Improvements of AlGaN/GaN p-i-n UV sensors with graded AlGaN layer for the UV-B (280–320 nm) detection

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Abstract

AlxGa1−xN/GaN p-i-n UV sensors grown by metal organic chemical vapor deposition (MOCVD) were fabricated for the UV-B (280–320 nm) detection. With a proper structure design by including a thin top p-layer and a graded AlxGa1−xN (x = 0.26 → 0.13) layer, the etching pit density (EPD) and the specific contact resistance of the top p-layer can be significantly decreased. Device dark current density decreased from 3.5 × 10−7 A/cm2 to 2.49 × 10−11 A/cm2 at −3 V and the spectrum responsivity at 310 nm UV-B range is 0.04 A/W, which is much better than traditional AlGaN-based devices without graded layer design.

Keywords: UV sensors; P-layer; Density

1. Introduction

AlxGa1−xN/GaN p-i-n UV sensors are the most promising materials for the applications such as combustion process monitoring, flame sensors, space-to-space communications or solar UV monitoring [1–6], due to their intrinsic visible-blindness and the possibility of tailoring the absorption edge from 365 to 200 nm by modifying Al content of the ternary compound. Although the well-established silicon technology offers cheap and efficient solutions for UV detection, however, they suffer from aging effect when exposed to high-energy radiation. Photo-detectors based on AlxGa1−xN/GaN wide band gap semiconductors can achieve UV selectivity without optical filters; moreover, these wide band gap materials are chemically, mechanically and thermally stable, which is particularly appropriate for the operation in harsh environments.

Recently, visible-blind UV-B (280–320 nm) sensitive AlGaN photocconductors and Schottky-based photodiodes with short cutoff wavelengths lower than 325 nm have been reported [7–9]. However, their performance is not fully satisfied for the difficulty to obtain a heavily doped p-type layer and hence a low-resistant ohmic contact on p-type AlxGa1−xN layer [10,11], which was attributed to the restraint in Mg doping efficiency with increasing Al content in AlxGa1−xN layer. In addition, a higher Al content in the AlxGa1−xN layer will lead to severe defects and cracking problems because it enlarges lattice and thermal expansion mismatch between sapphire and AlGaN layer. As a result, the thickness and Al composition of AlxGa1−xN layers grown on traditional GaN/sapphire substrates [12] will be limited. Nowadays, photodiodes grown on a low-defect lateral epitaxial overgrown (LEO) GaN layer [13]; low-temperature (LT) AlN interlayer [14] and strain-relief superlattice (SLs) interlayer [15] for the defect reduction have been proposed. In this study, an approach based on a graded AlGaN layer is proposed to improve the performance of AlGaN UV sensors; with a proper structure design by including a graded AlxGa1−xN layer company with a thin p-GaN layer on the top; not only a better film quality but also a reduced dark current and improved spectrum responsivity of the device can be achieved successfully.

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2. Experiments

Three samples with different structure were grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. All detectors consists of a LT–GaN buffer layer, 1 μm GaN layer, 2 μm lightly Si-doped GaN base layer ($n = 2.5 \times 10^{17} \text{ cm}^{-3}$), followed by a 1 μm heavily doped N-GaN layer ($n = 5 \times 10^{18} \text{ cm}^{-3}$) and a 0.2 μm thick undoped Al$_{0.3}$Ga$_{0.7}$N layer. Sample 1 was finally terminated with a 1000 Å thick Mg-doped p-Al$_{0.26}$Ga$_{0.74}$N contact layer. In sample 2, a 500 Å thick Mg-doped p-Al$_{0.26}$Ga$_{0.74}$N and a 500 Å thick Mg-doped p-GaN layer was deposited as the underlying and contact layers, respectively. In sample 3, a 100 Å thick Mg-doped p-Al$_{0.26}$Ga$_{0.74}$N was first grown on top of the undoped Al$_{0.3}$Ga$_{0.7}$N layer, followed by a 300 Å thick Al$_{x}$Ga$_{1-x}$N ($x = 0.26 \rightarrow 0.13$) grading layer, and finally a thin 300 Å thick Mg-doped p-GaN top contact layer was deposited. Three different layer structures are shown in Fig. 1. Mesa patterns were then performed by inductively coupled plasma reactive-ion etching (ICP-RIE) technique, using Cl$_2$ and Ar as etching gases for the device isolation and contact patterning. The device consists of two circular contact electrodes, Ti/Al/Ti/Au (20/100/20/150 nm) and Ni/Au (20/150 nm) as n- and p-contact electrodes, respectively, followed by furnace annealing process at 500–600 °C in N$_2$ ambient for 10 min. The contact resistance was measured by circular transfer length method (CTLM). Three samples were rinsed in H$_3$PO$_4$ at 280 °C for 5 min, and the density of etch pits was examined by scanning electron microscope (SEM). Atomic force microscopic (AFM) and a surface profiler (Dektak3) were used to characterize the surface morphology. The photocurrent or dark current of the p-i-n photo-detectors were characterized by an HP-4156 parameter analyzer, the studies of spectral responsivity were performed by using a 75W Xenon lamp with a monochromator. A standard Si-based UV enhanced photo-detector was also used for calibration.

