

General photogating: An emerging paradigm for low-dimensional photodetectors

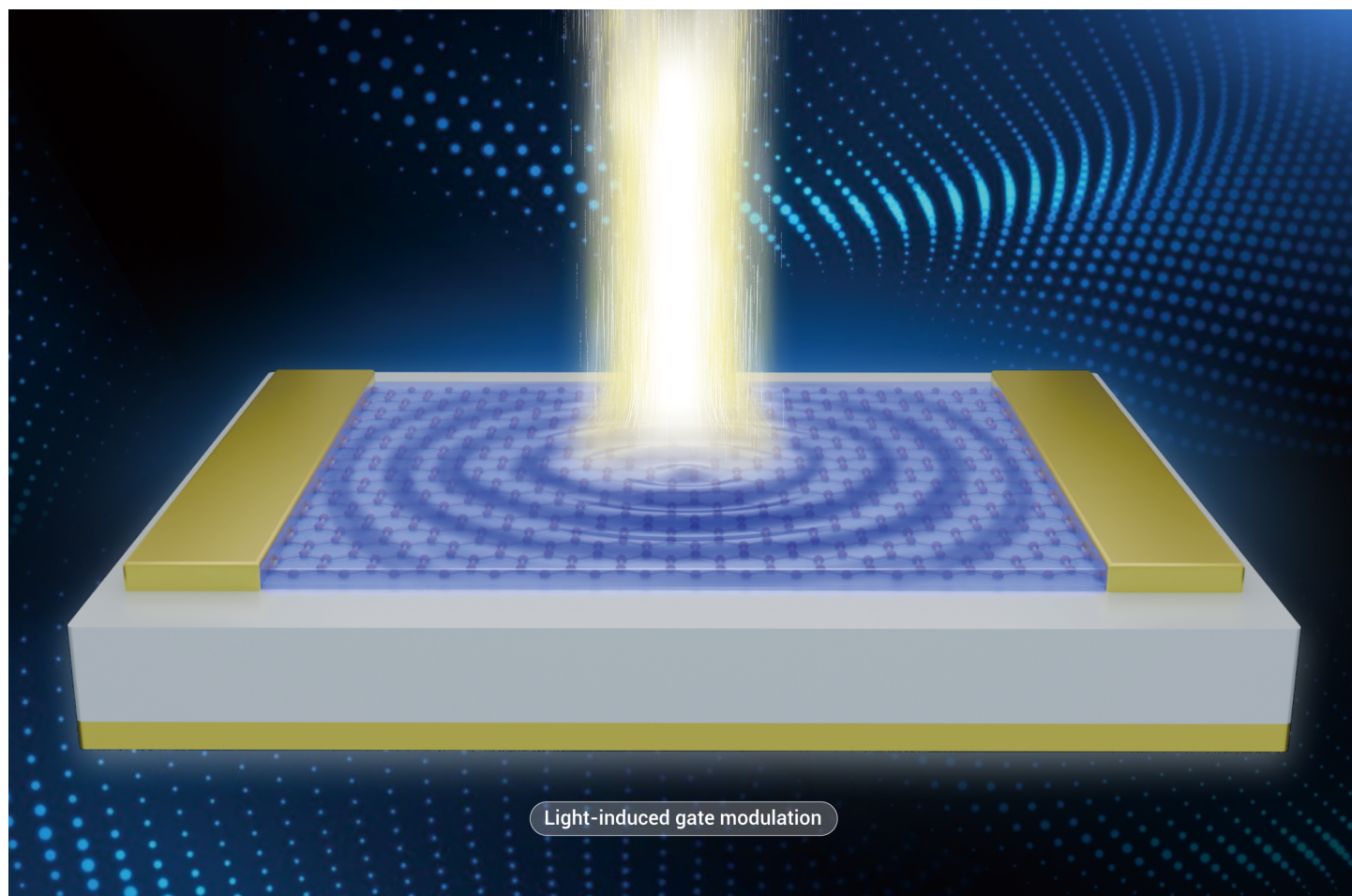
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- This Review introduces the General Photogating Effect (GPE) for low-dimensional photodetectors.
- The GPE unifies light-induced gate modulation across diverse materials and device structures.
- Design guidelines for high-performance and multifunctional GPE-based photodetectors are outlined.

General photogating: An emerging paradigm for low-dimensional photodetectors

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Low-dimensional materials have attracted tremendous attention as promising building blocks for novel photodetector construction, providing a versatile platform to explore intriguing photocurrent generation mechanisms. Among them, photogating has been extensively studied and demonstrated to play a pivotal role in low-dimensional photodetectors. Photogating refers to the formation of electric fields induced by localized photocarriers due to trap states or artificial heterostructures, which modulate the material conductance in a gate-like manner. However, with the rapid development of low-dimensional photodetectors, the strategies for realizing light-induced gate modulation have become increasingly diverse, rendering the conventional photogating framework insufficient to encompass emerging device operation mechanisms. To broaden the conceptual scope of photogating, this review revisits its literal meaning, light-induced gate modulation, and uses the concept of General Photogating Effect (GPE) as a framework for integrating and extending related phenomena. First, the underlying generation mechanisms of GPE are summarized, followed by an analysis of the performance characteristics and device architectures of GPE-based photodetectors. Subsequently, representative recent advances are reviewed. Furthermore, the potential of GPE in enhancing overall performance and enabling functional photodetection is discussed. This review aims to refine the framework of photogating, promote a unified understanding of its diverse manifestations, and inspire the design of next-generation low-dimensional photodetectors.

INTRODUCTION

Photodetectors play a vital role in driving the informationization of modern society, with broad applications in optical communication, machine vision, deep-space exploration, and environmental monitoring. The photocurrent generation mechanism not only forms the physical foundation of photodetector operation but also serves as a key criterion for selecting photosensitive materials and designing device architectures. To date, extensive research has been devoted to various photocurrent generation mechanisms,^{1–4} including the photovoltaic effect, photoconductive effect, internal photoemission effect, pyroelectric effect, and thermoelectric effect. Among them, the photovoltaic and photoconductive effects are the most widely utilized, although their effective operation range is typically limited by the semiconductor bandgap. The internal photoemission effect offers a viable pathway for detecting photons with energies below the semiconductor bandgap but above the interfacial barrier.^{5,6} However, in infrared detection, strong thermal excitation often necessitates cryogenic operation for these effects to perform effectively. In contrast, the thermoelectric and pyroelectric effects enable uncooled infrared detection,⁷ albeit with compromised efficiency and response speed. Furthermore, recent advances in the photothermoelectric effect, bulk photovoltaic effect, and photogalvanic effect have provided new approaches for realizing broadband, self-powered, or polarization/phase-sensitive photodetectors.^{8–13} These developments highlight that the exploration of photocurrent generation mechanism is crucial for breaking technical paradigms and guiding the rational design of photodetectors.

With the rapid advancement of photodetectors based on low-dimensional materials, such as two-dimensional (2D) materials, one-dimensional (1D) nanowires, and zero-dimensional (0D) quantum dots, a photocurrent generation mechanism has emerged in which illumination induces an electric field

that acts as an equivalent gate, modulating device conductivity and generating photocurrent. In short, this process can be viewed as light-induced gate modulation. Therefore, this mechanism is commonly referred to as the photogating effect. Photogating effect could be ascribed to the localization of photocarrier induced by defects/impurities or artificial heterostructures, which act as a gate voltage, modulating the material conductance.^{1–3,14–17} This mechanism explains several phenomena observed in low-dimensional photodetectors, such as transfer-curve shifts,^{18–20} ultra-high gain,^{21,22} and limited bandwidth.^{23,24} More importantly, photogating effect provides advantages for achieving high-performance photodetection in low-dimensional systems. Due to their ultrathin geometry, large surface-to-volume ratio, and high electrostatic susceptibility, low-dimensional materials are highly sensitive to light-induced gate modulation. Consequently, even with limited optical absorption, photogating effect can facilitate high gain and responsivity in low-dimensional photodetectors.^{25–28}

With the growing diversity of material combinations and device architectures, strategies for achieving light-induced gate modulation have considerably expanded, such as integrating vertical solar cell structures,^{29,30} incorporating photosensitive gates,^{31,32} or introducing pyroelectric substrates.^{33–35} These strategies have not only enabled breakthroughs in performance but also broadened the functionality of low-dimensional photodetectors. For instance, subtle device designs have been proposed to exploit photovoltage modulation to achieve photocurrent gain,^{24,36–38} thereby decoupling gain from photocarrier lifetime. As a result, high gain and fast response speed can be simultaneously achieved in low-dimensional photodetectors. In addition, combining 2D channel materials with pyroelectric substrates allows infrared-induced polarization fields to modulate channel conductance, enabling uncooled human body radiation detection.^{33–35} Such device also eliminates the need for mechanical choppers required in conventional pyroelectric devices. Furthermore, by applying an additional electrical gate voltage, the polarity of the light-induced gate modulation can be tuned, leading to bi-directional photoresponse.^{37,39,40} Unlike unidirectional positive photoresponse widely observed in conventional photodetectors, bi-directional photoresponse provides a physical basis for in-sensor computing.⁴¹ Moreover, the duration of the light-induced gate modulation can be tuned via photocarrier lifetime engineering, allowing control of the temporal response and even enabling persistent photoconductivity resembling memory behavior.^{42–45} Therefore, light-induced gate modulation has been employed to realize functional photodetection, such as edge extraction,⁴⁶ object recognition,⁴⁷ motion perception,³⁹ and optoelectronic logic operations.⁴⁸ Overall, as low-dimensional photodetectors continue to evolve in structure design, performance optimization, and functional expansion, the traditional photogating framework has become insufficient to encompass recent developments, underscoring the need for a more generalized conception.

This review revisits the shared phenomena of light-induced gate modulation and introduces the General Photogating Effect (GPE) as a unified analytical framework. GPE is defined as a process in which light generates an additional equivalent voltage or alters the effective electrical bias, thereby modulating the electrostatic characteristics of a photodetector in a gate-control manner. In contrast, traditional photogating is typically discussed in a narrower sense, mainly emphasizing gate-like modulation induced by localized photocarriers (via trap states or heterostructures).^{15–17} Accordingly, GPE treats traditional photogating as a specific subset and extends the concep-

tual scope to incorporate additional pathways, such as open-circuit photovoltage,^{29,36} pyroelectric-polarization-induced potential modulation,^{33,35} and photo-tunable electrical gating efficiency.^{31,37} By providing a more consistent physical language, the GPE framework facilitates cross-platform comparison and offers transferable guidance for device design amid rapidly diversifying mechanisms and architectures.

RESULTS

Description of general photogating effect

Photogating describes the process in low-dimensional material systems, where impurities/defects or artificial heterostructures capture photocarriers.^{1-3,14-16} The captured photocarriers creates a localized electric gate field that modulates channel conductance (Figure 1A). However, with the continuous evolution of low-dimensional photodetector designs, various strategies have been proposed that also generate or modulate gate fields through illumination, thereby influencing channel conductivity.^{29-36,49-52} In this section, these strategies are summarized and integrated with the conventional concept of photogating, thereby extending its scope and defining this expanded framework as General Photogating Effect (GPE).

Using whether an external electrical gate bias is required as the first-level boundary, GPE-based devices can be categorized into two operating modes: (i) devices that generate equivalent gate voltage under illumination solely via built-in fields or intrinsic material/structural processes,^{27-29,36,43,53} and (ii) devices in which an external gate bias participates to trigger or actively regulate the light-induced gate modulation.^{31,37,49,54-56} The same device may switch between these two modes under different biasing strategies, and multiple light-induced gating mechanisms may coexist in practical devices. Taking the first operating mode as example, in photodetectors using nanowires or 2D materials as channels, trap states with certain spatial distribution capture photocarriers and form localized fields (Figure 1A-i).^{25,43,56-59} The type of trapped photocarriers typically depends on the Fermi level of the channel material, such as n-type (p-type) channel mainly has hole-trap (electron-trap) states.¹⁵ In hybrid structures consisting of photosensitive and channel materials, the built-in field at the interface drives photogenerated electron-hole separation. When the interfacial barrier is high, electrons drift toward the channel but are blocked by the barrier and accumulate at the interface, while holes move in the opposite direction (Figure 1A-ii). By contrast, when the barrier is low, electrons can inject into the channel whereas holes remain in the sensitizer (Figure 1A-iii). Notably, the dominant carrier transport and accumulation pathways depend on the band bending in the heterostructure. The spatial separation of photocarriers produces a photovoltage, analogous to the open-circuit voltage in solar cells. Benefiting from the photovoltage-induced shrinkage of the depletion region, a channel that is closed under dark conditions can be opened under illumination (Figures 1B-i & ii).^{36,49,50,55,60-64} Depending on the material combinations, the junction can take the form of homojunctions,^{30,65,66} Schottky junctions,⁶⁰⁻⁶³ heterojunctions,^{49-51,67-69} or back-to-back p-n junctions (Figure 1B-iii).⁷⁰⁻⁷² Despite their structural differences, their core function is to separate photocarriers and generate photovoltage.

In addition to the "light → electrical" process, the "light → thermal → electrical" process can also produce photovoltage. Specifically, pyroelectric materials under infrared illumination can induce surface charge redistribution due to temperature changes, thereby generating a pyroelectric photovoltage that modulates channel conductance (Figure 1C).^{33-35,73} 2D materials are often selected as channel materials in such devices due to their ease of transfer integration and high susceptibility to external electric fields. It is worth noting that although these strategies generate GPE without external gate bias, the strength of GPE can still be modulated by an electrical gate voltage.

For the second operating mode (Figures 1D-F), in interfacial photovoltage gating, photocarriers accumulate near the dielectric layer under gate bias, forming a photovoltage that modulates channel conductance.^{38,74,75} For example, under negative gate bias, photogenerated electrons accumulate at the interface, inducing excess free holes in the channel (Figure 1D). If an interfacial electric field exists (e.g., due to interface states), similar effects can occur without external bias, while an applied gate voltage enhances or suppresses the process. Moreover, if photocarriers are mainly produced within the channel, gate bias can drive them toward the dielectric interface. These accumulated photocarriers can partially screening the gate bias.^{46,76-79}

If negative gate bias depletes the channel, the accumulated holes can mitigate this depletion effect through screening (Figure 1E). Another scenario arises when the photosensitizer serves as the gate dielectric (Figure 1F). In this case, changes in the resistivity of the photosensitizer affect the electrical gate modulation efficiency.^{31,32,80-82} In darkness, the photosensitizer has high resistance, causing most of the gate voltage to drop across it, resulting in limited electrical gate control. Under illumination, reduced resistance enhances electrical gate modulation. This phenomenon is equivalent to modifying the modulation effect of electrical gate via light, applicable to both top-gate and back-gate configurations.^{31,37,54,82,83} A common design employs narrow-bandgap photosensitizers and wide-bandgap channel materials to minimize channel interference by photoexcitation.

