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Ohmic Contacts to n-Type $Al_{0.6}Ga_{0.4}N$ for Solar-Blind Detectors

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Abstract: We investigate the contact characteristics of bi-layer thin films, Ti(20nm)/Al(200nm) on Si-doped n-type $Al_{0.6}Ga_{0.4}N$ films grown on sapphire substrate. The surface treatment was aqua regia boiling before metallization and annealing after metallization at different conditions in N_2 ambient. High resolution X-ray diffractometery analysis was carried out on the contacts and the surface interfaces of these conditions were compared. A specific contact resistivity ρ_c was determined using the circular transmission line method via current-voltage measurements. A ρ_c of $3.42\times10^{-4}\ \Omega\cdot cm^2$ was achieved when annealed at 670℃ for 90s. Then, this ideal ohmic contact was used in back-illuminated solar-blind AlGaN p-i-n detectors and the detectors' performances, such as spectral responsivity, dark-current, and breakdown voltage were optimized.

Key words: high-Al content n-AlGaN; ohmic contact; anneal; back-illumination; solar-blind p-i-n detector
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1　Introduction

At present, ultraviolet photodetectors have received much attention for their importance in solar-UV monitoring, space communications, missile detection, as well as flame and heat sensing applications. $Al_xGa_{1-x}N$ is the optimum choice for fabricating these photodetectors owing to its wide bandgap. For the fabrication of photodetectors with a sharp transmission cut off wavelength at $\lambda<280nm$, an Al mole fraction >0.4 is required. Until now, not much research has been done on ohmic contacts to n-type $Al_xGa_{1-x}N$ with $x>0.3$. Adivarahan *et al*.[1] reported that the specific contact resistivity of Ti/Al/Ti/Au ohmic contacts on n-type $Al_{0.4}Ga_{0.6}N$ was $2.5\times10^{-3}\Omega\cdot cm^2$.

The most widely used ohmic contact to n-type GaN is based on Al/Ti[2,3]. The Ti-layer can significantly improve the contact resistance[4]. The advantage of a Ti layer has been attributed to either the degenerate n^+-surface layer resulting from the N-vacancy donor for the formation of the TiN compound or the Ti acting to reduce the surface oxide[5]. In either case, the Al overlayer is superior to an Au overlayer, which suggests that Al/Ti alloy may play a role in the contact formation[6]. Analogously, ohmic contacts to n-AlGaN usually use the Ti/Al or Ti/Al/Ti/Au metallisation. Cao *et al*.[2] reported the specific contact resistivity of Ti/Al/Ti/Au ohmic contacts on n-$Al_{0.3}Ga_{0.7}N$ was $7\times10^{-5}\ \Omega\cdot cm^2$. Chen *et al*.[7] reported the specific contact resistivity of Ti/Al/Ni/Au ohmic contacts on n-$Al_{0.45}Ga_{0.55}N$ was $2.75\times10^{-4}\ \Omega\cdot cm^2$.

In this paper, we report a low resistance ohmic metallization for an $Al_{0.6}Ga_{0.4}N$ layer by pre-metallization treatment in the surface using aqua regia and annealing after metallization. Additionally, we study the influence of the ohmic contacts on solar-blind detectors.

2　Experiments

The samples used in this study were grown on *c*-plane (0001) sapphire substrates by a low-pressure Aixtron 200 RF horizontal flow reactor metal organic chemical vapor deposition (MOCVD) system. Trimethylgallium (TMGa), Trimethyllalumium (TMAl), and ammonia (NH_3) were used as Ga, Al, and N precursors, respectively. Silane was used as the n-type dopant and H_2 was the carrier gas.

Figure 1 shows the schematic cross-section structure of the $Al_{0.6}Ga_{0.4}N$ sample. A 500nm-thick high-temperature AlN template layer was initially grown at 1180℃. Afterward, a 60nm-thick super lattice (SL) layer (5 periods $Al_{0.7}Ga_{0.3}N$/AlN) was grown at 1120℃ to weaken the stress during the material growth. This layer was followed by a Si-doped n-AlGaN layer grown at 1120℃. The Si-doped AlGaN

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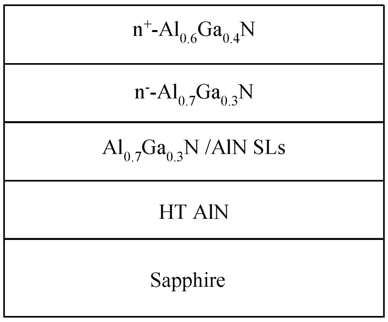

