An Introduction to Ultraviolet Detectors Based on III Group-Nitride Semiconductor

He Yang
School of Materials Science and Engineering, Northwestern Polytechnical University, Xi’an, Shaanxi Province, 71002, China
sunnyblue611@gmail.com

Abstract. Ultraviolet (UV) detectors are drawing increasing attention in the past decades due to their reliable application in industrial, environmental, and even spatial fields. Among all of the candidate materials for UV detector, III group-nitride semiconductors—typically (In, Al) GaN—have stand out for their good thermal stability and conductivity, high response speed and breakdown electric-field, as well as robust radiation hardness. In this article, the author comes up with possible improvements on structural defects-induced degradation of device by providing a comprehensive introduction to the conventional device classification and principles of UV detectors as well as up-to-date processing arts of III group-nitride materials for UV detectors. Finally, we conclude with the promising nano-structured GaN-based UV detectors and expect their applications under super thermo-stable requirements.

1. Introduction
In the ultraviolet (UV) field, photodetection has received considerable attention because of its significant application in both civil and military fields, and has raised higher standards for upgrading detectors generation by generation. Typically, UV light can be divided into the following bands: UVA (400-315nm), UVB (315-280nm), UVC (280-100nm), and VUV (200-100nm).[1][2][3] UV detectors based on III group-nitride semiconductors, or referred to as direct wide bandgap semiconductors (typically GaN-family based, with bandgap around or above 3.4 eV) show their superiority on critical environment applications because they do not need the insertion of optical filters and are more resistant to heat and/or high energy radiation.[5][6][7][8] Especially when they are compared with the well-established Si or Ge-based UV-enhanced detector, the latter will degrade in efficiency and current leakage as temperature increases.[9][10] In addition, wide bandgap semiconductors are inherently equipped with low permittivity, good thermal conductivity, high breakdown electric-field and electron saturation, which make them much more suitable for UV detection than Si or Ge-based technology.

Although the GaN-family based UV detectors are theoretically more applicable, it was not until the breakthrough of the epitaxy technique for GaN film via metal-organic chemical vapor deposition (MOCVD) in the 1990s that they could be universally reproduced for commercial use.[9] Typically, the wurtzite-structure AlGaN is grown over basal-plane sapphire substrates, which will inevitably create a high density of dislocations and other structural defects, and resultantly undermine their established advantages.[10] Therefore, it is highly desirable to break through the technical predicament in material preparation and device fabrication for GaN-family based UV detectors application. In this article, the author comes up with possible improvements on structural defects-induced degradation of device by reviewing a detailed classification of UV detectors and the pros and cons of those detectors as well as the most recent work on relevant processing fields. Finally, the author concludes with the promising
nano-structured GaN-based UV detectors and expects their super thermo-stable applications.

Figure 1. Typical category of UV detectors

2. Photoconductive detectors

Photoconductive detectors, also known as photoconductors, work on the basis of the photoconductive effect. As shown in Figure 2 (a), when the kinetic energy of a photon is bigger than the semiconductor bandgap energy $E_g$, it will be absorbed to generate electron-hole pairs, which will change the conductivity of the semiconductor. Afterward, the external circuit detects the signal of the change in conductivity.\[^{10}\] According to Khan et al., a unique switching atomic layer epitaxy (SALE) process was used to deposit a GaN layer on a sapphire substrate, and a GaN-based detector with a response rate of 2000 A / W was fabricated at a wavelength of 365 nm at a bias voltage of -5V.\[^{11}\] Photoconductive-type UV detector has relatively simple structures as well as high internal gain, and is easy to control in the fabrication process, but their slow response speed and large dark current (influencing the signal-to-noise ratio) remain challenging.

3. Photovoltaic detectors

Photovoltaic detectors are mostly based on the semiconductor photovoltaic effect. For different device structure, this category of detector can be further classified into several subsets: Schottky barrier-based detector, p-n junction-based detector, p-i-n junction-based detector, and metal-semiconductor-metal (MSM) type detector.

