Nanodevices at terahertz frequency based on 2D materials

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Abstract
Artificial semiconductor heterostructures played a pivotal role in modern electronic and photonic technologies, providing a highly effective mean for the manipulation and control of carriers, from the visible to the terahertz frequency range. Despite their exceptional versatility, they commonly require challenging epitaxial growth procedures, due to the need of clean and abrupt interfaces, lattice matching or limited and controlled lattice mismatch, which proved to be major obstacles for the development of room-temperature devices, like sources, detectors or modulators, especially in the far-infrared. The discovery of graphene and the related fascinating capabilities have triggered an unprecedented interest in inorganic two-dimensional materials. Layered materials such as graphene, hexagonal boron nitride, transition metal dichalcogenides, and the more recently re-discovered black phosphorus display an exceptional technological potential for engineering nano-electronic and nano-photonic devices and components ‘by design’, offering a unique platform for developing devices with a variety of properties. Here, I review our latest achievements in the design and developments of graphene based nanodetectors, saturable absorbers and near field probes operating across the far-infrared.

1. Introduction

Two-dimensional (2D) materials and related van der Waals heterostructures [1, 2] display an extraordinary technological potential for engineering nano-electronic and nano-photonic devices and components; they also provide an intriguing platform for fundamental investigations at the nanoscale, through the exploitation of their confined electronic systems.

Graphene, the most exploited 2D material, is the thinnest, the strongest, the largest mobility material, demonstrated so far. Graphene exploits a record thermal conductivity that, combined with its exceptionally high crystalline and electronic quality, allowed to open a new paradigm of ‘relativistic’ condensed-matter physics. Very importantly, such combination of properties cannot be found in any other material or material system. Furthermore, the optical properties of graphene (absorption, refractive index, plasmon velocity, etc) can be tuned via electrostatic grating or by increasing the number of layers. This implies that the material permittivity can be altered on purpose, so that graphene can behave like a semiconducting (absorbing) material, or a transparent one, and even as a metallic (plasmonic) material, meaning that it can be nowadays exploited for a plethora of applications in optical communications [3], spintronics [4], high-resolution sensing [5] and tomography, amongst many others.

However, a key requirement for applications is the development of industrial-scale, reliable, inexpensive production processes. Graphene research has recently led to enormous progresses in the material preparation and synthesis, by exploiting both bottom-up (graphene nanoribbons, graphene and carbon nanomembranes) [6] and top-down techniques [6, 7].

Dry exfoliation is the most easy and commonly exploited technique: it consists of the splitting of layered materials into atomically thin sheets via mechanical, electrostatic, or electromagnetic forces in air, vacuum or inert environments. Alternatively, graphite can be exfoliated in a liquid exploiting ultrasounds to extract individual layers and therefore defining inks or ink-jet printable compounds, or via electrochemical means. For
large area material production, different techniques have been proposed and implemented, like graphene growth on SiC, growth on metals by precipitation, or chemical vapor deposition techniques on either metals or insulators, which recently also allowed to reach mobilities up to three million cm² Vs⁻¹ [8].

After graphene discovery ≈700 two-materials have been predicted to be stable and many of them still remain to be synthesized.

Their electronic structure ranges from trivial insulators (like the hexagonally shaped boron nitride, hBN), to semiconductors with tunable gaps (like black-phosphorus (BP) [9, 10] or transition metal dichalcogenides (TMDs) [11]), to semi-metallic material or even superconducting materials, whose behavior depends on the substrate, chemical functionalization and strain. In a class of recently discovered low gap semiconductor materials, commonly named as Xene [12], the electronic structure can be tuned, for example, by changing the group IV-A element, the degree of spin–orbit coupling, the functionalization chemistry or the substrate.

Research on Van der Waals heterostructures has been also gaining increasing strength over the last years. It deals with heterostructures and devices made by stacking different 2D crystals on top of each other. The basic principle is simple: take a monolayer, put it on top of another mono- or few-layer crystal, add another 2D crystal and so on. The resulting stack represents an artificial material assembled in a chosen sequence with blocks defined with an individual atomic layer precision. Strong covalent bonds provide in-plane stability of while relatively weak, van der Waals-like forces are sufficient to keep the stack together. Remarkably, it turned out that such a kind of atomic-scale ‘Lego’ works extremely well [2].

