

Antenna-coupled graphene field-effect transistors as a terahertz imaging array

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Abstract—Terahertz radiation is extremely suitable for various imaging applications. In real life, these range from food or pharmaceutical quality control to illegal materials or human security control inspections. Despite its great potential, the wide usage and commercialization of terahertz imaging systems are still limited by the lack of compact technologies. The emerging graphene-based devices can efficiently contribute to fill this gap, offering higher versatility, scalability and superior electronic properties compared to conventional semiconductors. In this work, we study a new scheme for realizing a multielement terahertz sensor, which is capable of multipixel parallel detection. The array consists of linearly distributed antenna-coupled graphene field-effect transistors, which are realized by exploiting a deterministic growth by chemical vapour deposition of single-crystal graphene. This novel growth technique ensures high material quality and offers large adaptability to different electronic device architectures. Relatively uniform terahertz detection performances (with a maximum homogeneity degree of 80%) were obtained with a maximum responsivity of the order of 1 V/W and an estimated response time in the picosecond scale. These detectors have demonstrated to fulfill several main requirements for image sensors (pixel uniformity, operability and scalability), becoming very promising candidates for the realization of commercial high resolution room-temperature terahertz cameras.

Index Terms—Graphene, terahertz, imaging, detectors array

I. INTRODUCTION

THANKS to its strong interaction with the vibrational and rotational motions of molecules and its low energy photons, terahertz (THz) radiation is non-destructive, non-invasive and relatively safe radiation for probing structural properties of non-polar, non-metallic, biological and non-biological materials [1]. These properties make THz radiation extremely suitable for general imaging applications, like for quality control in pharmaceutical and food industries [2], [3]

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or in scientific fields, such as medicine (for ex-vivo skin cancer and dental caries diagnostics [4], [5]), chemistry/physics (for materials spectroscopy [6]) and space sciences (for investigation of interstellar medium of galaxies and galactic evolution [7]). THz radiation has also demonstrated its great potential as 'see through' technology for imaging of concealed weapons, explosives, drugs and chemical and biological agents, as well as for a new generation of body scanners [8].

Despite the great potential of THz imaging in such fields, its wide usage and commercialization are still limited by the lack of a compact technology: a nearly-collimated powerful source combined with a high sensitive imager, i.e. a two-dimensional array of detectors. In this context, many resources are currently invested to develop highly sensitive ($\ll$ pW/ $\sqrt{\text{Hz}}$), fast ($>$ GHz), high operating temperature [ideally room-temperature (RT)], compact and possibly portable multielement sensors, which are capable of multipixel parallel detection both in active and passive conditions. Indeed, acquiring images at high frame rate is imperative in real-time imaging. For example, in medical and security applications, a minimum frame rate of about 1 fps (frame per second) is acceptable, while a video-rate acquisition ($>$ 30 fps) is fundamental in industrial monitoring [9]. Currently, the most developed RT detectors arrays are based on microbolometers, which exploit the well-established - THz range adapted - infrared imager technologies [10]–[14]. However, their response time is in the millisecond range, thus allowing only direct (incoherent) detection. Competitive alternative is represented by antenna-coupled field-effect-transistors (FETs) [15]–[19]. These detectors work at room temperature and rely on plasmonic rectification phenomena [20], [21]. Their all-electronic character enables broadband spectral detection from 0.2 GHz to 4 THz [22] and an intrinsic response time of $\sim$ tens ps [23], thus fast enough for heterodyne (coherent) detection. Moreover, their easy implementation in CMOS (complimentary metal-oxide semiconductor) technology allows to fulfill the principal requirements for any image sensors: high pixel uniformity, temporal stability, operability, scalability and affordability [24], [25].

The recent advent of two-dimensional (2D) materials has given new life to FET sensors technology thanks to their extraordinary electronics properties [26]. Among the various 2D materials, graphene is a promising one for developing high-frequency transistors thanks to its high charge carrier saturation velocity and high carrier mobility [27], [28]. The first demonstration of THz detection by 2D materials-based FETs has been obtained in mechanically exfoliated graphene transistors (GFETs), which operate as a single direct detector

