Design and development Analysis of Deep UV photodetectors

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Abstract. The development of deep-ultraviolet (DUV) photodetectors has gained significant attention due to their broad applications. With the increasing demand for high-performance detectors that can operate in harsh environments, research on optimizing their materials and structural design has become a critical focus. This paper introduces the basic working principle, structural composition, and performance evaluation criteria of deep-ultraviolet (DUV) photodetectors, focusing on the analysis of the optimization of materials and structure to improve the performance of detectors. Deep ultraviolet photodetectors are based on the photovoltaic effect of semiconductor materials to realize the conversion of photoelectric signals. It is shown that the photo responsiveness and stability of the photodetector can be effectively improved by introducing a composite film of the rare earth element cerium tungstate (Ce-WO3). In addition, the structural optimization of graphene-β-Ga2O3 heterojunction and n-Ga2O3/p-GaN heterojunction is employed to significantly improve the spectral selectivity, responsivity and long-time stability of the detector. This paper also explores the potential of these improvements for applications in the fields of UV communications, UV optoelectronic integrated circuits, environmental monitoring and military spaceflight.

Keywords: Photodetectors, ultraviolet, heterojunction.

1. Introduction

With the advancement of science and technology, the demand for high-performance DUV detectors has been increasing, which has led to the continuous optimization of materials and structures. Conventional DUV detectors mostly use wide-band semiconductor materials, such as gallium nitride (GaN) and zinc oxide (ZnO), however, these materials have problems such as slow response speed and unstable photoelectric response in practical applications [1]. Therefore, researchers have begun to explore novel materials and heterojunction structures to improve the performance of DUV detectors.

In this paper, this essay resent an optimized design of DUV detectors based on graphene-β-Ga2O3 heterojunction and n-Ga2O3/p-GaN heterojunction in conjunction with the latest research. Through the introduction of new materials and structural optimization, the photoelectric conversion efficiency, response speed, and spectral selectivity of the detector are significantly improved, resulting in better sensitivity and stability of the device. These studies provide important reference directions for the future development of high-performance DUV detectors.

2. Principle analysis of photodetector

2.1. Basic concepts of DUV photodetectors

2.1.1 Definition of deep ultraviolet photodetectors

The basic working principle of deep ultraviolet photodetector is the same as that of general photodetector, but its main detection wavelength is deep ultraviolet light in the wavelength range of 200~280nm. Due to the strong absorption of atmospheric ozone layer, the ultraviolet light in this wavelength is almost non-existent on the earth's surface, which leads to the detection of this wavelength photodetector has the characteristics of low background noise, high sensitivity, and strong anti-interference [2].

2.1.2 Structure

A Photodetectors typically consist of four main parts, a photoelectric conversion part, an electronic amplifier part, an optical system and an external circuit. The photoelectric conversion part, such as photodiodes and photoconductors, such as the Ga2o3 film in the MSM structure shown in the figure 1.

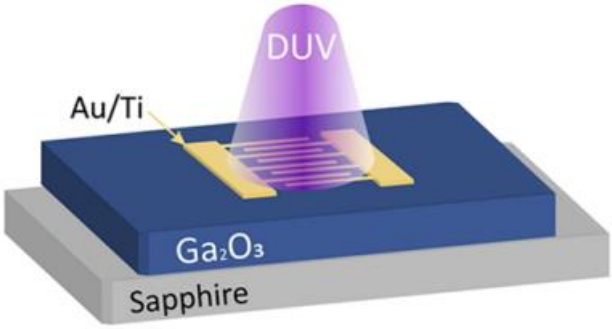


Figure 1. General structure of DUV detector

This film serves as a photosensitive element that generates photogenerated carriers when receiving deep ultraviolet light, converting the optical signal into an electrical signal [3]. The electronic amplifier section consists of preamplifiers and signal processing circuits that amplify these weak electrical signals, enhance signal strength and sensitivity, and filter, amplify and denoise the signals. The optical system consists of lenses, mirrors, optical fibers, and other components for collecting optical signals and focusing them onto photoelectric conversion elements. The external circuitry consists of a power supply and control circuitry that provides power to the photodetector and controls the operation of the photoelectric conversion element.

2.1.3 Working principle

The basic working mechanism of the photodetector includes three processes, first of all, generate carriers through light, carriers through diffusion or drift to form a current, and finally amplify the photocurrent in the circuit, when the surface of the detector is irradiated by light and the forbidden bandwidth of the material is less than the energy of the incident photons, the valence band electrons can be jumped to the conduction band to form a photocurrent, completing the transformation of the optical signal into an electrical signal.