Fig.1 Schematic structure of $Al_{0.6}Ga_{0.4}N$ sample

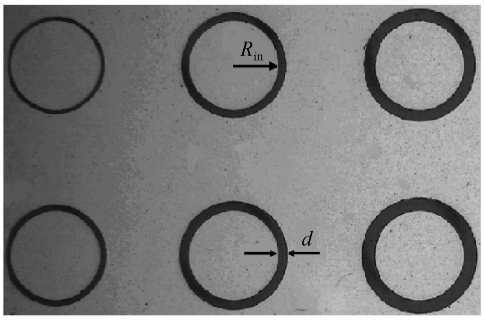

Fig.3 Pattern of CTLM etching mask

consisted of two AlGaN layers with Al contents of 0.6 and 0.7, respectively. The thickness of the $Al_{0.7}Ga_{0.3}N$ layer and $Al_{0.6}Ga_{0.4}N$ layer are 400 and 750nm. The sample is a part of back-illuminated solar-blind $Al_xGa_{1-x}N$ p-i-n photodiodes. So the $Al_{0.7}Ga_{0.3}N$ window layer was grown as the short wavelength cutoff region and $Al_{0.6}Ga_{0.4}N$ layer was used as the buffer layer. The Al mole fraction of 60% was established by Rutherford backscattering spectrometry (RBS). Room temperature Hall measurements exhibited the carrier concentration of $2.77 \times 10^{18} cm^{-3}$ and the mobility of $45.1 cm^2/(V \cdot s)$.

In-situ optical reflectometry measurement was used to monitor the growth process. As shown in Fig. 2, the indicated region corresponds to: (1) the growth of HT-AlN; (2) the growth of the $Al_{0.7}Ga_{0.3}N$/AlN super lattice layer; (3) the growth of the $Al_{0.7}Ga_{0.3}N$ layer; and (4) the growth of the $Al_{0.6}Ga_{0.4}N$ layer. That the peak values of the in-situ optical reflectance monitoring curves remain constant shows that the epitaxial layers are very smooth and have good quality.

The ohmic metallisation consisting of Ti (20nm)/Al (200nm) were deposited in a circular transmission line model (CTLM) pattern. Prior to the fabrication of the patterns, the layers were degreased using acetone and ethanol in 5min steps and were rinsed with de-ionized (DI) water. Thereafter, they were boiled in aqua regia for 20min to remove the native oxide. Figure 3 illustrates the actual etching mask imaged by microscopy. The CTLM ohmic pads were delineated using a lift-off process. The inner radius (R_{in}) of the pads is 120μm and the gap spacing (d) between the inner and outer contact pads are 5, 10, 15, 20, 25, and 30μm, respectively.

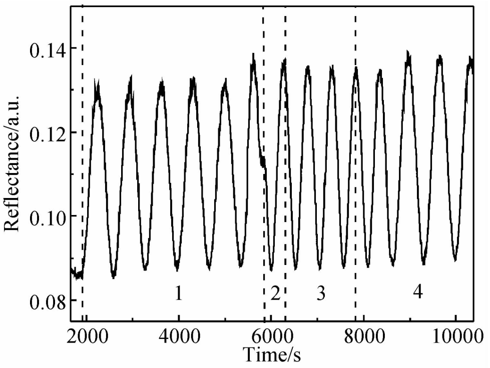

Fig.2 In-situ reflectance measurement of the sample

The As-deposited samples were annealed at 450, 550, 600, 650, 670, 700, 750, and 850℃ for 90s in an N_2 ambient using a rapid thermal annealing furnace (RTP-500). Then, the samples were annealed at 670℃ for 30, 60, 90, 120, 300, and 600s, respectively. To extract the specific contact resistance using the CTLM, a current was supplied by one pair of probes, and another pair was used to measure the voltage between contacts. The X-ray diffractometer (XRD) analysis was carried out by D1-type high resolution X-ray diffractometer (HRXRD) measurements of Bede to study the contact formation mechanism.

3 Results and discussion

Current-voltage (I-V) measurements were made at room temperature using a Keithley 4200-SCS semiconductor characterization system. The I-V characteristics of the annealed ohmic contacts at different temperatures (450, 550, 670, 750℃) for gap spacing of 15μm are shown in Fig. 4. The ohmic contacts an-

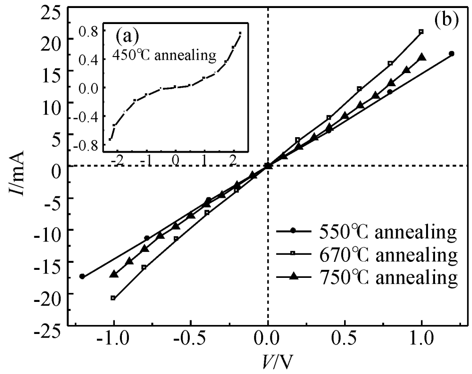

Fig.4 (a) I-V curve of the annealed ohmic contact at 450℃ for 90s; (b) I-V curves of the annealed ohmic contacts at 550, 670, and 750℃ for 90s

