

RESEARCH ARTICLE OPEN ACCESS

Temperature-Dependent Conduction and Gate-Tunable Photoresponse in Graphene Photodetectors

Daniel C. Nickel¹  | Daniele Capista¹  | Rasuole Lukose¹  | Aniello Pelella²  | Adolfo Mazzotti²  |
Sebastiano De Stefano²  | Filippo Giubileo³  | Christian Wenger^{1,4}  | Antonio Di Bartolomeo²  |
Mindaugas Lukosius¹ 

¹IHP – Leibniz Institute for High Performance Microelectronics, Frankfurt (Oder), Germany | ²Department of Physics “E. R. Caianiello”, University of Salerno, Fisciano, Salerno, Italy | ³CNR-SPIN, Fisciano, Salerno, Italy | ⁴Brandenburgische Technische Universität Cottbus-Senftenberg, Cottbus, Germany

Correspondence: Daniel C. Nickel (nickel@ihp-microelectronics.com) | Aniello Pelella (apelella@unisa.com)

Received: 11 June 2026 | **Revised:** 23 September 2026 | **Accepted:** 29 September 2026

Keywords: gate-tunable photoresponse | graphene | negative photoconductivity photodetector | photogating | positive photoconductivity | temperature-dependent conduction

ABSTRACT

Graphene photodetectors are promising candidates for broadband and high-speed optoelectronics, yet tunable photoconductive behavior without junction engineering remains elusive. Here, we report gate-controlled switching between positive and negative photoconductance in graphene field-effect transistors (GFETs) fabricated on Si/SiO₂ with Si₃N₄ passivation using a CMOS-compatible process. Temperature-dependent transport measurements (77–327 K) reveal impurity-limited mobility at low temperatures and phonon-dominated scattering at elevated temperatures, alongside pronounced hysteresis attributed to interfacial charge trapping and adsorbates. Under illumination, the devices exhibit a sublinear photocurrent dependence on incident power and saturation at higher intensities, consistent with a charge trap-mediated photogating effect. Remarkably, the application of a back-gate voltage induces a reversible transition from positive to negative photoconductance in the absence of heterojunctions. This behavior is attributed to the interplay of photogenerated carrier trapping at the graphene/SiO₂ interface, adsorbate-mediated charge transfer, and gate-induced Fermi level modulation, which collectively govern carrier density and scattering. These results establish a simple platform for electrically tunable photoconductance in graphene and provide new insights into interfacial effects governing photogating, enabling low-power and multifunctional optoelectronic devices.

1 | Introduction

The demand for novel devices with high speed and low power consumption has increased significantly in recent years. Photodetectors in modern optoelectronic systems convert incident photons into electrical signals and are essential for applications such as optical communication, imaging systems, and medical monitoring [1]. However, conventional materials often suffer from intrinsic limitations, including narrow bandgaps, limited tunability via doping, and susceptibility to thermal noise. Overcoming these challenges, one-dimensional chalcogenides such as bismuth sulfide (Bi₂S₃) nanorods [2] and related bismuth ba-

ed chalcogenides like Bi₂S₃ microrods [3] have emerged as promising lead-free photodetector materials that achieve high responsivity via photogating and anisotropic charge transport. This complements recent advances in carbon-based platforms, including graphene and sp²-hybridized graphyne [4]. Fundamentally, two-dimensional (2D) materials have attracted considerable attention due to their unique properties, such as broadband optical absorption, high carrier mobility, excitonic absorption, and high photoresponsivity, as well as their compatibility with a wide range of substrates [5]. Numerous devices have already been developed, demonstrating potential applications in photodetectors, transistor operations, sensing, and energy storage [6].

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Advanced Photonics Research* published by Wiley-VCH GmbH.

Graphene photodetectors commonly are based on p–n junctions [7, 8] or heterojunctions [9–12] for efficient carrier separation. The material exhibits high carrier mobilities of up to $40\,000\text{ cm}^2/\text{Vs}$ on SiO_2 substrates [13] and up to $200\,000\text{ cm}^2/\text{Vs}$ for suspended graphene [14]. As a zero-bandgap material, it has broadband optical absorption from the far-infrared to the ultraviolet range [15], with an optical absorbance of about 2.3% [16]. The electrostatic adjustable carrier concentration further enables gate-tunable electro-absorption [17]. Moreover, graphene is compatible with complementary metal–oxide semiconductor (CMOS) processes [18], enabling the integration into existing semiconductor technologies.

Persistent positive photoconductivity (PPC) and negative photoconductivity (NPC) were observed by Biswas et al. [19] in graphene on SiO_2 substrates, where the NPC was attributed to adsorbates on the graphene surface. By comparing these results with measurements on suspended graphene, they found that the PPC vanished, which they attributed to a reduction of trap sites in the SiO_2 substrate mediated by photogenerated carriers.

NPC has also been reported for graphene quantum dots [20] by Zhang et al., where the presence of moisture induced hysteresis in the transfer curves. It was proposed that, under dark conditions, holes accumulate in graphene due to charge exchange with adsorbates, while illumination promotes recombination, resulting in a decrease in photocurrent.

Especially graphene heterojunctions such as MoSe_2 /graphene, black phosphorus/graphene (BP/graphene), rhodamine/graphene have been discovered to show gate-tunable PPC and NPC [9–11]. These devices are based on the photogating effect and generate carrier trap states for one carrier type, which are filled or emptied depending on the carrier type. This switching capability between PPC and NPC enables control of current flow and power consumption [21].

Photogating devices commonly are fabricated on highly doped substrates (e.g., p- or n-doped silicon). Under illumination, photogenerated electron–hole pairs are spatially separated, with one carrier type becoming trapped [22]. These trapped charges act as a local gate, modulating the graphene channel conductance and shifting the transfer characteristics. The resulting prolonged carrier lifetime leads to high responsivity and gain [23–25], which enables low-light detection. However, in the absence of a junction, gate-tunable photoconductance has not been observed for graphene on SiO_2 substrates.

We present gate-tunable photodetectors with graphene embedded in SiO_2 and Si_3N_4 dielectrics and a metallic back gate, fabricated in a CMOS-compatible environment onto a Si/SiO_2 substrate. The devices can be switched from PPC to NPC through an applied back-gate voltage. Raman spectroscopy is used to assess graphene quality and to separate doping and strain contributions. The electrical properties of the graphene field-effect transistors (GFETs) are then characterized in terms of I – V behavior, hysteresis, and gate leakage, followed by temperature-dependent measurements to extract mobility, Dirac point voltage, and resistance. Finally, we study the photoresponse at room temperature for different

laser powers, source–drain voltages, and applied back-gate voltages. A sublinear dependence of the photocurrent on the incident laser power is observed, followed by a saturation at higher intensities, while the photocurrent increases linearly with increasing source–drain voltage. Under applied back-gate voltage, the devices exhibit negative photoconductance, which is attributed to photogating, charge trapping at the graphene/ SiO_2 interface, and a charge transfer between adsorbates and the graphene sheet.

This feature, which appears not to have been reported previously, endows graphene-based photodetectors with an additional functionality that could be particularly valuable in low-power applications. Specifically, the lower current flow under illumination ($I_{\text{illum}} < I_{\text{dark}}$) inherent to the NPC minimizes operational power consumption while lowering background dark currents. This lowering directly improves the signal-to-noise ratio, rendering graphene-based photodetectors highly sensitive for low-light intensity and broadband detection. Furthermore, controlling the switching behavior enables real-time photoelectronic logic gates, such as negated AND (NAND) and negated OR (NOR) operations [26, 27].

2 | Methods

2.1 | Sample Processing

The graphene FETs were fabricated on highly p-doped $\text{Si}(100)$ with a thermally grown SiO_2 layer. A tungsten back gate was first defined by optical lithography and subsequently planarized using chemical-mechanical polishing to ensure a flat surface. A 40 nm SiO_2 gate dielectric was then deposited by plasma-enhanced chemical vapor deposition (PECVD).

Monolayer graphene, synthesized by chemical vapor deposition on a $\text{Ge}(100)/\text{Si}(001)$ substrate in an Aixtron BM300T reactor, was transferred onto the prepared substrate using an electrochemical delamination process. A spin-coated PMMA layer was used to support the graphene during transfer and was later removed with acetone. The graphene channels were patterned with reactive ion etching (RIE) in an Ar/O_2 plasma using a lithographically defined photoresist mask. The resulting channel dimensions were $4\text{ }\mu\text{m}$ in width and $8\text{ }\mu\text{m}$ in length. To protect the active region, a 20 nm thick Si_3N_4 passivation layer was deposited and subsequently structured by lithography and etching.

