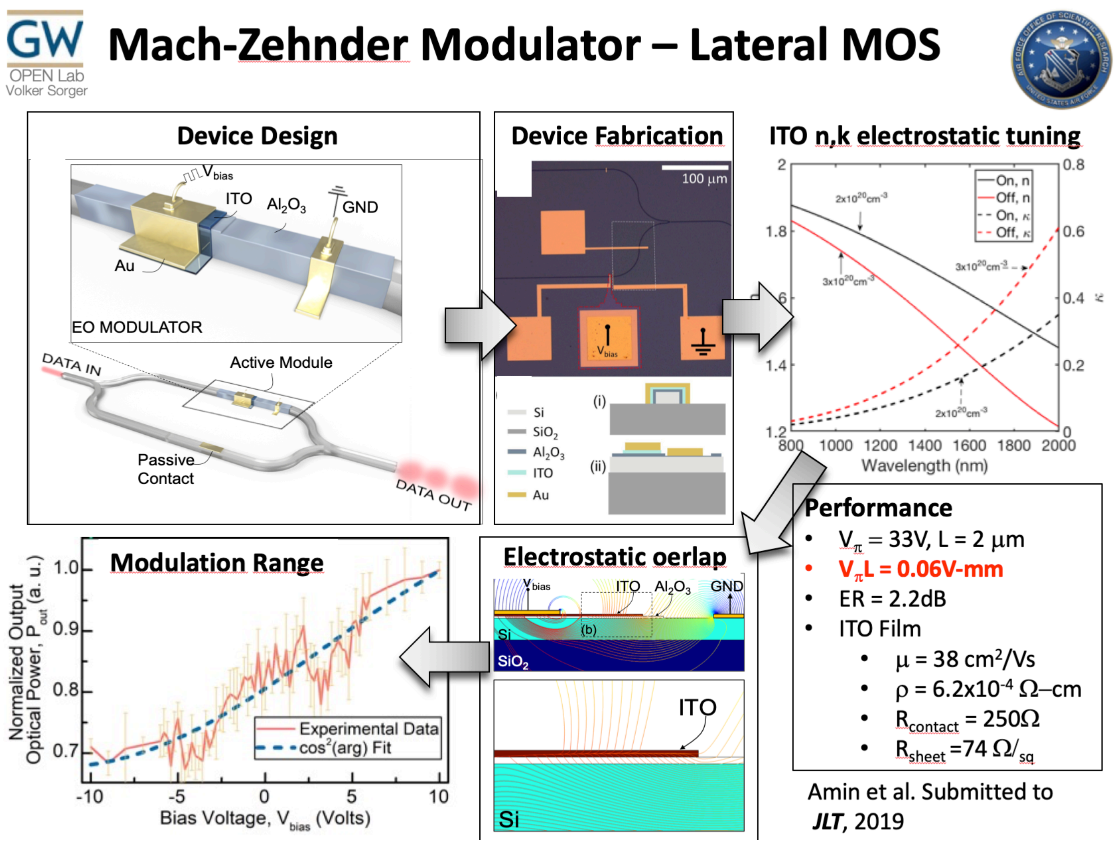


Figure 6: We have hereby demonstrated an MZI ITO-based electro-optic modulator, in a lateral capacitor configuration, which leads to favorable electrostatics and enhance the carrier tunability in the ITO film, thus delivering competitive performance in terms of figure of merit of VπL = 63 V·µm for a <2 µm compact phase shifter. Using this modulator as a phase shifter as a building block of a 128- waveguides end-fire optical phased array beam steering platform, we find a rather fine narrow shaping of the main beam lobe (<3°) and >10 dB suppression of the side lobes, while steering up to ±80° emission profile. This approach has the potential to reduce loss in current OPA design, and yet availing of the ITO GHz-fast modulation speed, for the next generation LiDAR system, holographic display, free-space optical communications, and optical switches.