Table 1　Specific contact resistivity ρ_c at different annealing temperatures

Annealing temperature /℃	Annealing time /s	ρ_c /(Ω · cm²)
550	90	1.21×10^{-3}
600	90	1.09×10^{-3}
650	90	5.75×10^{-4}
670	90	3.42×10^{-4}
700	90	7.34×10^{-4}
750	90	6.91×10^{-4}
850	90	9.40×10^{-4}

nealed over 550℃ exhibit ohmic behaviour, while the 450℃ annealing ohmic contact exhibits rectifying behaviour. This phenomenon indicates that the annealing temperature is an important factor for the mechanism of the ohmic contacts and that there is a limiting temperature in the formation of an ohmic contact. However, for different material and device structures, the temperature will be different. Chen *et al*.[7] studied the contact of Ti/Al/Ni/Au to n-AlGaN and they reported it was 400℃. In our experiment, the limiting temperature is about 550℃.

The values of the specific contact resistivity of the annealed ohmic contacts on pre-metallization treated surfaces are listed in Table 1. The CTLM results revealed that the contact resistance of the ohmic contacts decreased from 450 to 670℃, and thereafter increased as the annealing temperature increased to 850℃. The specific contact resistivity of the Ti/Al ohmic contact exhibited a minimum value of 3.42×10^{-4} Ω · cm² when the sample was annealed at 670℃ for 90s.

In addition, we performed a comparison of different annealing times at 670℃. The annealing time was changed in the range of 30 to 600s, and included 30, 60, 90, 120, 300, and 600s. Figure 5 shows the specific contact resistivity ρ_c of the Ti/Al ohmic contacts. The minimum value of ρ_c was still 3.42×10^{-4} Ω · cm² when the sample was treated under 670℃ annealing for 90s. So, for this sample structure, the best annealing condition was about 670℃ for 90s.

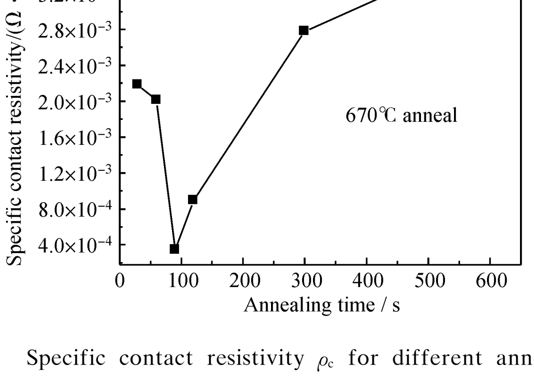

Fig. 5　Specific contact resistivity ρ_c for different annealing times

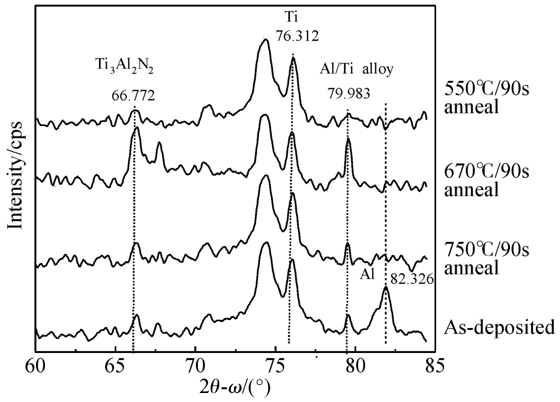

Fig. 6　XRD spectrums of the annealed ohmic contacts at different annealing temperatures

To characterize the chemical states of the samples, XRD examination was made of the Ti/Al contacts on n-$Al_{0.6}Ga_{0.4}N$ before and after annealing. Figure 6 shows the XRD spectra obtained from the metals/AlGaN interface regions of the sample. The figure reveals that the peak of Ti lowered a certain amount after annealing and reached the lowest level at 670℃, and the peak of Al is barely observable. Meanwhile, a new phase peak-$AlTi_3$ at 79.983° was detected after annealing and reached its highest level at 670℃. This indicated that annealing caused Al atoms to diffuse through the Ti layer to form Al-Ti intermetallic phases with low work functions. These Al-Ti intermetallic phases can promote the formation of an ohmic contact in the AlGaN surface[6]. So, the higher the peak of Ti-Al alloy is, the better the ohmic contact that can be formed. This is in good agreement with the *I-V* results.