Contact patterns were defined by a second lithography step and etched using RIE. Metal contacts consisting of Pd/Au were then deposited by thermal evaporation and structured via lift-off, forming edge contacts to the graphene channel.

2.2 | Sample Characterization

Raman spectroscopy was employed for material characterization using a laser with a wavelength of $\lambda = 532\text{ nm}$, corresponding to a photon energy of $E_{\text{laser}} = 2.33\text{ eV}$. A $100\times$ objective with a numerical aperture of $\text{NA} = 0.90$ was used, and the spectrometer was equipped with a grating of 1800 lines/mm. The spectra were acquired with an integration time of 1 s at 10% of the maximum

laser power, corresponding to 2.08 mW, covering the spectral range from 1000 to 3000 cm^{-1} .

Electrical and optoelectronic characterizations were carried out in a cryogenic probe station (Lake Shore Cryotronics) under vacuum at a pressure of the order of 1 mbar to limit ambient surface moisture adsorption and suppress parasitic leakage currents. Electrical characterization was performed using a Keithley 4200-SCS parameter analyzer equipped with three source meter units (SMUs). A two-probe setup was employed, where the source contact was grounded, the drain current I_d was measured at the drain contact, and the back-gate voltage was swept. Transfer characteristics were measured at a constant drain-source voltage of $V_{ds} = 20 \text{ mV}$ with forward and reverse-gate voltage sweeps. The leakage current I_L was obtained in a two-point configuration between the source and back-gate contacts. For the temperature-dependent measurements, a Lake Shore 336 temperature controller was used to adjust the temperature in the range from $T = 77$ to 327 K.

For photoresponse measurements, a supercontinuum white laser with a maximum output power of 16 mW, a spot area around 2 mm^2 , and a wavelength range of 450–2400 nm was used. For each measurement, the photocurrent was recorded over multiple illumination pulses, each with a duration of 20 s. The photocurrent was measured at the drain contact, both in the absence and presence of an applied back-gate voltage.

Temperature-dependent electrical transport measurements were conducted on 11 identical devices to assess reproducibility,

whereas optoelectronic characterization was performed on a single device and confirmed on a second one with consistent results.

3 | Results and Discussion

3.1 | Raman Characterization

Figure 1a shows an optical image of the investigated GFET device with a channel length equal to the back gate length. The source and drain contacts are patterned with a single rectangular geometry, which is visible in the optical image, while the back gate (BG) is contacted by an array of a squared pattern. Figure 1b shows a cross-sectional view of the GFET with edge-contacted graphene.

The graphene quality was assessed by Raman mapping performed in the central region of the channel. The Raman spectra were analyzed by fitting the 2D peak with a Lorentzian function, given by

$$I(\Delta\nu = \nu_0 - \nu_s) = \frac{I_0}{1 + \left(\frac{\nu_0 - \nu_s}{\gamma}\right)^2} \quad (1)$$

Here, I_0 denotes the maximum light intensity, ν_0 is the wave-number of the incident light, ν_s the Raman shift, and γ corresponds to half of the full width at half maximum Γ (FWHM) of the peak. To assess the homogeneity across the graphene sheet, the 2D-FWHM values are shown in a histogram in Figure 1c. The inset displays a representative symmetrical 2D

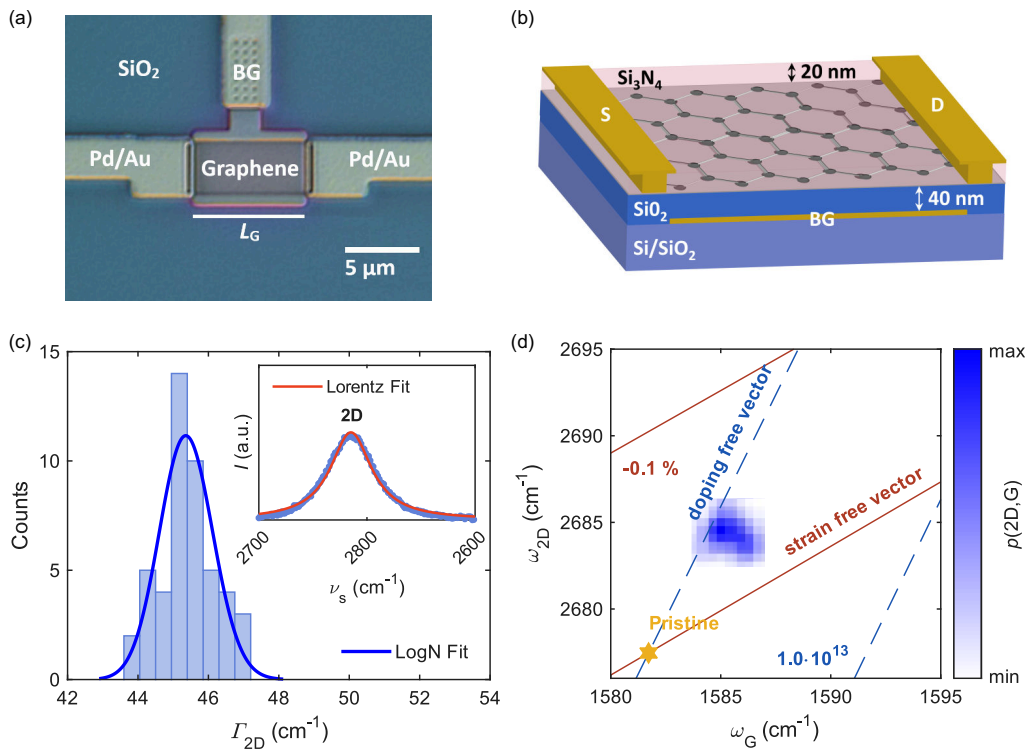


FIGURE 1 | (a) Optical image of the graphene channel area of the investigated GFET device. (b) Schematic cross-sectional view of the GFET with edge-contacted graphene. (c) Histogram of the full width at half maximum Γ_{2D} (FWHM) of the 2D peak obtained from Raman mapping data, fitted with a log-normal (LogN) distribution. (d) Doping-strain correlation diagram showing the probability density $p(2D,G)$ of the 2D and G peak frequencies.

mode together with the Lorentzian fit (red). The mean 2D FWHM value across the measured graphene area can be obtained by fitting the histogram with a log-normal (logN) distribution [28], given by

$$f(d) = \frac{1}{\sigma d \sqrt{2\pi}} \exp\left(-\left(\frac{\ln d - \ln d_0}{\sqrt{2}\sigma}\right)^2\right) \quad (2)$$

where d_0 is the mean value and σ is the standard deviation of the distribution. Values of $\sigma = 0.017 \pm 0.002$ and $d_0 = (45.37 \pm 0.13) \text{ cm}^{-1}$ for the 2D FWHM were obtained. Literature values for the 2D FWHM of supported monolayer graphene on SiO_2 typically range from 29 to 46 cm^{-1} [29–32]. The mean 2D FWHM of our graphene lies at the upper end of this range, suggesting the presence of substrate-induced nanoscale strain variations, which broaden the 2D peak [33, 34].

Doping and strain effects can be separated through a ω_{2D} versus ω_G frequency correlation plot [35], as shown in Figure 1d. The joint probability density $p(2D, G)$ is shown in blue, where darker (lighter) blue areas correspond to higher (lower) probability density. Dashed blue lines with a slope of 2.2 represent constant doping, while red, full lines with slopes of 0.7 correspond to constant strain. The star marks the pristine, undoped, and unstrained reference state of graphene. The graphene sheet is found to be slightly p-doped and subject to a small compressive strain.

3.2 | Electrical Characterization

Electrical characterization of the GFETs under dark conditions confirms ohmic behavior of the graphene-metal contacts, as shown in Figure 2a at $V_{bg} = 0 \text{ V}$. A linear fit of the I - V characteristics yields a total resistance of $R \approx 2797 \, \Omega$. The room-temperature transfer characteristics at a source-drain voltage of $V_{ds} = 20 \text{ mV}$ are shown in Figure 2b, where the arrows depict the sweep direction. The back-gate leakage current I_L , shown in the inset, remains around 1 pA for a voltage range of $V_{bg} = \pm 50 \text{ V}$.