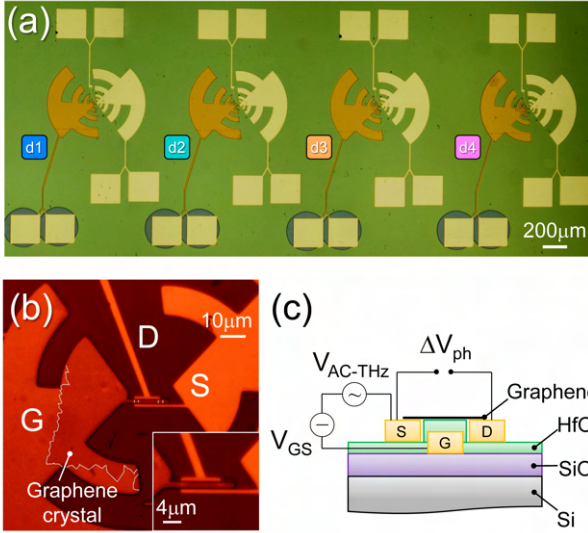


Fig. 1. a) Optical images of a 4-pixels linear array sensor. The pixels are named *d1*, *d2*, *d3* and *d4*; b) zoom on FETs contacts: source (S), drain (D) and gate (G). The residual of graphene crystal is clearly visible on the top of gate connected-antenna; c) lateral side view of the sketch of GFET THz detectors and the detection working principle scheme. The radiation-induced AC voltage (V_{AC-THz}) applied between source and gate and superimposed to a possible DC gate-to-source voltage (V_{GS}), generates an AC current within the FET channel, which nonlinearly rectifies it, creating a DC photovoltage (ΔV_{ph}) between source and drain.

[29]. The mature technology in graphene growth techniques, such as thermal decomposition or chemical vapour deposition (CVD), allows the synthesis of high quality monolayer graphene in large areas [30]–[32], guaranteeing scalability, compatibility with CMOS integration and thus possible realization of novel focal plane detectors for imaging applications. In this context, large area graphene, epitaxially grown on insulating silicon carbide substrate, has been already demonstrated as a promising candidate for novel THz imagers exploiting plasmonic effects [33]. These GFETs do not need high-fidelity transfer process to maintain good crystalline integrity, which is an important advantage when fabricating the detectors array. However, nowadays graphene transfer techniques are constantly improving, reaching high success yield, thus the potential of CVD graphene is starting to fulfil the large area single crystal domain requirements.

In this work, we present the results of direct power RT detection at 0.3 THz by linear array consisting of antenna-coupled FETs having channel made by spatially-ordered-grown single crystal CVD graphene. The deterministic growth offers the high versatility on device realization, well adapting the growth sites to the architecture of the final electronic chip as well as very high homogeneity among graphene crystal properties. Moreover, this technology is very suitable for implementing graphene in silicon-CMOS technology, as it offers the necessary flexibility to be integrated in CMOS production lines. As a result, the detectors linear array shows relatively high pixel uniformity both in detection properties and response speed, demonstrating the high potential of these detectors in the realization of high resolution RT THz cameras.

II. LINEAR DETECTORS ARRAY DESCRIPTION

The linear detectors array consists of four equally spaced antenna-coupled GFETs, forming four independent pixels (named pixel *d1*, *d2*, *d3* and *d4*) fabricated onto silicon dioxide/intrinsic silicon (SiO_2/Si) wafer (Fig. 1a). The fabrication steps comprise first the FETs electrodes realization and subsequently the graphene transfer and channel definition. The array pitch is 1 mm and it was chosen according to the dimension of the log-periodic circular-toothed antennas connected to source and gate electrodes of the GFETs (as shown in Fig. 1b). The antenna has been designed for working between 250 GHz and 400 GHz, similarly to Ref. [33]. Each pixel has identical antenna and FET channel geometry. The source-to-drain-length is 2 μm and total channel width is 6 μm, while the gate electrode is 1 μm-long. Antenna and metal contacts were patterned by electron beam lithography, followed by thermal evaporation of 5 nm/75 nm chromium/gold. Optical lithography can be potentially applied to obtain a similar pattern. Transferring few hundred-micrometer sized graphene crystals, the channel definition and the electrical isolation trenches were realized by selectively etching sacrificial areas through a polymethyl methacrylate mask via oxygen/argon reactive-ion etching. Buried gate configuration was adopted, meaning that graphene lies on top of an oxide layer (gate dielectric) that separates it from the gate electrode, as shown in Fig. 1c. This configuration was chosen in order to mimic the possible integration of graphene in CMOS chips. Indeed, due to current high damage risk of graphene during some fabrication processes of silicon CMOS integrated circuits and stringent rules regarding the production line contamination, graphene is preferably transferred on top of the final chip, as back-end-of-line part of the fabrication stage. A 35 nm-thick layer of hafnium oxide (HfO_2) was used as gate dielectric. This layer was grown at 200 °C by atomic layer deposition and has a gate capacitance per unit area of 0.5 μF/cm², as independently measured by using LCR meter. Atomic Force Microscopy (AFM) characterization has revealed a roughness of the HfO_2 surface of about 1-2 nm (Ra), indicating that the initial SiO_2 Ra is preserved and thus graphene is transferred on a surface having quality as high as possible.

