Photonic, Sensing Devices, and Systems

Ultra-thin, Reconfigurable, High-efficiency Meta-optical Devices in Mid-infrared 57

Reprogrammable Electro-Chemo-Optical Devices 58

Y-Branch Compact Model Including the Line Edge Roughness Effect 59

Particle Defect Yield Modeling for Silicon Photonics 60

See-through Light Modulators for Holographic Video Displays 61

Bio-inspired Photonic Materials: Producing Structurally Colored Surfaces 62

Reversible Electrothermal Switching of Nonvolatile Metasurfaces Based on Optical Phase Change Materials 63

Graphene Microheaters for Controlled Switching of Optical Phase Change Materials 64

Highly Sensitive Nanogap-based Mechanical Sensors for Infrared Detection 65

Oxide Passivation on MoS_2-based Field-effect Transistors for Sensing Applications 66

SynCells - Electronic Microparticles for Sensing Applications 67

Piezoresistive Sensor Arrays and Touch-sensitive Textile for Robot Manipulation and Control 68

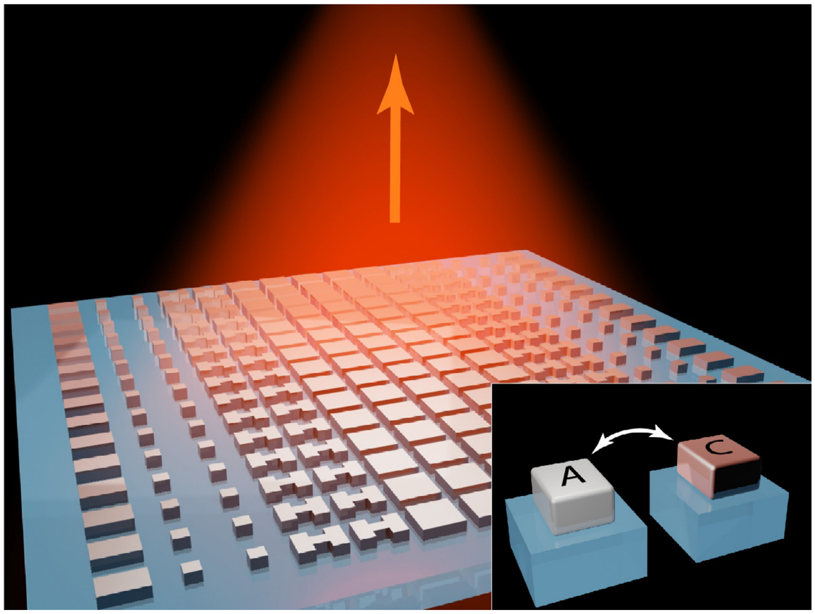
Ultra-thin, Reconfigurable, High-efficiency Meta-optical Devices in Mid-infrared

M. Y. Shalaginov, S. An, Y. Zhang, P. Su, A. Yadav, M. Kang, C. Rios, A. Agarwal, K. Richardson, H. Zhang, T. Gu, J. Hu
Sponsorship: DARPA EXTREME Program

The mid-infrared (MIR) is a frequency band strategically important for numerous biomedical, military, and industrial applications. Further development of MIR devices is hindered by the lack of inexpensive and efficient basic optical elements such as lenses, wave plates, filters, etc. Furthermore, the available components are typically bulky and passive. Our research addresses these challenges by leveraging novel low-loss optical phase-change materials (Ge-Sb-Se-Te) and their sub-wavelength patterning to achieve ultra-thin (thickness <⌊0/5), high-efficiency (>25%), and multi-functional MIR components.

As a proof-of-principle, we demonstrated a reconfigurable bifocal meta-lens with a switchable focus. Our metalens principle is based on collective Mie scattering of incident plane waves by subwavelength dielectric structures, which sustain both electric and magnetic dipolar resonances. Each of the scatterers, also known as Huygens' meta-atoms, contributes to the phase and amplitude of the incident beam. The amount of phase shift was controlled by the meta-atom geometry and its refractive index. Proper spatial arrangement of meta-atoms can reconstruct a desired phase profile. For instance, lens functionality can be achieved by introducing a hyperboloid phase distribution. In amorphous state (A-state) the lens focuses the incident light at a focal length of 1 mm; after the heating-induced material state transition, the focal length changes to 1.5 mm (C-state). The switching of the focal length was attained by changing the hyperboloidal phase profiles.

For simplicity, we performed binary discretization of original continuous phase distributions: 0° and 180° phase shifts. Then, we formed a library of four distinct meta-atoms that can realize the binary transitions. The metalens was fabricated by depositing a 1-m-thick $Ge_2Sb_2Se_4Te_1$ film onto CaF_2 substrate followed by patterning processes involving electron-beam lithography patterning and reactive ion etching with a mixture of fluoromethane gases. We believe that our findings will enable a new range of compact, multi-functional spectroscopic, and thermal imaging devices.



▲ Figure 1: Illustration of reconfigurable meta-lens, with properties that can be switched by transitioning non-volatile phase-change material (GeSbSeTe) from amorphous (A) to crystalline (C) state.