The transfer characteristics exhibit a positive shift, with the charge neutrality point exceeding 50 V. This indicates p-doping of the graphene, which is consistent with the Raman characterization results. P-doping can be caused by adsorbents

[36, 37] like H_2O and O_2 on the graphene surface and PMMA [38], which was used for the graphene transfer on the SiO_2 gate dielectric.

The hysteresis observed between the forward and reverse back-gate voltage sweeps in Figure 2b can be attributed to both adsorbates on the graphene surface and charge trapping effects in the SiO_2 gate dielectric and Si_3N_4 capping layer [39–41]. Adsorbates such as H_2O and O_2 induce charge doping and can exchange charges with the graphene sheet. Additionally, charge traps in the surrounding dielectric layers capture and release carriers during the gate sweep. Upon reversal of the sweep direction, these charges do not instantaneously return to their initial equilibrium state, resulting in a delayed electrostatic response of the GFET. This leads to a shift of the Dirac point voltage and the characteristic hysteresis behavior [42].

To investigate the temperature dependence of the field-effect mobility transfer measurements in a temperature range from $T = 77$ to 327 K in 25 K steps were conducted. Figures 3a–f show the temperature-dependent transfer characteristics in steps of 50 K . At each temperature, five consecutive sweeps were recorded to assess the stability and reproducibility of the device characteristics. To exclude charge accumulation at the graphene SiO_2 and graphene Si_3N_4 interfaces, a new device was measured at each temperature step. In the range of $T = 77$ – 227 K , the transfer curves have good reproducibility between successive sweeps. This stability is reached after the first sweep, which is indicated in light blue. At temperatures $T > 227 \text{ K}$, the transfer characteristics show variations between successive sweeps.

The field-effect mobility [43] was determined from the temperature-dependent transfer curves using the relation

$$\mu_{FE} = \mp g_m \frac{L_G}{W_G V_{ds} C_{bg}} \quad (3)$$

here, $g_m = \frac{\partial I_{ds}}{\partial V_{bg}}$ is the transconductance, L_G denotes the channel length, W_G the graphene channel width, and V_{ds} the source-drain voltage. The back-gate capacitance is defined as $C_{bg} = \epsilon_0 \epsilon_r / t_{ox}$, where ϵ_0 is the vacuum permittivity, $\epsilon_r = 3.9$ is the relative permittivity of SiO_2 [44] and t_{ox} is the gate dielectric thickness. For

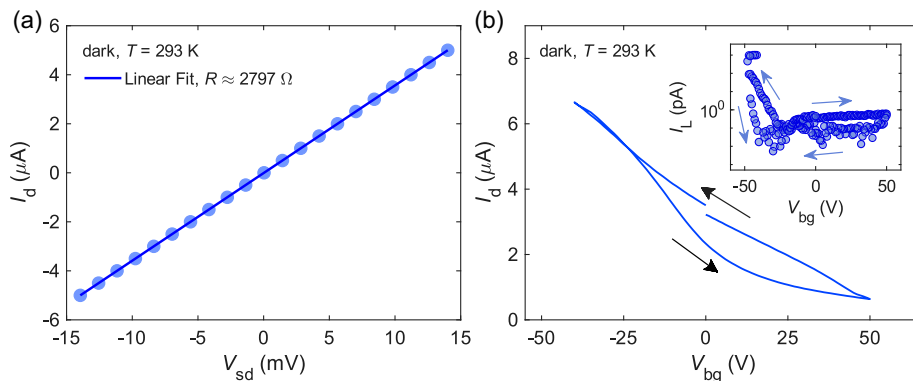


FIGURE 2 | (a) I - V characteristics measured at $V_{bg} = 0 \text{ V}$ under dark conditions, indicating ohmic source and drain contacts. (b) Transfer characteristics measured under dark conditions. The inset shows the leakage current I_L as a function of the back-gate voltage over a range of $V_{bg} = \pm 50 \text{ V}$.

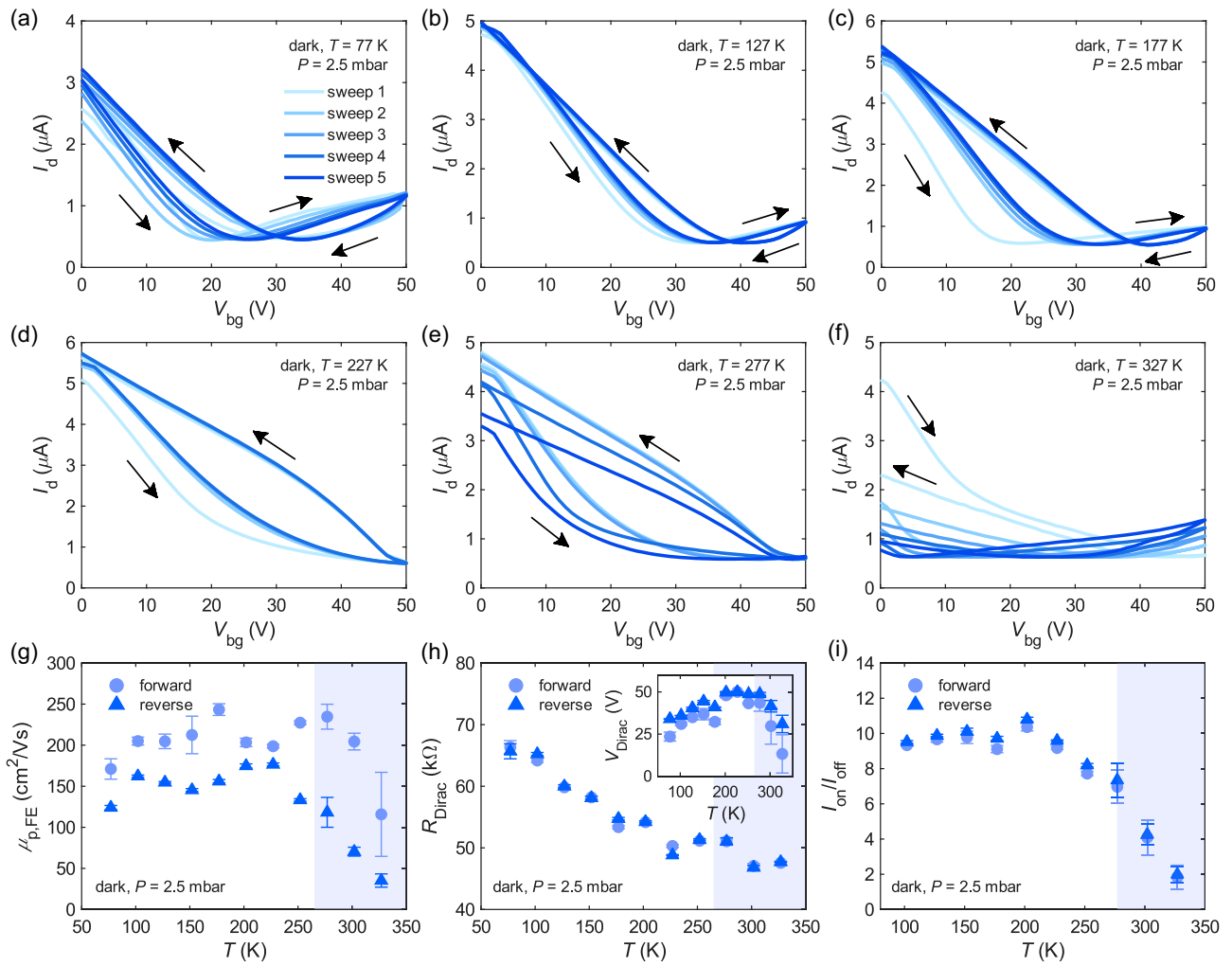


FIGURE 3 | Temperature-dependent transfer characteristics were measured from 77 to 327 K in steps of 25 K, with representative curves shown in (a–f) at 50 K intervals. From these measurements, the p-type maximum field-effect mobility $\mu_{p,FE}$, the Dirac point resistance R_{Dirac} (with V_{Dirac} shown in the inset), and the I_{on}/I_{off} ratio are extracted and shown in (g–i), respectively. The blue-shaded regions highlight the temperature range in which sweep-to-sweep variations in the transfer characteristics are observed.

$t_{ox} = 40$ nm, C_{bg} is calculated to be $0.86 \frac{fF}{\mu m^2}$. The p-type mobility is evaluated at the minimum transconductance near the Dirac point, where Coulomb scattering dominates the charge-carrier scattering [45].

