Electrically Tunable Plasmonic Resonances with Graphene

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Abstract: Real time switching of a plasmonic resonance may find numerous applications in subwavelength optoelectronics, spectroscopy and sensing. We take advantage of electrically tunable interband transitions in graphene to control the strength of the plasmonic resonance.
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1. Introduction

Plasmonics offers an exciting route to subwavelength optoelectronics by confining the optical fields below the diffraction limit [1]. This is achieved by employing metal nanostructures resonant at a particular optical wavelength. Dynamic control of these plasmonic resonances is critical for many applications like integrated modulators and switches. Active electrical control of resonances has been demonstrated at THz frequencies [2]. Real time switching of plasmonic resonances at optical wavelengths could open up many exciting possibilities. In this paper we demonstrate voltage controlled plasmonic resonance using graphene. Graphene is a hexagonal lattice of sp^2 carbon atoms in a single sheet with extraordinary electrical and optical properties [3, 4], that was proposed as a platform for integrated optoelectronics and transformation optics [5-7]. Strong graphene-based modulation has recently been demonstrated for on-chip applications [8].

2. Tunable Plasmonic Resonances

Graphene exhibits a unique linear dispersion relation shown in Fig. 1a. The carrier density (n_{2D}) can be electrically controlled by an applied gate voltage, leading hereby to voltage controlled Fermi energy E_F. A direct consequence of that is the gate tunable interband threshold, wherein an incident photon can generate an electron-hole (e-h) pair only if its energy is higher than $2E_F$. For photons of lower energy there will not be interband losses at 0K. At higher temperatures the interband threshold is broadened but shows qualitatively similar behavior. For realistic carrier densities in the range 10^{11} -10^{13} cm^{-2} the interband threshold can be continuously tuned up to near-infrared (NIR) frequencies. When metal nanostructures with resonant frequency in the NIR are fabricated on top of graphene sheet their optical properties can be tuned by the applied gate voltage. The resonance is also accompanied by a local field enhancement which causes interaction with the graphene sheet. Hence, if the resonant frequency is above the interband threshold then strong interband losses are present and the resonance is considerably weakened.

Fig. 2b shows a schematic of the experimental setup for demonstrating plasmon resonance tuning. The source-drain contacts were deposited by e-beam evaporation of 10 nm Ti and 50 nm Au on doped Si substrate with 100 nm silicon oxide. A large area graphene sheet grown by chemical vapor deposition (CVD) was transferred onto the substrate ensuring electrical contact with both source and drain. Then, bow-tie like plasmonic structures were fabricated by electron beam lithography, metallization (2 nm Ti and 30 nm Au) and subsequent lift-off processes. The gate voltage applied to the Si substrate controls the carrier concentration in graphene sheet because of the field effect. The resistance between source and drain contacts was monitored to verify the field effect. A Fourier Transform Infrared (FTIR) spectrometer was used to optically characterize the plasmonic resonance behavior. A scanning electron micrograph of the fabricated sample with plasmonic structures on top of the graphene sheet is shown in Fig. 1c. It is clearly seen that CVD graphene is mostly single layered (verified separately by Raman spectroscopy) over the area of ~16 mm^2. The optical transmission data shows a resonance at ~ 3µm that is in agreement with the simulated data for the chosen resonator design. The variation of the source-drain resistance with gate voltage is shown in Fig. 1d. Graphene shows minimum carrier concentration at a voltage of 8V that is referred as the Dirac point in literature. At voltages lower than the Dirac point, the hole concentration increases progressively moving the interband threshold towards NIR frequencies. Fig. 1e shows the initial results demonstrating weakening of the resonance with increasing carrier concentration. The percentage change in the resonance strength with applied

voltage is up to 6% in the current sample as shown in Fig. 1f. We note that the maximum change in resonance occurs at 3.6 μm and can be further improved with higher carrier concentration. Further, the observed change of 6% is seen off-resonance and we believe that the change would be much higher with plasmon resonance at 4.5 μm and improved fabrication processes. In summary, we have demonstrated electrically controlled plasmonic resonance using graphene, and efforts are underway to achieve even higher tunability.
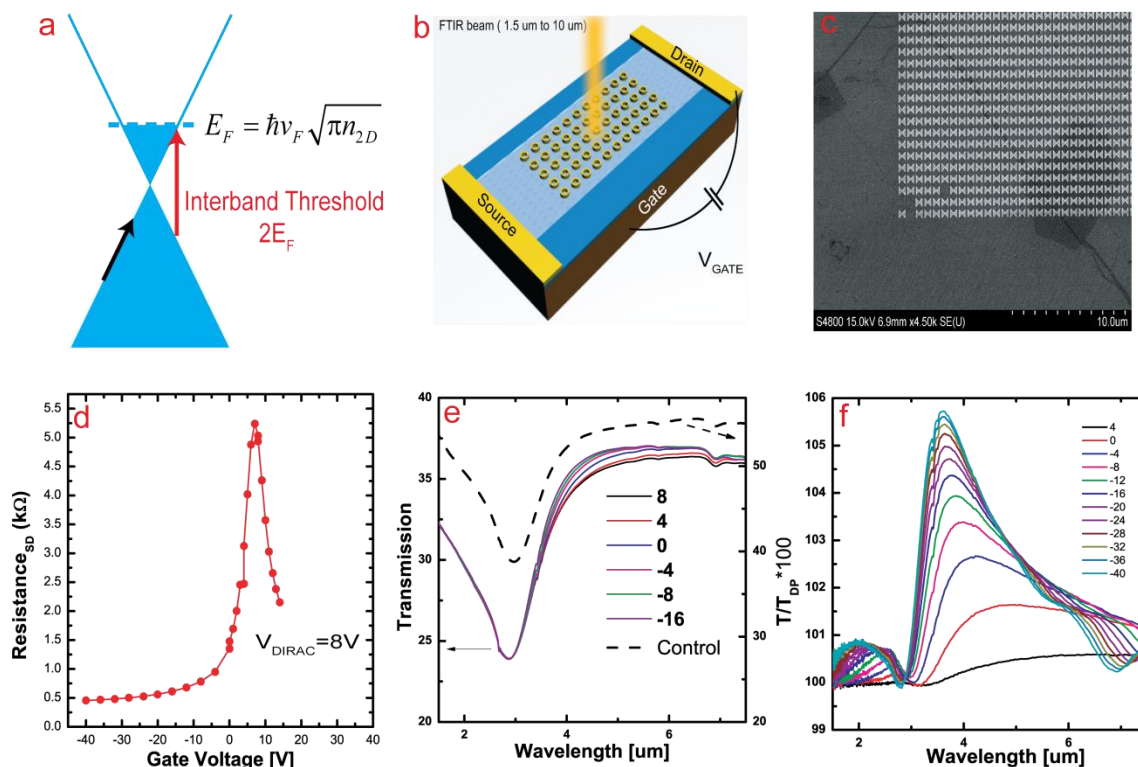

Fig 1. a) Band structure of graphene showing threshold for interband transitions which can be controlled by changing the carrier concentration; b) Schematic of the experimental setup for voltage controlled optical transmission measurements; c) SEM image of the fabricated sample showing the metal nanostructures on top of large area CVD grown graphene; d) In-situ electrical measurements showing carrier concentration change under applied voltage bias; e) Optical transmission measurements of bow-tie structures showing significant change in amplitude with applied voltage.; f) Percentage change in transmission showing peak change at 3.6 μm at 40 V bias.

3. References

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