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ABSTRACT

Energy consumption is one of the most important aspects of any electronic device which needs further improvements in order to achieve a better sustainable future. This is equally true for commercially available photodetectors, which consume a lot of energy by using huge external bias voltage. So far, thin films have been widely used for photodetection of various bands of electromagnetic radiation. The only property which holds them back is the slower performance and lower responsivity compared to nanostructure-based devices. However, the disadvantage associated with nanostructure-based photodetectors is that they lack scalability for mass production or commercialization, due to the complex and expensive device fabrication steps. One of the plausible solutions for this limitation could be the use of hybrid structures, which are the combination of high-quality crystal materials such as ZnO, (Al, Ga, In)N, and GaAs with 2D materials consisting of MoS$_2$, graphene, WSe$_2$, and SnS$_2$. This would provide extensive control over bandgap engineering, which could be used for scalable modular device fabrication. These approaches promise the development of photodetectors with relatively higher responsivities as well as self-powered photodetection. The current perspective focuses on the advancements in III-nitride-based photodetectors and their promising potentials for self-powered, broadband, and ultrafast photodetectors using hybrid III-nitride/2D interfaces.

INTRODUCTION

Photodetectors (PDs) are used in various applications from everyday consumer electronics (smoke detectors, compact disk players, remote control, relay switches, etc.) to more complex applications, such as space research, optical environmental monitoring, communication, etc. The fundamental working principle of photodetectors can be conceptualized from the photoelectric effect. In 1900, the German physicist Max Planck conceptualized that heat radiation is emitted and absorbed in the discrete units also known as quanta. Furthermore, in 1905, Einstein explained the photoelectric effect by using the concept of photon or light quanta which are packets of electromagnetic radiation. Subsequently, it was discovered that when light falls on some semiconductors, they increase their overall conductivity, which is also known as the photoconducting effect. PDs are the devices developed on the principle of the photoconducting effect and measure the amplitude (responsivity) and the speed (transit time) at which they gain maximum conductivity with respect to the variation in the incoming radiation.

Considerable research has been devoted in order to improve responsivity and the transit times (on/off time) of the modern photodetectors. However, recent research is focused more on the overall power consumption, the third most important but not much explored key requirement for the PDs. Most of the PDs require a constant electrical power source for realizing appreciable detectivity and, therefore, the overall circuitry turns out to be unprofitable in the recent energy framework of limited resources. Thus, it is of the utmost benefit if these devices can function without any...
external power supply (voltage source) or in simple words if they can be turned into a self-powered device or photovoltaic photodetectors. There are many reports on different types of self-powered PDs, such as p–n junctions, heterojunctions, Schottky junctions, and hybrid junctions.\textsuperscript{8,17,21–26} All the self-powered PDs are driven by a strong built-in electric field at the junctions, which effectively separate the electron-hole pairs instantly, thus favoring ultra-fast response and higher responsivity while no external bias is applied. Self-powered photodetectors have seen tremendous research growth recently;\textsuperscript{2,3,5,8,10,11,17–19,21,22,24,26–40} however, they are not on par with the commercially available PDs in terms of overall device performance; thus, it is extremely important to understand and improve the aspects which inhibit their potential and eventually self-powered photodetectors can be commercialized.

Below we present some of the important factors for self-powered PDs, which are necessary to drive the overall circuitry, and define their usability with respect to commercially available PDs. However, before we dive deep into self-powered devices, it is of utmost importance to investigate the photodetection parameters of commercially available detectors and what properties can be extracted from them for the benchmarking of self-powered PDs. Table I lists some of the commercially available Si-, Ge-, and InGaAs-based PDs used for visible to infrared (IR) region of the spectrum. Their responsivities are usually around few A/W, and the driving voltage for their circuit is very high (5–200 V). The aspect mismatch [\(14\%\) for GaN/Al\(_2\)O\(_3\), \(\sim\)12% for InN/AIN, \(\sim\)8% for InN/Si (111), \(\sim\)17% for GaN/Si (111), \(\sim\)11% for InN/GaN, \(\sim\)19% for AIN/Si (111)] and the mismatch in thermal expansion coefficients remain as main challenges for the growth of epitaxial III-nitride films. However, the growth of high-quality crystals not only requires complicated steps but the achieved crystal quality is also not sufficient to overcome the challenges they possess for device fabrication.

