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Advances in solution-processable near-infrared phototransistors

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Abstract

Solution processable near infrared (NIR) photodetectors provide a promising alternative due to their low cost, flexible design, adaptability to various fabrications, and large area manufacturability, removed the limitations of traditional wafer-based inorganic semiconductor techniques. There are three typical solution-processable NIR photodetectors: photodiodes (PDs), photoconductors (PCs) and phototransistors (PTs). PDs have a stack of functional layers sandwiched between an anode and a cathode. The external quantum efficiency (EQE) of the NIR PDs and PCs cannot be higher than 100%. In comparison, NIR PTs are three-terminal devices with an ultra-low noise current, providing high-sensitivity and tunable gain with an EQE in excess of 100%, achieved by controlling unbalanced charge transport through an optically controlled gate terminal. This review provides a brief introduction with regarding to the device configuration and operation mechanism of the PTs, following with a comprehensive overview on the recent advances in solution processable NIR PTs. This includes different approaches for attaining high-sensitivity NIR PTs using single component, heterojunction and nano-structured channel layers. The advances in solution-processable NIR PTs with novel device design knowledge and new materials processing technology are highlighted. The high sensitivity NIR photodetectors for applications in visualizing NIR light, health and safety monitoring are also discussed.
1. Introduction

Near-infrared (NIR) light covers the electromagnetic spectrum from 780 nm to 2500 nm and exhibits unique features including the ability for deeper penetration into bio tissues, high absorption sensitivity to the changes in molecular structures and more. The high sensitivity NIR light detection has attracted significant interest due to a broad range of applications in bio-imaging, thermal therapy, health monitoring, night-vision and telecommunication\textsuperscript{1–6}. The traditional NIR detection techniques are mainly based on the wafer-based inorganic semiconductor materials, such as crystalline Si, Ge and InGaAs semiconductor materials made with the high-temperature epitaxial growth processes. The crystalline inorganic semiconductor wafers are inherently brittle and rigid, limiting their applications in large area, flexible optoelectronics. The rapid progresses made in solution processable NIR sensitive semiconductors, including organic semiconductors and organic-inorganic hybrid semiconductors, offer additional advantages such as large area, flexibility and solution-based fabrication process, e.g., spray coating, spin coating, inject printing and blade coating, at low cost\textsuperscript{2,4}. An in-depth understanding of the device physics is a prerequisite for the design and fabrication of high sensitivity NIR photodetectors.

The solution processable NIR photodetectors have the freedom in device design and process tuning depending on the applications. There are generally three types of NIR photodetectors, e.g., a vertical multilayer structure photodiode (PD), the lateral device configurations including photoconductor (PC) and the phototransistor (PT)\textsuperscript{7}, as illustrated schematically in Fig. 1. In a PD type NIR photodetector, a stack of the functional layers is sandwiched between a cathode/anode pair, as shown in Fig. 1a. The photo-excited charge carriers in the active layer are generated in the presence of the NIR light passing through the transparent electrode, the photo-excited charge carriers are drifted under an internal built-in potential toward the respective electrodes forming a
photo current. The operation mechanism in an NIR PD is similar to that in a solar cell. The progresses made in the solar cells, in terms of material choice and device optimization, benefit the design and fabrication of the high sensitivity NIR PDs. An NIR PD can be operated in a powerless mode enabled by its built-in potential. To achieve higher quantum efficiency, a reverse bias is applied to improve the extraction probability of the photo generated charge carriers. The external quantum efficiency \((EQE)\) of the NIR PDs is smaller than 100\(^\%\) due to the lack of a photo gain mechanism. The photomultiplication type organic photodiodes with \(EQE > 100\%\) have been reported\(^8\)–\(^10\). However, in the solution processable NIR PDs, forming a multilayer stack can be a challenge, as the solvents used in the deposition of the subsequent layers can cause damages to or even wash of the underlying layers in the continuous solution-fabrication processes. The use of the interlayers to prevent the intermixing of the adjacent layers is subjective to the choice of the materials, involving additional process difficulties, extra cost and possible deterioration in device performance. In comparison, the lateral type PC or PT photodetectors, as illustrated schematically in Figs. 1b and 1c, enable charge injection from electrodes to the active channel and are capable of achieving \(EQE\) several orders of magnitude higher than that of the PDs. PTs are three-terminal devices, providing high-sensitivity and tunable gain with an \(EQE\) in excess of 100\(^\%\) and possible monolithic integration of the NIR PTs with the external circuits, rendering them potentially attractive for a variety of NIR light detections\(^7\)–\(^11\). In NIR PTs, the NIR sensitive active channel is formed between the two laterally placed electrodes (source and drain electrodes). The third gate electrode is located near the active channel with a dielectric layer in-between. An NIR PT is essentially a transistor with an NIR sensitive channel layer, where the channel current can be controlled either by the gate voltage or the intensity of the NIR light. High performing NIR PTs can be obtained by adjusting the operation modes in the PTs, e.g., the photovoltaic mode allowing
a high EQE and the photoconductive mode enabling a low noise level. Due to these advantages, the NIR PTs have attracted increasing attentions for NIR detection. Considerable efforts have been devoted to the development of high performing NIR PTs with regarding to the material synthesis and device design\textsuperscript{2,12}. The NIR PTs with a combination of high NIR light sensitivity, efficient photon to charge conversion process and enhanced carrier mobility in the channel are the prerequisites for achieving high sensitivity NIR detection. The generation of the photo excited charge carriers in the active layer depends not only on the materials or the blends used in the device, but also is largely dependent on the device architecture. In these regards, the composition and the quality of the active layers in the NIR PTs should be delicately designed for attaining efficient conversion between the NIR photons to photo-excited charge carriers. Therefore, the noise signal, mainly from the dark current, can be suppressed for achieving high sensitivity NIR PTs.

This review includes 5 Sections. The first part gives an overall overview on the recent development in solution-processable NIR photodetectors. The operation principle of NIR PTs is described in Section 2. The advances in solution-processable NIR PTs made with different channel layers, including material formulation, device design, process optimization, charge transport properties, fundamental PT characteristics and enhancement in the NIR detection, are discussed in Section 3. The solution-processable high-sensitivity NIR PTs with the functional superiority for applications in visualizing NIR light, health and safety monitoring are presented in Section 4. The progresses made in the solution-processed NIR PTs with novel device design knowledge and new materials processing technologies are highlighted in the Summary Section.
2. Operation principles of NIR phototransistors

2.1 Operation mechanisms

In NIR PTs, the lateral active channel serves simultaneously as the light absorption layer and the charge carriers transport in plane in the channel layer. The charge carriers in the PDs transport vertically across the stack of the active layers. Due to a relatively long channel length as compared to the active layer thickness in PDs, the charge carrier mobility is an important factor affecting the photo response of the PTs. Therefore, the optical and electrical properties of the semiconductor channel should be considered simultaneously for achieving high performance. In general, the formation of photo current in the active channel involves multiple processes including light absorption, charge photogeneration and carrier transportation. Each step has a profound impact on the resulting device performances.