(Journal Paper 7) Low Resistivity and High Breakdown Current Density of 10-nm Diameter van der Waals $TaSe_3$ Nanowires by Chemical Vapor Deposition (Fig. 7)

Abstract: Micron-scale single-crystal nanowires of metallic $TaSe_3$, a material that forms -Ta-Se_3-Ta-Se_3- stacks separated from one another by a tubular van der Waals (vdW) gap, have been synthesized using chemical vapor deposition (CVD) on a SiO_2/Si substrate, in a process compatible with semiconductor industry requirements. Their electrical resistivity was found unaffected by downscaling from the bulk to as little as 7 nm in nanowire width and height, in striking contrast to the resistivity of copper for the same dimensions. While the bulk resistivity of $TaSe_3$ is substantially higher than that of bulk copper, at the nanometer scale the $TaSe_3$ wires become competitive to similar-sized copper ones. Moreover, we find that the vdW $TaSe_3$ nanowires sustain current densities in excess of 10^8 A/cm^2 and feature an electromigration energy barrier twice that of copper. The results highlight the promise of quasi-one-dimensional transition metal trichalcogenides for electronic interconnect applications and the potential of van der Waals materials for downscaled electronics.

Reference: T.A. Empante, A. Martinez, M. Wurch, Y. Zhu, A. K Geremew, K. Yamaguchi, M. Isarraraz, S. Rumyantsev, E. J. Reed, A. A Balandin, L. Bartels**, Nano Letters** 19, 4355 (2019)

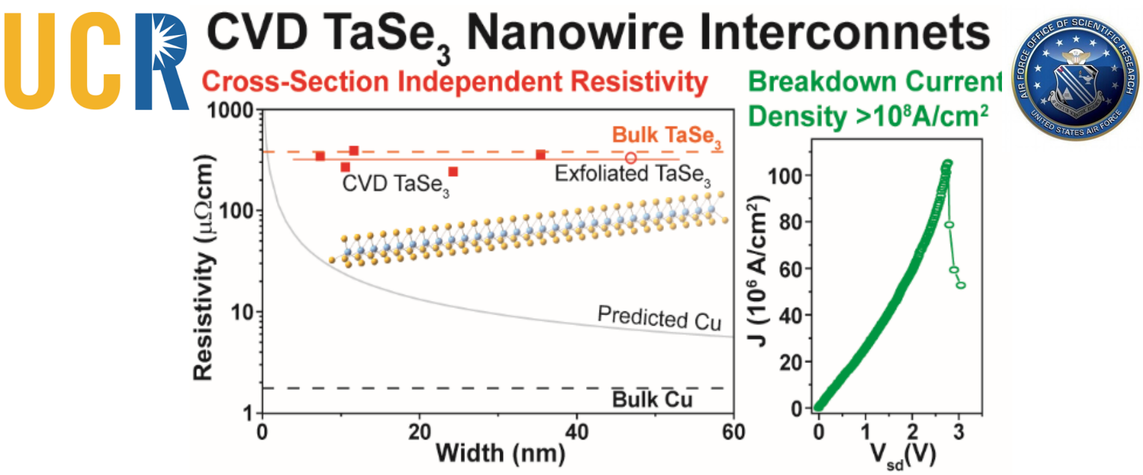


Figure 7: We developed BEOL-compatible CVD growth method for metallic transition metal trichalcogenide (TMT) material that shows scale-independent electrical conductivity, breakdown current 10x that of copper and an electromigration barrier of 2.5 eV, 3x that of copper.

