Graphene Plasmonics for Terahertz Photonics

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***Abstract*— Graphene plasmonics has the potential to revolutionize terahertz technology – the last great underdeveloped frequency band of electromagnetic waves. We describe here recent research on large-area tunable graphene plasmonic materials and devices for use in terahertz detectors, modulators, and filters.**

Keywords—graphene, terahertz, plasmonics

I. INTRODUCTION

Among its many outstanding properties, graphene supports terahertz surface plasma waves – sub-wavelength charge density oscillations connected with electromagnetic fields that are tightly localized near the surface. When these waves are confined to finite-sized graphene, plasmon resonances emerge that are characterized by alternating charge accumulation at the opposing edges of the graphene. The resonant frequency of such a structure depends on both the size and the surface charge density, and can be electrically tuned throughout the terahertz range by applying a gate voltage. Tunable graphene plasmonic resonators have been suggested for use in terahertz filters[1], modulators[2], detectors[3], and emitters. We describe here the design, fabrication, measurement and discuss potential applications of graphene plasmonic structures and materials.

II. PLASMONS IN GRAPHENE

Figure 1 illustrates a simple, one-dimensional graphene plasmonic structure, comprised of an array of micron-scale ribbons. The strong dip in transmission seen in Figure 1c is associated with a complementary peak in absorption at the plasmon resonant frequency. When this graphene structure is illuminated by a terahertz wave polarized perpendicular to the ribbons, the electrons (or holes) oscillate back and forth collectively in response to the applied field. The natural frequency (or resonant frequency) of oscillation scales in proportion to $n^{1/4}\, w^{-1/2}$, where w is the size of the graphene ribbon and n is the carrier concentration, which can be controlled electrically through the application of a gate voltage[4, 5]. The linewidth of the plasmon is inversely related to the mobility of the graphene.

The three plasmon resonances shown in Figure 1c were obtained using graphene ribbons with widths of w = 7, 1.5, and 0.75 µm. These devices were fabricated using a newly-developed large-area hydrogen-intercalated bilayer graphene that was epitaxially grown on silicon carbide substrates. The process of hydrogen intercalation yields a carrier concentration of 10^{13} cm^{-2} and mobility approaching 4,000 cm^{2}V^{-1}s^{-1}, a value that is unprecedented in wafer-scale graphene. Although higher mobility is available in micron-scale graphene flakes, terahertz devices typically require larger areas than can be readily achieved using exfoliated flakes.

The transmission and reflection of the graphene plasmon ribbons can be modeled using the equivalent circuit shown in Figure 1d. The semi-infinite transmission lines represent the free space region above and below the graphene layer, respectively. The graphene ribbons can be modeled as a

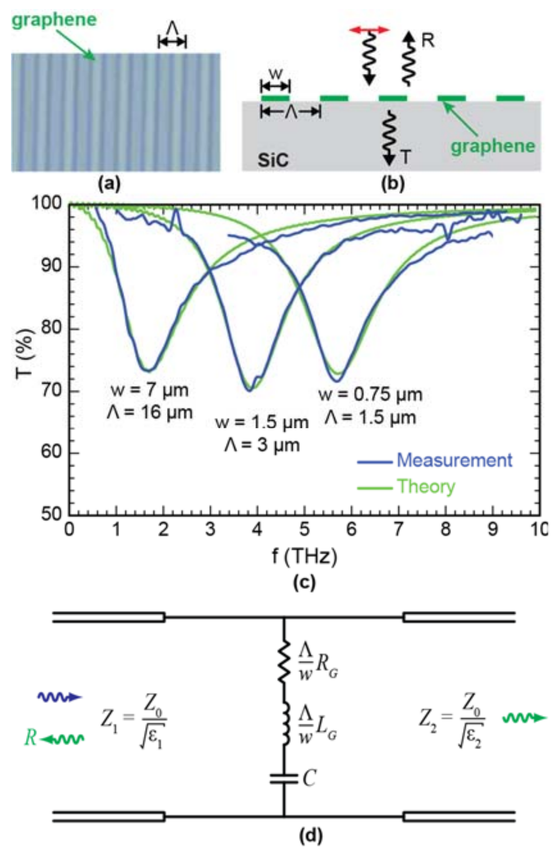

Figure 1 (a) Micrograph of graphene ribbons, (b) diagram of experimental measurement (c) transmission spectrum, showing plasmon resonances and (d) equivalent circuit model capacitive grid, with a series inductance to represent the kinetic inductance of the graphene electrons, and a resistance to represent the energy loss through scattering. This simple RLC equivalent circuit model has been shown to accurately reproduce the resonant features shown in Figure 1c, and correctly predicts the dependence of the resonant frequency on the carrier density and dimension.

