Analysis Of Output Characteristics of Three Different Ga_2O_3 Heterojunction UV Photodetectors

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Abstract. Phototransistors can be used as switches and amplifiers in digital and ultraviolet photodetectors, respectively. Gallium oxide (Ga_2O_3) is a common material used to make devices like transistors. However, these photodetectors usually face some problems of drain current saturation and bias saturation. But regulating the transistor switching ratio usually requires adding a voltage to the gate terminal, and will cause high current flow throughout the transistor if the gate power supply pressurized beyond the threshold. The structure of a LET is similar to that of a conventional field effect transistor (FET), and they also have similar current and voltage output characteristics, but the difference is that the LET is also subject to light regulation. This paper mainly concentrates on the analysis of LFT devices made of heterojunction of three different materials n-Ga_2O_3/p-GaN, Nanoporous Ga_2O_3/GaN and Graphene/β-Ga_2O_3, and analyzes and compares a series of key parameters such as switch ratio and responsiveness, etc. Through these comparisons, this paper can more clearly understand what LFT devices made of different materials can better adapt to the needs of different experiments. Under different voltage ranges and light intensity, LFT devices made of different materials can better adapt to the needs of experiments.

Keywords: Heterojunction; light effect transistor; deep UV.

1. Introduction

Phototransistors based on gallium oxide (Ga_2O_3) are used as switches and amplifiers, respectively, in typical digital and analog UV photonics applications [1]. Ga_2O_3 has very high capability in light detection. Some prepared LET devices consists of n-Ga_2O_3/p-GaN heterojunction with a structure like planar metal-semiconductor-metal. The special device has two modes to operate, 1-2.5V linear (photodetector) and 2.5-5V saturated respectively depletion width modulated light effect transistor (DM-LET)]. When use DM-LET mode, only the light intensity can control the drain terminal current. The current saturates with the change of the drain voltage. In this structure, it performs like a transistor. The pinching effect near the drain leads to a transistor-like action because of modulation of depletion width in the heterojunction, which is explained by using some concrete numerical simulations. In the future, this device can be applied to implement UV photon integrated circuit and UV technologies and UV non-line-of-sight communication.

In the paper, the paper collected and analyzed some performance tests of different heterogeneous light effect transistors to compare the advantages and drawbacks of each material. These performance tests mainly include FESEM, XRD, AFM, and XPS to characterize these different heterostructure materials. Then the paper also used some performance analysis of the photoelectric properties of different materials to determine what would be a better choice for application.

2. Theoretical Foundation Analysis of Photoelectric Effect Crystals

2.1. Principles of Deep Ultraviolet Photodetectors

The principle of deep ultraviolet (DUV) photodetectors is based on their ability to detect ultraviolet radiation with wavelengths below 200 nanometers. Deep ultraviolet light typically refers to light with wavelengths in the range of 100 to 280 nanometers. Due to the high-energy nature of deep UV light, these photodetectors find important applications in fields such as semiconductors, communications, and biomedical sciences. Photon Absorption and Electron Excitation. Deep ultraviolet photodetectors operate primarily on the photoelectric effect. When DUV photons strike the detector material (usually a wide range of bandgap semiconductor such as gallium nitride (GaN), diamond, or silicon carbide (SiC), the photons are absorbed by the atoms or molecules in the material. This process transfers the energy of the photons to electrons in the material, causing them to jump to the conduction band, thus creating photogenerated carriers (electron-hole pairs) in the material. Moreover, Charge Separation. The photogenerated carriers are separated when an electric field influence it, with the carriers moving in opposite directions. This movement generates a photocurrent in the material [2]. The magnitude of this current is proportional to the number of incident photons, i.e., the light intensity. Therefore, by measuring the photocurrent, one can determine the intensity of the incident light. In addition, Signal Amplification and Readout. Since the photocurrent generated by deep UV light is typically small, the detector usually incorporates amplification circuits to enhance the signal, ultimately the intensity of the incident light can be judged by the strength of the electrical signal, because they are proportional. This signal can be read and processed by electronic devices for various applications.