**TABLE I.** Commercially available PDs and their optical properties.\textsuperscript{41,42}

| Parameter                  | Silicon PIN\textsuperscript{a} | APD\textsuperscript{b} | Germanium PIN | APD | InGaAs PIN | APD |
|----------------------------|---------------------------------|-------------------------|---------------|-----|------------|-----|
| Wavelength range (nm)      | 400–1100                        | 800–1800                | 900–1700      |     |            |     |
| Peak (nm)                  | 900                             | 1550                    | 1300          |     | 1300       |     |
| Responsivity (A/W)         | 0.6                             | 0.65–0.7                | 3–28          |     | 0.63–0.8   | 0.75–0.97 |
| Quantum efficiency (%)     | 65–90                           | 50–55                   | 55–75         |     | 60–70      | 60–70 |
| Bias voltage (V)           | 45–100                          | 6–10                    | 20–35         |     | 5          | <30  |
| Rise time (ns)             | 0.5–1                           | 0.1–0.5                 | 0.5–0.8       |     | 0.06–0.5   | 0.1–0.5 |

\textsuperscript{a}PIN—p-type–intrinsic–n-type.  
\textsuperscript{b}APD—avalanche photodiode.

**TABLE II.** Expected performance values of broadband self-powered PDs.

| Parameter            | Value |
|----------------------|-------|
| Operational voltage (V) | 0     |
| Responsivity (A/W)   | >1    |
| Spectral range (nm)  | 300–1200 |
| Quantum efficiency (%)| >50   |
| Transit time (ms)    | <1    |

**SUITABLE MATERIALS FOR PHOTODETECTION**

Most extensively studied inorganic semiconductors (InGaAs, InGaSb, ZnO, GeSi, Ga\(_2\)O\(_3\), etc.)\textsuperscript{5,21,43–46} are being used for developing PDs, due to some of their striking properties, including high carrier mobility and high absorption coefficients, but suffer from downsides, such as large exciton binding energy, a narrow detection range, and low responsivities. For the growth of arsenic-based semiconductors (GaS, InGaAs, etc.), arsenic (As\(_2\)H\(_3\)) is often used as a precursor, which is an extremely toxic gas. Inhalation of these gases neutralizes oxygen absorption by the bloodstream and can be fatal. Antimony (Sb) is also an environmental hazard, which has similar effects such as “As” poisoning. Furthermore, the post-processing step of dicing produces very fine particles containing As or Sb, which could be extremely dangerous if inhaled and ingested as well as it can be an environmental hazard. Some of these materials use toxic precursors such as arsenic. On the other hand, III-nitride materials (Al, Ga, In)N have lower values of exciton binding energies; hence, they facilitate easier separation of electrons and holes.\textsuperscript{16} Consequently, III-nitride semiconductors are suitable candidates for self-powered PDs because of their direct and tunable bandgap, which can be varied from 0.7 eV to 6.2 eV, superior electronic properties, chemical inertness, radiation hardness, mechanical stability, and ability of establishing heterostructures over other materials.\textsuperscript{2,7,47} Based on the above-mentioned excellent properties, various efforts are evident on the development of III-nitride-based self-powered PDs.\textsuperscript{2,4,13,30,40,48,49}