The temperature dependence of the maximum field-effect p-type mobility of forward and reverse sweeps is shown in Figure 3g. Each data point represents the average over sweeps 2–5, with error bars indicating variations between individual sweeps. The p-type mobility for forward and reverse sweeps remains about constant at temperatures from 77 to 277 K and decreases for $T > 277$ K. For temperatures in the range of 77–277 K, long-range scattering from charged impurities impacts the mobility [46, 47]. The decrease of mobility at higher temperatures indicates that the charge carrier transport is limited by phonon scattering [48].

Charges stored in the surrounding dielectrics or trapped at the interface with SiO_2 and Si_3N_4 lead to formation of charge puddles in the graphene and act as scatter centers due to spatial potential fluctuations. Consequently, the Dirac point conductivity, which is theoretically expected to be $\sigma_{min} \approx 4e^2/h$ [49], is observed at higher

values, which is attributed to the residual charge carrier density n_0 , originating from electron–hole puddles.

The Dirac point resistance R_{Dirac} and Dirac point voltage V_{Dirac} were determined from the drain current minimum of the transfer characteristics. The temperature-dependent behavior of R_{Dirac} for forward and reverse sweeps is shown in Figure 3h, with the corresponding V_{Dirac} presented in the inset. A nearly linear decrease of R_{Dirac} with increasing temperature is observed. At elevated temperatures, thermally activated electrons contribute to the conduction, resulting in a reduction of R_{Dirac} . Similar behavior has been reported by Feng et al. [50], who attributed the semiconducting characteristics to thermal activation of charge puddles originating from charged impurities near the graphene/ SiO_2 interface, which dominate the transport at low carrier densities. The Dirac point voltage is lowest for 77 K and increases up to 227 K. In the temperature range of 252–327 K, V_{Dirac} decreases, and variations between sweeps are observed, resulting in larger error bars.

Figure 3i shows the I_{on}/I_{off} ratio as a function of temperature. Here, I_{on}/I_{off} is defined as the ratio of the maximum drain current to the drain current at the Dirac point. With decreasing temperature,

the ratio increases by approximately one order of magnitude, indicating improved switching performance due to a clearer separation between the maximum and minimum drain current states. Maximum $I_{\text{on}}/I_{\text{off}}$ ratios of 9.5 ± 0.1 at 102 K and 2.0 ± 0.5 at 327 K are obtained for the reverse sweep.

3.3 | Optoelectronic Characterization

After the electrical characterization, we investigated the photo-response behavior of the device at room temperature under a pressure of $P = 3.6$ mbar. First, we carried out time-resolved measurements of the drain current I_d under light pulses for varying incident laser powers P_{inc} in a range of 27–268 nW at constant $V_{\text{ds}} = 20$ mV, as shown in Figure 4a. Each light pulse

has a duration of 20 s, followed by a 20 s interval with the laser switched off. An increase of the drain current I_d is observed if the laser is turned on, followed by a small decrease over the duration of the light pulse.

The responsivity R , defined as [51]

$$R = \frac{I_{\text{ph}}}{P_{\text{inc}}} \quad (4)$$

where $I_{\text{ph}} = I_{\text{light}} - I_{\text{dark}}$ is the photocurrent and P_{inc} the incident power on the graphene channel area, is shown in Figure 4b. Further, to assess the performance of the graphene PD of detecting weak light signals, the shot noise limited specific detectivity D^* given by [52]

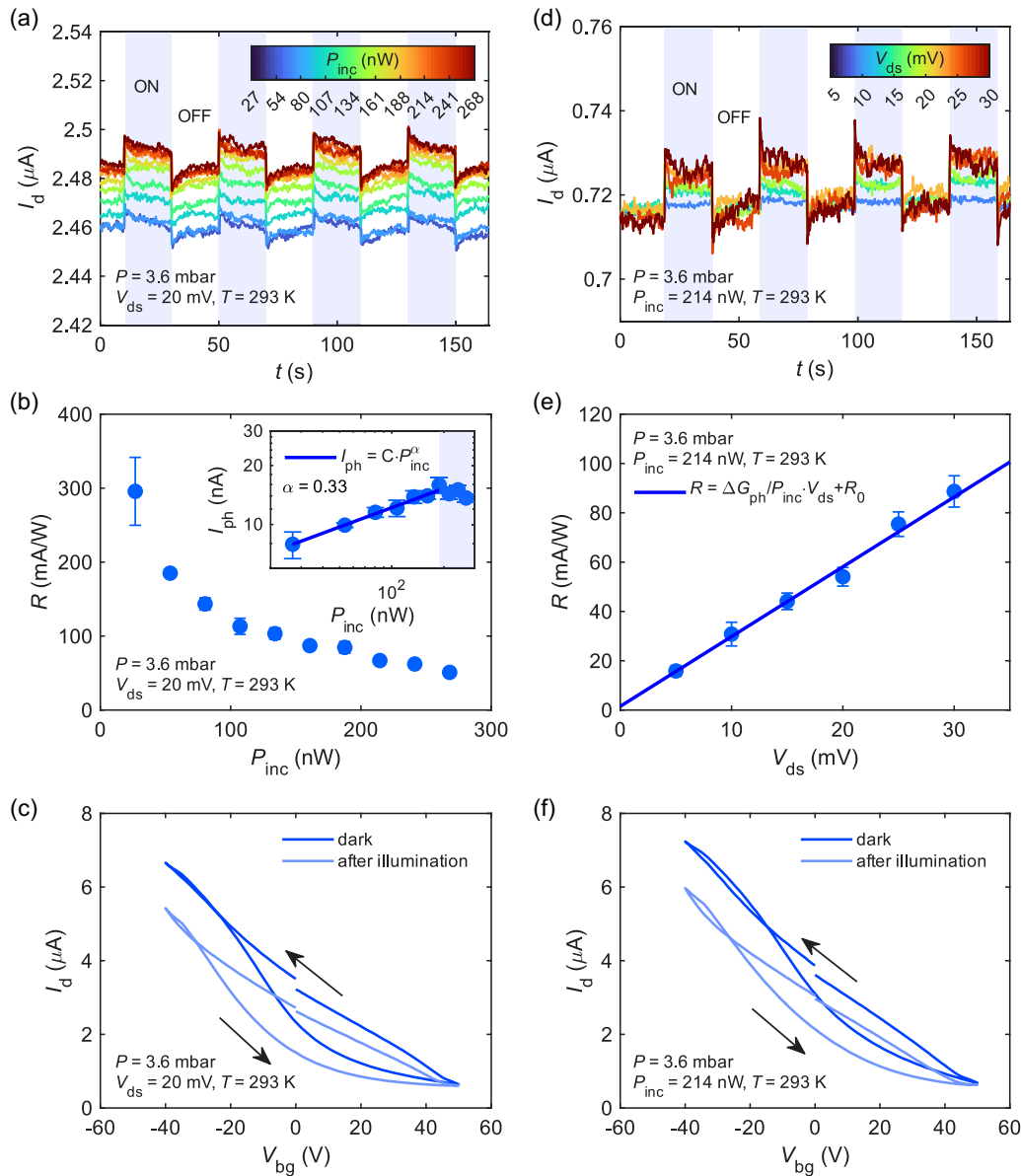


FIGURE 4 | Photoconductance measured at $P = 3.6$ mbar and without back-gate voltage. (a) Photoresponse for varying incident laser power P_{inc} . (b) Responsivity R as a function of P_{inc} . The inset shows the corresponding photocurrent I_{ph} fitted by a power law. (c) Transfer curves measured in the dark before and after illumination for different P_{inc} . (d) Photoresponse for varying source–drain voltages V_{ds} at $P_{\text{inc}} = 214$ nW, with the drain current I_d normalized to $V_{\text{ds}} = 5$ mV. (e) Responsivity as a function of V_{ds} . The solid line represents a linear fit. (f) Transfer curves measured in the dark before and after illumination for different V_{ds} .

$$D^* = \frac{R \cdot \sqrt{A}}{\sqrt{2q} \cdot I_{\text{dark}}} \quad (5)$$

was evaluated, with A the active area, q the elementary charge, and I_{dark} the dark current. A maximum responsivity of $R = 307.0 \text{ mA/W}$ and specific detectivity of $D^* = 1.9 \cdot 10^8 \text{ Jones}$ are achieved at $P_{\text{inc}} = 27 \text{ nW}$. We note that the reported responsivity and specific detectivity are not defined for a specific wavelength but instead correspond to an average over the full spectrum of the white laser source. In addition, D^* represents an upper limit, as thermal and $1/f$ noise contributions are excluded in the shot-noise limited calculation. With increasing incident laser power, responsivity and specific detectivity decrease to $R = 51.3 \text{ mA/W}$ and $D^* = 0.3 \cdot 10^8 \text{ Jones}$ at $P_{\text{inc}} = 268 \text{ nW}$. The reduction of responsivity R is commonly attributed to the photogating effect and increased recombination rate at higher carrier densities [23].