2.2. Evaluation criteria

The performance metrics of photodetectors are mainly composed of responsivity, response speed and intrinsic bandwidth, photocurrent, dark current and noise.

2.2.1 quantum efficiency

QE is used to define the percentage of photoreceptor components, e.g., negatives, charge-coupled devices, that convert photons received on their light-exposed surfaces into electron-hole pairs Example.

$$QE = \frac{electrons/sec}{photons/sec} \tag{1}$$

2.2.2 Responsivity

Defined as the ratio of photocurrent generated by a photodetector to the incident optical power, the unit is usually A/W. The responsivity is related to the magnitude of quantum efficiency and is an external manifestation of quantum efficiency. The responsivity R:

$$R = \frac{I_p}{P_r} \tag{2}$$

2.2.3 response speed and intrinsic bandwidth

The speed of response can be expressed in terms of the crossing time of the photogenerated carriers, and the frequency response extrinsic to the crossing time of the carriers is expressed in terms of the bandwidth of the detector. The transition time of the photogenerated carriers in the photogenerated current change is expressed in two parts: rise time and fall time. The response of the detector is usually measured by the larger of the rise time and the fall time.

3. Optimization research and analysis

3.1. Material optimization

In the design of deep ultraviolet photodetector, the selection and optimization of materials have an important impact on the detector, usually DUV detectors will use wide bandgap semiconductor materials, the most common are gallium nitride and zinc oxide, these two materials have good absorption of ultraviolet light and stable photoelectric response, however, although gallium nitride has a wider bandgap, but it is not fast enough for the corresponding speed, and the zinc oxide is not fast enough because of the pieces in the preparation process is easily affected by grain boundaries and defects, resulting in an unstable photoelectric response.

Therefore, it is necessary to optimize the materials of DUV detectors to achieve better detection results. After reviewing the available information, it is found that the performance of DUV detectors can be significantly improved by using cerium tungstate (Ce-WO3) composite films as the materials for device preparation of UV photodetectors.

3.1.1 Band gap modulation and light absorption enhancement

Marnadu's study states that the optical band gap (Eg) of Ce-WO3 thin films can be modulated by adjusting the Ce content. It has been shown that the band gap of the film decreases from 3.50 eV to 3.10 eV with the increase of Ce. This decrease in band gap helps to enhance the light absorption in the UV region and thus enhances the responsiveness of the photodetector [4]. The improvement of absorption efficiency is shown in Figure 2 and Figure 3.

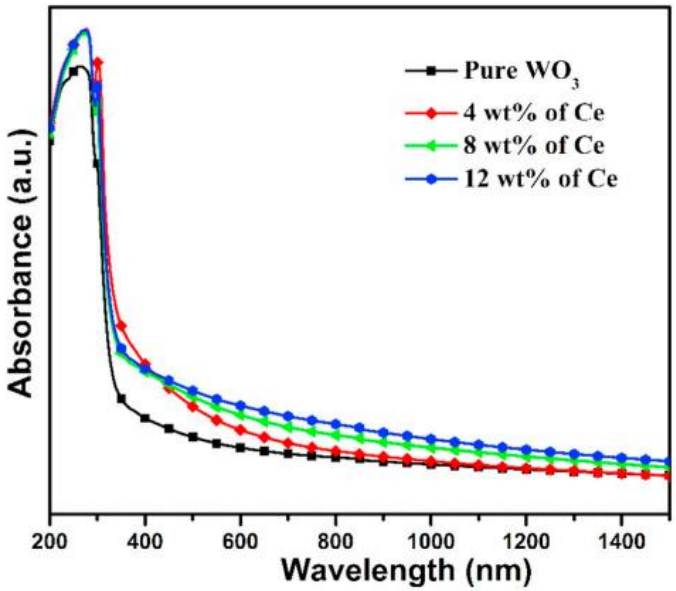


Figure 2. Absorption spectra of composite films prepared with different concentrations of Ce

