

Ohmic Contact to *p*-GaN Using a Strained InGaN Contact Layer and Its Thermal Stability

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We have formed ohmic contacts to *p*-GaN using a strained *p*-InGaN contact layer, and achieved the lowest contact resistance of $1.1 \times 10^{-6} \Omega\text{-cm}^2$ at room temperature by optimizing the contact layer thickness and its In mole fraction. We have also evaluated thermal stability of ohmic contacts to *p*-GaN using the strained *p*-InGaN contact layer. The contact resistance decreased to $2 \times 10^{-7} \Omega\text{-cm}^2$ at 100°C, and increased with elevating temperature above 100°C. In the temperature range up to 400°C, the contact resistances of the samples with the *p*-InGaN contact layer were smaller than those of the samples without the contact layer. Furthermore, the ohmic characteristics of the strained *p*-InGaN contact layer were less degraded even after the thermal process, compared with those of the sample without a contact layer. These results indicate that the strained *p*-InGaN contact layer is favorable for practical application. [DOI: 10.1143/JJAP.42.2254]

KEYWORDS: *p*-InGaN, ohmic contact, thermal stability, high-temperature operation, *p*-GaN, contact resistance

1. Introduction

Low-resistance ohmic contacts are necessary and become more important for further improvement of the device performance of GaN-based semiconductors. However, it is difficult to obtain ohmic contacts to *p*-GaN with low specific contact resistance (ρ_c) of less than $10^{-4} \Omega\text{-cm}^2$, because the hole concentration of *p*-GaN is less than 10^{18}cm^{-3} due to its relatively deep acceptor level of Mg atoms. To date, there have been various methods of reducing the contact resistance: surface treatment by chemical solutions, such as boiling aqua regia,¹⁾ metal deposition and annealing, for example, oxidation of Ni/Au metals in air or oxygen.²⁾ Another method is the use of the polarization field near the surface by *p*-AlGaIn/GaN superlattices. In this case, the polarization field due to the *p*-AlGaIn/GaN heterostructure near the surfaces enhanced the tunneling transport.³⁾ These methods had a strong effect in reducing the ρ_c values to the $10^{-4} \Omega\text{-cm}^2$ range or less.

Recently, we have proposed the ohmic contact for the reduction of ρ_c using a strained *p*-InGaN contact layer on *p*-GaN.^{4,5)} In this method, we have used *p*-InGaN with high hole concentration near 10^{19}cm^{-3} (refs. 6 and 7) as a contact layer without any special chemical and thermal treatments. The ρ_c value considerably decreased to $1.1 \times 10^{-6} \Omega\text{-cm}^2$ due to the enhancement of tunneling transport.^{4,5)} In this work, we evaluate the thermal stability of the ohmic contacts to *p*-GaN using a strained *p*-InGaN contact layer up to 400°C.

2. Experimental

Samples were grown by low-pressure metalorganic vapor phase epitaxy. Source materials were trimethylgallium and ammonia (NH₃) with hydrogen as a carrier gas for GaN growth, and triethylgallium, trimethylindium and NH₃ with nitrogen (N₂) as a carrier gas for InGaN growth. The *p*-type dopant source was bis-cyclopentadienylmagnesium. First, a GaN buffer layer was deposited at 500°C on a *c*-face sapphire substrate. Next, an undoped GaN layer and a 1- μm -thick Mg-doped GaN layer were grown at 1000°C. Then, Mg-doped InGaN was grown from 760 to 780°C. The thicknesses and In mole fractions of the InGaN layers were

varied from 1 to 15 nm and from 0.14 to 0.19, respectively. The Mg doping concentration in the Mg-doped GaN and Mg-doped InGaN was fixed at $4 \times 10^{19} \text{cm}^{-3}$, which was estimated by secondary ion mass spectroscopy. After the growth, all samples were annealed at 700°C in N₂ ambience. The ρ_c values were determined using circular transmission line model (CTLM) patterns with a contact inner radius (r_{in}) of 100 μm and spacings (d) from 5 to 30 μm . Pd (20 nm)/Au (130 nm) contact metals were deposited by electron beam evaporation after cleaning the surfaces by dipping in a HCl : H₂O (1 : 1) solution. To prevent parallel conduction in *p*-GaN and *p*-InGaN, exposed *p*-InGaN was removed by electron cyclotron resonance plasma etching. A schematic of the sample structure is shown in Fig. 1. We carried out CTLM current-voltage (*I*-*V*) measurements to determine the ρ_c values at temperatures from room temperature (RT) to 400°C.

3. Results and Discussion

To optimize the thickness and the In mole fraction for the *p*-InGaN contact layer, we have formed the contact layer with various structures. Figure 2 shows the room-temperature ρ_c values as a function of the *p*-InGaN contact layer thickness. The In mole fraction values were 0.14 and 0.19. The ρ_c value without an InGaN contact layer, that is, the contact resistance direct to *p*-GaN was $1 \times 10^{-3} \Omega\text{-cm}^2$. For all *p*-In_{*x*}Ga_{1-*x*}N contact layers except the 15-nm-thick one, ρ_c values were lower than that of *p*-GaN and were of the $10^{-4} \Omega\text{-cm}^2$ range or less. The lowest ρ_c value is $1.1 \times 10^{-6} \Omega\text{-cm}^2$ for a 2-nm-thick *p*-In_{0.19}Ga_{0.81}N contact layer.

