Electrical Control of Plasmon Reflectivity in Graphene

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Abstract

Properties of plasmons in graphene can be controlled electrically. My research colleagues and I have used this feature to verify that plasmons of desired frequencies can be excited in electrically specified regions. This technology can be applied to plasmonic devices such as waveguides and switches.

Keywords: plasmon, graphene, electrical control

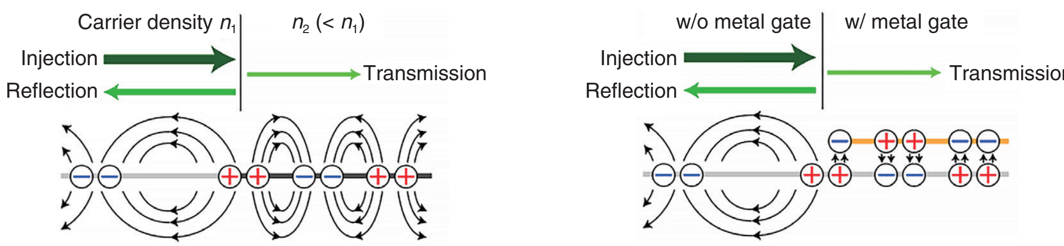
1. Graphene plasmons

Plasmons are collective oscillations of electric charges that have shorter wavelengths than electromagnetic waves at the same frequency and can be confined to regions below the diffraction limit. The technology for manipulating plasmons in nanoscale regions is referred to as plasmonics. Plasmonics has been used in practical devices such as biosensors, as described in the article, "Overview and Prospects for Research on Plasmons in Two-dimensional Semiconductor Systems" in this issue [1]. While surface plasmons excited on metal surfaces are commonly used for plasmonics experiments, they have limitations due to significant losses and poor controllability. These drawbacks have hindered the practical implementation of nanophotonics in which plasmons are used to transmit information in nanoscale structures. Graphene is attracting attention as a plasmonics material that can overcome these problems. Graphene plasmons are known to have low loss in the terahertz and mid-infrared frequency range. Another advantage is that they have a shorter wavelength than metal surface plasmons, which enables them to be confined in smaller regions. Specifically, electromagnetic waves converted into graphene plasmons can be confined to regions 1/1000th the wavelength of the electromagnetic waves. Moreover, the relationship between the wavelength and frequency of graphene plasmons varies with the charge carrier density, providing functions that are not available with metals, such as electrical control of the propagation speed and wavelength of the plasmons by gating. These advantages are expected to pave the way for electrically controllable nanophotonics and new applications, such as electrically tunable metamaterials*1.

2. Electrical control of graphene plasmons

The relationship between the graphene plasmon wavelength (λ) and frequency (f) varies with the charge carrier density (n): $\lambda \propto \sqrt{n}/f^2$. This indicates that the wavelength decreases as the carrier density decreases at a constant frequency. Therefore, plasmons are reflected at an interface where the charge density changes abruptly, akin to how light is reflected at an interface between media with different refractive indices. Since the carrier density can be varied electrically using a gate electrode, electrically controllable plasmonic devices and circuits can be implemented in principle (**Fig. 1(a)**). While a theory of such active control of graphene plasmons was reported in 2011, it is yet to be verified experimentally because of the technical difficulties in correctly implementing the theoretical concept. For effective control, it is necessary to induce a sharp change in carrier density within a region that is comparably shorter than the plasmon wavelength. However, implementing this using conventional metal gate

*1 Metamaterial: An artificial material the optical properties of which are designed by plasmon electric fields in periodic structures that are smaller than the wavelength of light.