III. Metal Contacted Plasmons

While the graphene ribbons shown in Figure 1a clearly show the enhanced absorption that can be obtained by exploiting graphene plasmons, these structures have only limited utility for active devices. Nearly all envisioned optoelectronic applications of graphene require electrical contacts in order to sense, probe, bias, actuate or gate the material. This poses significant problems because the metal electronic contacts dramatically alter the boundary conditions of the plasmon mode, and may also screen or reflect the incident radiation. The plasmon mode relies upon an accumulation of oscillating charge density at the opposing edges of each ribbon. Until recently, there was no experimental evidence that two-dimensional plasmons could be confined with conductive boundaries.

Figure 2a shows the structure of a hybrid graphene-metal structure that was developed recently[6]. In this device, the isolated graphene ribbons are replaced by narrow graphene-filled apertures in an otherwise continuous metallic film. The period Λ and slot width w are much smaller than the free-space wavelength. Notably, the graphene fill factor was optimized to approximately $\Lambda/20$, indicating only a 5% fill-factor. Contrary to expectations, the hybrid metal-graphene structure exhibits a strong plasmon resonance that can be even stronger than that of isolated graphene ribbons, as shown in Figure 2c.

The hybrid graphene-metal plasmon can be understood intuitively through a lumped-element circuit model shown in Figure 2d[7, 8]. The resonance of the graphene-metal grid is determined by the electrostatic capacitance, dominated by the metal grid capacitance C_M and the inductance, which is dominated by the kinetic inductance $L_G = R_G/\Gamma$ of the graphene itself, where R_G is the graphene resistance and Γ the scattering rate. The kinetic inductance depends on carrier density as $L_G \sim n^{-1/2}$, producing a resonance that is tunable with carrier density, controlled by a gate voltage. In the contacted graphene, the metal regions act as capacitive reservoir for charge accumulation, and the graphene serves as an inductive channel, thus forming a resonant circuit that interacts strongly with the incident radiation.

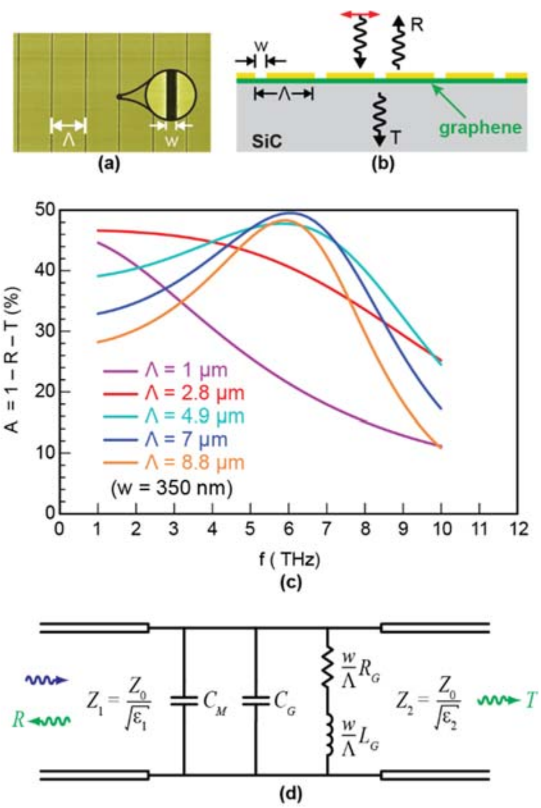

Figure 2 (a) Micrograph of hybrid metal-graphene plasmon resonance, (b) measurement diagram (c) calculated absorption in graphene (d) equivalent circuit model.

IV. Conclusion

Periodic, sub-wavelength graphene structures can exhibit tunable terahertz plasmon resonances that could find applications in modulators, filters, detectors and emitters. The methods described here allow for incorporation of metallic apertures and contacts, which greatly increases the scope of potential optoelectronic applications in science, medicine, security, and communications.

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References

[1] C. Pai-Yen & A. Alu, *IEEE Trans. THz* **3**, 748 (2013).
[2] B. Sensale-Rodriguez *et al.*, *Nat Commun.* **3**, 780 (2012).
[3] X. Cai *et al.*, *Nano Lett.* **15**, 4295 (2015).
[4] L. Ju *et al.*, *Nat. Nano.* **6**, 630 (2011).
[5] P. Nene *et al.*, *Appl. Phys. Lett.* **105**, 143108 (2014).
[6] M. Jadidi *et al.*, *Nano Lett.* **15**, 7099 (2015)
[7] S. H. Mousavi *et al.*, *Nano Lett.* **13**, 1111 (2013).
[8] L. B. Whitbourn & R. C. Compton, *Appl. Opt.* **24**, 217 (1985).