Light absorption and charge generation: Frenkel excitons generated in the organic semiconductor materials have a relatively higher binding energy of hundreds of meV\(^{13}\). This high binding energy results from a combination of relatively low dielectric constant and weak electron-electron correlation in the organic materials\(^7\). Consequently, the high exciton binding energy is not favorable for exciton dissociation compared to the ones in inorganic semiconductors. Indeed, the excitons undergo a complicated process to dissociate into free charge carriers with a high recombination loss. In pristine organic semiconductors, external activation, e.g., electric field is required to assist in exciton dissociation and charge separation. The binary organic donor/acceptor (D/A) system is often adopted to assist in improving the generation of the photo-excited charge carriers. The bulk heterojunction is used for attaining high performing organic solar cells, where the efficient exciton dissociation takes place at the donor/acceptor (D/A) interface in the organic bulk heterojunction structure. The heterojunction type hybrid channel either in the layer staking
layout or blending form is also applicable for use in PTs. The idea is to provide a charge separation D/A interface for enhancement in photo induced charge generation. In PTs with an organic-inorganic hybrid material based channel layer, e.g., perovskite materials the Wannier excitons in the perovskite with a lower binding energy of 20 meV to 100 meV can be easily dissociated for generating free charge carriers\textsuperscript{14–17}. The low binding energy of the Wannier excitons in the perovskite materials, as compared to the ones in the organic semiconductors, favors the charge dissociation forming free charge carriers at room temperature. This leads to a better light harvesting capability, thereby boosting the photo sensitivity. The perovskite semiconductor materials with the advantages of excellent photon to charge conversion capability, high light absorption coefficient\textsuperscript{18,19}, high carrier mobility\textsuperscript{20,21} and long charge diffusion length\textsuperscript{22} are favorable for making high efficiency solar cells\textsuperscript{23–25}. The perovskite materials have also attracted an increasing interest for application in high performing photodetectors. The perovskite semiconductor materials with absorption extended to the long wavelengths can be obtained by adjusting the composition in the materials\textsuperscript{26,27}, e.g., with absorption up to \textasciitilde1000 nm for NIR light detection\textsuperscript{28,29}. These perovskite semiconductors can be prepared using low-cost solution fabrication processes.

\textit{Charge transport:} A PT is essentially a field effect transistor (FET). The amplification feature in a FET enables the PT with a tunable photoresponsivity. The operation mode, e.g., the depletion or accumulation mode, can be controlled by its gate voltage. In the following discussion, we consider a p-type channel in an NIR PT, the transistor is operated at the depletion mode (under a positive gate bias), where the electrons induced near the vicinity of the dielectric/semiconductor interface in the channel suppress the channel current. The accumulation mode in a transistor is formed with a negative bias, the induced holes are accumulated near the vicinity of the
dielectric/semiconductor interface in the channel, allowing efficient hole transportation leading to an increase in the channel current. In comparison to a FET, light detection is realized in a PT with a desired photo sensitive channel. Under illumination, photo charge carriers generated in the semiconductor channel, producing the electrical signal in the PTs at a given external bias. The photovoltaic and photoconductive processes in the PTs are correlated to the accumulation mode and depletion mode of the transistor. At the depletion mode, light induces photoconductive process, the photocurrent in the PT increases linearly with the intensity of the incidence of light. At the accumulation mode, on the other hand, photovoltaic process dominates in the PT. The threshold voltage \( V_{th} \) in the transistor shifts as a result of the light illumination. The gate voltage repeals the photo generated electrons to the vicinity of the source electrode, facilitating the hole injection, and thereby leading the shift in the \( V_{th} \). The increase in hole injection contributes to the increase in the channel current. The shift in \( V_{th} \) in PT is associated with the reduced barrier for charge injection under light illumination. The photo gain \( G \) can be increased significantly due to a large difference in hole and electron mobility at this mode. \( G \) can be expressed as follows:

\[
G = \frac{\tau_{electron}}{t_{hole}},
\]

where \( \tau_{electron} \) is the life time of photo generated electrons (the minority carrier). \( t_{hole} \) is the transit time of holes (the majority carrier) in the channel layer in PT. The time scale for recombination between the photo generated electrons and the holes is relatively longer than the transit time of the holes in the channel. Therefore, the photo-induced holes can travel multiple times in the channel before they are recombined, leading to an \( EQE \) in excess of 100\%, due to an ultra-high photo gain in phototransistors. This process is also known as internal photo multiplication effect. Controlling the charge traps in the active channel layer is an effect approach for increase the lifetime of the minority charge carriers, and thereby attaining the high photo gain
in PTs.

2.2 Figure of merits of PTs

In addition to the fundamental transistor characteristics, such as the field-effect mobility ($\mu$) and on/off ratio, the performance of phototransistor is characterized in terms of several figure-of-merit parameters that are associated with efficiency, noise and response speed.

Photoresponsivity ($R$): Photoresponsivity is defined as the ratio of photocurrent in the photodetector to the incident optical power. Photoresponsivity is associated with the photon to charge conversion efficiency. It can be expressed as follows:

$$ R = \frac{I_{\text{light}} - I_{\text{dark}}}{P_{\text{light}}}, $$

(2)

where $I_{\text{light}}$ is the total current in the presence of light, $I_{\text{dark}}$ is the current in the absence of light and $P_{\text{light}}$ is the power of incident light.

EQE: EQE is a measure of the optical-to-electrical conversion efficiency as a function of light wavelength. It is defined as the ratio of the number of the extracted photo-generated charge carriers to the number of the incident photons:

$$ EQE(\nu) = \frac{(I_{\text{light}} - I_{\text{dark}})/q}{P_{\text{light}}/(h\nu)}, $$

(3)

where $q$ is the electron charge, $h$ is the Planck’s constant and $\nu$ is the frequency of light. EQE represents the spectral response of the photodetectors and is a function of the wavelength of the incident light. EQE and $R$ can be related by $EQE = Rh\nu/q$.

Photosensitivity ($P$): Photosensitivity is a measure of the photo-switching ratio of channel current in the phototransistors in the presence of light to that in the absence of light. It is defined as follows:
\[ P = \frac{I_{\text{light}} - I_{\text{dark}}}{I_{\text{dark}}}. \] (4)

**Specific detectivity (D*)**: Specific detectivity of a photodetector is a figure of merit considering a combination of characteristics including the photoresponsivity, device active area and noise level. It is defined by:

\[ D^* = \frac{R\sqrt{A}}{S_n}. \] (5)

In eq. (5), \( R \) is the photoresponsivity, \( A \) is the active area of the photodetector and \( S_n \) is the noise spectral density. The noise spectral density is generally a combination of noises, including shot noise, Johnson noise, flicker noise, \( 1/f \) noise and generation-recombination noise etc. In some photodetectors, the shot noise is dominated by the dark current in the devices. In this case, the noise spectral density can be expressed as \( S_n = \sqrt{2qI_{\text{dark}}} \).

**Response time (\( \tau \))**: rise time (\( \tau_r \)) and fall time (\( \tau_f \)) are used to evaluate the response speed of PTs in the presence of the incidence of light. \( \tau_r \) is defined as the time for the photocurrent in PTs rising from 10% to 90% of its steady state after exposing to light. \( \tau_f \) is defined as the time for the photocurrent decreasing from 90% to 10% of its maximum value after the removal of light signal. Both \( \tau_r \) and \( \tau_f \) in PTs are closely associated with the charge transport and collection in the channel.

### 3. Advances in solution processable NIR PTs

Apart from the progresses made in the small molecules and polymers, solution processable channel materials made with the organic-inorganic hybrid perovskite and quantum dots (QDs) have also been adopted for NIR PTs. The versatile characteristics and massive source from nature of these NIR sensitive materials render them as attractive candidates for application in NIR light detection. The optical and electrical properties, e.g., NIR light absorption, carrier mobility etc., of
these materials can be easily tailored using chemical methods. The solution processability of these functional materials makes them potentially attractive for use in light weight, flexible and large area NIR photodetectors. In parallel to the development of new NIR light absorbing materials, much effort has been devoted to the delicate design of the high performing NIR PTs through, e.g., enhanced charge separation and charge transfer in hybrid channels, for enhancing the NIR detection capabilities. A summary of the important characteristics obtained for some solution-processable thin film NIR PTs is listed in Table 1.

The NIR PTs with unique features of high carrier mobility, low dark current and good NIR sensitive spectrum are prerequisites for achieving high performing characteristics. Regarding these requirements, an appropriate selection of the channel geometry, using either single component or hybrid configurations, is important for enhancing the photoresponsivity, photosensitivity and detectivity of the NIR PTs.

3.1 NIR PTs with a single component layer channel

Solution-processable NIR PTs with a single component channel layer have the process advantages including the avoidance of layer erosion and process difficulty associated with the poor miscibility of the materials encountered in the multi-component channel layer. The light absorption, charge separation and transportation in the single active layer occur simultaneously. Therefore, NIR PTs with a single component channel also depends on the transistor performance.

