Device Concepts for Graphene-Based Terahertz Photonics

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(Invited Paper)

***Abstract*—Graphene is establishing itself as a new photonic material with huge potential in a variety of applications ranging from transparent electrodes in displays and photovoltaic modules to saturable absorber in mode-locked lasers. Its peculiar bandstructure and electron transport characteristics naturally suggest graphene could also form the basis for a new generation of high-performance devices operating in the terahertz (THz) range of the electromagnetic spectrum. The region between 300 GHz and 10 THz is in fact still characterized by a lack of efficient, compact, solid state photonic components capable of operating well at 300 K. Recent works have already shown very promising results in the development of high-speed modulators as well as of bolometer and plasma-wave detectors. Furthermore, several concepts have been proposed aiming at the realization of lasers and oscillators. This paper will review the latest achievements in graphene-based THz photonics and discuss future perspectives of this rapidly developing research field.**

***Index Terms*—Terahertz (THz), detectors, modulators, field effect transistors, far-infrared, lasers, plasma waves, plasmonics.**

I. Introduction

Since the initial demonstration of microwave devices and of the first semiconductor laser more than 50 years ago, both electronics and photonics have experienced a rapid evolution. The progress in solid-state high-frequency components was driven by the need of ever-shorter wavelength in precision Radar systems and by the demand for ever-higher bandwidth in wireless communication links. Likewise, the extension of the wavelength in semiconductor lasers from the near-infrared of the first GaAs laser diodes to the ultraviolet was stimulated by the need of small, compact visible sources for optical data storage and retrieval, displays, optical sensing, and medical treatment.

For the terahertz (THz) region (0.3–10 THz, $\lambda \sim 1$ mm–30 μm), on the contrary, the first compelling applications are just now being identified. The interaction between THz waves and matter was indeed a mostly neglected research area for a long time, until milestone progresses in the technology to produce and detect THz waves were achieved at the beginning of the 1980s. The most significant advancements were the design of ultrafast switches [1], [2], the demonstration of optical rectification [3], and the use of photoconductive antennas [4]. Even more important was the realization of free-space electrooptical sensing [5], which allows an extremely wide detection bandwidth from 100 GHz up to 50 THz.

The development of the above-mentioned components and techniques in turn allowed the invention of THz time-domain spectroscopy (TDS) [6] and, later on, the first use of THz TDS for imaging [7].

The availability of a reliable technology to produce and detect THz radiation with high SNRs has then prompted in the last decade a major surge of research aiming at the use of THz radiation for a variety of commercial applications in a variety of fields ranging from industrial process and quality controls, to medical diagnosis, biochemical analysis, and security screening [8]–[10].

Despite these advances, generation and detection of THz radiation in these systems takes place indirectly from the conversion of an optical beam, meaning also that the high dynamic range achievable is the result of a coherent detection scheme requiring a rather complex and costly setup. Although many competing, compact, electrically controlled, solid-state technologies already exist for the direct generation, manipulation, and detection of THz waves [11], they all suffer from one or more drawbacks that are currently still limiting the widespread exploitation of THz photonics.

The unique optoelectronic properties of graphene make it an ideal platform for a variety of photonic applications [12], including fast photodetectors [13], transparent electrodes in displays and photovoltaic modules [14], optical modulators [15], plasmonic devices [16], and ultrafast lasers [17]. Owing to its high carrier mobility, gapless spectrum, frequency-independent absorption, and the possibility to deeply alter its dielectric constant through electrical gating, graphene is a very promising material for the development of modulators, sources, and detectors operating across the far-infrared. Theoretical proposals have in fact been quickly formulated right after the first graphene breakthroughs, but in the last 1–2 years very promising device implementations have indeed begun to be realized. Here we will review the main achievements in this very recent, but rapidly progressing field, and will discuss the opportunities for new performance improvements and further exciting discoveries.

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II. Modulators and Plasmonic Devices

Many possible applications of THz photonics require high-speed modulation or switching of the THz beam. One can for instance consider high-throughput wireless communications in short-range links; another possibility is the development of fast spatial light modulators to circumvent the difficulties and costs of 2-D detector arrays in imaging systems. Among available THz sources, quantum cascade lasers [18] can already support very high modulations rates up to tens of GHz [19]; these, however, are not yet room temperature devices, and the direct current modulation of the lasers often poses other problems, like simultaneous AM and FM contributions, instabilities, necessity of using small low-power lasers, etc.

For such reasons, researchers have been pursuing the development of separate electrooptic modulation components that can be used independently of the chosen source-detector combination.