(Paper 9) Graphene- ITO Modulator to mimic Optical ReLU for Neural Networks (Fig. 8)

Abstract: The high demand for machine intelligence of doubling every three months is driving novel hardware solutions beyond charging of electrical wires, given a resurrection to application specific integrated circuit (ASIC)-based accelerators. These innovations include photonic-based ASICs (P-ASICs) due to prospects of performing optical linear (and also nonlinear) operations, such as multiply–accumulate for vector matrix multiplications or convolutions, without iterative architectures. Such photonic linear algebra enables picosecond delay when photonic integrated circuits are utilized via "on-the-fly" mathematics. However, the neuron's full function includes providing a nonlinear activation function, known as thresholding, to enable decision making on inferred data. Many P-ASIC solutions perform this nonlinearity in the electronic domain, which brings challenges in terms of data throughput and delay, thus breaking the optical link and introducing increased system complexity via domain crossings. This work follows the notion of utilizing enhanced light–matter interactions to provide efficient, compact, and engineerable electro-optic neuron nonlinearity. Here, we introduce and demonstrate a novel electro-optic device to engineer the shape of this optical nonlinearity to resemble a leaky rectifying linear unit—the most commonly used nonlinear activation function in neural networks. We combine the counter-directional transfer functions from heterostructures made out of two electro-optic materials to design a diode-like nonlinear response of the device. Integrating this nonlinearity into a photonic neural network, we show how the electrostatics of this thresholder's gating junction improves machine learning inference accuracy and the energy efficiency of the neural network.

Reference: R. Amin, J. K. George, H. Wang, R. Maiti, Z. Ma, H. Dalir, J. B. Khurgin, V. J. Sorger "An ITO-Graphene heterojunction integrated absorption modulator on Si-photonics for neuromorphic nonlinear activation" APL Photonics, doi:10.1063/5.0062830 (2021).

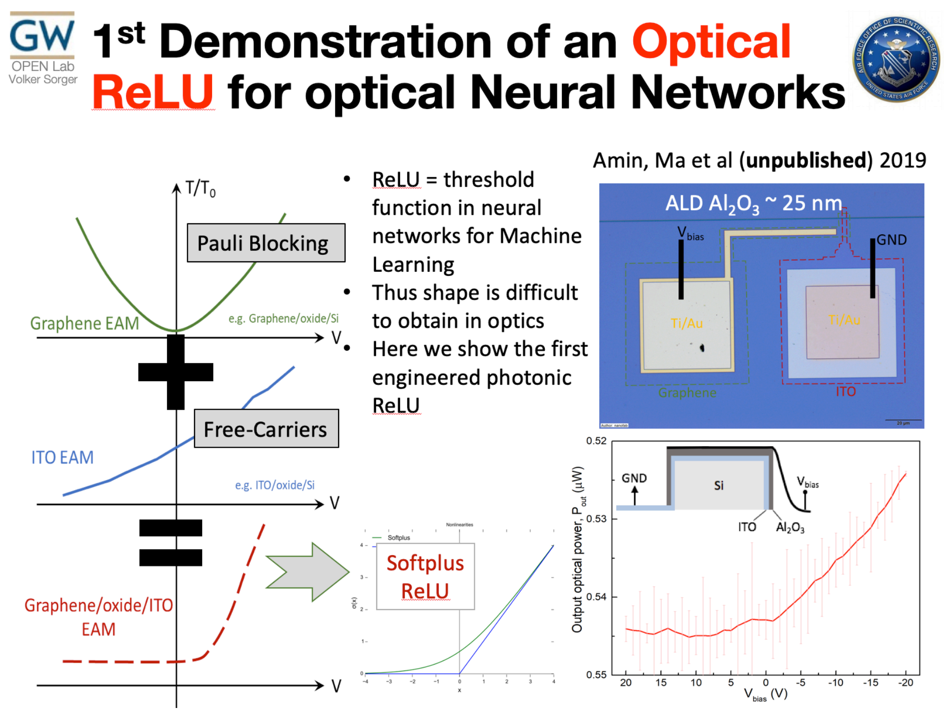


Figure 9. Here we demonstrate an optical version of an optical rectifying linear unit (ReLU) which is the most commonly used nonlinear activation function of neurons. We synergistically combine the two transfer function of Graphene modulators and ITO modulators to engineer this ReLU. We envision to integrate this optical thresholding into photonic integrated neural networks.