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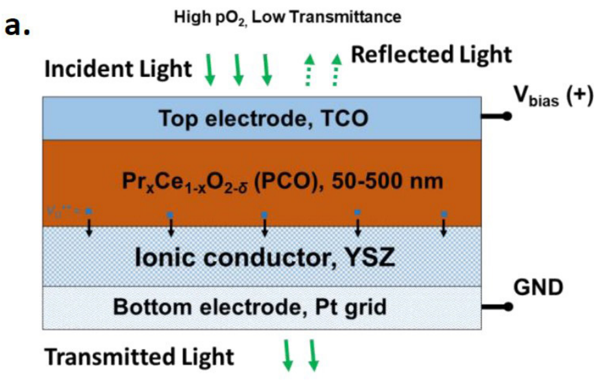
Reprogrammable Electro-Chemo-Optical Devices

D. Kalaev, H. L. Tuller

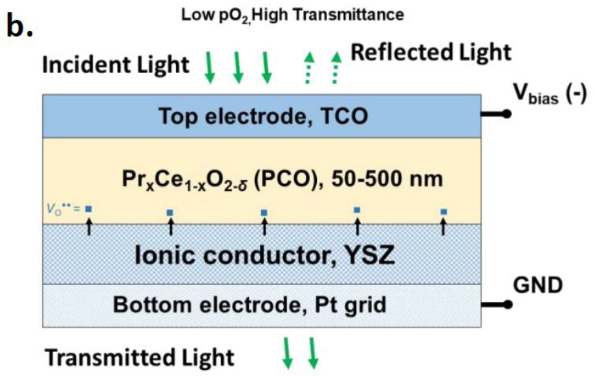
Sponsorship: U.S. Department of Energy, Basic Energy Sciences Program

Photonic devices with programmable properties allow more flexibility in the manipulation of light. Recently, several examples of reconfigurable photonic devices were demonstrated by controlling the local/overall index of refraction in thin films, either by a thermally induced phase change in chalcogenides or by intercalation of lithium into oxides. We propose a novel approach for design of reprogrammable photonic devices based on electrochemical modification of ceria-based electro-chemo-optical devices.

Previously, it was shown that the refractive index of $Pr_xCe_{1-x}O_{2-\delta}$ (PCO) is a function of oxygen nonstoichiometry δ, that can be controlled electrochemically via closely spaced electrodes in a lateral device configuration. For transverse modified configurations, a PCO thin film on yttrium-stabilized zirconia (YSZ) substrate with transparent conducting oxide (TCO) top electrode allows for voltage-controlled oxygen exchange. Enhanced spatial resolution can be further achieved with the aid of lithographically patterned nano-dimensioned oxide layers.



▲Figure 1a: Nonvolatile change in the optical transmission of $Pr_xCe_{1-x}O_{2-\delta}$ (PCO) thin film by electrochemical oxygen pumping. a. Oxygen pumped into the PCO thin film by an applied positive bias, resulting in the low optical transmission.



▲Figure 1b: Oxygen pumped out of the PCO thin film by an applied negative bias, resulting in the high optical transmission.

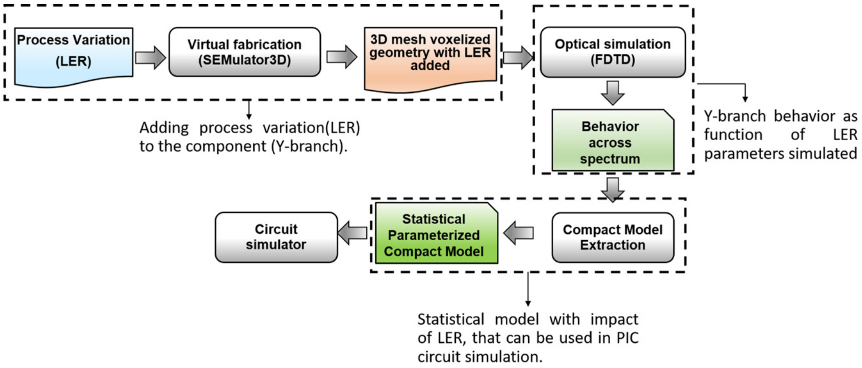
Y-Branch Compact Model Including the Line Edge Roughness Effect

S. I. El-Henawy, D. S. Boning
Sponsorship: AIM Photonics

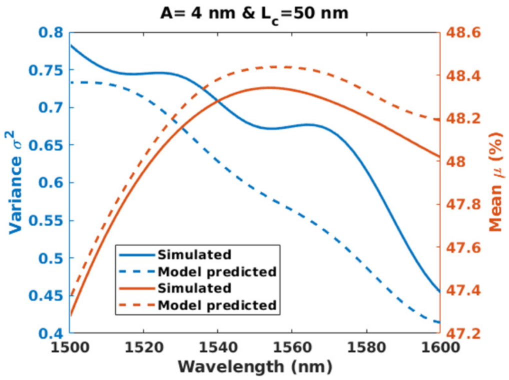
Silicon photonics is a booming design platform due to its ability to support high data rates and enable novel applications. Since the CMOS fabrication infrastructure is leveraged in silicon photonics, it becomes crucial to provide process-variation-aware compact models as optical components inherit the process variations found in CMOS. These models would help designers, enhance yield, and serve as a building block in the silicon photonics process design kit (PDK).

We develop a compact model for a basic photonic component, a Y-branch, that specifies the variations in the transfer characteristics against line-edge roughness (LER). LER is a common statistical random process variation that causes imbalanced transmission between the two output ports of the Y-branch, which is supposed to be balanced. As a random process variation, LER affects the Y-branch transmission in a random behavior, so the transmission can be described by its mean (μ) and variance ($\sigma2$). This model provides the transmission mean and variance as a function of LER parameters, amplitude (A) and correlation length (L_C), across the operating wavelength range of interest (λ).

The flow of modeling, shown in Figure 1, starts by simulating different A and LC combinations with multiple instantiations for each to get a statistical sense of the variations. Afterward, the optical behavior of the Y-branch with the imposed LER is extracted and used to develop the compact model. The model is developed using the Gaussian process regression method where the R^2 score for both mean and variance predictions is 0.99. Figure 2 shows the model's performance on test data for predicting mean and variance. This model can be used in photonic integrated circuit simulators to predict the performance across process variations and worst corner cases as the models we rely upon in CMOS design.



▲ Figure 1: Simulation flow used to develop a statistical compact model that includes the LER effect.



◀ Figure 2: Mean and variance prediction for test data using a Gaussian process regression model across the wavelength of interest.