Regardless of whether external gate bias is required, the essence of GPE lies in utilizing illumination to generate a photovoltage (V_{ph}) or alter the effective gate voltage (ΔV_g), thereby enabling electrostatic modulation of the photodetector. This light-induced gate modulation can alter device electrostatics, including electric field distribution, channel current, carrier density, depletion width, band bending, and barrier height (Figure 1G), ultimately affecting photocarrier separation and transport, and thus modifying the output photocurrent. By rationally selecting materials and optimizing device structures to engineer GPE, it is promising for achieving high-performance and multifunctional photodetection.

Characteristics of GPE-based photodetectors

This section discusses the characteristics of GPE-based photodetectors, including the gain-bandwidth relationship, power-dependent photoresponse, light-induced transfer curve shifts, and bi-directional photocurrents. The typical performance metrics and their definitions used in the following discussion are summarized in Table S1.

Gain and bandwidth

GPE can produce photovoltage (V_{ph}) or alter effective gate voltage (ΔV_g), both of which can modulate the conductivity of low-dimensional photodetectors. According to the gate-voltage modulation model of transistors,^{31,36} the photocurrent gain (G) can be approximately expressed as $G \propto (h\nu/q) \times (V_{ph}/g_m/P_{opt})$ or $G \propto (h\nu/q) \times (\Delta V_g/g_m/P_{opt})$, where h is Planck's constant, ν is the optical frequency, q is the elementary charge, P_{opt} is the incident optical power, and g_m is the transconductance. The transconductance is defined as $g_m = \partial I_{ds}/\partial V_g$, where I_{ds} is the source-drain current, and V_g is the gate voltage. It can be seen that a large g_m can lead to a strong modulation effect, thereby yielding high photocurrent gain. Hence, the corresponding gain mechanism can be described as transconductance-dominated gain (g_m -dominated gain). The bandwidth (f) of photodetectors with g_m -dominated gain can also be approximated using the transistor model³⁶, expressed as $f \propto g_m/C_{tot}$, where C_{tot} is the total capacitance. Therefore, both the gain and bandwidth scale proportionally with transconductance (Figure 2A), highlighting the feasibility in achieving simultaneously high gain and fast response speed.

In addition to g_m -dominated gain, various low-dimensional photodetectors can magnify photocurrent signal through the photoconductive gain (G_{PC}) mechanism. Photoconductive gain is theoretically related to the lifetime ($\tau_{lifetime}$) of photocarriers and their transit time ($\tau_{transit}$),⁸⁴ i.e., $G_{PC} \propto \tau_{lifetime} / \tau_{transit}$. By introducing trap states or constructing artificial heterojunctions to extend the lifetime of photocarrier, low-dimensional photodetectors can achieve high gain.^{22,25,53,59} However, since the bandwidth is inversely proportional to photocarrier lifetime, trap-assisted gain, while boosting responsivity, inevitably imposes severe bandwidth limitations.

When considering noise characteristics, low-dimensional photodetectors based on g_m -dominated gain benefit from high bandwidth, allowing sensitivity to be assessed using high-frequency noise. In contrast, for low-dimensional photodetectors constrained by trap-assisted gain, low-frequency noise sources such as $1/f$ noise and g-r noise must be taken into account. Neglect of the bandwidth characteristics of a photodetector could lead to an underestimation of the actual noise level (Figure 2B), resulting in inaccurate evaluations of the noise-equivalent power (NEP) and specific detectivity (D^*).^{85,86}

Light power dependence

The linear dynamic range (LDR) of a photodetector is defined as the range of optical power over which the photocurrent scales linearly with incident power. This range typically extends from the minimum detectable power to

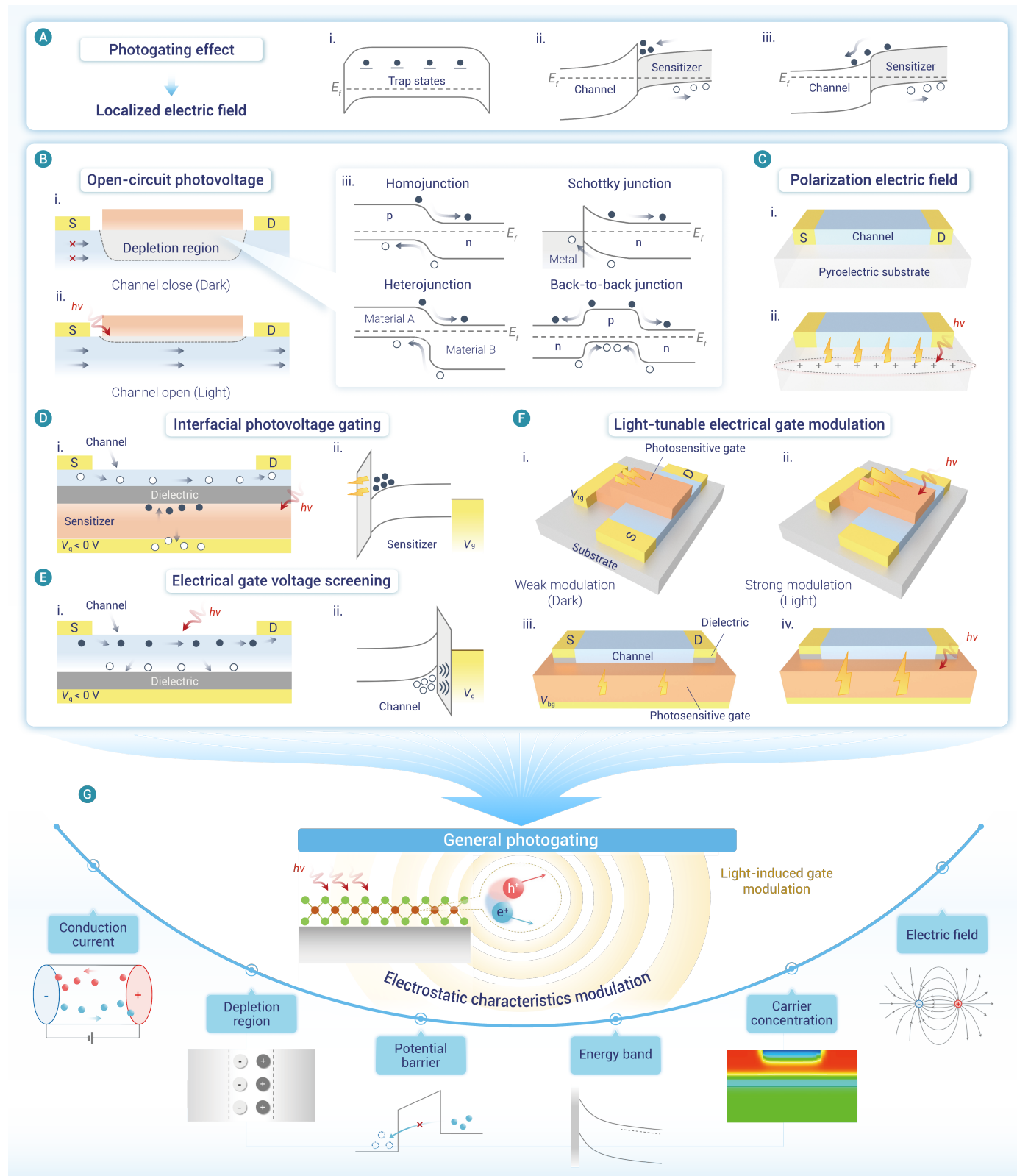


Figure 1. Illustration of the GPE (A-i) Carrier dynamics in a p-type semiconductor with electron trap states. (A-ii, A-iii) Carrier dynamic processes in heterojunctions with large and small electron barriers, respectively. (B-i, B-ii) Schematic illustration of the formation of open-circuit photovoltage. Under dark conditions, carrier transport in the channel is blocked by the depletion region. The photovoltage compresses the depletion region. (B-iii) Carrier dynamic processes in different junction configurations. (C-i, C-ii) Schematic diagrams of photodetectors composed of channel materials and pyroelectric substrates in the dark and under illumination, respectively. Upon light absorption by the pyroelectric substrate, the resulting temperature increase induces polarized surface charges (marked with "+"), which modulate the channel conductance. (D-i, D-ii) Carrier dynamics and corresponding band diagrams illustrating the process of interfacial photovoltage gating. The electrical gate drive photocarriers in the sensitizer to accumulate at the dielectric interface, generating a photovoltage that modulates the channel. (E-i, E-ii) Carrier dynamics and band diagrams illustrating the process of electrical gate voltage screening. Photocarriers generated in the channel accumulate at the interface under the attraction of the gate field, partially screening the applied gate voltage. (F) Schematic diagrams of photodetectors with top- and bottom-gate configurations. Under illumination, the resistance of the photosensitive gate decreases, allowing the gate voltage to more effectively modulate the channel conductance. Filled and open circles indicate electrons and holes, respectively. The lightning symbol denotes gate modulation, with its size qualitatively reflecting the modulation strength. S and D denote the source and drain, V_g denotes the gate voltage, and V_{tg} and V_{bg} denote the top- and bottom-gate voltages, respectively. (G) Schematic illustration showing how GPE modulates the electrostatic characteristics of low-dimensional photodetectors.

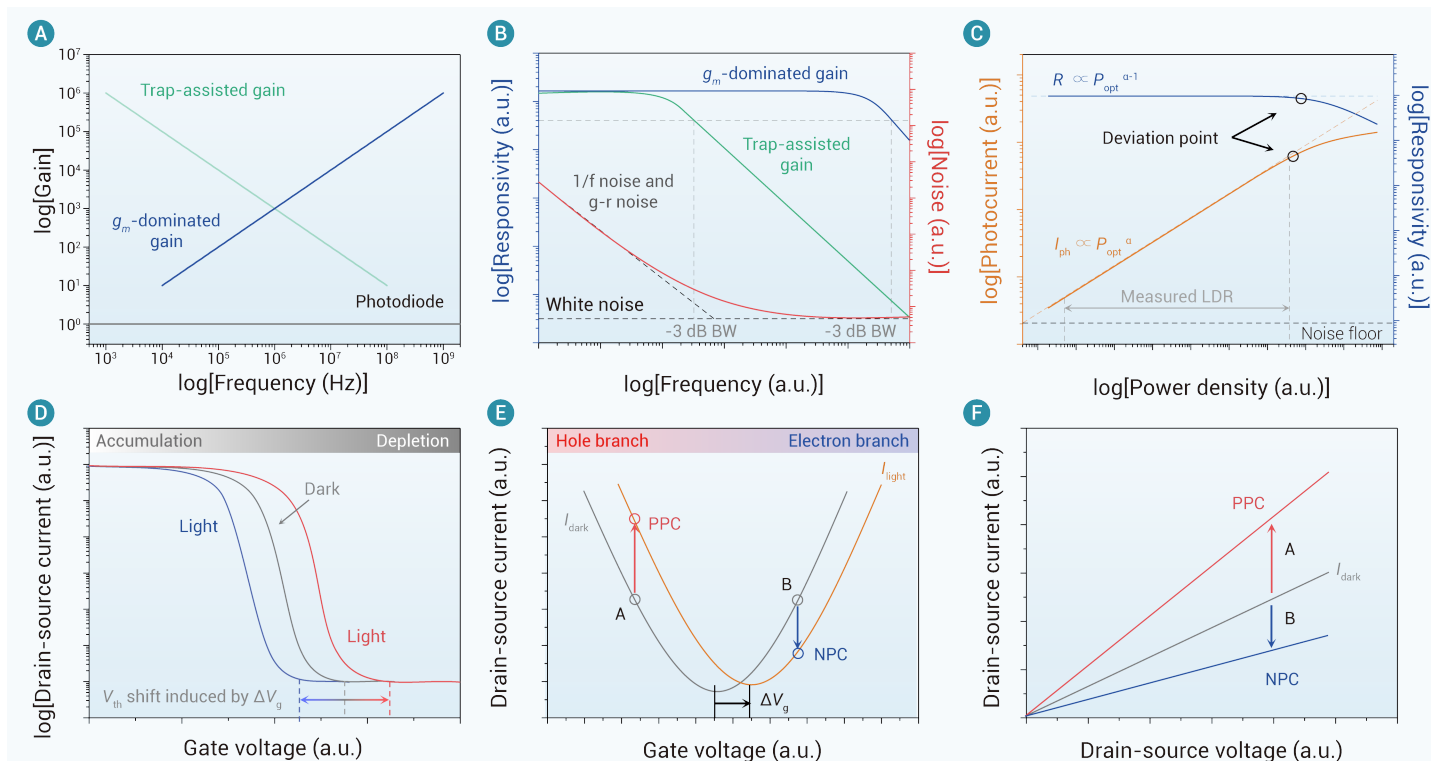


Figure 2. Characteristics of GPE-based photodetectors (A) Relationship between gain and frequency of various photodetectors. Trap-assisted gain and g_m -dominated gain belong to low-dimensional photodetectors with photoconductive gain and GPE, respectively. Photodiodes produce no gain, and their response speed is mainly related to doping profile, bias voltage and material thickness. (B) Responsivity and noise characteristics for photodetectors with different bandwidths. Green (blue) line represents the typical responsivity curve of photodetectors with low (high) bandwidth. For the responsivity-frequency analysis, the frequency-dependent responsivity $R(f)$ is normalized by the DC responsivity R_{DC} , i.e., $R(f)/R_{DC}$, to provide a benchmark for comparing g_m -dominated and trap-assisted gain mechanisms. Red line represents the typical noise characteristics. White noise includes thermal noise and shot noise. (C) Variation of photocurrent and responsivity with the light power density. (D) I_{ds} - V_g curves of unipolar devices in the dark and under illumination. Threshold voltage (V_{th}) is shifted by ΔV_g due to GPE. (E) I_{ds} - V_g curves of ambipolar devices in the dark and under illumination. (F) I_{ds} - V_{ds} curves corresponding to point A and point B in (E).

the saturation absorption limit of the material (Figure 2C). Within this regime, fitting the photocurrent (I_{ph}) versus optical power (P_{opt}) using the relation $I_{ph} \propto P_{opt}^a$ typically yields an exponent a very close to 1. According to the definition of responsivity, $R = I_{ph} / P_{opt}$, one obtains $R \propto P_{opt}^{a-1}$. Thus, when a approaches 1, the responsivity remains nearly independent of optical power.

The a values of most GPE-based photodetectors fall between 0 and 1,^{15,56-58,87-90} indicating a nonlinear relationship between photocurrent and optical power. This nonlinearity primarily arises from the complex processes of carrier generation, trapping, and recombination in semiconductors.⁹¹ In addition, a can be treated as an empirical exponent associated with trap-related weak trapping processes. When a deviates from 1, it often suggests that trap states near the band edges participate and affect the recombination dynamics.⁹² For low-dimensional photodetectors that rely on trap states to produce GPE, increasing optical power gradually fills the available trap states. Since the number of trap states is finite, even before the material reaches saturation absorption, a sufficiently high optical power may already occupy all traps. Beyond this point, further increases in optical power no longer enhance GPE but instead contribute only to free carrier generation. As a result, the growth rate of photocurrent lags behind that of optical power, leading to a nonlinear response manifested as a decrease in responsivity with increasing optical power. Nevertheless, within a certain weak optical power range, a sufficient density of trap states may sustain stable responsivity.^{21,26}

Compared with trap states, GPE-based photodetectors that exploit the photovoltaic effect to generate photovoltage in junction regions can achieve superior LDR.^{36,61} This advantage arises because the strong built-in field in semiconductor junctions provides more efficient carrier separation or extraction than a limited number of trap states. Furthermore, applying an electrical gate voltage to enhance carrier separation can facilitate photocurrent growth to keep pace with optical power, thereby improving LDR.^{93,94} It is important to note that a nonlinear relationship between photocurrent and optical power does not necessarily imply the presence of GPE.