The global market for 2D materials is expected to significantly increase in the next 5 years, mostly in the semiconductor, electronics, battery energy, and composites markets. Furthermore, vdW heterostructures and composite 2D material systems are gaining a renewed interest for non linear optics applications, especially after the discovery of exotic phenomena in graphene like four wave mixing [13], high harmonic generation at terahertz (THz) frequencies [14], and the proved huge enhancement of optical non-linearities in the visible or near-infrared region, achieved by integrating 2D materials with photonic crystal cavities, microdisks or microrings cavities [15]. The family of 2D materials is also now gaining a renewed interest in more unexplored frequency domains, like the terahertz frequency range [16].

Dynamical phenomena (scattering, recombination, and tunneling) in 2D and vdW materials indeed typically occur on a time scale of picosecond, i.e. frequencies in the THz range. Graphene and related materials can therefore offer an intriguing perspective for the engineering of novel photonic or plasmonic devices, at THz frequencies, based on the exploitation of the above dynamics.

Amongst the growing scale of required devices, the need for a photo-detection platform combining room temperature operation, high-speed, large quantum efficiencies, broad operational range and integrability with more conventional semiconductor-based technologies is becoming more eminent [17]. Similarly, near field optical probes as well saturable absorbers and mirrors can really benefit from the extraordinary mechanical, chemical and optical properties provided by 2D materials to extend their operational range in the far-infrared, which presently lacks of similar performing optical components.

Here, I provide an overview on our latest achievements in the developments of active and passive THz photonic and nano-electronic devices exploiting 2D nano-materials and combined heterostructures, and I will discuss future perspectives of this rapidly developing research field.

2. Fast and sensitive photodetectors at terahertz frequencies

Available photodetectors operating at THz frequencies can be classified in direct (incoherent) detection systems or indirect (coherent) detection systems [18]. To the first category belong cryogenic (bolometers) or deeply cryogenic (microbolometers) thermal sensors, usually displaying response times $\geq 10^{-8}$ s, narrow dynamic ranges (maximum detectable power 0.1 uW), low noise equivalent powers (NEP = 50–100 W Hz⁻¹/²), or room-temperature sensors like pyroelectric or optoacoustic (Golay cells) detectors, which are inherently slow (response times $> 0.5$ ms), show NEPs in the $10^{-7}$ W Hz⁻¹/² (Golay cells)—$10^{-8}$ W Hz⁻¹/² (pyroelectric) range and a performance drop at frequencies larger than 1 THz. The family of room temperature sensors also includes Schottky diodes, which only operate below 1 THz, but are extremely fast (ps response times), and highly sensitive (NEP = 10–100 pW Hz⁻¹/²) [18]. Coherent detections systems are very fast (ps), show high signal dynamics, but they need mixers to be implemented in a cumbersome or poorly tunable set-up [18].

An ideal THz photodetector should be highly sensitive, operate at room temperature, give a fast response over a wide dynamic range, and, most importantly, cover the spectral range 1–5 THz, which is of tremendous interest for many application fields spanning from metrology, to optical communications, to high-resolution sensing, high precision spectroscopy [19] and tomography.
In the last few years, graphene and related 2D materials have rapidly established themselves as intriguing building blocks for devising far infrared photo-detectors. Graphene exhibits ultrafast carrier dynamics, wavelength-independent absorption, tunable optical properties via electrostatic doping and high-mobility, which enables ultrafast conversion of photons or plasmons to electrical currents or voltages. As a major distinctive characteristic, graphene is gapless, allowing charge carrier generation by light absorption over a very wide energy spectrum, while always conducting a significant amount of electricity. Alternative layered 2D materials like BP or TMDS with a band gap have recently triggered an increasing scientific interest [9–12].

Behaving like semiconductors, they only conduct electricity whenever the electrons absorb enough energy through heat, light, and other means. Depending on their specific band structures, these materials can disclose peculiar functionalities to be exploited for highly efficient light detection.

As a further peculiar advantage, when a 2D material is placed on chip with flat integrated optical circuits [20], it can indeed allow maximal interaction with light, therefore optimally utilizing its unique and versatile properties for properly engineer and control the detection dynamics, through design. Very importantly, 2D materials are also generally compatible with silicon-based platforms, meaning that they offer a concrete perspective of low-cost and large-scale integration of THz sensors into optoelectronic networks.

Photodetection of light, i.e. conversion of photons into a stable electrical signal, at THz frequencies can be accomplished by several different mechanisms like photo-thermoelectric, photovoltaic, galvanic, bolometric, plasma-wave rectification or via a combination of different effects [17].