Graphene lends itself naturally as an excellent material for broadband electrooptic modulators in the infrared range, thanks to the possibility of controlling the absorption coefficient of interband transitions [15]. Shifting the chemical potential via electrostatic gating below and above half the frequency of the impinging radiation, the absorption can indeed be tuned from the flat characteristic 2.3% value of graphene to basically zero, owing to Pauli blocking of the transitions. Higher modulation amplitudes can then be achieved employing multiple stacked layers. In the THz, however, this mechanism is not directly applicable since, for such low energies, the optical properties are mainly dominated by the intraband electronic response of the 2-D electron gas (2DEG).

In the far-infrared region of the electromagnetic spectrum, the most successful approach to electrooptic modulation compatible with room temperature operation is to exploit the variation of dielectric constant (real and imaginary part) with the charge-carrier density of a semiconductor structure. This variation can in fact be quite large and easily obtained by electrical gating.

The simplest configuration is based on a gated 2DEG in a GaAs/AlGaAs heterostructure modulating the absorption (and hence the transmission) of the THz wave propagating across the device [20], [21]. Although the response of the 2DEG is largely broadband, the attainable modulation depth is just a few percents, with further limitations arising from the signal loss due to the metallic gates employed and from the relatively large *RC* constants resulting from the large wavelength-size gates, which restrict operation to the kilohertz range.

Despite the Dirac-like relativistic dispersion of the bands [22], the free-electron contribution to the ac conductivity of graphene is not different from that of a conventional massive 2DEG, provided the Drude weight expression is written in terms of the cyclotron mass [23]. A graphene-based THz modulator concept can then be easily implemented following the same configuration just described for semiconductor heterostructures [20]. On the other hand, the typically larger conductivity achievable in graphene sheets should immediately lead to higher modulation depths, with a further added possibility of substituting also the metallic gate with a graphene layer [24]. The latter configuration would be highly beneficial; a simple transfer-matrix analysis shows in fact that the achievable modulation amplitude for the transmitted THz wave is the largest when gate and channel possess similar conductivities [24]. Furthermore, a graphene gate would also decrease attenuation with respect to a metal one. Overall, modulation depths close to 100% have been predicted.

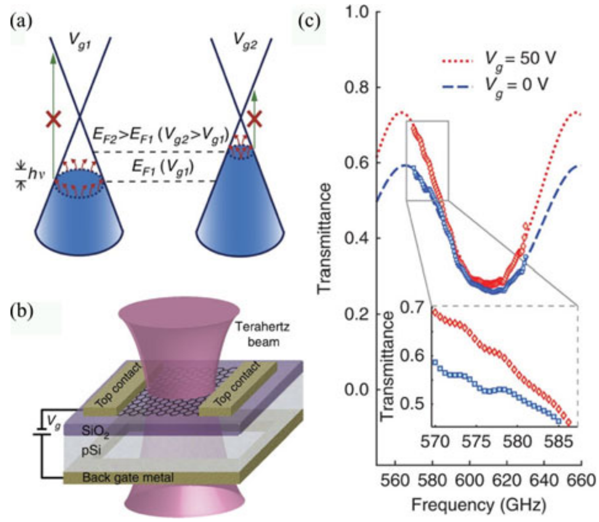

Fig. 1. (a) Operating principle of the graphene THz modulator: intensity of intraband absorption varies with chemical potential owing to the different density of states available. (b) Scheme of the actual device implementation. (c) Transmission as function of radiation frequency for zero and 50 V gate bias. (Adapted by permission from Macmillan Publishers Ltd: [25], copyright 2012).

First practical realizations have been obtained in the last year using a SiO_2/lightly p-doped Si substrate (sufficiently transparent in the THz) with a ring-shaped electrode to control the graphene charge density, as schematically sketched in Fig. 1 [25]. A modulation amplitude as large as 15% has been demonstrated around 600 GHz. As expected, the amplitude is also relatively frequency independent when interference effects and substrate contributions are removed. Soon after, a modified configuration devised to operate in reflection has been optimized to maximize the electric field amplitude at the graphene sheet position [26]. In this latter work, a modulation depth of about 64% has then been achieved. This latter device concept has also been developed into a 4×4 modulator array suitable for first practical imaging applications [27].

A more sophisticated configuration for electronic THz modulation relies on the use of plasmonic metamaterials. A periodic metallic structure is employed with the purpose of producing a resonance in the optical response, with an electric field intensity efficiently confined in specific regions of space. The width and intensity of this resonance are strongly dependent on the losses of the substrate material in the region where most of the field is localized, and the losses can then be tailored by locally changing the charge carrier density via electrical gating [28], [29]. Although in this case the operation of the modulator is limited to a relatively narrow bandwidth, roughly defined by the resonance, large modulations of more than 50% can be reached thanks to the field enhancement [30]. Furthermore, by

