ABSTRACT: Uncooled terahertz photodetectors (PDs) showing fast (ps) response and high sensitivity (noise equivalent power (NEP) < nW/Hz$^{1/2}$) over a broad (0.5–10 THz) frequency range are needed for applications in high-resolution spectroscopy (relative accuracy $\sim 10^{-11}$), metrology, quantum information, security, imaging, optical communications. However, present terahertz receivers cannot provide the required balance between sensitivity, speed, operation temperature, and frequency range. Here, we demonstrate uncooled terahertz PDs combining the low ($\sim$2000 k$_B$ μm$^{-2}$) electronic specific heat of high mobility (>50 000 cm$^2$ V$^{-1}$ s$^{-1}$) hexagonal boron nitride encapsulated graphene with asymmetric field enhancement produced by a bow-tie antenna, resonating at 3 THz. This produces a strong photo-thermoelectric conversion, which simultaneously leads to a combination of high sensitivity (NEP $\leq$ 160 pW Hz$^{-1/2}$), fast response time ($\leq$3.3 ns), and a 4 orders of magnitude dynamic range, making our devices the fastest, broad-band, low-noise, room-temperature terahertz PD, to date.

KEYWORDS: terahertz, photodetector, graphene, thermoelectric effect

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The low (~100 Ω) channel and contact resistances in SLG FETs (GFETs) help in reducing the detector noise. Contact resistance less than 100 Ω μm can be obtained with edge contacts to encapsulated SLG in hexagonal boron nitride (hBN) or with contact area cleaning and rapid thermal annealing. When terahertz rectification is mediated by the simultaneous modulation of carrier density (n) and drift velocity (v_d) in the channel, that is, in the PD-driven response, an increase in carrier mobility (μ) leads to a reduction of τ. This enables modulation frequencies > 10 GHz in the low-field limit (i.e., as long as velocity saturation effects can be neglected), since the maximum modulation frequency is expected to be proportional to μ.

SLG is also ideal for PTE PDs, owing to its gapless nature that allows broadband absorption from the UV to THz frequencies. The PTE effect entails a thermal gradient within the electronic distribution, which yields the diffusion of carriers away from the hottest region. In SLG, when electrons are heated by photon absorption, photogenerated carriers remain thermally decoupled from the crystal lattice. This is due to the difference between the electron–phonon scattering time (~20 fs) needed for thermalization of the electronic distribution and the slower (2 ps) electron–phonon relaxation time. Therefore, a quasi-equilibrium state is reached, where the electronic temperature T_e is considerably higher than the lattice temperature T_l. The electronic subsystem shows a low specific heat c_p (~2000 k_B μm^−2) at 300 K, where k_B is the Boltzmann constant, which can lead to the ultrafast (50 fs) onset of thermal gradients and to a rapid overheating of the electronic distribution. This is ideal for PTE-based devices, since all the absorbed electromagnetic energy is first transferred to electron heating, before being lost through other (slower) thermalization channels. Interaction with acoustic phonons occurs on a ps time scale, needed for thermalization of the electronic distribution.

The small c_p stems from the density of states shrinking in proximity of the charge neutrality point (CNP) as a consequence of the linear band dispersion. In particular, the analytical expression of the electronic specific heat c_p in proximity of the CNP (chemical potential < k_B T) is:

\[ c_p = 18\zeta(3) k_B^3 T^2 / n(hv)^2 \]

where \( \zeta(3) = 1.202 \) is the zeta function, \( h \) is the Planck constant, and \( n = 1.1 \times 10^8 \) ms\(^{-1} \) is the Fermi velocity. Therefore, \( c_p \) grows quadratically with \( T \) reaching ~2000 k_B μm^−2 at 300 K. In contrast, the lattice specific heat \( c_v \) is more than 1000 times larger. Hence, the combination of \( c_v/c_p < 1000 \) with \( \mu > 50000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) makes GFETs ideal for fast PTE terahertz PDs. Since SLG with \( \mu > 70000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) can be produced over a large area by encapsulating chemical vapor deposition (CVD) SLG in hBN, large-area multipixel architectures at terahertz frequencies are feasible.

