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A Solar-Blind AlGaN-Based p-i-n Back-Illuminated Photodetector with a High Temperature AlN Template Layer

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Abstract: The growth, fabrication, and characterization of a solar-blind AlGaN-based p-i-n back-illuminated photodetector with a high temperature AlN template are reported for the first time. The photodetector was fabricated from multilayer $Al_xGa_{1-x}N$ films grown by MOCVD on double-polished *c*-plane (0001) sapphire substrates. Crack free, high Al content (0.7) AlGaN multilayer structure, designed for the solar-blind p-i-n back-illuminated photodetector, was grown on a high temperature AlN template without a nuclear layer. The high quality of the epitaxial layers is demonstrated by *in-situ* optical reflectance monitoring curve, triple-axis X-ray diffraction, and atomic-force microscope. At a 1.8V bias, the processed p-i-n photodetector exhibits a solar-blind photoresponse with a maximum responsivity of 0.0864A/W at 270nm. The photodetector exhibits a forward turn-on voltage at around 3.5V and a reverse breakdown voltage above 20V, and the leakage current is below 20pA for 2V reverse bias.

Key words: solar-blind; high temperature AlN template; back-illuminated photodetector; p-i-n
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1 Introduction

Interest has always been high in the production and characterization of the Ⅲ-Ⅴ group wide-bandgap semiconductor materials for a wide range of short-wavelength and high-temperature applications. Photodetectors operating in the wavelength range of 240~280nm, referred to as the solar-blind region, can be used for applications such as missile detection and tracking, flame detection, chemical-biological agent sensing, and covert space-to-space communications[1]. $Al_xGa_{1-x}N$ ternary alloys have a direct wide band gap ranging from 3.4eV (GaN) to 6.2eV (AlN), corresponding to cutoff wavelengths of 365 and 200nm, which is well suited for the realization of solar-blind photodetectors. Breakthroughs in material growth have resulted in high aluminum composition and crack-free AlGaN heterostructures for use as solar-blind p-i-n photodetectors[2]. During the past several years, several reports on GaN-AlGaN based solar-bind p-i-n photodetectors have been published[3~8].

Most of the GaN-AlGaN based UV detectors have been designed for front-illuminated operation. However, due to a strong interest in the development of detector arrays, the material growth, device design, and fabrication technology have advanced to achieve back-illuminated devices, making it possible in the future to employ indium bump-bonding for the fabrication of photodiode plane arrays. In such structures, the light has to pass through the buffer layer and "window" layer before reaching the absorbing i-region. Because of the requirements for solar-blindness, the i-region requires an $Al_xGa1_{1-x}N$ alloy with $x \geqslant 0.45$ and the buffer and "window" layers require $x \geqslant 0.6$.

For back-illuminated photodetectors the design of the buffer and "window" layers are important. Traditional low temperature (~500℃) AlN buffer layers are widely used before the high Al content "window" layer growth. More than 1μm thick $Al_{0.6}Ga_{0.4}N$ epilayers were grown using a low temperature AlN buffer. But the quality of the epitaxial layer was not good. AlN is one of the best substrate materials of AlGaN. Yan *et al*. obtained atomically flat AlN epilayers using the IASA method (initially alternating supply of ammonia, IASA)[9]. Uehara *et al*. achieved atomically flat AlN epilayers by adjusting the velocity of the source flow without the low temperature buffer[10].

Recently, we reported the growth of atomically flat high quality AlN epilayers by low Ⅴ/Ⅲ ratio, avoiding nitridation of the substrate before AlN growth[11]. In this paper, we report the growth, fabri-

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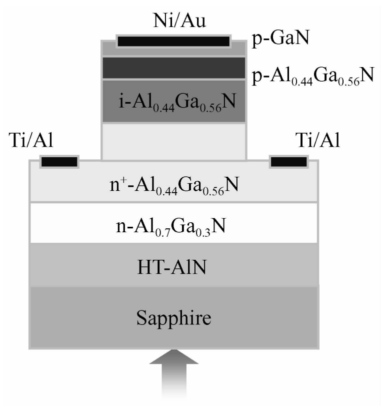

Fig. 1　Schematic structure of a back-illuminated p-i-n photodetector

cation, and measurement results for a solar-blind p-i-n back-illuminated photodetector based on the high temperature AlN template.

