Metasurface-Based Infrared Optical Devices

CNF Project Number: 2472-16

Principal Investigator(s): Gennady Shvets

User(s): Melissa Bosch, Minwoo Jung, Maxim Shcherbakov

Affiliation(s): School of Applied and Engineering Physics, Department of Physics; Cornell University

Primary Source(s) of Research Funding: Office of Naval Research (ONR) and National Science Foundation (NSF)

Contact: gs656@cornell.edu, mb2583@cornell.edu, mj397@cornell.edu, mrs356@cornell.edu

Website: http://shvets.aep.cornell.edu

Primary CNF Tools Used: JEOL 9500, CVC SC4500 evaporator, Zeiss Supra SEM

Abstract:

Planar metamaterials, or metasurfaces, provide strong and resonant light modulations both in near-and far-fields. We engineer several metasurface structures for near-to mid-infrared photonic applications. A plasmonic metasurface, for example, can be integrated with graphene to greatly enhance the absorption of incident radiation into graphene through ultrahigh field enhancement at its resonance. On the other hand, we also exploit low-loss dielectric metasurfaces with thermally tunable resonances to demonstrate tunable polarization control. These metasurface-based approaches are scalable and space-efficient, thereby promising versatile platforms for ultrathin optical devices.

Summary of Research:

High-Gain and High-Speed Mid-Infrared Graphene Photodetector with Plasmonic Metasurfaces. Graphene, owing to its gapless and semi-metallic electronic dispersion, is a broadband photo-diode, and graphene photodetectors can be in principle operated at ultrahigh speeds up to hundreds of gigahertz thanks to its linear Dirac electrons traveling at a relatively high Fermi velocity [1]. High-gain operation, however, is not guaranteed in graphene itself due to its monolayer nature and weak absorption. Strong field enhancement via resonant metasurfaces can increase the absorption into graphene by an order of magnitude without sacrificing high-speed capability [2]. We aim for even more efficient high-gain configuration, by using the metasurface structures themselves as the electrodes—source and drain—of the photodetector. In this way, the gain is enhanced not only due to the plasmonic resonances, but also by reducing the distance that the photo-generated carriers travel to get to the electrodes.

Furthermore, as seen in Figure 1, the source and the drain are interdigitated, thus increasing the photo-absorption area by a factor of the number of metasurface unit cells. The device is fabricated in a total of five e-beam lithography steps: (1) alignment marks, (2) graphene patterning, (3) source deposition, (4) drain deposition, and (5) contact pads deposition. The source and the drain are deposited in separate steps for introducing different materials (Ti and Pd) for the adhesion layer between graphene and gold. Two different contact metals dope graphene at slightly different Fermi levels, enabling photo-voltaic mode operation at zero source-drain bias voltage.

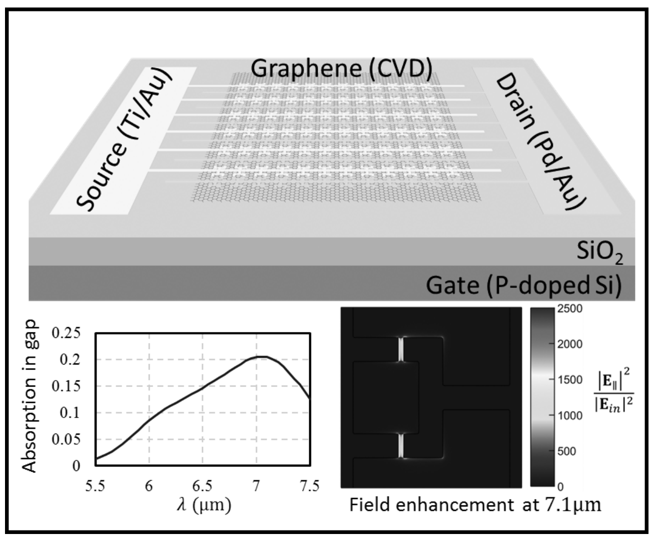


Figure 1: Top, Schematic of graphene photodetector integrated with a plasmonic metasurface. Bottom Left, Absorption of mid-infrared radiation into graphene in the gap region between the source and drain. Bottom Right, Field enhancement at the plasmonic resonance.

Figure 2 shows an SEM image zoomed on a gap between the source and the drain. The fabricated device is currently under electrical and optical characterization. Our simulation predicts a photocurrent of ~ 0.1A/W at the resonance.

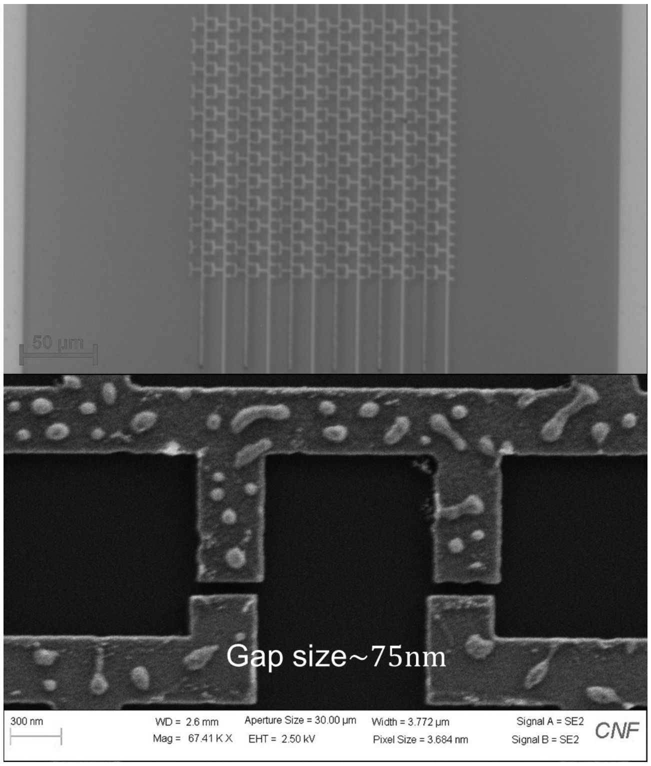


Figure 2: Top, Fabricated device imaged under optical microscope. Bottom, SEM image zoomed on a gap between the source and the drain.

