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Electrical tuning of reflectance of graphene metasurface for unpolarized long wavelength infrared light

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Abstract: We demonstrate a graphene-metal metasurface for unpolarized long wavelength infrared light with electrically-tunable reflectance. By applying a gate voltage, we shift the wavelength of a resonant reflectance dip centered at ~9.4 micron by~156 nm.

OCIS codes: (260.3060) Infrared; (230.2090) Electro-optical devices; (230.4110) Modulators

1. Introduction

Metasurfaces are ultrathin optical components that can impart abrupt changes to the phase, amplitude, and polarization of light upon reflection or transmission. Metasurfaces whose properties can be dynamically tuned would be advantageous for many applications [1-3]. Metasurfaces for the mid- and long-wave infrared (MWIR, LWIR) would be particularly useful, due to important applications in those spectral ranges such as molecular fingerprinting, remote sensing and thermal imaging. The integration of metallic nanostructures with graphene is a promising strategy for tunable MIR and LWIR metasurfaces, as the optical conductivity of graphene can be controlled by a gate voltage via electrostatic doping. Infrared tunable metasurfaces have been demonstrated, but the majority of previous studies were at near infrared (NIR) and MWIR wavelengths [1-4]. This motivates the demonstration of tunable metasurfaces in the technologically-important LWIR window (λ=8-12μm). Such a demonstration was recently made (at up to λ=8.7 μm) [5], but for light with a particular incident polarization. Here, we experimentally demonstrate electrical tuning of the reflectance of a metasurface further into the LWIR (at λ~9.4 μm) than Ref [5], measured with unpolarized LWIR light from a Fourier transform infrared (FTIR) spectrometer.

2. Design and Fabrication

Our metasurface comprises cross shaped nanoantennas over a single layer of graphene, separated from a metallic reflector (that also functions as a back gate) by a dielectric spacer (Fig. 1a). This type of structure in principle permits a resonance to be achieved with high absorption (i.e. reflection dip) and a phase shift of 2π. Here, our goal is for this resonance to be in the LWIR spectral range. We choose the structural parameters of our device (Fig. 1a) to produce a reflection dip at wavelength around 9.5 μm. Finite difference time domain (FDTD) simulations are employed with the goal of a reflection dip with minimized reflection. The parameters include the nanoantenna period (P), width (W), and gap (G), and the thickness (t) of the dielectric cavity layer. Simulated reflection spectra for a device with SiO_2 as the dielectric cavity are shown as Fig. 1b. In the simulation, the graphene is modelled as a infinitesimally thin conductive surface with a surface conductivity calculated by using the Kubo formula [6]. To mimic electrostatic doping via a gate voltage, the chemical potential of the graphene in these simulations is varied from 0.1 to 0.4 eV, while the scattering rate was set to be 0.008 eV. Simulated reflection spectra for a device for which the dielectric cavity is TiO_2 are shown as Fig. 1c. A 30nm thick Al_2O_3 is also included in the simulation in order to provide better gate dielectric medium for the device. The complex refractive indices of Au, Ti, TiO_2, Al_2O_3, SiO_2 and Si used in the simulations are taken from the compilation by Palik [7]. It can be seen that, for the TiO_2-based device, the spectral position of the reflection dip can be widely shifted by changing the chemical potential of the graphene. Equivalently, for this device, if operated at a fixed wavelength, changing the chemical potential can produce a large modulation of the reflectance. On the other hand, for the SiO_2 device, the spectral position of the dip remains almost constant at λ~9.7 μm. We attribute this to the response being dominated by the phonon resonance of SiO_2 that occurs in this spectral range. Based on these simulation results, we choose TiO_2 as the dielectric cavity material for our experimental demonstration. Further insight into the tunability of the spectral dip can be obtained from Fig. 2a. This figure plots the simulated intensity enhancement ($|E/E_0|^2$) in the plane of the graphene, for the TiO2-based device (Fig. 1c) at an illumination wavelength of λ=9.43 μm and with the graphene chemical potential being 0.1 eV. A clear enhancement of electric field intensity in the antenna gaps can be seen. The nano-antennas thus enhance the interaction of the incident optical field with the graphene sheet. This enables the metasurface's resonant wavelength to be tuned by controlling the optical conductivity of graphene.