NIR PTs made with the functional organic materials are inherently light weight, bendable that are suitable for applications in flexible and large area devices. The absorption of the organic materials can be extended to NIR region for use in NIR PTs. An obvious enhancement in light detection has been observed in PTs with a channel having improved crystallinity. The enhanced crystallinity in the channel, realized through annealing, was proved by observing the red shift in
the absorption peak in the Grazing-Incidence Wide-Angle X-ray Scattering (GIWAXS) measurements. The red shift in the absorption peak is a sign of enhanced inter-chain interactions between the polymer chains. The GIWAXS results reveal much improved polymer crystallinity in the channel after the thermal treatment. The improvement in long-range molecular ordering and edge-on alignments of the molecules in the channel layer is favorable for attaining higher charge transport mobility in the PTs, as illustrated in Fig. 2a. As a consequence, the photo current generation and the ratio of photo current over dark current in the PTs over the NIR light region were dramatically enhanced, as shown in Figs. 2b and 2c. This suggests that highly efficient photo-generated charge transport in the channel is a prerequisite for high performing NIR light detection PTs.

Despite thermally assisted processes for high thin film crystallinity, single crystals from organic semiconductors with well-ordered molecular arrangement can be readily achieved using solution processes. It has been reported that FETs with an air stable 2D crystalline n-type NIR light absorbing organic channel are favorable for application in NIR PTs. Despite an ultra-high photoresponsivity of $\sim 10^5$ A/W, achieved in the accumulation mode (see Fig. 2d) of the PTs with a channel having a 2D organic single crystal channel, the ultra-low dark current of the PTs in the depletion mode leads to a much higher photosensitivity as well as specific detectivity, as shown in Fig. 2e. The ultra-low dark current in the depletion mode of the PTs originates from the fully depleted state in the transistor, avoiding the leakage current in the channel in the dark condition. The NIR PTs take advantages of the low dark current in the depletion mode, and thereby achieving high signal to noise ratio.

Apart from the progresses made in the organic NIR PTs, some other solution processable materials, e.g., organic-inorganic hybrid perovskite with high absorption over the broadband
wavelength range from ultraviolet (UV) to NIR light, are also suitable candidates for NIR PT applications. The perovskite materials have attracted substantial attentions with unique optoelectronic properties for applications in solar cells, photo detection and light emission\textsuperscript{32–35}. The organo-lead triiodide (CH$_3$NH$_3$PbI$_3$) perovskite has been extensively used for application in solar cells, due to its suitable bandgap (~1.5 eV) and long charge diffusion length\textsuperscript{36}. Although perovskite materials face some challenge for use in FETs at room temperature\textsuperscript{37–39}, attempts have been made to explore application of PTs using solution-processed perovskite materials\textsuperscript{37}. Although the mobility of the holes and electrons in the perovskite FETs at room temperature is relatively low, the high light absorption coefficient allows perovskite PTs with a very high photoresponsivity over a broadband wavelength range from UV to NIR, as depicted in Fig. 2f, with very high photo sensitivity due to a low dark current. The transient photo response time is less than 10 µs, a promising candidate for high performing PTs. However, the CH$_3$NH$_3$PbI$_3$ perovskite has a limited response in wavelength beyond ~800 nm. Although the absorption of the perovskite materials can be further extended in the long wavelength range by changing the material composition, it has been mainly employed in solar cells\textsuperscript{40–42}, in comparison the work about PTs with perovskite channel is relatively less reported. Low bandgap semiconductor materials including lead sulfide (PbS) and mercury telluride (HgTe) have been used for NIR detection. PbS and HgTe wafers have been adopted for use in NIR photodetectors using the conventional vacuum fabrication process. Some research efforts have been attempted to synthesizing nanostructured functional PbS and HgTe materials, e.g., PbS and HgTe nanowires (NWs) and QDs, for making NIR PDs through solution fabrication processes. The progresses made in solution-processable NIR PDs with the nanostructured materials will be discussed in Section 3.3.
3.2 Heterojunction NIR PTs

The ultra-low transit time of the majority carriers ($t_{majority}$) is desired for attaining high photo gain ($G$) in PTs, which can be realized by reducing the channel length$^{37}$. However, the PTs with a narrow channel length increase the fabrication cost, requiring sophisticated and expensive lithography procedures. The use of a binary donor/acceptor system is an alternative approach to increase the lifetime of the minority carriers.

Compared to NIR PTs with a single component channel, the PTs with a heterojunction channel, either layer or bulk heterojunction configuration, have the advantages of complementary absorption, favored charge separation and charge transfer in the channel$^{43,44}$. The donor/acceptor interface in the hybrid channel facilitates the dissociation of the photo-generated excitons and charge separation. The charge carriers remain preferably in either n-type domains or p-type domains resulting slower de-trapping processes due to the difference in respective electron affinity.$^{45}$ Therefore, a higher photo gain can then be expected due to the increase in lifetime of the minority charge carriers in the channel.

Among the different types of hybrid channels, the binary blend donor/acceptor bulk heterojunction channel, similar to that of the active layer used in high performing organic solar cells, has been adopted in NIR PTs$^{46}$. The bulk heterojunction channel allows enhancing $EQE$ through efficient exciton dissociation at the donor/acceptor interface in hybrid channel layer in the PTs. The high photo gain can also be remained through tapping and de-trapping of the minority charge carriers in the channel.

The binary donor polymer/small molecule acceptor systems, commonly used in the high performing organic solar cells, have also been used in NIR PTs$^{45}$. The NIR donor with high hole mobility also acts as the charge transport layer in the channel. The fullerene acceptor in the binary
blend helps to disassociate the photo generated excitons and trap the electrons (see Fig. 3a). The simultaneously high hole mobility and slow de-trapping of electrons from the acceptor domains are favorable for achieving very high photo grain. The photoresponsivity in the accumulation mode is much higher than that in the depletion mode in the PTs, as shown in Fig. 3b, enabling good tunable photo gain by controlling the gate voltage. The profound difference in photoresponsivity in the two modes (Fig. 3c) arises from the inherent properties of the transistor, where the mobility is higher and charge separation is more efficient in the accumulation mode than that in the depletion mode. The ultra-low dark current in the depletion mode is more favorable in achieving higher detectivity (see Fig. 3d). This is because the noise current is much profound in the accumulation mode. The ultra-sensitive PT-based non-invasive photoplethysmogram (PPG) sensor has been demonstrated for heart rate measurements. In this example, the ultra-high photoresponsivity is realized through efficient charge transport by the donor molecules in the channel, while the prolonged minority (electron) lifetime is obtained by trapping the electrons in the acceptor.

The flexible PTs with a bulk heterojunction channel for cardiovascular monitoring has also been demonstrated as shown in Fig. 3e. The bio compatible flexible organic PTs can be readily used a portable sensor, as shown in Fig. 3f, for continuously monitoring of heart rate with reliable performance. The NIR PT PPG device has the high sensitivity and detectivity under ultra-low NIR intensity. In addition to the use of the fullerene acceptor and its derivatives in the bulk heterojunction, PTs with all polymer bulk heterojunction channel have additional advantages of superior mechanical and thermal stability. A broadband PT with an all polymer BHJ channel has been investigated. The complementary light absorption of the donor polymer and acceptor polymer is favorable to achieving a broadband light detection from 400 nm to 1100 nm. In addition,
the charge separation process between the donor and acceptor assists in an effective light detection. The formation of phase segregated nano-domain of the acceptor polymer and their randomly distribution in the donor matrix facilitate the charge separation process.

Light detection of an ambipolar organic FET with an all-polymer channel has been investigated\textsuperscript{50}. The all-polymer based PT also possesses a broadband light sensitivity due to the complementary absorption of the two polymer materials. It was found that the laterally phase-segregated donor and acceptor nanodomains and relatively large nanocrystalline structure formed in the binary polymer blend are responsible for enhanced light detection in the NIR region, due to more efficient charge separation and improved in-plane charge transport. The incorporation of binary blend donor/acceptor hybrid channel has the advantageous of efficient charge separation, short majority carrier transit time and long minority carrier lifetime, enabling the high photo gain.