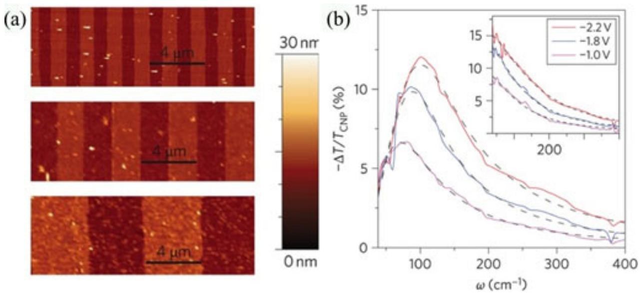

Fig. 2. (a) AFM images of graphene microribbon samples with widths ranging from 1–4 μm. (b) Electrical-gating control of plasmon resonance in a microribbon sample. The terahertz radiation is polarized in the plane orthogonal to the grating. The resonance blue-shifts and gains oscillator strength with increasing carrier concentration. The inset shows free-carrier absorption for polarization parallel to the grating. (Adapted by permission from Macmillan Publishers Ltd: [33], copyright 2011).

integrating a high-electron-mobility transistor into each unit cell of the metamaterial, switching speeds above 10 MHz can be obtained [31].

Collective charge excitations (plasmons) in graphene [16] naturally present strong similarities to the electromagnetic waves propagating at the boundary between a metal and a dielectric (surface plasmons). Specifically, they are characterized by a transverse magnetic polarization and by an exponentially decaying electric field amplitude in the direction orthogonal to the graphene plane. Being the electron motion frozen in the plane, and owing to the Dirac-like band profile, graphene plasmons present a qualitatively different dispersion and display tighter field localization and reduced propagation losses than metal surface plasmons [32]. Moreover, plasmon charge can be electrostatically controlled, making graphene the ideal solution for the implementation of reconfigurable metamaterials to be used as THz modulators.

Electromagnetic radiation cannot couple directly to 2-D plasmon excitations, but the issue can be addressed using structures engineered on a subwavelength scale. One simple geometry is a periodic grating of graphene microribbons as that described in Fig. 2 [33].

The plasmon resonance energy scales as $n^{1/4}$ (n being the carrier density) for Dirac plasmons in a microribbon array and with w^{-2}, w being the ribbon width. Providing electrical gating through an ion gel top electrode allows then a modulation of the THz transmission of up to 15% of the value at the charge neutrality point as reported in Fig. 2 [33].

More recently, THz switching devices in which the change in conductance of a graphene layer is used to externally modulate the *LC* resonance of a periodic pattern of metallic metaatoms have been proposed [34]. In this case, the graphene sheet is in direct contact with hexagonal metallic rings and is sandwiched between two metallic electrodes shaped in the form of strongly subwavelength gratings embedded in a dielectric. The latter are used to provide the necessary gate bias but are also transparent to THz radiation, acting basically as wire grid polarizers. Fig. 3 shows the device construction and a colormap of the relative modulation of the transmission as function of frequency and gate voltage.

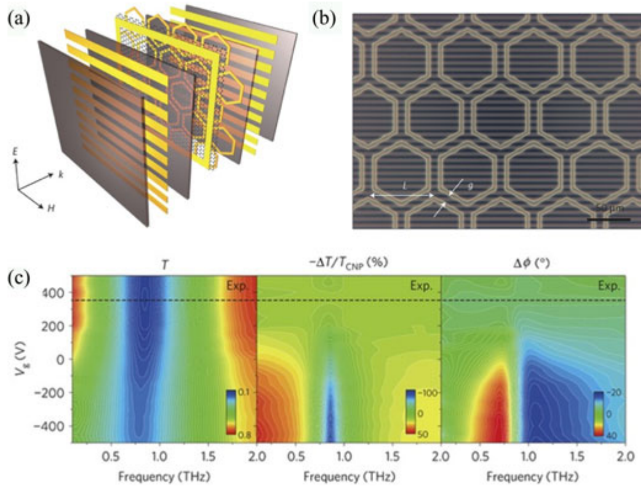

Fig. 3. (a) Schematic configuration of a reconfigurable graphene-based metamaterial. (b) Microscope image of the actual device; the hexagonal metaatoms and wire-grid electrode are visible. (c) Transmission, amplitude, and phase modulation as function of terahertz frequency and gate voltage. (Adapted by permission from Macmillan Publishers Ltd: [34], copyright 2012).

In the proximity of the resonance, modulation amplitudes as large as 47% have been recorded, with a phase modulation of about 32° [34]. In a further device featuring a metamaterial with multilayer graphene, record values of 58% (corresponding to 14%/μm) and 65° have been achieved [34]. Multilayer stacks, in fact, enhance plasmonic resonances, an effect that is a direct consequence of the $n^{1/4}$ scaling law for the energy ($n^{1/2}$ for the amplitude) of Dirac plasmon resonances [35].