Usually, field effect transistors (FETs) are the most commonly employed architectures for devising THz frequency photodetectors. FETs indeed provide some clear advantages at those frequencies, namely the inherent scalability and the combination of a fast response and high frequency operation (up to 22 THz), very differently from Schottky diodes, whose performances are strongly affected by parasitic capacitances and usually show a dramatic cutoff above 1 THz.

The rich physics involved in 2D materials can be exploited in a FET to engineer the detection dynamics from scratch, playing with the geometrical symmetry included in the FET. While indeed the bolometric effect, relying on a modulation of the channel conductance as a consequence of the homogeneous heating of the channel can be easily activated in a FET as a consequence of a source-to-drain bias [17], photothermoelectric and plasma wave rectification both require a certain degree of asymmetry in the detector structure [17]. Indeed, the photothermoelectric effect is driven by a temperature gradient along the FET channel, and plasma-waves can be rectified inside the transistor when the THz field is coupled between source and gate electrodes. The needed asymmetry can be attained either by asymmetrically coupling the free-space radiation to the active FET element by means of a dipole-like planar antenna [21], or by creating a pn-junction along the FET channel (via adjacent gate electrodes) [22], or by defining asymmetrical boundaries through inhomogeneous doping [23] or different contacting metals [24].

Following the first demonstrations of antenna coupled overdamped plasma wave photodetectors operating in the resistive self mixing regime [25, 26], several architectures have been proposed and implemented including graphene bolometers [27], ballistic rectifiers [28], and fast photo-thermoelectric sensors [22, 24, 29].

Recently, a novel THz thermoelectric sensor based on high-mobility, hBN-encapsulated graphene, have been implemented, involving a combination of a small-area graphene pn-junction and an H-shaped antenna that focuses the incident THz radiation onto a small active area. Room temperature operation over the 1.8–4 THz range has been demonstrated with NEPs \( \approx 80 \text{ pW Hz}^{-1/2} \), a dynamic range extending over four decades and a 40 ns response time [22]. THz photodetection has been also demonstrated in BP-based nano-detectors [21, 30], exploiting the semiconductor-like behavior of BP. By exploiting the inherent electrical and thermal in-plane anisotropy of a flexible thin flake of BP, we have recently proved that we can engineer the detection dynamics from scratch, devising plasma-wave, thermoelectric or bolometric nano-detectors with a selective, switchable and controllable operating mechanism. Room-temperature operation was demonstrated with \( > 1000 \text{ signal to noise ratio, state-of-the-art NEPs (10}^{-9} \text{ W Hz}^{-1/2}) \) [21], responsivities of about 10 V W\(^{-1}\), and response times of a few \( \mu \text{s} \) [31]. To preserve the chemical stability of the BP flakes we have also demonstrated time-stable hBN-BP encapsulated [32], detectors and Se-doped micro-sensors [33].

Here, we report on the development of THz graphene photodetectors exploiting a novel architecture, aiming to low on-chip parasitic capacitance and, consequently, very fast response times, all at room-temperature.

Single layer graphene flakes were transferred on Si/SiO\(_2\) substrates via mechanical exfoliation in ambient conditions. The crystalline quality of the exfoliated flakes was assessed by conventional polarized Raman spectroscopy (PRS).

Top-gated FETs embedding SiO\(_2\)/graphene/SiO\(_2\) heterostructure have been fabricated with an integrated resonant THz nano-antenna (figure 1(a)), having the novel scheme displayed in figure 1(b). The source (S) and drain (D) FET electrodes were lithographically defined along the graphene channel at a relative distance \( L_c = 2 \mu \text{m} \). The size of the S and D ohmic contacts defines the channel width \( W_c = 1 \mu \text{m} \). An 80 nm thick SiO\(_2\)
dielectric layer acting as top-gate oxide was then deposited on the top plane via sputtering. The gate (G) electrode was lithographically patterned on the top surface of the FET channel, over a length \( L_G = 1.5 \mu m \).