I_{ds} - V_g shift and bi-directional photoresponse

In GPE-based photodetectors, the transfer characteristics (I_{ds} - V_g curve) often exhibit a horizontal shift under illumination (Figures 2D-E).^{2,14,15} This shift can be understood as an optical gate voltage caused by GPE, which requires an additional electrical gate bias to compensate. The direction of the shift depends on the polarity of the optical gate voltage as well as the light-induced electrical gate voltage variation. The former is related to the type of trap states or energy band alignment at the junction, while the latter is associated with the polarity of the pre-applied electrical gate bias.

For instance, in a GPE-based photodetector with dual electrical gate, if illumination enhances the depletion effect of the positive top-gate voltage (V_{tg}) on the channel, a larger negative back-gate voltage (V_{bg}) is required to turn on the channel, leading to a shift of the I_{ds} - V_{bg} curve toward more negative voltages. However, non-ideal factors such as non-uniform doping or interface defects can affect the effective strength of GPE, making the shift of the transfer characteristics deviate from the theoretical prediction.¹⁵ It is worth noting that in most cases, illumination not only induces GPE but also leads to the accumulation of free carriers in the device, which results in an overall upward shift of the transfer curve in addition to the horizontal displacement.

An important feature of this transfer curve shift is that it can give rise to bi-directional photocurrent, i.e., positive photocurrent (PPC) and negative photocurrent (NPC).^{3,19,95} In contrast, conventional thin-film photodetectors usually exhibit a fixed photocurrent direction, where illumination reduces resistance and generates only PPC. Specifically, when GPE induces a negative optical gate voltage, the I_{ds} - V_g curve shifts toward more positive voltages (Figure 2E). If the electrical gate bias sets the channel into a hole-conduction regime (point A), the negative optical gate voltage induces more holes, producing a positive photocurrent. Conversely, if the channel is biased into an electron-conduction regime (point B), the negative optical gate voltage depletes electrons, resulting in a negative photocurrent. Figure 2F presents

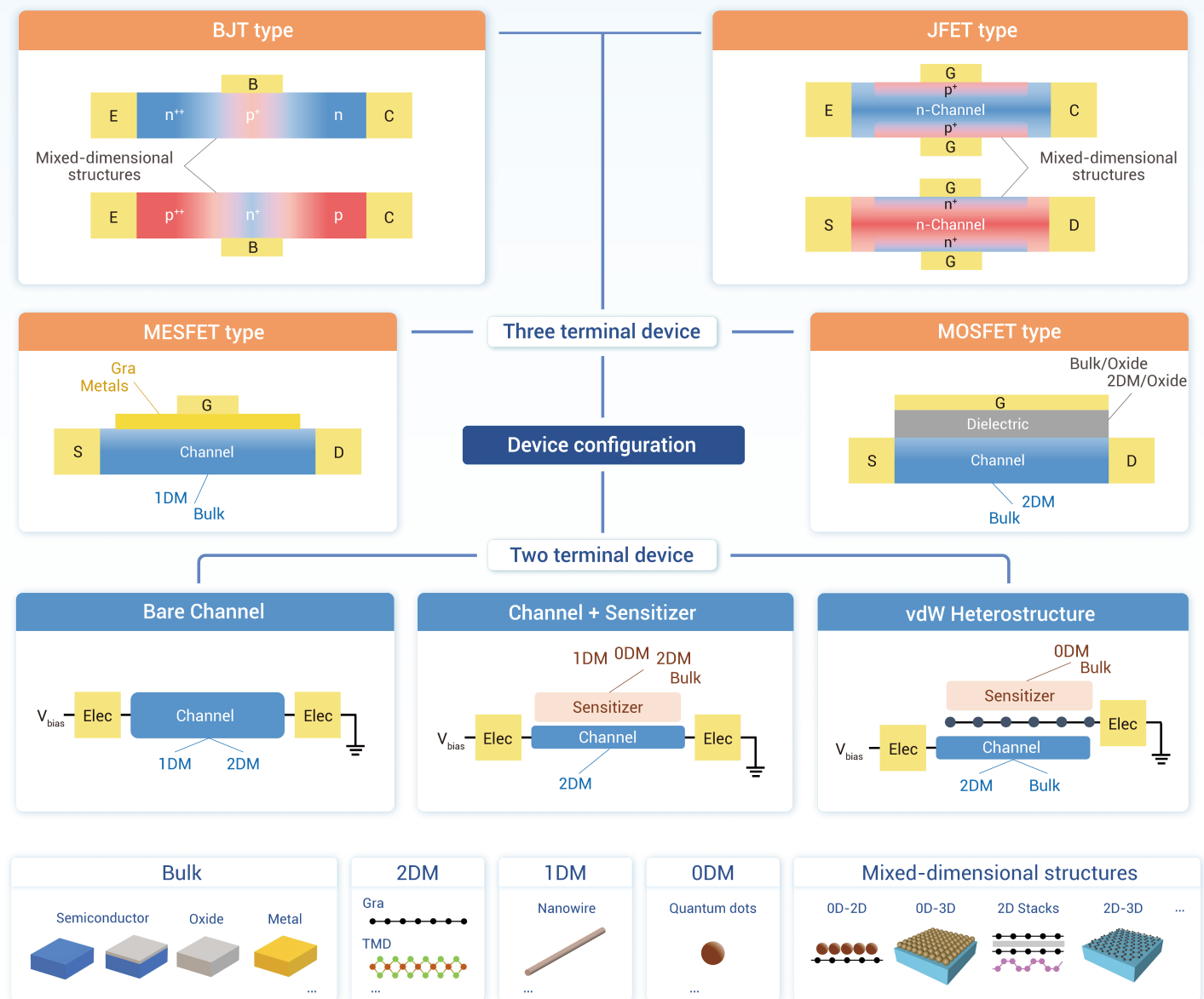


Figure 3. Main device configurations and material systems of GPE-based photodetectors.

the I_{ds} - V_{ds} curves corresponding to points A and B in Figure 2E. Although the dark current remains the same, the channel conduction type and the photocurrent polarity are completely opposite. Such bi-directional photocurrents provide direct device-level support for analog-domain weighting and differential operations, thereby underpinning functional photodetection concepts such as in-sensor computing, and enabling front-end tasks including contrast enhancement, noise suppression, and feature extraction.

Configurations of GPE-based photodetectors

Figure 3 and Supplemental Information (SI) Section 3 summarize the main device architectures for realizing GPE, which can be broadly categorized into three-terminal and two-terminal devices. These devices involve a wide range of material systems, including 3D thin films, 2D materials, 1D nanowires, and 0D quantum dots. By employing heterogeneous integration strategies to combine materials of different dimensions, mixed-dimensional structures can be constructed.^{96,97} Such designs not only exploit the unique advantages of individual materials but also allow band structure engineering, thereby enabling low-dimensional photodetectors with superior performance.

Three-terminal devices primarily include four classic transistor architectures: bipolar junction transistors (BJTs), junction field-effect transistors

(JFETs), metal-semiconductor field-effect transistors (MESFETs), and metal-oxide-semiconductor field-effect transistors (MOSFETs). BJT consists of two back-to-back p-n junctions (e.g., n-p-n or p-n-p). In addition to homojunctions, heterojunction BJTs can also be realized through mixed-dimensional material design. The three terminals of BJTs are the emitter, base, and collector. Current flows from the emitter through the base to the collector, and the collector current can be modulated by adjusting the base voltage. Similarly, in BJT-type photodetectors, a photovoltage generated at the emitter-base junction can tune the current at the collector.

Three electrodes in JFETs, MESFETs, and MOSFETs are source, drain, and gate. In JFETs, the middle channel forms a p-n junction with surrounding doped regions or other materials. Replacing the p-n junction with a metal-semiconductor Schottky junction yields a MESFET. The gate voltage modulates the depletion width of the p-n or Schottky junction, thereby controlling the source-drain current (I_{ds}) in JFETs and MESFETs. In MOSFETs, a dielectric layer separates the gate and the channel, and the gate voltage modulates both the type and concentration of channel carriers via capacitive coupling, thereby regulating I_{ds} . For JFET- and MESFET-type photodetectors, photocarriers redistribute under the built-in field of the junction, and the resulting photovoltage compresses the depletion region and expands the conducting

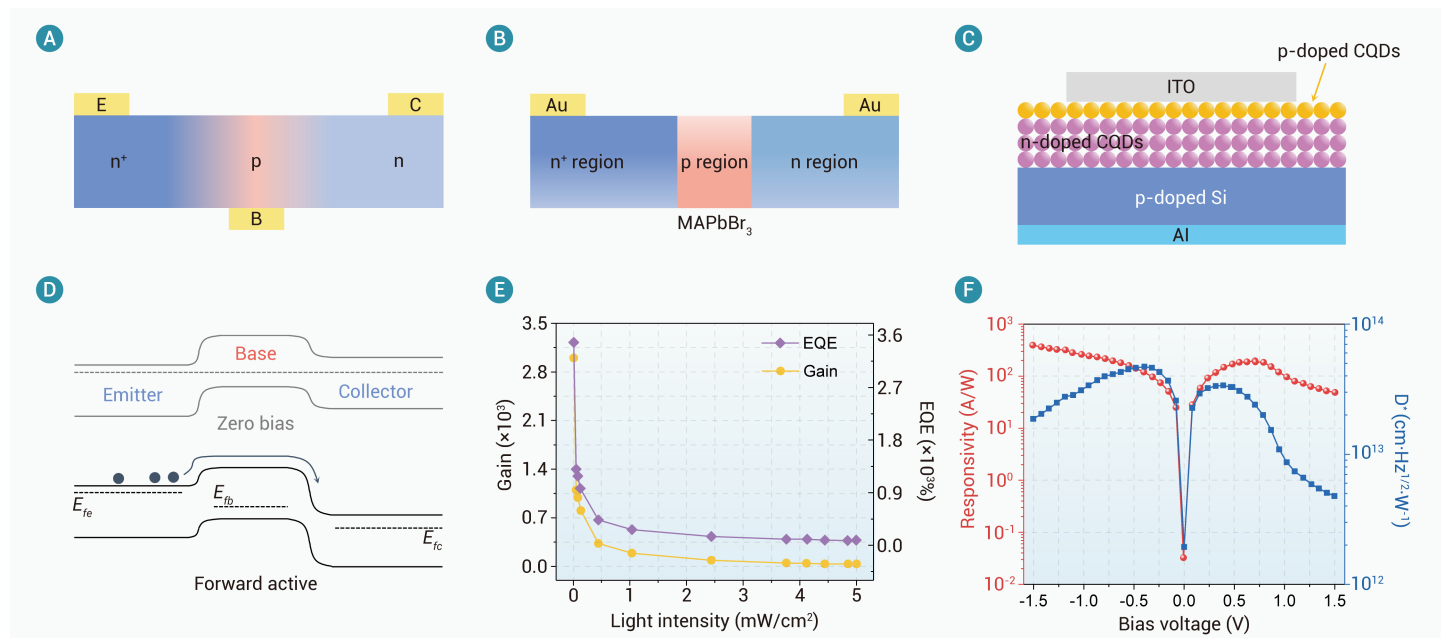


Figure 4. BJT-type photodetectors with GPE (A) Schematic diagram of a typical BJT photodetector with n⁺-p-n doping profile. E, B, and C denote the emitter, base, and collector, respectively. (B) Carrier transport diagram in a n⁺-p-n BJT photodetector under forward biased mode. (C) Schematic diagram of the MAPbBr₃ n-p-n BJT photodetector. (D) Gain and external quantum efficiency (EQE) versus the incident light intensity. (E) Schematic diagram of the PbS CQDs-Si BJT photodetector. (F) Responsivity and D^* as a function of bias voltages. Credit: reproduced with permission from ref. ¹¹³, Wiley (D); ref. ¹¹⁵, Nature (F).

channel. For MOSFET-type photodetectors, carrier accumulation at the dielectric interface induces a photovoltage that tunes channel carrier density. When the gate dielectric itself is photoactive (e.g., in JFET- or MOSFET-type photodetectors), illumination alters its conductivity, thereby affecting the electrical gate control over the channel. This process is equivalent to use light to “altering” the electrical gate voltage. Three-terminal devices also benefit from external electrical control, which enables optimization of dark current and sensitivity.^{98–100} Moreover, since the gain primarily depends on transconductance, such architectures are often explored to overcome the gain-bandwidth trade-off in traditional low-dimensional photodetectors.^{29,31,36,37} More importantly, electrical modulation also allows control over the “direction” of photocurrent, unlocking multifunctional photodetection.^{41,46–48,101–103}

For two-terminal devices, the most typical configuration is the “bare channel” structure, where the channel is usually composed of 1D or 2D materials. In these devices, trap states at the surface of 1D materials or within 2D materials capture photocarriers, leading to localized fields that modulate channel conductance. In particular, core-shell 1D nanowires can further enhance photocarrier localization.^{56,104} Incorporating ferroelectric materials to strengthen channel depletion and photocarrier localization can simultaneously optimize dark current and gain.^{20,105} The integration of 2D channels and photosensitizers yields “channel+sensitizer” structures, where the photosensitizer not only improves light absorption (compensating for the weak absorption of 2D materials), but also leverages built-in fields to promote photocarrier separation. This process can confine one type of carrier within the sensitizer, generating a localized field that modulates the channel and achieves ultrahigh gain.^{21,22} In addition, semiconductor or insulator substrates can also serve as sensitizers, providing both structural support and light absorption, thereby offering a simpler and more fabrication-friendly device layout for realizing light-induced gate modulation.^{106–109}

Another special category of two-terminal devices is based on sandwich-shaped van der Waals (vdW) heterojunctions. In these structures, graphene is sandwiched between the sensitizer and the channel. One electrode is connected to graphene, while the other is connected to the channel. Upon illumination, localized fields at the sensitizer/graphene interface shift the Fermi level of graphene, thereby modulating the Schottky barrier at the graphene/channel interface and influencing the conduction current.¹¹⁰ This architecture enables optimization of dark current, responsivity, and operating temperature, and is advantageous for sensitive infrared photodetection.^{5,111}

Recent progress of GPE-based photodetectors

In this section, previously reported representative GPE-based photodetectors are reviewed, organized by device architecture (with performance summarized in SI Section 4). The detection mechanisms of these devices involve the generation of a photovoltage (or a localized field) under illumination, or the variation of the electrical gate voltage by light. By carefully designing material combinations and device structures to harness the GPE for photocurrent generation, these photodetectors demonstrate excellent performance and diverse functionalities.