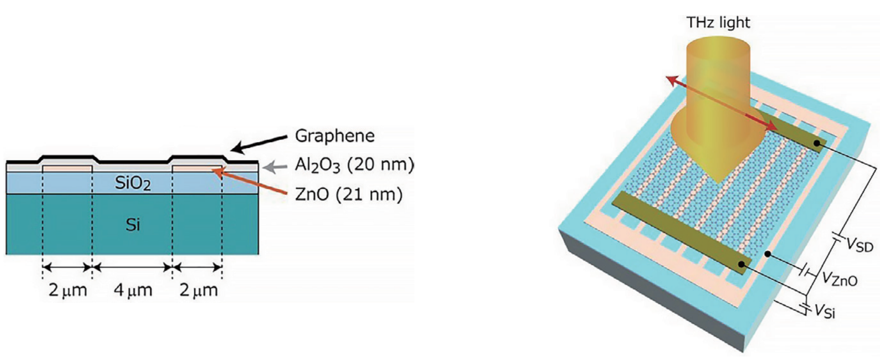
(a) Plasmon reflection at carrier density boundary

Reflectivity varies with the carrier density difference.

(b) Plasmon reflection due to the presence/absence of the metal gate

Uncontrollable plasmon reflection occurs at the boundary regardless of the carrier density profile.

Fig. 1. Graphene plasmon reflection.



(a) Sample structure

(b) Plasmon measurement by terahertz spectroscopy

SiO_2: silicon dioxide
Al_2O_3: aluminium oxide

Fig. 2. Sample structure and measurement method.

structures is challenging as the plasmon electric field distribution results in a substantial change at the boundary between regions with and without the gate resulting from the screening effect*2. This effect causes plasmon reflection at the boundary (**Fig. 1(b)**), which is determined solely by the presence or absence of the metal gate and not by the carrier density profile of the graphene, thus rendering plasmon reflection uncontrollable.

3. Demonstration of graphene plasmon control

The results presented in this article indicate that the confinement and reflection of graphene plasmons can be controlled electrically by using a high-resistivity zinc oxide (ZnO) thin film instead of metal as the gate material, thus avoiding the uncontrollable reflection caused by the metal gate [2]. The screening effect that is inherent in metal gates can be suppressed when the resistance of the gate electrode is high enough that the charges in the electrode cannot follow the oscillatory electric field at plasmon frequencies. To attain this condition, my colleagues and I used 20-nm-thick ZnO with high resistivity that was attained by adjusting the growth temperature as the gate material. The sample used in the experiments had a two-layer gate consisting of a ZnO thin film processed into strips of 2-µm width and 4-µm spacing on a low-doped silicon (Si) substrate (**Fig. 2(a)**), enabling independent control

*2 Screening effect: A phenomenon in which free electrons in a metal move when an external electric field is applied, canceling out the electric field inside the metal.

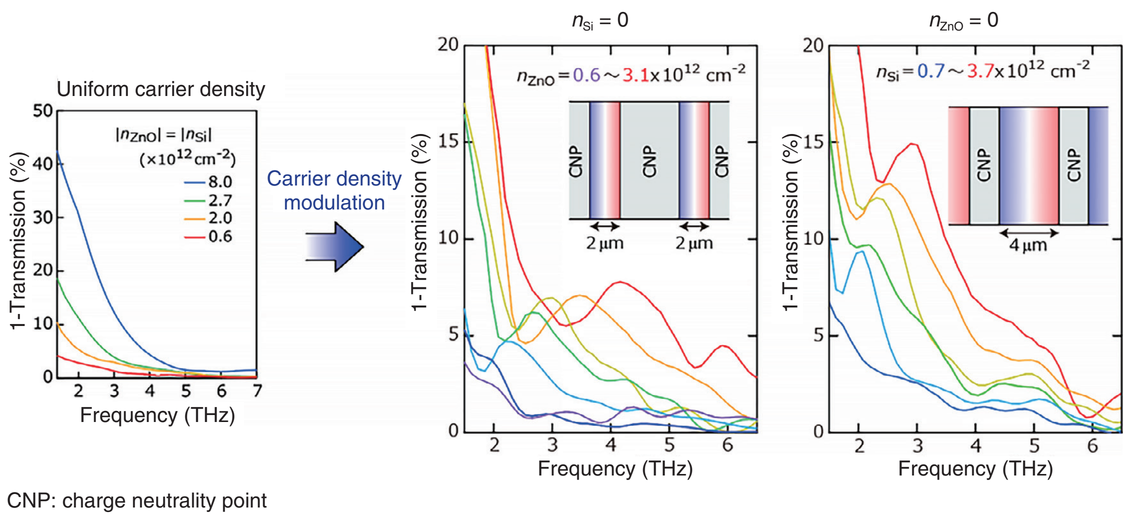


Fig. 3. Spectrum changes due to charge density modulation.