We then simulated a novel antenna scheme, which is intended to optimize the detection speed; it has been conceived as a bow-tie antenna with an integrated low-pass filter, as shown in the optical microscope image of figure 1(c). The S and G electrodes were shaped as the two opposite halves of the bow tie antenna, with a flare angle of 90° and a bow radius of 20 \( \mu m \). The S electrodes is then connected also to the right side of a properly defined band pass filter having a 300 GHz bandwidth [34], while the drain contact extends over its left side (see figures 1(b), (c)). The electrical bandwidth of the filter has been chosen on purpose so that signals modulated at high speeds can be detected and simultaneously the THz frequency light can pass through without experiencing any attenuation.

At 3.4 THz and for normal incidence, this geometry gives a field enhancement of ~40 between the S and G branches of the antenna, when the electromagnetic wave, polarized parallel to the antenna axis, reaches the detector from the air side. This has been estimated via a finite element method (FEM) simulation of the antenna architecture, through commercial software (Comsol Multiphysics).

The chip was then mounted on a dual inline package and the samples were electrically characterized in air, at room temperature, using two dc voltage generators, that independently provide voltage to the source-to-drain (\( V_{SD} \)) or to the source-to-gate (\( V_G \)) (figure 1(a)). The measured resistance curve, as a function of \( V_G \), is plotted in figure 2(a) and allows extracting a graphene FET mobility of 3000 \( cm^2 V^{-1} s^{-1} \).

Owing to the asymmetrical antenna geometry, THz detection in the graphene channel can be mediated either by the thermoelectric effect or the over-damped plasma wave effect or via a combination of both mechanisms. Usually, the latter effect is accompanied by a responsivity sign switch, which follows the trend \( R \approx -\frac{1}{\sigma} \cdot \frac{d \Delta P}{d V_G} \), being \( \sigma \) the channel conductivity. We should therefore expect that purely overdamped plasma wave detection dynamic should correspond to a single sign switch in the measured responsivity, in agreement with the resistance shape at the charge neutrality point (figure 1(d)).

However, the measured responsivity \( R = \frac{\Delta u}{P} \), extracted from the measured photovoltage signal (\( \Delta u \)) (figure 1(a)), the impinging optical power (\( P \)), and the ratio between the beam spot area (\( A_S \)) and the diffraction limited area (\( A_D \)) [25], clearly shows a double sign switch (figure 1(e)). The latter trend can be explained by assuming that the photothermoelectric effect is the main responsible of the observed behavior. Indeed the photothermoelectric voltage (\( \Delta u_{PTE} \)) is the result of a temperature gradient \( \Delta T \) arising in the p-n junction created along the FET channel. Hot carriers accumulate within the ungated region between S and G as a consequence of the THz-induced field provided by the antenna.

Conversely, electrons remain colder in the region underneath the D and G electrodes. The photovoltage given by the Seebeck effect can be written as \( \Delta u_{PTE} = (S_{SG} - S_{SU}) \cdot \Delta T \), where \( S_{SG} \) and \( S_{SU} \) are the Seebeck coefficients of the gated and ungated regions, respectively. The Seebeck coefficient \( S_{SG} \) (is not affected by \( V_G \) and can be ascribed to the slightly p-doped graphene section in the ungated regions. Vice versa, \( S_{SU} \) changes with \( V_G \) following the Mott equation [21]. Such a double sign switch is clearly evident in the shaded color plots in figure 2(b).

To unveil the role of the on-ship band pass filter on the response time of our photodetectors we have employed the same experimental set-up of [26], to test the detection speed limit. A pulsed quantum cascade laser (QCL) [35], operating at 3.4 THz, was employed and focused via two Picarin (tsupurica) lenses onto the fabricated photodetector. The speed was tested by rapidly switching the THz radiation on and off, by using our pulsed THz QCL.

Figure 1. (a), (b) Schematic diagram of the top gated graphene field effect transistor. The main geometrical dimensions are: channel length \( L_c = 2 \mu m \), channel width \( W_c = 1 \mu m \), gate length \( L_g = 1.5 \mu m \). A SiO\(_2\) layer of 80 nm was used as gate dielectric. The photovoltage signal is measured between the source and drain contacts; (c) False colour optical microscope image of the fabricated THz detector.
The detector photoresponse closely follows the laser switching behavior (figure 3); to quantify the speed we fitted the fall time with a standard exponential equation, achieving a response time of 14 ns, corresponding to an electrical bandwidth of 11.5 MHz.

It is worth mentioning that the retrieved speed value has to be considered as a lower limit, since it is affected by the employed measurement electronics [22].