Our obtained detectivity aligns well with reported values for pure 2D material photodetectors [53] and standard graphene/silicon heterojunctions (10^8 – 10^9 Jones) [54, 55]. Higher reported values $> 10^{11} \text{ Jones}$ typically require hybrid absorber schemes [53, 56, 57], indicating that the addition of targeted absorber layers could further enhance the sensitivity of our current platform.

The inset of Figure 4b shows the photocurrent I_{ph} , which increases up to an incident laser power of about 188 nW and then has a transition into a saturating regime highlighted in blue. The increasing region of I_{ph} as a function of the incident laser power P_{inc} can be described by a power law [58] as

$$I_{\text{ph}} = C \cdot P_{\text{inc}}^{\alpha} \quad (6)$$

where α is the power-law exponent. A fit to the data yields $\alpha = 0.33$ and indicates a sublinear increase of the photocurrent. Ideally, the photocurrent should depend linearly on the photogenerated carriers, corresponding to $\alpha = 1$. However, sublinear behavior with $\alpha < 1$ can be observed for thermoelectric effects, photogating, and charge carrier recombination or trapping [58, 59].

Patil et al. attribute the sublinear power coefficient to an additional thermoelectric effect [58]. In this regime, the photoelectric and the photothermoelectric effects can limit the photocurrent. In particular, at higher incident powers, the photocurrent saturates due to laser-induced local heating, which reduces carrier mobility at elevated temperatures and carrier concentration.

To investigate the contribution of the photothermoelectric effect, the source–drain voltage dependence of the drain current I_d was measured under illumination ($P_{\text{inc}} = 214 \text{ nW}$) for V_{ds} ranging from 5 to 30 mV in 5 mV steps, as depicted in Figure 4d. The corresponding I_d curves are scaled relative to the $V_{\text{ds}} = 5 \text{ mV}$ measurement. As shown in Figure 4e, the extracted responsivity R increases linearly with the source–drain voltage, ranging from 15.9 to 88.7 mA/W. The specific detectivity, D^* , follows this trend, reaching values from $0.2 \cdot 10^8$ to $1.0 \cdot 10^8 \text{ Jones}$. This observation is attributed to an enhanced electrical field between the electrodes at higher source–drain voltages, which leads to more efficient separation and collection of photogenerated charge carriers. Similar linear dependence of the photocurrent on V_{ds} has been reported previously [60].

The contributions of photogating and photothermoelectric effect were quantified by fitting the responsivity using the linear relation

$$R = \frac{\Delta G_{\text{ph}}}{P_{\text{inc}}} \cdot V_{\text{ds}} + R_0 \quad (7)$$

where $\Delta G_{\text{ph}} = \left(\frac{1}{R_{\text{light}}} - \frac{1}{R_{\text{dark}}} \right)$ represents the change in conductance and R_0 denotes the responsivity in the absence of a source–drain voltage ($V_{\text{ds}} = 0 \text{ V}$). An intercept value of $R_0 = (1.5 \pm 2.6) \text{ mA/W}$ was extracted. Given that this value is close to zero and the entire graphene channel is uniformly illuminated, we conclude that the thermoelectric effect does not contribute significantly to the observed photoresponse. Consequently, photogating and photoconduction are identified as the primary photocurrent generation mechanisms.

Photogating is confirmed by the measured transfer characteristics before and after illumination for varying laser power and source–drain voltages, as shown in Figure 4c,f, respectively. The leftward shift of the transfer curves observed after illumination is characteristic of the photogating effect [24, 25, 58].

Because trap-mediated phenomena are sensitive to environmental fluctuations, reliable device operation requires effective surface passivation. Si_3N_4 encapsulation preserves intrinsic photoconductive properties while subtly improving the signal-to-noise ratio via increased baseline resistance [61]. By blocking atmospheric H_2O and O_2 ingress, Si_3N_4 mitigates ambient degradation. Passivated devices have been demonstrated to maintain high long-term stability, exhibiting a relative resistance drift of only 11.6% over 60 days, compared to a severe 129.8% variation in unencapsulated devices [61]. Therefore, Si_3N_4 encapsulation effectively ensures the long-term environmental stability of our devices.

Photoresponse measurements were additionally conducted at applied back-gate voltages of $V_{\text{bg}} = \pm 20$ and -5 V as shown in Figure 5a–c. All measurements were carried out at an incident laser power of $P_{\text{inc}} = 214 \text{ nW}$ at room temperature and a pressure of $P = 3.6 \text{ mbar}$. The blue-shaded regions represent the time intervals during which the device was illuminated via an optical fiber. As shown in the electrical characterization section, the graphene channel is in a p-doped condition, and a hole current flows under a back-gate voltage of $V_{\text{bg}} < V_{\text{Dirac}}$. For the back-gate voltages of 20 and 5 V, shown in Figure 5a,c, the hole current in the dark increases with time t and reaches a saturation. In contrast, for $V_{\text{bg}} = -20 \text{ V}$ in Figure 5b, the hole current in the dark decreases until it saturates.

This behavior can be attributed to charge trapping in the surrounding dielectrics. The process is primarily governed by electron or hole trapping at the graphene/ SiO_2 interface and the SiO_2 layer (the field at the graphene- Si_3N_4 interface is screened by graphene), continuing until all available electron traps are filled under positive bias or all hole traps are filled under negative bias [62]. The type of trapped carrier depends on the potential difference between the channel and the gate. When both potentials are equal, a constant dark current is expected.

Under illumination and in the presence of a positive applied back-gate voltage, the channel current initially exhibits a positive