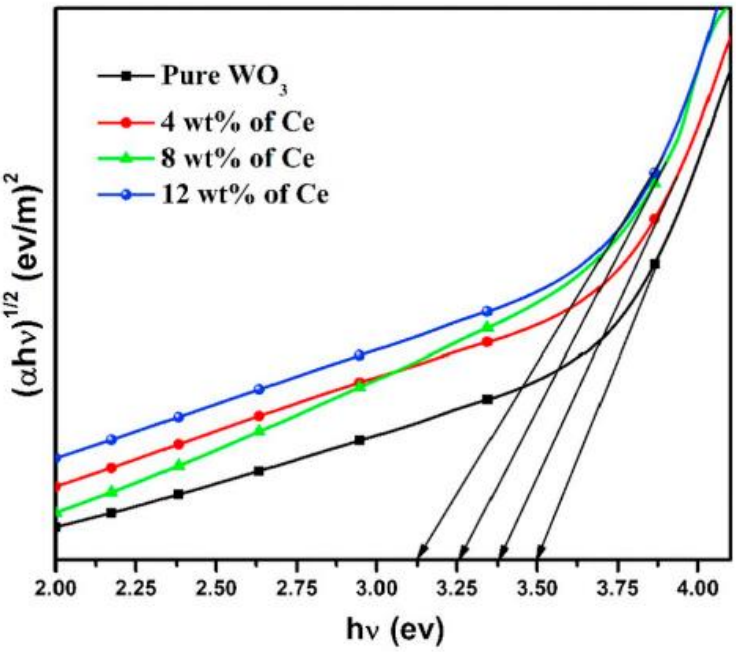


Figure 3. Comparison between the hv curve after Ce is added and the $h\upsilon$ curve without Ce

By introducing Ce, the optical absorption of the films is significantly enhanced, especially in the UV and visible regions, which results in higher absorption efficiency of Ce-WO3 films over a wider spectral range.

3.1.2 Optimization of surface morphology and grain size:

FE-SEM and AFM analyses show that the grain size of Ce-WO3 thin films decreases gradually with the increase of Ce content, show in figure 4.

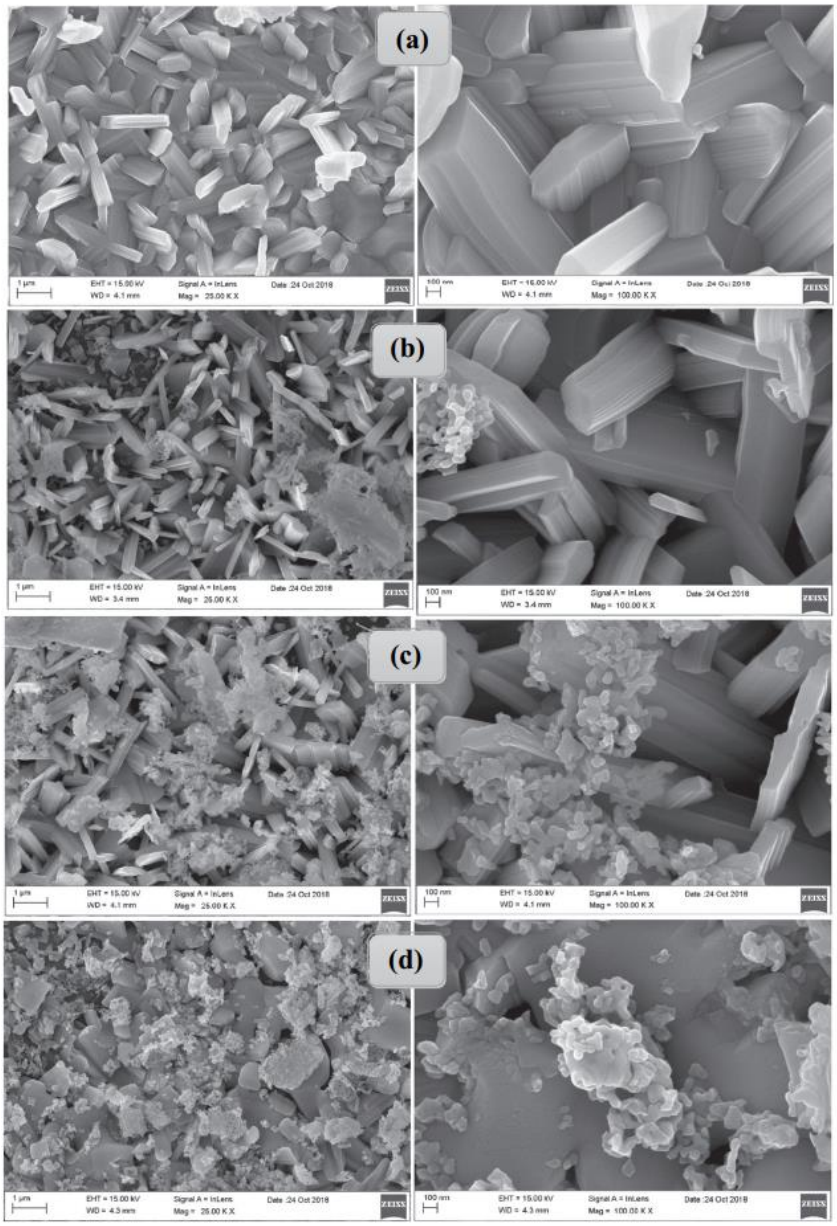


Figure 4. FE-SEM images of Ce films at different concentrations

And the surface roughness decreases as well, shown in figure 5.