2　Growth and fabrication

The $Al_xGa_{1-x}N$ p-i-n device layers were grown by low-pressure metalorganic chemical vapor deposition (MOCVD) in an Aixtron 200 RF horizontal flow reactor on 50mm in diameter *c*-plane (0001) double-polished sapphire substrates. The AlGaN epitaxial layers were grown at ~6kPa and the p-GaN cap layer was grown at ~18kPa in a pure hydrogen ambient. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as Ga, Al, and N precursors, respectively. Silane (SiH_4) and biscyclopentadienylmagnesium ($(C_2H_5)_2Mg$) were used as donor and acceptor dopants, respectively.

The epitaxial structure of the AlGaN photodetector was designed for back illumination, as shown in Fig. 1. To achieve solar-blind photodetector application, i. e., cutoff wavelengths less than 280nm, an $Al_xGa_{1-x}N$ window layer with $x>0.7$ and an absorption layer with $x>0.4$ were used. The growth was initiated by a 500nm-thick AlN template layer on top of a *c*-plane sapphire substrate without a low temperature buffer layer. A high Al content n-AlGaN window

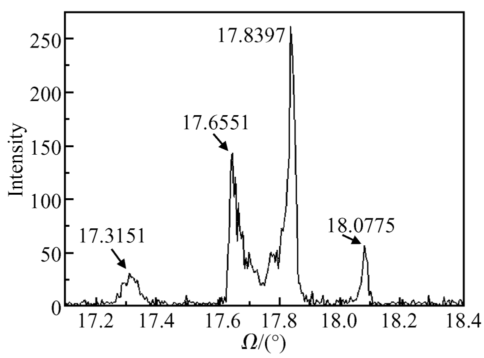

Fig. 2　TAXRD curve of the (002) reflection for the detector

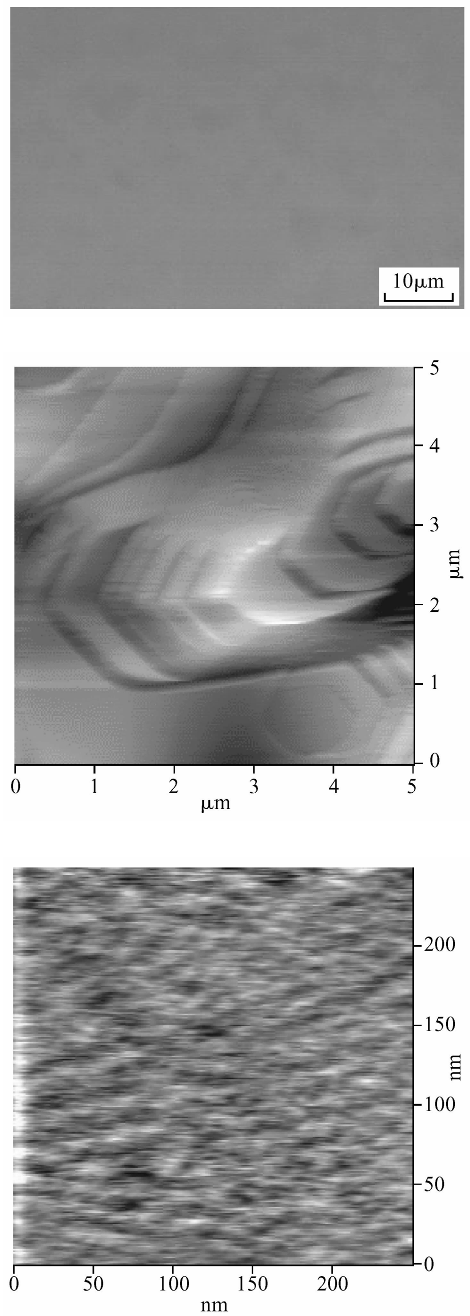

Fig. 3　Surface morphology of the AlGaN based p-i-n structure on Al_2O_3 substrate

layer was grown as the short wavelength cutoff region on top of the AlN buffer layer. This was followed by a 100nm-thick $Al_{0.44}Ga_{0.56}N$ n^+ layer, a 150nm-thick $Al_{0.44}Ga_{0.56}N$ unintentionally doped absorption layer, and a 120nm-thick $Al_{0.44}Ga_{0.56}N$ p^+ layer. To form a high-quality ohmic contact to the p-type doped AlGaN layer, a 20nm-thick p^+ GaN cap layer was added on top of the p^+ AlGaN layer. A 750℃ anneal was performed for 10min to ensure magnesium activation after the multilayer growth.