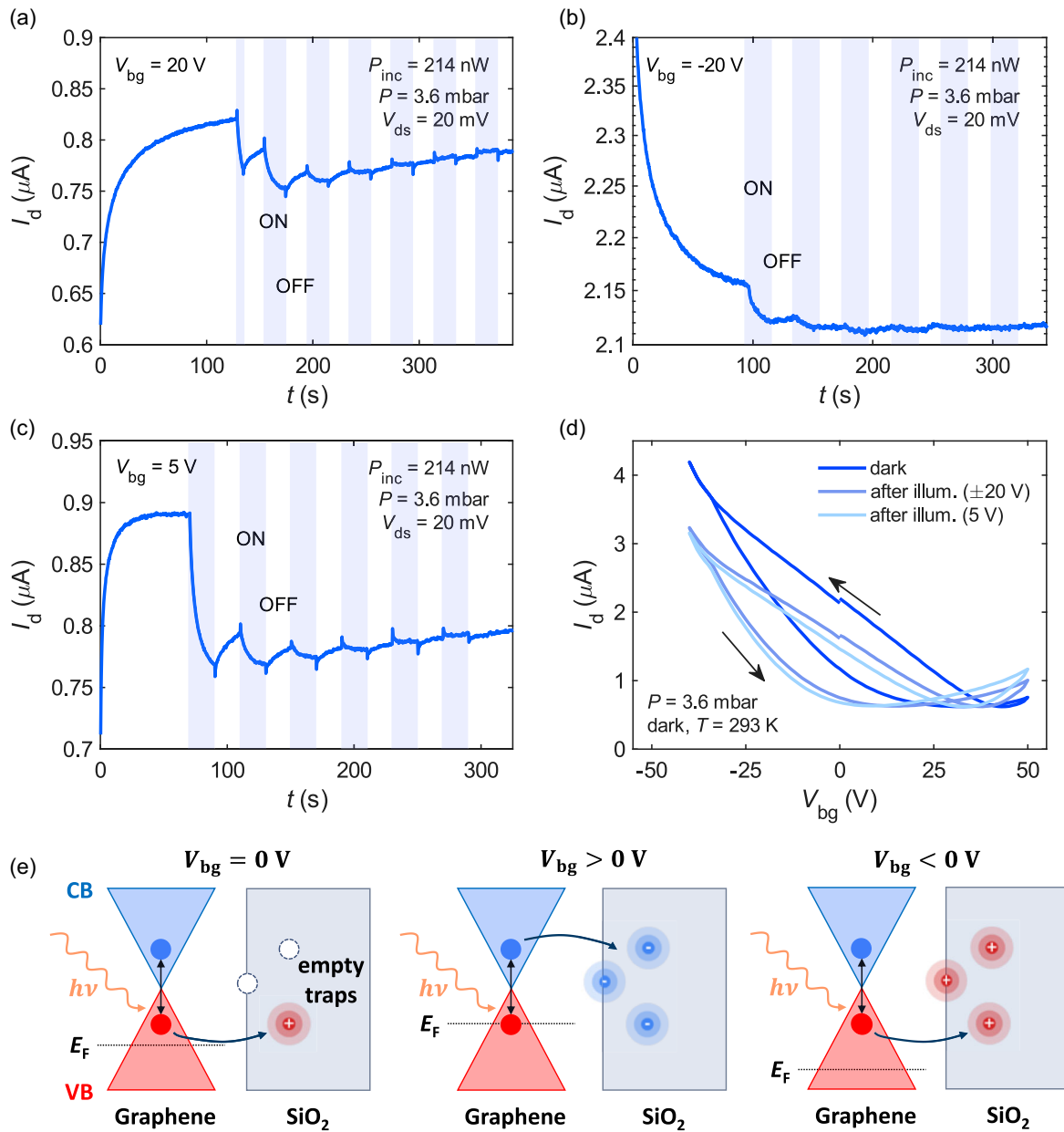


FIGURE 5 | Photoconductance measured at $P = 3.6$ mbar, $V_{ds} = 20$ mV, under applied back-gate voltages V_{bg} and an incident laser power of $P_{inc} = 214$ nW. (a–c) Show the photoresponse measured at back-gate voltages of $V_{bg} = 20$, -20 , and 5 V, respectively, where a negative photoresponse is observed under illumination. (d) Shows the transfer curves measured in the dark before and after illumination under applied V_{bg} . (e) Schematic of the NPC mechanism showing baseline trapping at $V_{bg} = 0$ V and enhanced carrier trapping under back-gate voltage. The resulting trapped charges act as Coulomb scatterers, leading to negative photoconductance (NPC).

spike, followed by a pronounced decrease. This decrease corresponds to NPC, accompanied by a left shift of the transfer curves, as shown in Figure 5d. Similar to the ungated measurements, this shift is attributed to the photogating effect, where trapped photogenerated (positive) charges modulate the effective back-gate voltage. Consequently, the applied back-gate voltage enables a transition from PPC to NPC. The transfer curve shift can be understood by considering charge trapping at the graphene/ SiO_2 interface and inside SiO_2 . Under illumination, photogenerated charge carriers become trapped, thereby altering the density of free charge carriers in the graphene channel. As a result, the effective-gate voltage acting on the graphene channel changes by field-effect doping or photogating, respectively [51]. A similar

behavior has been obtained in hybrid IR GFETs on PbS quantum dot-modified graphene [63].

In the NPC regime, the device achieves a peak responsivity of $R = 574.0$ mA/W and a maximum specific detectivity of $D^* = 6.1 \cdot 10^9$ Jones for the first light pulse at $V_{bg} = 5$ V. This enhancement of responsivity and specific detectivity under NPC conditions arises because the photogating-induced modulation improves the signal-to-noise ratio by suppressing the impact of the inherently high dark current baseline.

NPC further has been reported for graphene quantum dots with adsorbed moisture and hysteresis by Zhuang et al. [20]. In the

dark, O₂ and H₂O molecules capture free electrons due to their electronegativity, leading to p-type doping and hole accumulation in graphene, which also contributes to hysteresis in transfer characteristics observed in this work. Under illumination, photo-generated holes recombine with electrons trapped in moisture, while photogenerated electrons recombine with accumulated holes in graphene. This reduces the hole concentration, resulting in negative photoconductance $I_{\text{dark}} > I_{\text{light}}$.

Biswas et al. also reported both positive and negative photoconductance in graphene on a SiO₂ substrate [19]. They attributed the negative photoconductance to adsorbates on the graphene surface, which act as scattering centers under illumination and thereby reduce the conductivity, indicating the presence of impurity scattering. Charge traps at the graphene/SiO₂ interface may further contribute to this effect. Additionally, annealing was found to suppress the NPC due to the removal of adsorbates [19].

Similarly, we propose that the transition from positive to NPC in our device is governed by gate-induced charge trapping, as shown in Figure 5e. Although photogating is present even at zero gate bias, it is enhanced by applying either a positive or a negative gate voltage. The trapped charges act as an additional effective gating field that shifts the transfer characteristic, thereby contributing to either negative or positive photoconductivity. In contrast, in the absence of a gate bias, photogeneration dominates over photogating, resulting exclusively in PPC. Charge trapping, evidenced by the initial increase or decrease in drain current, introduces localized Coulomb potentials that progressively reduce carrier mobility as trap occupancy increases, until an equilibrium is reached and the current saturates. Under illumination, the interplay between photogating due to positive or negative charge storage and photoconductive effects can lead to NPC. The pulse count-dependent transition from negative to positive photoconductance further highlights the competition between photogating and photoconduction. At low pulse counts, unoccupied traps favor photogating and trapping to generate a negative photocurrent. With progressive trap filling, charge trapping is suppressed, allowing photoconduction to dominate at higher pulse counts. The hysteresis observed in the transfer characteristics further supports the proposed scenario in which charge trapping modulates the local carrier density and can drive the emergence of NPC.

In contrast to semiconductor/graphene heterostructures [9–11], where the photoresponse typically originates from Fermi-level E_F mismatch, built-in junction fields, and carrier recombination, the NPC in our GFETs is governed by gate-field-driven charge storage in the SiO₂ substrate. Rather than heterojunction-mediated recombination, the emergence of NPC here is primarily driven by mobility degradation via enhanced Coulomb scattering from dynamically filled oxide traps, highlighting a distinct electrostatic- and scattering-dominant mechanism.

4 | Conclusions

We investigated the electrical and photoresponse properties of back-gated GFETs with Pd/Au edge contacts on a SiO₂ gate dielectric. The transfer characteristics exhibit hysteresis due to charge trapping and residues. With decreasing temperature, the

Dirac point voltage shifts to lower values, and the graphene channel shows a semiconducting behavior, attributed to thermally activated electron–hole pairs. The devices exhibit a clear photoresponse, with a photocurrent that increases sublinearly and saturates at higher intensities. The photoresponse further increases with the increasing source–drain voltage. Illumination induces a leftward shift of the transfer characteristics due to trapped carriers and photogating. Applying a back-gate voltage can change the photoconductivity from positive to negative. This can be attributed to the facilitated charge transfer and trapping in the surrounding dielectrics. The data indicate that the trapped charge is positive and induces a photogating effect that shifts the transfer characteristics to the left, enabling the occurrence of NPC.

Acknowledgments

This research has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101120938 (GATEPOST) and under grant agreement No. 101189797 (2D-PL).

Funding

This study was supported by the HORIZON EUROPE Framework Programme (Grants 101120938 and 101189797).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. A. A. Odebowale, A. M. Berhe, D. Somaweera, et al., “Advances in 2D Photodetectors: Materials, Mechanisms, and Applications,” *Micromachines* 16 (2025): 776, <https://doi.org/10.3390/mi16070776>.
2. K. Mistewicz, T. K. Das, B. Nowacki, et al., “Bismuth Sulfoiodide (BiSI) Nanorods: Synthesis, Characterization, and Photodetector Application,” *Scientific Reports* 13 (2023): 8800, <https://doi.org/10.1038/s41598-023-35899-7>.
3. M. Godzierz, K. Mistewicz, A. Gawron, K. Kurtyka, Ł. Otulakowski, and T. Kanti Das, “Visible Light Photodetectors Based on the Bi₂S₃ Flower-Like 3D Microrods with Schottky Emission,” *Journal of Alloys and Compounds* 1008 (2024): 176820, <https://doi.org/10.1016/j.jallcom.2024.176820>.
4. M. D. Ali, A. Starczewska, T. K. Das, and M. Jesione, “Exploration of Sp²-Sp² Carbon Networks: Advances in Graphyne Research and Its Role in Next-Generation Technologies,” *IJMS* 26 (2025): 5140, <https://doi.org/10.3390/ijms26115140>.
5. M. Long, P. Wang, H. Fang, and W. Hu, “Progress, Challenges, and Opportunities for 2D Material Based Photodetectors,” *Advanced Functional Materials* 29 (2019): 1803807, <https://doi.org/10.1002/adfm.2019.19>.
6. Y.-C. Lin, R. Torsi, R. Younas, et al., “Recent Advances in 2D Material Theory, Synthesis, Properties, and Applications,” *ACS Nano* 17 (2023): 9694, <https://doi.org/10.1021/acsnano.2c12759>.
7. F. Xia, T. Mueller, Y. Lin, A. Valdes-Garcia, and P. Avouris, “Ultrafast Graphene Photodetector,” *Nature Nanotech* 4 (2009): 839, <https://doi.org/10.1038/nnano.2009.292>.

