Ultraviolet photodetectors based on wide bandgap semiconductors: A Review

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Abstract. This review focuses on ultraviolet (UV) photodetectors based on wide bandgap semiconductors, which are gaining increasing attention for applications in defense, environmental monitoring, and biomedical fields. Materials such as ZnO and Ga_2O_3 offer high thermal stability, strong radiation resistance, and suitable band gaps for solar-blind UV detection. The paper summarizes various detector architectures' characteristics and device performance, including photoconductive, Schottky, metal–semiconductor–metal (MSM), p–n junction, and p–i–n junction types. Their responsivity, response time, dark current, and structural advantages are compared. Key performance enhancement strategies—doping, nanostructuring, and interface engineering—are discussed. Although significant progress has been achieved, challenges remain, including persistent photoconductivity, trade-offs between sensitivity and speed, and fabrication constraints. Future research should focus on novel materials, optimized device structures, and scalable integration techniques to enable high-performance and reliable wide bandgap UV photodetectors for next-generation optoelectronic systems.

Keywords: UV photodetector; ZnO; Ga_2O_3; Schottky structure; p–n junction.

1. Introduction

Ultraviolet (UV) detection technology, an advanced detection method following infrared and laser detection technologies, has found extensive applications in civilian and military fields. With broad prospects, it plays a significant role in missile early warning, UV communication, fire alarm systems, environmental pollution monitoring, industrial production inspection, and medical and healthcare applications [1-6]. UV light refers to a general term for specific electromagnetic radiation in the wavelength range of 10-400 nm and power distribution range of 3.1-12.4 eV, which is enabled to be separated into UVA (320-400nm), UVB (280-329 nm), UVC (100nm-280 nm) and VUV (10-200 nm) [7]. Due to the strong absorption of solar ultraviolet radiation with wavelengths below 280 nm by the ozone layer in Earth's atmosphere, this spectral region is nearly free from solar background interference, making it highly suitable for high-sensitivity ultraviolet detection. This region is commonly referred to as the solar-blind ultraviolet (SBUV) band, corresponding to a material bandgap of typically $\geq$ 4.43 eV [8]. Wide bandgap semiconductors exhibit various advantageous properties, including low dielectric constant, high breakdown electric field, excellent thermal conductivity, high electron saturation velocity, and strong radiation resistance. These characteristics enable their reliable operation under high-temperature conditions, making them ideal candidates for developing high-frequency, high-power, and radiation-resistant semiconductor devices. In recent years, with the growing demand for advanced optoelectronic systems, wide bandgap materials have attracted significant attention in next-generation device design. Their relatively large bandgap allows devices to operate efficiently under short-wavelength (ultraviolet), high-power, and high-frequency conditions while maintaining stability in harsh environments [9].

This review focuses on wide bandgap semiconductor-based ultraviolet (UV) photodetectors, aiming to provide a comprehensive overview of their design principles and recent research progress. Emphasis is placed on the performance optimization of UV detectors through comparative analysis of representative wide bandgap materials, including ZnO, Ga_2O_3as, and diverse device architectures. Key enhancement strategies are summarized, current technical challenges are identified, and future research directions are discussed. Based on their fundamental operation mechanisms, wide bandgap UV photodetectors can be generally divided into photoconductive and photovoltaic types. Photovoltaic detectors can be categorized into Schottky barrier, metal–semiconductor–metal (MSM), p–n junction, and p–i–n junction structures.

2. Wide Bandgap Metal Oxide Semiconductor Materials

High-performance ultraviolet (UV) photodetectors typically require high quantum efficiency, fast response speed, and an excellent signal-to-noise ratio. The intrinsic physical properties of the semiconductor materials determine these key performance indicators. Among these properties, the bandgap width (Eg) is one of the core parameters influencing device performance, as it not only determines the cutoff wavelength for UV response but also directly affects the selective detection ability in the solar-blind region. In recent years, research on UV photodetectors has primarily focused on wide bandgap metal oxide semiconductor materials such as ZnO and Ga_2O_3. Among the various wide bandgap metal oxide semiconductors, ZnO and Ga_2O_3 stand out due to their superior optical and electronic properties and have thus become the two most representative candidates for next-generation UV photodetectors. ZnO offers high carrier mobility and tunable bandgap through alloying, while Ga_2O_3 exhibits deep-UV sensitivity and strong solar-blind selectivity due to its intrinsically wider bandgap. These distinct features make them complementary in application scenarios: ZnO is more suitable for broadband UV detection and transparent electronics, whereas Ga_2O_3 is ideal for solar-blind detection in harsh environments. A comparative study of these two materials provides valuable insights into material selection and device design for high-performance UV photodetectors [10].