3.1 Schottky barrier-based detector

The Schottky structure is a commonly used structure in wide band gap semiconductor ultraviolet detectors. The translucent Schottky contact and ohmic contact\[^{12}\] form a Schottky diode, which is shown in Figure 2(b). Due to the difference in work function between metal and semiconductor, the electrostatic barrier between metal and semiconductor will cause the rectification characteristics of the metal-semiconductor contact, so the rectification behavior is shown on the metal-semiconductor junction.\[^{13}\] Chen et al. The fabrication and characteristics of a vertical geometric transparent and transparent Schottky barrier ultraviolet detector on an n_ / n + -GaN epitaxial layer on a sapphire substrate are reported. Its response time is 118 ns, which is significantly shorter than other GaN detector types. However, Schottky UV detectors also have weaknesses.\[^{14}\] High responsivity, high quantum efficiency, low dark current and short response time are its weaknesses. At the same time, since incident light interacts with the semiconductor (photosensitive layer) through the metal electrode, the metal electrode is usually formed as a semi-transparent thin layer, and the high absorption coefficient of the metal electrode is also a problem. In addition, the surface state effects and shallow metal-semiconductor contacts further limit the development of Schottky structure UV detectors.\[^{12}\]

3.2 p-n junction-based detector

A p-n junction detector is shown in Figure 2 (c). When light of the appropriate frequency hits the active area of the detector, the carriers generated by the photons will form a photocurrent in the external circuit under the action of the electric field, which is not beneficial to the normal photovoltaic operating mode. When a forward bias is employed in the p-n junction, the dark current is much larger than the photocurrent, and the detector cannot work due to the characteristics of the unilateral conductivity. Moreover, the dark current will be suppressed under reverse bias. In addition, the carrier transmission time and diode capacitance are also decreased, which is beneficial to improve the sensitivity.\[^{15}\][16][17][18]
Monroy et al. fabricated and characterized ultraviolet photodetectors based on GaN p-n junctions with responsivities of 145 mA/W at a wavelength of 360 nm corresponding to a 50% quantum efficiency.\cite{19}

3.3 p-i-n junction-based detector

As shown in Figure 2 (d), an intrinsic i layer can be put between the p and n layers to increase the width of the depletion region, thus improving the sensitivity of the device and the speed of response. When the reverse bias increases, the depletion region will be widened and the junction capacitance will be reduced.\cite{20} As a result, the responsivity as well as the response speed will be enhanced.\cite{20} Increasing the light transmission rate is important to improve the performance of a p-i-n device and it requires a structure to ensure that the light is absorbed in the depletion region. Hence, it is beneficial to select a translucent metal as the Ohmic contact and to decrease the thickness of the p layer.\cite{21} Xu et al. prepared AlGaN/GaN p-i-n UV photodetectors by reactive molecular beam epitaxy on sapphire substrates, with responsivities up to 0.15 A/W and response times as short as 12 ns.\cite{22}

Although the detector based on the pin junction has the following advantages: fast response speed, high impedance, low dark current, low bias or zero bias operation, high frequency operation capability, compatible with pn pin photodiode manufacturing technology and planar processing technology, but their time response is usually limited by the behavior of p-type dopants, resulting in poor spectral response.

3.4 Metal-semiconductor-metal (MSM) type detector

The MSM detector consists of double "back-to-back" semiconductor Schottky barriers, and uses interdigital electrodes with planar linearity on top of the active light collection area, as shown in Figure 2(e).\cite{23}\cite{24} These devices have a linear relationship with optical power and exhibit a UV/visible light contrast ratio of 10^4. A UV photodetector based on AlxGa1-xN based on organic metal vapor phase epitaxy is reported.\cite{25} These photodetectors fabricated on low-density dislocation layers exhibit greatly reduced long-lasting photoconductivity and achieve a three-orders of magnitude suppression ratio between ultraviolet and visible light.