The PTs with a hybrid channel having high carrier mobility enables efficient charge transportation, allowing much shorter transit time. These hybrid channel PTs enable simultaneously good NIR absorption, charge transport and collection, leading to an enhanced NIR photo-detection capability. The choice for charge transporting channel in the heterojunction type NIR PTs can be targeted on high carrier mobility materials, including indium gallium zinc oxide (IGZO), graphene and some other innovative 2D materials. The staggered hetero-interface in the heterojunction channel also provides favorable charge separation efficiency contributing to the photo current generation\textsuperscript{51}.

Solution processable CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3} has a broadband photoresponse over the wavelength from the UV to NIR region\textsuperscript{37,39,52}. To take the advantage of the excellent optoelectronic merits of perovskite materials in the PT application, an extra charge transport channel with excellent carrier mobility is usually introduced, forming hybrid channel PTs. The concept of a broadband PT with
a bilayer perovskite/IGZO channel (see Fig. 4a) has been reported. The perovskite layer in the bilayer channel is responsible for light absorption, while the highly conductive IGZO layer in the channel serves as an efficient charge transport path. The favorable matching in the energy levels between the perovskite and the IGZO in the bilayer channel, as shown in Fig. 4b, enables the efficient charge carriers generated in the perovskite layer are able to transfer to the IGZO layer, enabling the broadband light detection as illustrated in Fig. 4c.

High carrier mobility graphene is another hybrid channel choice for use in PTs. NIR PTs with bilayer CH$_3$NH$_3$PbI$_3$/graphene channel, as shown schematically in Fig. 4d, was reported. The combination of excellent light absorption in CH$_3$NH$_3$PbI$_3$ layer and efficient charge transport in the graphene layer is favorable for application in light detection. The empty states in the valence band of the perovskite can be occupied due to the electron transfer between the graphene and CH$_3$NH$_3$PbI$_3$, prolonging the lifetime of the photo excited electrons and thereby suppressing the recombination of photo generated electron and hole in the perovskite layer. The reduction in the intensity of the photoluminescence (PL) reflects the charge transfer taking placing at the perovskite/CH$_3$NH$_3$PbI$_3$ interface in the bi-layer channel (Fig. 4e). As a consequence, the resulting hybrid channel PT achieves a very high photoresponsivity and quantum efficiency. It shows that the PT with a bilayer channel exhibits high photoresponse extended to a long wavelength of 1000 nm, as shown in Fig. 4f.

The improvement in the performance of NIR PTs with a tri-layer perovskite/poly(3-hexylthiophene) (P3HT)/graphene, as shown schematically in Fig. 5a, were reported. The introduction of the organic absorbing P3HT layer helps to improve the exciton dissociation and charge separation in the channel layer. The holes generated in the perovskite layer can be transferred to the graphene effectively in the perovskite/P3HT/graphene channel, leaving photo
generated electrons remained in the perovskite layer, as shown schematically in the inset in Fig. 5b. The high carrier mobility in the graphene layer enables efficient photo-generated charge transportation, leading to a very short hole transit time in the tri-layer channel. The trapping of the photo-generated electrons in the perovskite layer also leads to an increase in the electron lifetime. The combination of the reduced hole transit time and prolonged electron lifetime is a prerequisite for attaining an ultrahigh photo gain. The trapping of the electron in the perovskite also introduces the charge carriers in the graphene layer due to the photogating effect, resulting in an increase in photocurrent. The photoresponsivity of the PTs with a hybrid channel is then realized over a broadband light wavelength range from 400 nm to 1200 nm (see Fig. 5c).

All solution processed broadband PTs with a hybrid channel comprising perovskite composite and chemically modified graphene were also reported. The solution processable materials, e.g., nitrogen-doped graphene QDs (NGQDs)-perovskite composite light absorbing layer and mildly reduced graphene oxide (mrGO) layer, have also been adopted for the channel in the PTs. The efficient electron transfer between perovskite and mrGO in the channel (see Fig. 5d) is enabled due to a favorable energy level gradient in the NGQDs (see Fig. 5e). The photo generated holes in the perovskite also induce photogating effect, thereby further contributing to the carrier density in the channel, leading to high photoresponsivity and high gain in PTs with a hybrid channel (Fig. 5f). The ultra-high photoresponsivity in these NIR PTs was attained by taking the advantages of simultaneous high light absorption and efficient charge transfer properties in the hybrid channel. However, some of the PTs with a hybrid channel may associate with a high noise level, reducing the photosensitivity due to the high dark channel current.

3.3 Nanostructured NIR PTs

Nanostructured materials have the advantages of tunable absorption in different wavelength
range, improved charge transport, plasmonic enhanced absorption, large surface to volume ratio etc., offering an attractive option for applications in optical sensor and bio imaging. To enhance photoresponse of NIR phototransistors, it is critical to control the charge carrier transport and trap density in the channel layer. Nano-structured materials, e.g., one-dimensional NWs or QDs, are emerging for high sensitive PTs. A summary of the performance of NIR PTs with different solution-processable nano-structured channel layers is listed in Table 2.

3.3.1 NIR PTs with nano-structured organic semiconductors

The well-ordered molecular packing of the organic semiconductor materials and conjugate polymers, enabled by post-deposition annealing treatment or addition of some additives, are beneficial for achieving efficient charge transport. It has been demonstrated that the enhanced π-π interactions between organic semiconducting molecules assist in the formation of unique anisotropic molecular arrangement, facilitating charge transport. The use of the channels with a variety of organic nano-crystals with unique feature of high carrier mobility has been studied extensively for application in high performance FETs. The efficient charge transport in channel with improved molecular packing results in enhanced photoresponsivity and respond speed. For example, high carrier mobility was observed in porphyrin based organic molecules with high degree of crystallinity. Needle-like crystalline organic semiconductor layers, as shown in Fig. 6a, form well-arranged molecular packing. The thin film of organic layer with nanowire structure has a superior light absorption (Fig. 6b) and carrier mobility to that of the amorphous thin film made with the same material system. The PTs with a nanowire network channel possess higher NIR light sensitivity as compared to the PTs made an amorphous channel layer using the same system, as shown in Fig. 6c, demonstrating a high NIR detection capability.

The organic channel layer with highly ordered molecular packing facilitates the efficient
transport of the NIR light generated charge carriers across the channel, thus enhance the NIR light
detection in the PTs\textsuperscript{62}. The enhanced NIR light detection in PTs with n-type small molecule
channel with improved crystallinity, attained by annealing processes, was demonstrated. The
annealing assists in forming striped crystalline domains (\textbf{Fig. 6d}) in the channel layer with
preferred orientation direction as compared to the smooth neat film. The increase in absorption of
the crystalline film was observed, as shown in the X-ray diffraction (XRD) measured for the
annealed film, indicating an enhanced film crystallinity and optical response. The efficient charge
transport is then attained in the channel layer with strip-featured crystal structure. An obvious
increase in channel current was observed having the long axis of the striped crystal domains
aligned parallel to the channel direction, seen in \textbf{Fig. 6e}. As a result, NIR PTs with an apparent
increase in photoresponsivity and sensitivity were obtained, due to a combination of efficient NIR
light absorption and efficient charge transportation properties in the channel. The NIR PTs exhibit
good photoresponsive extended to the long wavelength of 940 nm (\textbf{Fig. 6f}). It becomes clear that
the performance of NIR PTs depends not only on the electrical properties, but also counts on the
optical characteristics of the active channel layer. High carrier mobility and light absorption are
the prerequisite for attaining high performing NIR PTs.