Single-pixel, RT broadband GFET detectors with NEP ~80 pW Hz\(^{−1/2}\) or τ ~0.1 ns have been already reported. However, in both refs 28 and 29, the PD ultrafast and broadband response was associated with a quite poor NEP > 1 mW Hz\(^{−1/2}\) in ref 28 and > 8 nW Hz\(^{−1/2}\) in ref 29. These NEP are larger than those required for a practical exploitation of terahertz RT PDs, especially for imaging, high-resolution spectroscopy and near-field microscopy, where NEP < 1 nW Hz\(^{−1/2}\) is preferable. This motivates the effort to devise SLG PDs combining fast τ (~1 ns), broadband operation (0.1–10 THz), large (>3 orders of magnitude) dynamic range, and low (<1 nW Hz\(^{−1/2}\)) NEP.

In ref 36, a PTE SLG PD was reported with NEP < 100 pW Hz\(^{−1/2}\), τ ~40 ns, a 3 orders of magnitude dynamic range, and operating over a 0.3–4 THz bandwidth. This employed a dual-gated narrow gap (100 nm) dipolar antenna, which, while creating a p-n junction in the SLG channel, concentrates the terahertz field at the junction, where the photoresponse arises. However, the ~40 ns response time (set-up limited) still hinders the application in pulse characterization or high repetition-rate detection.

Here, we increase the speed (electronic bandwidth) and dynamic range of RT SLG PDs, exploiting a much simpler architecture than ref 36, relying on the on-chip patterning of a broadband bow-tie antenna (δω/δω_0 > 20%) to couple terahertz radiation to a sub-wavelength hBN-SLG-hBN heterostructure with \( \mu \sim 53000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \). By combining both PW and PTE mechanisms we get a low-noise (NEP <160 pW Hz\(^{−1/2}\)) RT terahertz PD with a 4 orders of magnitude dynamic range and τ ~3 ns, i.e., 1 order of magnitude faster than any other low NEP (τ<10^−9 W Hz\(^{−1/2}\)) LM based terahertz PD operating at RT reported so far, to the best of our knowledge. A SLG is encapsulated within hBN, forming a clean hBN-SLG-hBN heterostructure. hBN and SLG flakes are prepared by micromechanical exfoliation on intrinsic Si +285 nm SiO_2 wafers. The flakes are then picked up sequentially (top hBN, SLG, bottom hBN) with poly(dimethylsiloxane) (PDMS) and polycarbonate (PC) stamps. The stack is then released at 180 °C on the final Si/SiO_2 wafer. This T is higher than the glass transition T of PC (~150 °C), enabling a better control during transfer thanks to the decreased viscosity of PC. Blisters of trapped contaminants at the interface between hBN and SLG become mobile at this T and can be pushed along the LMH until they reach an edge, leaving the interfaces contaminant-free.

Once the LMH is placed on the substrate, the FET channel is defined by dry etching, leaving the edge of the SLG channel exposed. The channel has a rectangular shape with length L_C = 5.4 μm and width W_C = 0.8 μm (Figure 1a). One-dimensional edge contacts are then realized by electron beam lithography (EBL) followed by metal deposition (Cr/Au, 10/100 nm). The source (S) and drain (D) electrodes are asymmetrically shaped to favor the required asymmetry for which either PTE or PW or their combination take place within the SLG channel (Figure 1a). Before defining the top-gate (G) electrode, a thin oxide layer (Al_2O_3, 10 nm) is deposited via atomic layer deposition (ALD). This prevents leakage current between G and the SLG through the edges of the channel itself. The G contact, covering a length L_G = 5 μm over the SLG channel, is then patterned by EBL and finalized by metal deposition (Cr/Au, 10/100 nm). Similar to the S electrode, the G contact is shaped as the branch of a planar bow-tie antenna, with radius r_B = 21 μm and flare angle 90° (Figure 1a).