2.1 ZnO

ZnO is a wide-bandgap semiconductor showing a bandgap of 3.37 eV and has strong ultraviolet absorption at room temperature, with good radiation resistance, thermal stability, and high carrier mobility. ZnO expands the available materials because it has a relatively low material cost and known fabrication processes, and can form a solid solution with MgO, thus creating $ZnxMg_{(1-x)}O$ alloys with tunable band gaps between 3.37 eV and 7.8 eV [11]. This tunability allows for a flexible design platform for UV photodetectors depending on the wavelength information of interest. Because of ZnO's excellent optoelectronic and physical properties, it is widely viewed as one of the best materials for high-performance ultraviolet photodetectors. [12]. In addition, ZnO exhibits intrinsic piezoelectric properties and good biocompatibility, which broaden its application prospects in flexible electronics, wearable devices, and biomedical sensing technologies [13].

2.2 $Ga2O_3$

Ga_2O_3 is a wide bandgap oxide semiconductor with quasi-direct characteristics that finally has exciting deep-ultraviolet (DUV) absorption properties. Its bandgap can range from 4.5 to 5.3 eV, corresponding to a cutoff wavelength near 280 nm. With good radiation hardness, high thermal and chemical stability, low noise, high sensitivity, and low cost, Ga_2O_3 has garnered worldwide attention as an essential material for solar-blind photodetectors [15-17]. Of the five polymorphs of Ga_2O_3—α, β, γ, δ, and ε phases—the β-phase is the only phase that is thermodynamically stable at room temperature, possesses a monoclinic crystal structure, and has a direct bandgap of ~4.9 eV, which would enable detecting solar-blind UV radiation in the 200–280 nm range. Therefore, β-Ga_2O_3 has many features that should make it suitable for high-performance solar-blind UV photodetectors. This unique combination of properties makes β-Ga_2O_3 particularly ideal for high-performance, solar-blind UV photodetectors in applications such as space-based UV monitoring, flame detection, and high-temperature optoelectronic systems [14].

3. UV Photodetectors

Wide bandgap semiconductor ultraviolet (UV) photodetectors can be delineated into two general categories based on their operating mechanisms - photoconductive and photovoltaic detectors. The photovoltaic category has also been subcategorized into various structural types, i.e., Schottky barrier, metal–semiconductor–metal (MSM), p-n junction, p-i-n junction types [18-20].

3.1 Photoconductive Detectors

Photoconductive detectors operate based on the photoconductive effect. A typical device consists of a semiconductor material with two ohmic contacts at both ends. When the incident photon energy (hν) exceeds the semiconductor's bandgap energy (Eg), electron–hole pairs are generated, increasing electrical conductivity. An external circuit can detect this conductivity change. The primary advantage of photoconductive detectors lies in their ability to achieve high photoconductive gain. However, they often suffer from persistent photoconductivity, slow response times, and nonlinear relationships between photocurrent and incident light intensity [21-22]. Research on photoconductive ultraviolet detectors based on oxide micro/nanomaterials remains limited.

3.2 Schottky Detectors

The Schottky structure is a standard configuration in wide bandgap semiconductor ultraviolet photodetectors [23]. It consists of a Schottky diode formed by a transparent Schottky contact and an ohmic contact. The rectifying characteristics of the metal-semiconductor contact arise from the electrostatic potential barrier between the metal and semiconductor, which is attributed to the difference in work functions [24]. Schottky UV photodetectors offer advantages such as high responsivity, high quantum efficiency, low dark current, short response time, and operation at zero bias voltage. However, one challenge with Schottky contacts is that the incident light must pass through the metal electrode and interact with the semiconductor (photosensitive layer). As a result, metal electrodes are typically made thin and semi-transparent. The high absorption coefficient of the metal electrode can be a limiting factor in the performance of Schottky detectors. Additionally, surface state effects and shallow metal-semiconductor contacts can hinder the development of Schottky-based UV photodetectors [23]. Recent studies have increasingly focused on optimizing electrode material selection and improving the quality of metal-semiconductor interfaces. CHEN X et al. from CIOMP proposed a facile fabrication strategy for vertical β-Ga_2O_3 Schottky devices, in which Ga metal was spin-coated onto the substrate and subsequently oxidized to form vertically aligned β-Ga_2O_3 nanowire arrays. An Au layer was deposited as the top electrode, while the partially oxidized Ga acted as the bottom contact. The device exhibited an exceptionally low dark current of 10 pA at −30 V and a fast fall time of only 64 μs. Notably, this self-powered architecture enables simultaneous formation of the active region and bottom contact, ensuring intimate electrical contact and excellent device performance [25]. Zhang et al. synthesized a UV photodetector based on Ag nanowire@ZnO nanorod composite materials with Au electrodes [26]. Due to the large depletion region formed between the ZnO nanorods and Ag nanowires, a Schottky barrier is established at their interface, which results in high sensitivity and fast response under UV illumination.