The core and key aspects of deep ultraviolet (DUV) photodetectors are as follows: Material Selection. Wide Bandgap Semiconductor Materials: Selecting semiconductor materials with a sufficiently wide bandgap is crucial for ensuring the detector’s effective response to DUV light. These materials not only efficiently absorb DUV light but also avoid interference from visible and near-UV light. Typical materials include gallium nitride (GaN), silicon carbide (SiC), and diamond. In addition, High Quantum Efficiency. Quantum Efficiency refers to the efficiency with which the detector converts incoming photons into electrical signals [3]. High quantum efficiency means that the detector can effectively convert most of the incident DUV photons into electrons, thereby enhancing detection sensitivity.

2.2. Structure of Photoelectric Effect Transistors

Conventional field effect transistors (FET) having source (S), drain (D), and gate (G) terminals and the ability to detect light. The source and drain conductivity are modulated to switch ON or OFF respectively when transistor apply a voltage on gate terminal, which is shown in Figure 1.

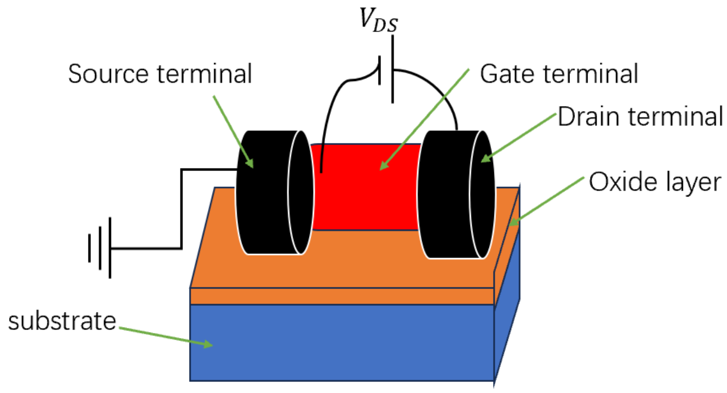

Figure 1. Structure of Field Effect Transistors

A UV illumination on the device generates additional electron–hole pairs on the S–D channel, increasing the overall current. One of the advantages of the phototransistor is reducing the dark current by applying voltage in the G-terminal, thus, improving the overall light detection performance. However, the major disadvantages with phototransistors are the inferior drain current (ID) saturation with drain bias (VDS) or the non-ideal output characteristics under illumination [2-4]. The ID saturation is essential to achieve high output resistance, which eventually helps to achieve better transistor performance in both analog and digital applications. Additional complications also arise, such as gate fabrication intricacies, random doping fluctuations, and poor response speed due to gate capacitance [5, 6]. Furthermore, switching of the FET occurs through the gate terminal voltage; a fault in the gate voltage supply will lead to an unexpected high current currently flow through FET, ensuing fatal damages in the control driver circuit. This type of phototransistor with both bias and illumination in the gate terminal is limited to specific applications only.

A new double-terminal device that can perform pure light regulation at the gate terminal is used for research, which is called the light effect transistor (LET). The structure of a LET is similar to that of a conventional field effect transistor (FET), and they also have similar current and voltage output characteristics, but the difference is that the LET is also subject to light regulation. In addition, compared with traditional FET, LET has the advantages of effective cost.

A simple metal–semiconductor–metal (MSM) structure on CdSe nanowires can behave like a LET in the visible range and can be used as an optical logic gate and an optical amplification because of its near-ideal output characteristics. For UV radiation, Ga_2O_3 is the suitable material for such LET devices, but in state-of-the-art Schottky or Ohmic MSM Ga_2O_3 photodetectors, the typical pinch-off condition in the current conducting channel required to achieve ID saturation is absent. Ga_2O_3 p–n heterojunctions are more promising as the depletion width can be exploited to generate pinch-off conditions in the device under illumination. Ga_2O_3 p–n heterojunction devices have been developed with different materials like p-GaN, p-SnO_2, p-ZnO, and p-Graphene with more emphasis on the n-Ga_2O_3/p-GaN heterojunction [7-12].

