An Analysis of GaN-based Ultraviolet Photodetector

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Abstract. The GaN-based UV photodetectors have been a hot topic in semiconductor field. To present the existing research, this paper introduces the development of GaN-based UV photodetectors and the common types of detectors. The difficulties and new technologies of UV photodetector are also introduced. About the difficulties, the whole paper would focus on the substrate of the GaN. To solve this problem, this paper have introduced the PSS, an enhancement of sapphire substrate. Also this paper have put a hypothesis on the shape of PSS. The surface plasmon, which is not a common technology in photodetectors is also introduced. It is hoped that this paper will provide research background and direction for researchers who want to enter this field.

1. Introduction
Ultraviolet detection technology is becoming more and more important in military and civilian fields nowadays, such as medical analysis, flame sensors, missile warning, ozone monitoring, and even UV astronomy. Compared with infrared detection technology, ultraviolet detection is a better choice.

Si-based ultraviolet detectors have been widely used in semiconductor ultraviolet detectors. However, due to its low band gap, it has a large limitation in practical applications. Therefore, ultraviolet detectors with wider band-gap materials are needed. Third-generation semiconductor materials such as GaN and their alloys AlGaN, are one of the hottest research topics in the UV detectors. They own the properties of small volume, low working voltage, low energy consumption, long lifetime, high temperature resistant, and good anti-irradiation stability [1]. Besides, the high chemical and thermal stability of GaN-based detectors have increasingly attracted fundamental research interest.

The study of photoconductive properties of GaN was started by Pankove and Berkeyheiser in 1974[2]. In the 1990s, the first GaN-based UV photoconductor was developed by Khan et al. in 1992.[3] And then many fabricating techniques are invented, such as Lateral epitaxial Growth [4][5]. Homogeneous epitaxial Growth [6]. Massive research have been done on the substrate of GaN nowadays. Considering many factors, sapphire substrate is widely used in industrial production. However, there are still some problems needed to discover.

The most important one is that we still have not found a perfect substrate of GaN. What’s more, the performance of many devices are unsatisfactory. In this paper, I would like to make a review of the current research and discuss some new ways to enhance the devices’ performance.

2. Types of photodetectors

2.1. Photoconductive photodetectors
The photoconductive detector is one of the simplest structures. It is formed from a semiconductor thin film and two ohmic contact electrodes. When photons with energy greater than the width of semiconductor band-gap are incident into semiconductor materials, electron-hole pairs would be generated either by intrinsic transition and extrinsic transition. The intrinsic transition means the band-to-band transition while the extrinsic transition means transition involving forbidden-gap energy levels. Therefore, the conductivity of the semiconductors would change. When applied bias voltage, these changes in conductivity will form a directional photogenerated current. This is how the photoconductive photodetectors works.

However, there is a strong drawback of p.p called persistent photoconductivity (PPC), which means the photogenerated current would persist for a long time after the light is shut off[7], [8]. As a consequence of PPC, The measured responsivity is determined not just by the optical absorption in the semi-conductor, but also the time that the sample has been kept in the dark. Thus such a device is not suitable in real applications unless we make some change in the measuring technique.

In conclusion, photoconductive photodetector, for its low response speed and poor UV/contrast, is not an ideal device in real application, where the response speed and spectral contrast is required.

2.2. p-i-n photodetectors

In order to enhance the responsivity, the p-i-n diode has been fabricated. By adding an intrinsic layer in the p-n diode, the doping concentration in n region could be reduced. Therefore, the depletion region is widened. The width of depletion region could be changed by altering the thickness of intrinsic layer. This can improve the quantum efficiency and response rate of the device. Very high-speed GaN p-i-n photodiodes have been reported by Carrano et al. [9]

As Fig.1 shows, the cut-off shifts to shorter wavelengths and becomes smoother for increasing Al content. A visible rejection of more than four orders of magnitude is obtained in all the devices. III-nitride detectors provide an intrinsically sharp long-wavelength cut-off, which enables high resolution in detection.

In conclusion, the device has better performance than the photoconductive photodetectors. This type of device has a high UV/visible contrast, so it has a good UV resolution. In addition, due to the presence of potential barrier, the dark current of the device is low. Thus, the p-i-n photodetectors could be used in many situations.