The antenna dimensions are chosen following electromagnetic simulations with Comsol Multiphysics (see Supporting Information S1 for further details): a 3 THz radiation, matching the frequency of a terahertz quantum cascade laser (QCL), impinges on the GFET on Si/SiO_2 integrated within a
Figure 1. PD layout. (a, bottom) Schematic of PD active area. SLG is encapsulated between two flakes of hBN (bottom 30 nm, top 10 nm). The heterostructure is capped by a~10–15 nm Al₂O₃ after edge-contact fabrication. (a, top) Detector layout. The GFET is embedded in a planar bow-tie antenna (radius r₀ = 21 μm). The inset shows the main geometrical parameters of the GFET: channel width (Wᵣ = 0.8 μm), channel length (Lᵣ = 5.4 μm), gate length (Lₛ = 5 μm). (b) Antenna simulations showing the enhancement of the in-plane component of the electric field E₁ at the position of the GFET due to the presence of the antenna, plotted as a function of r₀ for an impinging frequency of 3 THz. (inset) Maps of the out-of-plane component of the electric field for r₀ = 20 μm and r₀ = 52 μm, showing λ/2 and 3λ/2 resonances. (c) RT two-terminal resistance as a function of top-gate voltage (V₆) from which μ is extracted.

planar bow-tie antenna, whose radius r₀ is changed in discrete steps from 6 to 69 μm. Figure 1b plots the simulated enhancement of the in-plane electric field component (E₁) provided by the antenna as a function of r₀ with respect to the case where the hBN-SLG-hBN heterostructure is not connected to the antenna. The antenna response shows two maxima at r₀ = 20 and 52 μm, corresponding to the λ/2 and 3λ/2 resonances. The inset of Figure 1b shows the out-of-plane component of the electric field on the plane of the antenna. The maximum |E₁|² enhancement is 3500, concentrated in the gap between S and G, creating the required asymmetry for the activation of PW and PTE effects.

The devices are then electrically characterized at RT. Figure 1c shows the channel resistance (R่อ), extrapolated by probing the source-drain current (I_SD) as a function of top-gate voltage (V₆), while keeping the source-drain voltage V_SD = 2 mV. The CNP is at V₆ = 0.2 V. The R̃(V₆) plot can be used to extract the field effect mobility (μₑₒₚ), the residual carrier density (n₀), and the contact resistance (Rₑₒₚ) by fitting R with ̃R = Rₑₒₚ + (Lₑₒₚ/Wₑₒₚ)(1/nₑₒₚμₑₒₚ), where nₑₒₚ is the gate-dependent charge density, given by nₑₒₚ = [n₀ + (Cₑₒₚ/Cₑₑ₇ – CNP)]/2. Here, Cₑₑ₇ is the gate-to-channel capacitance per unit area (Cₑₑ₇ = 0.2 μF cm⁻²), and CNP is used as fixed parameter for the fitting function. We get μₑₒₚ(holes) ~ 41 000 ± 800 cm² V⁻¹ s⁻¹, μₑₒₚ(electrons) ~ 53 000 ± 400 cm² V⁻¹ s⁻¹, n₀ ~ 1.52 ± 0.01 × 10¹¹ cm⁻², Rₑₒₚ ~ 3.3 ± 0.01 kΩ, and 4.0 ± 0.01 kΩ for hole and electron doping, respectively. μ are consistent with those of ref 57, and they are the highest reported in any terahertz GFET, to the best of our knowledge.

