Fabrication of high quantum efficiency p-i-n AlGaN detector and optimization of p-layer and i-layer thickness

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Abstract

In this paper, the fabrication process and structure of AlGaN based p-i-n photodetectors with different layer thicknesses are described. The maximum external quantum efficiency (EQE) of back illumination is 87.87% at zero bias. According to the Poisson equation, the electric field distribution of the devices is analysed, and a detailed method to estimate the reverse bias voltage required for the p-layer and i-layer to be completely depleted is proposed. The reliability of the method is also well proven by the responsivity measurement results under zero bias and reverse bias. Finally, based on the experimental data and theoretical calculation, the optimization method of p-layer and i-layer thickness in p-i-n photodetector is analysed.

1. Introduction

Ultraviolet detection technology is widely used in the field of production and life. It plays an important role in smoke alarm, UV guidance, UV safety communication, weather detection and other fields [1–3]. Because of the lack of solar blind band light in the natural atmosphere, the solar-blind photodetectors can more effectively avoid the impact of natural light sources. In the process of metal organic chemical vapor deposition (MOCVD) growth, direct band gap GaN-based materials with a band gap width of 3.4–6.2 eV can be prepared by changing the alloying ratio of AlN and GaN, which can detect ultraviolet light in the range of 200–365 nm [4, 5].

But there are still many problems to be solved. AlGaN lattice mismatch to the sapphire substrate is large. Various reaction processes are complicated and difficult to control, and the activation efficiency of doping becomes lower [6, 7]. Moreover, because of the high UV photon energy detected, there is a great loss in the p layer due to the front illumination. Therefore, the method of back illumination is generally used. The back-illuminated type is also advantageous to combine with the silicon-based circuit to form focal plane array imagers [7, 8].

The p-i-n structure AlGaN detector has always been the focus of research because of its simple structure, high responsivity, and relatively fast response. There are many researches on the thickness of p-i-n layers, but most of them are based on software simulations [9–12], and there are few experimental comparisons of several actual samples. In this work, four high quality AlGaN samples with different thickness of p and i layers were prepared. Under zero voltage, the maximum quantum efficiency can reach 87.87%. The distribution of electric field intensity in the diode is analysed by the Poisson equation, and the calculation method of reverse bias voltage for p-layer and i-layer is proposed. According to this calculation method, the optimization scheme of p-layer and i-layer thickness is suggested. It has important reference value for subsequent p-i-n device preparation.
2. Samples preparation

The structure of the four samples is shown in figure 1. The thickness of p layer and i layer of each sample is shown in table 1. To reduce the lattice mismatch problem, a layer of AlN template is grown before the growth of AlGaN materials. The AlN monolayers grown under the same conditions were tested by omega scanning in diffraction of X-rays (XRD). The full width at half maxima (FWHM) of (002) plane diffraction is less than 80 arcsec, (102) plane is less than 400 arcsec which shows relatively high quality in recent researches [13–16]. The n-AlGaN, i-AlGaN and p-AlGaN layers were grown in order. The i-AlGaN is an unintentionally doped layer, but it presents a weak n-type because of the residual impurity. The Al composition of p layer and i layer is 40%, and that of n layer is 65%. The intrinsic response wavelength of Al0.65Ga0.35N is about 250 nm. When backside irradiation, light with a wavelength below 250 nm will be absorbed in the thicker n-layer. Therefore, in the case of back illumination, the response of low wavelength light can be filtered out through the n-layer with high Al content.

Using the monolayer samples grown under the same conditions for Hall test and XRD scanning, we can get the following data. The Hall tests show that the carrier concentration of p, i, n layers is about $1.2 \times 10^{17} \text{cm}^{-3}$.
The Omega scan (002) diffraction FWHM is less than 300 arcsec, (102) FWHM is less than 500 arcsec for all AlGaN single-layer samples which also show high quality [17]. Because the light spot area is about $1 \times 1$ mm$^2$, to better calibrate the responsivity, the photosensitive area of the sample is $1.2 \times 1.2$ mm$^2$.