3. Multilayer graphene-based saturable absorbers at THz frequencies

Semiconductor saturable-absorbers and saturable-absorber mirrors are routinely used for mode-locking in the visible and infrared ranges. However, they are poorly suitable for applications at THz frequencies for several reasons: (i) the photon energy is smaller than the semiconductor band gap; (ii) the free carrier absorption induced by the semiconductor doping is a dominant loss source; (iii) they require complex fabrication and challenging integration. Recently, n-type semiconductors showed saturable absorption in the THz [36] although their integration with existing THz lasers is difficult to prove.

Graphene is a potential candidate for crafting saturable absorbers at THz frequencies, thanks to its fast carrier dynamics (<100 fs) [37], large absorption of incident light (2.3% per layer), the possibility to saturate this absorption in a broad spectral range with relatively low incident power, and its tunable modulation depth.
As its optical conductivity is mainly determined by intraband transitions (with a further interband ps timescale relaxation dynamic, due to hot phonons cooling) [37], graphene optical absorption can be easily modulated by electrical/optical control of its Fermi level. Therefore, a proper combination of graphene with metamaterial patterns can be ideal to induce local modulations of refractive index via optical Kerr effect [38]. Furthermore, large-area (compared to a typical laser spot), low-cost, single or multi-layer graphene can be easily grown and integrated in a variety of lasers. The sufficiently short temporal response of the absorption saturation in graphene can be well matched with the gain recovery time (few picoseconds) of THz QCLs.

We recently demonstrated THz saturable absorbers by transfer coating and ink-jet printing 50 layer (randomly distributed) graphene films prepared by liquid phase exfoliation of graphite [39]. Through the combination of open-aperture z-scan experiments and Fourier transform infrared (FTIR) spectroscopy, we demonstrate 80% transparency modulation at 3.4 THz [39].

Despite this technology is very appealing for intracavity embedding, since the graphene is printable and flexible, the thickness uniformity along a large surface is usually poor, meaning that achieving large transparency modulation over large areas (>0.5 cm) could be demanding.

Alternative reports on THz graphene saturable absorbers rely on the use of multi-layer graphene grown on the carbon-face of silicon carbide [40]. However, with this procedure a maximum absorption modulation of ~10% was achieved, that is inherently limited by disorder, demonstrating that the THz nonlinear absorption properties of turbostratic graphene can be engineered via a proper control of the crystalline disorder and of the layers number.

Here, we report on the first evidence of THz saturable absorption in multilayer graphene films, grown via CVD on Nickel. The as-grown multilayer graphene films was transferred onto an intrinsic silicon substrate, and tested by means of an open aperture z-scan transmission experiment following the same experimental procedure described in [39].

The estimated thickness of the flakes is ≈50 nm, corresponding to a multilayer graphene film, comprising N = 50 layers.

PRS is used to monitor the quality of the flake. Raman spectra have been acquired at 514.5 nm with a Renishaw InVia with a 50x objective (N.A. = 0.85). The power on the sample is kept below 1 mW to avoid possible thermal damage. About 20 measurements are taken in different positions over the sample surface.

The Raman spectra (figure 4(a)) features a pronounced G peak at 1584 cm\(^{-1}\) and a broad 2D peak with a maximum at 2730 cm\(^{-1}\). The ratio between the intensity of the G and 2D peaks is \(I(G)/I(2D) \approx 2.4\), while the full width at half maximum of the 2D peak is FWHM\((2D) \approx 60\ \text{cm}^{-1}\), indicating that the graphene is multilayer.

FTIR spectroscopy was used to determine the linear absorption \(\alpha_0\) in the THz frequency range [41]. Spectra are acquired with deuterated triglycine sulfate (DTGS)-polyethylene. In the frequency range comprised between 2.5 THz and 9.0 THz, the linear absorption coefficient is almost flat around an average value of 70%.

A single-plasmon quantum cascade laser operating at 2.7 THz and operating in pulsed mode regime (10% duty cycle) was focused onto a set of two convergent lenses \((L_1, L_2)\) having the same focal length \(f = 3\ \text{cm}\), and conveyed onto the sample with perpendicular incidence. The graphene sample was hosted on a custom-made holder and its position was swept with a micrometric stage along the optical axis \((z\ \text{direction})\) between \(L_2\) and a graphene room temperature photodetector, kept in a fixed position.

