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ABSTRACT

Unique properties of graphene are combined to enable graphene plasmonic devices that could revolutionize the terahertz (THz) electronic technology. A high value of the carrier mobility allows us to excite resonant plasma waves. The graphene bipolar nature allows for different mechanisms of plasma wave excitation. Graphene bilayer and multilayer structures make possible improved THz device configurations. The ability of graphene to form a high quality heterostructure with h-BN, black phosphorus, and other materials systems supports advanced heterostructure devices comprised of the best properties of graphene and other emerging materials. In particular, using black phosphorus compounds for cooling electron–hole plasma in graphene could dramatically improve the conditions for THz lasing. High optical phonon energy allows for reaching higher plasma frequencies that are supported by high sheet carrier densities in graphene. Recent improvements in graphene technology combined with a better understanding of the device physics of graphene THz plasmonics and graphene plasmonic device designs hold promise to make graphene THz plasmonic technology one of the key graphene applications. Commercialization of plasmonic graphene technology is facing the same challenges as other graphene applications, which have difficulties in producing uniform large graphene layers, bilayers, and heterostructures of high quality and making good low resistance stable Ohmic contacts. The time projection for large scale graphene electronic device applications now extends into the 2030s. However, emerging graphene mass production technologies might bring commercial applications of the graphene plasmonic terahertz technology closer.

Out of the many potential applications of graphene,[1] THz and infrared applications of graphene stand out because of their potential to bridge the famous terahertz gap and enable beyond 5G technology. A long (up to 400 nm) mean free path of carriers in graphene,[2,3] significant THz absorption just in one monoatomic layer (2.3%),[4] graphene ability to form bilayer[5] and multilayer[6] structures, graphene bipolar conduction,[7] high quality heterostructures that graphene forms with h-BN,[8,9] and black phosphorus compounds[10–12] open up unique opportunities for THz[13] device and system engineering. A graphene monolayer is all surface, making it extremely sensitive to all kinds of chemical and biological agents.[14–16] This sensitivity makes graphene very promising for THz and sub-THz sensors, which demonstrated much higher sensitivity than more conventional CHEMFET sensors.

Starting from the first analysis of plasma waves in graphene,[17–19] plasmonic excitation at THz frequencies has been the focus of many investigations aiming to use graphene for THz detection,[20–24] modulation,[25] frequency mixing,[26] emission,[27,28] and lasing.[29] In this paper, we review emerging ideas for further development of graphene plasmonic THz technology and comment on the prospects of graphene commercialization.

The dispersion relation for the plasma waves—oscillations of the carrier density—in graphene is given by[22]

$$\omega = sk. \tag{1}$$

Here, ω is the plasma frequency, k is the wave vector,

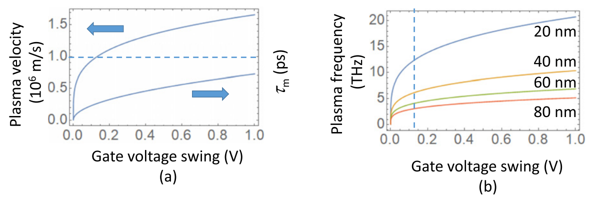


FIG. 1. Plasma velocity and momentum relaxation time for graphene vs gate voltage swing (a) and fundamental plasma frequency (b) for single layer graphene. The regions where Eqs. (1)–(3) are applicable are above the dashed line in Fig. 1(a) and to the right of the dashed line in Fig. 1(b).

$$s = \sqrt{q|V_g|/m_c}, \tag{2}$$

$$\omega_p = \frac{q^{3/4}|V_g|^{1/4} v_F k}{\pi^{1/2} C_g^{1/2}}. \tag{3}$$

(For comparison, the fundamental plasma velocity in the channels of conventional FETs is proportional to $V_g^{1/2}$ for a somewhat larger tunability.) As shown in Ref. 17, the plasma velocity in graphene should be larger than the carrier (Dirac) velocity, $v_o \sim 10^6$ m/s. However, accounting for the electron–electron collisions[30] shows that the plasma velocity could be smaller than v_o in the hydrodynamic regime, making it possible to observe Cherenkov type emission[33] and enabling "plasmonic boom"[31,32] instabilities.