Deterministic patterned growth of large graphene crystals was obtained following the same procedure as described in [30]. After electropolishing for surface cleaning and morphology improvement, natively-oxidised copper foils were patterned by optical lithography to achieve an ordered pattern of circular openings. Subsequent thermal evaporation of 25 nm of chromium and lift-off create the final nucleation sites. The growth of large single-crystals is performed using a low-pressure (25 mbar) CVD growth procedure using a commercially-available Aixtron BM Pro cold-wall reactor. The copper foils were annealed for 10 min in non-reducing argon atmosphere in order to preserve surface oxidation, while graphene is grown with a gas flow comprising 900 standard cubic centimetres per minute (sccm) of argon, 100 sccm of hydrogen and 1 sccm of methane at a temperature of 1060 °C. An example of seeded-growth graphene crystals on copper foil is reported in Fig. 2a.

A semi-dry transfer technique, which is based on electrochemical delamination [30], is used to detach graphene crystals from the copper foil and transfer them onto the GFETs electrodes (Fig. 2b). This technique minimises the transfer-related contamination and allows precise placement of graphene arrays on the target substrate at micrometer scale resolution. All these fabrication processes and detectors design can be conveniently scaled up, satisfying the scalability requisites for imagers. For example, larger number of graphene crystals can be simultaneously transferred and shorter pitch can be potentially used by simply designing more compact resonant antennas to increase the number of pixels and thus improve the image resolution.

III. GRAPHENE QUALITY AND ELECTRONIC PROPERTIES

When a two-dimensional matrix of detectors has large non-uniformity in the photoresponse of individual detectors in the array, fixed-pattern noise is superimposed on the true image. This deteriorates the final image quality and imposes the use of non-uniformity correction methods to compensate the pixel-to-pixel variation [34]. In order to maintain the imaging system as simple as possible and limit the use of subsequent processing algorithms, intrinsic pixels uniformity is fundamental. In GFET detectors, photoresponse inhomogeneity originates from variations in graphene sheet electrical transport properties due to defects, domain boundaries, contamination or residual tensile strain that may be introduced during graphene synthesis and/or transfer process or generically to air-exposure. Hence, graphene sheet quality and electronic properties of each pixel of the linear array were firstly investigated by micro-Raman spectroscopy and GFET transfer characteristic measurements, respectively. Subsequently, the array detection properties were investigated by using a linearly polarized broadband THz source.

A. Micro-Raman spectroscopy characterization

Micro-Raman spectroscopy was carried out in 2D scanning mode at 532 nm. Fig. 3a shows the spatial distribution of the

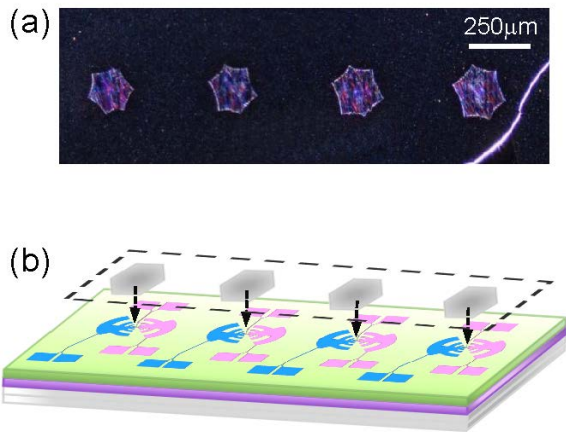


Fig. 2. a) Dark field optical image of seeded-CVD grown graphene crystals on copper foil; b) Sketch of 2D arrayed graphene crystals transfer on antenna-coupled FETs.

intensity of the 2D Raman mode, making clear the presence of graphene within the GFET channel and on top of the gate-connected antenna arm (residual crystal after channel definition by plasma etching). From the analysis of the main graphene Raman modes, both 2D and G peaks result having Raman shift (ω_{2D} and ω_G , respectively) uniformly distributed over the scanned area, as shown in Fig. 3b, indicating high homogeneity in the crystalline structure. The correlation plot (ω_G , ω_{2D}) was also constructed (Fig. 3c). This analysis provides useful information on the actual status of graphene sheet, differentiating the effects of strain and charge accumulation [35]. The mean value for ω_G and ω_{2D} was determined by fitting with a Gaussian curve the histograms extracted from the distribution of G and 2D peak Raman shifts over the scanned area for each pixel of the array. As shown in Fig. 3c, all pixels lie in a small area of (ω_G , ω_{2D}) space, which corresponds to strain of about 0.15% and doping in the range between $1 \cdot 10^{12} \text{ cm}^{-2}$ and $5 \cdot 10^{12} \text{ cm}^{-2}$. The obtained residual strain is tensile and is attributed to the in-plane stress induced during the transfer process. Its magnitude is in the range of values also achievable in mechanically exfoliated graphene on SiO_2 [35]. The doping is p-type, as also confirmed by electrical measurements, and is ascribed to extrinsic contamination, like exposure to air and residual impurities of polymer used during the transfer step. Within the Gaussian distribution variances, all pixels have also highly homogeneous full-width-half-maximum (FWHM) of both Raman modes, resulting in 2D FWHM of about 32 cm^{-1} , as a consequence of the residual strain, and in G FWHM of about 20 cm^{-1} (Fig. 3d). The small variation revealed by Raman modes among the different crystals indicates the highly uniform structural quality achieved in this transferred CVD graphene, demonstrating its high potentiality when dealing with scalable devices. Finally, the absence of defects-related peak at 1340 cm^{-1} confirms the integrity of the crystalline lattice (inset in Fig. 3a).