The spot size of the QCL was measured via a bidimensional scan in the x-y plane orthogonal to the optical axis \(z\) by using a graphene-based FET thermoelectric detector with a step size of 20 \(\mu\text{m}\), as shown in figure 4(b). The unveiled Gaussian profile allows to extract a radial spot size \(w_0 = (108.6 \pm 0.1)\ \mu\text{m}\).

![Figure 4](image-url)

Figure 4. (a) Raman spectra acquired at 514.5 nm. (b) Intensity profile of a 2.7 THz QCL, measured at room-temperature, in the x-y focal plane orthogonal to the beam axis, with the FET graphene detector of figures 1–3, and with a step size of 20 \(\mu\text{m}\).
Figure 5 shows the measured transmittance, normalized to the measured transmittance through the SiO2/Si substrate. We unveiled a clear transmission increase around $z \approx 0 \mu m$, corresponding to the region of highest laser intensity impinging on the sample. The absorption bleaching increases the graphene sample transparency by $\approx 19\%$, which is a signature of saturable absorption. The Si/SiO2 substrate shows no significant variation of the transmission along the z-direction, confirming that the saturation effect is associated to the multilayer graphene film.

The dependence of the absorption coefficient on the pump intensity is expressed as:

$$\alpha(I) = \alpha_{NS} + \frac{\alpha_S}{1 + \frac{I(I)}{I_S}},$$

where $\alpha_{NS}$ and $\alpha_S$ represent the non-saturable and saturable components of the linear absorption $\alpha_S = \alpha(I = 0) = \alpha_{NS} + \alpha_S$, respectively, $I(z)$ is the beam intensity along the optical axis, and $I_S$ is the saturation intensity (i.e. the intensity at which the saturable absorption is reduced by 50%). $I(z)$ can be written as a function of the beam intensity at the focal point $I_0$, and of the Rayleigh length $z_R$:

$$I(z) = \frac{I_0}{1 + \left(\frac{z}{z_R}\right)^2},$$

which can be retrieved from the radial spot size and is, in the present case $z_R \sim 330 \mu m$. From the measured power and the beam waist, the pump laser provides an average value $I_0 \approx 1.2 \text{ W cm}^{-2}$ at the focal point.

The overall normalized transmittance can be written as [39]:

$$T(z) = \left[1 - \alpha_0 + \alpha_S - \frac{\alpha_S}{1 + \frac{z^2}{z_R^2} + \frac{I_0}{I_S}}\right] \frac{1}{1 - \alpha_0}$$

The experimental normalized transmittance was fitted with the above-mentioned formula for $T(z)$, retrieving a saturable absorption coefficient $\alpha_S = 0.39 \pm 0.07$ and a non-saturable absorption coefficient $\alpha_{NS} = 0.12 \pm 0.05$. The saturation intensity is estimated to be $I_S = (5.8 \pm 0.9) \text{ W/cm}^2$.

Typically, non-saturable losses originate from scattering at the interfaces between the layers, free carrier absorption, or defects, which depend on the quality of the fabrication techniques. For THz excitation, owing to the long wavelength, the multi-interface effect makes only a minor contribution. Additionally, when graphene is doped, non-saturable absorption can be linked to either free carrier absorption or to the reflectivity from the sheets, since in this regime, the optical conductivity is well described by the Drude model. Here, at low pumping photon energies (THz frequencies), the optical absorption in graphene is attributed mostly to intraband transitions.

4. Near field THz probes

Imaging at THz frequencies is severely restricted by diffraction. To overcome this major limitation, near-field scanning probe microscopy is commonly employed to map the THz electromagnetic fields with sub-wavelength
Scattering-type scanning THz near-field microscopy [43, 44] is the most exploited technique: it relies on an atomic force microscope (AFM) tip that induces strongly concentrated THz fields at the tip apex, then scatter a fraction of this field, retrieving information on the dielectric constant underneath the tip, in its amplitude and phase. Usually, the scattering efficiency of the AFM tip is prohibitively low in the THz frequency range, thus requiring the use of sophisticated signal demodulation techniques [43, 44], powerful THz lasers, cooled bolometers, costly THz time-domain spectroscopy systems, or detectorless self-mixing approaches [45].

An alternative method relies on aperture near field microscopy systems, in which the resolution is limited by the strong reduction of light transmission (T) through an aperture (dimension a), and whose major limits is the transmittance drop, according to the Bethe and Bouwkamp law, that follow the power law: \( T \sim a^6 \) [39].