Use of an n-Ga_2O_3/p-GaN heterojunction based LET consisting of an MSM structure on top of n-Ga_2O_3. The metal electrodes serve as either the source or drain terminal. The device works as a depletion width modulated light effect transistor (DM-LET). Though a DM-LET has the same MSM structure as a typical photodetector, the uniqueness emanates from its device architecture, operating mechanism, and optoelectronic characteristics, which distinguish it from typical Ga_2O_3 photodetectors and phototransistors. The DM-LET can imitate the current–voltage characteristics of a conventional FET and offer inimitable functions that are not available in existing photodetectors and phototransistors. The DM-LET shown here relies on a p–n junction structure, where the depletion width modulation and the carrier concentration modulation in S–D channel are controlled solely through optical energy, unlike typical phototransistors where S–D channel's conductivity is controlled through both electrical and optical energy. Again, a simple photodetector cannot be controlled like FET and does not have FET's typical applications like amplification and logic switching due to lack of saturation in ID. When use DM-LET mode, only the light intensity can control the drain terminal current. The current saturates with the change of the drain voltage. In this structure, it performs like a transistor. The pinching effect near the drain leads to a transistor-like action because of modulation of depletion width in the heterojunction.

3. Growth of n-Ga_2O_3/p-GaN Materials and Heterojunction Stacking

Having five different phases (a, b, c, d, and e) with b being the most stable one, Ga_2O_3 has a typical ultra-wide bandgap of ~4.8 eV along with a high photoconductive gain. The fabrication of the LET starts with a 500nm thick Mg-doped GaN grown on a Si wafer using metal-organic chemical vapor deposition technique (MOCVD). The $Al_xGa_{(1-x)}N$ layer below the p-GaN layer acts as a template to grow GaN. With the $Al_xGa_{(1-x)}N$ layer and gradient variation of aluminum (Al) in GaN, high quality and very low lattice mismatch GaN layers with low dislocation densities can be obtained on Si wafer. The details for the unintentionally doped n-Ga_2O_3 and p-GaN growth method can be found elsewhere [13, 14]. Next, a low-pressure chemical vapor deposition method called (LPCVD) was employed to grow 180nm thick Ga_2O_3. With the growing performed by LPCVD where Gallium metal trace, it was provided in a 99.999% purity and at the same time, O_2 gas (99.99% purity) was used in order to grow of Ga_2O_3 as a basic precursor. The fabricated heterojunction structures were characterized using FESEM, XRD, AFM, and XPS. Reflection electron energy loss spectroscopy (REELS) was employed to evaluate the bandgap of Ga_2O_3. The LET device was fabricated by depositing circular Ti/Au (20/60 nm) electrodes on top of Ga_2O_3, and Ni/Au (20/60 nm) electrode was deposited on p-GaN to verify the p–n junction behavior with Ga_2O_3.

4. Performance test and analysis

The fabricated heterojunction structures there were characterized using FESEM, XRD, AFM, and XPS. Reflection electron energy loss spectroscopy (REELS) was employed to evaluate the bandgap of Ga_2O_3. The X-ray diffraction (XRD) 2θ scan of the Ga_2O_3 film can show that ε-phase Ga_2O_3 mainly consists the layer. Powder XRD of Ga_2O_3 /GaN heterojunction. The same as GaN/Al_2O_3, which is also shown for comparison in Figure 2 [15, 16].

