Mechanism of defects and electrode structure on the performance of AlN-based metal semiconductor metal detectors

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Keywords: AlN, metal-semiconductor-metal, MOCVD, electrode structure, UV detector

Abstract

We used the metal-organic chemical vapor deposition (MOCVD) method to grow AlN material on a c-plane sapphire substrate and fabricate an AlN-based metal-semiconductor-metal (MSM) detector. Analyzing the influence mechanism of different dislocation densities in AlN materials and detector electrode structure on the detector performance, it was found that the lower the dislocations can effectively reduce the dark current of the detector under zero bias voltage, and help improve the performance of the detector. The study also found that when the finger spacing of the detector remained the same and the finger width increased, the efficiency of the detector decreased, while the response time of the detector increased, when the finger width of the detector electrodes remained unchanged and the finger spacing increased, the response time of the detector increased. Therefore, the electrode finger width and finger spacing must be compromised in the design of the electrode structure to improve the performance of the AlN-based MSM detector.

1. Introduction

Ultraviolet (UV) detection technology [1] has important applications in flame detection, ultraviolet sterilization, space detection, and other fields [2]. Aluminum nitride (AlN) has large bandgap, high electron mobility, saturation speed, good high-temperature resistance, and radiation resistance, thus it is one of the best materials for preparing ultraviolet detectors [3]. At the same time, AlN-based ultraviolet detectors have the advantages of high quantum efficiency, high sensitivity, high response rate, and low power consumption [4, 5], and can be used in deep ultraviolet (DUV) to provide excellent performance in the deep ultraviolet (EUV) range [6–9]. Therefore, AlN-based ultraviolet detectors have a wide range of applications in military and civilian fields, such as space communications, environmental monitoring, flame detection, and missile warning [10–12].

Although studies have shown that AlGaN-alloy-based Schottky detectors can be grown and prepared on SiC or sapphire substrates [13], p-i-n detectors have excellent performance [14]. However, because the bandgap of AlN is as high as 6.1 eV and has good thermal conductivity, the material advantages in the vacuum ultraviolet and deep ultraviolet fields are very prominent [15, 16], actually, it is also employed in photoelectric conversion, the electrode structure directly affects the detector’s response time, quantum efficiency, response speed, etc. Therefore, it is necessary to study the effect of dislocations on AlN materials and how to design electrodes with MSM structures to improve the performance of the detector. The detectors surrounding AlN have not been fully studied [17]. In this article, we prepared AlN-based MSM ultraviolet detectors, studied the influences of dislocation defects and electrode structure on their performance. It is also found that low dislocations can effectively reduce the zero bias, dark current of detectors, and electrode structure design has a significant impact on the response speed of the detector.
2. Materials and methods

In our experiment, we first used a metal-organic chemical vapor deposition (MOCVD) system to grow a 0.5μm undoped AlN buffer layer on a c-plane sapphire substrate at a low temperature. The sources of Al and N were trimethylaluminum and ammonia, respectively. Then grow a 2μm thick undoped AlN epitaxial layer was grown at a high temperature. We prepared four groups of AlN thin film samples, labeled A, B, C, and D. The growth conditions of the AlN buffer layer of the four groups of samples were the same. The growth temperature of the epitaxial layer was the same. The pressure, the growth time, the ammonia flow, and the Al flow were different. These AlN samples have different dislocation densities.

During photoelectric signal conversion, the structure of the metal finger electrode, such as the width and spacing of the interdigital electrodes directly affect the performance of the MSM structure detector, such as responsivity, quantum efficiency, and response speed. Considering reflection and absorption and other factors, if the external quantum efficiency of the device is \( \eta \), the internal quantum efficiency is \( \eta_i \), the surface reflection coefficient is \( r \), the light absorption coefficient of the active layer is \( \alpha \), the thickness of the active layer is \( d \), the width of the interdigital electrode is \( W \), and the distance between the interdigital electrodes is \( L \), the quantum efficiency [18] formula is:

\[
\eta = \eta_i (1 - r) \frac{L}{L + W} (1 - e^{-\alpha d})
\]

To increase the external quantum efficiency, the value of \( L/(L + W) \) needs to be maximized. Therefore, the smaller the width of the interdigital electrode and the larger the spacing, the higher is the external quantum efficiency [19].

In contrast, the resistance and capacitance of the interdigital electrode affect the RC time constant of the device, and the distance between the electrodes affects the carrier transit time; therefore, the response speed of the detector is affected by the two factors [20], where \( l \) is the length of the interdigital electrode, \( H \) is the thickness of the interdigital electrode, \( \rho \) is the resistivity of the electrode, and \( n \) indicates the number of interdigital electrodes. The RC time constant \( \tau_{RC} \) caused by the electrode resistance and capacitance is:

\[
\tau_{RC} = \left(1 - \frac{1}{n}\right) \varepsilon_0 \varepsilon_{\text{r}} \rho \frac{l^2}{HL}
\]

The carrier transit time between the interdigital electrodes \( \tau_D = \frac{L}{V_s} \), where \( V_s \) is the migration speed of the carriers, so the response time \( \tau \) of the device is:

\[
\tau = \tau_{RC} + \tau_D = \left(1 - \frac{1}{n}\right) \varepsilon_0 \varepsilon_{\text{r}} \rho \frac{l^2}{HL} + \frac{L}{V_s}
\]

In practical devices, the response time mainly depends on the carrier transit time \( \frac{L}{V_s} \). Therefore, the larger the finger spacing \( L \), the longer the response time [21].

