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Chip-Scalable, Graphene-Based Terahertz Thermoelectric Photodetectors

Leonardo Viti[1], Mahdi Asgari[1], Elisa Riccardi[1], Osman Balci[2], Domenico De Fazio[3], Sachin M. Shinde[2], Jincan Zhang[2], Sandro Mignuzzi[2], Frank H. L. Koppens[3], Andrea C. Ferrari[2] and Miriam S. Vitiello[1]

[1] NEST, Istituto Nanoscienze - CNR and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy
[2] Cambridge Graphene Centre, University of Cambridge, 9, JJ Thomson Avenue, Cambridge CB3 0FA, UK
[3] ICFO-Institut de Ciencies Fotoniques, 08860 Castelldefels, Barcelona, Spain

Abstract— **We report room temperature terahertz detection in large-area single layer graphene (SLG) grown by chemical vapor deposition (CVD), integrated in antenna-coupled field effect transistors. We employ different dielectric thin layers as substrate termination (SiO_2, Al_2O_3) and different layers as top encapsulation (HfO_2 or large-area CVD-grown hexagonal boron nitride), to investigate the effect of the surrounding layers on SLG thermoelectric properties underpinning photodetection. With these scalable architectures, response times ~5 ns and noise equivalent powers ~1 $nWHz^{-1/2}$ are achieved under zero-bias operation.**

I. INTRODUCTION

Terahertz (THz) technology is attracting a renewed interest thanks to emerging applications, such as high-frequency communications [1] and quantum technologies [2,3], which are driving a considerable research effort [4] along two main directions: the first aims at devising novel high-end prototypes for proof-of-concept demonstrations, the second aims at realizing high-performance scalable devices to be integrated in technologically mature (i.e. silicon-based) industrial platforms [5].

In the case of THz detectors, on one hand developers are realizing room-temperature multi-pixel commercial cameras with microbolometers [6] or using CMOS platforms [7], while on the other hand, researchers are pushing the limits of sensitivity, reaching single photon detection in quantum capacitance detectors [2].

In this context, single layer graphene (SLG) can play an important role for the development of scalable and efficient THz detectors operating at room-temperature (RT), with demonstrated single-pixel performance competitive with the state-of-the-art in high-quality hexagonal boron nitride (hBN)-encapsulated SLG [8-10]: sub-ns response time and noise equivalent power (NEP) < 100 $pWHz^{-1/2}$ at 3 THz. These performances are enabled by the photothermoelectric (PTE) detection mechanism. Interestingly, the broadband PTE effect, which relies on the thermal gradient within the electronic distribution as a consequence of the absorption of electromagnetic radiation [11], takes full advantage of the unique opto-electronic properties of SLG: low electronic specific heat and ultrafast (<100 fs) carrier-carrier scattering, accompanied by relatively slower (~1 ps) energy relaxation channels for hot-carriers [12], lead to carrier distributions with elevated temperatures [13]. Unlike photovoltaic or bolometric effects, PTE can be activated in field effect transistors (FETs) under zero-bias operation [8] (i.e., zero dark current), thus ensuring low power consumption and low flicker noise.

The wide application of graphene-based devices entails the use of scalable synthesis techniques, such as chemical vapor deposition (CVD), and the implementation of wafer-scale fabrication methods. This technological transition is currently hampered by the typically lower material quality, and, in turn, worse SLG properties (i.e. mobility, impurities), upon up-scaling. In order to address this issue, here we develop THz detectors with CVD-grown large-area (~1×1 cm^2) SLG encapsulated in different material layers: SiO_2/SLG/HfO_2 [14], Al_2O_3/SLG/HfO_2 [15] and Al_2O_3/SLG/hBN [15]. The latter is realized by consecutive transfer of CVD graphene and CVD hBN [15], a fabrication technique that is fully compatible with standard complementary metal oxide semiconductor (CMOS) processing.

II. RESULTS

We engineer SLG-based FETs, coupled to on-chip planar antennas, whose operation frequency can be in principle extended over the whole 0.1-10 THz range. Figure 1a shows a bow-tie architecture. We engineer either planar bow-tie antennas, asymmetrically connected to the source (*s*) and top-gate (*g*) electrodes, or double split-gates connected to the two branches of a dipole (linear or bow-tie) antenna, defining a *p-n* junction at its center. Both architectures allow for the optimization of the PTE response by tuning the applied gate voltages [10].