3. Results and discussion

Fig. 2a shows the dark current density of three p-i-n detectors with the active region of 1 mm × 1 mm. It is known that defect, such as dislocations originated from the lattice mismatch between epilayers and sapphire substrate, can reveal themselves in a high dark current of p-i-n device. It is also known that dry etching induced crystal damages could result in a high dark current. Experimental results show that the high Al content in the p-Al$_{0.26}$Ga$_{0.74}$N contact layer of sample 1 has resulted in high density V-shape defects and cracking in Al$_{0.26}$Ga$_{0.74}$N layer due to the severe lattice mismatch between epilayers and sapphire substrate. The relatively high dark current density of $3.5 \times 10^{-7} \text{ A/cm}^2$ at −3 V measured in sample 1 can be attributed to the severe hopping of charge carriers occurred via localized defects in the epilayers. For sample 2 with p-Al$_{0.26}$Ga$_{0.74}$N/GaN contact layers, the measured dark current density was reduced to $5.24 \times 10^{-9} \text{ A/cm}^2$ at −3 V because a lower resistance ohmic contact can be obtained in GaN film as shown in Fig. 2b. Dark current can be further suppressed in sample 3 with a grading Al$_{x}$Ga$_{1-x}$N ($x = 0.26 \rightarrow 0.13$) layer. With such a grading layer, the stress in Al$_{x}$Ga$_{1-x}$N film can be released and cracking problems can be prevented. In this case, a thin GaN (300 Å) layer was also used as the top contact layer to...
obtain a low ohmic contact resistance in Fig. 2b. The dark current density was significantly reduced to $2.49 \times 10^{-11}$ A/cm$^2$ at $-3$ V, which is the lowest dark current in this work. Sample 3 presents much lower device contact resistance due to the less dislocations and photo ionization of deep levels at the surface. The devices fabricated on samples 1, 2 and 3 have a turn-on voltage of 2.07, 1.69 and 1.2 V, respectively, with the corresponding ideality factors of 5.5, 3.4 and 1.8 (Fig. 2a).

Using a graded Al$_x$Ga$_{1-x}$N layer, a lower turn-on voltage, lower contact resistance, and lower ideality factor [16] could be achieved in sample 3.

Fig. 3 shows SIMS measurement of p-contact metal (Ni/Au) diffusion on top of samples 1 and 3, after annealing (550°C/10 min), respectively. It is observed that due to sample 3 with graded layer present a better films quality on top p-layer than sample 1. An enhanced (Ni/Au) diffusion depth and a higher (Ni/Au) intensity on SIMS profile (i.e. about 2 order larger intensity at diffusion depth 300 nm than sample 1) could be achieved on sample 3, which also presented a better ohmic contact on sample 3 than sample 1 is discussed in Fig. 2b.

Fig. 4. Zero-bias spectrum responsivity of samples 1–3, respectively.

Fig. 5. (a) SEM image of EPD = $3.6 \times 10^{10}$ cm$^{-2}$ on top of sample 1 and (b) SEM image of EPD = $1.2 \times 10^{10}$ cm$^{-2}$ on top of sample 3.
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Fig. 6. (a) AFM image of Ra = 0.128 nm on top of sample 1 and (b) AFM image of Ra = 0.118 nm on top of sample 3.