BJT-type photodetectors

In BJT photodetectors, the base-collector (B-C) junction is typically employed as the photosensitive region rather than the emitter-base (E-B) junction. This is because, in order to inject a large number of carriers from the emitter into the base under forward bias, the emitter region is usually heavily doped (Figure 4A). The strong indirect recombination in heavily doped semiconductors results in short carrier lifetimes, making the E-B junction unsuitable as a photosensitive region. When incident light excites electron-hole pairs at the B-C junction, one type of carrier is injected into the base and gradually accumulates, leading to the formation of a photovoltage. This photovoltage further forward-biases the E-B junction and drives a large electron current from the emitter, across the base, and into the collector (Figures 4B & S1A). This working mechanism is analogous to the amplification mode of electrical BJTs.

Homojunction BJT photodetectors are relatively common in various works.¹¹² For instance, by employing controlled doping technologies, an n⁺-p-n homojunction BJT photodetector based on MAPbBr₃ perovskite can be fabricated (Figure 4C).¹¹³ Under reverse bias at the B-C junction and forward bias at the E-B junction, photogenerated electrons at the B-C junction are collected by collector, while holes are injected into the base. As the hole concentration in the base increases, the resulting photovoltage further strengthens the forward bias of the E-B junction, enabling a large electron injection from the heavily doped emitter. Consequently, the device exhibits an enhanced photocurrent with a current gain factor as high as 2.9×10^3 (Figure 4D).

Heterojunction BJT photodetectors can be realized by combining distinct materials with different doping types.¹¹⁴ Figure 4E illustrates a BJT photodetector based on a PbS CQDs-Si heterojunction,¹¹⁵ in which p-type Si, n-type PbS CQDs, and p-type PbS CQDs serve as the emitter, base, and collector,

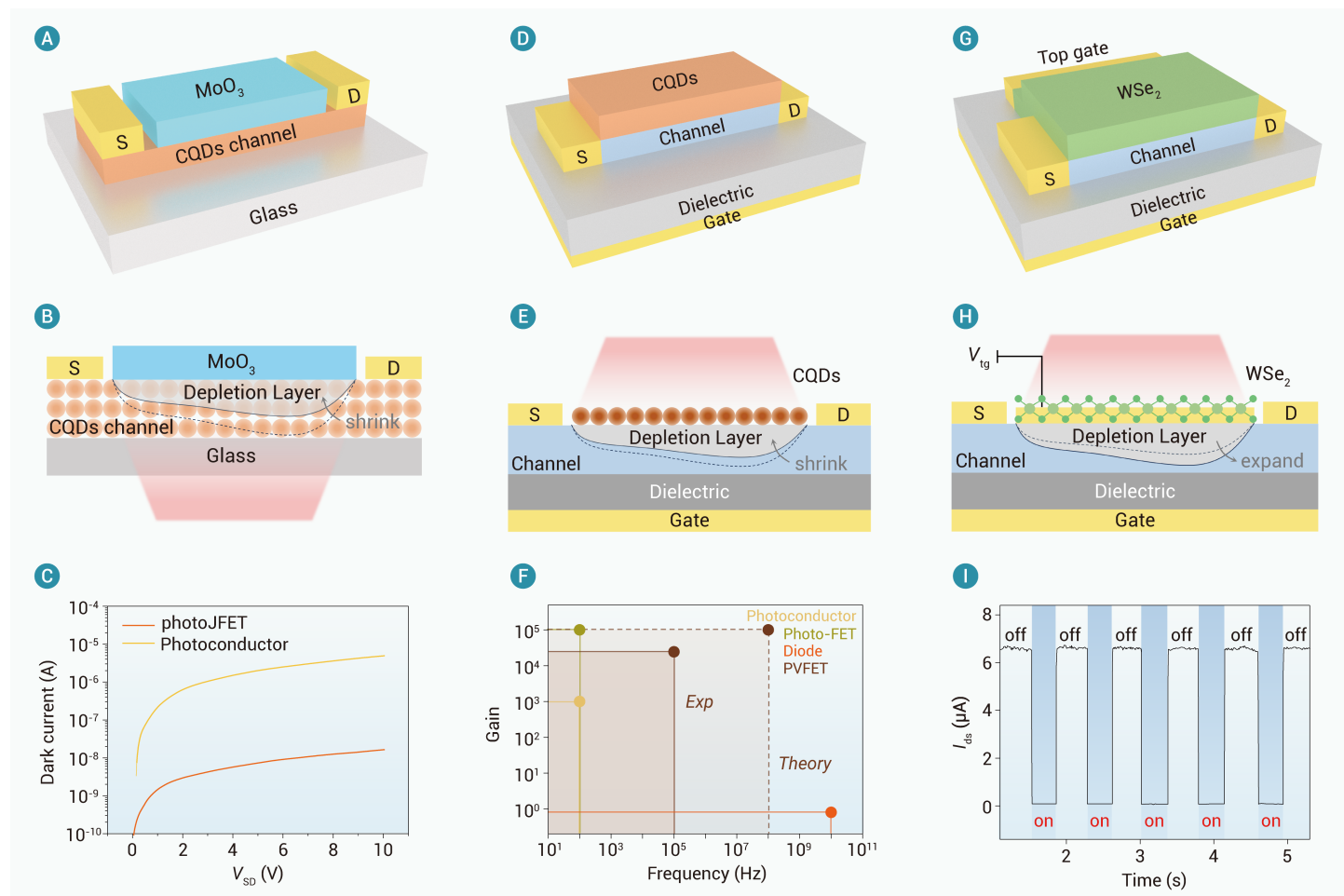


Figure 5. JFET-type photodetectors with GPE (A) Schematic diagram of the photoJFET. (B) Shrinkage of the depletion layer under illumination. (C) Quantitative comparison, in terms of dark current, between the photoJFET and a pure CQDs photoconductor. (D) Schematic diagram of the PVFET. (E) Shrinkage of the depletion layer under illumination. (F) Gain-frequency plot for diodes, photo-FETs (CQD-based), photoconductors (CQD-based) and the PVFET. (G) Schematic diagram of the LJFET. (H) Expansion of the depletion layer under illumination. (I) I-T curve of the LJFET. Credit: reproduced with permission from ref. ⁶², American Chemical Society (C); ref. ³⁶, Nature (F); ref. ³¹, Wiley (I).

respectively. The device operates under forward bias at the p-Si:n-CQDs junction and reverse bias at the n-CQDs:p-CQDs junction. When illuminated with 1550 nm light, electrons excited in the PbS CQDs are injected into the base. Due to the large conduction band offset at the Si-PbS CQDs interface, these electrons are confined within the base, forming a negative photovoltage. This negative photovoltage attracts a large number of holes from Si into the base, thereby producing current gain. In addition, the reverse-biased CQD homojunction helps maintain a low dark current ($\sim 10^{-3}$ A/cm²). As a result, the device achieves not only a high responsivity of 410 A/W but also an impressive specific detectivity of 4.73×10^{13} cm·Hz^{1/2}·W⁻¹ (Figure 4F).

JFET-type photodetector

Similar to BJT photodetectors, typical JFET photodetectors are also based on n-p-n or p-n-p structures. However, unlike BJTs, the conduction current in a JFET mainly flows through the central channel. For instance, in an n-p-n JFET photodetector, due to the depletion effect of n-p junctions, carriers mainly transport through the non-depleted region in the center of the p channel. When illumination generates a photovoltage at the p-n junction, the photovoltage compresses the depletion width and expands the conductive channel, thereby enhancing I_{ds} . Theoretical modeling has shown that this mechanism can lead to high gain in Si homojunction JFET photodetectors.⁷¹ In addition, single p-n homojunctions or heterojunctions can also be utilized for JFET photodetector design (Figure S1B). For example, a heterojunction JFET photodetector composed of an Si channel and a Ge infrared-sensitive gate exhibits a similar working mechanism.^{51,116}

Low-dimensional materials are suitable for channel design in JFET photodetectors. In 2015, a photojunction field-effect transistor with a PbS

CQDs channel was reported.⁶² A layer of MoO₃ was deposited on top of the PbS CQDs channel, forming a heterojunction that depleted free carriers in the channel (Figure 5A). Upon light absorption by PbS CQDs, the built-in field of the heterojunction separated photogenerated electron-hole pairs and produced a photovoltage, leading to depletion layer shrinkage (Figure 5B). The device achieved a gain of ~ 10 and a response time of 10 μ s. Furthermore, thinning the PbS CQD channel can enhance depletion effect. As a result, the dark current is reduced to a level significantly lower than that of conventional PbS CQD photoconductors (Figure 5C).

Integrating broadband infrared-sensitive materials with Si provides a strategy to overcome the intrinsic spectral limitations of Si.⁵⁰ In 2017, a vertical PbS CQDs-Si heterojunction photovoltage field-effect transistor (PVFET) was reported,³⁶ where Si served as the channel and PbS CQDs as the infrared-sensitive layer (Figure 5D). Under infrared illumination, interfacial photovoltage weakened the built-in field at the PbS CQDs/Si junction, narrowing the depletion region (Figure 5E). Since both the gain and bandwidth of the PVFET are proportional to its transconductance, it simultaneously achieved a gain of 10^4 and a bandwidth of 100 kHz. Compared with conventional CQD-based photoconductors, photo-FETs, and photodiodes, the PVFET demonstrated a much higher gain-bandwidth product (Figure 5F).

In addition to photovoltage, incorporating photosensitive gate dielectrics enables light to alter the electrical gate modulation effect.⁴⁹ In 2020, a device named the light-driven junction field-effect transistor (LJFET) was reported.³¹ The LJFET employs ZnO as the channel and WSe₂ as the photosensitive gate dielectric, which is connected to the electrical top gate (Figure 5G). In the dark, the high resistance of WSe₂ hinders effective top-gate modulation on the ZnO channel, whereas under illumination, the increased conductivity of

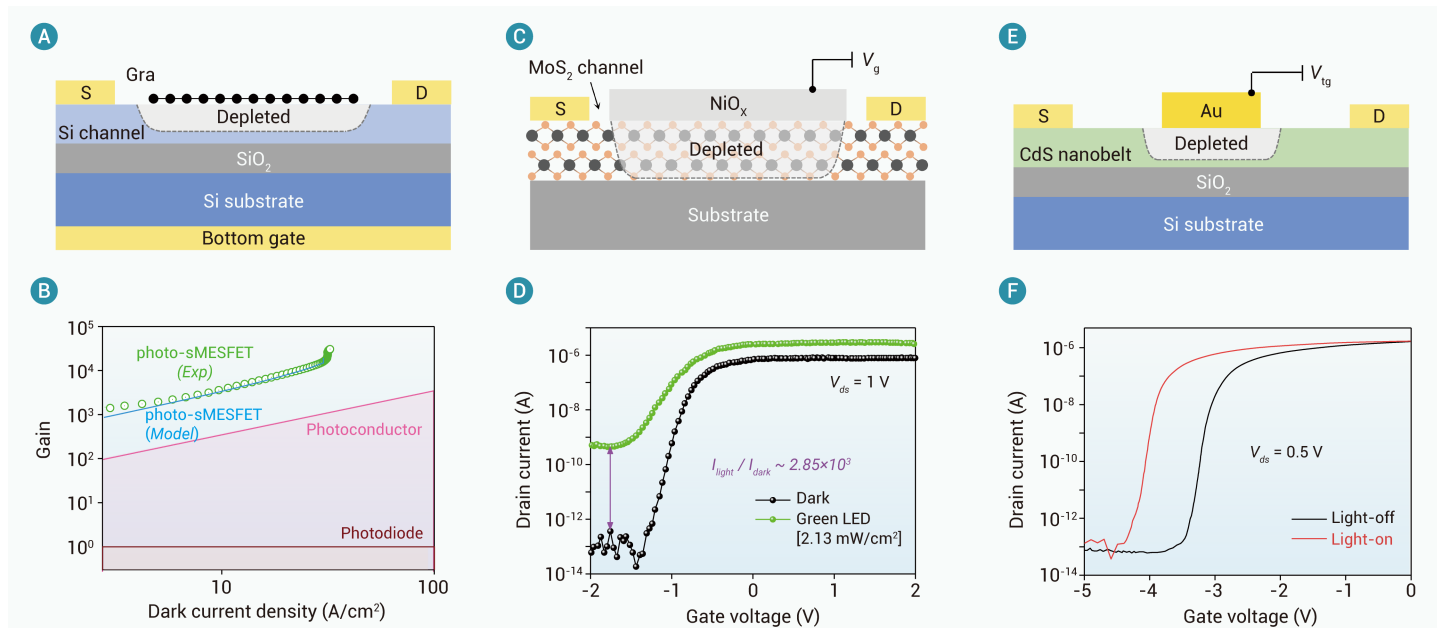


Figure 6. MESFET-type photodetectors with GPE (A) Schematic diagram of the photo-sMESFET. (B) Relationship between gain and dark current for photodiode, photoconductor, and the photo-sMESFET. (C) Schematic diagram of the NiO_x-MoS₂ MESFET photodetector. (D) Photoinduced transfer curves of the NiO_x-MoS₂ MESFET photodetector. (E) Schematic diagram of the CdS nanobelt MESFET photodetector. (F) Transfer characteristic curves of the CdS nanobelt MESFET photodetector. Credit: reproduced with permission from ref. ⁶¹, Wiley (B); ref. ¹²¹, American Chemical Society (D); ref. ¹²², American Chemical Society (F).

WSe₂ enhances gate control. Since the top gate reverse biases the WSe₂-ZnO junction, depleting the ZnO channel (Figure 5H), the LJFET produces a negative photocurrent (Figure 5I). A notable advantage of the LJFET design is that its gain and response time are independently determined by field-effect modulation and transistor switching speed, respectively, thereby achieving both a high gain of 10⁴ and a fast response speed of 10 μs.

MESFET-type photodetector

The operating mechanism of MESFET photodetectors is similar to that of JFET photodetectors, in which the channel can be depleted by the built-in field of the junction. Under illumination, the depletion region is compressed, allowing more carriers to traverse the channel (Figure S1C). A representative example is the GaAs-based MESFET photodetector,⁶³ which simultaneously achieves high gain and fast response,^{117,118} including a bandwidth approaching the GHz regime and a responsivity of ~10³ A/W. The fast response originates from the high carrier mobility of GaAs, particularly through band structure engineering that introduces a two-dimensional electron gas to further enhance carrier transport.¹¹⁹ The high responsivity, on the other hand, is associated with photoconductive gain and photovoltage modulation.⁶³

Because metallic films reflect incident light, the metal gate cannot fully cover the channel surface if sufficient optical absorption by the channel material is to be ensured. Nevertheless, part of the channel inevitably remains shadowed by the metal gate. Graphene, as a zero-bandgap semimetallic 2D material, not only forms Schottky junctions with semiconductors but also provides high optical transmittance.¹²⁰ As a result, graphene has become an attractive candidate for the gate electrode of MESFET photodetectors. As illustrated in Figure 6A, a photo-driven semimetal-semiconductor field-effect transistor (photo-sMESFET) employs a graphene-Si Schottky junction to deplete the channel, thereby suppressing dark current.⁶¹ Moreover, owing to the GPE-induced photocurrent gain, this device achieves higher gain than conventional photoconductors and photodiodes under the same dark current conditions (Figure 6B).