Beyond modulators, further electrooptic THz devices are obviously possible and being considered. Among these, the most interesting are probably reconfigurable graphene-based antennas where response frequency and radiation pattern are electrically controlled [36], [37]. Dynamically tunable metamaterials for "cloaking" applications have also been proposed [38].

Finally, it has to be mentioned that optically controlled THz modulators exploiting the interband absorption of a laser pump to change the semiconductor carrier density are also possible. In this respect, the use of graphene on top of the semiconductor (e.g., silicon) has been shown to yield better results, thanks to a transfer of photoexcited electrons from the semiconductor to the higher mobility graphene layer [39].

III. Detectors

Photodetection of far-infrared radiation is relevant for a variety of strategic imaging applications, ranging from medical diagnostics to process control and homeland security. THz rays can in fact penetrate commonly used dielectric materials, otherwise opaque for visible and mid-infrared light, allowing detection of substance-specific spectroscopic features and a submillimeter diffraction-limited lateral resolution. In this perspective, the development of a breakthrough solid-state technology for fast, room-temperature (RT) THz detectors, eventually integrated in high-speed multipixel arrays, is highly desired.

Commercially available THz detectors are based on thermal sensing elements that are either very slow (10–400 Hz modulation frequency for Golay cells or pyroelectric elements, with noise equivalent powers (NEP) in the 10^{-10} $\mathrm{WHz}^{-1/2}$ range) or require deep cryogenic cooling (4 K for superconducting hot-electron bolometers), while those exploiting fast nonlinear electronics (Schottky diodes) are usually limited to low-THz frequencies for best performances [40].

More recently, electronic devices based on the gate-modulation of the conductance channel by the incoming radiation have been realized in high-electron-mobility transistors (HEMT), FET, and Si-MOSFET architectures, showing fast response times and high detectivities [41], as well as the possibility of implementing multipixel focal-plane arrays [42]. This approach was also recently extended to InAs nanowire FETs operating as RT detectors in the 0.3–3 THz range [43], [44].

The operating mechanism of a FET detector is not trivial [41], [45], [46], but can intuitively be interpreted as deriving from the nonlinear dependence of the FET channel current on the gate voltage near the pinch-off point. These devices have the advantage that the responsivity can be maximized with the gate bias V_G, while measuring the output at the drain with no source–drain bias applied, thus dramatically improving the SNR. THz detection in FETs is mediated by the excitation of plasma waves in the transistor channel. On one hand, a strong resonant photoresponse is predicted in materials having plasma damping rates lower than both the frequency ω of the incoming radiation and the inverse of the wave transit time τ in the channel. This requires mobilities of at least several thousand cm^2/Vs at frequencies >1 THz. Under these conditions, stationary states arising from the quantization of plasma waves over the gate length are excited whenever V_g is such that $n\pi s/(2L_g) = \omega$, where n is an odd integer, s the plasma-wave velocity, and L_g the gate length. On the other hand, when plasma oscillations are overdamped, i.e., decay on a distance smaller than the channel length, broadband THz detection is predicted [41]. In this case, the oscillating electric field of the incoming radiation applied between source and gate electrodes produces a modulation of both charge density and carrier drift velocity. Carriers travelling toward the drain generate a continuous source–drain voltage, Δu, controlled by the carrier density in the channel. This can be then maximized by varying V_g.

Resonant photodetection is still to be fully demonstrated at RT, although some suggestive evidences were reported for high-electron-mobility transistors [47], [48], while the large, spectrally sharp, and tunable responsivity enhancements with respect to the nonresonant case are still to be achieved. High mobility at RT is therefore crucial to take full advantage of resonant detection.

The naturally occurring 2DEG in a doped graphene sheet has a very high mobility even at RT [22]. Furthermore, it supports plasma waves that are weakly damped in high-quality samples [16], [32]. Thus, single-layer and bilayer graphene FET (GFET) plasma-based photodetectors could outperform other THz detection technologies.

The practical development of graphene-based photodetectors has been mainly limited so far to the visible to near-infrared range, exploiting the creation of electron–hole pairs following light absorption [13], [49]–[51]. In the THz range, however, the photon energy is just a few meV, and light absorption is prevented by Pauli blocking, owing to the unavoidable doping of as-produced graphene samples, and charge inhomogeneities [52]. In the last few years, however, two technological approaches have been proposed and theoretically investigated.

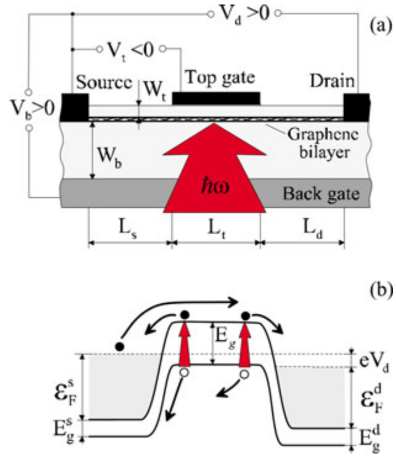

Fig. 4. (a) Schematic diagram of a graphene bilayer phototransistor. (b) Corresponding band profile. (From ref. [53], copyright (2009) by the American Physical Society).