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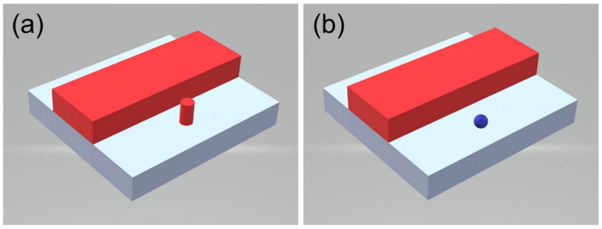
Particle Defect Yield Modeling for Silicon Photonics

Z. Zhang, M. B. McIlrath, D. S. Boning
Sponsorship: AIM Photonics

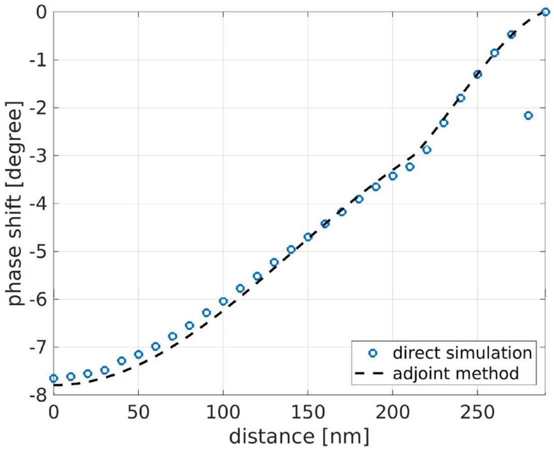
Silicon photonics, where photons instead of electrons are manipulated, shows promise for higher data rates, lower energy communication and information processing, biomedical sensing, and novel optically based functionality applications such as wavefront engineering and beam-steering of light. In silicon photonics, both electrical and optical components can be integrated on the same chip, using a shared silicon integrated circuit (IC) technology base. However, silicon photonics does not yet have a mature process, device, and circuit variation models for the existing IC and photonic process steps; this lack presents a key challenge for design in this emerging industry.

Our goal is to develop key elements of a robust design for manufacturability methodology for silicon photonics. As one part of the goal, here we focus on the impact of particle defects in silicon photonics, which can arise in photolithography, deposition, etching, and other processes. The model and result will be used to help generate layout design rules and critical area extraction methods, predicting and optimizing the yield of complex silicon photonic devices and circuits for tomorrow's silicon photonics designers, just as IC designers do today.

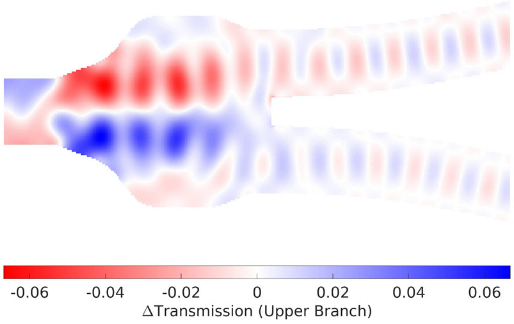
We model the impact of different types of particle defects (Figure 1) on different device components, e.g., straight waveguides (Figure 2) and y-splitters (Figure 3). We modify and apply the adjoint method, which is widely used in optimization, to accelerate the speed of simulation and reduce numerical error. The result from the adjoint method shows good consistency with direct simulation over different types of particles, different device components, and wavelengths ranging from 1500 to 1600 nm. The same methodology can be used on the circuit level and thus predict the yield of the chip. Present research also focuses on generating layout design rules and critical area extraction based on results from the adjoint method.



▲Figure 1: Examples of modeling of particle defects: (a) silicon pillar photolithography defect and (b) metal ball for foreign metal particle.



▲Figure 2: Phase shift impact of a dioxide pillar hole of radius 40 nm on a straight silicon waveguide, from both direct simulation and adjoint methods. Distance is measured from the center of the waveguide to the center of the particle.



▲Figure 3: Mapping of transmission impact of a dioxide pillar hole of radius 40 nm on a y-splitter, as the function of the location of the defect, predicted by the adjoint method.

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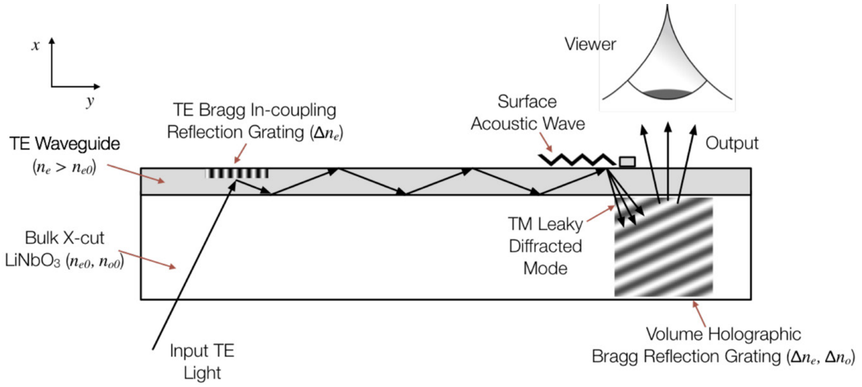
See-through Light Modulators for Holographic Video Displays

S. Jolly, T. Schoeppner, B. Datta, V. M. Bove, Jr. in collaboration with Daniel Smalley (Brigham Young University)

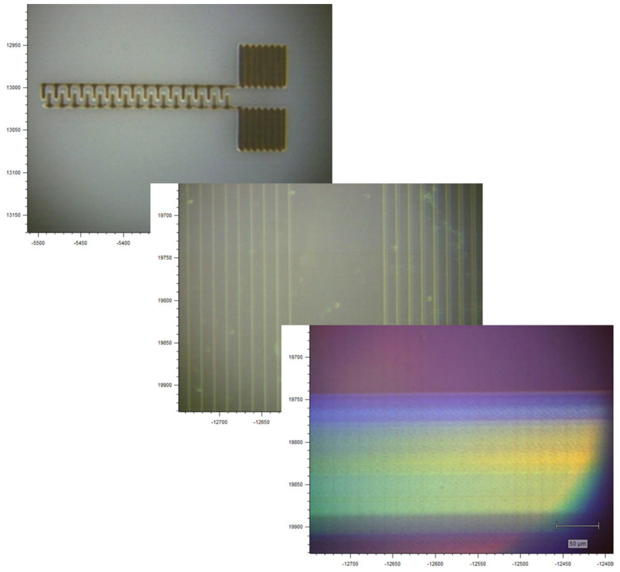
Sponsorship: MIT Media Lab Research Consortium, U.S. Air Force Research Laboratory

In this research, we design and fabricate acousto-optic, guided-wave modulators in lithium niobate for use in holographic and other high-bandwidth displays. Guided-wave techniques make possible the fabrication of modulators that are higher in bandwidth and lower in cost than analogous bulk-wave acousto-optic devices or other spatial light modulators used for diffractive displays; these techniques enable simultaneous modulation of red, green, and blue light.