The GFET is then optically tested using a single-plasmon 2.8 THz QCL, operating at a heat sink temperature T = 30 K in a tabletop Stirling cryostat (model Ricor K535). The QCL is driven in pulsed mode (pulse width 1.6 μs; repetition rate 40 kHz). The average QCL output power is progressively varied from a few nanowatts to 820 μW, at the corresponding maximum lattice temperature T = 170 K (estimated assuming a substrate thermal resistance ~20 K/W²). The 30° divergent terahertz beam is collimated and focused by using two picarin (tsupurica) lenses with focal lengths of 25 and 50 mm (Figure 2a). The resulting Gaussian beam at the focal point has a waist of ~120 μm. The average optical intensity is increased to a maximum of ~10 W/cm². The SLG PD is then mounted onto a roto-translation stage, to move it over the focal plane and modify the relative angle (α in Figure 2a) between the bow-tie antenna axis and the vertically polarized terahertz electric field.

Optical measurements are then performed at RT and at liquid nitrogen T (77 K). The sample is electrically connected as follows: the S electrode is grounded, the G contact is connected to a dc voltage generator (Keithley 2400), and the generated photo-voltage signal Δu is measured at the D electrode, connected to a lock-in amplifier (Stanford Research 830, reference/modulation frequency f̃ref = 1.33 kHz) through a voltage preamplifier (FEMTO HVA200, gain 100, bandwidth 200 MHz). For the 77 K measurements, the sample is mounted on the cold unit of a gas-refrigerated cryostat (QMC, TK 1800), and the terahertz beam reaches the PD through a 2 mm polymeric window (TPX, transmission 76% at 3 THz). Δu is then estimated from the photovoltage recorded with the lock-in V计划生育 as Δu = 2.2 × V计划生育/η², where η is the voltage preamplifier gain coefficient.

Figure 2b shows the map of |Δu| (log scale) at RT on the focal plane (xy in Figure 2a) of the terahertz beam, for an impinging average power of ~100 μW. The GFET has a signal-to-noise ratio (SNR) >10⁴ at the optimal V₆ = 0.36 V.
To verify the polarization selectivity of our antenna geometry,\textsuperscript{56} we measure the THz photoresponse as a function of angle $\alpha$ between antenna axis and THz beam polarization. The photoresponse (Figure 2c) reaches its maximum when the antenna axis is parallel to the polarization and decreases when $\alpha$ is increased from 0° to 90°. The experimental data (black dots) are in good agreement with simulations (solid blue line).

An important figure of merit for a terahertz PD is the dynamic range,\textsuperscript{32,36} i.e., the range of impinging optical power that the PD is capable to sense. To determine it, we vary in regular steps the average output power of the QCL from 0 to 820 $\mu$W (Figure 2d, and Supporting Information Figure S2). The GFET detects a minimum power $\sim 90$ nW and a maximum power $\sim 820$ $\mu$W. The dependence of the response with respect to power is almost linear over more than 3 orders of magnitude (setup limited), following a power law $|\Delta u| \sim P^\gamma$ with $\gamma = 0.85 \pm 0.007$ (the fit to the data is reported in Figure 2d, black solid line). This quasi-linear dependence of the terahertz photoresponse is expected for both PW and PTE-based PD operating in the weak-heating regime;\textsuperscript{36,47} i.e., when the thermal gradient along the GFET channel is smaller than the heat sink $T$: $\Delta T \ll 300$ K.\textsuperscript{35} The small deviation from the linear ($\gamma = 1$) power dependence can be ascribed to the temperature dependence ($\sim T^{-1}$) of the graphene thermal conductivity at RT.\textsuperscript{38}