Nevertheless, lack of appropriate substrates in terms of lattice mismatch \([-14\%\) for GaN/Al\(_2\)O\(_3\), \(\sim\)12\% for InN/AIN, \(\sim\)8\% for InN/Si (111), \(\sim\)17\% for GaN/Si (111), \(\sim\)11\% for InN/GaN, \(\sim\)19\% for AIN/Si (111)] and the mismatch in thermal expansion coefficients remain as main challenges for the growth of epitaxial III-nitride films. However, the growth of high-quality crystals not only requires complicated steps but the achieved crystal quality is also not sufficient to overcome the challenges they possess for device fabrication.
and high output. On the other hand, 2D materials such as graphene, MoS$_2$, SnSe$_2$, and WS$_2$ look very promising if integrated with III-nitride materials because of their amazing electronic properties such as very high mobility, bandgap engineering by varying number of layers, and their flexibility to reshape them according to the anticipated device structures. Most importantly, individual layers of MoS$_2$ are bound together with the help of van der Waals bonds between them; thus MoS$_2$, in general, does not require any epitaxial substrate to grow and is expected to be easily integrated with III-V and other semiconductors.

Graphene is a well-known 2D material; however, the lack of bandgap in graphene limits its application as a switch and, hence, hinders its usage in photodetection applications. On the other hand, MoS$_2$, a layered transition metal dichalcogenide (TMDC), looks very promising due to its bandgap (1.2 eV) in the IR region. A bandgap of 1.2 eV in MoS$_2$ promises enormous outcomes while integrated with Si (1.1 eV) but also a great feat of band engineering can be achieved with the combination of TMDCs and III-nitride semiconductor materials or their insertion between MoS$_2$ and Si. Another interesting property of MoS$_2$ is the tuning of the bandgap with the variation in the number of layers, and it has been shown by various reports that its bandgap increases from $\sim$1.2 eV (bulk) to $\sim$1.8 eV (monolayer). This property also promises a great deal of scientific outputs with the numerous possible achievable configurations while integrating with III-nitrides.

The current perspective begins with the discussion about different methods for the growth and deposition of these materials followed by some of the very important early photodetection results observed for III-nitrides and other materials. In addition to the different device configurations for the self-powered and broadband photodetection, their merits, demerits, and limitations are discussed with the introduction of 2D matrix on a 3D semiconductor. In the end, the importance of such combinations of 2D (MoS$_2$) materials with III-nitrides, future challenges, expected device properties, and usage are discussed.

**EXPERIMENTAL TECHNIQUES**

**Molecular beam epitaxy**

Molecular beam epitaxy (MBE) is an epitaxial growth technique for the fabrication of advanced structures with a control over composition and doping profiles at nanometer scales. The schematic diagram of MBE is shown in Fig. 1. Growth mechanisms in MBE allow the growth of (i) two-dimensional thin films with atomically smooth interfaces, (ii) one-dimensional nanorods, and (iii) zero-dimensional quantum dots that can completely confine carriers with lattice-matched and lattice-mismatched substrates. MBE is based on interactions of atomic or molecular beams from ultra-pure effusion sources with reactive gases or plasma of gases, on a heated crystalline substrate. The growth relies on the kinetic processes such as adsorption, desorption, surface diffusion, migration, incorporation, and decomposition of the reactive atoms or molecules. These features allow real-time and in situ control during the film growth to ensure ultra-high quality and clean interfaces. Because of these advantages of MBE, it is being widely used to demonstrate most of the novel semiconductor-based devices which are of interest for electronics and optoelectronics at the nanoscale.

**Pulsed laser deposition**

Pulsed laser deposition (PLD) is a physical vapor deposition technique, which uses the high energy of a pulsed laser to excite the target surface. This energy leads to electronic excitations, local heating, and physical ablation of the surface atoms or molecules. The species that get ablated from the surface of the target form a plasma plume, which in turn is directed toward a heated substrate where deposition occurs. The physical and chemical processes that occur at the target and the substrate surfaces are complex and depend on the deposition parameters such as target chemistry, laser fluence, target to substrate distance, deposition pressure, and the carrier gas in the chamber present during deposition; these parameters are tuned according to the deposition requirement. The biggest advantage associated with PLD is the capability of exact stoichiometric transfer of the target material onto a substrate, i.e., the replication of the exact chemical composition of a complex compound in the deposited film. This provides the capability to virtually deposit anything (a metal, a semiconductor, or an insulator) using PLD, with precise control over the thickness.