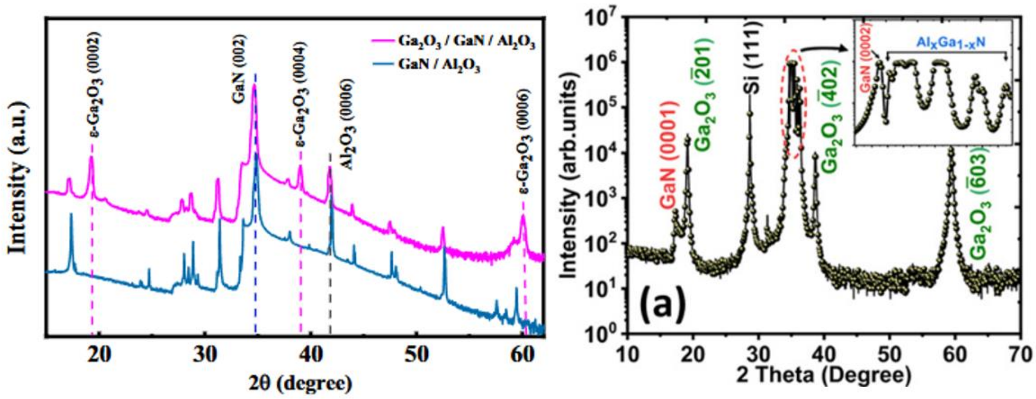

Figure 2. XRD pattern of the n-Ga_2O_3/p-GaN heterostructure. Powder XRD of the Ga_2O_3 /GaN heterojunction [15,16]

The LPCVD grown n-Ga_2O_3 on p-GaN forms a single crystalline thin film along (201) plane denoting the b phase of Ga_2O_3. XRD pattern of the n-Ga_2O_3/p-GaN heterostructure. The inset shows the XRD peaks of $Al_xGa_{(1-x)}N$ with different Al compositions. An atomic force microscopy (AFM) image as Figure 3 shown of the Ga_2O_3-GaN heterojunction, and AFM imaging for a $5 \times 5\ \mu m^2$ Ga2O3 layer [15,16].

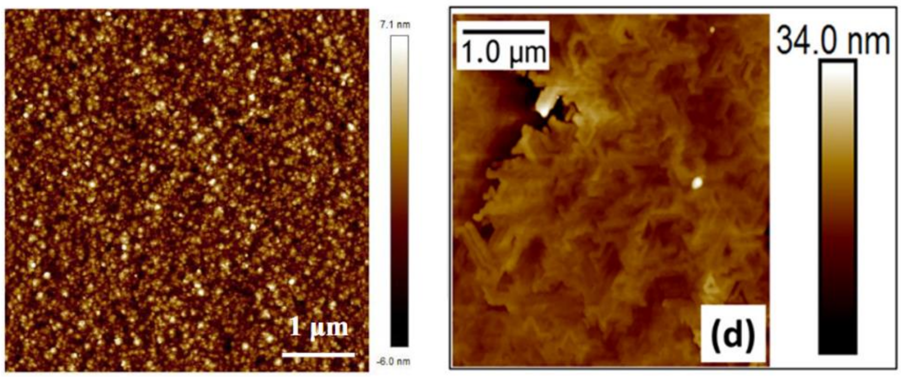

Figure 3. AFM images of the Ga_2O_3 film surface respectively [15,16]

In order to quantitatively assess the performance of these deep UV devices, both responsivity (R) and detectivity (D*) should be calculated. The responsivity is defined as light current generated the incident light's per unit power on the effective area of photodetectors and R can use following equation to express

$$R = \frac{I_\lambda - I_d}{P_\lambda S} \quad (1)$$

where I_λ is the light current, P_λ is the light intensity, I_d is the dark current, S is the effective illuminated area. The high V_o is attributed to the wide bandgap and high series resistance in Ga_2O_3. The rectification behavior of the n-Ga_2O_3/p-GaN heterojunction diode proves that a depletion region or a built-in potential (Vbi) exists between n-Ga_2O_3 and p-GaN.