We are investigating multichannel variants of these devices with an emphasis on maximizing the number of modulating channels to achieve large total bandwidths. To date, we have demonstrated multichannel full-color modulators capable of displaying holographic light fields at standard-definition television resolution and video frame rates. Our current work explores a device architecture suitable for wearable augmented reality displays and other see-through applications, in which the light outcouples toward the viewer (Figure 1), fabricated using femtosecond laser micromachining (Figure 2).



▲ Figure 1: Diagram of near-eye version of our device.



▲ Figure 2: Metal features, waveguides, and reflection gratings fabricated using femtosecond laser processing.

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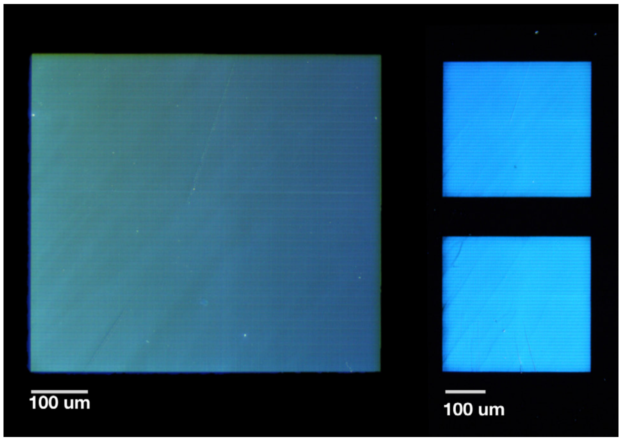
Bio-inspired Photonic Materials: Producing Structurally Colored Surfaces

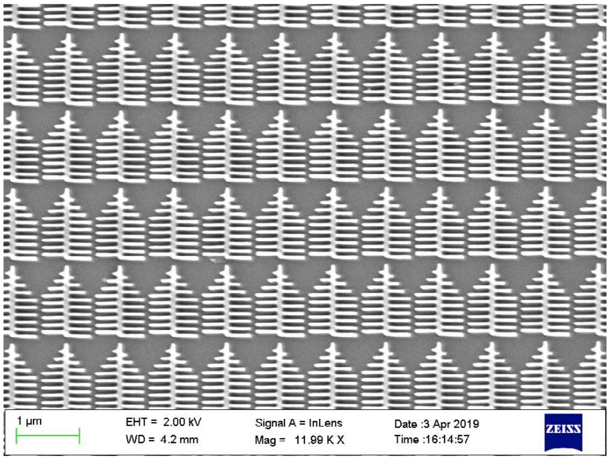
B. Datta, S. Jolly, V. M. Bove, Jr.
Sponsorship: MIT Media Lab Research Consortium

Advances in science and engineering are bringing us closer and closer to systems that respond to human stimuli in real time. Scientists often look to biology for examples of efficient, spatially tailored multifunctional systems, drawing inspiration from photonic structures like multilayer stacks similar to those in the morpho butterfly. In this project, we develop an understanding of the landscape of responsive, bio-inspired, and active materials, drawing on principles of photonics and bio-inspired material systems. We are exploring material processing techniques (starting with electron beam lithography and moving to direct laser writing) to produce and replicate structurally colored surfaces while developing simulation and modeling tools (such as inverse design processes) to generate new structures and colors. Such complex biological systems require advanced fabrication techniques. Our designs are realizable through fabrication using direct laser writing techniques such as two-photon polymerization. We aim to compare our model system and simulations to fabricated structures using optical microscopy, scanning electron microscopy, and angular spectrometry. This process provides a toolkit with which to examine and build other bio-inspired, tunable, and responsive photonic systems and expand the range of achievable structural colors.

Unlike with natural structures, producing biomimetic surfaces allows researchers to test beyond tunability that occurs naturally and explore new theory and models to design structures with optimized functions. The benefits of such biomimetic nanostructures are plentiful: they provide brilliant, iridescent color with mechanical stability and light-steering capabilities. By producing biomimetic nanostructures, designers and engineers can capitalize on unique properties of optical structural color and examine these structures based on human perception and response.



▲Figure 1: "Tree-like" structures replicating the ridge structure of morpho butterflies, fabricated in poly (methyl methacrylate) on silicon using electron beam lithography.



▲Figure 2: Color responses generated with incident reflective illumination using a broadband light source, demonstrating proof-of-principle optical response.