For a bilayer graphene, Eq. (2) still applies, but the relevant effective mass m_{bl} is a much weaker function of n_s and could be even assumed to be approximately independent of n_s ($m_{bl} \approx 0.036 m_e$),[33] resulting in the fundamental plasma frequency,

$$\omega_p = \frac{q^{1/2}|V_g|^{1/2} k}{m_{bl}^{1/2}}. \tag{4}$$

Therefore, a bilayer graphene device has a better tunability by the gate bias.

Figures 1 and 2 show the plasma velocity, momentum relaxation time, and fundamental plasma frequencies, $f_p = \frac{\omega_p}{2\pi} = \frac{s}{4L}$ for single and bilayer graphene FETs (BLG FETs), respectively, for the gate lengths ranging from 20 nm to 80 nm. (The fundamental plasma wave depends on the boundary conditions at the ends of the channel. Here, we assume a short circuit boundary condition at the source and the open circuit boundary conditions at the drain corresponding to the fundamental mode of the plasma wavelength $\lambda = 4L$, where L is the channel length.[34]) Figure 3 shows the quality factor defined as $Q = \omega_p \tau$ calculated for the bilayer graphene FET. As seen, the typical plasma frequencies are in the THz range. In these calculations, we assume the mobility values of 20 000 cm^2/V s (much smaller than the record values achieved for graphene, even at room temperature,[35] but higher than typical measured values), 10 000 cm^2/V s and 5000 cm^2/V s. (At 77 K, the plasmonic propagation length can exceed 10 μm.[36])

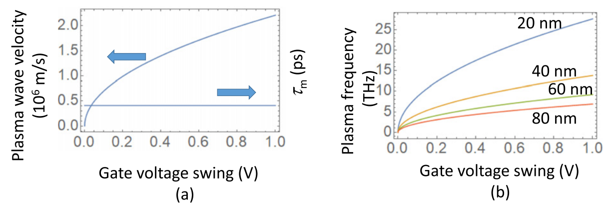


FIG. 2. Plasma velocity and momentum relaxation time for graphene vs gate voltage swing (a) and fundamental plasma frequency (b) for bilayer graphene.

For $Q > 1$, the FET channel behaves as a resonant cavity for the plasma waves and could support resonant tunable THz detection,[22] mixing,[28] and amplification[37] of the THz radiation, and electrical or optical excitations could trigger the plasma wave instabilities. The Dyakonov–Shur instability[37] and transit delay plasma instability[38] could be achieved both in single channel graphene FET and potentially in graphene plasmonic crystals.[39] Since the resonant excitation of the plasma waves is possible using the high mobility graphene layer, one possible application of a graphene plasmonic Terahertz FET (TeraFET) is for tunable absorbers or tunable modulators.[40] For longer samples and/or samples with lower mobility values (when $Q = \omega_p \tau < 1$), the device nonlinearities still lead to the plasma wave rectification, enabling the broadband THz detection similar to that discussed in Refs. 41 and 42. Another mechanism is the "plasmonic boom" instability.[34,35] This type of instability might be harder to reach in graphene because the plasma wave velocity is quite high (see Figs. 1 and 3).

Double-graphene-layered FETs (DGL-FETs) could better perform as THz detectors than single layer graphene FETs due to their photon/plasmon-assisted inter-layer tunneling mechanisms.[2,43,44]

Figure 4 (from Ref. 22) shows possibly the best demonstration of the sub-THz and THz detection using BLG.