We have reported that the contact characteristics are very

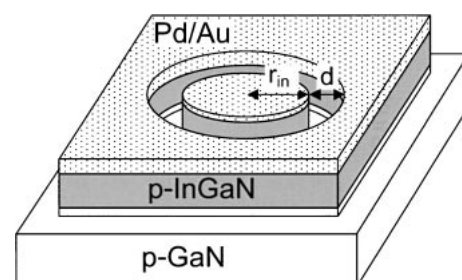


Fig. 1. Schematic illustration of the sample structure.

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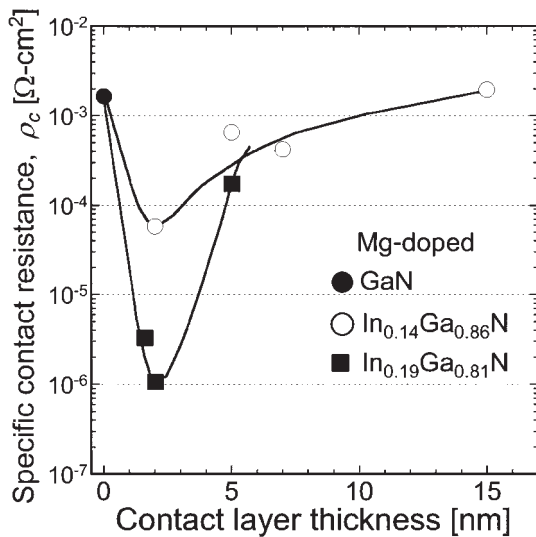


Fig. 2. Room-temperature ρ_c as a function of the p -InGaN contact layer thickness. The closed circle, open circles, and closed squares correspond to the ohmic contacts without a contact layer, with p -In_{0.14}Ga_{0.86}N, and p -In_{0.19}Ga_{0.81}N, respectively.

sensitive to the polarization field induced at the InGaN contact layer.^{4,5)} If the InGaN/GaN heterostructure exists near the surface, the large band bending occurs due to both the large piezoelectric polarization field and the electric field for the ionized acceptors at the surface depletion layer. The hole concentration for p -In_{0.19}Ga_{0.81}N near the 10^{19} cm⁻³ also results in the reduction of the surface depletion layer. Therefore, the tunneling barrier becomes thinner as shown in Fig. 3(a), resulting in the drastic reduction of the contact resistance.

On the other hand, if the InGaN contact layer exceeds the critical layer thickness, the strain-induced piezoelectric field disappears due to the lattice relaxation, resulting in the increase of the tunneling barrier width. In addition, the potential spike at the InGaN/GaN heterointerface disturbs the hole transport as shown in Fig. 3(b). Therefore, the contact resistance increases with the contact layer thickness, since the strain is gradually relaxed with the thickness. The critical layer thickness of In_{0.19}Ga_{0.81}N was theoretically estimated to be from 3 to 5 nm⁸⁾ and experimentally estimated to be 4 nm.⁹⁾ At the p -In_{0.19}Ga_{0.81}N contact layer

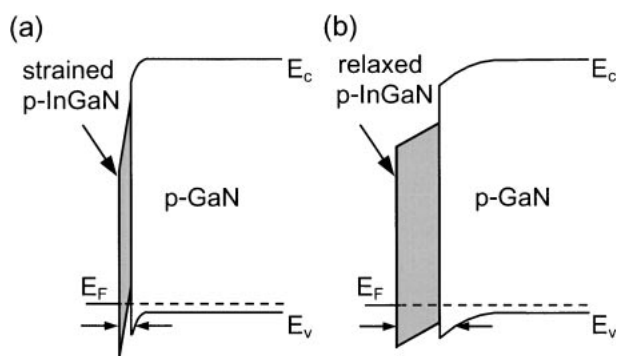


Fig. 3. Band diagrams of p -InGaN/ p -GaN heterointerface near the surface: (a) with a strained InGaN contact layer and (b) with a relaxed InGaN contact layer.

thickness of 2 nm, the minimum ρ_c value was obtained due to the largest piezoelectric polarization effect among the samples in this study.

Next, we evaluate the thermal stability of an ohmic contact using a 1.6-nm-thick p -In_{0.19}Ga_{0.81}N contact layer. Its room-temperature ρ_c value was 3.3×10^{-6} Ω-cm². Figure 4 shows the measurement temperature dependence of ρ_c . The measurement temperature ranged from RT to 400°C. In all the temperatures, the ρ_c values of the sample with a p -InGaN contact layer were smaller than those of the sample without a contact layer. The minimum value of contact resistance of 2×10^{-7} Ω-cm² was obtained at 100°C. This ρ_c value of the sample with a p -InGaN contact layer is three orders of magnitude lower than that of the sample without a contact layer. On the other hand, ρ_c increases with elevating measurement temperature. The possible reasons why the ρ_c value measured at 100°C decreases with an increase in the temperature are the decrease in the tunneling barrier height due to band-gap narrowing and/or the improvement of adhesion between Pd and the p -type layer.