Compared with Si thin-film channels, 2D material channels are more susceptible to depletion by the metal gate as well as modulation by a gate bias. Figure 6C presents a MESFET photodetector with a MoS₂ channel, in which a semitransparent conductive oxide (NiO_x) forms a Schottky junction with MoS₂.¹²¹ Notably, the high-quality vdW interface between NiO_x and MoS₂ prevents contamination, thereby preserving intrinsic high mobility of MoS₂. In photodetection measurements, the device exhibits a high on/off ratio of

2.85×10³ (Figure 6D). Further reducing the physical dimensions of the channel, a MESFET photodetector employing 1D CdS nanobelts not only achieves a more efficient optical gate voltage modulation but also substantially suppresses dark current (Figure 6E).¹²² As shown in Figure 6F, the photoinduced localized field shifts the transfer curve toward negative gate voltages. With an appropriate gate bias, this device attains an ultrahigh on/off ratio of 2.7×10⁶.

MOSFET-type photodetectors

In MOSFET photodetectors, the blocking effect of the oxide layer on photo-carriers facilitates the formation of a photovoltage, thereby modulating the channel conductance (Figure S1D). A typical graphene-based MOSFET photodetector is illustrated in Figure 7A, where graphene serves as the channel, Si acts as the photosensitive layer. The photoresponse of this device originates from the modulation effect of the Si/SiO₂ interfacial photovoltage on graphene.³⁸ Specifically, the built-in field induced by interface states attracts photogenerated holes and causes them to accumulate near SiO₂ (Figure 7B). The positive photovoltage induced by these holes shifts the transfer curve of the device toward negative gate voltages (Figure 7C). Due to the susceptibility of graphene to external modulation, the photovoltage can alter its Fermi level, thereby generating a photocurrent. This device achieved a responsivity as high as 10⁵ A/W and a response time of 1.8 μs.³⁷ Furthermore, by applying a pulsed gate voltage to Si to form a deep depletion well for photocarrier accumulation, the photovoltage can be enhanced. Subsequently, the photovoltage modulation effect on graphene enables the readout of charges stored in the potential well. This process integrates in situ signal readout from complementary metal oxide semiconductor (CMOS) sensors with the charge integration feature of charge-coupled device (CCD) technology, offering a promising route toward sensitive infrared photodetection.⁷⁵

In graphene MOSFETs with an ultrathin oxide layer (Figure 7D), the competitive effect between the oxide capacitance and the Si depletion capacitance gives rise to a new phenomenon.^{37,54} As shown in Figure 7E, under dark condition, the total capacitance of the device is dominated by the depletion capacitance. In this case, the gate voltage primarily modulates the depletion width rather than tuning graphene, leading to only a slight increase in its Fermi level. In contrast, under illumination, the depletion region is compressed, and the total capacitance becomes dominated by the oxide

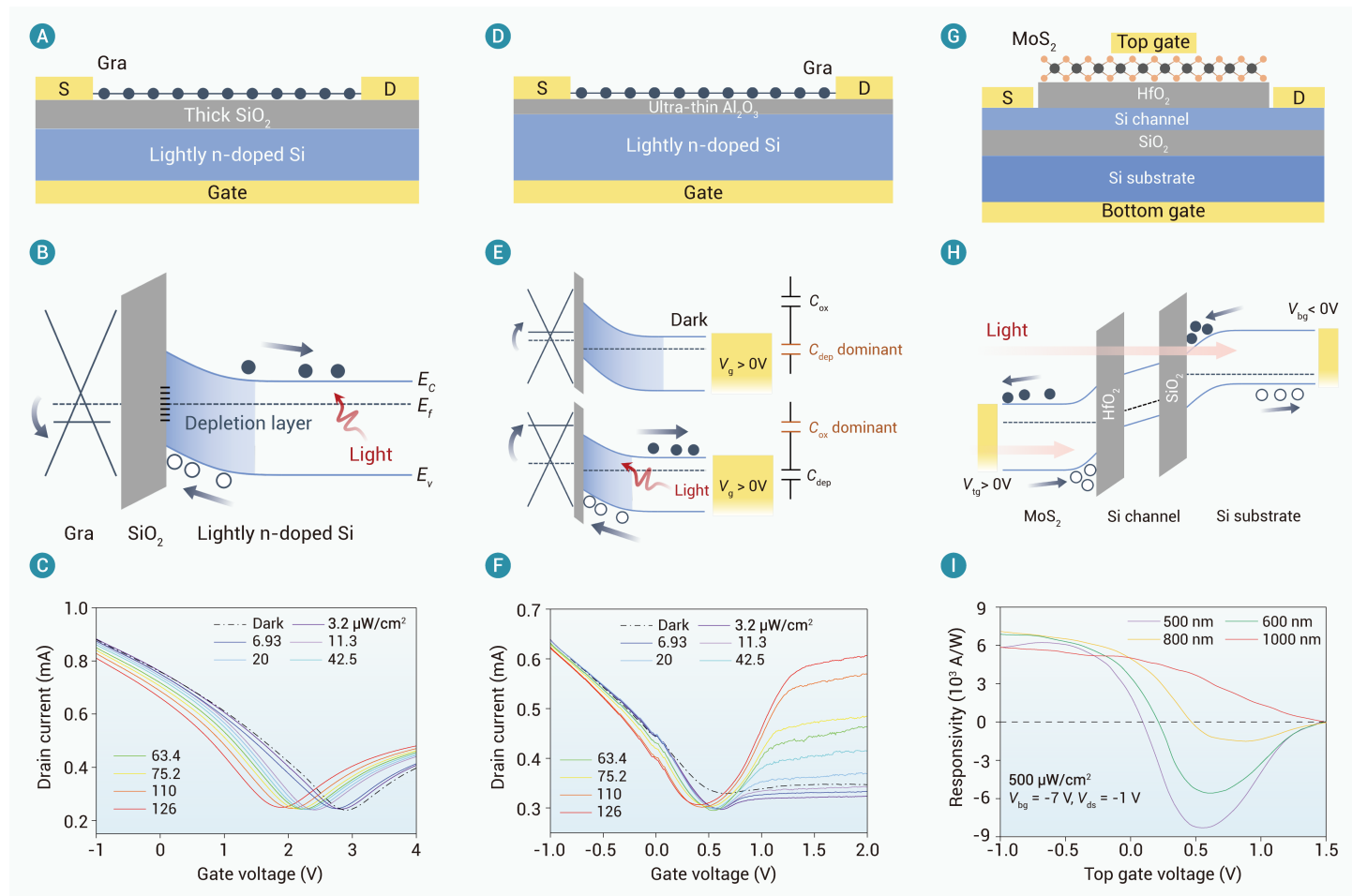


Figure 7. MOSFET-type photodetectors with GPE (A) Schematic diagram of the graphene-based MOSFET photodetector with a thick oxide layer. (B) Energy band diagram of the lightly n-doped silicon/SiO₂ interface with interfacial states. (C) Transfer characteristic curves of the device under varying light power. (D) Schematic diagram of the graphene-based MOSFET photodetector with an ultra-thin oxide layer. (E) Energy band diagram of the graphene/ultra-thin Al₂O₃/Si hybrid structure in the dark and under illumination. (F) Transfer characteristic curves of the device under different light intensities. (G) Schematic diagram of the MOSFET photodetector based on the MoS₂/HfO₂/silicon-on-insulator hybrid structure. (H) Energy band diagrams along the vertical direction from MoS₂ to the Si substrate when $V_{tg} > 0$ V and $V_{bg} < 0$ V. (I) Relationship between responsivity and V_{tg} . Credit: reproduced with permission from ref. ³⁷, American Chemical Society (C, F); ref. ⁴⁰, Wiley (I).

capacitance, enabling the gate voltage to modulate graphene. Thus, illumination can be considered to enhance the electrical gating capability over graphene, resulting in a transition of the transfer characteristics from unipolar to bipolar (Figure 7F). This polarity transition gives rise to a strong photocurrent. Moreover, the acceleration of photocarriers by the gate voltage, along with the leakage pathway provided by tunneling current through the ultrathin oxide, enables fast response and yields a gain-bandwidth production up to 9.14×10^{10} Hz.

A dual-gate MOSFET photodetector design allows the exploitation of GPE interactions induced by different photosensitizers, thereby endowing the device with functionalities.⁴⁰ As shown in Figure 7G, the photosensitive layers above and below an ultrathin Si channel are MoS₂ and Si substrate, respectively. When a positive V_{tg} is applied, photogenerated holes in MoS₂ accumulate near the oxide; conversely, when a negative V_{bg} is applied, photogenerated electrons in the Si substrate migrate toward the oxide (Figure 7H). The two oppositely polarized photovoltages exert competing modulation effects on the Si channel. By tuning the V_{tg} , the GPE induced by MoS₂ can be enhanced or suppressed, causing the responsivity to decrease from a positive value to zero and then transition to a negative value. Notably, due to the distinct spectral responses of MoS₂ and the Si substrate, the V_{tg} corresponding to 0 A/W shifts with the incident wavelength (Figure 7I). Based on the magnitude of this voltage shift, the incident light wavelength can be deduced. In addition, under similar visible-near-infrared dual-band operating schemes, incorporating a floating-gate design can further regulate the photoresponse state and enable wavelength-selective response.¹²³

Two-terminal GPE-based photodetectors

In two-terminal photodetectors, GPE can lead to an additional optical gate voltage, playing a crucial role in achieving high-performance photodetection. For "bare channel" devices using purely 2D materials such as MoS₂, In₂Se₃, and bP as channels,^{57,58,100,124} responsivity can sometimes reach several hundred to several thousand A/W. Transfer characteristics and time-dependent photocurrent analyses confirm that GPE, arising from trap-assisted capture of photocarriers, makes a positive contribution to high gain.⁴³ Moreover, substrate geometric engineering that tailors the potential distribution in a 2D channel can enhance light-induced gate modulation, thereby improving device responsivity.¹²⁵ The surface states of 1D nanowires can also capture photocarriers, forming localized fields that modulate channel conductance.²⁵ A 2020 study proposed a photocurrent gain model for Si nanowire photodetectors (Figure 8A).¹²⁶ In these Si nanowires, surface states induced by micro/nano-fabrication and molecular adsorption give rise to depletion regions. Under illumination, a photovoltage (V_{ph}) is generated within the depletion region, compressing its width and allowing more carriers to pass through the nanowire. Based on this mechanism, the Si nanowire can be modeled as a combination of a photodiode and a resistor (Figure 8B), and by applying the open-circuit voltage equation together with Ohm's law, explicit gain equations can be derived. As shown in Figure 8C, this model fits the experimental gain characteristics well.

For "channel+sensitizer" structures, a 2017 study reported a pyroelectric bolometer based on a graphene-LiNbO₃ hybrid structure (Figure 8D), combining the high carrier mobility of graphene with the infrared absorption of

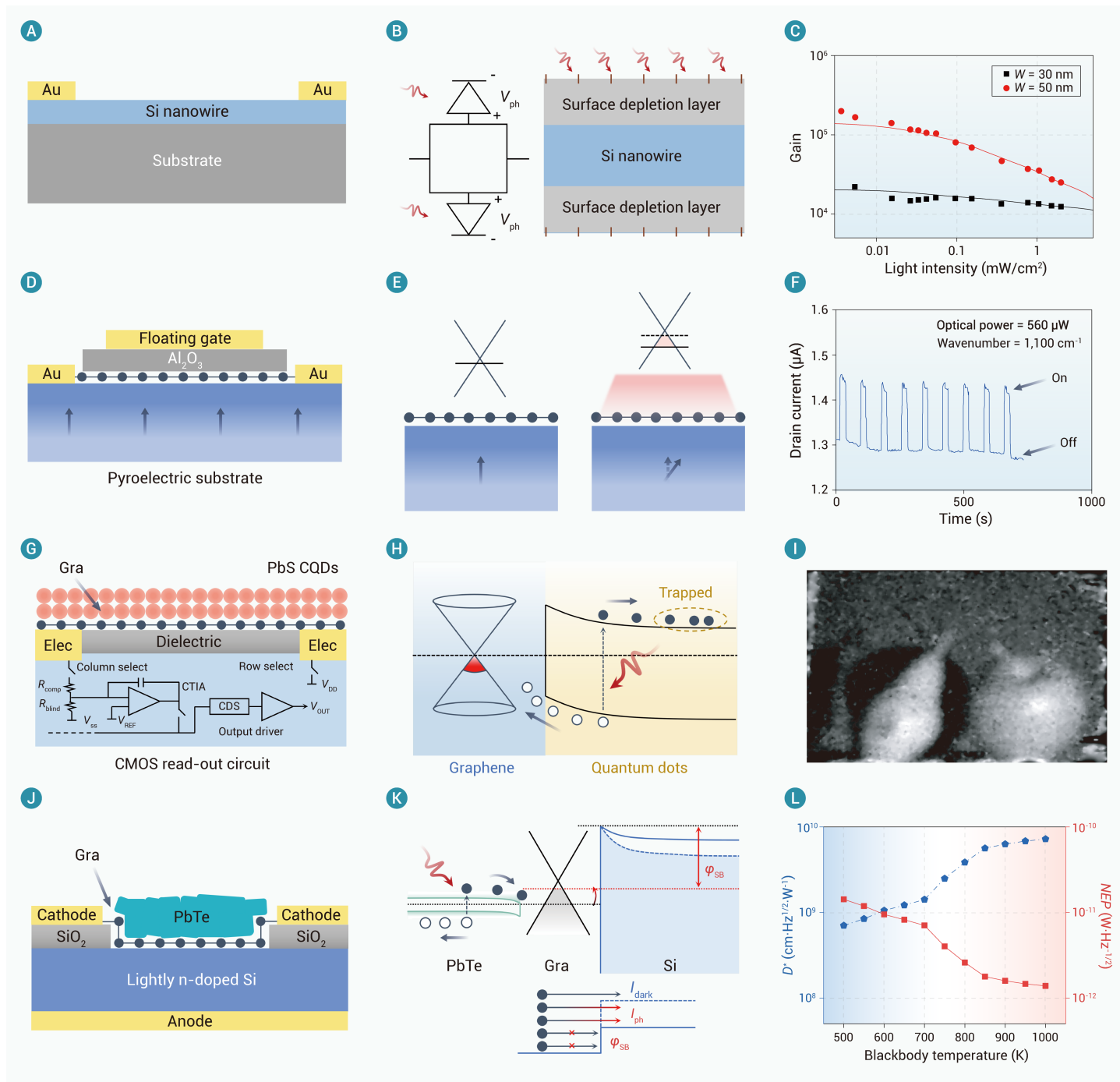


Figure 8. Two-terminal GPE-based devices (A) Structure and (B) equivalent device model diagrams of the Si nanowire photodetector. (C) Gain as a function of light illumination intensity. Solid lines are fitting curves. (D) Schematic diagram of the graphene-LiNbO₃ pyroelectric bolometer. (E) Graphene Fermi level variation induced by pyroelectric effect under infrared illumination. (F) Response at 1,100 cm⁻¹ (~9 μm) over several ON/OFF cycles induced by a manual shutter. (G) Side view of the PbS CQDs-graphene imaging sensor and the underlying read-out circuit. (H) Energy band diagram of the PbS CQDs-graphene interface. (I) Photoresponse versus power measured from twilight (~10⁻⁶ W·cm⁻²) down to starlight (10⁻¹⁰–10⁻⁹ W·cm⁻²) conditions. (J) Structure and (K) working mechanism diagrams of the PbTe-graphene-Si photodetector. (L) D* and NEP of this device under different blackbody temperatures. Credit: reproduced with permission from ref. ¹²⁶, American Chemical Society (C); ref. ³³, Nature (F); ref. ¹²⁷, Nature (I); ref. ⁵, Cell (L).