The device processing began with standard photolithographic mesa patterning on the as-grown wafer. The square mesas were defined with a planar in-

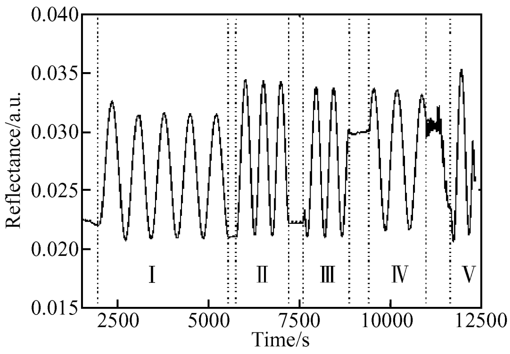

Fig. 4 *In-situ* reflectance measurement of the growth process of the AlGaN p-i-n structure on Al_2O_3 substrate

ductively coupled Cl_2/Ar plasmas. Then, etch masks were removed and the surface was cleaned without any etch byproducts. Subsequently, the samples were annealed at 300℃ for 20min to heal etch damage. This was followed by a Ti-Al (10nm/50nm) metallization for n-type contact. Then, Ni-Au (10nm/20nm) was deposited for p-type contact. Both contacts were annealed at 650℃ for 10min. The fabrication process ended with a 200nm thick Si_3N_4 layer deposited using plasma-enhanced chemical vapour deposition.

In order to investigate the structure of AlGaN multilayers, TAXRD analysis corresponding to the (002) diffraction was carried out, as shown in Fig. 2. Intensity peaks for GaN, $Al_{0.42}Ga_{0.58}N$, $Al_{0.69}Ga_{0.31}N$, and AlN were observed at 17.3151°, 17.6551°, 17.8397° and 18.0775°, respectively. These data prove that the multilayer structure was realized successfully.

Figure 3 shows the surface morphology of the AlGaN p-i-n structure on an Al_2O_3 substrate with differential interference contrast microscope and atomic-force microscope. No cracks are clearly observed, even though the Al content of the AlGaN "window" layer is up to 0.7.

In-situ reflectometry measurement was used to monitor the growth process of the AlGaN p-i-n structure on Al_2O_3. Figure 4 shows the *in-situ* reflectance measurement curve. Laser reflectometry is useful to determine, in real time, the development of surface morphology from the intensity change of the Fabry-Perot oscillations of the reflected beam. An overall decreasing or increasing roughness on the nanometer scale will tend to increase or decrease the overall average intensity of the oscillations, respectively. The regions indicated in Fig. 4 correspond, respectively, to (1) the growth of a HT-AlN template layer, (2) the growth of an n-$Al_{0.7}Ga_{0.3}N$ "window" layer, (3) the growth of a Si-doped n^+ $Al_{0.44}Ga_{0.56}N$ layer, (4) the growth of an $Al_{0.44}Ga_{0.56}N$ unintentionally doped active layer, and (5) the growth of a Mg-doped p-type $Al_{0.44}Ga_{0.56}N$ and GaN contact layer. The reflected intensity of each epilayer reaches the maximum and remains constant, thus, indicating that each layer is flat and smooth.

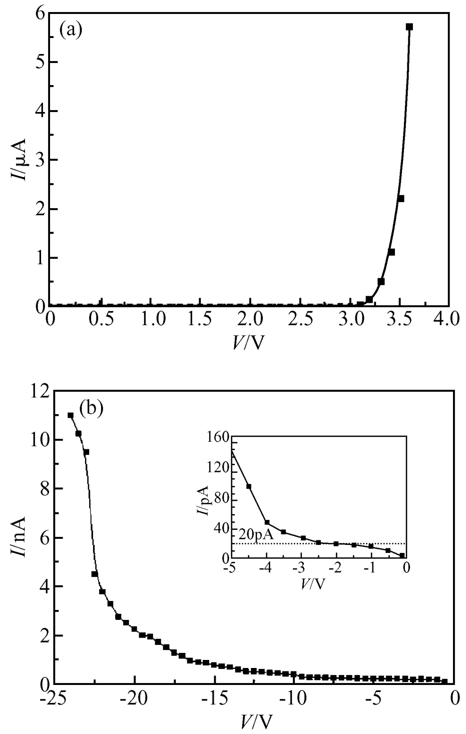

Fig. 5 *I-V* curves for forward bias (a) and reverse bias (b)