Figure 5 shows room-temperature CTLM I - V characteristics with and without a strained p -InGaN contact layer. Solid and broken lines correspond to the measurements before and after elevating the temperature at 400°C, respectively. The sample without a contact layer showed non-ohmic characteristics at room temperature after the high-temperature measurements. Therefore, we could not determine the accurate ρ_c values anymore. On the other hand, the I - V characteristics of the sample with a contact layer showed ohmic characteristics even after the high-temperature measurements. However, the ρ_c value at room temperature was degraded from 3.3×10^{-6} to 8.7×10^{-4} Ω-cm² after elevating the temperature.

These results indicate that an irreversible reaction occurred around the metal and semiconductor interfaces by elevating the temperature. The possible reasons for the increase in ρ_c above 100°C shown in Fig. 4 and for the degradation of ohmic characteristics at room temperature

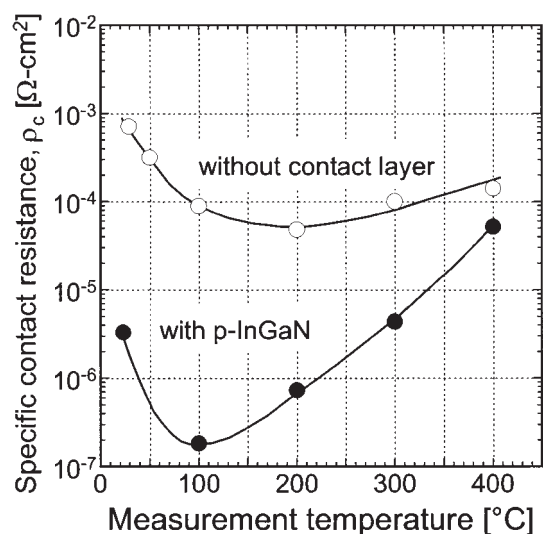


Fig. 4. Measurement temperature dependence of ρ_c from RT to 400°C. Open and closed circles correspond to the ohmic contacts with and without a 1.6-nm-thick p -In_{0.19}Ga_{0.81}N contact layer, respectively.

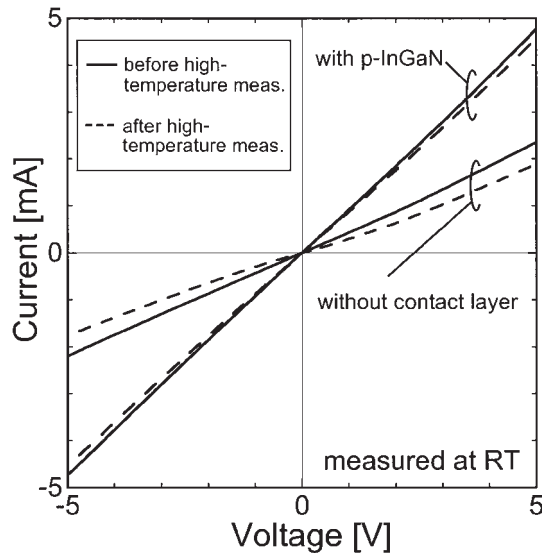


Fig. 5. Room-temperature CTLM I - V characteristics of the samples with and without a strained p -InGaN contact layer. Solid and broken lines correspond to the measurements before and after elevating the temperature at 400°C , respectively.

after elevating the temperature shown in Fig. 5 are the interfacial reaction between metal and semiconductors, or desorption of the nitrogen atoms from the p -type layer. While it has not been clarified from the values of the thermal expansion coefficients for GaN and InGaN, the change of the strain at the contact layer by elevating the temperature is also a possible reason for the increase in ρ_c values. The diffusion of Au atoms to the Pd layer was not observed by Auger electron spectroscopy and transmission electron microscopy, so the diffusion of Au is not responsible for the increase in ρ_c in this temperature range. Further investigation is needed to clarify the high-temperature characteristics. Considering the upper temperature limit of 100°C for device operation, this result indicates that the ohmic contacts using a strained p -InGaN contact layer are favorable for practical application.

4. Conclusions

We have formed low-resistance ohmic contacts to p -GaN using a strain InGaN contact layer, and have evaluated their thermal stability. By optimizing the thickness and In mole fraction of the p -InGaN contact layer, we obtained the minimum specific contact resistance of $1.1 \times 10^{-6} \Omega\text{-cm}^2$ for a 2-nm-thick p -InGaN contact layer. In the temperatures up to 400°C , the specific contact resistances of the samples with a p -InGaN contact layer were smaller than those of the samples without a contact layer. Furthermore, the room-temperature I - V characteristics of the ohmic contact using a strained p -InGaN contact layer were less degraded even after the thermal process. These two results indicate that the ohmic contacts using a strained p -InGaN layer are favorable for practical application.

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