To ensure the conductivity and reduce the loss of front light on the metal, most of the surface in p-layer is covered by thin metal 15/50 nm Ni/Au. Because Ni/Au is relatively thin, it cannot withstand higher voltages. The thickness of Ti/Al/Ti/Au is 15/250/50/250 nm which is used to make p and n electrodes.

3. Testing and analysis

We first measure the responsivity of four samples at zero bias voltage. Different wavelengths of light can be modulated by the xenon lamp and spectrometer. The measurement wavelength range of four samples is 220–320 nm. To reduce the influence of environmental noise, a 400 Hz chopper and a lock-in amplifier are used to extract the optical signal. To determine the accurate value of responsivity, S1226-BQ UV enhanced Si detector of HAMAMASTU company was used for calibration. Figure 2 shows the responsivity curves obtained for four samples A, B, C, and D under front and back illumination at zero bias voltage. The responsivity of sample D at 270 nm is 190.96 mA/W, and the corresponding external quantum efficiency is 87.87% which is one of the highest quantum efficiencies among p-i-n detectors currently reported [13, 18–23]. Because of the uniformity of
Figure 5. The electric field distribution of a p-i-n device under different reverse bias voltage. The red line indicates that the i layer is just completely depleted, and the blue line indicates that the p layer is just completely depleted.

Table 2. The calculated results of the corresponding voltage values when the p and i layers are just completely depleted. The dotted line means that no additional voltage is required.

| Sample | $V_{total1}$/V | $V_{R1}$/V | $V_{total2}$/V | $V_{R2}$/V |
|--------|----------------|------------|----------------|------------|
| A      | 0.36           | —          | 9.04           | 6.34       |
| B      | 1.46           | —          | 12.82          | 10.12      |
| C      | 3.28           | 0.58       | 16.03          | 13.33      |
| D      | 1.46           | —          | 4.66           | 1.96       |

Figure 6. The responsivity Versus wavelength for samples A(a), B(b), C(c), and D(d).
AlGaN samples, there is only a slight component fluctuation in the AlGaN composition of four samples, and the obtained responsivity peaks are only slightly different for four samples.

By the reason of the n-layer AlGaN with Al content of 0.65, there is basically no response for back-illuminated in the wavelength region below 250 nm. By comparing the sample B and the sample D, it is found that the responsivity slightly increases when the thickness of the p layer becomes thinner. For front illumination, the main reason for the higher responsivity of sample D than that of sample B is that the thickness of the p-layer decreases, which can greatly reduce the loss of light absorbed in the p layer. Because of the high energy of short-wavelength light, the loss in the p-layer is more serious when the device is exposed to the front illumination, so it has an obvious improvement in the short-wave region to reduce the p-layer thickness. For back illumination, the decrease of p-layer thickness can reduce the loss of carrier recombination before reaching the p electrode, so the responsivity will be slightly improved. However, the decrease of p-layer thickness can bring other problems. The first is that the processing is more difficult, and the device life can be shorter. Then there is the more obvious problem of dark current growth under reverse bias.

It is known that p-AlGaN cannot prepare ohmic contacts by traditional methods because of its high work function. The actual metal and p-layer AlGaN contacts are Schottky contacts, but the tunnelling effect can be achieved by increasing the carrier concentration of p-layer, which is then like ohmic contacts [24–26]. With the decrease of p-layer thickness, the tunnelling effect becomes more obvious as the thickness of the potential barrier width decreases. We test the reverse bias current of samples B and D, and the results are shown in figure 3. The dark current of sample D can be stable for a limited range of reverse voltage, and then increases rapidly at the end of about 2 V reverse bias. In fact, when the applied voltage is about 2 V, the p layer of sample D is just depleted. The depletion of p layer will be discussed in detail later in this paper.