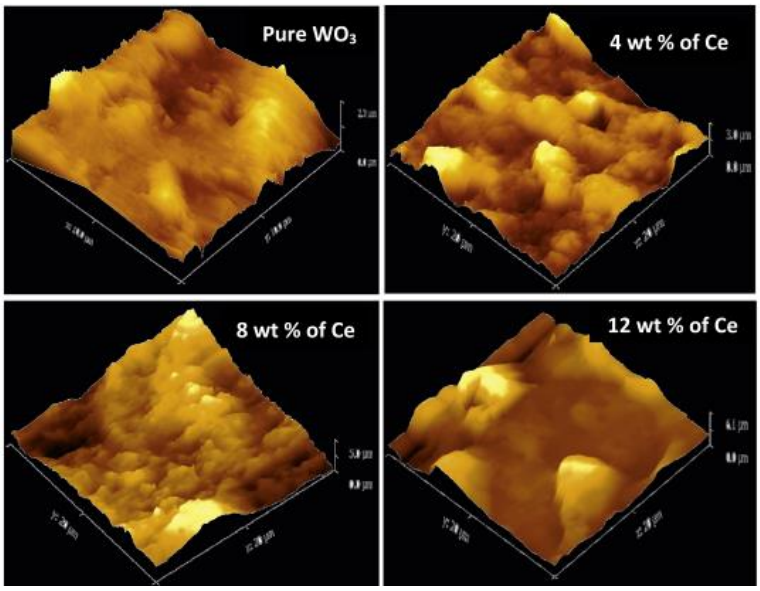


Figure 5. AFM images of Ce films at different concentrations

This optimized surface topography helps to improve the optoelectronic performance of the device, especially in photocurrent generation and transmission, and the smaller grain size and smoother surface can effectively reduce the carrier complexation rate, thus improving the photoelectric conversion efficiency

3.1.3 Optimization effect

The Ce-WO3 thin films exhibit significant improvement in electrical properties at different Ce contents. In particular, the conductivity (σ) of the films increases significantly with increasing Ce content, while the resistivity (ρ) and activation energy (Ea) gradually decrease. This improvement is illustrated in Figure 6. These improvements enable the Ce-WO3 thin films to provide higher photo response in photodetector.

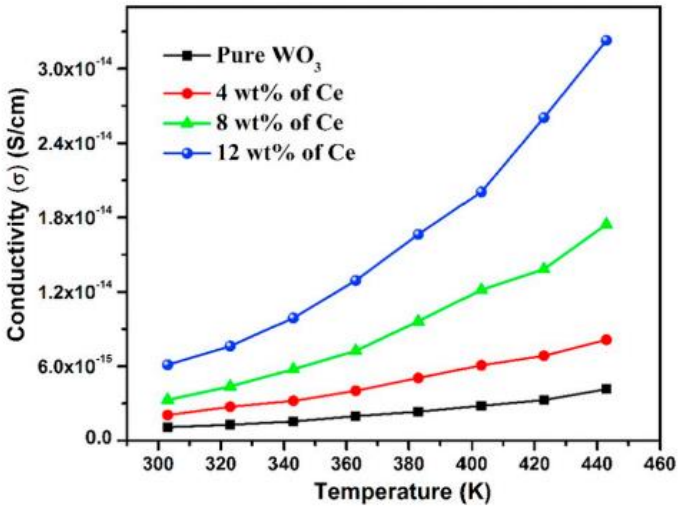


Figure 6. Plots of temperature (K) vs. conductivity (σ) for different concentrations of Ce

Compared with the common DUV detectors, the Ce-WO3-based MIS-structured photodetectors exhibit lower ideal factors (n) and higher photoresponsivity (R) at different light intensities. The improved effect is shown in Figure 7.