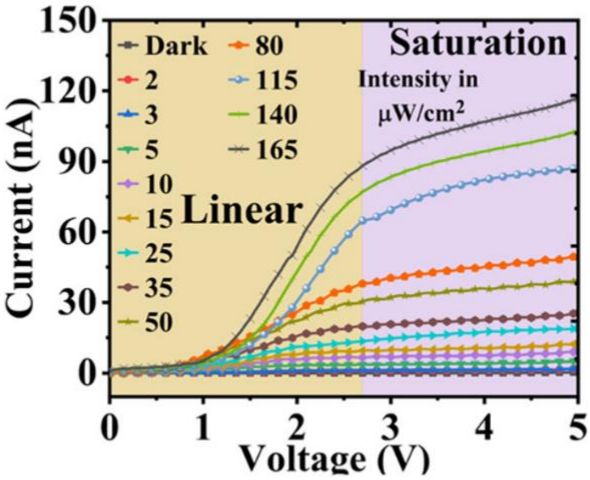

Figure 4. I–V characteristics of lateral n-Ga_2O_3/p-GaN based LET device in dark and illuminated conditions [15]

The Figure 4 shows the I–V characteristics of the lateral n-Ga_2O_3/p-GaN based heterojunction in the dark and different illuminated intensities [15]. After illumination, the I–V characteristics confirm two distinct regions, linear (linear increment in the photocurrent from 1 to 2.5V) and saturation (photocurrent saturates from 2.5 to 5V). These regions at first glance, look like the characteristics of a junction field effect transistor (JFET) first proposed by Shockley in 1952 [17]. The linear region can operate in photodetector mode and the saturation region in the DM-LET mode where transistor characteristics can be used in digital and analog applications. In both operation modes, two crucial parameters need to be evaluated, photo-to-dark current ratio (PDCR) and responsivity (R) defined by Eqs, respectively,

$$PDCR = (I_{phtot} - I_{dark})/I_{dark} \tag{2}$$

$$R = \frac{I_{phtot} - I_{dark}}{P_o I_e} \tag{3}$$

Here, I_{phtot} is the photocurrent under illuminated conditions, I_{dark} is the dark current, P_o is the input light power density, and A_e is the effective conduction area respectively.

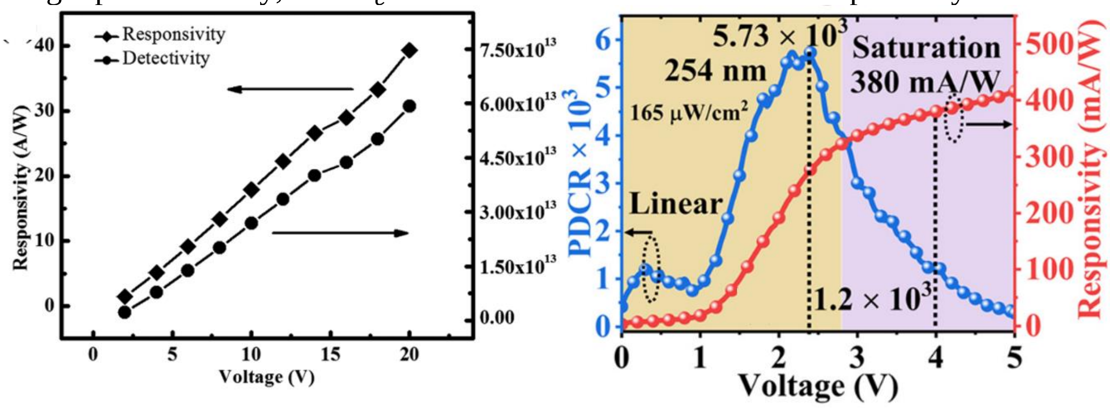

Figure 5. Both responsivity and detectivity of the MLG-Ga_2O_3 heterojunction DUVPD at different bias voltages. Variation of PDCR and responsivity with voltage responsibility [15, 18]

The behavior of Responsivity in the Figure 5 is attributed to photocurrent dependence with voltage. After exceeding the voltage control range, the light intensity begins to control the responsiveness curve [15, 18]. In the Figure 6, the paper compares the two materials can be obtained Graphene-β-Ga_2O_3 Heterojunction have a better responsivity and lager scope in not only Voltage and Light intensity [15, 18].