To identify the dominant physical mechanism governing the photodetection process, the PD response is then recorded as a function of $V_G$ at 77 and 300 K. The responsivity $R_v$ is evaluated by normalizing the photovoltage $\Delta u$ with respect to the optical power impinging on the detector: $R_v = \Delta u/P \times A_{\text{spot}}/A_{\text{diff}}$\textsuperscript{33} where $P$ is the total terahertz power, $A_{\text{spot}}$ is the beam spot area, and $A_{\text{diff}}$ is the diffraction-limited area, calculated as $\lambda^2/4$,\textsuperscript{32,33} as shown in Figure 3a (left vertical axis). At RT a maximum $|R_v| = 49$ $V$ $W^{-1}$ is found for $V_G = 0.36$ V. At 77 K, $|R_v|$ reaches $\sim 180$ $V$ $W^{-1}$. Both at 300 and 77 K, the $R_v$ plot as a function of $V_G$ shows a double sign switch. Unlike a purely or a dominant overdamped PW (resistive self-mixing) regime, we do not see a single sign change in $\Delta u$ at the CNP, caused by the sign change in the derivative of the static channel conductance $\sigma$ in the expression of the PW photovoltage $\Delta u_{\text{PW}} \propto -\sigma / \partial V_G$.\textsuperscript{34}

![Figure 2. Optical characterization. (a) Schematic of the terahertz experiment: a 2.8 THz QCL is focused on the GFET, whose position (xy plane) and orientation with respect to the laser polarization (angle $\alpha$) can be controlled. (b) 1 × 1 mm |$\Delta u$| map for an impinging power $\sim 100$ $\mu$W. The map is obtained by scanning the detector position on the focal xy plane and recording the measured photovoltage when $V_G = 0.36$ V. The ratio between $\Delta u$ measured at the center ($x = 0.5$ mm, $y = 0.5$ mm) and $\Delta u$ measured outside the terahertz beam is more than 3 orders of magnitude. (c) Polar plot of the detected signal as a function of $\alpha$, ranging from 0° (antenna axis parallel to the light polarization) to 90° (antenna axis perpendicular to the light polarization). Black dots: experimental data. Solid blue line: simulation. (d) Absolute value of the photovoltage plotted as a function of the incident power in log–log scale ($V_G = 0.36$ V). The solid line is a fit to the data using $|\Delta u(P)| \sim a_0 + P^\gamma$, where $a_0$ is the experimental noise floor, and the exponent $\gamma = 0.85$. The dashed black line is for $\gamma = 1$. The error bars are the root-mean-square deviations of the measured $\Delta u$.](https://dx.doi.org/10.1021/acs.nanolett.9b05207)
The PTE response is given by the asymmetric funneling of terahertz radiation by the bow-tie channel. This thermal imbalance is a direct consequence of the PTE.36,43 In this case, the PTE photovoltage is a function of the Johnson-noise dominated noise spectral density. Minimum NEPs are expected close to the gated regions near the cold (D-side) and the ungated regions close to the S-side.33,34 where \( S_G \) is the Seebeck coefficient of the SLG below the Fermi level. \( S_G \) is the Seebeck coefficient of the observed Seebeck co-efficient between gated \( S_G \) and ungated \( S_u \) as a function of \( V_G \) at RT and at 77 K. (c) Comparison between experimental \( \Delta u \) (measured at \( P = 100 \mu W \)) and theoretical PTE, PW, and combined \( \Delta u_{PTFE} + \Delta u_{PW} \) photo-voltages. (d) NEP at 300 and 77 K evaluated by assuming a Johnson-noise dominated noise spectral density. Minimum NEPs \( \sim 160 \) and 18 pW Hz\(^{-1/2} \) are obtained at 300 and 77 K.