**Chemical vapor deposition**

Chemical vapor deposition (CVD) is a growth technique in which semiconductor films of various configurations are grown from the vapor phase, by the decomposition of chemical(s) on the surface of a heated substrate. The growth of the film is controlled by chemical reactions on the heated substrate; therefore, this method is more versatile compared to other deposition techniques. Mostly, the process is thermally driven; however, photo- and plasma-assisted methods can also be used. Growth occurs under non-equilibrium conditions, and the nature of chemical precursors can be used to
control the phase formation and its morphology. One of the most significant advantages of CVD methods over the other growth methods is the high growth rate, which helps in producing very thick films and sometimes high-quality crystal substrates.

FIGURES OF MERIT FOR PHOTODETECTORS

In the previous sections, we briefly focused on the importance and applications of III-nitride-based devices, the important figure of merits of these PDs as well as the different growth techniques to fabricate high-quality thin films. Numerous reports are evidently demonstrating the photodetection properties of GaN-based PDs as GaN still remains one of the most widely exploited wide bandgap semiconductors. In this section, we will briefly discuss the recent state-of-the-art PDs based on III-nitrides and their heterostructures. A special and elaborate emphasis on the different approaches unveiled to achieve self-powered photodetection with III-nitride-based PDs and the associated challenges, which must be addressed, has been included.

GaN/perovskite junction

Pandey et al.\textsuperscript{63} have shown the fabrication of BaTiO$_3$/GaN (BTO/GaN)-based Schottky junction on c-plane sapphire using PLD and its performance in high temperature selective ultraviolet photodetection in the range of 313–423 K. The responsivity was found to increase with respect to the temperature up to 393 K and then it decreases. Such a behavior has been explained in terms of the enhancement in the dark current with temperature, which is evident from the ideal diode equation, and promises to be used as UV PDs in high-temperature applications.

Non-polar III-nitrides

For the epitaxial growth of GaN, the lack of lattice-matched substrates is still one of the major hindrances for the development of high-performance devices. Growth of epitaxial GaN in non-polar direction seems to be a viable way because the lattice mismatch between non-polar a-plane (11–20) GaN and r-plane (1–102) sapphire is lowest (1.19%) along one of the azimuths.\textsuperscript{35,20,64,65} Heterostructures grown along the polar axis exhibit large internal electric fields at the interface, which can affect the radiative recombination rates.\textsuperscript{66,67} To overcome this polarization issue, non-polar nitrides are being widely explored because of their advantages over the polar nitrides, as the latter develops spontaneous polarization along with the piezoelectric polarization. Mukundan et al.\textsuperscript{38} have shown better performance of non-polar GaN as compared with that of polar GaN in terms of device performance and stability.

The mechanism of higher performance of nonpolar a-GaN was explained by Pant et al.\textsuperscript{22} by using azimuth angle-dependent interdigitated-electrodes (IDEs). They showed that the defects are not uniform along the different azimuth directions as the strain between the substrate (r-plane sapphire) and film (a-plane GaN) is not symmetric because of the asymmetric lattice mismatch along different in-plane crystal directions. The lattice mismatch along the [0002] direction is ~1% while that along [1–100] is ~13%, which induces a lot of defects along [1–100] compared to the [0002] azimuth direction.\textsuperscript{20,64,68} In Figs. 2(a)–2(c), the relationship and alignment between r-sapphire and a-GaN, the schematic of IDEs on a-GaN, and an actual image of IDEs have been shown. Furthermore, Pant et al.\textsuperscript{21} have shown that the overall current and also the responsivity in the UV region and the internal gain are dependent on the azimuth angle [Figs. 2(d) and 2(e)] and are in the order of [0002] > [1–102] > [1–100]. The highest responsivity found was 1.88 A/W and 13.0 A/W at 1 V and at 5 V, respectively. These results emphasized the need for aligning the electrodes to restrict the transport along the favorable azimuth directions while a wide variety of nonpolar materials are concerned. Pant et al.\textsuperscript{21} have shown further improvements in the photodetection properties by controlling the growth parameters and improving the overall crystal quality. They were able to achieve 25 A/W at a very low bias of 1 V; this is the highest reported responsivity at such low voltages.\textsuperscript{21}