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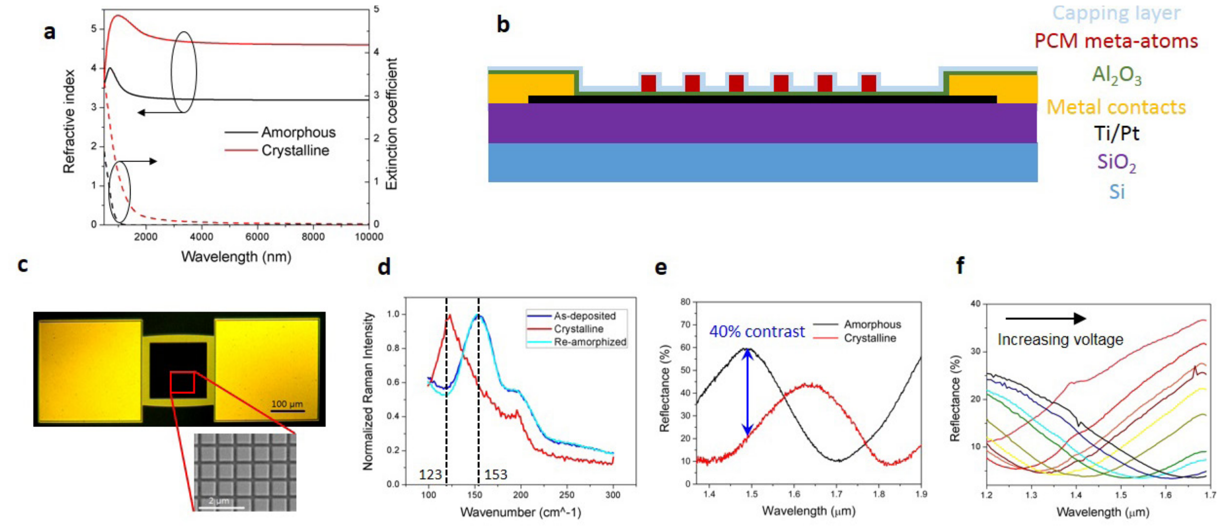
Reversible Electrothermal Switching of Nonvolatile Metasurfaces Based on Optical Phase Change Materials

Y. Zhang, J. Liang, M. Shalaginov, S. Deckoff-Jones, C. Ríos, J. B. Chou, C. Roberts, S. An, C. Fowler, S. D. Campbell, B. Azhar, C. Gonçalves, K. Richardson, H. Zhang, D. H. Werner, T. Gu, J. Hu
Sponsorship: DARPA ASD (R&E)

Chalcogenide phase change materials (PCMs) are highly attractive for active metasurface applications due to their nonvolatile switching capability. So far, reversible switching of PCM-based metasurfaces is realized via either laser pulsing or electrical-current-induced phase transition. Both methods require raster-scanned writing and bulky off-chip instruments (lasers or AFM setups), making them incompatible with large-scale on-chip integration. A robust and scalable, on-chip, PCM-based metasurface switching method is therefore highly desired. Here we report an electrothermal switching method employing on-chip metal heaters, enabling large-area reversible switching for PCM-based metasurfaces.

Figure 1a shows the optical constants of the low-loss optical PCM (O-PCM) we choose for this application: $Ge_2Sb_2Se_4Te_1$ (GSST), which exhibits low-loss at both its amorphous and crystalline phases over a broad spectral range. Moreover, its improved amorphous phase stability gives rise to a larger critical switching thickness than that of traditional PCMs (e.g., GST-225). These two factors make GSST a preferred material for metasurface applications. Figure 1b illustrates the design of the switching platform. Ti/Pt are used as a metal heater for its excellent conductivity. After an atomic layer deposition of Al_2O_3, GSST is subsequently deposited and patterned via electron beam lithography. The thickness of the GSST meta-atoms is designed to be 220 nm. Finally, a SiO_2 capping layer is deposited to prevent oxidation and evaporation of the PCM. The devices are wire-bonded onto a custom printed circuit board carrier to enable *in-situ* Raman and Fourier transform infrared (FTIR) characterizations. Figure 1c shows the SEM and optical microscope images of a fabricated device. The boundary of the heat is optimized for uniform heating in the PCM area. Figure 1d confirms the complete reversible switching of the PCM utilizing the distinct Raman peaks of amorphous and crystalline states. Figure 1e shows that more than 40% reflection contrast is achieved using this platform. Figure 1f, on the other hand, demonstrates that applying different voltages can achieve any arbitrary levels of crystallization, therefore providing possibilities for quasi-continuous tuning using this platform.



▲ Figure 1: (a) Optical properties of a- (black) and c- (red) state GSST alloys; (b) Sketch of the device; (c) Optical and scanning electron microscope images of the device; (d) Raman spectra of as-deposited, crystallized and re-amorphized PCM metasurfaces; (e) FTIR response of a device in its a- and c- states after 35+ cycles of switching; (f) Demonstration of quasi-continuous switching.

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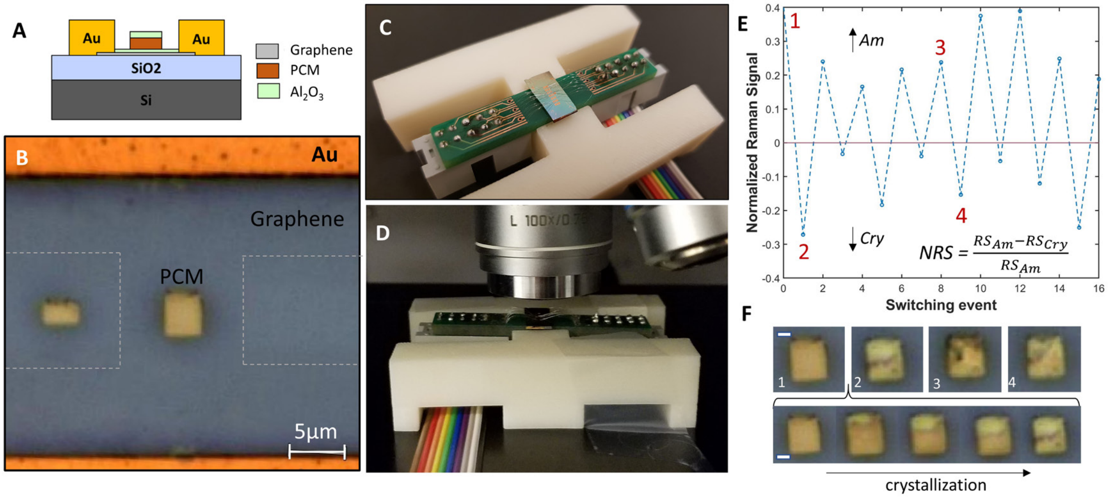
Graphene Microheaters for Controlled Switching of Optical Phase Change Materials