Figure 1. Spectral response of AlGaN p-i-n photodiodes [10].
2.3. Schottky photodiodes

The schottky structure can be divided into three parts, including semiconductor thin film, ohmic contact and schottky contact. Metals with high work function, such as Pt, Ni, Pd or Au, are commonly used for Schottky contact processing. The specific working principle of Schottky photodiode is similar to that of the p-n junction diode, the electron-hole pairs are generated by the incident photons and then form the photogenerated current with the help of electric field. The holes will then be pulled to the schottky barrier. As Fig.2 shows, when it is not approaching the cut-off wavelength, the response curve of the Schottky photodiode is relatively smooth.

Generally, the influence of incident light intensity and temperature can be ignored. This is mainly because the depletion region of schottky devices is usually located in the shallow layer of semiconductor materials. Even though the incident photon energy is increased, photocarriers can still form in the depletion region of the materials’ surface and then form photocurrent. Compared to p-n photodiodes, Schottky photodiodes have more stable quantum efficiency, which makes it stable in most frequencies. Regarding device geometry, in theory, vertical structure could make the device to obtain better quality ohmic contacts, higher responsivity and lower capacitance.

To sum up, Schottky photodetector has the advantages of simple manufacturing process, high responsivity and smooth response curve, high quantum efficiency.

2.4. Metal-semiconductor-metal photodetectors

MSM photodiodes are particularly suitable for high-speed applications. It consists of two Schottky contacts, the two contacts are co-planar and opposite. Therefore, when one junction is forward conductive, another is reverse. MSM detectors has many advantages: low capacitance, high UV/vis contrast, and simple manufacturing process. The low capacitance decrease the RC delay, which makes the devices to work in a high responsivity. Due to the high UV/vis contrast, the device has high resolution.

The two Schottky contacts are usually interdigitated, which absorb more photons due to the clearance in the contacts. An enhancement of the MSM detector can be achieved by using semi-transparent electrodes, which enables photons pass through the electrodes, increasing the optical area. An increase of the responsivity by a factor of seven is observed when reducing the Au thickness of the electrodes from 60 to 20 nm [11].

In fact, the MSM photodetectors, compared with the p-i-n photodiode, the MSM structure is simpler, and its response is faster. In addition, it has the characteristics of small junction capacitance and high responsivity.
2.5. Avalanche photodiodes
Avalanche photodiodes (APDs) present the advantages of high speed, high sensitivity and large optical gain. APD is a special kind of pn junction structure or p-i-n junction detector working at avalanche breakdown point, it can also use the MSM structure or Schottky structure. An APD has the advantages of a PIN photodiode (cheap, small, high insensitivity) and those of a photomultiplier (high gain and speed).

An avalanche is formed as Fig 3[12]. The gain of APDs can be 1000 or more. The gain exponentially depends on the bias voltage and therefore the relative change of the gain with voltage is a linear function of the gain. At a gain of 100, the relative change is 10%/V and increases linearly to more than 30%/V at gain 1000. Similar is the dependence of the gain on temperature changes. APDs must work at moderate internal gain and need low noise amplifiers because of the strong sensitivity to voltage stability and temperature [12].

![Figure 3. Structure and operation principle of an APD][12].

The advantages of APD are very significant, it is very suitable for detecting weak light and even single photon detection because of its extremely high internal gain. APD has applications in the military, aviation and life sciences. However, APD works under the high voltage, the noise will be amplified accordingly. Therefore, in the design of APD, both noise and gain parameters should be well balanced.

3. Discussion
3.1. Technical Challenges
Advances in WBG semiconductors have opened the possibility of developing high-performance UV photodetectors, capable of operating in harsh atmospheres. However, the technology of these materials is not mature yet. The development of high-quality substrates for homoepitaxial growth of GaN is a constant challenge, although the most serious difficulty lies in the achievement of high doping levels and reproducible ohmic and Schottky contacts. In industrial production, the development of high-quality substrates for homoepitaxial growth is the key point to improve the reproducibility and reduce costs.

The main problem is that high quality substrates have not yet been found. The GaN often grows on heteroepitaxy, and would face problems of high lattice mismatch, thermal mismatch, which would cause high dislocation concentration in materials. Among these dislocations, the spiral dislocation has the greatest influence. The main harm of dislocation is that it exists as a non-radiative composite center in forbidden band, which leads to a large loss of photogenerated electron-hole pair. Which has a negative effect on the optical properties of the device.
In addition to dislocation, there may be other non-ideal conditions in heteroepitaxial GaN, such as doping without activation, defect state and so on. These non-ideal conditions all require optimization of process technology. Therefore, how to improve the quality of GaN epitaxial layer becomes the key to study GaN-based devices. The key to solve this problem is to improve GaN heteroepitaxial substrate technology.