The above-mentioned results showed a huge jump in the photodetection properties with regard to III-nitride and its heterostructures. They require some operational voltage. It would be extremely important if a significant reduction or complete removal of the external bias can be achieved while still maintaining the required photodetection properties to make it a usable device.

SELF-POWERED PHOTODETECTORS AND THE CHALLENGES ASSOCIATED

All the above-mentioned reports demonstrate PDs that require an external bias for photodetection. Now, we will shift our focus to self-driven PDs, which have numerous advantages. Here, we will restrict our discussion to III-nitride-based PDs and their heterostructures with 2D layered materials. There are various reports in literature of utilizing asymmetrical electrodes or making heterojunctions in order to generate a built-in electric field for the effective separation of photogenerated charge carriers at a zero biasing condition.

Asymmetrical electrodes

Prakash et al.\textsuperscript{32} have demonstrated a self-powered photodetector utilizing an rGO and GaN heterojunction [Fig. 3(a)]. This integration of transparent rGO electrodes with GaN has been realized via a simple drop-casting technique, thus leading to a simple device fabrication process and reduced cost and processing time. The hybrid device shows a low responsivity of 0.0015 mA/W at zero bias in the UV region with fast response recovery times of 60 ms and 267 ms. The mechanism of generation and the transport of photocurrent have been explained with the help of an energy band diagram with the equivalent circuit, as shown in Figs. 3(c) and 3(d). The difference between the work functions of the two semiconducting materials leads to the formation of a depletion region at the rGO/GaN interface. Because of the inhomogeneous nature of the drop casted electrodes, two unlike built-in electric fields from GaN to rGO surface develop at the interface. The difference between the two unlike electric fields results in a net electric field in the device, which leads to the self-powered transport of the photogenerated charge carriers.

Another way is to use different materials as electrodes for fabricating self-driven electronic devices. Peng et al.\textsuperscript{31} reported a self-powered photo-switch based on a flexible GaN thin film, utilizing the piezo-phototronic effect to enhance the on/off ratio.
The film was prepared by low-pressure metal organic chemical vapor deposition (MOCVD) and, later, transferred onto a flexible polyethylene terephthalate (PET) substrate. An unsymmetrical metal–semiconductor–metal (MSM) structure with Pt and Ni electrodes was made, and an ordered aluminum nanoparticle array was spread on the c-face GaN active layer to enhance the UV absorption property of GaN. A responsivity of 0.03 A/W could be attained for low-intensity UV illumination at 0 V, with rise and fall times of ∼0.1 s.

The limitation of such devices lies with the photoresponse, which is dependent entirely on the degree of asymmetry between the contact electrodes. This decides the difference in the barrier heights and ultimately the net internal electric field, thus limiting the device performance.

**Heterojunctions**

The most efficient way for achieving self-driven photodetection is by utilizing the built-in potential of a heterojunction. Tchernycheva et al. reported the optoelectronics properties of p-GaN/InGaN (50 nm)/n-GaN core-shell nanowires operated at zero bias. The core-shell nanowires were grown by the metal-organic vapor-phase epitaxy (MOVPE) technique to ensure a conformal coverage on the nanowire sidewalls. The responsivity of the core-shell nanowire photodetector was found to be 0.075 A/W at a wavelength of 382 nm at zero applied bias, whereas the response time was found to be below 0.5 s. However, handling and processing such nanostructured semiconductors exhibit a huge challenge while scaling the photodetectors dimensions for industrial purpose, unless they promise better performance as compared to commercially available photodetectors.