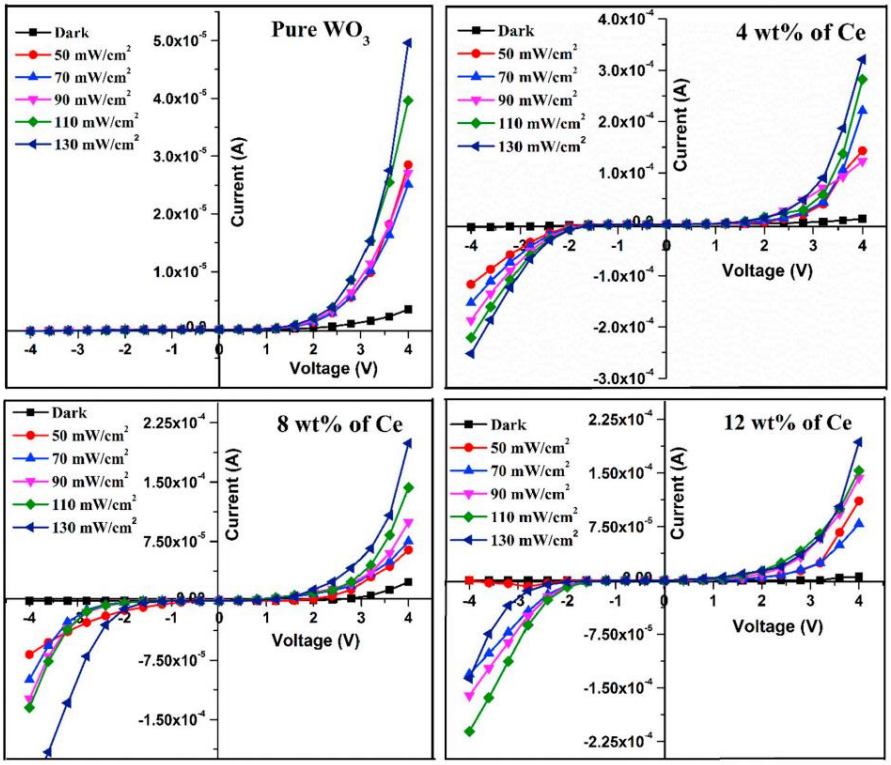


Figure 7. I-V characteristics of films prepared with different Ce concentrations

In particular, the photoresponsivity of the device reaches 20.61 mA/W at 12 wt% Ce content, which is significantly higher than that of the photodetectors prepared from conventional materials.

By introducing Ce elements and optimizing the preparation conditions of WO3 films, Ce-WO3 composite films perform significantly better than conventional materials in UV photodetectors. This material optimization not only improves the photoresponsivity and photoelectric conversion efficiency of the device, but also enhances the stability and sensitivity of the device. Therefore, Ce-WO3 composite film is a promising new material that can play a key role in the development of high-performance DUV detectors.

3.2. Structure optimization

3.2.1 Graphene-β-Ga2O3 heterojunction

A heterojunction is an interfacial structure composed of two different semiconductor materials with unique electronic and optical properties. The heterojunction mainly involved in this article is of the p-n type, which was identified as a type of heterojunction capable of effectively accelerating electron-hole migration and improving photocatalytic performance by Low et al. It is formed by the combination of a p-type semiconductor and an n-type semiconductor. During the combination, the electrons in the p-type semiconductor diffuse into the n-type semiconductor, while the holes in the n-type semiconductor diffuse into the p-type semiconductor, forming a built-in electric field. Under the irradiation of deep ultraviolet light, this built-in electric field promotes the migration of electrons to the conduction band of the n-type semiconductor and the migration of holes to the valence band of the p-type semiconductor, thus realizing the spatial separation of photogenerated carriers [5].

Kong et al. from the School of Electronic Science and Applied Physics, Hefei University of Technology, noted that deep-ultraviolet photodetectors based on graphene-β-Ga2O3 heterojunctions demonstrated high sensitivity to 254 nm UV light with very good stability and reproducibility [6]. Heterojunction can achieve efficient photo-generated carrier separation and collection, and improve the photoelectric conversion efficiency and responsiveness of the detector.

Graphene has excellent electrical conductivity and optical transparency, and combining with β-Ga2O3 can improve the performance of DUV detectors. Most conventional DUV detectors are

composed of a single material, such as GaN, ZnO, or Ga2O3. These devices are usually constructed with Schottky junction or MSM structures, which mainly rely on the intrinsic absorption of the material to generate photogenerated carriers. However, these structures have limitations in enhancing the response speed and quantum efficiency of the devices, especially performing poorly under low light intensity conditions.

A heterojunction structure was constructed by combining multilayer graphene (MLG) with β-Ga2O3. Graphene, as a transparent conducting material, has high conductivity and excellent carrier mobility, which effectively improves the photogenerated carrier separation efficiency of the device. The heterojunction structure not only improves the current transport characteristics, but also enhances the photoresponsivity of the device, especially at the deep ultraviolet (254 nm) wavelength.