In the design of the detector, it is generally hoped that the external quantum efficiency of the detector is as high as possible, and the response time is as short as possible. According to the external quantum efficiency equation and the time response equation, in the design of the interdigital electrode size, the smaller the finger width and the larger the spacing, the higher the quantum efficiency. However, the greater the finger spacing, the longer the response time will be, which is not conducive to the performance of the detector. Therefore, we need to compare the finger width and finger spacing of different sizes, and analyze the size of the finger width and finger spacing to make it have better performance.

We designed four samples of interdigital electrodes with different sizes. While studying the effects of defects on detector performance, we also studied the effects of different electrode structures on detector performance. The area of the active area was 400 \( \times \) 400 \( \mu \text{m}^2 \), the finger widths were 5 \( \mu \text{m}, 10 \mu \text{m}, \) and 15 \( \mu \text{m} \) respectively, and the finger spacing is 5 \( \mu \text{m}, \) and 10 \( \mu \text{m} \) respectively. Each of the four groups of samples A, B, C, and D was designed with the size of these four groups. The dislocation density and fork-finger electrodes of the four groups of samples formed a four-group control design together. The effects of different electrode sizes and dislocation defects on the performance of the detector were studied. Finally, we designed AlN MSM interdigital structure detectors as schematically shown in figure 1(a) and a top view of the interdigital electrode structure (unit: \( \mu \text{m} \)), as shown in figure 1(b). We studied the electrical performance of the MSM detector. In figure 1, the metal fingers are connected to the metal electrodes on both sides. All interdigital and metal electrodes were made of evaporated Ni/Au films.

The detectors were processed by photolithography. We first design four groups of patterns of digital electrodes with different size parameters for the purpose of comparison. Then, we clean the AlN samples A, B, C,
and D, making photolithography, vapor deposition of 50 nm Ni and 50 nm Au electrodes, and finally making a rapid annealing treatment at 550 °C for 5 min to obtain the fabricated MSM detectors.

3. Results and discussion

It is the edge dislocation density that may have a greater impact on the carrier transport and photoresponse performance of the devices. We performed x-ray crystal diffraction (XRD) tests on the samples under the study. The diffraction peaks obtained by \( \omega \) scanning x-ray diffraction (XRD) on the (002) plane of each group of samples are shown in figure 2. From figure 2, an obvious diffraction peak with a peak position at 18.01° can be seen, and the position of this peak corresponds to AlN.

Defects in crystals often cause the surface to twist or tilt, and the half-width of the swing curve can characterize the quality of the crystal. In this article, XRD scan measurements are employed to check the dislocation density. Through XRD, we can calculate the screw and edge misalignment density of four groups of samples based on the (002) and (102) omega scan. The screw misalignment density \( D_s \) and edge misalignment density \( D_e \) of the samples can be calculated by the following formula, in which \( b_1 \) and \( b_2 \) is the half-width of the rocking curve of the (002) face and the 102 face, \( \varphi \) is the inclination angle of face 002 compared to face 102. 

$$D_s = \frac{b_1}{q \cdot \cos^2 \varphi}$$

$$D_e = \frac{b_2}{q \cdot \cos^2 \varphi}$$

and \( b_1 \) and \( b_2 \) are desirable for 0.5185 nm and 0.3189 nm.

**Figure 1.** The schematic drawing of sample pattern of the AlN MSM detector with interdigital electrode structure (a) and a top view of the 400 × 400 μm² device (b).

**Figure 2.** XRD \( \omega \) scan results of the (002) surface of the four groups of AlN samples A, B, C, and D.
Therefore, the forward photocurrent under illumination can effect on the forward Schottky junction, but it can greatly reduce the series resistance of the reverse junction. MSM structure can be regarded as a series connection of two back-to-back Schottky junctions. Light has little values.

We found that the dark currents of the four groups of samples under the same electrode structure, as shown in figure 3 below. We can see that the surface morphology of the sample in group D is the best. We know that the surface morphology of a sample has an impact on the electrode contact of the sample, and good surface morphology can better facilitate the adhesion of the electrode metal during the evaporation of the electrode.

We measure the electrical properties of the samples. A direct current voltage is applied to the electrodes at both ends of the interdigital fingers to measure the current. The photocurrent and darkcurrent voltage curves of the four groups of samples under the forward and reverse voltages are shown in figure 4. It can be seen that the I–V curves of the ultraviolet detector conform to the symmetrical characteristics, indicating that good Schottky contact is formed between the interdigital electrode and the AlN sample. The black curve is the result of no light illumination, and the red curve is the result of light illumination. We found that the dark currents of the four groups of samples under the same electrode structure under zero bias voltage of the detectors obtained under the experimental conditions were 0.746 nA, 0.899 nA, 0.620 nA, and 0.616 nA, respectively, with extremely low values.