Spectrum response of AlGaN p-i-n UV detectors at zero bias is shown in Fig. 4. The measured responsivity is 0.012, 0.018 and 0.04 A/W for samples 1, 2 and 3, respectively. Compared to samples 1 and 2, the responsivity of sample 3 does not fall off as the energy is larger than bandgap energy, indicating low surface recombination since the carriers are created close to the surface and must diffuse to the junction to be collected. The decrease of responsivity at shorter wavelengths for samples 1 and 2 can be attributed to a higher absorption in the p-layer. The sharp cutoff (320 nm) obtained in sample 3 with the Al0.26Ga0.74N layer shows that the carriers generated in the p-GaN layer do not contribute to the photocurrent and hence, only the photons reaching the i-AlGaN layer could result in the photocurrent. Meanwhile, sample 3 (without antireflection coating) exhibits a high responsivity with the peak external quantum efficiency ~46% at 280 nm and a high rejection ratio of 2.8 × 103 (280/360 nm), which is higher than that of sample 2 (~7.8 × 102) and sample 1 (~4.7 × 102) and almost comparable to that of the state-of-the-art conventional p-i-n detectors [12,16,17]. The origin of the long-wavelength response in sample 1 is that a p-schottky contact will attract photo-generated electrons in the top p-Al0.26Ga0.74N layer; this effect decreases the responsivity and rejection ratio was observed. In addition to a high epitaxial film quality due to the inclusion of grading p-AlxGa1-xN layer, a better device performance obtained in sample 3 could be attributed partially to the total thickness of p-layer. The thinner p-GaN layer (300 Å) in sample 3 causes the minimum absorption and will enhance the UV irradiation penetration into the depletion region i-layer, which favors the photo-generated carriers to be created in this region and hence, a higher quantum efficiency can be obtained. In other words, a thin p-layer with a large band gap energy could lead to a wider spectral range.
and a higher peak responsivity due to the absence of so-called "optical dead space", where carriers recombine without being collected.

We also observed that at the short wavelength between (330–340 nm), there is a little stage on this spectrum range due to the behavior of Al<sub>x</sub>Ga<sub>1−x</sub>N graded layer (Al content from 26% graded to Al = 13%) which is not graded very well during epitaxy and presented an absorption stage. However, the responsivity at this short wavelength stage (330–340 nm) is still higher than samples 1 and 2, respectively. Meanwhile, at 360 nm (beyond the absorption edge on AlGaN layer) the defect related behavior on responsivity at this wavelength is quite low on sample 3, and a higher rejection ratio on sample 3 than samples 1 and 2 were observed.

Fig. 5 shows the SEM images of etching pit density (EPD) on top p-layer of samples 1 and 3 etched by H<sub>3</sub>PO<sub>4</sub>. The highest EPD on sample 1 is 3.6 × 10<sup>9</sup> cm<sup>−2</sup>, which is two orders larger than sample 3 (EPD = 1.2 × 10<sup>8</sup> cm<sup>−2</sup>). The hopping of charge from these localized defects state, which is one of the reasons why the relatively high dark current density of 3.5 × 10<sup>−10</sup> A/cm<sup>2</sup> at −3 V measured in sample 1 is observed. On the other hand, sample 3 with a graded layer, the stress in Al<sub>x</sub>Ga<sub>1−x</sub>N film can be released, which presented a lower EPD and prevent the cracking problem. In this case, the dark current density was significantly reduced to 2.49 × 10<sup>−11</sup> A/cm<sup>2</sup> at −3 V.

Fig. 6 shows the AFM roughness analysis on top p-layer of samples 1 and 3, respectively. The mean roughness (Ra) of sample 3 is 0.118 nm, which is lower than that of sample 1 (Ra = 0.128 nm). The improved grain alignment on sample 3 presented a lower specific contact resistance R<sub>c</sub> = 3.3 × 10<sup>−4</sup> Ω cm<sup>2</sup> than sample 1 (R<sub>c</sub> = 4 × 10<sup>−4</sup> Ω cm<sup>2</sup>), respectively, at 300 K shown in Fig. 2b. On the other hand, the low-resistivity on sample 3 could expand the depletion region into the n-region, which result a higher responsivity or rejection is thus formed.

4. Conclusions

Al<sub>x</sub>Ga<sub>1−x</sub>N/GaN p-i-n UV sensors with different layer structures were fabricated by low-pressure MOCVD. With the inclusion of a graded Al<sub>x</sub>Ga<sub>1−x</sub>N layer company with a thin p-GaN layer contact layer on the top, a much improved epitaxial film quality and specific p-contact resistance could be achieved. Using this proper layer structure design, the dark current and the rejection ratio can be improved significantly.

References