3.2.2 Optimization effect of Graphene-$\beta - Ga_2O_3$ heterojunction

Conventional DUV detectors typically utilize simple metal-semiconductor-metal (MSM) or Schottky junction structures, which limit the responsiveness, sensitivity, and quantum efficiency of the devices to some extent. In contrast, the Graphene-$\beta - Ga_2O_3$ heterojunction structure demonstrates significant performance advantages, mainly in the following aspects:

Enhancement of built-in electric field. In conventional structures, the built-in electric field usually depends on the intrinsic properties of the material and cannot be significantly optimized by structural design, which leads to the limited separation efficiency of the photogenerated electron-hole pairs. Due to the energy band matching between graphene and $\beta - Ga_2O_3$, a strong built-in electric field is formed at the heterojunction, which effectively improves the separation efficiency of the photogenerated carriers. Especially at high bias voltage, this enhanced built-in electric field can further accelerate the carrier migration and reduce the compounding, thus improving the quantum efficiency of the device.

Spectrally selective optimization. Conventional Ga_2O_3 or ZnO based DUV detectors are sensitive to photons over a wide spectral range, have weak spectral selectivity, and are susceptible to ambient light interference. Through structural optimization, the heterojunction exhibits extremely high sensitivity to DUV light below 220 nm and little sensitivity to light at wavelengths above 280 nm. This excellent spectral selectivity gives the device an obvious advantage for use in solar-blind UV detectors, effectively avoiding interference from solar radiation.

Response speed and stability. Due to the structural limitations of a single material, conventional detectors tend to perform poorly in terms of response speed and long-term stability, and performance may be significantly degraded especially in high light intensity or harsh environments. The structure-optimized DUV detector maintains good performance with fast response time after multiple cycles. This is attributed to the stability of graphene and the excellent photovoltaic properties of Ga2O3, which ensures the device's stability over long periods of time under high performance conditions.

3.2.3 $n - Ga_2O_3/p - GaN$ heterojunction

Arnab Mondal et al. from the Indian Institute of Technology (IIT) Mandi state that they grew Mg-doped p-GaN layers on a silicon substrate using metal-organic chemical vapor deposition (MOCVD) and $n - Ga_2O_3$ layers on top of it using a low-pressure chemical vapor deposition (LPCVD) method [7]. These heterojunction-structured light-effective transistors (LETs) demonstrate transistor-like output characteristics under UV irradiation, and the pinch-off effect near the lead electrode is verified by TCAD simulation.

The heterojunction in $n - Ga_2O_3/p - GaN$ light-effective transistors (LETs) combine n-type gallium oxide (Ga_2O_3) and p-type gallium nitride (GaN), forming a p-n junction in between. The built-in electric field of this structure enhances the separation efficiency of photogenerated electron-hole pairs, dramatically increasing the optoelectronic response of the device.

Ga_2O_3 has an ultra-wide bandgap (~4.8 eV), making it particularly suitable for deep-ultraviolet light detection. The built-in electric field in the heterojunction structure allows for faster separation and transport of photogenerated carriers, which improves the overall response speed and efficiency of the device. The optimization effect is shown in Figure 8.