The challenge associated here is to get high responsivity with faster transit times, which may be overcome by realizing heterojunctions where the semiconductors have a considerable difference in their electron affinities. The advances on the high growth quality of InGaN thin films on Si substrates by MBE and the maturity of the Si-based technology resulted in the demonstration of high-performance PDs, as demonstrated by Chandan et al. They reported a UV PD based on an n-InGaN/n-Si...
isotype heterojunction, which operates at 0 V. The n-InGaN/n-Si heterostructure was grown by plasma-assisted molecular-beam epitaxy (PAMBE). The x-ray rocking curve revealed the presence of a large number of threading dislocations at the interface of the heterostructure, which was also confirmed by the cross-sectional, transmission electron microscopy (TEM) image of the InGaN/Si (111) heterojunction [Fig. 4(b)]. The heterojunction formed showed a non-linear behavior [Fig. 4(a)] and the photodetection properties...
of the heterostructure exhibited a responsivity of 0.094 A/\text{W}, with rise and fall times less than 0.1 s. The authors have explained the mechanism of self-powered detection on the basis of an equivalent band diagram to understand the presence of internal built-in electric field at the interface as shown in Figs. 4(c) and 4(d).

Song et al.\textsuperscript{18} reported a broadband photodetector with wavelength photoresponse from the ultraviolet to near-infrared region based on the GaN microwire array/Si heterojunctions. The GaN microwire array has been prepared by MOCVD on a patterned SiO\textsubscript{2}/Si substrate. Introduction of a thin AlN layer in between GaN and Si produces large band offsets on both sides, which act as the driving force for self-driven detection. The detector exhibits a responsivity of 0.470 A\text{W}\textsuperscript{-1} at zero bias in the wavelength range of 320–850 nm. A fast response has also been recorded with rise/fall times as low as 2 ms. The advantage of such structures is the increased surface to volume ratio, which leads to more exposed sites for light absorption. The self-powered mechanism in the different wavelength ranges have been depicted in Fig. 5.

Exploiting this criterion of the difference in the electron affinities, a similar improvisation in the InGaN/Si structure has been reported by Chowdhury et al.,\textsuperscript{2} where the introduction of an AlN layer sandwiched between InGaN and Si leads to multifold enhancement in the photoresponse. The n\textsuperscript{+}-InGaN/AlN/n-Si(111) heterojunction is realized by growing an InGaN thin film on an AlN/Si template using PAMBE. The heterojunction exhibits an excellent self-powered and broadband photodetection under UV-visible (300–800 nm) light illumination [Fig. 6(a)]. The self-powered photodetector shows a high responsivity of 9.64 A/\text{W} at a wavelength of 580 nm, with an ultrafast response and recovery times of 19.9 $\mu$s and 21.4 $\mu$s, respectively [Fig. 6(b)]. The maximum response is believed to be due to the deep donor defect states, present near the InGaN/AlN interface. The self-powered photodetection mechanism has been explained with the help of a proposed band diagram, as depicted in Fig. 6(c).

### 2D/III-nitride-based heterostructures

In the past three decades, a lot of efforts have been made in III-nitride-based structures for low power and high-performance electronic devices. However, the issue of lattice-matched substrates is still a concern considering the performance of these devices. This limitation can be overcome using 2D materials such as graphene because the weak interlayer van der Waal forces and the absence

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**FIG. 5.** Band diagrams to show the self-powered photoresponse in (a) UV, (b) visible, and (c) near IR regions [Reprinted with permission from Song et al., J. Mater. Chem. C 5, 11551 (2017). Copyright 2017 Royal Society of Chemistry.]