LiNbO₃.³³ Upon infrared illumination, LiNbO₃ undergoes a temperature rise, leading to changes in its polarization direction and surface charge density. This process generates a potential difference that can be regarded as a photovoltage. By designing floating-gate patterns to enhance the photovoltage, the Fermi level of graphene can be modulated (Figure 8E), thereby improving photocurrent. Experiments demonstrated that this device could detect 9 μm infrared light (Figure 8F) and human body radiation at room temperature. Unlike conventional pyroelectric detectors, this mechanism enables direct-current-mode (DC-mode) operation without the need for chopping.³⁴ Further optimization was achieved by introducing an ultrathin Al₂O₃ layer at the graphene-LiNbO₃ interface to strengthen the pyroelectric

photovoltage.³⁵

The PbS CQDs-graphene photodetector is another representative “channel+sensitizer” device. It not only exhibits ultrahigh gain but has also been extended to CMOS-compatible infrared image sensors (Figure 8G). This device relies on the separation of photocarriers at the PbS CQDs-graphene interface: holes are injected into graphene, while electrons remain confined in PbS CQDs, generating a localized field that modulates graphene (Figure 8H).²¹ This mechanism yields a responsivity as high as ~10⁷ A/W. Owing to the high-performance infrared photodetection, graphene-PbS CQDs image sensors are capable of capturing infrared images of objects (Figure 8I).¹²⁷

The modulation of graphene Fermi level provides an approach to control-

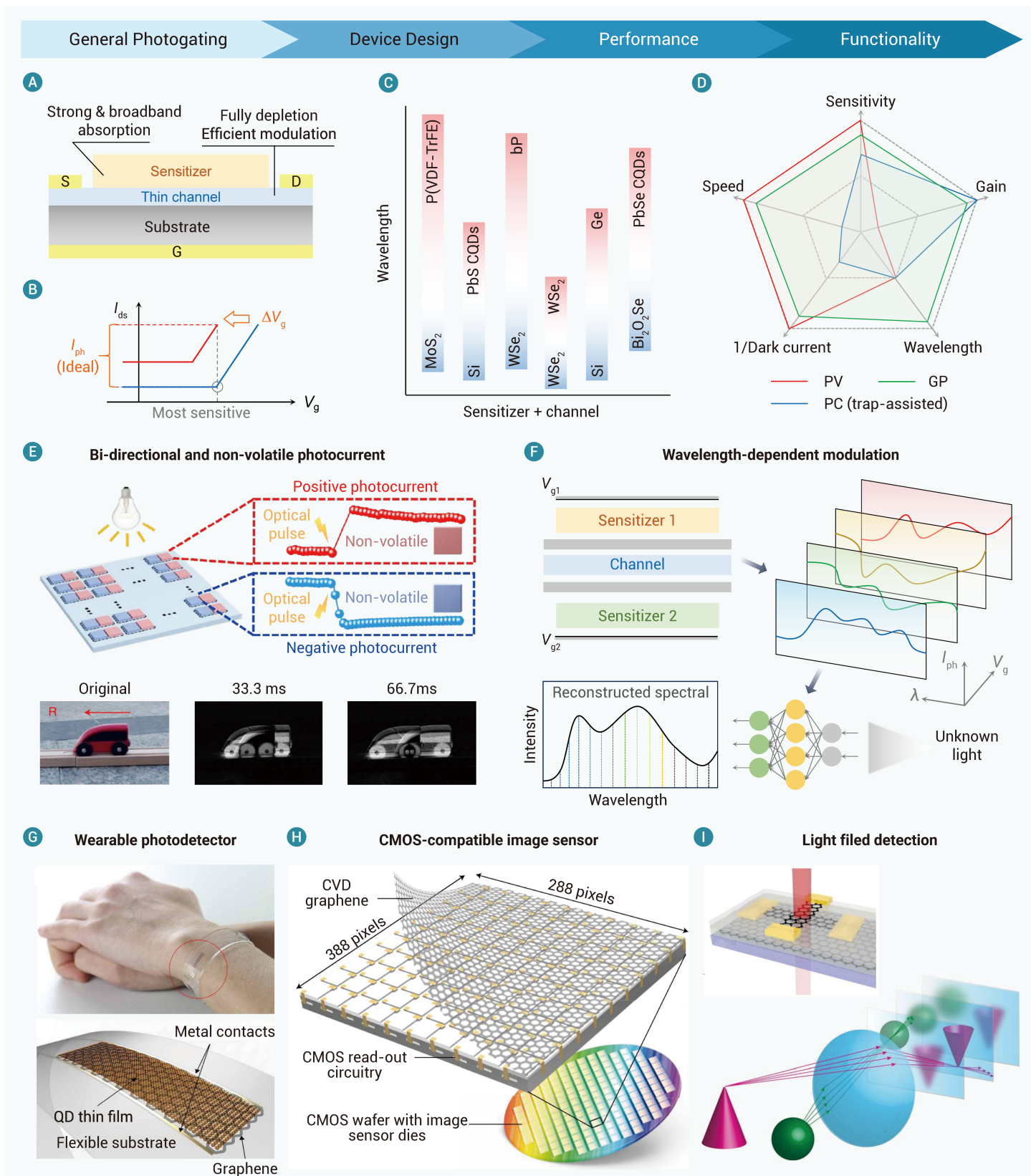


Figure 9. Perspectives for photodetectors with GPE. (A) Typical configuration of a hybrid structure photodetector based on channel material and sensitizer. The bandgap of the sensitizer is generally smaller than that of the thin channel. (B) Ideal transfer characteristic curves of the device in (A) in the dark and under illumination. ΔV_g is produced by GPE. (C) Response wavelength of hybrid structure photodetector based on different channel materials and sensitizers. (D) Performance comparison of photodiodes (PV), photoconductors (PC) with trap-assisted gain, and GPE-based photodetectors with g_m -assisted gain. Photodiodes possess low dark current, high sensitivity and fast response speed, but produce no gain. Photoconductors with trap-assisted gain generally achieve high gain at the cost of high dark current and slow response speed. Compared to photodiodes and photoconductors based on a single photosensitive material, GPE-based photodetectors exhibit a wider spectral response range. (E) Bi-directional and non-volatile photocurrent enabled by GPE and its application in motion detection. (F) Device spectral response modulation enabled by electrically modulating GPE and its possible application in spectral reconstruction. (G, H) Wearable photodetector and CMOS-compatible image sensor based on PbS CQDs-graphene hybrid structure photodetector, respectively. (I) Double layer graphene photodetector enables light field detection. GPE brings considerable photoresponse in devices presented in (G-I), which is crucial for efficient photodetection. Credit: reproduced with permission from ref. ³⁹, Nature (E); ref. ¹³⁴, AAAS (G); ref. ¹²⁷, Nature (H); ref. ¹³⁷, Nature (I).

ling the Schottky barrier at graphene-semiconductor interfaces.¹²⁸ In 2024, a photodetector based on a PbTe-graphene-Si sandwich-shaped vdW heterostructure was reported (Figure 8J).⁵ In this device, the PbTe-graphene junction separates electron-hole pairs generated in PbTe under infrared illumination: electrons are injected into graphene while holes remain localized in PbTe. The combined effect of electron injection and localized holes shifts the Fermi level of graphene upward, thereby lowering the Schottky barrier at the graphene-Si interface and enabling a photocurrent (Figure 8K). This mechanism allows the device to suppress dark current using a large Schottky barrier, while detecting infrared photons with energies below the Schottky barrier. Experimental results showed that the device responded to blackbody radiation at room temperature (Figure 8L), with a D^* of $7.2 \times 10^9 \text{ cm}^2 \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1}$. In addition, other novel structures, such as PbS CQDs-graphene-TiO₂-Au¹¹¹ and graphene-MoS₂-graphene,¹¹⁰ also exploit light-induced interface barrier modulation to achieve sensitive photodetection.

Perspective

With the deepening understanding of GPE, device design can be more targeted to achieve further enhanced performance and expanded functionalities. Figure 9A illustrates a representative hybrid photodetector design that leverages GPE, consisting of a channel material coupled with a photosensitizer. Typically, the photosensitizer is required to exhibit strong and broadband light absorption, while the channel material should be sufficiently thin to ensure full depletion and effective modulation by the light-induced gate field.¹²⁹ By applying an appropriate operating voltage, such devices can suppress dark current while generating large photocurrents via GPE-induced transfer curve shifts (Figure 9B), which is crucial for achieving high sensitivity. Compared with photoconductive detectors with normally open channels, the concurrent dark-current suppression and photoresponse enhancement enabled by GPE-based operation can improve the signal-to-noise ratio under appropriate conditions. Moreover, this mechanism allows fast response speed since the gain does not rely on the long lifetime of photocarriers.^{15,36} The combination of channel and photosensitizer also enables spectral superposition, thereby broadening the spectral response range of the device (Figure 9C). Consequently, hybrid structure photodetectors based on GPE hold promise for optimization of multiple performance metrics (Figure 9D).

In terms of functionality, GPE not only enables bi-directional photocurrents, but also facilitates nonvolatile characteristics through tailored energy bands for carrier storage. Specifically, pre-stored interfacial electrons or holes can be erased by light, while the remaining carriers modulate the channel conductance, giving rise to a persistent photocurrent. Memory states can be re-established by applying pulsed gate voltages to trap carriers at the interface. Such features are appealing for the development of intelligent photodetectors with motion perception capabilities (Figure 9E).^{39,130} Furthermore, GPE-enabled bi-directional photocurrents can be harnessed for visual information preprocessing^{46,101} and various optoelectronic logic operations within a single unit.⁴⁸ By rational device design, GPE can also be tailored to modulate the spectral response of photodetectors.⁴⁰ For instance, incorporating two photosensitizers together with a dual-gate architecture enables control over GPE via both the incident wavelength and gate bias. The GPE generated by the two photosensitizers can synergistically modulate channel conductance, thereby reshaping the spectral response curve and enabling spectral information encoding. Based on the constructed hyperspectral response database of the device and reconstruction algorithms,¹³¹⁻¹³³ the incident spectrum can be recovered (Figure 9F).

Low-dimensional photodetectors also offer opportunities in applications such as wearable optoelectronics^{134,135} (Figure 9G) and CMOS-compatible image sensors (Figure 9H).¹²⁷ These advantages stem from the intrinsic mechanical flexibility of low-dimensional materials and their ease of integration with diverse material platforms.¹³⁶ In addition, their high optical transmittance allows the realization of "transparent" low-dimensional photodetectors. By vertically stacking several transparent devices along the optical path, advanced systems such as ranging and light-field imaging can be constructed (Figure 9I).¹³⁷ Note that, GPE plays a vital role by ensuring that even under limited photon utilization, the devices can produce significant photocurrent signals and fulfill the desired functionalities.

CONCLUSION

This review summarizes the phenomena of light-induced gate modulation in low-dimensional photodetectors and proposes GPE as a unifying framework that integrates and extends diverse related strategies, thereby broadening the traditional concept of photogating. The performance characteristics and representative device architectures of GPE-based photodetectors are analyzed, and recent advances in this field are reviewed. By viewing diverse devices through the common lens of light-induced gate modulation, the GPE framework also provides a consistent language to compare mechanisms across platforms and helps translate previously scattered observations into transferable design guidelines. Current studies demonstrate that GPE offers advantages for achieving high-performance photodetection, particularly in overcoming the gain-bandwidth trade-off in low-dimensional photodetectors, realizing ultrahigh sensitivity, and enabling uncooled broadband infrared detection. Moreover, GPE endows low-dimensional photodetectors with reconfigurable bi-directional photoresponse and shows great promise for in-sensor visual signal preprocessing, motion recognition, and optoelectronic logic operations.

Despite these encouraging advances in performance and functionality, the practical deployment of GPE-based devices still faces challenges in scalability, device uniformity, and long-term stability (SI Section 5). Encouragingly, continued progress in wafer-scale growth of low-dimensional optoelectronic materials, high-quality array fabrication, and large-area heterogeneous integration is helping to lower these barriers. With further advances along these directions, GPE is expected to support the development of high-performance and multifunctional low-dimensional photodetectors and to inspire innovation in key components of next-generation optoelectronic systems.