The carrier mobility of the D-A polymer increases with its molecular weight. However, high-
molecular weight D-A polymer semiconductors generally suffer from processing complications
due to their limited solubility. Recently, we demonstrated that incorporation of polar or non-polar
insulator polymer into the diketopyrrolopyrrole-dithienylthieno[3,2-b]thiophene (DPP-DTT)
polymer semiconductor solution with an appropriate weight ratio of insulator polymer to DPP-
DTT polymer greatly improves its stability, forming high crystalline ordering semiconductor films.
In the DPP-DTT/polystyrene blend systems, we found that the DPP-DTT polymer can self-
assemble and crystallize out in the polystyrene insulator matrix as an interpenetrating, nanowire semiconductor network with the help of cooperative shifting motion of polystyrene chain segments. Atomic force microscopy (AFM) images measured for the neat DPP-DTT film and polystyrene blended DPP-DTT film, with a weight ratio of DPP-DTT to polystyrene of 40/60 wt.%. It is seen that the neat DPP-DTT film displayed mostly grainy, defused nano-domain features without any long-range orders. The polystyrene blended film formed well-defined nanowire-like structures, as seen in Fig. 6g, providing significantly enhanced mobility of >8 cm²/V·s and high on/off ratio of 10⁷, together with other desirable organic FET properties⁶³–⁶⁵. The red-shift in the peak absorption of the nanowire film as compared to the planer thin films, shown in Fig. 6h, indicate an improved molecular ordering⁶⁴. The nanowire network based NIR PTs have superior optoelectronic properties than that of the PTs with a planner pristine DPP-DTT channel layer. With NIR light illumination, the nanowire film based PTs showed higher photocurrent in the active channel, benefiting from improved carrier mobility that facilitated the photo-generated charge transport and collection. Meanwhile, the reduced contact resistance in NIR PTs with a nanowire featured channel also is responsible for the improvement in NIR detection, providing an effective charge collection at the electrode/channel interface. As a result, the NIR PTs with a nanowire channel exhibited an improved photoresponsivity under 850 nm illumination (see Fig. 6i), which is one order of magnitude higher than that of the PTs with a planner DPP-DTT channel layer. Observable improvements in transient photoresponse also were achieved mainly due to the improved carrier mobility in the NIR PTs having a nanowire network channel layer.

Nanowire phototransistors can also be fabricated through nano-transfer printing processes⁶⁶. The optoelectronic properties of the low bandgap polymer nanowires, fabricated using nano-transfer printing method, were analyzed. It shows that the imprinted nano-structured films with a
high surface-to-volume ratio help to improve the charge separation and transportation. The stronger photosensitive behavior was obtained in the PTs with a nanowire network channel, leading to a simultaneous improvement in both photoresponsivity and photosensitivity, as compared to the control PT having a planar channel layer.

### 3.3.2 NIR PTs with nano-structured inorganic semiconductor materials

Inorganic semiconductor materials, e.g., PbS, HgTe etc., based NWs and QDs can also be prepared using solution fabrication processes. The nano-structured inorganic materials are promising candidates for application in NIR PTs, due to their advantages of low-cost fabrication process and tunable absorption characteristics\(^{67}\). These materials have excellent light absorption over the long wavelength range from 1000 nm to 2000 nm\(^{12,68}\), broader than that of the photo responses of most organic semiconductor materials. The light detection over the wavelength range from 1000 nm to 1350 nm, the second biological window, is of great interest for application in bio-imaging\(^{69,70}\).

NIR PTs with a solution-processed PbS nanowire channel has been reported for use in NIR light detection\(^{71}\). The crystalline PbS nanowires with an average length of 10 µm and a diameter of 30-60 nm, synthesized via oriented attachment of nanoparticles, possess a high hole mobility of 31.6 \(\text{cm}^2\text{V}^{-1}\text{s}^{-1}\). The NIR PTs with a PbS nanowire-based channel have high photoresponsivity of \(1.9\times10^4 \text{A/W}\) and fast switching time of 15 ms. The PbS QDs with tunable dimeter can also be prepared. FETs with a PbS QD-based channel having a high carrier mobility of \(>30 \text{cm}^2\text{V}^{-1}\text{s}^{-1}\) have been demonstrated\(^{67}\). With tunable light absorption\(^{72}\) in the NIR region, PbS QDs are very attractive for application in NIR PTs. A vertical configuration phototransistor with a 110 nm long PbS QD channel, sandwiched between the transparent graphene source and gold drain electrodes,
was reported. The PbS QDs have a high absorption over the NIR region up to long wavelength of 1400 nm and an absorption peak at 1175 nm. A PT with a 110 nm long PbS QD channel having a fast transient photo response of ~10 ms was demonstrated\textsuperscript{73}. The development of PTs with a solution-processable HgTe QD channel has been also attempted. In comparison to PbS QDs, the light absorption of HgTe QDs covers a broader wavelength range and extended to a long wavelength of 2 μm\textsuperscript{74–76}. A PT with a solution-processed HgTe QD-based channel, prepared using spray coating method, with photo detection up to 2 μm was reported\textsuperscript{76}.

3.3.3 NIR PTs with nano-structured hybrid materials

The hybrid channel materials based on the combinations of PbS QDs with other functional materials, e.g., organic semiconductor materials, inorganic semiconductor materials and 2D materials, are very attractive for application in NIR PTs. The interfaces between different materials in the hybrid channel layers have the advantages for exciton dissociation and charge separation for NIR PTs\textsuperscript{51,77}, as compared to the process in single component channel layer of different materials.

NIR PTs with a P3HT: PbS QD blend channel were reported\textsuperscript{78}. PbS QDs and P3HT form a matrix, as depicted schematically in Fig. 7a, for exchanging the charge carriers between the PbS and P3HT in the blend, enabled due to the favorable energy alignment in the blend, as shown schematically in Fig. 7b. PbS QDs act as the charge generator in the presence of NIT light, and the p-type P3HT is responsible for effective charge transport in the blend channel layer. Vertical configuration NIR PTs with a bilayer layer P3HT/PbS QD composite channel were reported\textsuperscript{79}, taking the advantages of efficient exciton dissociation at the P3HT/PbS QD interface the short channel length, highly efficient carrier transport and collection for enhanced NIR light detection.

The characteristics of high charge carrier mobility and high sensitivity of electrostatic perturbation by photo-generated carriers near the surface of 2D materials, NIR PTs with a 2D-
based channel have been explored. NIR PTs with a channel layer made with different hybrid systems that consist of solution-processable inorganic nano-materials, e.g., PbS QDs, and 2D materials have been attempted. The combination of PbS QDs, acting as the efficient NIR light absorber, and the 2D materials, serving as the efficient charge transport path, is favorable for high performing NIR PTs.

The blend of graphene and PbS QDs is another promising channel candidate for application in NIR PTs. The efficient charge transfer between the PbS QDs and graphene in the hybrid channel, as shown schematically in Fig. 7c, is also desired for efficient operation of the NIR PTs. It is shown that NIR PTs with a hybrid PbS QD/graphene channel had a tunable light sensitivity over the wavelength range from 800 nm to 1600 nm, as shown in Fig. 7d. The ultra-high photo gain and EQE of the NIR PTs are attributed to the photogating effect, where photo-generated charge carriers can transfer to the graphene channel and the oppositely charged carriers remain trapped in the QDs, leading to a photogating effect by the capacitive coupling. The NIR PTs with a hybrid channel resulted in an ultra-high photoresponsivity of $10^9$ A/W and specific detectivity of $7 \times 10^{13}$ Jones.

Chemical vapor deposition was attempted for making a large area NIR PT with a PbS QD/graphene hybrid channel, as there is a technical challenge for obtaining high quality large area graphene layer using the exfoliation method. By carefully transfer the single layer graphene prepared on copper foils to the substrate, followed the subsequent coating of the PbS QD layer, PTs with a hybrid PbS QD/graphene channel exhibited an excellent NIR light detection capability. The PTs with a hybrid channel can also be fabricated on flexible substrates, showing good bendability due to the outstanding mechanical properties of the hybrid channel material.

It was shown that the ligands attached to the QDs also have an effect on charge transfer
efficiency at the QD/graphene interface. It is found that the choice of ligands attached to the PbS QDs has a dramatic impact on the photoresponsivity of the NIR PTs with a hybrid PbS QD/graphene channel layer. The decrease in length of the ligands attached to the QD surface leads to an increase in the efficiency of the photo-generated charge transferring from QDs to graphene due to the reduced dielectric barrier at the interface.