As seen, the responsivity changes its sign at the Dirac point ($V_g = 0$) and follows the factor

$$F = \frac{1}{\sigma}\frac{d\sigma}{dV_g}. \tag{5}$$

As shown in Ref. 45, this factor is more accurately given by

$$F = \frac{1}{n_s}\frac{dn_s}{dV_g}. \tag{6}$$

However, Eq. (5) still yields the same qualitative dependence. Figure 4 clearly show the difference between the broadband and resonant detection regimes. The measured quality factor varied between 4 and 11 for the resonant detection and between 0.2 and 0.7 for the

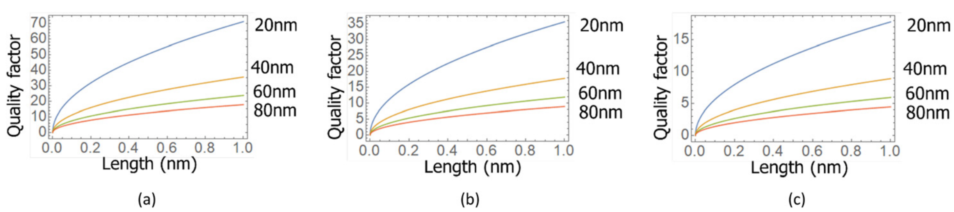


FIG. 3. Quality factor vs gate voltage swing for BLG FET: (a) mobility 20 000 cm^2/V s, (b) 10 000 cm^2/V s, and (c) 5000 cm^2/V s.

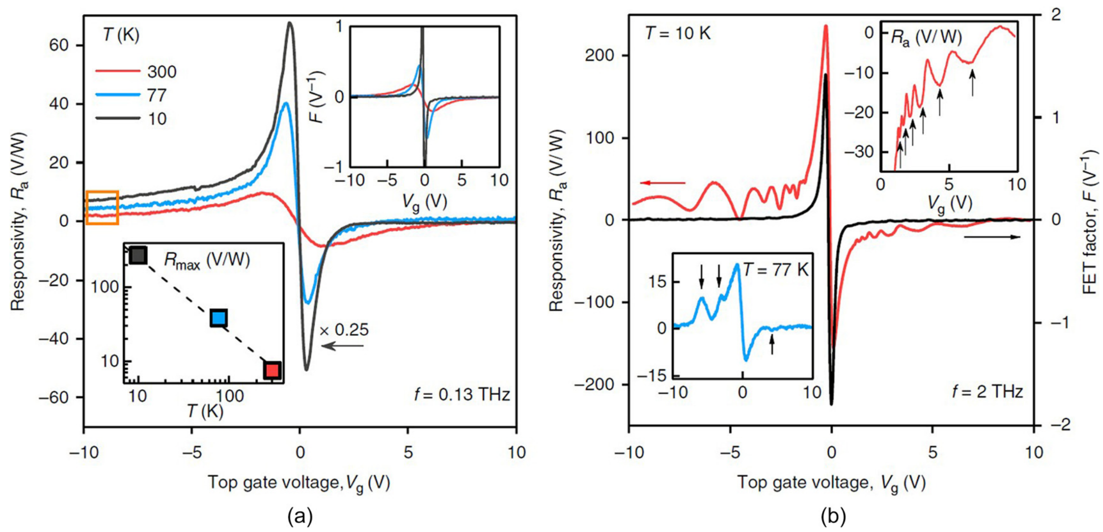


FIG. 4. THz detection by BLG FET: (a) frequency $f = 130$ GHz. The rectangle highlights an offset due to the rectification by the p–n junction between the p-doped graphene channel and the n-doped area near the contact. Upper inset: FET-factor F as a function of the gate bias V_g. (b) $f = 2$ THz radiation. The upper inset shows a zoomed-in region of the photovoltage for positive gate voltage. Lower left inset: responsivity at 77 K. Lower right inset: The shape of the current voltage characteristics at 10 K, 77 K, and 300 K (Dirac point $V_g = 0$). Reproduced with permission from Bandurin *et al.*, Nat. Commun. **9**, 5392 (2018). Copyright (2018) Authors, licensed under a Creative Commons Attribution 4.0 License.[22]

broadband detection.[22] The resonant quality factor was consistent with the measured momentum relaxation (transport) time τ_m because the samples were very long (6 μm) and the viscosity related decay frequency was much smaller than 1/ τ_m. It would be very interesting to perform similar measurements for much shorter channels to extract the viscosity values from the measured quality factors since viscosity is expected to play an important role in graphene.[46,47]