**FIG. 6.** (a) Dark and illuminated $I$–$V$ characteristics of the InGaN/AlN/Si heterojunction, (b) time response of the device, and (c) mechanism for self-powered detection [Reprinted with permission from Chowdhury et al., ACS Appl. Mater. Interfaces 11, 10418 (2019). Copyright 2019 American Chemical Society.].
of dangling bonds help in realization of van der Waal epitaxy and can provide an open platform for the design of various electronic devices. In addition, the 2D-layered materials, such as MoS$_2$, have relatively smaller bandgap and excellent light abortion properties, which makes them a suitable candidate for applications such as PDs, and flexible electronic and optoelectronic devices.

In recent times, MoS$_2$ has gained immense popularity due to its extraordinary electronic and optoelectronic properties such as high mobility and high current on–off ratio.

Zhuo et al. demonstrated a high-performance and self-powered deep ultraviolet photodetector based on the MoS$_2$/GaN p–n junction. To the best of our knowledge, this is the only early

TABLE III. Comparison of characteristic parameters of various III-nitride-based PDs.

| Materials               | Rise time (ms) | Fall time (ms) | Applied bias (V) | Responsivity (A W$^{-1}$) | Spectral range |
|-------------------------|----------------|----------------|------------------|---------------------------|----------------|
| GaN thin-film-based devices |                |                |                  |                           |                |
| a-GaN$^{20}$            | 210            | 1200           | 1.0              | 1.880 3                   |                |
| a-GaN$^{4}$             | 280            | 450            | 5                | 0.340                     |                |
| Graphene/ZnO$^{77}$     | 0.037          | 0.037          |                  | ≥0.02                     | 380 nm         |
| a-GaN$^{16}$            | 163            | 1980           | 1                | 25                        |                |
| c-GaN$^{41}$            | 15 000         | 2540           | 2                | 0.00576                    |                |
| GaN/β-Ga$_2$O$_3$       | 150            | 120            | 2                | 0.19846                    |                |
| GaN/Si$^{8}$            | ~95            | ~95            | 5                | 0.218                      |                |
| Pt-GaN-N$^{11}$         | <100           | <100           | 0                | 0.03                       | UV             |
| Self-powered UV PDs     |                |                |                  |                           |                |
| r-GO/GaN$^{32}$         | 60             | 267            | 0                | 0.00154                    | UV             |
| ZnO-nano/GaN$^{39}$     | 350            | 350            | 0                | 0.0176                     |                |
| InGaN/n-Si$^{19}$       | 20             | 33             | 0                | 0.0942                     | 310–380 nm     |
| InGaN/AlN/n-Si$^{5}$    | 0.0199         | 0.0214         | 0                | 9.64                       | Broadband      |
report on self-powered hybrid photodetectors. The MoS\textsubscript{2} thin film was synthesized on a SiO\textsubscript{2}/Si substrate via a two-step decomposition method. Then, the as-synthesized MoS\textsubscript{2} film was transferred to a p-GaN substrate to form a p-n junction. Under light illumination of 265 nm (deep UV—the intensity of 1 \textmu W cm\textsuperscript{-2}), the photodetector exhibited a responsivity of 0.187 A W\textsuperscript{-1} \textsuperscript{[4]}. A specific detectivity of \(2.34 \times 10\textsuperscript{14}\) Jones and fast response/recovery times of 46.4/114.1 \mu s (5 kHz) at a zero bias voltage. The mechanisms for photodetection have been presented with the help of band diagrams as shown in Figs. 7(c) and 7(d).

Before realizing any perspective for the future of photodetectors, it is of the utmost importance to compare the existing photodetection results of III-nitride materials and their heterostructures with other wide bandgap materials such as ZnO or BaTiO\textsubscript{3} and Ga\textsubscript{2}O\textsubscript{3} and also with exotic 2D materials such as graphene and MoS\textsubscript{2}. In Table III, we have compared the photodetection properties, such as responsivity, operational voltage, spectral range, and transit times, of state-of-the-art photodetectors, which further allow us to testify the usability of a photodetector. First, PDs that were characterized using a very low voltage (\(0 < V < 5\)) and self-powered devices are being compared. Based on the results compared within the framework of III-nitrides and their integration with 2D materials, it can be postulated that 2D/V-III can play a vital role in the future when PDs are concerned, and these results give us the perspective of future photodetection devices and the important photodetection properties needed to testify their usability.