Polarization States Synthesizer Based on a Thermo-Optic Dielectric Metasurface. The dynamic control of light polarization is ubiquitous to free-space and integrated photonics applications. Low-loss dielectric metasurfaces have recently emerged as an attractive platform for efficient polarization synthesizers, however most implementations exhibit static functionalities. Germanium (Ge), one of the most promising materials for nanophotonics [3] due to its infrared transparency and high refractive index, also has one of the largest thermo-optic coefficients in the mid-infrared range [4].

In our work, we exploit the thermo-optic properties of germanium to demonstrate a resonant dielectric metasurface that acts as a thermally-actuated polarization state generator. This is accomplished through the design of a germanium-based anisotropic resonant metasurface (ARM) which supports a spectrally-sharp (high-Q) resonance that can be excited by one of the principal linear polarizations of incident light. Enabled by the high thermo-optic coefficient of germanium, the central frequency of the high-Q mode can be adjusted by almost its bandwidth within a 100°C window. Due to the anisotropic nature of the mode, light that is initially linearly polarized becomes elliptically polarized upon transmission through the ARM, with a polarization state that can be widely tuned by heating the sample. For device fabrication, we use the following procedure: a standard two-layer PMMA spin-coat, baking, and e-beam exposure at 1000 µC/cm^2 (JEOL 9500); development in MIBK:IPA 1:3 for 90s; e-beam evaporation of 300 nm of Ge (CVC SC4500), and liftoff in room-temperature sonicated acetone for 60s.

Figure 3 presents an SEM image of the fabricated metasurface and its temperature-dependent transmittance spectra. An example of the experimental thermal polarization tuning is shown in Figure 4; by varying both temperature and the polarization angle of incident light, we find the full polarization tuning range of the device covers near 40% of the upper Poincare hemisphere surface.

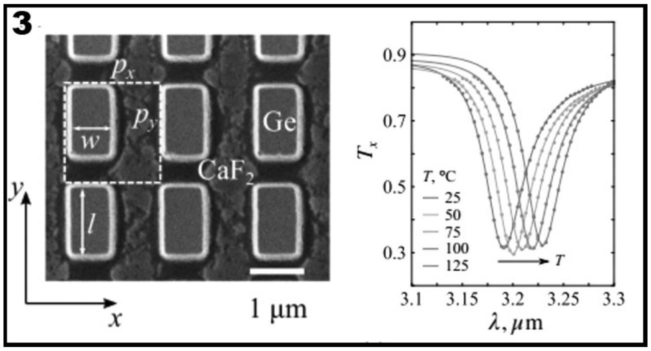
References:

[1] Photodetectors based on graphene, other 2D materials and hybrid systems. F. Koppens, T. Mueller, P. Avouris, A. Ferrari, M. Vitiello and M. Polini; Nature Nanotechnology 9, 780-793 (2014).

[2] High-Responsivity Mid-Infrared Graphene Detectors with Antenna-Enhanced Photocarrier Generation and Collection. Y. Yao, R. Shankar, P. Rauter, Y. Song, J. Kong, M. Loncar, and F. Capasso; Nano Letters 14(7), 3749-3754 (2014).

[3] Mid-infrared photonics in silicon and germanium. Soref, Richard; Nature photonics 4.8 (2010): 495.

[4] Temperature-dependent refractive index of silicon and germanium. Frey, B.J., D.B. Leviton, and T.J. Madison; Optomechanical technologies for Astronomy. Vol. 6273. International Society for Optics and Photonics, 2006.



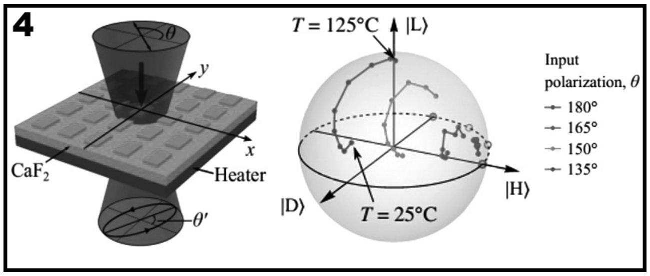


Figure 3, top: Left, An SEM image of the fabricated metasurface. Right, Experimental temperature-dependent mid-IR transmittance spectra of the metasurface, with Q-factor near 70.

Figure 4, bottom: Left, Schematic depicting the temperature-tunable polarization conversion of light transmitted through the ARM. Right, A Poincare sphere depicting the maps of experimental polarization modulation by the metasurface at a wavelength of 3.21 µm, corresponding to the maximum Poincare sphere coverage. Individual curves describe the transformation of the transmitted polarization state with increasing metasurface temperature for different incident polarizations.