BLG FETs also have advantages in photomixing applications[48] and terahertz generation.[49] An experimental demonstration of the emission and detection of THz radiation in a DGL-FET was reported in Ref. 48. Figure 5 shows one possible implementation of such a bipolar tunneling graphene device.[49,54] In this device, the electron–hole injection provides energy for growing the plasma wave instability. It could also be used as a unit cell of a plasmonic crystal, provided that a proper match in boundary conditions between the cells is met by using variable width geometry[39,50]

In addition to the plasmonic instabilities previously considered for standard heterostructures, the proposed plasma wave instability mechanisms in graphene also include the self-excitation of the plasma waves in the G-TUNNET device[51,52] and super radiant lasing in graphene nanocavities.[27]

The proposed resonant THz graphene FETs also include devices with split gates, electrically induced lateral p–n junctions, and perforated graphene layer (PGL) channels.[53] The perforated depletion regions form an array of nanoribbons creating the barriers for the holes and electrons, leading to the rectification of the AC across the lateral p–n junction enhanced by the excitation of plasmonic oscillations in the p- and n-sections of the channel. Such detectors are predicted to have a very high responsivity at the THz radiation frequencies close to the frequencies of the plasmonic resonances tunable by the gate bias.[53]

The plasma waves support a THz response of the graphene lateral Schottky diodes. The possibility of the negative dynamic conductivity in fairly large graphene areas could promote an efficient THz lasing[27,51] (see Fig. 6). Vertical hot-electron graphene-base transistors could also operate as resonant plasmonic terahertz detectors.[54]

Gate voltage tunability is an important property of graphene plasmonic devices that enabled graphene plasmonic applications for tunable THz transparent absorbers[55,56] and electro-optic modulators.[57] Low loss graphene plasmonic waveguides have promise for realizing ultra-compact optoelectronic systems.[58] Another suggested application is in photovoltaics.[59]

GL-based heterostructures can include the black arsenic injecting layers and other injecting layer materials with a proper band alignment to the GLs.[60] Such graphene-black phosphorus heterostructures have been shown to cool the electron–hole plasma in graphene helping to meet conditions for stimulated emission of THz radiation.

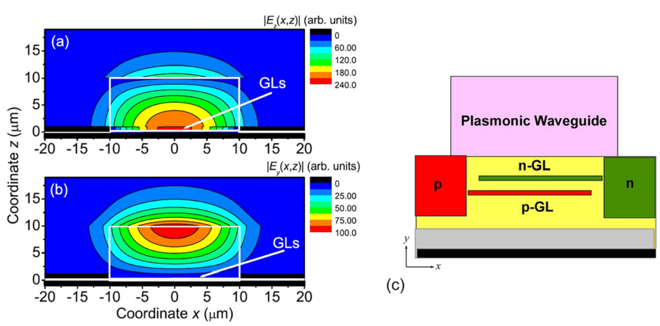
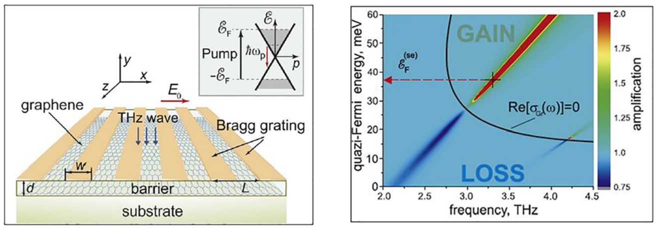


FIG. 5. Spatial distributions of THz electric field components: (a) $|E_z(x, z, \omega)|$ and (b) $|E_y(x, z, \omega)|$ in a DGL waveguide structure. Reproduced with permission from Dubinov *et al.*, "Surface-plasmons lasing in double-graphene-layer structures," J. Appl. Phys. **115**, 044511 (2014). Copyright 2014 AIP Publishing.[4] (c) The schematic of the device.