C. Ríos, Y. Zhang, S. Deckoff-Jones, M. Shalaginov, H. Wang, H. Li, J. Kong, T. Gu, J. Hu

Sponsorship: Defense Advanced Research Projects Agency Extreme Program

The integration of optical phase change materials (O-PCMs) into photonic devices enables a long-sought functionality: nonvolatile reconfiguration, the ability to switch between at least two distinct configurations with no power consumption to retain either one. Energy-efficient, highly cyclable integrated optical devices such as switches, memories, metasurfaces, color pixels, and brain-inspired computing elements are successful examples of O-PCMs applications. However, these results use optical switching mechanisms that are challenging to scale up for architectures comprising hundreds of large-area active cells. To tackle this challenge, we present a hybrid electro-optical framework in which we use graphene microheaters for thermal switching of $Ge_2Sb_2Se_4Te_1$ (GSST). We choose GSST because of its broadband transparency in the infrared beyond 18.5-µm wavelengths in both the amorphous and the crystalline states. Similarly, we choose graphene for our integrated approach because of its minimal optical loss (~ 0.1–1.2 dB/mm), high thermal conductivity, and stability. Such a device benefits from scalable electrical control, while having a reconfigurable optical response.

We demonstrate large-area switching of 50-nm thick, 4×3-µm2 GSST using a 5×10-µm2 graphene heater (Figures 1A and 1B). The chip was wire-bonded onto a printed circuit board to enable in-situ Raman probing while electrically testing each integrated device (Figures 1C and D). To switch the as-deposited GSST to the crystalline state (heat up over ~280˚C), we used 6V pulses with varying lengths between 10-20 ms. To reamorphize (melt over 650˚C and quench), we triggered 13-µs electrical pulses with a peak voltage of 7.5V. We demonstrate repeatable electrical switching by *in-situ* Raman spectroscopy of GSST after each pulse excitation (Figure 1E), done by tracking the amorphous and crystalline signature peaks at 159 cm^{-1} and 120cm^{-1}, respectively (Figure 1F). Furthermore, the change in color observed in the inset microscope images of Figure 1F demonstrates the nonvolatile modulation of the optical properties upon GSST switching.



▲Figure 1: A sketch of a reconfigurable PCM device using a graphene heater. B. Optical microscope image of the device. C. Switchable wire-bonded device arrays. D. Assembly inside a Raman microscope using long working distance objectives. E. Demonstration of 10 switching events by measuring the Raman signal (RS) at the characteristic peaks of both states. F. Raman spectra of GSST for the four points highlighted in E.

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Highly Sensitive Nanogap-based Mechanical Sensors for Infrared Detection

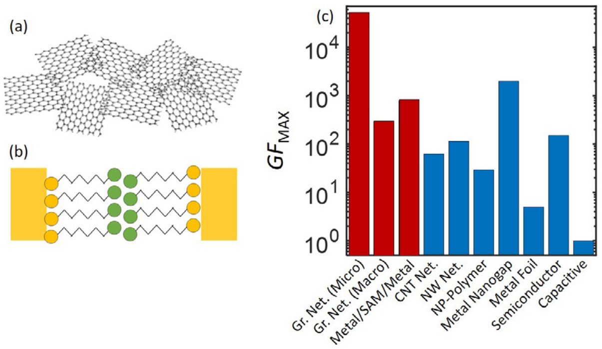
Y. Lin, X. Ji. R. J. Catalano, E. N. Tas, J. Han, J. H. Lang, F. Niroui, J. Kong, T. Palacios

Sponsorship: Army Research Office MIT-ISN, Air Force Office of Scientific Research-MURI

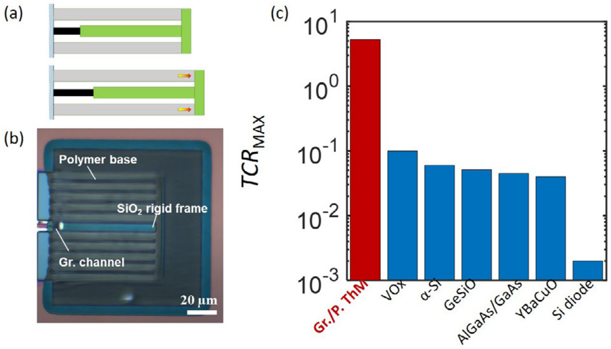
Many new physical phenomena show up only on nanoscale structures; with these phenomena, we can design novel devices with unprecedented functionality. Nanoengineering makes it possible to fabrication nanometer-sized quantum tunneling barriers that can be tuned mechanically. Such a tremendous mechanical tunability can be harnessed for mechanical sensors and many other types of sensors with extremely high sensitivity.

Here we demonstrate two nanostructures that implement such a mechanically tunable tunneling barrier and use them for either a mechanical/strain sensor or a mid-infrared bolometric detector. The first nanostructure is the self-assembled graphene nanoflake network (Figure 1 (a)). It is composed of a resistance network of sub-micron graphene flakes that connect with <100 nm overlap. The second nanostructure is a metal nanogap with the gap defined by self-assembled monolayers (SAMs) (Figure 1 (b)).

The proposed structures show high gauge factors and/or improved linear dynamic range as strain sensors (Figure 1 (c)). Such mechanical sensors can also be integrated with a thermal actuator to realize a highly sensitive, uncooled bolometer-type mid-infrared detector (Figure 2(a) and (b)). The measured temperature coefficient of resistance (TCR) can be as high as 5 K-1, which is more than one order of magnitude better than the state of the art (Figure 2(c)).



▲ Figure 1: Nanogap based mechanical/strain sensors. (a) Schematic of graphene nanoflake network. (b) Schematic of metal/SAM/metal nanogap structure. (c) Measured maximum gauge factors (GF_{max}) of graphene nanoflake network and metal/SAM/metal structure vs. state of the art .



