Nanowire and graphene architectures for Room Temperature THz detection

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***Abstract*—Antenna-coupled field effect transistors have been developed as plasma-wave THz detectors in both InAs nanowire and graphene channel material. Room temperature operation has been achieved up to frequencies of 1.5 THz, with noise equivalent powers as low as a few 10^{-11} W/Hz$^{1/2}$, and high-speed response.**

I. INTRODUCTION AND BACKGROUND

TERAHERTZ technology has become of large interest over the last few years for its potential in non-invasive imaging, spectroscopic and biological applications. In this context, the development of a breakthrough solid-state technology for fast and high-temperature THz detectors is highly desired. Commercially available THz detectors are indeed based on thermal sensing elements being either very slow (10-400 Hz) (Golay cells, pyroelectric elements), or requiring deep cryogenic cooling (hot-electron bolometers) [1], while those exploiting fast non-linear electronics (Schottky diodes) are mostly limited to the range < 1 THz [1].

A more recent approach exploits FETs [2] either as III-V high-electron-mobility transistors or Si-based complementary metal-oxide-semiconductors. THz detection in a FET originates from the excitation of plasma waves in the FET channel by the oscillating radiation field applied between the source and the gate electrodes. If the plasma waves are overdamped a broadband response is obtained from the simultaneous modulation of the carrier density and carrier drift velocity [2]. As a result, the THz signal is rectified and leads to a dc signal between source (S) and drain (D) proportional to the received power, whose value is mainly controlled by the gate (G) bias. Semiconductor nanowires (NWs) represent an ideal building block for implementing fast electronic components thanks to their typical attofarad–order capacitance. On the other hand, a strong resonant photoresponse is predicted in materials having plasma damping rates lower than both the frequency of the incoming radiation and the electron transit time in the transistor channel. A material having high carrier mobility at RT is therefore crucial to take full advantage of the performance enhancement expected from resonant detection, and to make FET detectors equally performing at operating frequencies > 1 THz. In this perspective graphene, owing to its record-high mobilities, gapless spectrum and frequency-independent absorption coefficient has been precognized as a very promising element for the development of THz detectors and modulators. Here we demonstrate room temperature (RT) detection in the 0.3 – 1.5 THz range, by combining top-gated graphene FETs and InAs NWs with THz receiver architectures designed to achieve the desired device sensitivity.

II. METHODS AND RESULTS

InAs nanowire grown bottom-up by Chemical Beam Epitaxy (CBE) and n-doped with Se at a level of 10^{16} cm^{-3} have been employed to fabricate FETs (fig. 1a) having a broad-band bow-tie (Fig. 1b) dipole antenna patterned between the source and the gate contact.

Photoresponse experiments were performed by using either a 1.5 THz QCL [3] cooled at T =10 K, and operating in pulsed mode, with a train of 2168 pulses (1.7 A amplitude, 435 ns pulse width, 62.8% duty cycle) repeated at a modulation frequency of 333 Hz, or a 0.3 THz electronic source [4]. The radiation was collimated and focused by a set of two f/1 off-axis parabolic mirrors and the photo-induced source-drain voltage was measured by using a lock-in without any pre-amplification stage. The vertically polarized incoming radiation impinges from the free space onto the nanowire devices while the detector was moved with a motorized X-Y translation stage. Responsivity values up to 12 V/W (Fig. 1c) with impressive noise equivalent powers (NEP ~ 6 $\times 10^{-11}$ W/√Hz) and a wide modulation bandwidth (> 300 kHz) have been reached at 1.5 THz [3].

Top-gated FETs of similar geometries have been also realized from exfoliated graphene by deposition of a ∼ 35 nm thick HfO$_2$ insulating layer.

To access the photoresponse, we employ the 0:3 THz radiation generated by an electronic source based on frequency multipliers. This is collimated and focused by a set of two f/l off-axis parabolic mirrors. The intensity is mechanically chopped at frequencies between 90 Hz and 1 kHz, and Δu is measured by means of a lock-in amplifier in series with a voltage preamplifier, having an input impedance of 10 MΩ and an amplification factor G = 1000.

The vertically polarized incoming radiation impinges on the GFET mounted in a dual-in-line package, with an optical

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power P_t = 2.1 mW. The photoresponse is measured at zero V_{SD}, as a dc voltage Δu at the drain, while the source is grounded.

In this first implementation, room temperature operation at 0.3 THz was achieved, with promising noise equivalent powers of a few nW/(Hz)$^{1/2}$. By analyzing the photoresponse dependence on the gate voltage (Fig. 1d), a change of sign is identified in correspondence of the charge neutrality point, reflecting the switch of the chemical potential from the valence to the conduction band.

Large area fast imaging applications of the detectors have been performed by using as test object a fresh leaf. Fig. 1e shows the THz transmission image, consisting of 200×550 scanned points, collected by raster-scanning the object in the beam focus, with an integration time of 20 ms/point. This shows that our devices are beyond proof-of-concept, and can already be used in a realistic setting, enabling large area, fast imaging of macroscopic samples

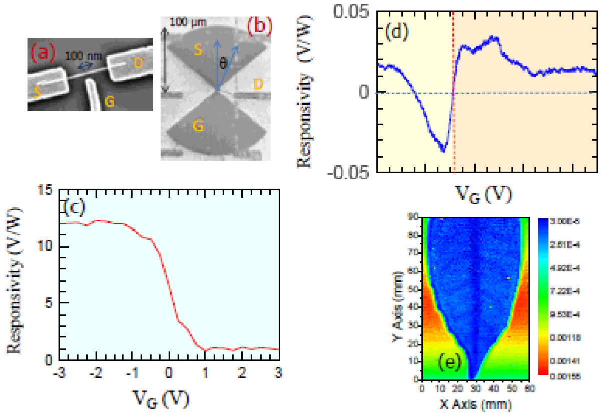

Fig. 1. (a) SEM picture of a fabricated NW FET with bow-tie antennas (b); (c) Responsivity (R_v) of the NW FET to the radiation of a 1.5 THz QCL, measured as a function of the gate voltage V_g at RT; (d) R_v of a graphene FET to a 0.3 THz beam modulated at 500 Hz measured as a function of V_g at RT; d) 0.3 THz transmission mode image of a green leaf consisting of 200x550 points and collected by raster-scanning the leaf in the beam focus, with an integration time of 20 ms/point.

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