![Figure 2. Schematic structure of UV detectors for (a) Photoconductor type, (b) Schottky barrier type, (c) p-n junction type, (d) p-i-n junction type, and (e) MSM type.](image)

4. Nano-structured GaN-based UV detectors

Up to date, given the fact that various mature technologies of GaN-family materials on substrate are rather well-established, the quality of thin films such as AlGaN is still far from satisfaction. Particularly, the growth of AlGaN especially with a high Al percentage has proved to be extremely hard, which lies in the lower migration of Al atoms than that of Ga atoms, and strong parasitic reaction.\cite{25} As a result, high-density defects, such as dislocations, grain boundaries, or stacking faults, are much easier to generate, which consequently cause the device performance to deteriorate.
Generally, nano-structured materials are more uniform than bulk and thin film materials, and usually exhibit better crystallinity. Therefore, it would be fundamentally promising to investigate the GaN family in nano dimensionality for UV detection use. In recent years, one-dimensional (1D) nanostructured (nanowires etc.) UV detectors are gaining increasingly significance because of the improved sensitivity to light on account of their large surface-to-volume ratio and Debye length compared to their small size.\[26\] Liu et al. prepared ultra-long AlN nanowire arrays by CVD with a fast response speed and high photocurrent response. What’s more, it has a reproductive working performance in the air environment.\[27\] Bugallo et al. reported a visible-blind UV photodetector based on \(p-i-n\) GaN nanowire that ensembles on Si substrate. The peak responsivity, UV-visible light rejection ratio, and operating speed of the detector perform very good.\[28\] Li et al. reported on the fabrication of fully nanowires-based photodetectors. Their active parts are made of GaN nanowire, and their electrodes are made of Ag nanowire networks. Through proper thermal annealing process, the dark current and photodetector response time have been greatly improved.\[29\]

However, UV detection based on the nanostructured semiconductors may face predicament under harsh environments such as elevated temperatures or different gas atmospheres, as a result of the surface-state-dominated photocurrent transport mechanism. The photocurrent, device sensitivity and stability will receive a sharp decline under the mentioned conditions due to the environmentally-dependent nature of surface states. To counter with this shortcoming, Zou et al. successfully fabricated the stable DUV photodetectors under high temperature based on individual \(\beta\)-Ga\(_2\)O\(_3\) nanowires, in which the photoresponse behavior is dominated by the bulk instead of the surface states, and the device thus achieved high detectivity, high speed, and high thermal stability at temperatures even as high as 553 K.\[30\] According to Zhang et al., nanowires containing InGaN / GaN core / shell quantum wells were synthesized by a catalyst-free metal-organic vapor phase epitaxy method in the middle of a radial pn junction. They also found that the switching time is less than 0.1 s.\[31\][32]

5. **Super thermo-stable UV detectors based on GaN-family**

The GaN-family materials, also known as direct wide bandgap semiconductors, have always been accepted as a candidate for military and aerospace use where high energy radiation/particles and heat resistance are required. One promising strategy to counter the high temperature environment is the adoption of metal-insulator-semiconductor (MIS) structure. Sang et al. demonstrated that by using CaF\(_2\) as the insulation layer, the InGaN-based visible-blind photodetector showed good performances at high-temperatures up to 523 K.\[33\] The reverse current leakage remained at a low level (10\(^{-7}\)–10\(^{-8}\) A), while...
the UV responsivity is as high as 5.6 A/W at −3 V bias. The insight mechanism has also been discussed. The photocurrent gain was interpreted in terms of thermionic-field emission and field-emission tunneling mechanism from room temperature to high temperature, while thermionic-field emission became the dominant mechanism at high temperature.\[33\]

6. Conclusion and outlook
A broad introduction has been presented in this paper to the device and materials progress in the fields of III group-nitride semiconductors, or referred to as GaN-family semiconductors, UV-based detectors. A detailed summary of various device categories is included in this paper, containing photoconductive detector, Schottky barrier-based detector, p-n junction-based detector, p-i-n junction-based detector, and MSM type detector. The special focus has been put on the nano-structured materials and the device thermal stability: the bulk-dominant semiconductor and MIS-structured device are proved to be effective. However, in order to keep up with the well-established Si or Ge-based detection technology, device reliability and reproducibility are still requiring improvements. In the future, more researches should be done on basis of more accurate control of material preparation (crystallization, growth) and device fabrication, to further build up the III group-nitride semiconductor-based UV detectors for more reliably countering various applications, especially at high temperature or under high energy radiation.

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