▲ Figure 2: Thermo-mechanical bolometric mid-IR detectors. (a) Schematic of device composed of nanogap-based mechanical sensing component (black), thermal actuator (grey), and rigid frame (green). (b) Optical microscopic image of as-fabricated device. (c) Measured maximum TCR (TCR_{max}) vs. state of the art.

Oxide Passivation on MoS_2-based Field-effect Transistors for Sensing Applications

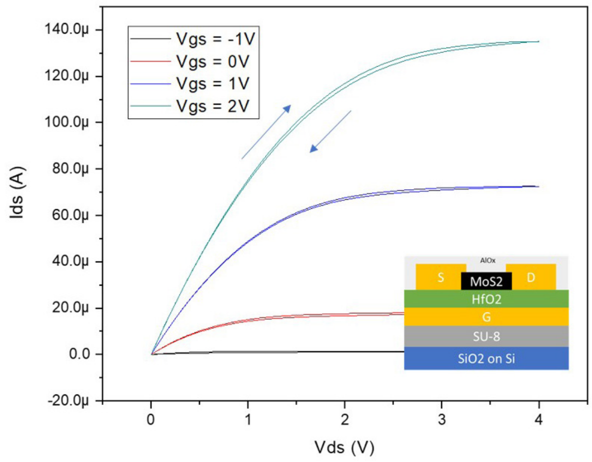
M. Xue, T. Palacios

Sponsorship: MIT-ARL ISN, NSF CIQM

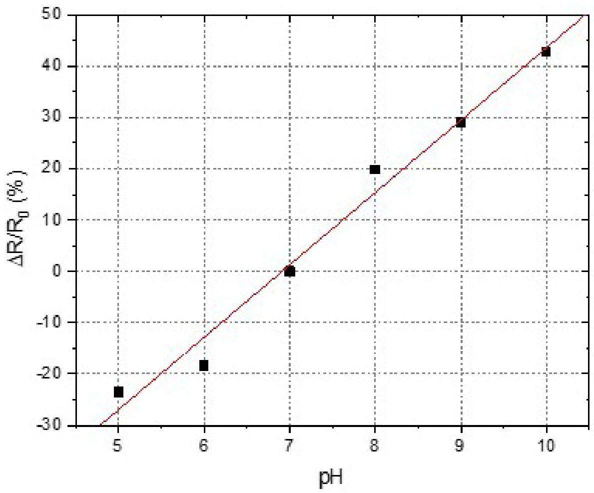
Two-dimensional materials have attracted much attention as candidates for next-generation sensing platforms because of their unique electrical, optical, mechanical, and chemical properties. Due to its natural bandgap, MoS_2 is one of the most popular two-dimensional materials for sensing. The sensing signal can be amplified as charges transfer onto the MoS_2 channel and result in strong modulations in current with the present of the analyte. The large surface-to-volume ratio also contributes to the high sensitivity of a MoS2-based sensor. However, high sensitivity also results in much noise as vapor molecules and other interfering molecules absorb on the exposed MoS_2 surface. Also, unprotected MoS2 can degrade in an ambient environment due to oxidation and surface contaminants. Therefore, a suitable passivation layer is needed to protect the channel surface but still preserve the sensitivity of MoS_2.

In this work, back-gated MoS_2 field-effect transistors (FETs) were fabricated, and a thin layer of Al_2O_3 was deposited to passivate the channel surface. Prior to atomic layer deposition of Al_2O_3 as a seed layer, 2 nm of aluminum was deposited. Approximately 13 nm of $Al_2O_3$was added to the final device. With the oxide passivation, the hysteresis of both output and transfer characteristics was greatly reduced, indicating effective protection from fast absorbent-type trapping site.

The sensing ability of oxide-passivated MoS2 FETs was also tested with a series of the electrolyte solution of pH ranging from 5 to 10. As shown in Figure 2, a near-linear relationship between relative change in resistance and change in pH was achieved. This work proves that $Al_2O_3$is a great passivation layer for MoS_2-based sensor devices. With oxide being the outmost layer, other oxide-compatible surface functionalization can also be used to improve the selectivity of such sensors while still benefiting from MoS_2's natural sensitivity.



▲Figure 1: Output characteristic of oxide-passivated MoS_2 FETs. The inset shows the device structure.



▲Figure 2: Relative change in channel resistance as function of pH values of electrolyte. The channel size is 50 µm x 10 µm, V_{gs} = 0V.

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SynCells - Electronic Microparticles for Sensing Applications

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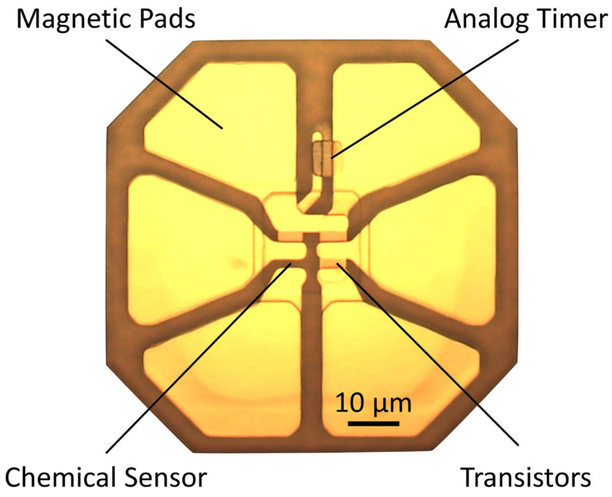
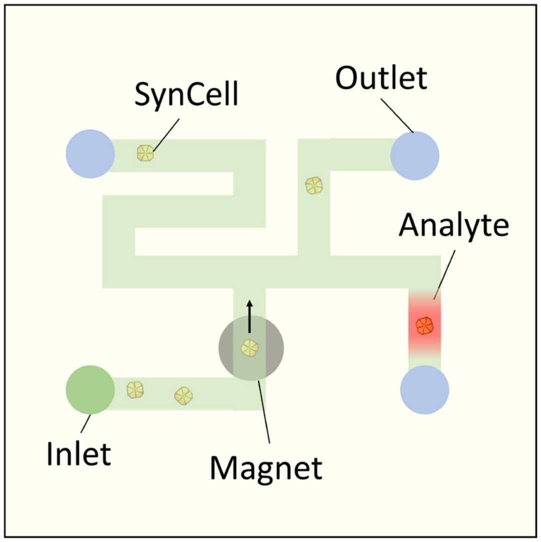
Although transistors have dramatically decreased in size over the past decades, thanks to Moore's law, the overall size of electronics has roughly stayed constant. However, shrinking electronics systems to the size of biological cells presents a big opportunity for sensing applications because it allows us to interact with the environment at a much smaller scale. These microsystems could be used, for example, to detect chemicals in very confined spaces like the human body or microfluidic channels. Alternatively, they are small enough to be sprayed on surfaces to form distributed sensor networks or even be incorporated into fibers to make smart clothing.