3.2. Patterned sapphire substrate

During heteroepitaxial growth, there are serious problems in lattice constant mismatch and thermal expansion coefficient mismatch between GaN and sapphire substrate [13]. Aiming at these two problems, many methods have been proposed, such as Lateral Epitaxy Growth [4][5] and Homogeneous Epitaxial Growth [6]. However, these methods cannot improve both crystal quality and quantum efficiency.

Patterned sapphire substrate (PSS) technology developed in recent years has very good advantages. Using PSS as the substrate of GaN epitaxial material can effectively reduce the line dislocation density generated in the growth process of GaN epitaxial material, so as to improve the quantum efficiency of the device. On the other hand, PSS can scatter photons emitted from the optical region, which can improve the performance of LED devices [14]. The Fig. 4 shows a kind of PSS.

![Cross-section SEM images of GaN exit-axial layer grown on the groove-shaped patterned sapphire substrate with different growth time [15].](image)
PSS is mainly prepared by using materials with periodic patterns as mask on sapphire substrate, and etching the sapphire substrate with wet or dry etching methods to transfer the mask patterns to the sapphire substrate. Finally, remove the mask and then get the PSS.

At present, the graphic morphology of the sapphire substrate mainly includes groove shape, round hole shape, conical shape, trapezoid shape and hemispherical shape. There have been many studies on how PSS reduces material dislocation. However, there is still no agreement on which shape substrate works best because the exact mechanism of PSS is not completely clear. Based on the hypothesis, a conical shape substrate may be the best substrate. Due to the crystal structure of GaN, the formation of dislocation and the propagation mechanism of dislocation, the dislocation will produce inner triangular cone during lattice mismatch. When surface (0001) becomes the main growth direction, the dislocation will propagate upward. When the crystal grows in the substrate of the conical shape, the internal dislocation matches the slope of the conical shape, which may lead to the bending and annihilation of the dislocation growth in the subsequent lateral growth. However, more experiments are needed to confirm this hypothesis.

3.3. Surface plasmon

With the improvement of theory and processing technology, surface plasmon can have many applications such as in optoelectronic devices, photocatalytic enhancement, biological sensor, and super resolution imaging. In recent years, surface plasmon has provided new approaches to fabricating high-sensitivity UV detectors. Due to the enhancement of surface plasmons, the highest responsivity of GaN-based UV photodetectors with annealed Ag NPs has increased more than 30 times[16].

The principle of SP enhanced photodetector is to use SP to enhance or regulate the light absorption of active layer. When the photon energy is larger than the band gap of the active layer, the active layer absorbs the photon and then generates electron-hole pair to form photocurrent. As shown in Fig.5 [17], SP enhanced light absorption can be explained in three aspects: the first is the scattering of metal nanoparticles, the second is the local field enhancement, and the third is the effective absorption of light enhanced by the propagation of SP.

![Figure 5. Plasmonic light-trapping geometries for thin-film. a, Light trapping by scattering from metal nanoparticles at the surface. b, Light trapping by the excitation of localized surface plasmons in metal nanoparticles embedded in the semiconductor. c, Light trapping by the excitation of surface plasmon polaritons at the metal/semiconductor interface [17].](image)

Silver (Ag) nanoparticle is one of the best choices for near-UV photodetector due to its low parasitic absorption, high scattering efficiency, and easy preparation. There are many WBG semiconductors using Ag nanoparticles to form SP. In 2008, surface plasmon enhanced InGaN/GaN MQWs blueLEDs containing embedded Ag NPs layers were fabricated, whose optical output power was enhanced by 32.2% [18].

Aluminium (Al) is a highly promising material for commercial applications and it has the advantages of low price, high natural abundance and strong plasmon resonance. However, the disadvantages of Al as SP are the high parasitic absorption of Al nanoparticles and fabrication of Al nanoparticles.
In conclusion, the SP enhanced UV photodetectors has much potential to achieve remarkable progress, and there is also lots of technical problems need to be solved.

4. Conclusion
UV photodetector has very important practical value, among which, the third generation semiconductor material based UV photodetector has a good prospect. Various structures of photodetectors according to their different properties can be due to different practical conditions. However, there are still problems needed to be overcome, and the most important problem is to find a more suitable substrate. Meanwhile, the discovery of new technologies such as PSS and SP also provides good condition for the development of GaN UV photodetectors. The PSS is a more suitable substrate. Meanwhile, the discovery of new technologies such as PSS and SP also provides good condition for the development of GaN UV photodetectors. Therefore, we should do more research on it to make enhancement. Except the substrate, the Ohmic contact problem in GaN devices is also important, which would also be focuses on in days to come.

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