PART C = Results on *2D Photodetectors*

Here we showcase ongoing work where we have preliminary results. In all cases we are working on a paper draft and aim to submit the work in the next 2 months (within 2019).

(Paper 10) Strain-Engineered Integrated $MoTe_2$ Photodetector for High Responsivity at 1.55 µm (Fig. 10)

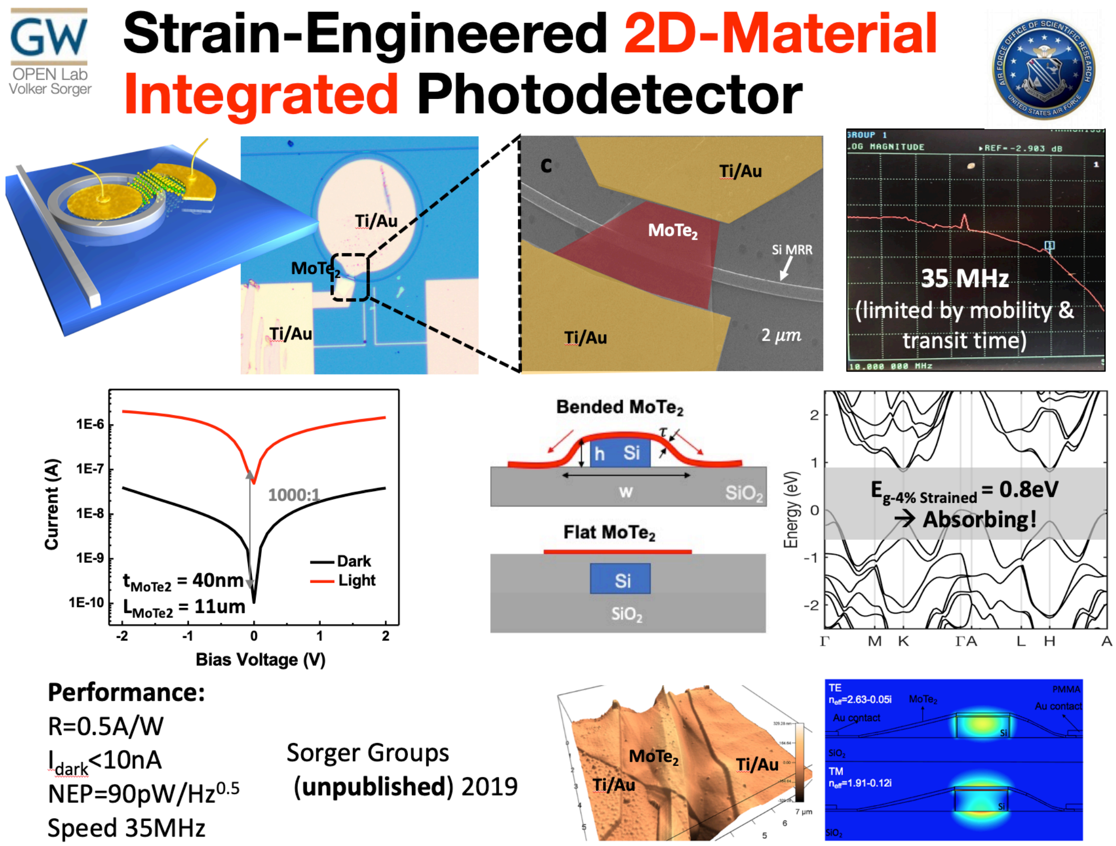


Figure 10. Triggered by the demands for high-performance computing requires much higher bandwidth density for inter-chip communication pushes the limit of device miniaturization. Hence, 2-dimensional (2D) materials have recently emerged as promising building blocks for photonics due to their number of fascinating features. Tuning of electronic band structure by engineering local strain is an exciting avenue for tailoring optoelectronic properties for 2D atomic layered materials. Here, we study the effect of large localized strain in the electronic band structure of a multilayer $MoTe_2$ by wrapping the 2D material around a non-planarized Silicon-on-insulator waveguide etched down to the buried oxide. Interestingly, induced tensile strain (4%) shifts the bandgap of $MoTe_2$ to about 0.8 eV obtained using DFT calculation, thus significantly increasing the absorption as compared to their pristine counterpart of bandgap (~1 eV). Here, the device is realized in a two-terminal in-plane electrode configuration without applying external gating, showing a high responsivity of (~0.5 A/W) and NEP of 90 $pW/Hz^{0.5}$ at -2 V at 1550 nm. Our device demonstrates a response rate of ~35 MHz which is limited by the low mobility (~1 cm^2/Vs) of the $MoTe_2$. The integration of a few-layer $MoTe_2$ on Si MRR as active photodetector is envisaged to offer a potential pathway toward the realization of integrated on-chip interconnects for Telecommunication band.

F. DISSEMINATION