Fabrication of our device starts with the deposition of Au (120 nm thick), TiO_2 (800 nm thick) and Al_2O_3 (30 nm thick) layers on a highly doped silicon wafer. We next transfer a graphene monolayer (grown by chemical vapor deposition on Cu) onto the sample. We next fabricate the nanoantenna array and metal contacts by e-beam lithography, e-beam evaporation of Ti and Au (5 & 25 nm thick) and liftoff (Fig. 2a). Graphene is removed from the regions of the chip surrounding the device by e-beam lithography and dry etching (oxygen plasma). Fig. 2b shows the scanning electron microscopy (SEM) images of a fabricated structure.

3. Results and Discussion

We measure reflection spectra of the fabricated device at different gate voltages with an FTIR microscope system (Spotlight 200i, Perkin Elmer) using unpolarized light. To normalize the results, reflection spectra are measured from a reference sample comprising a gold film. The results are shown as Fig. 2c. It can be seen that as the gate voltage is varied from -5V to 30V, the wavelength of the reflectance dip (i.e. the resonance wavelength) is tuned from 9390 nm to 9546 nm (~156 nm).

In summary, we have demonstrated efficient dynamic control of unpolarized LWIR light by tuning the resonance of a metasurface that combines graphene with metal nanoantennas. In addition to reconfigurable metasurfaces, this demonstration paves a way for compact LWIR optoelectronic devices such as photodetectors.

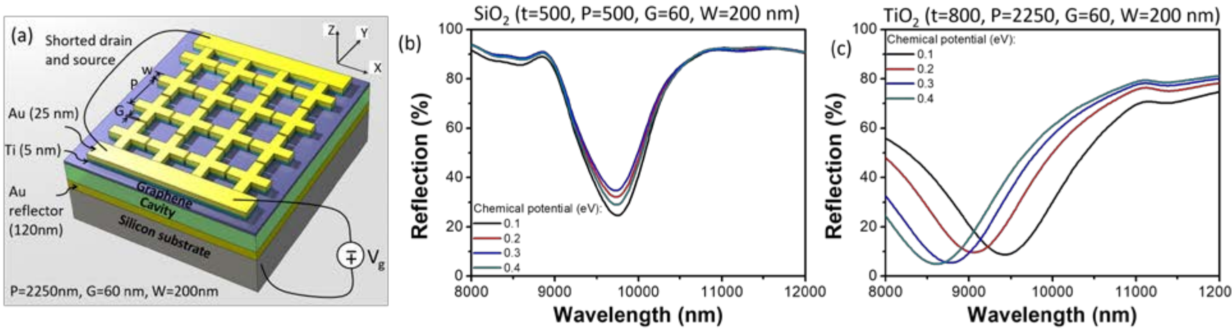

Fig. 1. (a) Schematic of the tunable metasurface device with a backgate. (b) Simulated reflection spectra of the device for different chemical potential of graphene with (b) SiO_2 and (c) TiO_2 as cavity material.

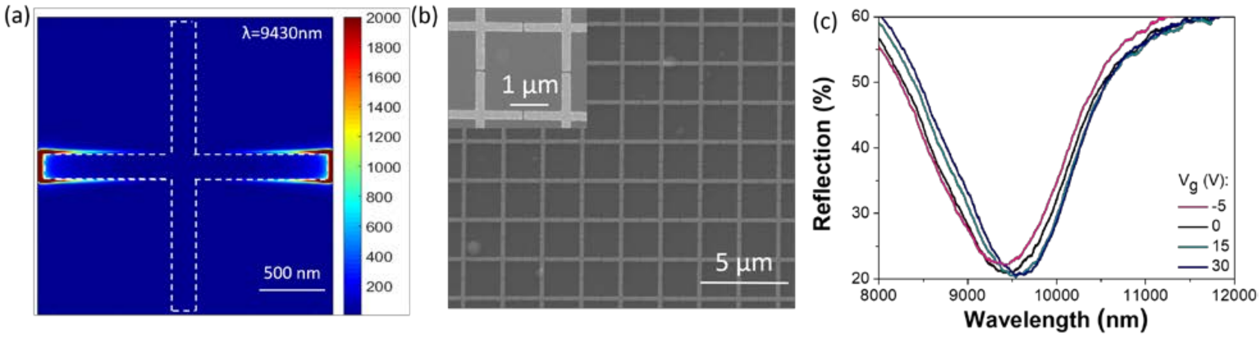

Fig. 2 (a) Simulated electric field intensity($|E/E_0|^2$) distribution in plane of graphene for TiO_2–based device illuminated at λ=9430 nm. (b) SEM image of cross-shaped antennas with *P*=2250 nm, gap *G*=60 nm, width *W*=200 nm Inset: higher magnification SEM. (c) Measured reflection spectra for fabricated device at different gate voltages.

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