The transient photoresponse of the PTs with a hybrid PbS QD/graphene channel layer is usually in the scale of seconds, limiting their applications that require high response speed, e.g., video imaging and telecommunication. An approach for obtaining simultaneously the response speed, $EQE$ and linear dynamic range was obtained by monolithic integration of a PbS QD photodiode with a graphene PT, as schematically shown in Fig. 7e. In this design, the transient response and gain of the photodetector are enabled simultaneously taking the advantages of the high response speed of the QD photodiode and the carrier mobility of the graphene channel, respectively, as illustrated in Fig. 7f. Apart from using graphene in the hybrid channel layer, some other 2D materials, e.g., molybdenum disulfide (MoS$_2$), tungsten disulfide (WS$_2$) and tungsten diselenide (WSe$_2$) with high carrier mobility, are also demonstrated for application in high performing NIR PTs.

Solution processed inorganic semiconductor materials are relatively more stability as compared to most of the organic counterparts in air. NIR PTs with an all solution processed bilayer PbS QD/cesium lead bromide (CsPbBr$_3$) QD channel possess a photoresponsivity than the ones with a single component channel layer of PbS QD or CsPbBr$_3$ QD over the wavelength range from 400 nm to 1500 nm. The high performing NIR PTs with a bilayer PbS QDs/IGZO channel were also reported. The solution processable PTs having high photo sensitivity in the long wavelength of > 2 μm were also demonstrated by incorporating HgTe QDs with MoS$_2$ and infrared glass.
NIR PTs with a channel using other nano-structured materials, e.g., metal nanoparticles, Si QDs, carbon nano-tubes, have also been attempted. NIR PTs with a channel having gold nanorod (NR) decorated single-crystalline organic nanowires were reported for UV-vis-NIR photodetection. The enhanced light sensitivity was observed in NIR PTs with a channel containing gold NRs, achieved due to light scattering and localized surface plasmon resonance induced by the gold NRs the in channel layer, as shown in Fig. 8a. The enhanced electric field induced near the vicinity of gold NR surface in the presence of NIR light (see Fig. 8b) results in hot-carrier injection to the adjacent organic semiconductor, enabling the photocurrent under NIR light in the hybrid channel system. The NIR PTs with a gold NR channel had a boarder spectral response compared to the control NIR PTs with a pristine organic channel, as shown in Fig. 8c. The use of the gold NRs in the active channel layer helps to improve the performance of the NIR PTs through enhanced photo-absorption.

Apart from using metal nano-materials, the presence of the boron-doped Si QDs in the graphene channel also benefits the NIR absorption, caused by the plasmonic effect. The obvious enhancement in light detection over the mid-infrared region was realized in the PTs with a bilayer Si QD/graphene channel layer. The enhanced electric field at the Si QD/graphene interface, induced by the boron-doped Si QDs under the infrared light, assists in the photoexcitation in the graphene, as shown in Fig. 8d. The absorption of Si QDs over the UV-NIR wavelength region also contribute to channel current, created via charge transfer at the Si QD/graphene interface in the channel (see Fig. 8e), giving rise to the carrier density in the channel.

Carbon based materials are versatile in structure, chemical and optoelectronic properties, implying their potential in a broad range of applications. Semiconducting single wall carbon nanotube (SWNT) also is practically suitable for NIR photo detection due to the high
photosensitivity in the NIR range\textsuperscript{95}. NIR PTs with a hybrid SWNT/C\textsubscript{60} channel for enhanced infrared photo detection have also been demonstrated. It shows that the PTs with a hybrid channel possess a high photo gain due to the efficient electron transfer from carbon nano-tubes to C\textsubscript{60} (see Fig. 8f) and the electron trapping in the C\textsubscript{60} domains in the presence of NIR light, allowing multiple transport of holes in the SWNT channel and thereby leading to much improved photoresponsivity than that in photodiodes. A variety of materials and combinations of different material systems for hybrid channels offer the freedom for advancing NIR PT technology.

4. Applications of NIR PTs

High sensitivity NIR PTs have attracted significant interests due to a broad range of applications, e.g., thermal imaging, night-vision, health and safety monitoring, etc. The NIR phototransistors provide ultra-high photoresponsivity and ultra-low noise current by tuning the gate voltage. The PTs also are integrated and comparable with the external circuits and systems for data acquisition.

4.1 Visualizing NIR light

Conventional Si- or InGaAs-based based photodetectors are limited due to the high cost and fragile, rigid properties. Remarkable progress has been made over the past decade in the development of solution-processable devices for visualizing NIR light. Solution processable NIR photodetectors made with the organic, inorganic and organic/inorganic hybrid semiconductor materials demonstrate a great potential for use in NIR imaging applications\textsuperscript{96}. A prototype NIR imager operated at a wavelength of 1300 nm was demonstrated using a NIR PT with a hybrid PbS QD/IGZO cannel (Fig. 9a)\textsuperscript{90}. The imager made with single pixel photodetector was capable of imaging an NIR object made from a metal mask by scanning the NIR object at 1 Hz, as shown in Fig. 9b. The NIR PTs with a hybrid channel layer are potentially very attractive as an alternative
to the existing expensive commercial NIR imagers. The versatile NIR PT technologies provide more choices for application in NIR imaging. Recently, a high performing solution-processable NIR to visible light up-conversion organic/perovskite hybrid device, comprising a DPP-DTT/nonfullerene acceptor bulk heterojunction NIR charge generation layer and a perovskite light-emitting emitter, also was demonstrated for visualizing the NIR light.

4.2 Health monitoring

Due to the deeper penetration of NIR light into human tissue, NIR light is often used in medical monitoring applications, such as cardiovascular monitoring, blood pressure measurement etc. A PPG sensor that measures the volumetric data of an organ, is important in different health monitoring systems. In the cardiovascular monitoring system, the signal light is partially absorbed by the pulsed blood in human tissue, and the reflected or transmitted signal light can be detected by photodetectors, resulting in pulsed electrical signal, containing important data e.g., heart rate and blood oxygen level. During the systolic and diastolic processes, the detected optical density of the signal light varies due to the variation of erythrocytes and light-absorbing hemoglobin. Such variations of erythrocytes induce very weak change of the signal light intensity, therefore a highly sensitive photodetector becomes essential to precisely monitor the optical changes.

NIR PTs have the advantages of high sensitivity and low dark current, benefiting from its working principles. NIR PTs with an organic bulk heterojunction channel layer have an ultra-low noise current and thereby a high photo detection ability. The low noise level enables a high on/off ratio of channel current in the presence of NIR light, offering PTs an attractive option for application in detecting weak NIR light. An integration of NIR light emitting diode with an NIR PT for a reflection-type PPG sensor, as shown in Fig. 9c, was demonstrated. In this configuration, NIR light emitted from the LED is partially reflected by the microvascular bed in human finger
and then detected by the NIR phototransistor. The change of reflection of NIR signals is quite weak due to the tiny change in the volume of the pulsed blood. By using the NIR PTs with a bulk heterojunction channel, operated in the depletion mode with an ultra-low noise level, clear continuous systolic and diastolic process were captured by the NIR PTs without any amplifier or filter circuits, as shown in Fig. 9d. This indicates NIR PTs have the superiority over other sensors for application in compact and low-power microvascular monitoring.

The NIR PTs with an organic bulk heterojunction channel can also be fabricated on a flexible substrate for light weight and portable cardiovascular monitoring. Benefiting from the soft nature of the substrate and active materials, the flexible PPG sensors can be either attach to or surround the fingers. Such simple forms of PPG sensors also allow transfer printing the devices directly onto human skin, making the NIR PTs a very promising component for the next generation low-cost, mobile biomedical and monitoring devices.