A. Graphene Bilayer Field-Effect Phototransistor

The proposed technology is based on a graphene bilayer channel separated by a dielectric layer from the back gate [53]. The latter provides the formation of a 2DEG in the channel when the back gate is biased positively with respect to the source and the drain: a top electrode serving as the top gate is also present and biased negatively (see Fig. 4). The device operation is associated with the variation in the source–drain electron current under illumination, when electron–hole pairs are generated across the bilayer bandgap created in the high-transverse field region below the gate. The photogenerated electrons are swept out to the conducting sections, whereas the photogenerated holes accumulate in the depleted section, lowering the potential barrier for the injected electrons. High-k dielectrics for the gates are predicted to allow a rather high detectivity in the range of photon energies above a bias-dependent cut-off frequency in THz. The responsivity (R_v) values can be larger, even at RT, than those of cryogenically cooled quantum well and quantum dot infrared photodetectors (QWIPs and QDIPs), mainly thanks to the relatively large quantum efficiency of the interband absorption and to the photoelectric gain. Moreover, since the cutoff photon energy depends on the applied voltages such device technology can be easily implemented to realize detectors with voltage-tuned spectral characteristics and multicolor RT detector arrays.

B. Multiple Graphene-Layer (GL) Structures With Reverse Biased p–i–n Junctions

Devices with multiple graphene structures have been proposed with either p- and n-doped sections in the GLs near

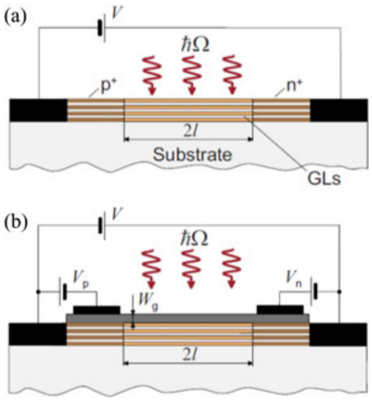

Fig. 5. Schematic diagram of multiple-GL structures with (a) doped and (b) electrically induced p–i–n junctions. (Reprinted with permission from ref. [54], copyright 2010, American Institute of Physics).

the Ohmic side contacts [see Fig. 5(a)], or with split gates which provide the formation of the electrically induced p- and n-sections [see Fig. 5(b)]. The gates are properly separated from the graphene by an insulating SiO_2 or HfO_2 layer [54].

The predicted operating principle is here similar to a standard p–i–n photodiode, i.e., associated with the interband photogeneration of the electrons and holes in the intrinsic sections by the incoming THz radiation. The photogenerated electrons and holes propagate under the electric field created by the bias voltage in the directions toward the n-section and p-section, respectively. A dc or ac photocurrent is therefore induced in the circuit. The authors underline the increased R_v of the proposed structures with respect to QWIPs having a number N of quantum wells equal to the number of graphene layers. Here indeed $R_v \propto N$, while in a QWIP R_v is N-independent. Another interesting point is that such proposed detector, if operating in different spectral ranges, would exhibit the same dark current, in contrast to QWIPs or QDIPs where any transition of lower photon frequency would require lower ionization energy and, hence, exponentially higher dark current. Multiple-GL structures could also surpass narrow-gap and gapless semiconductor photodetectors like HgCdTe, owing to the relatively low thermogeneration rate mediated by optical phonon absorption, with respect to the high rate mediated by strong Auger processes that is typical of the latter class of materials.

From an experimental point of view, cryogenic graphene bolometric detectors have been recently developed, and their operation demonstrated in the mid-infrared [55]. Graphene is indeed particularly well suited for bolometer devices that detect temperature-induced changes in the electrical conductivity caused by the absorption of light. Its small electron heat capacity and weak electron–phonon coupling lead in fact to large changes in the electron temperature. The proposed technology indeed exploits the small electron–phonon scattering and broadband photon absorption of graphene to realize a sensitive and broadband photon detector. When light is absorbed by a dual-gated bilayer graphene (DGBLG), the electrons heat up easily due to their small specific heat (see Fig 6). The weak electron–phonon interaction creates a bottleneck in the heat path, decoupling elec-

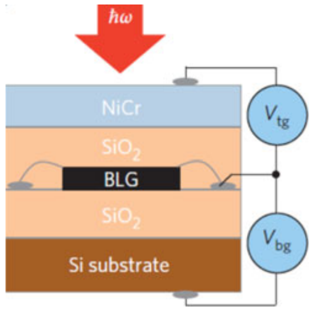

Fig. 6. Schematic of bolometer device geometry with electric-field-effect gating. (Reprinted by permission from Macmillan Publishers Ltd: [55], copyright 2012).

trons thermally from the phonon bath. Light illumination causes a resistance change ΔR in the sample. This photon absorption-induced ΔR is then converted to a detectable electrical signal.