B. Two-probe transfer characteristics

Each detector of the array was electrically characterized by measuring the two-probe transfer characteristics, while keeping source/drain voltage at 1 mV (Fig. 4a). The transfer characteristic curves are symmetric in the gate voltage range between -1 V and 1 V, indicating similar mobility of holes and electrons and have the Dirac points all located in a narrow range of gate voltages (V_G) centered at about 0.45 V. By fitting the total resistance data (R_{tot}) assuming a simple model that considers the series of the total contacts (R_c) and graphene sheet (R_{sh}) resistances and a gate-independent mobility [36], the transistors parameters were extracted (Fig. 4b). The residual carrier density varies in a small interval from $0.45 \cdot 10^{12} \text{ cm}^{-2}$ in pixel *d1* to $0.85 \cdot 10^{12} \text{ cm}^{-2}$ in pixel *d4*, in agreement with Raman spectroscopy results. The carrier mobility values are fairly homogeneous among the GFETs and they range from a minimum of about $1200 \text{ cm}^2/\text{Vs}$ in pixel *d4* to a maximum of $2300 \text{ cm}^2/\text{Vs}$ in pixel *d3*. This small discrepancy may be attributed to combined effects of residual tensile strain and extrinsic impurities. Very similar total contact resistances have been estimated for pixels *d2*, *d3* and *d4*: $R_c \sim$