The double sign change in the \( R_x \) versus \( V_G \) plot can be interpreted as the fingerprint of a dominant PTE.36,43 In this case, the PTE photovoltage is \( \Delta u_{PTFE} = (S_G - S_u) \Delta T \),33,34 where \( S_G \) is the Seebeck coefficient of the ungated regions close to the \( S \) and \( D \) contacts, and \( \Delta T \) is the T difference between the \( S \)-side and the \( D \)-side of the GFET channel. This thermal imbalance is a direct consequence of the asymmetric funneling of terahertz radiation by the bow-tie antenna. The PTE response is given by the diffusion of hot carriers from the hot \( (S) \) toward the cold \( (D) \) side of the GFET, which results in a measurable electrical signal. \( S_G \) can be evaluated from the dc conductivity \( \sigma \) of the GFET, using the Mott equation:35

\[
S_{\text{Mott}} = -e\alpha T \times \sigma^{-1}(\partial\sigma/\partial V_G) \times (\partial V_G/\partial E_b),
\]

where \( L_b = (\pi \alpha)^2/(3e^2) \) is the Lorenz number, and \( E_b \) is the Fermi energy. \( \partial V_G/\partial E_b \) can be evaluated from \( E_b = h \nu \pi (\pi C_e \partial V_G/e)^{1/2} \), where \( \partial V_G = V_G - V_{\text{CNP}} \). At RT, \( S_G \) reaches a maximum \( \sim 130 \mu V \) K\(^{-1} \) for \( V_G = 0.36 \) V (see Supporting Information figure S4). \( S_u \) is expected to be \( \sim S_G \) when \( V_G = 0 \) \( V_i \); therefore, it is positive and constant with respect to \( V_G \). \( S_G - S_u \) is plotted in Figure 3b for \( T = 300 \) K and \( T = 77 \) K; in both cases, the two sign changes as a function of \( V_G \) are expected.

A more rigorous interpretation can be given by considering the simultaneous interplay of PW and PTE. Figure 3c plots \( \Delta u \) at RT as a function of \( V_G \) obtained for an optical power of \( \sim 100 \mu W \) (orange curve), together with the estimated \( \Delta u_{PTFE} \) and \( \Delta u_{PW} \). The solid black line represents the combined theoretical photovoltage \( \Delta u_{\text{theo}} = \Delta u_{PTFE} + \Delta u_{PW} = a \times (S_G - S_u) + b \sigma^{-1}(\partial\sigma/\partial V_G) \), where \( a \) and \( b \) are the fitting parameters. The PW contribution is only relevant close to CNP, whereas PTE dominates at higher carrier densities \( (W_G - V_{\text{CNP}} > 0.3 \) V). From the separate evaluation of the two contributions, and the knowledge of \( a \) and \( b \), we can estimate \( \Delta T \) driving the PTE response. By dividing \( \Delta u_{PTFE} \) (Figure 3c) by \( (S_G - S_u) \) at RT (Figure 3b), we get \( \Delta T = \Delta u_{PTFE}/(S_G - S_u) \sim 0.8 \) K when the terahertz power is \( \sim 100 \mu W \), which results in a \( T \) gradient \( \sim 0.2 \) K \( \mu m^{-1} \) along the SLG channel. This confirms that the PD operates in the weak-heating regime36,47 for all the investigated range of optical terahertz power (0–820 \( \mu W \)).

To assess the PD sensitivity, we evaluate NEP as the ratio between PD noise spectral density (NSD) and \( R_x \). A correct evaluation of NSD is extremely important for a proper estimate of NEP. In our system there are four mechanisms that can have a role in the total noise figure: the Johnson-Nyquist noise \( (N_J) \), the shot noise, the generation-recombination noise, and the flicker noise \((1/f)\) or telegraph noise.36 The first is related to the thermal voltage fluctuations \( (V_T) \) at the ends of the GFET channel, and its power spectral density is, in turn, related to \( R \) and to the heat sink \( T \) via \( N_J = (V_T)^2 = 4kTTR \). In our case, the \( N_J \) contribution to NSD is \( \sim 10 \) nV Hz\(^{-1/2} \) at 300 K and \( \sim 4 \) nV Hz\(^{-1/2} \) at 77 K.