In addition, the peak of $Ti_3Al_2N_2$ was found to be 66.772° after 670℃ annealing. The formation of $Ti_3Al_2N_2$ at the interface region indicates the outdiffusion of N atoms from the AlGaN layer surface and hence the generation of N vacancies near the surface region of AlGaN. These N vacancies are known to serve as donors in n-AlGaN. Therefore, the annealing-induced improvement of the *I-V* characteristics of Ti/Al contacts could be attributed to the formation of $Ti_3Al_2N_2$ and as well as an Al-Ti intermetallic phase.

For solar-blind detectors, it is necessary to develop good ohmic contacts to improve the detectors' performances, such as small dark-current, large breakdown voltage, and high spectral responsivity. We fabricated back-illuminated solar-blind AlGaN p-i-n detectors with the same structures but different ohmic contacts at 670℃ annealing for 90s and with no annealing, respectively. Reverse bias *I-V* characteristics

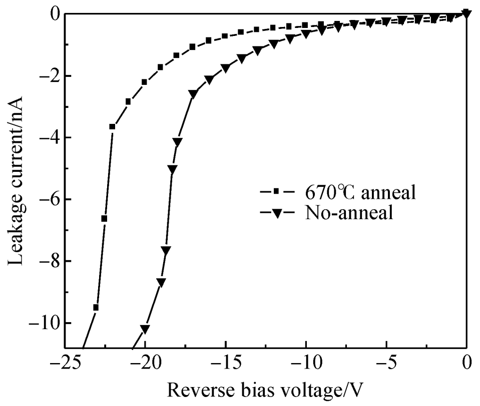

Fig. 7 *I-V* curves of p-i-n detectors at reverse bias in the dark

of the p-i-n detectors in the dark are given in Fig. 7. The dark-current decreased after the 670℃ annealing and its breakdown voltage improved.

In addition, spectral responsivity measurements of the two photodiodes were carried out in the 230～340nm spectral range at −1.5V reverse bias. Figure 8 shows the results of spectral responsivity measurements. The peak responsivities of the two samples all appeared at about 272nm. The annealed sample reached a maximum responsivity of 0.0764A/W at −1.5V bias and the non-annealed sample was only 0.0696A/W. Thus, the treatments on ohmic contacts can enhance the performances of the solar-blind p-i-n detectors.

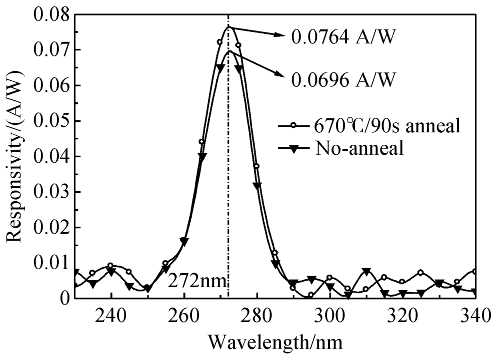

Fig. 8 Spectral responsivity versus wavelength curves at −1.5V bias for back-illuminated solar-blind AlGaN p-i-n photodiode

4 Conclusion

To summarize, we have investigated the Ti/Al metallization scheme for the formation of ohmic contact on high-Al content $Al_{0.6}Ga_{0.4}N$ for solar-blind detectors. We show that the electrical properties of the Ti/Al contacts improved as the annealing temperature increased. In particular, the contact produced a very low specific contact resistivity, $3.42 \times 10^{-4} \Omega \cdot cm^2$, when annealed at 670℃ for 90s. By X-ray diffraction measurement analysis, we found that the annealing-induced improvement of the *I-V* characteristics of Ti/Al contacts could be attributed to the formation of $Ti_3Al_2N_2$ and as well as an Al-Ti intermetallic phase. Using the ideal contact on back-illuminated solar-blind AlGaN p-i-n detectors improved the spectral responsivity, dark-current, and breakdown voltage.

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日盲探测器高 Al 组分 n-$Al_{0.6}Ga_{0.4}N$ 欧姆接触

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摘要： 研究了应用于日盲探测器的高 Al 组分 Si 掺杂 n 型 $Al_{0.6}Ga_{0.4}N$ 与两层金属层 Ti(20nm)/Al(100nm)之间的欧姆接触.在制作金属电极前用煮沸王水对样片进行表面预处理,金属制作后再在 N_2 氛围中做快速热退火处理.使用高精度 XRD 测试样品表面特性,并对不同温度下的情况进行比较.样品的比接触电阻率是用环形传输线模型通过 *I-V* 测试得到.670℃下 90s 退火得到最优 ρ_c 为 $3.42\times10^{-4}\Omega\cdot cm^2$.将该处理方法应用到实际的背照式 AlGaN p-i-n 日盲探测器中,探测器的光谱响应度和反向特性等参数得到很大的优化.

关键词： 高铝 n-AlGaN；欧姆接触；退火；背光照；pin 日盲探测器
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