REFERENCES

- Koppens F. H., Mueller T., Avouris P., et al. (2014). Photodetectors based on graphene, other two-dimensional materials and hybrid systems. *Nat. Nanotech.* **9**:780–793. DOI:10.1038/nnano.2014.215
- Buscema M., Island J. O., Groenendijk D. J., et al. (2015). Photocurrent generation with two-dimensional van der Waals semiconductors. *Chem. Rev.* **44**:3691–3718. DOI:10.1039/c5cs00106d
- Long M., Wang P., Fang H., et al. (2018). Progress, challenges, and opportunities for 2D material based photodetectors. *Adv. Funct. Mater.* **29**:1803807. DOI:10.1002/adfm.201803807
- Chen Y., Wang Y., Wang Z., et al. (2021). Unipolar barrier photodetectors based on van der Waals heterostructures. *Nat. Electron.* **4**:357–363. DOI:10.1038/s41928-021-00586-w
- Fu J., Guo Z., Nie C., et al. (2024). Schottky infrared detectors with optically tunable barriers beyond the internal photoemission limit. *The Innovation* **5**:100600. DOI:10.1016/j.xinn.2024.100600
- Scales C. and Berini P. (2010). Thin-film Schottky barrier photodetector models. *IEEE J. Quantum Electron.* **46**:633–643. DOI:10.1109/jqe.2010.2046720
- Peng Y., Liu J., Fu J., et al. (2025). Emerging thermal detectors based on low-dimensional materials: Strategies and progress. *Nanomaterials* **15**:459. DOI:10.3390/nano15060459
- Gabor N. M., Song J. C. W., Ma Q., et al. (2011). Hot carrier-assisted intrinsic photoresponse in graphene. *Science* **334**:648–652. DOI:10.1126/science.1211384
- Dai W., Liu W., Yang J., et al. (2020). Giant photothermoelectric effect in silicon nanoribbon photodetectors. *Light Sci. Appl.* **9**:120. DOI:10.1038/s41377-020-00364-x
- Wei J., Li Y., Wang L., et al. (2020). Zero-bias mid-infrared graphene photodetectors with bulk photoresponse and calibration-free polarization detection. *Nat. Commun.* **11**:6404. DOI:10.1038/s41467-020-20115-1
- Ji Z., Liu W., Krylyuk S., et al. (2020). Photocurrent detection of the orbital angular momentum of light. *Science* **368**:763–767. DOI:10.1126/science.aba9192
- de Juan F., Grushin A. G., Morimoto T., et al. (2017). Quantized circular photogalvanic effect in Weyl semimetals. *Nat. Commun.* **8**:15995. DOI:10.1038/ncomms15995
- Dhara S., Mele E. J. and Agarwal R. (2015). Voltage-tunable circular photogalvanic effect in silicon nanowires. *Science* **349**:726–729. DOI:10.1126/science.aac6275
- Fu J., Nie C., Sun F., et al. Photodetectors based on graphene-semiconductor hybrid structures: recent progress and future outlook. *Adv. Devices Instrumen.* **4**:0031. DOI:10.34133/adi.0031
- Fang H. and Hu W. (2017). Photogating in low dimensional photodetectors. *Adv. Sci.* **4**:1700323. DOI:10.1002/advs.201700323
- Shin J. and Yoo H. (2023). Photogating effect-driven photodetectors and their emerging applications. *Nanomaterials* **13**:882. DOI:10.3390/nano13050882
- Liu H., Yi Z. and Chen C. (2025). Advances in photodetectors via photogating effect. *Mater. Res. Bull.* **192**:113628. DOI:10.1016/j.materresbull.2025.113628

18. Zheng L., Zhou W., Ning Z., et al. (2018). Ambipolar graphene-quantum dot phototransistors with CMOS compatibility. *Adv. Opt. Mater.* **6**:1800985. DOI:10.1002/adom.201800985
19. Han J., Wang J., Yang M., et al. (2018). Graphene/organic semiconductor heterojunction phototransistors with broadband and bi-directional photoresponse. *Adv. Mater.* **30**:e1804020. DOI:10.1002/adma.201804020
20. Tu L., Cao R., Wang X., et al. (2020). Ultrasensitive negative capacitance phototransistors. *Nat. Commun.* **11**:101. DOI:10.1038/s41467-019-13769-z
21. Konstantatos G., Badioli M., Gaudreau L., et al. (2012). Hybrid graphene-quantum dot phototransistors with ultrahigh gain. *Nat. Nanotechnol.* **7**:363–368. DOI:10.1038/nnano.2012.60
22. Ni Z., Ma L., Du S., et al. (2017). Plasmonic silicon quantum dots enabled high-sensitivity ultrabroadband photodetection of graphene-based hybrid phototransistors. *ACS Nano* **11**:9854–9862. DOI:10.1021/acsnano.7b03569
23. Liu M., Wei J., Qi L., et al. (2024). Photogating-assisted tunneling boosts the responsivity and speed of heterogeneous $\text{WSe}_2/\text{Ta}_2\text{NiSe}_5$ photodetectors. *Nat. Commun.* **15**:141. DOI:10.1038/s41467-023-44482-7
24. Han J., Tuo T., Deng W., et al. (2025). 2D/organic photovoltage field-effect transistors. *Laser Photonics Rev.* **19**:2500268. DOI:10.1002/lpor.202500268
25. Soci C., Zhang A., Xiang B., et al. (2007). ZnO nanowire UV photodetectors with high internal gain. *Nano Lett.* **7**:1003–1009. DOI:10.1021/nl070111x
26. Roy K., Padmanabhan M., Goswami S., et al. (2013). Graphene-MoS₂ hybrid structures for multifunctional photoresponsive memory devices. *Nat. Nanotechnol.* **8**:826–830. DOI:10.1038/nnano.2013.206
27. Lopez-Sanchez O., Lembke D., Kayci M., et al. (2013). Ultrasensitive photodetectors based on monolayer MoS₂. *Nat. Nanotechnol.* **8**:497–501. DOI:10.1038/nnano.2013.100
28. Zhang W., Huang J.-K., Chen C.-H., et al. (2013). High-gain phototransistors based on a CVD MoS₂ monolayer. *Adv. Mater.* **25**:3456–3461. DOI:10.1002/adma.201301244
29. Li Y., Chen G., Zhao S., et al. (2022). Addressing gain-bandwidth trade-off by a monolithically integrated photovoltaic transistor. *Sci. Adv.* **8**:eabq0187. DOI:10.1126/sciadv.abq0187
30. Pak S., Cho Y., Hong J., et al. (2018). Consecutive junction-induced efficient charge separation mechanisms for high-performance MoS₂/quantum dot phototransistors. *ACS Appl. Mater. Interfaces* **10**:38264–38271. DOI:10.1021/acsami.8b14408
31. Guo N., Xiao L., Gong F., et al. (2020). Light-driven WSe_2 -ZnO junction field-effect transistors for high-performance photodetection. *Adv. Sci.* **7**:1901637. DOI:10.1002/advs.201901637
32. Tuo T., Wei L., Han J., et al. (2025). Light-driven $\text{Ta}_2\text{NiSe}_5/\text{MoSe}_2$ van der Waals heterostructure field-effect Phototransistors. *Infrared Phys. Techn.* **150**:106057. DOI:10.1016/j.infrared.2025.106057
33. Sassi U., Parret R., Nanot S., et al. (2017). Graphene-based mid-infrared room-temperature pyroelectric bolometers with ultrahigh temperature coefficient of resistance. *Nat. Commun.* **8**:14311. DOI:10.1038/ncomms14311
34. Gopalan K. K., Janner D., Nanot S., et al. (2017). Mid-infrared pyroresistive graphene detector on LiNbO_3 . *Adv. Opt. Mater.* **5**:1600723. DOI:10.1002/adom.201600723
35. Peng Y., Yang Q., Fu J., et al. (2025). Uncooled graphene infrared detectors enabled by pyroelectric photogating for human radiation perception. *Laser Photonics Rev.* **19**:2500218. DOI:10.1002/lpor.202500218
36. Adinolfi V. and Sargent E. H. (2017). Photovoltage field-effect transistors. *Nature* **542**:324–327. DOI:10.1038/nature21050
37. Fu J., Jiang H., Nie C., et al. (2023). Polarity-tunable field effect phototransistors. *Nano Lett.* **23**:4923–4930. DOI:10.1021/acs.nanolett.3c00728
38. Guo X., Wang W., Nan H., et al. (2016). High-performance graphene photodetector using interfacial gating. *Optica* **3**:1066–1070. DOI:10.1364/optica.3.001066
39. Zhang Z., Wang S., Liu C., et al. (2022). All-in-one two-dimensional retinomorphic hardware device for motion detection and recognition. *Nat. Nanotechnol.* **17**:27–32. DOI:10.1038/s41565-021-01003-1
40. Deng J., Zong L., Zhu M., et al. (2019). MoS₂/HfO₂/Silicon - On - Insulator dual - photogating transistor with ambipolar photoresponsivity for high - resolution light wavelength detection. *Adv. Funct. Mater.* **29**:1906242. DOI:10.1002/adfm.201906242
41. Wu G., Zhang X., Feng G., et al. (2023). Ferroelectric-defined reconfigurable homojunctions for in-memory sensing and computing. *Nat. Mater.* **22**:1499–1506. DOI:10.1038/s41563-023-01676-0
42. Jang H., Liu C., Hinton H., et al. (2020). An atomically thin optoelectronic machine vision processor. *Adv. Mater.* **32**:2002431. DOI:10.1002/adma.202002431
43. Furchi M. M., Polyushkin D. K., Pospischil A., et al. (2014). Mechanisms of photoconductivity in atomically thin MoS₂. *Nano Lett.* **14**:6165–6170. DOI:10.1021/nl502339q
44. Chen J., Zhou Z., Kim B. J., et al. (2023). Optoelectronic graded neurons for bioinspired in-sensor motion perception. *Nat. Nanotechnol.* **18**:882–888. DOI:10.1038/s41565-023-01379-2
45. Xu H., Xu Z., Ren Q., et al. (2026). Two-dimensional materials for integrated sensing. *Nat. Mater.* DOI:10.1038/s41563-026-02551-4.
46. Wang C.-Y., Liang S.-J., Wang S., et al. (2020). Gate-tunable van der Waals heterostructure for reconfigurable neural network vision sensor. *Sci. Adv.* **6**:eaba6173. DOI:10.1126/sciadv.aba6173.
47. Choi W., Yoon J. S., Lee W. W., et al. (2025). DPP-DTT nanowire phototransistors for optoelectronic synapses in EMG and ECG signal classification. *Small* **21**:e06440. DOI:10.1002/sml.202506440
48. Fu J., Ji L., Wu Z., et al. (2024). An all-in-one optoelectronic logic device with self-distinguishable dual-band photoresponse. *Device* **2**:100321. DOI:10.1016/j.device.2024.100321
49. Wang H., Li Z., Li D., et al. (2021). Junction field - effect transistors based on PdSe₂/MoS₂ heterostructures for photodetectors showing high responsivity and detectivity. *Adv. Funct. Mater.* **31**:2106105. DOI:10.1002/adfm.202106105
50. Fu J., Leng C., Ma R., et al. (2024). Photo-driven fin field-effect transistors. *Opto-Electronic Science* **3**:230046. DOI:10.29026/oes.2024.230046
51. Wang J., Zang H., Yu M. B., et al. (2009). Enhanced sensitivity of small-size (with 1- μm Gate length) junction-field-effect-transistor-based germanium photodetector using two-step germanium epitaxy by ultrahigh vacuum chemical vapor deposition. *IEEE Electron Device Lett.* **30**:1066–1068. DOI:10.1109/led.2009.2029125
52. She J., Liu X., Liu H., et al. (2025). Ferroelectric tailorable WS₂/graphene phototransistors. *Nano Lett.* **25**:11578–11585. DOI:10.1021/acs.nanolett.5c02241
53. Tsai T. H., Liang Z. Y., Lin Y. C., et al. (2020). Photogating WS₂ photodetectors using embedded WSe₂ charge puddles. *ACS Nano* **14**:4559–4566. DOI:10.1021/acsnano.0c00098
54. Tao L., Li H., Sun M., et al. (2018). Enhanced photoresponse in interfacial gated graphene phototransistor with ultrathin Al₂O₃ dielectric. *IEEE Electron Device Lett.* **39**:987–990. DOI:10.1109/led.2018.2843804
55. Wu J., Wen Z., Guo B., et al. (2025). Dielectric-free MoS₂/VO₂ junction field-effect transistor with sensitive and ultrafast photoresponse for light encrypted communication. *Adv. Mater.* **37**:2503294. DOI:10.1002/adma.202503294
56. Guo N., Hu W., Liao L., et al. (2014). Anomalous and highly efficient InAs nanowire phototransistors based on majority carrier transport at room temperature. *Adv. Mater.* **26**:8203–8209. DOI:10.1002/adma.201403664
57. Guo Q., Pospischil A., Bhuiyan M., et al. (2016). Black phosphorus mid-infrared photodetectors with high gain. *Nano Lett.* **16**:4648–4655. DOI:10.1021/acs.nanolett.6b01977
58. Island J. O., Blanter S. I., Buscema M., et al. (2015). Gate controlled photocurrent generation mechanisms in high-gain In₂Se₃ phototransistors. *Nano Lett.* **15**:7853–7858. DOI:10.1021/acs.nanolett.5b02523
59. Fu J., Yang C., Nie C., et al. (2023). Vertical photodetectors based on in-situ aligned single-crystalline PbS nanocuboids sandwiched between graphene electrodes. *Adv. Opt. Mater.* **11**:2300584. DOI:10.1002/adom.202300584
60. Li C., Wu Z., He M., et al. (2025). Photo-driven all-2D van der Waals metal-semiconductor field-effect transistors for high-performance photodetection. *J. Mater. Chem. C* **13**:10650–10657. DOI:10.1039/D5TC001016K
61. Fu J., Nie C., Sun F., et al. (2022). Photo - driven semimetal-semiconductor field - effect transistors. *Adv. Opt. Mater.* **11**:2010102. DOI:10.1002/adom.202201983
62. Adinolfi V., Kramer I. J., Labelle A. J., et al. (2015). Photojunction field-effect transistor based on a colloidal quantum dot absorber channel layer. *ACS Nano* **9**:356–362. DOI:10.1021/nn5053537
63. Madjar A., Paolletta A. and Herzfeld P. R. (1993). Light interaction with GaAs MESFET and its applications—a review (invited paper). *Microwave Opt. Technol. Lett.* **6**:22–27. DOI:10.1002/mop.4650060107
64. Li X., Wang S., Yang Y., et al. (2024). Photovoltage junction memtransistor for optoelectronic in-memory computing. *J. Mater. Chem. C* **12**:12763–12768. DOI:10.1039/D4TC003015J
65. Shan Y., Yin Z., Zhang Y., et al. (2021). Ultrafast and highly sensitive dual-channel FET photodetector based on a two-dimensional MoS₂ homojunction. *ACS Appl. Mater. Interfaces* **13**:54194–54203. DOI:10.1021/acsami.1c16891
66. Liu X., Zhu J., Shan Y., et al. (2024). An ultrasensitive and broad-spectrum MoS₂ photodetector with extrinsic response using surrounding homojunction. *Adv. Sci.* **11**:2408299. DOI:10.1002/advs.202408299
67. Xiao L., Nie C., Jiang Y., et al. (2024). Ultralow-noise MoS₂/Type II superlattice mixed-dimensional van der Waals barrier long-wave infrared detector. *ACS Appl. Mater. Interfaces* **16**:30478–30484. DOI:10.1021/acsami.4c00956
68. Xiao L., Fu J., Zhu P., et al. (2024). Pixel-integrated Mie metasurface long-wave multispectral type II superlattice detector. *Appl. Phys. Lett.* **124**:091108. DOI:10.1063/5.0185320
69. Xiao L., Zhu P., Li N., et al. (2022). Gradual funnel photon trapping enhanced InAs/GaSb type-II superlattice infrared detector. *Opt. Express* **30**:38009–38015. DOI:10.1364/OE.468812
70. Lohstroh J. (1974). The JFET as a photosensitive cell in image sensor arrays. 1974 IEEE International Solid-State Circuits Conference. Digest of Technical Papers.
71. Shannon J. M. and Lohstroh J. (1974). JFET optical detectors in the charge storage mode. *IEEE T. Electron Dev.* **21**:720–728. DOI:10.1109/T-ED.1974.17999
72. Shu X., Wu J., Zhong F., et al. (2024). High-responsivity, high-detectivity, broadband infrared photodetector based on MoS₂/BP/MoS₂ junction field-effect transistor. *Appl. Phys. Lett.* **124**:181101. DOI:10.1063/5.0205803
73. Guan H., Hong J., Wang X., et al. (2021). Broadband, high-sensitivity graphene photodetector based on ferroelectric polarization of lithium niobate. *Adv. Opt. Mater.* **9**:2100245. DOI:10.1002/adom.202100245