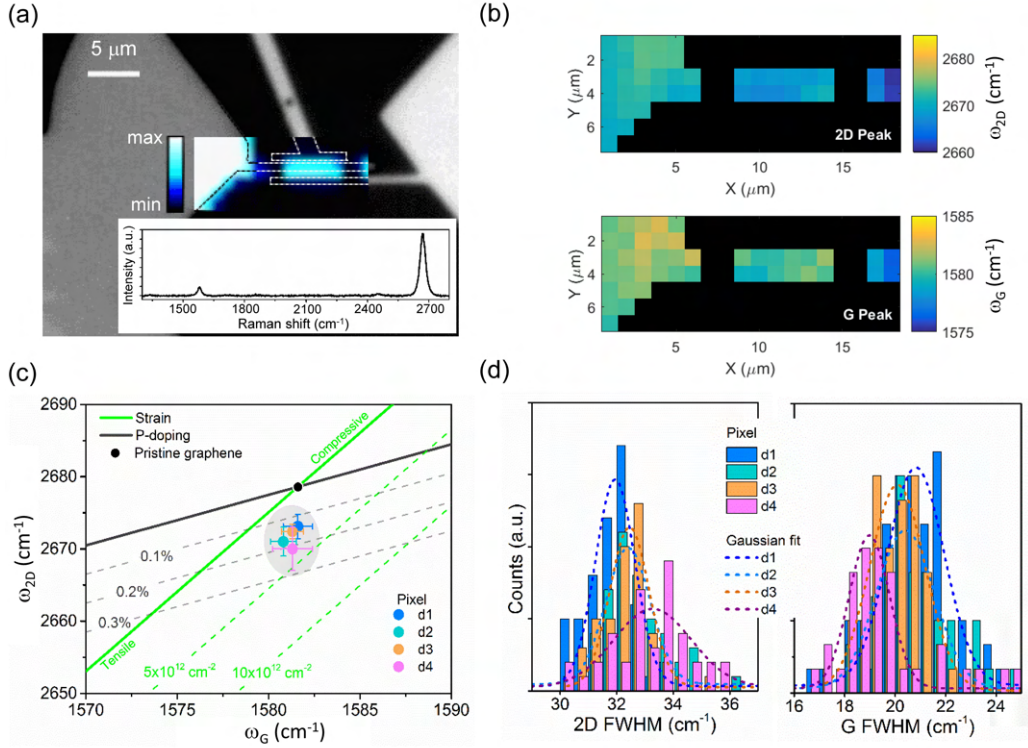


Fig. 3. Micro-Raman spectroscopy analysis: a) two-dimensional map of the graphene 2D peak intensity and representative Raman spectrum acquired in the GFET channel area (inset); b) spatial distribution of Raman shift of 2D (top) and G (bottom) peak; c) correlation plot of the G and 2D peak Raman shift (ω_G , ω_{2D}) of each pixel extracted from Raman images (colored dots). The green solid line represents (ω_G , ω_{2D}) of doping-free graphene when varying uniaxial strain, while green dashed lines are for p-doped graphene. The black solid line represents (ω_G , ω_{2D}) of strain-free graphene when varying p-doping, while grey dashed lines are for strained graphene; d) histograms for 2D (left) and G peak (right) FWHM. Dashed lines are Gaussian fits to the data.

1.1 k Ω , corresponding to contact resistivity of about 3 k $\Omega\mu\text{m}$ (assuming symmetric contact resistance for source and drain electrodes). Instead, pixel *d1* has larger total contact resistance, $R_c \sim 2$ k Ω . Based on the analysis, the elements of the linear array have comparable transistor parameters. However, the overall ability in modulating the sheet resistance by field-effect is dissimilar, as shown in Fig. 4c, where the sheet resistance has been calculated as $R_{sh} = R_{tot} - R_c$. Indeed, between -1 V and 1 V gate bias, the sheet resistance of pixels *d2* and *d3* has very similar functional dependence on gate voltage and the carrier density can be changed such that R_{sh} can be varied by about 67% with respect to its maximum value. Instead, in pixels *d1* and *d4*, the sheet resistance can be modulated by about 88%, but pixel *d1* has a sharper curve than pixel *d4* due to the smaller residual carrier density.

IV. PLASMA WAVE RECTIFICATION THZ DETECTION

The detection mechanism in THz FETs sensors is based on plasma wave rectification occurring from the excitation of plasmonic waves in the transistors channel when they satisfy asymmetric boundary conditions, i.e. source short circuit and drain open circuit [20]. This condition is automatically achieved when connecting the arms of an antenna to source and gate electrodes to improve the radiation coupling efficiency. The resulting simultaneous modulation of the carrier density and drift velocity at the incoming radiation frequency

ν rectifies the light-induced AC current and generates a DC photovoltage between the source and drain contacts (Fig. 1c), whose magnitude is proportional to the incident power.

The detection performances of the linear array were characterized at RT when individually illuminating each sensing element with a broadband THz source covering a spectral range from 260 GHz to 375 GHz. The output power is frequency dependent and ranges from 0.5 mW to 1 mW (calibrated after the focusing lens). The source output has fixed horizontal polarization and was modulated at 442 Hz. A frequency sweep was used to precisely identify the maximum resonance frequency of the antennas in the spectral range of the source emission, corresponding to a maximum photovoltage of ~ 5 μV . Finally, the detector responsivity was estimated as the ratio between the photovoltage and incident power, where the latter is weighted by the beam spot size and the detector active area (i.e. diffraction limit).

Figure 5a shows the gate-dependent photoresponsivities obtained for an incident radiation at 360 GHz, when grounding the source electrode. A clear change of the responsivity sign was observed, as predicted in Dyakonov-Shur detectors. A responsivity ($\mathcal{R}$) of several hundreds mV/W was quantified with an error of 30%, as estimated by repeated measurements. This uncertainty may be attributed to small hysteretic effects arising from the gate oxide and/or instability of extrinsic doping due to the graphene air exposure. Generally, encapsulation with