3.3 Metal–Semiconductor-Metal (MSM) Detectors

Metal – semiconductor – metal (MSM) photodetectors, commonly employed in wide-bandgap UV detection, consist of two symmetric Schottky contacts formed on a semiconductor substrate [27]. When an external bias is applied, one Schottky junction is forward biased. At the same time, the other is reverse-bias, effectively suppressing dark current and enhancing the signal-to-noise ratio of the device. MSM detectors exhibit fast response times due to low capacitance and short carrier transit times. Moreover, these devices show a linear photocurrent response to light intensity and possess a UV-to-visible rejection ratio exceeding 10^4, indicating excellent spectral selectivity. The MSM structure is also favored for its simple fabrication process, low cost, and compatibility with monolithic integration. However, the metal electrodes partially block the incident light, reducing the efficiency of the active region and limiting the overall light response. The MSM structure bears similarities to photoconductive detectors, with the primary difference being the use of Schottky contacts instead of ohmic contacts [28]. In 2022, LU et al. enhanced the photoelectric performance of Ga_2O_3 microwire-based MSM detectors through Sn doping [29]. Their device achieved an outstanding light-to-dark current ratio of 10^7 and a responsivity of 2,409 A/W under a 40 V bias. Additionally, a clear solar-blind imaging capability was demonstrated using a parallel array of ten Sn-doped Ga_2O_3 microwires, showing significant promise for deep ultraviolet detection applications.

3.4 p-n and p-i-n Junction Detectors

p-n junction photodetectors are specially engineered semiconductor diodes that allow incident photons to penetrate the active region near the metallurgical junction. When illuminated with light of appropriate energy, electron‑hole pairs are generated and separated by the built-in electric field, resulting in a photocurrent in the external circuit. In typical photovoltaic operation, these devices do not exhibit internal gain. Under forward bias, the dark current significantly exceeds the photocurrent, rendering the detector inoperative due to its unidirectional conductivity. In contrast, reverse bias effectively suppresses the dark current, reducing the junction capacitance and carrier transit time, thereby enhancing sensitivity and response speed [30-32]. To further improve performance, an intrinsic layer can be inserted between the p and n regions to form a p-i-n structure, which broadens the depletion region and enhances carrier collection. P-i-n photodiodes typically operate at zero or reverse bias to achieve the maximum differential between the photocurrent and the dark current and improve performance. As reverse bias increases, the time response increases with the expanded depletion region, while the junction capacitance decreases, increasing responsivity and speed. The most critical hurdle to improving device performance is maximizing photon absorption in the depletion region, which can only be achieved with proper structural and material design [33]. p-n and p-i-n photodiodes are fast response, high impedance, low dark current, low or zero-bias, high frequency, and compatible with plane fabrication processes. Still, it is the event of p-type dopants that are often limiting and eat up the entire spectrum of performance.

4. Conclusion

In conclusion, ultraviolet (UV) photodetectors based on wide bandgap semiconductors have shown great promise in high-performance optoelectronic applications based on the beneficial properties of these materials, namely considerable bandgap energy, high thermal and chemical stability, and strong radiation tolerance. This review provided a complete overview of UV photodetectors based on wide bandgap semiconductors, with a specific focus on ZnO and Ga_2O_3, and summarized different device structures including photoconductive, Schottky, MSM, p‑n, and p‑i‑n structures. Each device type has certain advantages and disadvantages for responsivity, response time, dark current, and complexity of manufacture.

Recent progress in doping strategies, nanostructuring, and device integration has dramatically enhanced the performance of these detectors, thus allowing for applications in areas such as solar-blind imaging, environmental monitoring, and detection in space. While there has been an impressive amount of progress, there are still many challenges to overcome—persistent photoconductivity, the trade-offs in sensitivity vs. speed, and limiting cases due to electrode design or defects in the materials.

Future studies should investigate how new wide bandgap semiconductors can continue to improve interface engineering and scalable fabrication processes to improve device efficiency and applications. Through multidisciplinary collaboration in materials science, device physics, and microfabrication technology, many wide bandgap UV photodetectors are anticipated to play important roles in the next generation of ultraviolet detection systems.

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