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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

$Al_xGa_{1-x}N$/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 $Al_xGa_{1-x}N$ ($x = 0.26 \rightarrow 0.13$) layer, the etching pit density (EPD) and the specific contact resistance of top p-layer can be significantly decreased. Device dark current density decreased from 3.5×10^{-7} to 2.49×10^{-11} A/cm^2 at -3V 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 sensor; SIMS; Responsivity

1. Introduction

$Al_xGa_{1-x}N$ alloys 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 $Al_xGa_{1-x}N$/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 photoconductors 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-resistive ohmic contact on p-type $Al_xGa_{1-x}N$ layer [10,11], which was attributed to the restraint in Mg doping efficiency with increasing Al content in $Al_xGa_{1-x}N$ layer. In addition, a higher Al content in the $Al_xGa_{1-x}N$ 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 $Al_xGa_{1-x}N$ 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 $Al_xGa_{1-x}N$ 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 ($n = 2.5 \times 10^{17}$ cm^{-3}), followed by 1 μm heavily doped N-GaN layer ($n = 5 \times 10^{18}$ cm^{-3}) and a 0.2 μm thick undoped $Al_{0.26}Ga_{0.74}N$ 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 $Al_{0.26}Ga_{0.74}N$ layer, followed by a 300 Å thick $Al_xGa_{1-x}N$ ($x = 0.26 \rightarrow 0.13$) grading layer, and finally a thin 300 Å thick Mg-doped p-GaN top contact layer were 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_3PO_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 75 W Xenon lamp with a monochrometer. 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 epitaxial layers 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 3.5×10^{-7} 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 5.24×10^{-9} 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 $Al_xGa_{1-x}N$ ($x = 0.26 \rightarrow 0.13$) layer. With such a grading layer, the stress in $Al_xGa_{1-x}N$ 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

<table>
<tr><th>Sample 1</th><th>Sample 2</th><th>Sample 3</th></tr>
<tr><td rowspan="3">P-Al_{0.26}Ga_{0.74}N (1000Å)</td><td rowspan="2">Top GaN (500Å)</td><td>Top GaN (300Å)</td></tr>
<tr><td>Graded Al_xGa_{1-x}N (x = 0.26→ 0.13) layer (300Å)</td></tr>
<tr><td>P-Al_{0.26}Ga_{0.74}N (500Å)</td><td>P-Al_{0.26}Ga_{0.74}N (100Å)</td></tr>
<tr><td colspan="3">Un-doped Al_xGa_{1-x}N (2000Å) Al ~26%</td></tr>
<tr><td colspan="3">N-GaN (1um) heavily doped ~ 5x10¹⁸cm⁻³</td></tr>
<tr><td colspan="3">N-GaN (2um) slightly doped ~ 2.7x10¹⁷cm⁻³</td></tr>
<tr><td colspan="3">GaN (1um)</td></tr>
<tr><td colspan="3">GaN buffer layer</td></tr>
<tr><td colspan="3">Sapphire</td></tr>
</table>

Fig. 1. Three different layer structures of AlGaN/GaN p-i-n UV detectors.

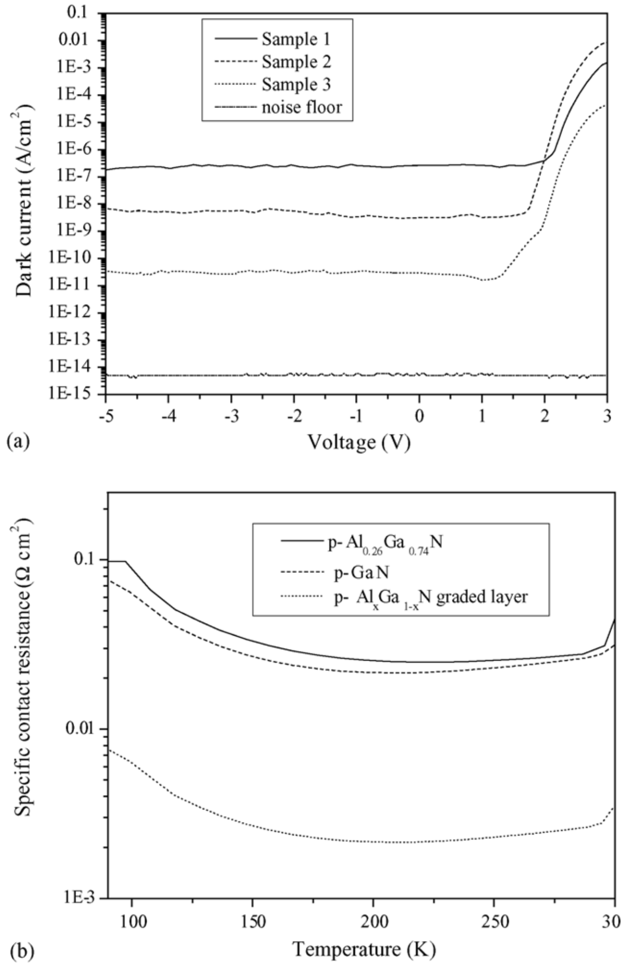

Fig. 2. (a) Dark current density (1 mm × 1 mm active region) of samples 1–3, respectively. (b) Specific contact resistance with temperature on top p-layer of samples 1–3, respectively.