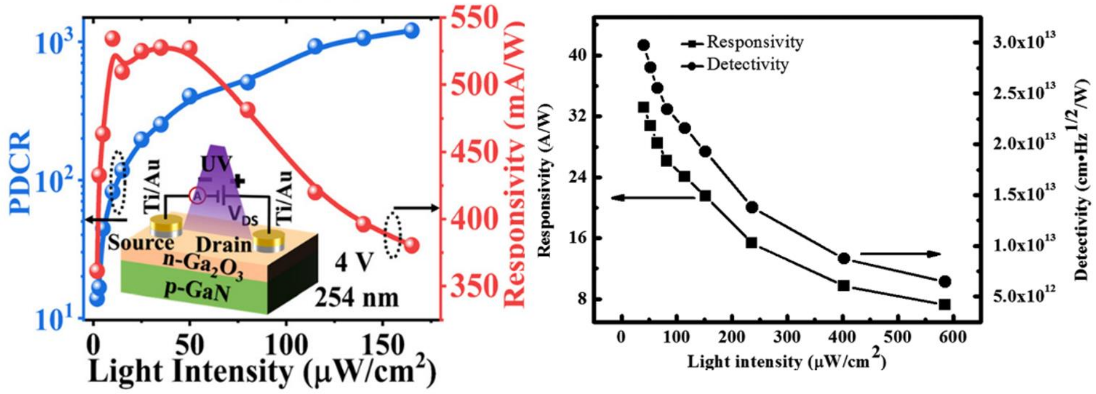

Figure 6. optical intensity respectively. Both responsivity and detectivity the MLG-Ga_2O_3 heterojunction DUVPD under light illumination with different intensities [15, 18]

The I–V curve of MLG-Ga_2O_3 heterojunction, n-Ga_2O_3/p-GaN heterojunction and Graphene-β-Ga_2O_3 respectively.

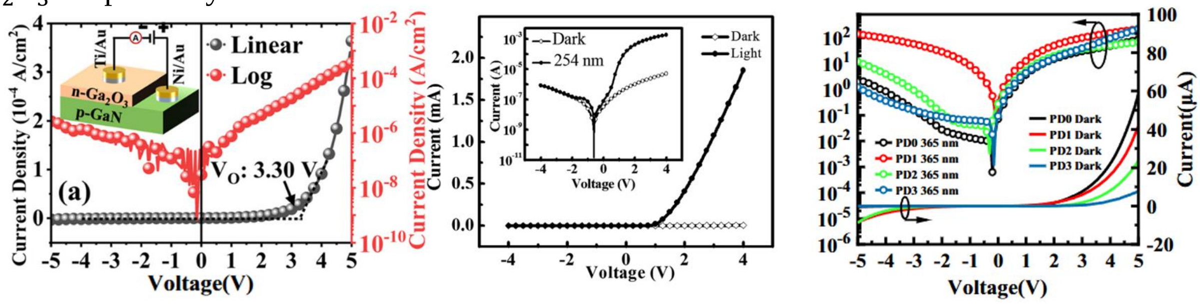

Figure 7. J–V characteristics of the nGa_2O_3/p-GaN heterojunction, I−V characteristics of the Graphene/β-Ga_2O_3, I–V curves of the nanoporous Ga_2O_3/GaN heterojunction respectively [15, 16, 18]

The Figure 7 are nearly as the same to that in dark, indicating that MLG-Ga_2O_3 device is nearly blind to 365 nm light's illumination [15, 16, 18]. However, the thing we should concentrate on is further light illumination of ultraviolet light with 254 nm wavelength will lead to a obviously increase in currently current at forward bias voltage, the typical J–V characteristics of n-Ga_2O_3/p-GaN heterojunction. When a forward bias is applied, the heterojunction shows a rectifying behavior and a high current flow after the turn-on voltage (V_o ≈3.30V). Montes et al. demonstrated mechanically exfoliated Ga2O3 and p-GaN heterojunctions where they observed a similar high VO of around 3.6V [19].