Compared samples A and B, we can see that the responsivity increases with the increase of thickness of i layer. The broadening of the depletion layer can collect more photogenerated carriers. However, comparing samples B and C, the responsivity decreases with a further increase of thickness of i layer. This is because that the i layer of C sample is not completely depleted at 0 bias [27]. As a result, a three-part structure of depletion-region/ intrinsic-region/ depletion-region appears in the i-layer, which makes it difficult for photo generated carriers to be swept to the collection electrodes.

To further study the depletion of the device. We use simplified Poisson equation shown as formula 1 to analyse the distribution of electric field intensity.
Where $\phi$ is the electric potential, $E$ is the electric field strength, $x$ is the distance, $q$ is the charge, $\varepsilon_r$ is the dielectric constant of AlGaN material, $\rho$ is the charge density, and $N$ is the carrier concentration. According to the simple weighting of the composition of AlN and GaN and Vegard’s law, it is considered that the relative dielectric constant of AlGaN is about 9.3 [26, 28]. Ignoring the contact potential between the p-layer and the metal and the uneven distribution of carriers in each layer, we can assume that the slope in the $E$-x relation is directly proportional to the carrier concentration in the layer. The area covered by the E-x curve is all the reverse bias voltage $V_{total}$. $V_{total}$ is equal to the sum of $V_b$ and $V_i$. And $V_b$ is the built-in electric pot. $V_b$ is the applied reverse voltage.

$V_b$ is generally considered to be related to the carrier concentration of the p-layer and i-layer and the intrinsic carrier concentration of the material itself. Because there are many factors that affect $V_b$, the values employed in different documents are quite different. This article uses experimental method to obtain $V_b$. As shown in figure 4, it can be considered that the forward turn-on voltage is $V_{bi}$, which is about 2.7 V.

Figure 5 depicts the distribution of electric field intensity in the space of a p-i-n diode as $V_{total}$ increases. The red curve indicates that the i layer is just completely depleted, and the blue line represents the situation in which the p layer is just completely depleted. The total voltage and the applied reverse voltage for complete depletion of i layer are set as $V_{totali}$ and $V_{bi}$. The total voltage and the applied reverse voltage for complete depletion of p layer are set as $V_{total2}$ and $V_{b2}$. According to the integral area $V_{total}$ covered by the E-x curve, the corresponding relationship between the slope of the $E$-x relation, and the carrier concentration analysed by the Poisson equation, the relevant voltage values can be calculated in table 2.

Before the p-layer is depleted, when the carriers are swept into the p-layer, the electric field in the undepleted region of the p-layer can be weak, resulting in lower responsivity. To verify the accuracy of the analysis, four samples were tested for responsivity under reverse bias. To protect the device, the highest applied reverse bias is limited up to 10 V, and the measurement result is shown in figures 6 and 7. Before reaching the depletion voltage of the p-layer, the responsivity increases quickly as the reverse bias becomes larger. It can be seen from the samples A and D that when the reverse bias reaches 6.34 V and 1.96 V, with the voltage continues to increase, then the increase in responsivity will slow down. It shows that the analysis method is basically reasonable.

4. Conclusion and perspectives

Based on improving the material quality and optimizing the device structure, we fabricated p-i-n type AlGaN photo-detector devices with a quantum efficiency up to 87.87% under zero bias. At the same time, the optimization plan for the thickness of the p-layer and i-layer is proposed to provide some help and guidance for an optimization of the p-i-n structure photo-detector. That is, to improve the peak responsivity of the back-illuminated p-i-n device, the thickness of the p-layer should be thinner under zero bias. However, the increase in dark current and the difficulty of process preparation must also be considered. The i-layer is best to be just completely depleted. In this way, a longer collection channel for photo-generated carriers can be ensured, and a three-part channel of depletion layer-intrinsic region-depletion layer can be employed to prevent from hindering carrier transmission. At the same time, if the detection is performed under reverse bias, considering the lifetime and responsivity of the device, the applied reverse bias voltage should just make the p-layer completely depleted.

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