74. Fukushima S., Shimatani M. and Ogawa S. (2023). Graphene infrared photodetectors using type-II InAs/InGaSb superlattices. *Infrared Technology and Applications XLIX. SPIE*.
75. Liu W., Lv J., Peng L., et al. (2022). Graphene charge-injection photodetectors. *Nat. Electron.* **5**:281–288. DOI:10.1038/s41928-022-00755-5
76. Deng J., Shao J., Lu B., et al. (2018). Interface coupled photodetector (ICPD) with high photoresponsivity based on Silicon-on-Insulator substrate (SOI). *IEEE J. Electron Dev.* **6**:557–564. DOI:10.1109/jeds.2017.2788403
77. Liao F., Deng J., Chen X., et al. (2020). A dual-gate MoS₂ photodetector based on interface coupling effect. *Small* **16**:1904369. DOI:10.1002/smll.201904369
78. Pang Y., Zhou Y., Tong L., et al. (2024). 2D dual gate field-effect transistor enabled versatile functions. *Small* **20**:2304173. DOI:10.1002/smll.202304173
79. Deng J., Guo Z., Zhang Y., et al. (2019). MoS₂/Silicon-on-Insulator heterojunction field-effect-transistor for high-performance photodetection. *IEEE Electron Device Lett.* **40**:423–426. DOI:10.1109/LED.2019.2892782
80. Li L., Li S., Wang W., et al. (2024). Adaptive machine vision with microsecond-level accurate perception beyond human retina. *Nat. Commun.* **15**:6261. DOI:10.1038/s41467-024-50488-6
81. Xiong J., Yu Q., Hou X., et al. (2024). Short-wave infrared photodetectors based on β -In₂Se₃/Te heterojunctions for optical communication and polarimetric imaging applications. *Adv. Funct. Mater.* **34**:2314972. DOI:10.1002/adfm.202314972
82. Huang Z., Wang W., Wang S., et al. (2024). Gate-tunable positive and negative photoresponses based on a mixed-dimensional Ga₂O₃/WSe₂ junction field-effect transistor for logic operation. *Photonics Res.* **12**:2804–2811. DOI:10.1364/PRJ.534338
83. Zhou Y., Li F., Li W., et al. (2024). MoS₂/GaN junction field-effect transistors with ultralow subthreshold swing and high on/off ratio via thickness engineering for logic inverters. *Adv. Funct. Mater.* **34**:2410954. DOI:10.1002/adfm.202410954
84. Sze S. and Ng K. K. (2006). Physics of semiconductor devices: third edition. *Physics of Semiconductor Devices: Third Edition*:1–815. DOI:10.1002/9780470068328
85. Wang F., Zhang T., Xie R., et al. (2023). How to characterize figures of merit of two-dimensional photodetectors. *Nat. Commun.* **14**:2224. DOI:10.1038/s41467-023-37635-1
86. Bielecki Z., Achtenberg K., Kopytko M., et al. (2022). Review of photodetectors characterization methods. *Bulletin of the Polish Academy of Sciences-Technical Sciences B Pol. Acad. Sci-Tech.* **70**. e140534. DOI:10.24425/bpasts.2022.140534.
87. Hu C., Dong D., Yang X., et al. (2017). Synergistic effect of hybrid PbS quantum dots/2D-WSe₂ toward high performance and broadband phototransistors. *Adv. Funct. Mater.* **27**:1603605. DOI:10.1002/adfm.201603605
88. Luo P., Zhuge F., Wang F., et al. (2019). PbSe quantum dots sensitized high-mobility Bi₂O₃/Se nanosheets for high-performance and broadband photodetection beyond 2 μ m. *ACS Nano* **13**:9028–9037. DOI:10.1021/acsnano.9b03124
89. Zheng D., Fang H., Wang P., et al. (2016). High-performance ferroelectric polymer side-gated CdS nanowire ultraviolet photodetectors. *Adv. Funct. Mater.* **26**:7690–7696. DOI:10.1002/adfm.201603152
90. Huang H., Wang J., Hu W., et al. (2016). Highly sensitive visible to infrared MoTe₂ photodetectors enhanced by the photogating effect. *Nanotechnology* **27**:445201. DOI:10.1088/0957-4484/27/44/445201
91. Kind H., Yan H. Q., Messer B., et al. (2002). Nanowire ultraviolet photodetectors and optical switches. *Adv. Mater.* **14**:158–160. DOI:10.1002/1521-4095(20020116)14:2<158::Aid-adma158>3.0.Co;2-w
92. Vashishtha P., Abidi I. H., Giridhar S. P., et al. (2024). CVD-grown monolayer MoS₂ and GaN thin film heterostructure for a self-powered and bidirectional photodetector with an extended active spectrum. *ACS Appl. Mater. Interfaces* **16**:31294–31303. DOI:10.1021/acsnano.1c03902
93. Nikitskiy I., Goossens S., Kufer D., et al. (2016). Integrating an electrically active colloidal quantum dot photodiode with a graphene phototransistor. *Nat. Commun.* **7**:11954. DOI:10.1038/ncomms11954
94. Chow P. C. Y., Matsuhisa N., Zalar P., et al. (2018). Dual-gate organic phototransistor with high-gain and linear photoresponse. *Nat. Commun.* **9**:4546. DOI:10.1038/s41467-018-06907-6
95. Wang L., Wang H., Liu J., et al. (2024). Negative photoconductivity transistors for visuomorphic computing. *Adv. Mater.* **36**:2403538. DOI:10.1002/adma.202403538
96. Jariwala D., Marks T. J. and Hersam M. C. (2017). Mixed-dimensional van der Waals heterostructures. *Nat. Mater.* **16**:170–181. DOI:10.1038/nmat4703
97. Liu Y., Weiss N. O., Duan X., et al. (2016). Van der Waals heterostructures and devices. *Nat. Rev. Mater.* **1**:16042. DOI:10.1038/natrevmats.2016.42
98. Kufer D., Nikitskiy I., Lasanta T., et al. (2015). Hybrid 2D-0D MoS₂-PbS quantum dot photodetectors. *Adv. Mater.* **27**:176–180. DOI:10.1002/adma.201402471
99. Choi W., Cho M. Y., Konar A., et al. (2012). High-detectivity multilayer MoS₂ phototransistors with spectral response from ultraviolet to infrared. *Adv. Mater.* **24**:5832–5836. DOI:10.1002/adma.201201909
100. Kufer D. and Konstantatos G. (2015). Highly sensitive, encapsulated MoS₂ photodetector with gate controllable gain and speed. *Nano Lett.* **15**:7307–7313. DOI:10.1021/acs.nanolett.5b02559
101. Fu J., Nie C., Sun F., et al. (2024). Bionic visual-audio photodetectors with in-sensor perception and preprocessing. *Sci. Adv.* **10**:eadk8199. DOI:10.1126/sciadv.adk8199
102. Han C., Liu X., Han X., et al. (2022). High-performance phototransistor based on graphene/organic heterostructure for in-chip visual processing and pulse monitoring. *Adv. Funct. Mater.* **32**:2209680. DOI:10.1002/adfm.202209680
103. Pi L., Wang P., Liang S.-J., et al. (2022). Broadband convolutional processing using band-alignment-tunable heterostructures. *Nat. Electron.* **5**:248–254. DOI:10.1038/s41928-022-00747-5
104. Luo W., Weng Q., Long M., et al. (2018). Room-temperature single-photon detector based on single nanowire. *Nano Lett.* **18**:5439–5445. DOI:10.1021/acs.nanolett.8b01795
105. Zheng D., Wang J., Hu W., et al. (2016). When nanowires meet ultrahigh ferroelectric field-high-performance full-depleted nanowire photodetectors. *Nano Lett.* **16**:2548–2555. DOI:10.1021/acs.nanolett.6b00104
106. Zhang K., Peng M., Yu A., et al. (2019). A substrate-enhanced MoS₂ photodetector through a dual-photogating effect. *Mater. Horiz.* **6**:826–833. DOI:10.1039/c8mh01429a
107. Fu J., Que L., Jiang H., et al. (2020). Effects of doping graphene on the performance of graphene-silicon hybrid photoconductive detectors. *Nanotechnology* **31**:485201. DOI:10.1088/1361-6528/abb108
108. Hao J., Changbin N., Jintao F., et al. (2020). Ultrasensitive and fast photoresponse in graphene/silicon-on-insulator hybrid structure by manipulating the photogating effect. *Nanophotonics* **9**:3663–3672. DOI:10.1515/nanoph-2020-0261
109. Jiang H., Wang M., Fu J., et al. (2022). Ultrahigh photogain short-wave infrared detectors enabled by integrating graphene and hyperdoped silicon. *ACS Nano* **16**:12777–12785. DOI:10.1021/acsnano.2c04704
110. Lee I., Kang W. T., Kim J. E., et al. (2020). Photoinduced tuning of Schottky barrier height in graphene/MoS₂ heterojunction for ultrahigh performance short channel phototransistor. *ACS Nano* **14**:7574–7580. DOI:10.1021/acsnano.0c03425
111. De Fazio D., Uzlu B., Torre I., et al. (2020). Graphene-quantum dot hybrid photodetectors with low dark-current readout. *ACS Nano* **14**:11897–11905. DOI:10.1021/acsnano.0c04848
112. Joy R. C. and Linvill J. G. (1968). Phototransistor operation in the charge storage mode. *IEEE T. Electron Dev.* **15**:237–248. DOI:10.1109/T-ED.1968.16172
113. Liang F.-X., Jiang J.-J., Zhao Y.-Z., et al. (2020). Fabrication of MAPbBr₃ single crystal p-n photodiode and n-p-n phototriode for sensitive light detection application. *Adv. Funct. Mater.* **30**:2001033. DOI:10.1002/adfm.202001033
114. Li H., Ye L. and Xu J. (2017). High-performance broadband floating-base bipolar phototransistor based on WSe₂/BP/MoS₂ heterostructure. *ACS Photonics* **4**:823–829. DOI:10.1021/acsp Photonics.6b00778
115. Zhou W., Zheng L., Ning Z., et al. (2021). Silicon: Quantum dot photovoltage triodes. *Nat Commun* **12**:6696. DOI:10.1038/s41467-021-27050-9
116. Sahni S., Luo X., Liu J., et al. (2008). Junction field-effect-transistor-based germanium photodetector on silicon-on-insulator. *Opt. Lett.* **33**:1138–1140. DOI:10.1364/ol.33.001138
117. Edwards W. D. (1980). Two and three terminal gallium arsenide FET optical detectors. *IEEE Electron Device Lett.* **1**:149–150. DOI:10.1109/EDL.1980.25268
118. Macdonald R. I. (1981). High-gain optical-detection with GaAs field-effect transistors. *Appl. Opt.* **20**:591–594. DOI:10.1364/ao.20.000591
119. Chen C. Y., Cho A. Y., Bethea C. G., et al. (1983). Ultrahigh speed modulation-doped heterostructure field-effect photodetectors. *Appl. Phys. Lett.* **42**:1040–1042. DOI:10.1063/1.93835
120. Nair R. R., Blake P., Grigorenko A. N., et al. (2008). Fine structure constant defines visual transparency of graphene. *Science* **320**:1308–1308. DOI:10.1126/science.1156965
121. Lee H. S., Baik S. S., Lee K., et al. (2015). Metal semiconductor field-effect transistor with MoS₂/conducting NiOx van der Waals Schottky interface for intrinsic high mobility and photoswitching speed. *ACS Nano* **9**:8312–8320. DOI:10.1021/acsnano.5b02785
122. Ye Y., Dai L., Wen X., et al. (2010). High-performance single CdS nanobelt metal-semiconductor field-effect transistor-based photodetectors. *ACS Appl. Mater. Interfaces* **2**:2724–2727. DOI:10.1021/am100661x
123. Wang B., Zhang N., You J., et al. (2025). Visible–near-infrared wavelength-selective photodetection and imaging based on floating-gate phototransistors. *InfoMat* **7**:e12661. DOI:10.1002/inf2.12661
124. Prajapat P., Vashishtha P. and Gupta G. (2025). High-temperature resilient neuromorphic device based on optically configured monolayer MoS₂ for cognitive computing. *Small* **21**:241596. DOI:10.1002/smll.20241596
125. Jiang H., Wei J., Sun F., et al. (2022). Enhanced photogating effect in graphene photodetectors via potential fluctuation engineering. *ACS Nano* **16**:4458–4466. DOI:10.1021/acsnano.1c10795
126. He J., Chen K., Huang C., et al. (2020). Explicit gain equations for single crystalline photoconductors. *ACS Nano* **14**:3405–3413. DOI:10.1021/acsnano.9b09406
127. Goossens S., Navickaite G., Monasterio C., et al. (2017). Broadband image sensor array based on graphene–CMOS integration. *Nat. Photonics* **11**:366–371. DOI:10.1038/nphoton.2017.75
128. Yang H., Heo J., Park S., et al. (2012). Graphene barristor, a triode device with a gate-controlled Schottky barrier. *Science* **336**:1140–1143. DOI:10.1126/science.1220527
129. Kufer D. and Konstantatos G. (2016). Photo-FETs: phototransistors enabled by 2D and 0D nanomaterials. *ACS Photonics* **3**:2197–2210. DOI:10.1021/acsp Photonics.6b00391

130. Gao H., Jiang X., Ma X., et al. (2025). Bio-inspired mid-infrared neuromorphic transistors for dynamic trajectory perception using PdSe₂/pentacene heterostructure. *Nat. Commun.* **16**:5241. DOI:10.1038/s41467-025-60311-5
131. Yang Z., Albrow-Owen T., Cai W., et al. (2021). Miniaturization of optical spectrometers. *Science* **371**:eabe0722. DOI:10.1126/science.abe0722
132. Zhang Y., Yang E., Yoon H. H., et al. (2025). Reconstructive spectrometers: hardware miniaturization and computational reconstruction. *eLight* **5**:23. DOI:10.1186/s43593-025-00101-0
133. Fu J., Jiang H., Liu X., et al. (2026). Transistor-type optoelectronic sensors from light intensity detection to multifunctional perception. *Nat. Sens.* **1**:209–221. DOI:10.1038/s44460-026-00035-1
134. Polat E. O., Mercier G., Nikitskiy I., et al. (2019). Flexible graphene photodetectors for wearable fitness monitoring. *Sci. Adv.* **5**:eaaw7846. DOI:10.1126/sciadv.aaw7846
135. Kim J., Kwon S.-M., Kang Y. K., et al. A skin-like two-dimensionally pixelized full-color quantum dot photodetector. *Sci. Adv.* **5**:eaax8801. DOI:10.1126/sciadv.aax8801.
136. Liu Y., Huang Y. and Duan X. (2019). Van der Waals integration before and beyond two-dimensional materials. *Nature* **567**:323–333. DOI:10.1038/s41586-019-1013-x
137. Lien M.-B., Liu C.-H., Chun I. Y., et al. (2020). Ranging and light field imaging with transparent photodetectors. *Nat. Photonics* **14**:143–148. DOI:10.1038/s41566-019-0567-3

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J.F. and X.W. conceived the idea. J.F., C.N., and F.S. researched data for the article. J.F. and X.W. wrote the manuscript and drafted the figures with the help of F.S., C.N., P.M., and H.S. X.W. supervised the writing and edited the manuscript before submission. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data that support the findings of this review are available from the corresponding authors upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-mater.2026.100229>.