3 Device characteristics

The electrical properties of the device were characterized by current-voltage (*I-V*) measurements using a KEITHLEY 4200-SCS Semiconductor Characterization System at room temperature. *I-V* curves for forward bias and reverse bias are shown in Figs. 5 (a) and 5 (b), respectively. Figure 5 (a) shows that the p-i-n diode exhibits a forward turn-on voltage at around 3.5V and reverse breakdown voltage above 20V. In Fig. 5(b), the leakage current is below 20pA for 2V reverse bias, which is much higher than the results of other groups, which may be due to the unoptimized p-AlGaN and p^+ GaN layer[8].

Studies of spectral responsivity were performed at room temperature using a 30W Deuterium lamp companied with a monochromator, chopper, UV-grade focusing optics, and a lock-in amplifier in a standard synchronous detection scheme. As a reference, a calibrated, UV-enhanced Si detector was measured to determine the output power of the lamp and the absolute responsivity of the AlGaN p-i-n photodetector. The spectral current responsivity for photodetectors is defined as

$$R_\lambda = \frac{\lambda\eta}{hc}qg$$

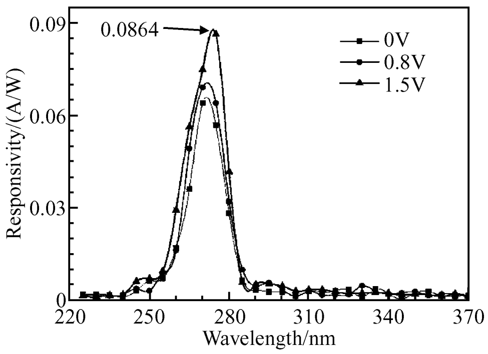

Fig.6　Measured spectral responsivity of the AlGaN p-i-n photodetector as a function of reverse bias

where λ is the wavelength, η is the quantum efficiency, h is the Planck's constant, c is the speed of light, q is the electron charge, and g is the gain of the detector, which has been assumed to be equal to unity[1].

Spectral responsivity measurements of the AlGaN p-i-n photodetector were carried out in the 220～370 nm spectral range. Bias-dependent spectral responsivity with true solar-blind characteristics was observed in the processed photodetector. Figure 6 shows the measured spectral responsivity of processed solar-blind p-i-n photodetector under different bias conditions. The peak responsivity increases as applied reverse bias increases. It reaches a maximum responsivity of 0.0641A/W at 270nm without bias, corresponding to an external quantum efficiency of 29.39%. With a 1.8V reverse bias, the responsivity increases to 0.0864A/W, corresponding to an external quantum efficiency of 38.93%.

4　Conclusion

A solar-blind AlGaN-based p-i-n back-illuminated photodetector with a high temperature AlN template was demonstrated. The p-i-n AlGaN back-illuminated photodetector exhibits a peak responsivity of 0.0864A/W at 270nm with a 1.8V reverse bias, corresponding to an external quantum efficiency of 38.93%. The photodetector demonstrated the feasibility of the fabrication of a AlGaN-based p-i-n back-illuminated photodetector using a high temperature AlN layer as the template.

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高温 AlN 为模板的 AlGaN 基 p-i-n 背照式日光盲探测器

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摘要：第一次报道了以高温 AlN 为模板层的 AlGaN 基 p-i-n 背照式日光盲探测器的制作和器件特性. 利用 MOCVD 方法在(0001)面的蓝宝石衬底上生长了探测器的 $Al_xGa_{1-x}N$ 多层外延材料. 在无需核化层的高温 AlN 模板上生长了 p-i-n 背照式日光盲探测器的无裂纹高 Al 组分(0.7)AlGaN 多层外延结构. 利用在线反射监测仪、三轴 X 射线衍射及原子力显微镜表征了外延材料的晶体质量. 在 1.8V 的反向偏压下，制作的探测器表现出了日光盲响应特性，在 270nm 处最大响应度为 0.0864A/W. 具有约 3.5V 的正向开启电压，大于 20V 的反向击穿电压，在 2V 的反向偏压下暗电流小于 20pA.

关键词：日光盲；高温 AlN 模板；背照式探测器；p-i-n

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