(a) (b)

FIG. 6. Asymmetric double gated GFET plasmonic lasing device (ADGG-GFET): (a) schematic of the device and (b) simulated amplification. Reproduced with permission from Popov *et al.*, "Amplification and lasing of terahertz radiation by plasmons in graphene with a planar distributed Bragg resonator," J. Opt. **15**, 114009 (2013). Copyright 2013 IOP Publishing.[27]

Of special interest is the graphene plasmonic detectors integrated with silicon[61] and silicon-on-insulator technology[62] that demonstrated a high responsivity of 85 mA/W at 1.55 mm (about an order of magnitude higher than that of the standard silicon Schottky photodetectors). High responsivity and compact size are the key features of graphene-based plasmonic detectors.[63,64]

The recently predicted Giant Inverse Faraday Effect[65] (still to be observed) is for controlling magnetization by light. It needs a high mobility sample, and graphene, and, therefore, might be a superb material for its observation using plasma waves in graphene nanorings. Another direction in the graphene plasmonic TeraFET research is exciting plasma waves and controlling the phase shift at the ends of the channel. This could yield superior "ratchet effect"[66] THz detectors and implement vector detection, allowing us to determine not only the intensity but also the phase and propagation direction of the impinging radiation.

The key challenges in plasmonic graphene technology are bridging the gap between the predicted and demonstrated performance and bringing this technology to a market. The roadblocks in addressing these challenges are common to all graphene electronic devices and are related to the difficulty of producing graphene of high quality,[67] making good low resistance stable Ohmic contacts and large-scale processing. Graphene edges, vacancies, variation in the number of layers, and local disorder all affect the graphene quality, reproducibility, and, as a consequence, the device performance and scale-up.[68] The time projections for large scale graphene electronic device applications extend into the 2030s.[69] However, recent developments[70–72] in graphene mass production technology might shrink this time frame and bring commercial applications of the graphene plasmonic terahertz technology closer.[73] In addition to beyond 5G communications,[74] the graphene plasmonic technology could impact many other system applications relying on sensing and communications including biotechnology,[75,76] gas,[77,78] chemical sensing,[79] and photovoltaics.[80]

In our opinion, the graphene science and technology development has been evolutionary, not revolutionary. But of the greatest attributes of science and technology is that nothing could be unlearnt, and recent developments, such as the reported discovery of how to cheaply produce graphene from biological waste,[81] might be but precursors of more dramatic developments still to come. Graphene plasmonics is expected to play a special role because it takes full advantage of the unique properties of graphene ranging from its two-dimensional structure to high optical phonon energy and a long momentum relaxation time. It has demonstrated potential for enhancing the response by several orders of magnitude using tunable resonance modes and allows for the direct coupling of THz, infrared, and optical signals, avoiding the detrimental contributions from interconnects and contacts. Some important developments such as integration with silicon and 2D heterostructures, grating gate graphene structures, and graphene plasmonic antennas and waveguides, will undoubtedly be explored further. Other issues, such as plasmonics of rippled [82] and 3D [83] graphene and viscous [84] graphene plasmonics, need to be investigated further. Another important system is carbon nanotubes (CNTs), which are simply graphene rolled into nanotubes and have promise for plasmonic applications, both as individual nanotubes[85] and as CNT mats,[86] especially near the percolation point. Plasmonics will be explored in other 2D monolayer materials[87] that try to emulate, reproduce, or even improve the unique properties of graphene.

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