To realize this vision, we have developed a microscopic sensor platform built a on 3-µm- thick SU-8 polymer substrate that we call synthetic cells or SynCells. The SynCells contain a variety of electric components, including molybdenum disulfide-based transistors and chemical sensors, analog timers based on eroding germanium films, and magnetic iron pads (see Figure 1). Over the past years, we have optimized the SynCell fabrication and lift-off process, and we recently demonstrated a yield close to a hundred percent of fully working SynCells. Additionally, we have shown high sensitivities of the MoS_2 sensors to amines such as putrescine in both water and air. Using rare-earth magnets, we are also able to move and pivot the SynCells in solution from over 50 cm away.

As the next step, we want to use SynCells in a complex task, where we move them to a specific location in a microfluidic channel using a magnet to measure the chemical concentration (see Figure 2). Additionally, the germanium timer will measure the time spent in water, while the transistors will be used to amplify the chemical sensor signal. If successful, SynCells could enable microscale smart sensors for healthcare, environmental monitoring, or smart material composites.



▲ Figure 1: Microscope image of a SynCell (80 x 80 x 3 µm) with molybdenum disulfide-based transistors and amine sensors, germanium-based analog timer, and magnetic iron pads.



▲ Figure 2: Schematic of a complex SynCell demonstration. SynCells are introduced into a microfluidic channel, positioned precisely using a magnet to detect local chemical concentration.

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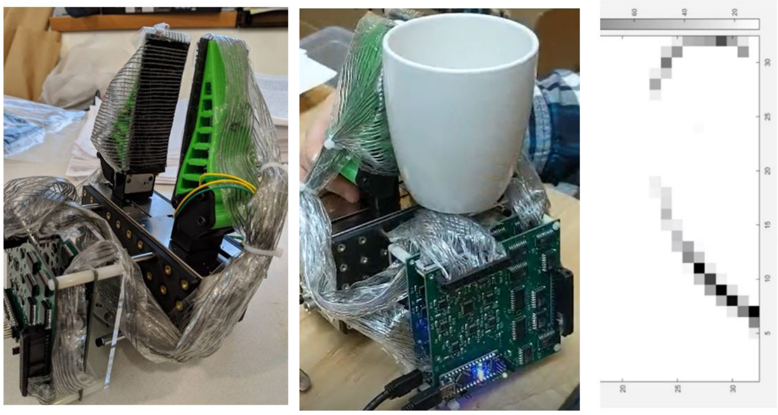
Piezoresistive Sensor Arrays and Touch-sensitive Textile for Robot Manipulation and Control

Y. Luo, T. Palacios

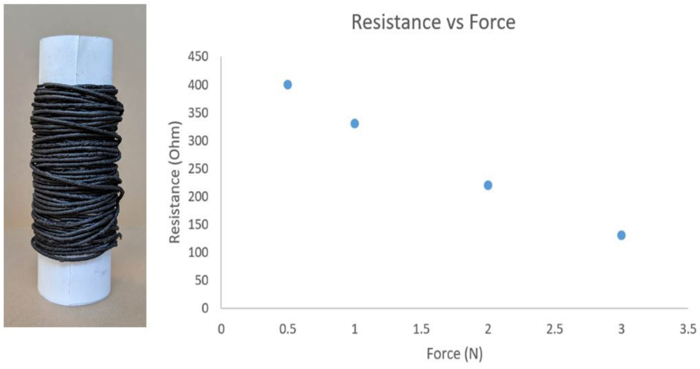
Humans rely on tactile feedback for object manipulation as well as many other dexterous tasks. In contrast, modern robots are tactile-blind; therefore, tactile sensors have been widely applied in robotic manipulation, policies control, and human-computer interaction. Large-scale electronic skins and touch-sensitive textiles with high densities, durability, and flexibility will be important tools to understand human behavior as well as to monitor and improve robot manipulation and control.

In this work, a high density flexible piezoresistive pressure sensor array with high robustness is fabricated. Commercial piezoresistive films are sandwiched between two layers of stainless-steel threads to assembly a 32×10 sensor array, which is then attached to the surface of a robot gripper (Figure 1). The shape and densities can be customized for different applications. Pressure maps will be recorded during the operation of gripper by a printed circuit board with a buffered reading circuit. Data retrieved from the sensor array will be further analyzed to monitor or improve robot manipulation.

Moreover, smart garments with tactile sensors are fabricated by incorporating electronic textiles into a fully knitted garment, which will have huge opportunities in human-computer interaction. Piezoresistive fibers are fabricated by coating graphite/polydimethyl-siloxane mixture over stainless conductive thread (Figure 2). We are presently working to improve the compatibility between piezoresistive fibers and the fully automated knitting machine.



▲ Figure 1: (a) Gripper with 32×10 piezoresistive sensor array and (b) real-time pressure map during operation.



▲ Figure 2: (a) Piezoresistive fibers and (b) its performance characterization.

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