The shot noise of a quantum conductor typically increases under terahertz illumination due to the possibility of photon-assisted shot noise (PASN).36 However, in our \( T \) range and under zero bias (no external \( V_{\text{bias}} \)), the contribution of the shot noise to the total noise figure is expected to be orders of magnitude lower than \( N_J \) therefore, it can be neglected. The same argument applies to the generation-recombination noise, whose amplitude drops below \( N_J \) under zero bias and for current densities less than 1 \( \mu A/mm \). The \( 1/f \) noise can be neglected with respect to \( N_J \) due to the combination of zero-bias detection (no direct current applied) and more than kilohertz modulation frequency \( (f_{\text{mod}} = 1.334 \) kHz).38 Thus, we approximate NSD \( \sim N_J \). The NEP is then calculated as \( N_J/\sqrt{R_x} \), and the resulting NEP \( (V_G) \) plots are in Figure 3d for \( T = 300 \) and 77 K. We get minimum NEP \( \sim 160 \) and 18 pW Hz\(^{-1/2} \) for 300 and 77 K, respectively. Notably, the RT NEP is minimum

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**Figure 3.** Main figures of merit. (a) Left vertical axis, solid lines: \( R_x \) as a function of \( V_G \) at RT and 77 K. The double sign switch in the \( R_x \) versus \( V_G \) plot can be interpreted as the fingerprint of a dominant PTE. Right vertical axis, dotted lines: estimated \( \Delta u_{PTFE} \) normalized to the maximum at RT. The grey vertical line at \( V_G = 0.2 \) V indicates the CNP at RT. (b) Estimated difference in the Seebeck coefficient between gated \( S_G \) and ungated \( S_u \) as a function of \( V_G \) at RT and at 77 K. (c) Comparison between experimental \( \Delta u \) (measured at \( P = 100 \mu W \)) and theoretical PTE, PW, and combined \( \Delta u_{PTFE} + \Delta u_{PW} \) photo-voltages. (d) NEP at 300 and 77 K evaluated by assuming a Johnson-noise dominated noise spectral density. Minimum NEPs \( \sim 160 \) and 18 pW Hz\(^{-1/2} \) are obtained at 300 and 77 K.
when the GFET is n-type, which corresponds to the regime
where a p-n junction is established between the S and G
electrodes, i.e., the region where the antenna funnels terahertz
radiation.

Finally, we evaluate the bandwidth (BW) of our terahertz
PD by taking advantage of the employed QCL. When the QCL
is driven with high-voltage pulses ($V_{QCL} > 29 \text{ V}$), it enters
the so-called negative differential resistance (NDR) regime.\textsuperscript{66}
From an electrical point of view, this corresponds to a very
unstable high field domain regime, in which the driving current
fluctuates randomly under increased applied bias. From an
optical point of view, the QCL average output power
progressively decreases when increasing the voltage, due to
the increased overall temperature of the laser lattice, which,
in turn, reduces the population inversion.\textsuperscript{67} In the NDR, the
QCL turns off and on many times during a single pulse, as in
Figure 4a,b. These abrupt transitions are an intrinsic property
of the QCL and are governed by the exchange of energy
between electrons, photons, and lattice within the QCL cavity.
Thus, the switching from the off to the on state (and vice versa)
is not dictated by external circuitry (power supply and pulse
generator) and can be significantly faster than the onset
of externally driven pulses (the switching time is expected to be
$\sim 1 \text{ ns}$.\textsuperscript{68}

Figure 4a,b show the time trace of the current flowing
through the QCL ($I_{QCL}$) during a single 1.6 $\mu \text{s}$ pulse, recorded
with an oscilloscope (resolution 5 GS/s, corresponding to 200
ps) and the corresponding voltage time trace at the output of
the GFET, collected at $V_G = 0 \text{ V}$, by using a voltage preamplifier
(model A1423, CAEN) with input impedance 50 $\Omega$, gain 46 dB and bandwidth 1.2 GHz. The instantaneous power $P_i$ switches on and off in an almost periodic way, with a period $\sim 210 \text{ ns}$. In coincidence with the off-state condition, $I_{QCL}$ shows pronounced dips (indicated by vertical arrows in
Figure 4a), ascribed to the sudden reduction in the current
flow due to the unstable transport arising from the off-on
turning state within the QCL active region.