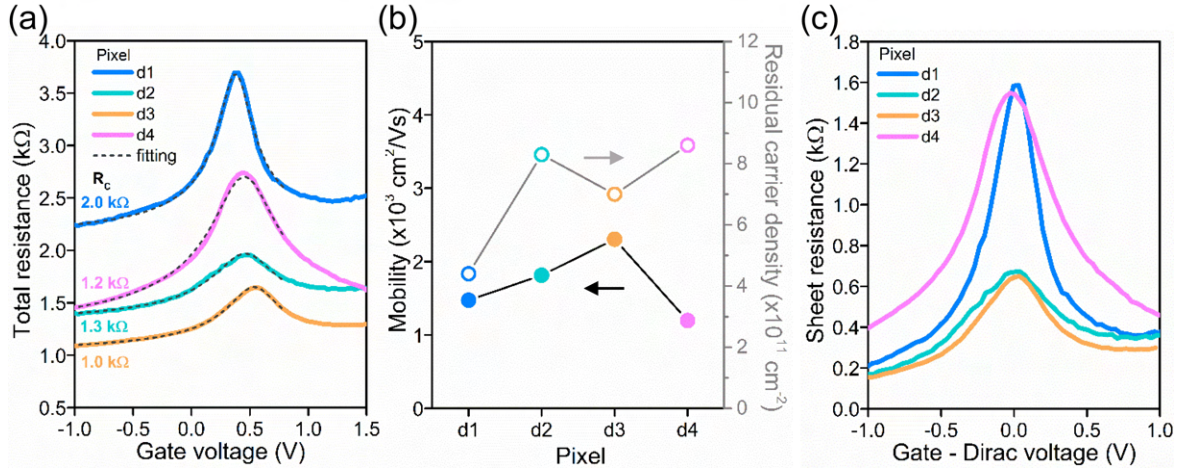


Fig. 4. Electronic properties analysis: a) total resistance as a function of gate bias for all pixels-related GFETs at source/drain voltage of 1 mV. Short dashed grey lines are nonlinear fitting curves as $R_{tot} = R_c + R_{sh} = R_c + \frac{L}{W} \frac{1}{e\mu\sqrt{(n_0^2 + n_G^2)}}$, where L and W are the channel length and width, respectively, e the elementary charge, μ the carrier mobility, n_0 the residual carrier density and n_G the field-effect-induced carrier density; b) mobility and residual carrier density extracted by nonlinear fitting for all GFETs; c) sheet resistance as a function of gate bias.

multilayer hexagonal boron nitride (ideally, large area) can solve both problems, because it can work as both gate oxide with minimal hysteresis and protecting and isolating material. The maximum responsivity ($\mathcal{R}_{max}$) is reached when applying a gate bias of 0.8 V (Fig. 5b). This varies around a mean value of 0.5 V/W, resulting in a spatial non-uniformity of 25%. The latter was calculated as σ/mean , where mean is the mean value of $\mathcal{R}_{max}^i$ and $\sigma = [\max(\mathcal{R}_{max}^i) - \min(\mathcal{R}_{max}^i)]/2$, with $i = 1, 2, 3, 4$. Alternatively, the array can be, instead, operated at 0.5 V gate voltage. At this bias, although lower (~ 0.15 V/W), a more homogeneous responsivity can be achieved ($\sigma/\text{mean} = 20\%$, corresponding to a homogeneity degree of 80%, calculated as $100\% - \sigma/\text{mean}$), as indicated in Fig. 5c. To the best of our knowledge, in literature a photoresponse analysis of multiple CVD graphene-based THz detectors is absent, thus a direct comparison with similar structures is not possible. However, a graphene-based imager working in the ultraviolet-near field spectral range has been reported in Ref. [37]. In this system, the spatial distribution of pixel resistances after correction with compensation resistors has a 20% non-uniformity. Although the much lower number of pixels, our uncorrected devices have total resistances at 0.8 V with similar spreading, pointing out the possibility to reach at least a comparable homogeneity degree.

Finally, the null-responsivity points occur around gate voltages of about 0.6 V, in good agreement with the voltage position of the Dirac points (inset in Fig. 5b), as expected for plasmonic detection. Indeed, in the regime when plasma waves are overdamped during their propagation within the FET channel, the solution of both Euler and continuity equations predicts that the rectified photovoltage (ΔV_{ph}) depends on the gate voltage according to the relation $\Delta V_{ph} \propto \sigma^{-1} d\sigma/dV_G$, where σ is the total source/drain conductance. The inset in Fig. 5a shows the photovoltage ΔV_{ph} as a function of the gate bias, as calculated for each pixel by using the measured σ . This model reproduces very well the experimental data, both in null-responsivity points ($\sim 20\%$ deviation from the

experimental data) and in sensitivity distribution within the array. Interestingly, this model helps in understanding how the difference in transistor parameters influences the detection performances. For example, pixel *d1* has larger R_c and μ than pixel *d4*, but sharper carrier density modulation due to the lower residual carrier density. While the differences in mobility only marginally contribute to the overall responsivity, R_c of *d1* is expected to largely reduce ΔV_{ph} . However, the residual carrier density in pixel *d1* is roughly half of that in pixel *d4*, thus it compensates the lowering effect of R_c , resulting in very similar maximum photoresponse. Instead, when comparing the transport properties of pixels *d3* and *d4*, the contribution from R_c is minimal, whereas the gain in responsivity in pixel *d4* due to the lower mobility is strongly mitigated by the much larger residual carrier density, justifying the reduction in maximum responsivity. Similar analysis can be carried out by comparing pixel *d1* with *d2* and pixel *d2* with *d3*.