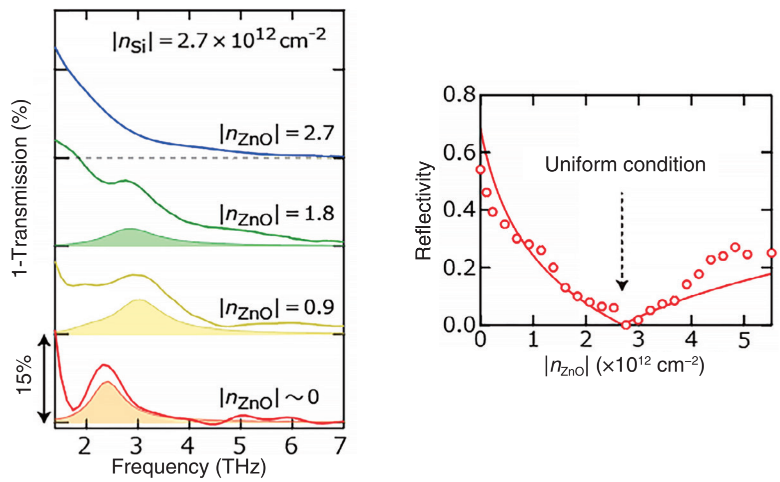
of the carrier density of graphene on the ZnO gate and Si gate (n_{ZnO} and n_{Si}). The plasmonic response in this sample was examined by irradiating terahertz light with an electric field perpendicular to the strips and measuring the transmission spectrum (**Fig. 2(b)**).

Figure 3 shows the extinction spectra of this sample in the terahertz range. When the carrier density is uniform, the absorption of terahertz light by graphene increases monotonically with decreasing frequency. This is typical behavior observed in pristine graphene, indicating the absence of uncontrolled plasmonic reflections caused by the ZnO gate. However, a peak appears in the spectrum when the ZnO gate and Si gate are adjusted such that the carrier density in either region is set to zero (at the charge neutrality point). Because plasmons are not excited in the region at the charge neutrality point, the spectrum peak can be attributed to plasmon resonance in a cavity formed in a region where the charge density is nonzero. We also succeeded in changing the resonance frequency by using the gate. This shows that it is possible to excite plasmons at the desired location and frequency by adjusting the gate voltages. This active spatial control of plasmon excitation can be applied to waveguides, switches, and resonators.

Continuously tuning of the plasmon reflectance at the boundary is also possible by varying the difference between n_{ZnO} and n_{Si}. **Figure 4** shows spectra for several n_{ZnO} values at a constant n_{Si}. As the density difference is increased from a uniform condition, the resonance peak increases with increasing reflectivity. The experimentally obtained plasmon reflectivity (red line in Fig. 4(b)) is consistent with Fresnel's law $R = \left|\frac{\sqrt{n_{ZnO}} - \sqrt{n_{Si}}}{\sqrt{n_{ZnO}} + \sqrt{n_{Si}}}\right|$ used for light reflection. This continuous control of plasmon reflectance can be applied to plasmon modulators and splitters.

4. Future prospects

These achievements provide a platform for implementing the theoretical concept for electrically controllable plasmon circuit. For future work, we plan to advance to experiments on directed plasmon propagation with controlled velocity and phase.



(a) Spectra for several n_{ZnO} at a fixed n_{Si} values

(b) Plasmon reflectivity as a function of n_{ZnO} at a fixed n_{Si}

Fig. 4. Plasmon reflection control.

References

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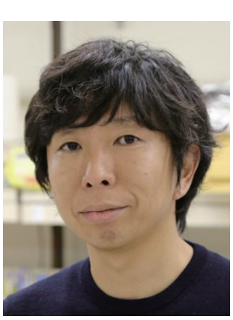

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