Metasurface-Integrated Graphene for Mid-Infrared Optical Devices

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Primary CNF Tools Used: JEOL 9500, CVC SC4500 evaporator, Zeiss Supra/Ultra SEM, PT740 or Anatech resist strip

Abstract:

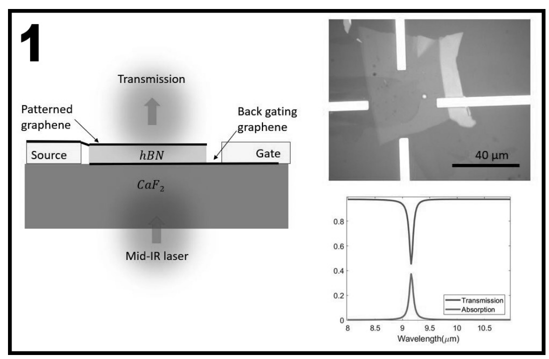
Plasmonic metasurfaces, when integrated with graphene, can greatly enhance the absorption of incident radiation into graphene through resonant field enhancement. This metasurface structure can be obtained simply by patterning graphene itself, or it may take a form of thin metallic film periodically patterned on graphene. The former approach was used to achieve an on/off notch filter of mid-infrared radiation with narrow linewidth, and the latter approach was used to make a high-responsivity and ultrafast graphene photodetector.

Summary of Research:

Graphene Based Mid-IR High *Q* Active Notch Filter. Graphene's high electronic mobility and ultrawide tunability owing to the linear Dirac electronic dispersion makes it an exceptional candidate for optoelectronic applications. However, its inherent weak absorption of only 2.3% of normally incident light in the visible and infrared spectrum acts as a bottleneck. To enhance its optical absorption, we can make use of the strong absorption properties of localized surface plasmon resonance (LSPR) in graphene. Nanopatterning of monolayer graphene using e-beam lithography and subsequent etching using RIE or FIB can be used to produce structures like nanorings and nanodisks [1], which support LSPR and have been reported to show an enhanced absorption of 25% [2]. For our structure, shown in Figure [1], we design a nano patterned graphene structure that maintains electrical connectivity and thus foregoes the requirement of an ion gel layer [1,2] — reducing the complexity in fabricating and handling such an optoelectronic device.

The device is fabricated in a total of four steps: (1) gold alignment marks and electrodes are deposited on CaF_2 (the substrate), (2) the heterostructure of graphene/hBN/graphene is transferred on to the substrate carefully to make sure each graphene layer is connected to one set of electrodes only, (3) the resonator pattern is etched on the top graphene using e-beam lithography, and (4) the graphene is etched through the developed PMMA, to get the required pattern using PT740 or the Anatech resist strip.

Figures 1 and 2 show two different fabricated resonator designs for the device. Device fabrication is at the stage of optimizing the etch recipe for graphene.



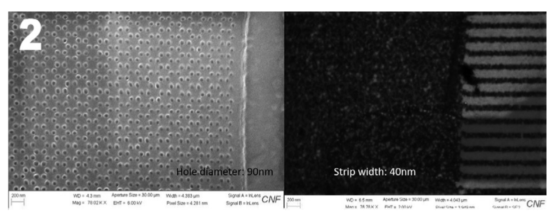


Figure 1, top: Left, schematic of the mid-IR notch filter showing the heterostructure stack. Top right, fabricated device under optical microscope, the opaque material visible in between the electrodes is the hBN layer. Bottom right, simulated mid-IR spectra of the fabricated device with the top graphene having a hexagonal pattern of holes (see Figure 2).

Figure 2, bottom: Left, SEM of developed pattern of hexagonal lattice of holes on PMMA covering the top graphene before plasma etch. Right, SEM of another possible 1D resonator pattern, rectangular strips etched on graphene, transferred on Si/SiO_2 substrate.

Graphene Photodetector with High Responsivity Enhanced by Plasmonic Metasurface. In a similar way, we resonantly boost the absorption into graphene by integrating a gold metasurface with graphene.

While graphene photodetectors enhanced by plasmonic metasurfaces are previously demonstrated [3], we aim for even greater enhancement by (1) interdigitating the source and drain and (2) using high-quality exfoliated graphene. Especially, the latter advancement is expected to give a huge improvement on the quality of detector performance, as the previous works were mostly done with CVD graphene with lower quality.

As depicted in the Figure 3 inset, we place graphene-hBN stack on top of the pre-fabricated gold metasurface structures deposited on SiO_2-Si substrate. The gold metasurfaces are fabricated by using e-beam lithography. We use PMMA for the e-beam resist, and deposit 7 nm of Cr and 43 nm of gold using CVC SC4500 evaporators.

The device is under characterization, and here we report on its optical characterization. The photocurrent measurement is to be done in a near future.

Figure 3 shows the reflection spectra of the gold metasurfaces with and without the graphene-hBN stack. While there are some modifications to the resonance structure due to the phonon bands of hBN, the original reflection dips are well-conserved. Thus, we expect that the absorption enhancement would be maintained at the similar order of magnitude even under the perturbation by hBN. We introduce this additional hBN layer for better graphene quality. The current experiment will be followed by the electrical characterization of the devices.

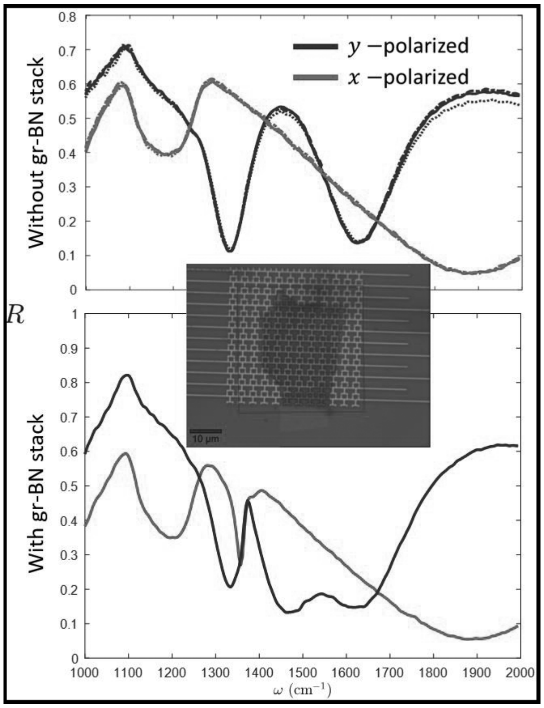


Figure 3: Optical characterization of photodetector device. Top, reflection spectra without graphene-BN stack on top of metasurface. Bottom, reflection spectra with graphene-BN stack on top of metasurface. Inset (middle), an optical microscopy image of a device with graphene-BN stack.

References:

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[2] Fang, Z.; Wang, Y.; Schlather, A. E.; Liu, Z.; Ajayan, P. M.; de Abajo, F. J. G.; Nordlander, P.; Zhu, X.; Halas, N. J. Active Tunable Absorption Enhancement with Graphene Nanodisk Arrays. Nano Lett., 14, 299-304 (2013).

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