Due to the zero-bias configuration, the thermal Johnson-Nyquist noise was assumed as the dominant contribution to calculate the noise-equivalent-power (NEP):

$$NEP = \frac{\sqrt{4k_B T R}}{\mathcal{R}} \quad (1)$$

where k_B is Boltzmann constant, T is the temperature, R is the total channel resistance and $\mathcal{R}$ is the detector responsivity. Pixels *d1* and *d4* have minimum $NEP \sim 1 \cdot 10^{-8} \text{ W}/\sqrt{\text{Hz}}$, while for pixels *d2* and *d3* $NEP \sim 1.5 \cdot 10^{-8} \text{ W}/\sqrt{\text{Hz}}$ (see Fig. 5b), which is comparable with state of the art microbolometers working at 0.3 THz [26]. It is worth noticing that, in addition to limit the noise source to mainly thermal fluctuation, zero-bias configuration has the advantage that the array can potentially operate in power-line free mode. Indeed, an electric battery could be sufficient to generate the required gate voltage, making this array a low power consumption device, ideally zero for a perfect gate oxide (gate resistance = ∞).

As discussed in the introduction, real-time imaging applica-

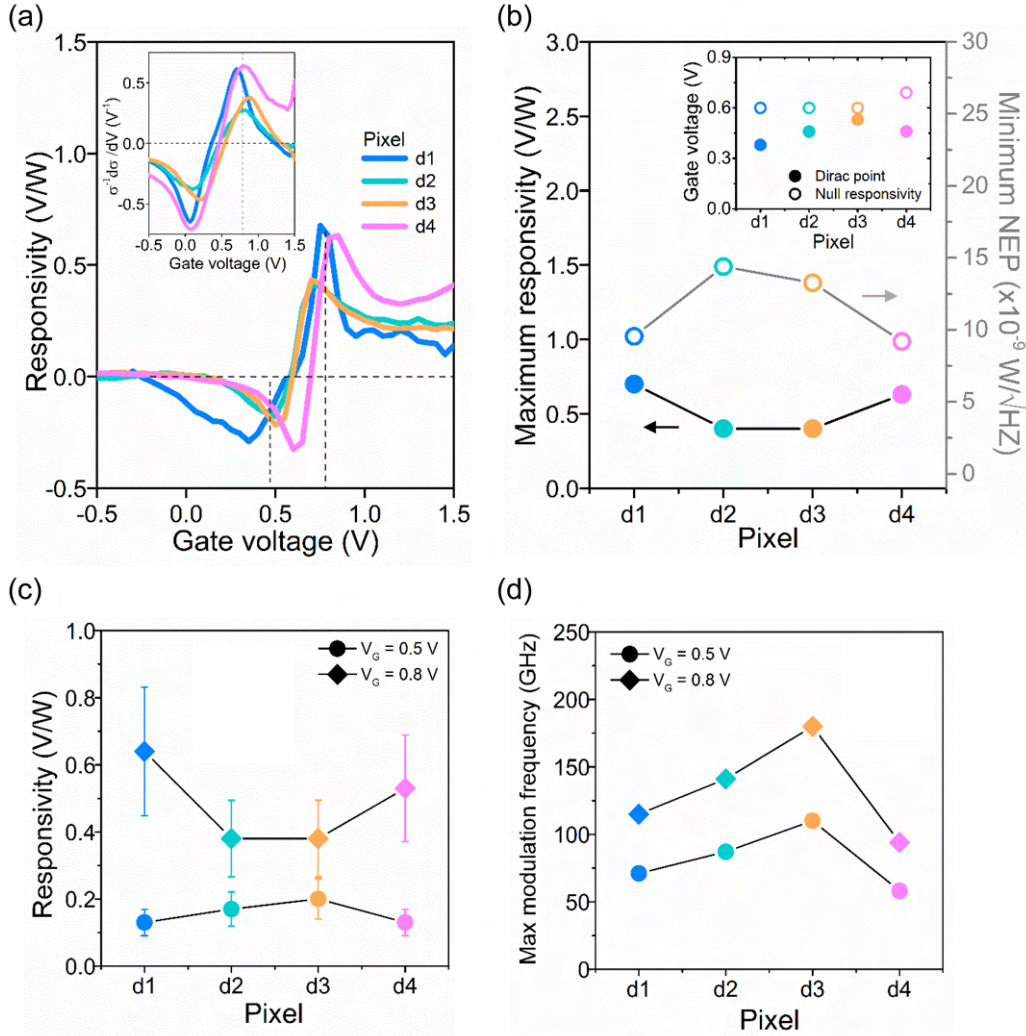


Fig. 5. THz detection performances: a) responsivity as a function of gate voltage measured at 360 GHz and calculated plasmonic photovoltage versus gate voltage for all pixels (inset). Dashed lines indicate the photoresponse zero and possible optimal operational conditions of gate voltage (0.5 V and 0.8 V); b) maximum responsivity (empty dots) and NEP (full dots) for all GFETs. In the inset, the comparison between Dirac (full dots) and null-response voltages (empty dots) is reported. Errors in Dirac and zero-response points estimation is about 15% and 30%, respectively, as quantified from repeated measurements; c) responsivity and d) maximum modulation frequency for each pixel calculated at gate voltage equal to 0.5 V (dots) and 0.8 V (diamonds).