LOOKING INTO THE FUTURE

High-quality TMDC 2D materials (MoS\textsubscript{2}, graphene, SnS\textsubscript{2}, and WSe\textsubscript{2}) are generally grown by CVD on suitable substrates or exfoliating bulk crystals subsequently transferred onto the desired substrates.\textsuperscript{18,31,53,57,99,74,76,79-85} This process causes multiple problems (absence of ultrahigh vacuum during fabrication, residual impurities at the interface after the transfer, lack of control over the size and location of the transferred flake, and formation of the films of sizes limited to a few micrometers) and the overall device structure does not work to its full potential. These are some of the main challenges that need to be addressed in order to produce large-area devices with high figure of merits suitable for industrial-scale production.\textsuperscript{30} Direct growth techniques such as pulsed laser deposition or MBE, which involve ultrahigh vacuum and precise control of various growth parameters, are promising for the realization of the hybrid 3D/2D interface. These growth techniques are expected to pave the way to produce clean and defect-free junctions, which will favor the development of high-performance devices. Another insinuating advantage of layered TMDCs with 3D materials (III-nitrides, ZnO, GaAs, etc.) will be electronic band engineering with very large band offsets, which would result in an effective method for fabricating self-powered and ultrafast devices. The large area integration of 2D layered materials with 3D semiconductors will promote fabrication of highly efficient devices that can further be matured for industrial scale production. There are only a few reports for such heterojunction combinations,\textsuperscript{28,29} and there are no reports demonstrating the self-powered photodetection properties of any such configuration. The 3D/2D heterojunctions based on III-nitrides need to be explored further and this will pave new avenues for the next generation high-performance and ultrafast PDs.

So far, researchers have mostly exploited heterojunctions of III-nitrides with 2D materials in the form of thin films. Heterojunctions based on nanostructures may offer new technical routes for high-performance devices. The nanorod-based heterojunctions with a possible core-shell structure will provide a higher surface to volume ratio and a larger active interface,\textsuperscript{77} which will enhance the photodetection, and the high crystal quality (fewer defects compared to thin films) of nanorods will result in a smooth interface and superior optoelectronic properties. Thus, a reduction in the recombination centers will result in faster response times. Therefore, one-dimensional nanostructure-based 3D–2D hybrid-heterojunctions have a huge potential, which needs to be exploited in order to fabricate high-performance electronic and optoelectronic devices.

Another interesting and efficient possibility would be combining layered materials with non-polar nitrides, as the latter have emerged as excellent devices for photodetection applications.\textsuperscript{78} The absence of internal polarization should provide a band to band transition, which is absent in polar devices due to the quantum stark effect at the interfaces. This property is extremely important for efficient photodetection, which is evident from some of the early reports on nonpolar a-GaN.\textsuperscript{79-85} Moreover, the presence of anisotropy in mobility and electrical conductivity might be helpful in tuning the electronic properties of the device. Thus, heterojunctions of 2D layered materials with non-polar nitrides is possibly an excellent route for self-powered electronics.

Overall, excellent properties of III-nitride materials (lower exciton binding energies, bandgap tuning, direct bandgap, chemical inertness, radiation hardness, mechanical stability) combined with exceptional characteristics of 2D materials (high electron mobility, bandgap modulation with number of layers, flexibility for deposition substrate variation) such as MoS\textsubscript{2}, WSe\textsubscript{2}, and SnS\textsubscript{2} make their combination a promising candidate for future ultrafast, self-powered, and broadband photodetectors.

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