The observed photoresponse is dominated by thermal effects, with the majority of the optical energy lost first to hot electrons and then to acoustic phonons. The developed detector exhibits an electrical NEP of about 33 $\mathrm{fWHz}^{-1/2}$ at 5 K), which corresponds to an optical NEP of about 1.5 $\mathrm{pWHz}^{-1/2}$ when considering the 2.3% absorption coefficient of a graphene monolayer. A high intrinsic speed (>1 GHz at 10 K) is also demonstrated [55].

Recent theoretical papers [56], [57] have analytically shown the advantages of graphene as a basis for novel THz plasma waves devices. The spectrum of plasma waves is extremely sensitive to the electron (hole) mass and the plasma properties of a 2DEG become more pronounced with decreasing effective masses and increasing electron mobility. Although the dispersion of plasma waves in gated graphene is strongly nonlinear and density dependent, for fairly long wavelengths compared to the gate-graphene distance, a linear approximation holds quite well. The resulting plasma velocity s considerably exceeds that of electron (hole) III-V 2DEGs, being $s = \omega_p/k \gg 10^6$ m/s, even at rather low electron densities. As a result THz plasma waves could be resonantly excited even in relatively large-scale devices. Moreover, since s is strongly electron density dependent, ω_p should be tuneable in a wide range with the gate voltage V_G. Furthermore, since $s \gg v_F$, with v_F being the electron Fermi velocity, the Landau damping of plasma waves is negligible, and the plasma wave damping is $\approx 1/2\tau$ where $\tau = \mu E_f / v_F^2 e$, i.e., it is mainly associated with single-particle electron (hole) scattering. As a result the quality factor Q determining the sharpness of the plasma resonances $Q = \omega_p \tau$ is directly linked to the mobility μ, meaning that graphene-based heterostructures with elevated mobilities should show very pronounced plasma resonances.

A first device concept proposed is based on the use of a two-layer graphene heterostructure; the graphene layers are separated by a thin barrier and each of them is supplied with an ohmic contact (see Fig. 7) and connected with a properly designed antenna. In this case, THz detection is achieved thanks to both the resonant excitation of plasma oscillations by the incoming THz beam and the nonlinearity of the intergraphene-layers [57] tunneling current.

The developed analytical model clearly shows that at frequencies close to ω_p or its harmonics, the detector responsivity

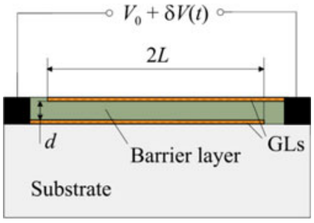

Fig. 7. Schematic diagram of a double gated graphene heterostructure. (From ref. [57], copyright 2012, Institute of Physics).

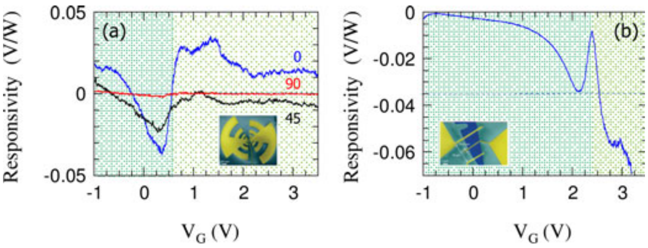

Fig. 8. RT responsivity as a function of V_G for detectors based on SL-FET (with data for different angles between the beam polarization axis and the antenna axis) (a) and BL-FET. (b) Different background colors identify regions below and above the Dirac point. Insets: SEM micrographs. The detector consists of a log-periodic circular-toothed antenna patterned between the source and gate of a GFET. The drain is a metal line running to the bonding pad. (From ref. [58])

exhibits sharp maxima provided the plasma oscillation quality factor $Q \gg 1$. Since s depends on the bias voltage V_0, both ω_p and, hence, the position of the responsivity peaks can also be voltage tuned according to $\Delta\omega_p = \omega\Delta V_0/(4V_0)$. Of course a pronounced resonant response of the detector requires the frequency of electron and hole collisions with impurities and acoustic phonons to be sufficiently low; predictions indicate that electron collision rates of the order of a THz (i.e., mobilities of 10^6 cm^2/Vs) are sufficient. A substantial shift of the positions of the resonant maxima toward lower frequencies with increasing graphene length 2 L is expected, due to the decrease in the characteristic plasma frequency. Moreover, the use of an inter-GL layer material having lower potential barrier and a pronounced exponential behavior of $I - V$ characteristics is predicted to further improve the detector performance.