8. P. Tian, L. Tang, K. S. Teng, J. Xiang, and S. P. Lau, "Recent Advances in Graphene Homogeneous p-n Junction for Optoelectronics," *Advanced Materials Technologies* 4 (2019): 1900007, <https://doi.org/10.1002/admt.v4.7>.
9. B. L. B. Liu, C. Y. C. You, C. Z. C. Zhao, et al., "High Responsivity and Near-Infrared Photodetector Based on Graphene/MoSe₂ Heterostructure," *Chinese Optics Letters* 17 (2019): 020002, <https://doi.org/10.3788/COL>.
10. J. Xu, Y. J. Song, J.-H. Park, and S. Lee, "Graphene/Black Phosphorus Heterostructured Photodetector," *Solid-State Electronics* 144 (2018): 86, <https://doi.org/10.1016/j.sse.2018.03.007>.
11. Y. Lee, H. Kim, S. Kim, D. Whang, and J. H. Cho, "Photogating in the Graphene-Dye-Graphene Sandwich Heterostructure," *ACS Applied Materials & Interfaces* 11 (2019): 23474, <https://doi.org/10.1021/acsami.9b05280>.
12. A. Di Bartolomeo, "Graphene Schottky Diodes: An Experimental Review of the Rectifying Graphene/Semiconductor Heterojunction," *Physics Reports* 606 (2016): 1, <https://doi.org/10.1016/j.physrep.2015.10.003>.
13. J.-H. Chen, C. Jang, S. Xiao, M. Ishigami, and M. S. Fuhrer, "Intrinsic and Extrinsic Performance Limits of Graphene Devices on SiO₂," *Nature Nanotech* 3 (2008): 206, <https://doi.org/10.1038/nnano.2008.58>.
14. R. S. Shishir, D. K. Ferry, and S. M. Goodnick, "Room Temperature Velocity Saturation in Intrinsic Graphene," *Journal of Physics: Conference Series* 193 (2009): 012118.
15. K. F. Mak, L. Ju, F. Wang, and T. F. Heinz, "Optical Spectroscopy of Graphene: From the Far Infrared to the Ultraviolet," *Solid State Communications* 152 (2012): 1341, <https://doi.org/10.1016/j.ssc.2012.04.064>.
16. K. F. Mak, M. Y. Sfeir, Y. Wu, C. H. Lui, J. A. Misewich, and T. F. Heinz, "Measurement of the Optical Conductivity of Graphene," *Physical Review Letters* 101 (2008): 196405, <https://doi.org/10.1103/PhysRevLett.101.196405>.
17. M. Romagnoli, V. Sorianello, M. Midrio, et al., "Graphene-Based Integrated Photonics for Next-Generation Datacom and Telecom," *Nature Reviews Materials* 3 (2018): 392, <https://doi.org/10.1038/s41578-018-0040-9>.
18. S. Goossens, G. Navickaite, C. Monasterio, et al., "Broadband Image Sensor Array Based on Graphene-CMOS Integration," *Nature Photonics* 11 (2017): 366, <https://doi.org/10.1038/nphoton.2017.75>.
19. C. Biswas, F. Güneş, D. D. Loc, et al., "Negative and Positive Persistent Photoconductance in Graphene," *Nano Letters* 11 (2011): 4682, <https://doi.org/10.1021/nl202266h>.
20. S. Zhuang, Y. Chen, Y. Xia, et al., "Coexistence of Negative Photoconductivity and Hysteresis in Semiconducting Graphene," *AIP Advances* 6 (2016): 045214, <https://doi.org/10.1063/1.4948313>.
21. N. K. Tailor, C. A. Aranda, M. Saliba, and S. Satapathi, "Negative Photoconductivity: Bizarre Physics in Semiconductors," *ACS Materials Letters* 4 (2022): 2298, <https://doi.org/10.1021/acsmaterialslett.2c00675>.
22. A. Pelella, A. Grillo, E. Faella, G. Luongo, M. B. Askari, and A. Di Bartolomeo, "Graphene-Silicon Device for Visible and Infrared Photodetection," *ACS Applied Materials & Interfaces* 13 (2021): 47895, <https://doi.org/10.1021/acsami.1c12050>.
23. F. Luo, M. Zhu, Y. Tan, et al., "High Responsivity Graphene Photodetectors from Visible to Near-Infrared by Photogating Effect," *AIP Advances* 8 (2018): 115106, <https://doi.org/10.1063/1.5054760>.
24. L. Howe, K. H. Ellepola, N. Jahan, et al., "Characterization and Modeling of Interfacial Photogating Effect in Graphene Field-Effect Transistor Photodetectors on Silicon," *ACS Applied Electronic Materials* 7 (2025): 1305, <https://doi.org/10.1021/acsaelm.4c02268>.
25. S. Nashashibi, S. M. Koepfli, R. Schwanninger, et al., "Engineering Graphene Phototransistors for High Dynamic Range Applications," *ACS Nano* 18 (2024): 12760, <https://doi.org/10.1021/acsnano.3c11856>.
26. H. Shi, S. Tang, J. Shi, et al., "Negative Photoconductive Effect for Novel Photoelectric Sensors: A Review," *IEEE Sensors Journal* 25 (2025): 5935, <https://doi.org/10.1109/JSEN.2024.3506725>.
27. C. Walleni, N. Hamdaoui, S. B. Malik, M. F. Nsib, and E. Llobet, "High-Performance UV Photodetector Based on Nickel Oxide Loaded with Low Amount of Nitrogen and Boron Co-Doped Reduced Graphene Oxide for Bias-Switchable Photoconductance," *Journal of Alloys and Compounds* 976 (2024): 173248, <https://doi.org/10.1016/j.jallcom.2023.173248>.
28. F. Akhtar, J. Dabrowski, R. Lukose, C. Wenger, and M. Lukosius, "Chemical Vapor Deposition Growth of Graphene on 200 mm Ge(110)/Si Wafers and Ab Initio Analysis of Differences in Growth Mechanisms on Ge(110) and Ge(001)," *ACS Applied Materials & Interfaces* 15 (2023): 36966, <https://doi.org/10.1021/acsami.3c05860>.
29. Y. Y. Wang, Z. H. Ni, T. Yu, et al., "Raman Studies of Monolayer Graphene: The Substrate Effect," *The Journal of Physical Chemistry C* 112 (2008): 10637, <https://doi.org/10.1021/jp8008404>.
30. J. Hofrichter, B. N. Szafrank, M. Otto, et al., "Synthesis of Graphene on Silicon Dioxide by a Solid Carbon Source," *Nano Letters* 10 (2010): 36, <https://doi.org/10.1021/nl902558x>.
31. D. S. Lee, C. Riedl, B. Krauss, K. Von Klitzing, U. Starke, and J. H. Smet, "Raman Spectra of Epitaxial Graphene on SiC and of Epitaxial Graphene Transferred to SiO₂," *Nano Letters* 8 (2008): 4320, <https://doi.org/10.1021/nl802156w>.
32. C. Faugeras, A. Nèrrière, M. Potemski, et al., "Few-Layer Graphene on SiC, Pyrolytic Graphite, and Graphene: A Raman Scattering Study," *Applied Physics Letters* 92 (2008): 011914, <https://doi.org/10.1063/1.2828975>.
33. C. Neumann, S. Reichardt, P. Venezuela, et al., "Raman Spectroscopy as Probe of Nanometre-Scale Strain Variations in Graphene," *Nature Communications* 6 (2015): 8429, <https://doi.org/10.1038/ncomms9429>.
34. S. Berciaud, X. Li, H. Htoon, L. E. Brus, S. K. Doorn, and T. F. Heinz, "Intrinsic Line Shape of the Raman 2D-Mode in Freestanding Graphene Monolayers," *Nano Letters* 13 (2013): 3517, <https://doi.org/10.1021/nl400917e>.
35. J. E. Lee, G. Ahn, J. Shim, Y. S. Lee, and S. Ryu, "Optical Separation of Mechanical Strain from Charge Doping in Graphene," *Nature Communications* 3 (2012): 1024, <https://doi.org/10.1038/ncomms2022>.
36. H. Park, C. Lim, C.-J. Lee, et al., "Optimized Poly(methyl Methacrylate)-Mediated Graphene-Transfer Process for Fabrication of High-Quality Graphene Layer," *Nanotechnology* 29 (2018): 415303, <https://doi.org/10.1088/1361-6528/aad4d9>.
37. Y. Yang, K. Brenner, and R. Murali, "The Influence of Atmosphere on Electrical Transport in Graphene," *Carbon* 50 (2012): 1727, <https://doi.org/10.1016/j.carbon.2011.12.008>.
38. W. H. Lee, J. W. Suk, J. Lee, et al., "Simultaneous Transfer and Doping of CVD-Grown Graphene by Fluoropolymer for Transparent Conductive Films on Plastic," *ACS Nano* 6 (2012): 1284, <https://doi.org/10.1021/nn203998j>.
39. H. Wang, Y. Wu, C. Cong, J. Shang, and T. Yu, "Hysteresis of Electronic Transport in Graphene Transistors," *ACS Nano* 4 (2010): 7221, <https://doi.org/10.1021/nn101950n>.
40. Z.-M. Liao, B.-H. Han, Y.-B. Zhou, and D.-P. Yu, "Hysteresis Reversion in Graphene Field-Effect Transistors," *Journal of Chemical Physics* 133 (2010): 044703, <https://doi.org/10.1063/1.3460798>.
41. A. D. Bartolomeo, F. Giubileo, S. Santandrea, et al., "Charge Transfer and Partial Pinning at the Contacts as the Origin of a Double Dip in the Transfer Characteristics of Graphene-Based Field-Effect Transistors," *Nanotechnology* 22 (2011): 275702, <https://doi.org/10.1088/0957-4484/22/27/275702>.
42. A. D. Bartolomeo, F. Giubileo, F. Romeo, et al., "Graphene Field Effect Transistors with Niobium Contacts and Asymmetric Transfer