4.3 Safety monitoring

Most vibrational modes of chemical bonds are located in the mid-infrared regime, making it important for the mid-infrared light detection, especially in safety monitoring applications, e.g., sensing toxic and hazardous gases. The traditional techniques for this purpose is based on expensive and size-limited inorganic materials, limiting their application in compact, large area and flexible electronics. PTs with a HgTe QD-based channel having a high specific detectivity and a high photo-detection at a long wavelength of >2 μm were demonstrated. This has been used for carbon monoxide (CO) detection, as CO molecules have a characteristic absorption at 2327 nm. In the CO detection, the intensity of a laser beam decreases after it passes through the gas tube with CO gas, resulting in a decrease in current in the HgTe QD-based PT, as illustrated
in Fig. 9e. The photograph taken for the measurement set-up is shown in Fig. 9f. The response of
the PT was quite sensitive to the variation in the concentration of the CO gas in the tube, implying
a high sensitive technique for detecting CO gas. The analysis of the drop in photocurrent because
of light absorption by the CO molecules, the CO concentration in the tube can also be calculated.

NIR PTs are highly versatile, flexible and can be prepared using flexible substrates. The recent
progresses made in high response speed and narrowband NIR photoresponse spectrum in NIR
PTs$^{101,102}$ are very encouraging. The solution-processed high-sensitivity NIR PT technologies
provide the functional superiority for application to large area NIR photodetection devices at low
cost. The emerging solution-processable nano-structured functional materials offer additional
advantages and process flexibility for NIR PTs with a range of applications in visualizing NIR
light, health and safety monitoring.

5. Summary

In this review, we discuss the recent advances in development of high performance NIR PTs
with novel device design knowledge and new materials processing technology. The advantages
and the performance of the NIR PTs with different channel configurations, e.g., matrix-mediated
nanowire networks of NIR-absorbing conjugate polymers, single component and heterojunction
inorganic semiconductor and organic/inorganic hybrids, are discussed. The high performance NIR
PTs with a single component channel layer benefit from the high carrier mobility, efficient charge
collection and easy fabrication process. However, the charge separation in NIR PTs with a single
component channel is limited due to the absence of the interface for efficient exciton disassociation
and charge separation. The NIR PTs with a bulk heterojunction type channel are adopted for
enhancing the NIR light detection, as the donor/acceptor interface in the bulk heterojunction
channel assists in an efficient charge separation. NIR PTs with a multi-layer channel were adopted
to further improve the photo gain. The high carrier mobility in a multi-layer channel leads to a combination of simultaneous achieving an ultra-low transit time for the majority carriers and a long lifetime for minority charge carriers via charge trapping process. The NIR PTs with a multi-layer channel take the advantages of the combined optical and electrical merits in the channel. Considerable research effort on low-cost solution fabrication process, e.g., assisted crystal growth of polymers with efficient charge transport and photonic structures in NIR PTs, are being carried out through new materials innovation and process optimization for achieving high-sensitivity NIR PTs.

With rapid technological development and economic growth, the development of technologies related to environmental pollution detection, health and security monitoring have attracted increasing interest. We are currently facing a series of environmental challenges including ocean pollution, soil quality deterioration, fog and haze, and so on. To prevent further harm to the environment, as well as to people, normative rules and systematic monitoring techniques should be established. The emerging solution-processable nano-structured functional materials offer additional advantages and process flexibility for NIR PTs with a range of applications in visualizing NIR light, environment, health and safety monitoring. The development of high performing solution-processable NIR PTs constitutes the next major step in this field.

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Figures and Tables

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<table>
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<tr>
<th>Channel type</th>
<th>Channel material</th>
<th>Mobility (cm$^2$V$^{-1}$s$^{-1}$)</th>
<th>Detection region (nm)</th>
<th>R (A/W)</th>
<th>P</th>
<th>$D^*$ (Jones)</th>
<th>Transient response</th>
<th>Ref.</th>
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<td>Single layer</td>
<td>pTTDPP-BT</td>
<td>0.066 ($\mu_h$) 0.115 ($\mu_e$)</td>
<td>405-850</td>
<td>NA</td>
<td>~60 (800nm)$^a$</td>
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<td>1.36 ($\mu_e$) 808</td>
<td>9×10$^4$ (808nm)</td>
<td>5×10$^5$ (808nm)</td>
<td>6×10$^{14}$ (808nm)</td>
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<td>$\tau_r$=6.5µs, $\tau_f$=5µs (white light)</td>
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<td>Single layer</td>
<td>CH$_3$NH$_3$PbI$_3$</td>
<td>0.18 ($\mu_h$) 0.17 ($\mu_e$)</td>
<td>400-800</td>
<td>~200 (750nm)$^a$</td>
<td>3.32×10$^4$ (p-type, white light) 8.76×10$^3$ (n-type, white light)</td>
<td>NA</td>
<td>$\tau_r$=6.5µs, $\tau_f$=5µs (white light)</td>
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<td>Bulk heterojunction</td>
<td>DPP-DTT:PCBM</td>
<td>0.3 ($\mu_h$) 8×10$^{-6}$ ($\mu_e$)</td>
<td>400-1050</td>
<td>8×10$^5$ (808nm)</td>
<td>1.6×10$^4$ (808nm)</td>
<td>3.5×10$^{12}$ (850 nm)</td>
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<td>DPP-DTT:PCBM</td>
<td>NA</td>
<td>810</td>
<td>3.5×10$^5$ (810nm)</td>
<td>NA</td>
<td>5.7×10$^{13}$ (810nm)</td>
<td>NA</td>
<td>$\tau_r$=100ms (810nm)</td>
</tr>
<tr>
<td>Bulk heterojunction</td>
<td>P3HT:PEHTPPD-BT</td>
<td>$3×10^{-4}$ ($\mu_h$)</td>
<td>550-1000</td>
<td>0.17-0.25 (800-1000nm)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>49</td>
</tr>
<tr>
<td>Bulk heterojunction</td>
<td>P3HT:PDPPTTT</td>
<td>0.14 ($\mu_h$) 0.06 ($\mu_e$)</td>
<td>450-795</td>
<td>~0.34 (795nm, p-type)$^a$ $~0.6$ (795nm, n-type)$^a$</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>50</td>
</tr>
<tr>
<td>Absorber/Channel</td>
<td>MAPbI$_3$/IGZO</td>
<td>12.9 ($\mu_e$) 385-850</td>
<td>$~10^{-3}$ (850nm)</td>
<td>1.33×10$^6$ (550 nm)</td>
<td>9.5×10$^8$ (550 nm)</td>
<td>$\tau_r$=40ms, $\tau_f$=100ms (550 nm)</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Absorber/Channel</td>
<td>CH$_3$NH$_3$PbI$_3$/graphene</td>
<td>NA</td>
<td>400-850</td>
<td>180 (520nm)</td>
<td>NA</td>
<td>$&gt;10^9$ (520 nm)</td>
<td>$\tau_r$=87ms, $\tau_f$=540ms (520 nm)</td>
<td>54</td>
</tr>
<tr>
<td>Absorber/Channel</td>
<td>CH$_3$NH$_3$PbI$_3$/P3HT/graphene</td>
<td>1840 ($\mu_h$) 2120 ($\mu_e$)</td>
<td>350-1300</td>
<td>4.3×10$^9$ (598nm)</td>
<td>NA</td>
<td>NA</td>
<td>$\tau_r$=several seconds, $\tau_f$=hundreds of seconds (598 nm)</td>
<td>55</td>
</tr>
<tr>
<td>Absorber/Channel</td>
<td>NGQDs-perovskite/mrGO</td>
<td>NA</td>
<td>365-940</td>
<td>1.92×10$^4$ (660nm)</td>
<td>NA</td>
<td>2.71×10$^{13}$ (660nm)</td>
<td>$\tau_r$=1.3ms, $\tau_f$=10ms (660 nm)</td>
<td>56</td>
</tr>
</tbody>
</table>

$^a$: estimated from the reference.
### Table 2 Summary of the characteristics measured for the solution-processed nano-structured NIR PTs