We optically characterize THz SLG photodetectors with pulsed quantum cascade lasers (QCLs) operating in the frequency range 2.7-3.4 THz. PTE-dominated detection is demonstrated in all the realized devices by measuring the device responsivity as a function of applied gate voltage(s). By characterizing more than 50 photodetectors, we obtain a minimum NEP ~1 $nWHz^{-1/2}$ (Figure 1b) and response times ~5 ns (Figure 1c) [14,15]. According to the PTE model [15], the residual carrier density (n_0) in SLG is the main electrical property that determines the amplitude of the Seebeck coefficient. In good agreement with this prediction, our statistical analysis (Figure 1b) indicates that detectors NEP decreases for lower n_0, confirming a PTE-driven detection.

Moreover, our analysis indicates that Al_2O_3/SLG/hBN heterostructures present a two times lower performance variability in the NEP figure of merit with respect to the other material platforms [14,15]. This feature is one of the main requirements towards the realization of multi-pixel THz cameras: pixel uniformity, operability, and scalability. We expect that a further improvement in device electrical and optical performance will result from the full large-area encapsulation of SLG in CVD-based hBN/SLG/hBN heterostructures.

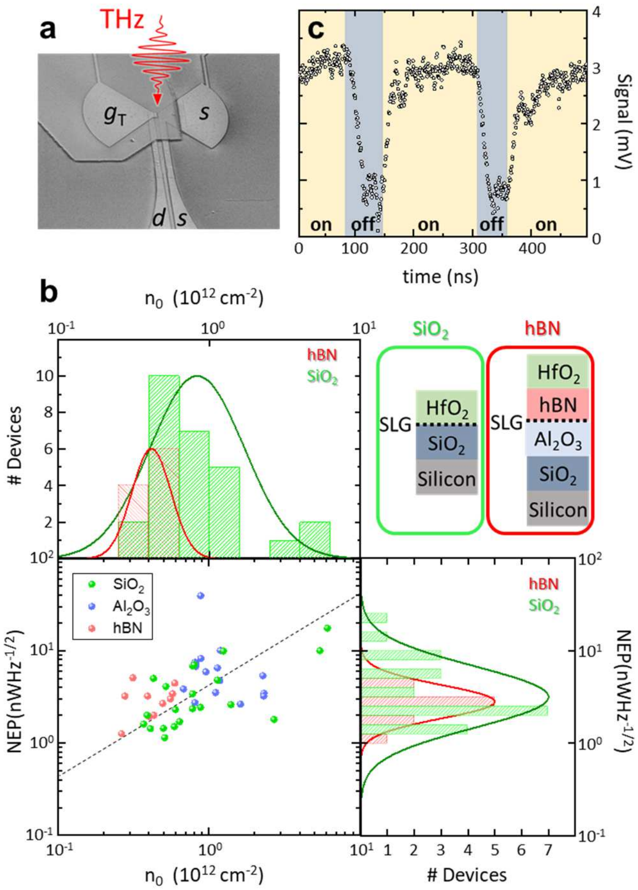

Fig. 1. (a) Optical experiment: a THz beam generated by a QCL is focused onto the THz detector. The SEM image shows a SLG FET integrated in a planar bow-tie antenna with total length 44 μm. (b) Scatter plot of NEP *vs*. n_0 including all the investigated devices. The dashed line is a guide for the eye. Inset: schematic diagrams of SiO_2/SLG/HfO_2 and Al_2O_3/SLG/hBN heterostructures. The direct comparison of performance variability between SiO_2- and hBN-based systems shows that devices realized with Al_2O_3/SLG/hBN heterostructures have more uniform electrical (n_0) and optical (NEP) performance. (c) Time trace of the signal from a representative photodetector, recorded with a fast oscilloscope during an intensity fluctuation of the QCL output. Yellow (grey) shaded areas indicate the intervals when the THz beam is on (off). The detector response time can be calculated by fitting the waveform with exponential functions.

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