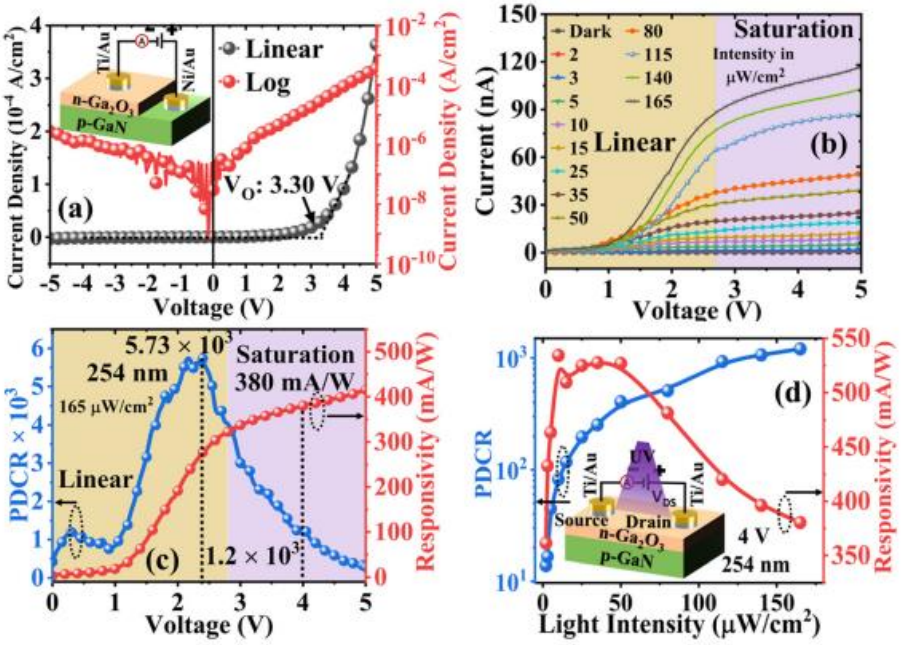


Figure 8. (a) Current-voltage (J-V) characteristic diagram of heterojunction diode, (b) I-V characteristic diagram of transverse LET device in dark state and light condition, (c) relationship diagram of PDCR and voltage. (d) Relationship diagram of PDCR and light intensity

Bringing $n-Ga_2O_3/p-GaN$ LETs into the saturation region at operating voltages above 2.5 V exhibits characteristics are similar to those of field effect transistors (FETs). In this mode, the drain current of the device saturates and is regulated only by the light intensity and is no longer dependent on the drain voltage. This "pinch-off effect" saturates the current by regulating the width of the depletion region with light energy. With this design, the device exhibits significant responsivity (380 mA/W) and detectability (5.73×10^3) under light conditions, far exceeding conventional DUV detectors.

3.2.4 Optimization effect of $n-Ga_2O_3/p-GaN$ heterojunction

TCAD simulation results show that the electric field distribution in the Ga_2O_3 layer changes significantly under light illumination, which enhances the width regulation of the depletion region between $p-GaN$and $n-Ga_2O_3$. This regulation makes the pinch-off effect more pronounced, which ensures the saturation of the current and enhances the optoelectronic performance of the device. Unlike conventional FETs, DM-LETs rely entirely on light intensity to control the drain current. This light-control mechanism makes the devices more flexible in practical applications, and they are particularly suitable for use in photovoltaic integrated circuits (PICs) and non-line-of-sight ultraviolet communications (UV-NLOS).

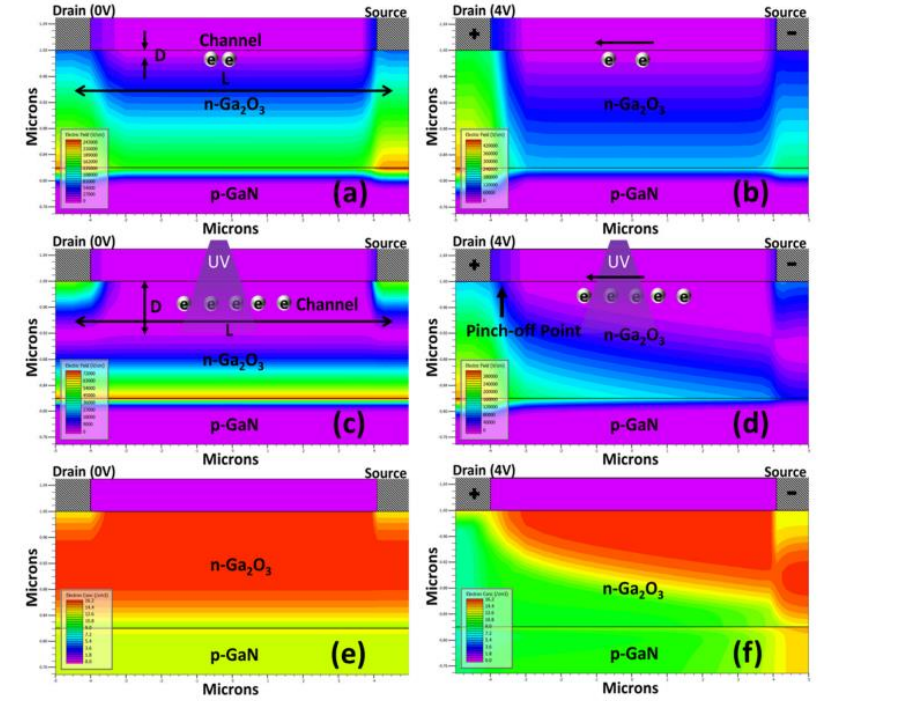


Figure 9. Simulation results of n-Ga2O3/p-GaN heterostructure.