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Channel material</th>
<th>Mobility (cm$^2$ V$^{-1}$ s$^{-1}$)</th>
<th>Detection region (nm)</th>
<th>$R$ (A/W)</th>
<th>$P$</th>
<th>$D^*$ (Jones)</th>
<th>Transient response</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline needle</td>
<td>ZnTP</td>
<td>1.2 (thin film, $\mu_h$) 2.9 (crystalline-needle, $\mu_h$)</td>
<td>365-850</td>
<td>2.2×10$^4$ (474nm)</td>
<td>4.6×10$^6$ (474nm)</td>
<td>NA</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Crystalline texture</td>
<td>BODIPY-BF2</td>
<td>1.13×10$^{-1}$ ($\mu_e$) 760-940</td>
<td>1.14×10$^4$ (850nm) 1.04×10$^4$ (850nm)</td>
<td>2.2×10$^4$ (474nm)</td>
<td>4.6×10$^6$ (474nm)</td>
<td>NA</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Organic NW</td>
<td>DPP-DTT</td>
<td>4.0 ($\mu_h$) 850 246 (850nm)</td>
<td>1.3×10$^4$ (p-type) 3.1×10$^4$ (n-type)</td>
<td>2.2×10$^4$ (474nm)</td>
<td>4.6×10$^6$ (474nm)</td>
<td>NA</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Organic NW</td>
<td>PBIBDF-TT</td>
<td>0.005 808 0.44 (p-type) 0.07 (n-type)</td>
<td>3.1×10$^4$ (p-type) 3.1×10$^4$ (n-type)</td>
<td>2.2×10$^4$ (474nm)</td>
<td>4.6×10$^6$ (474nm)</td>
<td>NA</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>Inorganic NW</td>
<td>PbS NW</td>
<td>166 ($\mu_h$) 850 1.9×10$^4$ (850nm)</td>
<td>1.3×10$^4$ (p-type)</td>
<td>3.3×10$^4$ (n-type)</td>
<td>1.9×10$^13$ (850nm)</td>
<td>$\tau_r$=15.3ms, $\tau_f$=15.6ms (850 nm)</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD</td>
<td>PbS QD</td>
<td>3.3 ($\mu_h$) 3.5 ($\mu_e$) 808 4.2×10$^2$ (808nm)</td>
<td>2.1×10$^9$ (808nm)</td>
<td>1.9×10$^{11}$ (808nm)</td>
<td>1.9×10$^{13}$ (808nm)</td>
<td>$\tau_r$=12ms, $\tau_f$=198ms (n-type, 808nm)</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD</td>
<td>HgTe QD</td>
<td>~10$^{-3}$ ($\mu_h$ at RT) 1600-2400</td>
<td>2.1×10$^6$ (1600nm)</td>
<td>1.2×10$^{15}$ (1600nm)</td>
<td>1.9×10$^{13}$ (850nm)</td>
<td>$\tau_r$=10ms, $\tau_f$=100ms (p-type, 808nm)</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD: polymer</td>
<td>PbS QD:P3HT</td>
<td>0.01 ($\mu_h$) 895 2×10$^4$ (895nm)</td>
<td>1.3×10$^4$ (p-type)</td>
<td>3.3×10$^4$ (n-type)</td>
<td>1.9×10$^{13}$ (850nm)</td>
<td>$\tau_r$=0.26s (895nm)</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD: polymer</td>
<td>PbS QD/P3HT</td>
<td>0.43 ($\mu_h$) 0.06 ($\mu_e$) 400-2100</td>
<td>9×10$^4$ (808nm)</td>
<td>1.9×10$^{13}$ (808nm)</td>
<td>1.9×10$^{13}$ (850nm)</td>
<td>$\tau_r$=10ms, $\tau_f$=100ms (p-type, 808nm)</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD: graphene</td>
<td>PbS QD/ graphene</td>
<td>10$^{5}$ 600-1100</td>
<td>~5×10$^7$ (950nm)</td>
<td>7×10$^{13}$ (808nm)</td>
<td>7×10$^{13}$ (950nm)</td>
<td>$\tau_r$=9.4ms, $\tau_f$=9ms (808nm)</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD: graphene</td>
<td>PbS QD/ graphene</td>
<td>NA 895nm</td>
<td>10$^7$ (895nm)</td>
<td>NA</td>
<td>NA</td>
<td>$\tau_r$=0.26s (895nm)</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Inorganic nano-plate/ MoS$_2$</td>
<td>PbS nano-plate/MoS$_2$</td>
<td>1.4 ($\mu_e$) 800-1064</td>
<td>4.5×10$^4$ (800nm)</td>
<td>1.3×10$^{13}$ (800nm)</td>
<td>3×10$^{13}$ (800nm)</td>
<td>$\tau_r$=7.8ms (800nm)</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD/ MoS$_2$</td>
<td>PbS QD/MoS$_2$</td>
<td>10-20 ($\mu_e$ of MoS$_2$) 600-1200</td>
<td>~10$^5$ (1000nm)</td>
<td>5×10$^{11}$</td>
<td>$\tau_r$=0.35s</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic QD/ WS$_2$</td>
<td>PbS QD/WS$_2$</td>
<td>0.32 ($\mu_h$) 0.68 ($\mu_e$) 808</td>
<td>4×10$^8$ (808nm)</td>
<td>3.9×10$^{10}$ (808nm)</td>
<td>3×10$^{13}$ (808nm)</td>
<td>$\tau_r$=153µs, $\tau_f$=226µs (808nm)</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>Inorganic QD/ WSe$_2$</td>
<td>PbS QD/WSe$_2$</td>
<td>110 ($\mu_h$) 400-1400</td>
<td>7×10$^5$ (970nm)</td>
<td>5×10$^{11}$</td>
<td>$\tau_r$=7ms, $\tau_f$=0.48s (970nm)</td>
<td>88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic QD hybrid</td>
<td>PbS QD/ CsPbBr$_3$ QD</td>
<td>4083</td>
<td>400-1500</td>
<td>$10^4$ (808nm)</td>
<td>NA</td>
<td>$1.26\times10^{13}$</td>
<td>$\tau_r=6.5$ms, $\tau_f=7.5$ms (808nm)</td>
<td>89</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------------</td>
<td>------</td>
<td>-----------</td>
<td>----------------</td>
<td>-----</td>
<td>-------------------</td>
<td>----------------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Inorganic QD and oxide</td>
<td>PbS QD/IGZO</td>
<td>13.1</td>
<td>700-1400</td>
<td>$&gt;10^6$ (1000nm)</td>
<td>$\sim3\times10^4$ (1000nm)$^a$</td>
<td>$&gt;10^{13}$ (1000nm)$^a$</td>
<td>$\tau_r=0.1-0.2$s, $\tau_f=0.2-$0.3s (1300nm)</td>
<td>90</td>
</tr>
<tr>
<td>Inorganic QD/ MoS$_2$</td>
<td>HgTe QD/ TiO$_2$/MoS$_2$</td>
<td>18 ($\mu_e$ of MoS$_2$)</td>
<td>600-2100</td>
<td>$\sim10^5$ (2000nm)$^a$</td>
<td>NA</td>
<td>$10^{12}$ (2000nm)$^a$</td>
<td>$\tau_r$ , $\tau_f$ in sub-milliseconds (1310nm)</td>
<td>75</td>
</tr>
<tr>
<td>Organic NW/ metal NR</td>
<td>BPE-PTCDI/ Au NR</td>
<td>0.324</td>
<td>350-1200</td>
<td>10.7 (980nm)</td>
<td>$9.54\times10^4$ (980nm)</td>
<td>NA</td>
<td>$\tau_r\leq3.9$s, $\tau_f\leq1.82$s (980nm)</td>
<td>92</td>
</tr>
<tr>
<td>Inorganic QD/ graphene</td>
<td>Si QD/graphene</td>
<td>NA</td>
<td>375-3900</td>
<td>$\sim10^9$ (1450nm)$^a$</td>
<td>NA</td>
<td>$\sim10^{13}$ (1450nm)$^a$</td>
<td>$\tau_f=3.4-9$s</td>
<td>94</td>
</tr>
<tr>
<td>Organic/SWNT</td>
<td>C$_60$/SWNT</td>
<td>NA</td>
<td>1000-1400</td>
<td>97.5 (IR)</td>
<td>23</td>
<td>$1.17\times10^9$ (IR)</td>
<td>$\tau_r$ , $\tau_f$ in the order of 2-4ms</td>
<td>95</td>
</tr>
</tbody>
</table>

ToC