The waveform in Figure 4b is used to assess the detector
BW. Figure 4c shows a zoom on a single $P_i$ oscillation, from
which the rise-time $\tau_{on}$ and fall-time $\tau_{off}$ are extracted using the
fitting functions:\textsuperscript{36}

$$V_{out} = c_0 + V_{on} \times \left[ 1 - \exp(-(t - c_1)/\tau_{on}) \right]$$

and

$$V_{out} = c_2 + V_{off} \times \exp(-(t - c_3)/\tau_{off}).$$

The fitting parameters $c_0$, $c_1$, $c_2$, $c_3$, $\tau_{on}$, $\tau_{off}$ are constants representing voltage
offsets and time offsets, respectively; $V_{on}$ and $V_{off}$ are the
voltage jumps in the waveform. We obtain a rise (fall) time of
$3.3 \text{ ns} (4.2 \text{ ns})$, corresponding to BW $\sim 53 \text{ MHz} (38 \text{ MHz})$, where BW = $1/2\pi\tau$, 1 order of magnitude better than what was
observed in ref 36 for a comparable NEP. The GFET itself is
expected to show response time of the order of 100 ps.\textsuperscript{28,29,36}
The observed rise and fall times are limited by external factors.
The first is the detector circuitry, consisting of the cables and
preamplifiers (BW $> 1.2 \text{ GHz}$) attached to the device itself, by
the chip mount and on-chip components. These are expected
to add a parasitic (simulated) capacitance $\sim 1 \text{ pF}$, which, in
combination with the 5 $\text{k}\Omega$ resistance of the SLG channel,
gives rise to a response time of a few ns, the largest limitation
to our rise-time. In addition, the impinging terahertz QCL
source is driven by a pulse generator, which has an intrinsic
time jitter $\sim 100 \text{ ps}$.\textsuperscript{68} Moreover, in the present setup, the laser
can undergo thermal fluctuations of the order of $\pm 1 \text{ K}$ during
operation. This effect can smear out the pulses as a consequence of power fluctuations. Our 53 MHz BW is thus a lower limit. This, combined with the 160 pW/Hz$^{1/2}$ NEP, identifies our device as state-of-the-art among any other
uncooled broadband SLG terahertz detectors reported.\textsuperscript{11,29,36}

In conclusion, we demonstrated a record performance
GFET PD with a 53 MHz modulation BW, operating at 3
THz. The device operation frequency is set by the coupling
scheme, given here by a planar bow-tie antenna, and can be
tailored across the whole terahertz range by engineering the
antenna design. Changing the size of the antenna would tune
its resonance frequency, and changing the type of antenna can
narrow or broaden its frequency coverage. We took advantage
of the peculiar power instabilities of the QCL source in specific
transport regimes, to achieve a response time $\sim 3.3 \text{ ns}$. This,
when combined with our NEP, makes this PD the fastest, low-noise, RT terahertz PD operating at frequencies >1.5 THz. We attribute the BW performance improvement to the high mobility of our hBN-SLG-hBN heterostructure. Further improvements are expected integrating our PDs with on-chip microstrip lines, to reduce the overall circuit capacitance, therefore avoiding possible BW limitations induced by the external FET circuitry. Refinements of the experimental system electronics (e.g., a larger BW, low-noise amplifier) can help to assess the real intrinsic speed limit of our PDs, which is expected to be in the ~10 ps range.36

## ASSOCIATED CONTENT

1 Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.9b05207.

Bow-tie antenna simulation, quantum cascade laser characterization, description of the photothermoelectric model (PDF)

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### Notes

The authors declare no competing financial interest.

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