The team is quite active in promoting the work both in person, through group members and online. We published and submitted (publication pending) 7 new papers in the preceding 12 months acknowledging this grant and submitted one new patent to the USPTO on integrated modulators. In addition to featuring our work on the PI's respective websites, we moreover, presented our work at major conferences and topical meetings. This projects work is also featured in a large number (~30) of conference talks and subsequent proceedings over the preceding 12 months, where the joint work on 2D opto-electronic devices and exciton fundamentals were featured. Below a list are (only) ***invited talks*** given by the PIs:

PI Sorger: (titles omitted)

1. SPIE Optics and Photonics, 2020
2. OSA APC, 2020
3. OSA OFC, 2020
4. SPIE, Photonics West, 2020
5. Infrared Terahertz Quantum Workshop (ITQW) (Ojai, Ca, USA) 2019
6. NanoP (Munich, Germany), 2019, 3 Presentations
7. IEEE RAPID, (Miramar, FL, USA), 2019
8. SPIE Optics&Photonics (San Diego, CA, USA), 2019 (2x).
9. OSA Advanced Photonic Congress (San Francisco, CA, USA) 2019.
10. META (Lisbon, Portugal), 2019.
11. IEEE Summer Topicals, (Ft. Lauderdale, FL, USA), 2019.
12. SPIE DCS (Baltimore, MD, USA), 2019.
13. IPS (Singapore, Singapore), 2019.
14. OSA OFC (San Jose, CA, USA), 2019.
15. SPIE Photonics West (San Francisco, CA, USA), 2019, 4x Presentations.
16. N2D Nanophotonics of 2D Materials (Shanghai, China), 2019
17. SPIE Optics&Photonics (San Diego, CA, USA), 2018 (2x).
18. IEEE Summer Topicals, (Waikoloa, Hawaii, USA), 2018.
19. Seminar: NIST (Gaithersburg, MD), 2019.
20. Seminar: IBM, (Zurich, Switzerland), 2019.
21. Colloquium: University of Southern California, (LA, CA, USA), 2019.
22. Seminar: NASA Goddard, (Washington, DC, USA), 2019.
23. Colloquium: University of California Los Angeles, (LA, CA, USA), 2019.
24. Colloquium: POSTECH, (Pohang, South Korea), 2019.
25. Korea-GW Research Symposium, (Seoul, South Korea), 2019.
26. Colloquium: University of California San Diego, (San Diego, CA, USA), 2019.

Co-PI Bartels:

27. Colloquium North Dakota State University (Fargo, ND, USA), 2018
28. Physical Electronics Conference, (Orlando, FL, USA)
29. IWNN (Beijing, China), 2018, 2 Presentations
30. TECHCON (Austin, TX, USA), 2019
31. MRS (Phoenix, AZ, USA), 2019