We found that the cutoff wavelength of AlN on the short-wavelength side was approximately 200 nm. The MSM structure can be regarded as a series connection of two back-to-back Schottky junctions. Light has little effect on the forward Schottky junction, but it can greatly reduce the series resistance of the reverse junction. Therefore, the forward photocurrent under illumination can reflect the forward characteristics of the Schottky junction, while the dark current curve is mainly limited to the characteristics of the reverse Schottky junction, so it reflects the reverse characteristics of the Schottky junction. Therefore, we tested the photocurrent and dark current of the four groups of samples under the same electrode structure, as shown in figure 5. The photocurrent

| Samples | A     | B     | C     | D     |
|---------|-------|-------|-------|-------|
| FWHM(arccs) (002) | 52    | 140   | 105   | 77    |
| FWHM(arccs) (102) | 373   | 334   | 353   | 247   |
| Screw dislocation (cm\(^{-2}\)) | 5.84E + 06 | 4.24E + 07 | 2.38E + 07 | 1.28E + 07 |
| Edge dislocation (cm\(^{-2}\)) | 1.64E + 09 | 1.20E + 09 | 1.41E + 09 | 6.89E + 08 |

\[ D_i = \frac{\beta^2}{4.35\beta_1^2} \]

\[ D_E = \frac{\theta^2 - (\beta \cos \theta)^2}{4.35\beta_1^2 \sin^2 \varphi} \]
and dark current in the figure 5 are the vertical axis, and the current difference is the relative measurement result of the spectral response, which is convenient for directly comparing the influence of the MSM structural parameters on the responsivity.

By comparing the photocurrent and dark current of the tested samples, we found that there were significant differences in the photocurrent and dark current of the four groups of different samples under the above conditions. Within a certain range, at a relatively low voltage, A, the IV difference of the detectors of the three
groups of samples B and C did not change significantly. Similarly, the three groups of samples A, B, and C have similar edge dislocations, so their differences are also similar. When the voltage exceeded 100 V, the difference between the photocurrent and the dark current of the three groups A, B, and C changed significantly. The D group samples have good material properties due to their low dislocation density, and their current varies with the voltage, indicating that the difference between the photocurrent and the dark current of the detector for testing under different voltages The obvious change indicates that the detectors of this group of samples have the highest responsivity. This is because the lower edge dislocation defect acts as a charge trap in AlN, which can increase the recombination probability of electron-hole pairs generated by light. Therefore, the electron-hole recombination probability of the D samples under illumination is much larger than that of the other three groups, and the edge dislocations of the three groups A, B, and C are similar, and their electron-hole

Figure 5. The difference between the photocurrent and the dark current of the four groups A, B, C, and D under different dislocations.

Figure 6. Results of relative spectral response characteristics under different battery structures.
recombination probability is also roughly the same, and their photocurrent and dark current do not change significantly with the change in voltage.

At the same time, we analyzed the D sample with the lowest dislocation density and analyzed the performance of the detector under different electrode structures. As shown in figure 6, it can be found that the distance between the fingers has not changed. When the finger width increases, the current difference does not change significantly with the voltage change, while the finger width does not change. When the finger distance increases, the current difference increases with the increase of the voltage. We believe that in the time response equation, the carrier transit time is determined by the finger spacing L. The smaller the finger distance, the smaller the transit time and the smaller the response time. However, the smaller the finger spacing, the lower the external quantum efficiency, and the performance of the detector will decrease. Therefore, it is better when the finger spacing in the experiment is 10 um. At the same time, when the finger width is 5 um, compared with the finger width of 10um, the effective photosensitive area is too small at 5 um, which will also reduce the performance of the detector, so it is better when the finger width is 10 um in the experiment.

We analyzed the reason for this situation because the finger spacing remains unchanged. When the finger width increases, the effective photosensitive area decreases, weakening the effect of the carrier transit time, while the finger width remains unchanged, and the finger spacing increases. At this time, the effective photosensitive area will increase, and the increase in the effective photosensitive area dominates.

4. Conclusions

In this study, an AlN-based MSM UV detector is fabricated. The study found that reducing the defect density of AlN material under zero bias is beneficial for increasing the probability of electron-hole recombination generated by light and improving the performance of the detector. At the same time, by analyzing the spectral response characteristics of MSM detectors with different finger widths and finger spacings, we found that the smaller the finger spacing, the faster the response rate; on the other hand, when the spacing decreases, the quantum efficiency of the detector will decrease. Therefore, considering the effects of increased effective photosensitive area and weakened carrier transit time, when the finger width is 10 um and the finger spacing is 10 um, the UV detector based on the AlN-based MSM structure has a better performance. This work promotes the design and manufacture of UV detectors.

Acknowledgments

The authors acknowledge support from the National Natural Science Foundation of China (Grant Nos.61474142 and 61974162). The authors would like to thank Professor D. S. Jiang for his help in editing the manuscript.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Disclosures

The authors declare no conflicts of interest

Ethics statement

Therefore, informed consents from patients were not needed and the institutional review board (IRB) reviews were waived based on the institutional policy.

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