tions require imagers having very fast response time. The temporal response of our GFET detectors can be estimated by the analytical drift model describing the dynamic of the plasmonic response [38]. When the incoming THz radiation is modulated at a frequency ω_{mod} , that is much lower than the radiation frequency ω , the detector response adiabatically follows the modulation amplitude of the radiation signal until the modulation frequency is much lower than a maximum value ω_{mod}^{max} . In non-resonant detection and diffusive electronic transport regime, the maximum modulation frequency in the long gate limit can be expressed by [38]

$$\omega_{mod}^{max} = \frac{\mu V_G}{L_G^2} \quad (2)$$

which increases as the mobility μ and gate voltage V_G increases or when shortening the gate length L_G , until the electronic transport changes into ballistic or viscous regime, where this model is no more valid. For example, having the

largest mobility, pixel *d3* has an estimated ω_{mod}^{max} of about 110 GHz at 0.5 V and 180 GHz at 0.8 V, corresponding to a response time $\tau \sim 9$ ps and 6 ps, respectively. Figure 5.d shows the maximum modulation frequency estimated for each pixel at gate bias equal to 0.5 V and 0.8 V. It is important to notice that Equation 2 is valid until $\mu V_G/L \ll v_{sat}$, where v_{sat} is the electron saturation velocity. Hence, the qualitative upper limit of the maximum modulation frequency for GFETs in diffusive transport is estimated as [38]

$$\omega_{mod}^{lim} = \frac{v_s}{L_G} \quad (3)$$

Considering the extremely high saturation velocity measured on HfO₂-based GFETs ($v_{sat} \sim 5.5 \cdot 10^5$ m/s [39]), in this linear array ω_{mod}^{lim} is expected to be as high as ~ 550 GHz (or equivalently $\tau \sim 2$ ps). As a consequence, for practical applications, the response speed of an array made by plasmonic detectors is mainly imposed by the electronic read-out scheme.

V. CONCLUSION

In conclusion, we demonstrated a linear array of THz detectors based on graphene field-effect transistors. The used deterministic CVD growth of graphene was proved to be largely suitable for producing multi-device architecture, thanks to the simultaneous transfer of single crystal graphene that can be grown according to desired chip geometry. This growth offered both high quality of the graphene sheet that arises from single crystal character and quite homogeneously distributed RT ambient air electronics properties, as demonstrated by micro-Raman spectroscopy and two-probe transfer characteristics measurements. The best performances of these detectors correspond to a maximum responsivity of about 0.8 V/W, a minimum NEP $\sim 1 \cdot 10^{-8}$ W/ $\sqrt{\text{Hz}}$ and an estimated response speed of about 6 ps. Although the obtained GFETs responsivity and NEP are worse compared to Si-FETs [18], the higher expected response speed with respect to nanosecond-time scale in Si-CMOS FETs [40] makes GFETs highly appealing if combined with pulsed sources, like for example free electron lasers, in time-domain experiments, where good temporal resolution is required. A significant improvement of the maximum responsivity and the minimum NEP of our array may be achieved by better optimizing the THz radiation funneling into the active area and the impedance matching between antenna and graphene-channel, like for example in Ref. [41]. Despite the detectors being measured at RT and in ambient exposure that unavoidably alters the operating conditions of the FET channel, the observed variations among transistor parameters did not significantly influence the detectors responsivity. A spatial uniformity up to 80% was obtained, helping in minimizing possible photovoltage post-processing. Although real THz imagers based on GFETs with integrated read-out are still at their infancy, the proposed linear array helps to make a step further, proving that almost uniform fast detection performances can be already obtained from single crystals graphene, that is grown in a highly versatile way and can be integrated at the back-end-of-line part of the fabrication stage in silicon CMOS integrated circuits, demonstrating the high potential application of this array in realizing THz graphene-based imagers.

During the review process of the present manuscript, the authors were informed of an article published after the submission of the present manuscript. In this article, a 16 linear array of antenna-coupled GFET detectors has been implemented on a flexible substrate [42]. The detectors show maximum responsivity in the range from 20 V/W to 70 V/W and noise equivalent powers in the range from 0.06 nW/ $\sqrt{\text{Hz}}$ to 0.2 nW/ $\sqrt{\text{Hz}}$. Although the detection performances are superior, these detectors suffer from large non-uniformity (sigma/mean $\sim 55\text{-}60\%$ calculated at the gate voltage where the highest responsivity was measured).

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