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Plasmon reflection at artificial electronic boundary in monolayer graphene

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Abstract

Graphene plasmons promise unique possibilities for controlling light in nanoscale devices and for merging optics with electronics. Here we demonstrate a plasmonic reflector consisting of monolayer graphene with an artificial electronic boundary fabricated by spatially modulating carrier densities. Carrier densities were spatially modulated by partially covering a substrate with a self-assembled monolayer of organosilane. The reflection coefficient was tuned by gating the graphene. The artificial electronic boundary enables us to design and realize nanoscale graphene plasmonic circuits and devices.

1. Introduction

Graphene plasmons, which are electromagnetic surface waves propagating along graphene layers, offer unique possibilities for controlling light in nano-devices and for optoelectronics due to their short wavelengths [1]. One of the attractive features of graphene plasmons is that their properties can be tuned by a local modulation of the surface conductivity of graphene, which is the basis of graphene-based transformation optics [2]. The conductivity of graphene depends on the radian frequency, carrier scattering rate, temperature, and Fermi energy. The Fermi energy depends on the carrier density and can be controlled by electrical or chemical doping. In other words, by varying the carrier density spatially, we can engineer the graphene plasmon waves so that they are reflected or refracted.

In this study, we experimentally show that boundary between different carrier densities acts as a plasmonic reflector and that its reflectivity can be tuned by gating. We used a self-assembled monolayer (SAM) for substrate modification to achieve spatial modulation of the graphene carrier density. By partially covering a SiO_2 substrate with the SAM, the graphene carrier density was spatially modulated.

2. Experiments

A schematic of a sample is shown in Fig. 1(a). We used 3-amino-propyltriethoxysilane to form a SAM at the interface between graphene and a SiO_2 substrate. The SAM was formed by a vapor deposition method at room temperature on the substrate surface terminated with a silanol group. To spatially vary the carrier density, we made the SAM into stripe patterns using oxygen plasma. Monolayer graphene grown by the chemical vapor deposition method was transferred onto the patterned substrate. In an optical microscopy image, it is easy to distinguish the SAM-modified and bare SiO_2 areas [Fig. 1(b)].

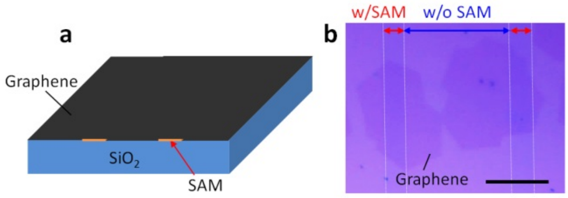

Fig. 1 (a) Schematic and (b) an optical microscopy image of a sample. Scale bar is 10 µm. White lines are visual guides for the SAM area.

We used a scattering-type scanning near-field optical microscope (s-SNOM) [3, 4] to directly observe the reflection of graphene plasmons. The s-SNOM is based on atomic force microscopy (AFM), where infrared light focused on a metallized AFM tip generates a strong localized field around the sharp tip apex. This concentrated electric field provides the necessary momentum to excite plasmons in graphene. The excited graphene plasmon waves are reflected at edges, defects, and domain boundaries. The interference between the tip-launched and reflected plasmons provides a characteristic fringe pattern.

3. Results and Discussion

We first show a spatial difference in the carrier density of graphene by a Raman measurement. The peak positions of Raman 2D and G bands are directly related to the carrier density in graphene [5]. A map of the Raman G band frequency clearly shows that the carrier density is modulated by the doping from the SAM [Fig. 2(a)]. From the peak position, we found that the carrier densities are $\sim 4\times10^{12}$ cm^{-2} with the SAM and $\sim 1\times10^{13}$ cm^{-2} without it. The lower carrier density with the SAM is due to electrostatic potential induced by molecular dipole moments [6].

The typical topography and near-field amplitude images obtained with the s-SNOM at an incident wavelength of 10.7 µm are shown in Figs. 2(b) and (c), respectively. A boundary between the graphene on the substrate with and without the SAM is clearly seen at the center of the image from a height difference. Along the boundary, interference fringe patterns appear on both of its sides in the near-field amplitude image. These fringes are signatures of plasmonic reflections at the boundary [3, 4]. This is clear from the line profile across the boundary [Fig. 2(d)]. These results demonstrate that the boundary between different carrier densities acts as a plasmonic reflector.

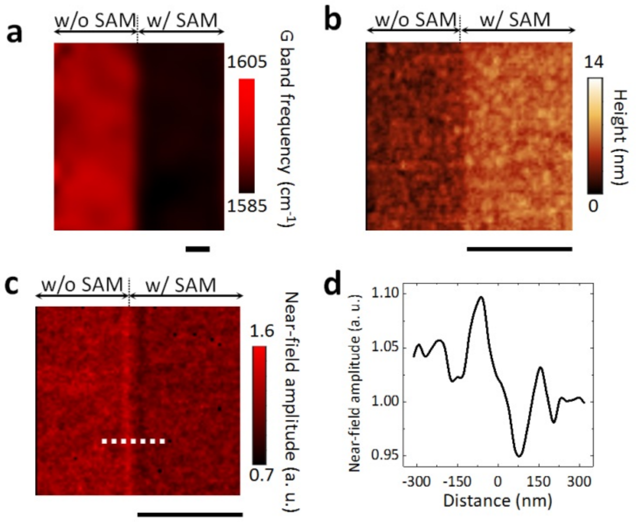

Fig. 2 (a) Raman map for G band frequency. (b) Topography and (c) near-field amplitude images of graphene at infrared wavelength of 10.7 μm. Scale bars are 1 μm. (d) Line profile along a white dashed line in (c).

We finally discuss the tunability of the plasmonic reflection at the boundary. We estimated the reflection coefficient r_p from the reflection amplitude of the fringe pattern. Since graphene plasmon waves are completely reflected at the graphene edge, we determined r_p from the ratio of the fringe amplitude at the boundary to that at the graphene edge. We examined the tunability of r_p by imaging the fringe pattern at several gate biases V_g. The value of r_p showed non-monotonic dependence on V_g. Very recently, a distinct result has been reported [7]. Here, we found that our non-monotonic dependence can be simply explained by the discontinuity of the plasmon dispersion due to the difference in the carrier density. We carefully estimated the carrier density from Raman measurements and other measurements (not shown here). The analytical calculation based on the difference in carrier density showed good agreement with our experiments.

4. Conclusions

We demonstrated that a boundary between different carrier densities acts as a plasmonic reflector as a consequence of the discontinuity of the plasmon dispersion. Substrate modification with a SAM is used to spatially modulate the carrier density of graphene. The spatial modification was confirmed by a Raman map of the G band frequency. The interference pattern observed with the s-SNOM proved that boundaries between graphene regions with different carrier densities act as plasmonic reflectors. The reflection coefficient can be tuned by a gate. Our results will open the way to designing graphene-based plasmonic devices.

References

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