Usually, although the field conveyed at the aperture, includes both the transmitted and the reflected beam components, only transmitted signals are collected, meaning that the evanescent fields remain practically undetected in most near-field imaging systems.

We recently introduced a novel near-field THz probe concept, where the evanescent THz field is converted into a detectable electrical signal at the nanoscale [46, 47].

To do that, we have exploited the inherent flexibility and easy of integration of thin crystalline flakes of 2D nano-materials, demonstrating that a thin crystalline flake can be easily integrated into an aperture near-field probe, simultaneously acting as a probe and as an evanescent field-sensitive photodetector. We here chose black phosphorus (BP) as the preferred material, since its inherent in-plane anisotropy can allow selecting the dominant photodetection mechanism through the choice of the crystalline axis along which the probe channel is defined.

With this trick, a THz thermoelectric nanodetector based on a thin sequence of SiO\(_2\)/BP/SiO\(_2\) is integrated into the evanescent field region of a trapezoidal shaped sub-wavelength aperture to enable efficient detection of the transmitted wave (figure 6(a)).

The BP single crystal was synthesized using a chemical vapor transport method [21, 31]. The evacuated quartz tube containing red phosphorus has been placed into a double-zone tube furnace with temperatures set at 600 °C and 500 °C for the hot and cold end, respectively. Large-size single crystals of BP can be obtained after a week of transport. Exfoliation of the BP flakes has been performed under vacuum to avoid the quite fast degradation of the exfoliated BP flake to ambient exposure (moisture, oxygen), prior to SiO\(_2\) encapsulation.

To feed the THz field to the FET channel, defined along the BP armchair direction asymmetrically, we engineered a special gate electrode, which simultaneously acts as a metallic screen with a sub-wavelength aperture. The electrode extends asymmetrically from one side of the aperture to the FET placed in the aperture center (figure 6(a)). An electrically isolated S electrode, having the same trapezoid shape, extends to the aperture center from the opposite side. When exposed to the incident THz field, these electrodes concentrate the field in the FET channel (see figure 6(b)). The drain (D) electrode is fully covered by the G electrode and kept electrically isolated through the top 40 nm thick SiO\(_2\) layer. This aperture geometry breaks the symmetry of the S and D electrodes and results in the alternating THz field between G and S that activates the THz detection mechanisms.
This THz near-field probe provides sub-wavelength resolution at room temperature in a compact THz imaging system without the need for the mode-locked table-top femtosecond pulse lasers, atomic force interaction or demodulation techniques. By funnelling the radiation of a 3.4 THz QCL operating in pulsed mode with an average output power of 45 μW we have demonstrated coherent THz near-field imaging with a resolution set by the aperture size (10–15 μm), as evident in the scanned image of the THz electromagnetic field (figure 6(c)).

5. Conclusions and perspectives

The superior mechanical pliability of 2D vdW heterostructures encloses an enormous potential for developing a novel generation of devices, optical components and systems in the infrared, and particularly in the terahertz frequency range (1–10 THz) where many challenging applications in quantum science, metrology, and spectroscopy are still in their infancy.

The development of novel high-performance nanoscale optoelectronic devices, like fast and room temperature photodetectors, prospect great impacts on future emerging signal processing and computer technologies. These new capabilities promise to allow easy integration into silicon CMOS based electronics.

Nanoscale probe based on 2D layered materials offer brilliant prospects for the development of high resolution near field optics in the far-infrared. The possibility to unveil the plasmonic properties of 2D-material and heterostructures will push forward the development of plasmonic devices, offering unique opportunities to provide fully integrated on-chip high-Q elements with a wide tunability. Optical/optoelectronic applications include photodetectors, photovoltaics, light-emitting structures, and integrated photonics. 2D plasmonic devices also offer a concrete opportunity to provide fully integrated on-chip high-Q elements with a wide tunability.

Finally, the demonstrated potential of 2D materials as saturable absorbers and mirrors at THz frequencies paves the way for the integration of graphene-based absorbers with electrically-pumped THz semiconductor micro-sources to drive them, by modulating their intra-cavity field, into the passive mode locking regime, which is yet to be reached. This would open up new frontiers in research fields where excitation of specific transitions on short time scales is essential as: THz real-time pulsed imaging and time of flight tomography, coherent manipulation of quantum systems and optical communication.

Large area material production, combined with larger mobility, is presently the critical ingredient for a stable and reproducible production of the above technologies, which is a mandatory requirement for a wide impact on market and research.

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