- Characteristics," *Nanotechnology* 26 (2015): 475202, <https://doi.org/10.1088/0957-4484/26/47/475202>.
43. H. Zhong, Z. Zhang, H. Xu, C. Qiu, and L.-M. Peng, "Comparison of Mobility Extraction Methods Based on Field-Effect Measurements for Graphene," *AIP Advances* 5 (2015): 057136, <https://doi.org/10.1063/1.4921400>.
 44. T. R. Lenka and A. K. Panda, "AlGaIn/GaN-Based HEMT on SiC Substrate for Microwave Characteristics Using Different Passivation Layers," *Pramana* 79 (2012): 151, <https://doi.org/10.1007/s12043-012-0290-9>.
 45. J. H. Gosling, O. Makarovskiy, F. Wang, et al., "Universal Mobility Characteristics of Graphene Originating from Charge Scattering by Ionised Impurities," *Communications Physics* 4 (2021): 30, <https://doi.org/10.1038/s42005-021-00518-2>.
 46. J.-H. Chen, C. Jang, S. Adam, M. S. Fuhrer, E. D. Williams, and M. Ishigami, "Charged-Impurity Scattering in Graphene," *Nature Physics* 4 (2008): 377, <https://doi.org/10.1038/nphys935>.
 47. C.-J. Shih, G. L. C. Paulus, Q. H. Wang, Z. Jin, D. Blankschtein, and M. S. Strano, "Understanding Surfactant/Graphene Interactions Using a Graphene Field Effect Transistor: Relating Molecular Structure to Hysteresis and Carrier Mobility," *Langmuir* 28 (2012): 8579, <https://doi.org/10.1021/la3008816>.
 48. F. Urban, G. Lupina, A. Grillo, N. Martucciello, and A. Di Bartolomeo, "Contact Resistance and Mobility in Back-Gate Graphene Transistors," *Nano Express* 1 (2020): 010001, <https://doi.org/10.1088/2632-959X/ab7055>.
 49. J. Nilsson, A. H. C. Neto, F. Guinea, and N. M. R. Peres, "Electronic Properties of Graphene Multilayers," *Physical Review Letters* 97 (2006): 266801, <https://doi.org/10.1103/PhysRevLett.97.266801>.
 50. T. Feng, D. Xie, G. Li, et al., "Temperature and Gate Voltage Dependent Electrical Properties of Graphene Field-Effect Transistors," *Carbon* 78 (2014): 250, <https://doi.org/10.1016/j.carbon.2014.07.001>.
 51. J. Li, L. Niu, Z. Zheng, and F. Yan, "Photosensitive Graphene Transistors," *Advanced Materials* 26 (2014): 5239, <https://doi.org/10.1002/adma.v26.31>.
 52. S. Rath, I. Lee, D. Lim, et al., "Tunable Electrical and Optical Characteristics in Monolayer Graphene and Few-Layer MoS₂ Heterostructure Devices," *Nano Letters* 15 (2015): 5017, <https://doi.org/10.1021/acs.nanolett.5b01030>.
 53. B. Liu, Y. Chen, C. You, et al., "High Performance Photodetector Based on Graphene/MoS₂/Graphene Lateral Heterostructure with Schottky Junctions," *Journal of Alloys and Compounds* 779 (2019): 140, <https://doi.org/10.1016/j.jallcom.2018.11.165>.
 54. Z. Alavi and Y. Abdi, "High-Gain Graphene/SiO₂/Si Avalanche Photodetectors via Engineered SiO₂ Interfaces," *IEEE Sensors Journal* 26 (2026): 25798, <https://doi.org/10.1109/JSEN.2026.3715703>.
 55. H. Jiang, J. Fu, J. Wei, et al., "Synergistic-Potential Engineering Enables High-Efficiency Graphene Photodetectors for Near- to Mid-Infrared Light," *Nature Communications* 15 (2024): 1225, <https://doi.org/10.1038/s41467-024-45498-3>.
 56. Y. Wang, V. X. Ho, P. Pradhan, M. P. Cooney, and N. Q. Vinh, "Interfacial Photogating Effect for Hybrid Graphene-Based Photodetectors," *ACS Applied Nano Materials* 4 (2021): 8539, <https://doi.org/10.1021/acsanm.1c01931>.
 57. J. Wu, J. Zhang, R. Jiang, et al., "High-Sensitivity, High-Speed, Broadband Mid-Infrared Photodetector Enabled by a Van der Waals Heterostructure with a Vertical Transport Channel," *Nature Communications* 16 (2025): 564, <https://doi.org/10.1038/s41467-025-55887-x>.
 58. V. Patil, A. Capone, S. Strauf, and E.-H. Yang, "Improved Photoresponse with Enhanced Photoelectric Contribution in Fully Suspended Graphene Photodetectors," *Scientific Reports* 3 (2013): 2791, <https://doi.org/10.1038/srep02791>.
 59. G. F. Jones, R. M. Pinto, A. De Sanctis, et al., "Highly Efficient Rubrene-Graphene Charge-Transfer Interfaces as Phototransistors in the Visible Regime," *Advanced Materials* 29 (2017): 1702993, <https://doi.org/10.1002/adma.v29.41>.
 60. Y. Liu, Q. Xia, J. He, and Z. Liu, "Direct Observation of High Photoresponsivity in Pure Graphene Photodetectors," *Nanoscale Research Letters* 12 (2017): 93, <https://doi.org/10.1186/s11671-017-1827-0>.
 61. F. Su, Z. Zhang, S. Li, P. Li, and T. Deng, "Long-Term Stability of Photodetectors Based on Graphene Field-Effect Transistors Encapsulated with Si₃N₄ Layers," *Applied Surface Science* 459 (2018): 164, <https://doi.org/10.1016/j.apsusc.2018.07.208>.
 62. J.-M. Park, D. Lee, J. Shim, et al., "Analysis and Suppression of Drain Current Drift in Graphene FETs," *Semiconductor Science and Technology* 30 (2015): 105013, <https://doi.org/10.1088/0268-1242/30/10/105013>.
 63. Z. Sun, Z. Liu, J. Li, G. Tai, S. Lau, and F. Yan, "Infrared Photodetectors Based on CVD-Grown Graphene and PbS Quantum Dots with Ultrahigh Responsivity," *Advanced Materials* 24 (2012): 5878, <https://doi.org/10.1002/adma.v24.43>.