More recently graphene has been used for THz detection by employing a simple top-gate antenna-coupled configuration for the excitation of overdamped plasma waves in the channel of a FET [58]. Single- (SL) and double-layer (BL) graphene flakes mechanically exfoliated on Si/SiO_2 substrates were used to fabricate the top gate FETs. Log-periodic circular-toothed antennas at the source and gate electrodes were used to couple the 0.3 THz radiation of an electronic source. A 35-nm-thick HfO_2 layer was used as the gate dielectric. The whole channel length was 7–10 μm, while the gate length was 200–300 nm.

Fig. 8(a), (b) plots R_v measured in SL and BL graphene FETs at RT, while sweeping V_G from –1 to +3.5 V and modulating the THz source at 500 Hz. Each SL curve corresponds to a different relative orientation between the source electric-field polarization and the antenna axis. In the case of the SL device the photoresponse drops rapidly with angle until it becomes almost zero when the incoming polarization is orthogonal to the antenna axis, confirming the efficacy of the dipole antenna. The dependence of Δu from σ^{-1}dσ/dV_G is in qualitative agreement with the prediction of a diffusive theoretical model [58], thereby proving that the detectors operate in the so-called broadband overdamped regime [45]. Together with the expected photovoltage change in the vicinity of the Dirac point, a further sign switch around $V_G = 0$ is observed in all cases, suggesting a possible contribution of thermoelectric origin [51], [59]. This arises from the presence of the ungated p-doped graphene regions, and subsequent formation of p–p–p or p–n–p junctions, depending on V_G.

In the case of the BL device, the responsivity curve is in excellent agreement with that predicted by the diffusive plasma-wave detection model up to the Dirac point (2.5 V). However, no change of sign is here visible, with a strongly enhanced response above the Dirac point with respect to that predicted. This suggests an additional contribution to the photovoltage, this time of constant sign. Its magnitude grows rapidly with V_G, eventually dominating in the regime in which a p–n–p junction is present. Interband transitions driven by the THz field at the p–n junction with the resulting generation–recombination noise could here play a nonnegligible role. Maximum responsivity values of 150 mV/W and minimum NEPs = 30 nWHz$^{1/2}$ have been reached [58]. Further advances are expected by achieving the resonant detection regime, and also by understanding and exploiting the new physics emerging in BL samples, which may lead to even better device concepts.

Similar results were obtained at higher frequencies up to 3.11 THz for back-gated graphene transistors [60] reaching maximum photovoltage signals of a few μV.

IV. Lasers and Other Sources

Research aiming at the development of compact, monolithic, electrically driven THz sources has seen in the last years the emergence of quantum cascade lasers (QCLs) [18], [61] and resonant tunneling diodes (RTDs) [62], [63] as the most promising device technologies. RTDs, however, are still restricted to maximum emission frequencies around 1 THz, with output powers of the order of a μW. QCLs, instead, still require cryogenic cooling below 200 K [61], and the implementation of complex mechanical systems to achieve broad tuneability of the emission wavelength [64].

The gapless energy spectrum of electron and hole bands in graphene, together with the strong interaction with optical phonons of relatively high energy, has prompted scientists to examine the possibility of achieving interband population inversion and THz gain through optical pumping [65]. The problem is definitely nontrivial, owing to the contribution of both interband and intraband processes to the dynamic conductivity in the THz range (and hence to absorption or gain) [66]. Furthermore, the electron relaxation dynamics is far from obvious, with the interplay of optical phonon emission, electron–electron scattering, etc. While population inversion does seem to occur when only electron relaxation mediated by phonons is considered, thanks to a bottlenecking effect, electron–electron collisions provide a very quick thermalization channel and tend to wash out peaks of negative optical conductivity [67].

Experimental results are at the moment rather inconclusive on the effective presence of gain in optically pumped graphene. Several time-resolved optical-pump/THz probe studies have been performed and are consistent with a fast subps intraband thermalization process followed by a slower interband recombination [68]–[71]. They report, however, different spectral dependence and sign for the differential THz transmission, as a consequence of the varying experimental conditions: quality and doping of the graphene sample, frequency and intensity of the pump, etc. The extraction of the absolute value of the dynamic conductivity from the data is then further complicated by the likely modifications of the sample reflectance under optical pumping conditions.

In any case it is clear that the maximum amplification by a single graphene layer, for an electromagnetic wave traversing the layer, is limited by the same 2.3% constant value characterizing interband absorption. For this reason, laser device configurations employing waveguide propagation in the graphene plane have been proposed [72]. A clever idea is also to couple the interband stimulated emission to a plasmon mode. Plasmon gain values in graphene are, in fact, predicted to be very large due to the small group velocity and the strong confinement of the plasmon field [73]. It is also apparent that the larger the exciting photon energy, the more electron–electron collisions are effective in thermalizing the carrier distribution and suppressing bottlenecking effects. Therefore, the use of a low-energy mid-infrared pump has been suggested [66] as well as the possibility of current injection in a planar p–i–n configuration [74].