To demonstrate that DM-LET can act as an optically controlled switch, I-t measurements have been conducted. Figure 8 shows the temporal response of the drain current for 254 at 4V. By switching ON and OFF the UV light, the device can be turned ON or OFF [15]. The rising time (sr) and falling time (sd) have been calculated from the exponential fitting and are given as 0.21 and 0.11 s, respectively. The devices' I_{dark} and I_{phtot} will became larger as reverse bias increase. The reason why I_{dark} increase in the devices can be attributed to the release of more electrons and holes from the oxygen vacancy traps and drift velocity enhancing [20].

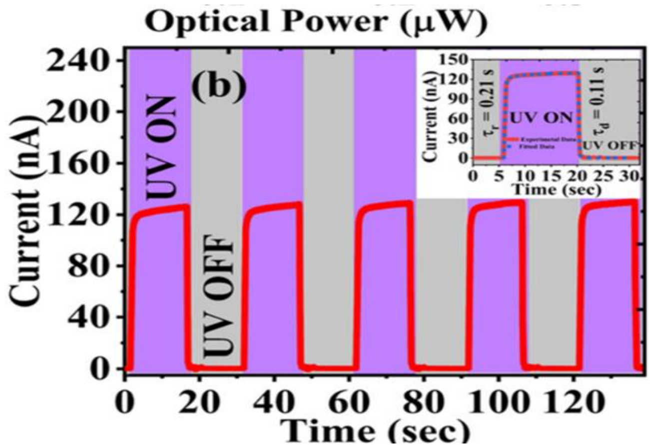

Figure 8. I-t response of DM-LET under 4 V bias and light intensity of 165 $\mu W/cm^2$ [15]

After the paper analyzed and tested the performance of photodetectors made of these different advanced materials, Table 1 compares these 3 different advanced Ga_2O_3 materials heterojunction n-Ga_2O_3/p-GaN, Ga_2O_3/GaN, and Graphene/β-Ga_2O_3 respectively based phototransistors and photodetectors showing superior performance.

Table 1. 3 different advanced Ga_2O_3 materials heterojunction

Devices	Device type	Detectivity (Jones)	R(A/W)	Response band(nm)
n-Ga_2O_3/p-GaN [15]	2-terminal	9.43×10^{11}	0.38	254
Nanoporous Ga_2O_3/GaN [16]	2-terminal	2.7×10^{11}	0.043	254
Graphene/β-Ga_2O_3 [18]	3-terminal	5.92×10^{13}	39.3	254

A UV-NLOS can establish short-range optical data communication, and UV-PIC can process the information efficiently. The main applications and prospects of light-effect transistors (optoelectronic transistors) span a wide range of high-tech industries, leveraging the unique combination of light and electronic signal processing. They are used in optical communication systems to modulate, receive, and amplify optical signals and integrated into high-speed communication systems, enhancing data transmission speed and bandwidth, which is crucial for internet infrastructure and global data centers. The future will see further integration into 5G/6G wireless networks and beyond, offering more advanced and efficient optical-electronic conversion, boosting internet speed and connectivity.

5. Conclusion

In this paper, three kinds of LFT devices made of Ga_2O_3 heterojunction n-Ga_2O_3/p-GaN, Nanoporous Ga_2O_3/GaN and Graphene/β-Ga_2O_3 are analyzed. Their performance increases in different voltage range and light intensity. By comparing their responsibility, the results show that Graphene/β-Ga_2O_3 is the most sensitive material, its detectivity is also the largest at the same time. However, the switching ratio of such a sensitive material may not perform well. In addition, according to the above analysis, I-V curves also have different characteristics under different voltage and light intensity intervals. For instance, When the voltage falls in 0-5V, responsibility of Ga_2O_3/GaN has a obviously increase, but Graphene/β-Ga_2O_3 has a gradully increase in 0-25V. For different materials, their response to different wavelengths is mainly due to differences in their band gaps. According to these characteristics under different voltages and light intensities, researchers can choose the device made of appropriate materials to adapt to the needs of different experiments, which is of great significance for the protection of the device and the improvement of experimental efficiency.

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