The device consumes extremely low power in operation, only 0.35 nW in the off state and 41.92 nW in the on state. this low power consumption makes the device particularly suitable for UV detection applications that require long operating times. As shown in Figure 9, the device has a rise time (τr) of 0.21 s and a fall time (τf) of 0.11 s at a 4V bias voltage, showing good response speed.

Compared with common DUV detectors, these two heterojunction structures achieve significant performance improvement by optimizing the material selection and structural design, which enhances the spectral selectivity optimized by the built-in electric field and makes the devices outstanding in terms of high sensitivity, fast response, and long-time stability. Therefore, this structural optimization provides an important reference direction for the development of future high-performance DUV photodetectors.

3.3. Application scenario analysis

3.3.1 Ultraviolet communication (UV-NLOS)

In Guo Liang's study. from the Institute of Semiconductor Research, Chinese Academy of Sciences (CAS), noted that ultraviolet communication (UVC) technology, especially non-line-of-sight (NLOS) UVC, takes advantage of the atmosphere's scattering and reflecting ability of UV radiation to enable data transmission in environments blocked by obstacles [8]. The detectors based on graphene-β-Ga2O3 heterojunctions and $n-Ga_2O_3/p-GaN$ lets in this paper are well suited for applications in UV-NLOS due to their high sensitivity and low power consumption. These detectors are able to operate efficiently under low light intensity conditions and have excellent signal detection capabilities, contributing to the reliability and speed of data transmission.

3.3.2 Ultraviolet Photoelectric Integrated Circuits (UV-PICs)

Yan Jiabin et al. from Nanjing University of Posts and Telecommunications (NUPT), in their study, presented for the first time a monolithic integrated UV photoelectric switch based on a GaN on-Silicon platform, demonstrating its potential for application in optoelectronic integrated circuits (UV-PICs). The integrated switch is structurally designed with a UMOSFET, InGaN/GaN multi-quantum well UV photodiode (PD), and thin-film resistor, which provides very high response speed and reliable UV light detection capability [9].

Ultraviolet photoelectric integrated circuits (UV-PICs) offer significant advantages in processing and transmitting optical signals, especially in applications requiring high precision and stability. The excellent spectral selectivity of graphene-β-Ga_2O_3 heterojunctions and the optimization of the built-in electric field make UV-PICs have a wide range of application potential. The structure is optimized so that the device can exhibit extremely high detection accuracy and fast response in the UV region, making it suitable for high-performance UV-PICs.

3.3.3 Environmental monitoring and safety

DUV detectors have important applications in environmental monitoring, especially in flame detection, ozone leakage detection and water quality monitoring. graphene-β- Ga_2O_3 heterojunction and $n-Ga_2O_3/p-GaN$ LETs can be used for real-time detection of weak signals in the UV spectrum due to their fast response and high sensitivity, helping to improve environmental monitoring. weak signals, helping to improve the accuracy and efficiency of environmental monitoring and guaranteeing safety.

3.3.4 Military and Aerospace

In the military and aerospace fields, DUV photodetectors can be used for missile detection, target tracking, and battlefield surveillance. Adam J. Hopkins, et al. Deep-ultraviolet detector-based PRIEDs excel in the detection of explosives, narcotics, and industrially toxic chemicals and materials, detecting and identifying large and minute quantities of chemicals from long distances [10]. The high stability and long-time reliability of graphene-β- Ga_2O_3 heterojunction gives it an advantage for applications in these extreme environments. Its ability to maintain stable operation under high-intensity UV irradiation makes it suitable for environmentally demanding military equipment.

3.3.5 Scientific Research and Instrumentation

DUV detectors are also used in a wide range of applications in UV microscopy, spectral analysis and optical experiments. These detectors can accurately detect UV light to help scientists perform microanalysis and material characterization. the high responsivity and excellent spectral selectivity of Graphene-β- Ga_2O_3 heterojunction and $n-Ga_2O_3/p-GaN$ LETs enhance the performance of scientific instruments and make them suitable for more complex experimental environments. environment.

4. Conclusion

This paper focuses on the design of graphene-β- Ga_2O_3heterojunctions and $n-Ga_2O_3/p-GaN$ heterojunctions and their significant enhancement of detector performance. By optimizing the material properties and structural design, these novel DUV detectors demonstrate high sensitivity, fast response, and excellent spectral selectivity, which are significantly better than conventional single-material detectors. However, the preparation process of the new materials and structures is relatively complex, and how to ensure high performance while realizing large-scale fabrication and cost reduction remains a challenge. Secondly, the long-term stability and durability of these new detectors under high-intensity UV illumination or extreme environmental conditions need to be further verified.

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