The ultrafast electron relaxation in graphene can however be strongly suppressed in a magnetic field sufficiently high to create well-separated Landau levels. Indeed pump-probe results in the near-infrared, thereby probing high-index ($n \approx 100$) Landau states, show a reduction of a factor of about two in the Auger-like electron–electron scattering rate when going from 0 to 6 T magnetic field [75]. These data also suggest that for lower Landau levels such processes may then be almost completely suppressed, making graphene an interesting candidate for the implementation of a tuneable THz Landau-level laser [76].

Beyond the development of a THz source based on stimulated emission arising from optical transitions between electronic states, graphene can be considered as an interesting template also for the implementation of an electronic high-frequency oscillator. This approach is based on the availability of an electronic device exhibiting a negative differential resistance (NDR) in the transport characteristics; when inserted into a proper resonant circuit, this would then lead to self-oscillation, like is the case for RTD and Gunn diode microwave and THz sources.

Recent studies have shown that three-terminal graphene devices based on FETs show a clear NDR regime for high source–drain bias (see Fig. 9) [77]. This behavior is peculiar of the ambipolar nature of transport in zero-bandgap graphene transistors. It is in fact associated with the competition between electron and hole conduction as the source–drain bias $V_{\rm ds}$ becomes larger that the gate–source one $V_{\rm gs}$.

In essence, in this regime, a portion of the channel close to the drain starts developing where the chemical potential is in the valence band, with low carrier density, thereby increasing the channel resistance. This region keeps extending till at $V_{\rm ds} = 2V_{\rm gs}$ the channel becomes symmetric with equal extension and charge of the n and p regions. Further increase of $V_{\rm ds}$ produces this time a reduction of the resistance (superlinear $I_{\rm ds} - V_{\rm ds}$ curves). This concept is particularly appealing for the development of radiation sources because the gate electrode offers the possibility to control and modulate the NDR, and thereby the operation and output power of the oscillator [77].

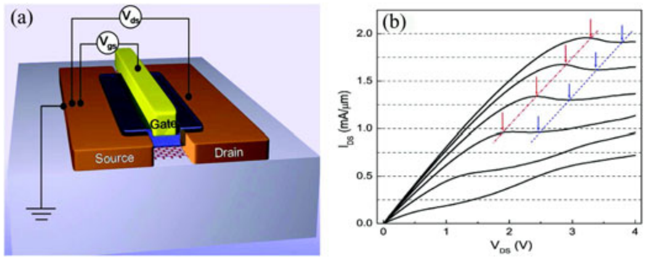

Fig. 9. (a) Schematic of a three-terminal top-gated graphene NDR device. (b) Source–drain current as function of source–drain bias for top-gate voltages ranging from 0 to 2.5 V. (Adapted with permission from ref. [77], copyright 2012, American Chemical Society).

Theoretical investigations have also examined the characteristics of ballistic transport in a graphene tunneling transit time device based on a lateral p–i–n junctions induced by appropriate gates [78]. Regions of negative (though small) dynamic conductivity are predicted to arise in the THz frequency range for reasonable device parameters. An alternative solution would be to employ electron tunneling across a graphene (n)–insulator–graphene (p) heterostructure, which has indeed been predicted to show a very pronounced NDR regime in the transport across the junction [79], [80]

Finally, photocurrent measurements, performed with high temporal resolution employing a pump-probe scheme, have been performed on freely suspended graphene samples featuring coplanar metal stripline electrodes that act as a near-field antenna and waveguide up to THz frequencies [81]. Photocurrent oscillations with Fourier components up to 1 THz have been recorded, which are interpreted to originate from the THz radiation emitted by the photocurrent transient optically excited in the electron–hole graphene plasma. This result is quite encouraging for the prospective development of graphene-based photoconductive switches for time domain spectroscopy.

V. Conclusion

Graphene has great potential to revolutionize electronics and photonics worlds in the next decade. It is then quite fitting that scientists are now pinning great hopes on this material as a new low cost solid-state technology that would finally allow full tackling of the THz portion of the electromagnetic spectrum. In the space of just a few years graphene has already shown state-of-the-art modulator performances, and detectors are rapidly coming along. On the source side the potential is instead almost completely unexplored, and a lot of new physics is bound to emerge in the near future from research in this direction. Perspectives are anyway very bright and more possibilities will open up when graphene elements will be integrated with existing technologies, like quantum cascade lasers, to improve specific device parameters. With photonics dominated by III–V semiconductor compounds and electronics by Silicon, is possibly Carbon the actual future of what is in between?

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