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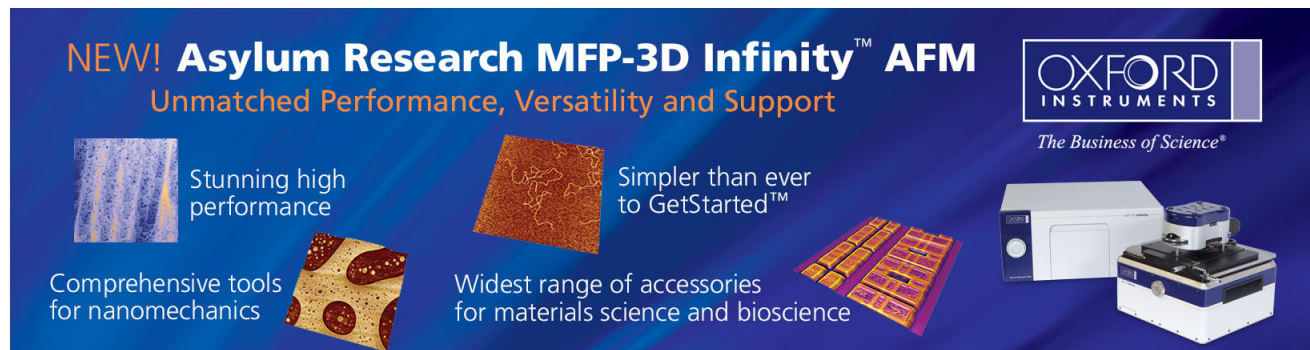
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Improved contact performance of GaN film using Si diffusion

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In this letter, we investigate a metalization process for reducing the contact resistance on undoped GaN layers. The Si metal source was diffused successfully into the GaN films by using $\text{SiO}_x/\text{Si}/\text{GaN}/\text{Al}_2\text{O}_3$ structures. By using a high-temperature annealing process, we diffused and activated the Si atoms into the GaN film. This caused a heavy doped *n*-type GaN layer to be formed near the GaN surface. Under high temperatures, such as a diffusion process at 1000 °C, the as-deposited Ni/Al/Ti contact had good ohmic properties and a low specific contact resistivity (ρ_c) of $1.6 \times 10^{-3} \Omega \text{ cm}^2$. Rapid thermal annealing the contact at 800 °C for 30 s caused the ρ_c to decrease rapidly to $5.6 \times 10^{-7} \Omega \text{ cm}^2$. The Ni/Al/Ti contact characteristics on the GaN films diffused at various temperatures are also discussed. © 2000 American Institute of Physics.

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Gallium nitride is a direct wide-band-gap semiconductor. It has attracted considerable interest for applications in blue-green, green, and ultraviolet light-emitting diodes, laser diodes, high-electron mobility transistors, and photoconductive detectors. Conventional metalization gives high-contact resistance that limits the GaN device's performances. Lin *et al.* achieved a low-resistance ohmic contact to *n*-GaN using Al/Ti metalization with 900 °C rapid thermal annealing (RTA) for 30 s. The resulting value for the specific contact resistivity was $8 \times 10^{-6} \Omega \text{ cm}^2$.¹ It has also been reported that using Si-doped² and Si-implanted^{3,4} *n*-type GaN layers has been successful in reducing contact resistance. For ohmic contact to be enhanced in heavy Si-doping GaN films, the tunneling process is the best way to reduce specific contact resistivity. In this work, the Si-diffusion process and ohmic contact properties on GaN films are discussed. Our results show that the nonalloyed Ni/Al/Ti metal layers on Si-diffused GaN films exhibit ohmic behavior. We achieved our lowest specific contact resistivity by using the Si-diffusion and metal-alloyed process to undoped GaN films.

The undoped GaN films were grown by metal-organic chemical-vapor deposition on polished optical-grade C-face (0001) sapphire substrates. The sapphire was placed on a graphite susceptor in a horizontal-type reactor with a rf heater. Triethylgallium (TEGa) and ammonia (NH_3) were used as the Ga and N sources, respectively. The carrier gas was hydrogen (H_2) and the growth pressure was kept at 100 mbar. The GaN buffer layer was grown at 525 °C, which was lower than the normal-grown 1025 °C temperature for the GaN epitaxial layer. Once the buffer layer was grown, the temperature was raised to 1025 °C for the GaN epitaxial layer growth.⁵ After the material was grown, the undoped

GaN films were prepared for the Si-diffusion experiment. The schematic diagram of the deposited Si metal films on the GaN epitaxial layers prior to the SiO_2 caps is illustrated in Fig. 1. The specimens were cleaned in BOE etchant for 5 min before evaporating the Si metal. The sandwich structure consisted of a 500-Å-thick Si metal layer deposited directly on the GaN, followed by a 1000-Å-thick SiO_2 cap layer. The Si metal layers were deposited by an e-gun deposition system with the evaporation chamber below 2×10^{-6} Torr. The SiO_2 cap layer was deposited by photo-CVD. The $\text{SiO}_x/\text{Si}/\text{GaN}/\text{Al}_2\text{O}_3$ structures were used to prevent the Si metal from out-diffusing on the GaN surface so that the Si atoms were diffused into GaN films. In this series of samples, the GaN films were diffused at varied the temperatures as follows: 825 °C (sample B), 875 °C (sample C),

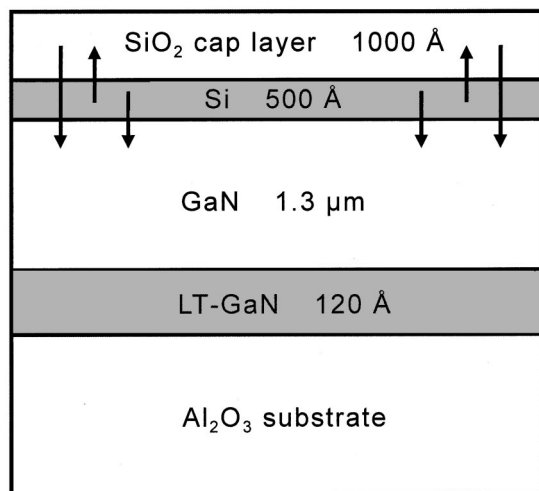


FIG. 1. Schematic drawing showing the structure of Si-diffused samples that contain diffusion metal layers and SiO_x cap layers.

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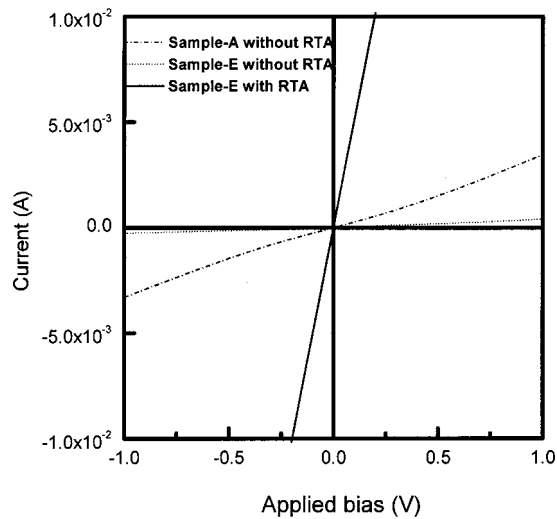


FIG. 2. Current–voltage (I – V) characteristics of the metal contact on sample A without RTA and sample E with and without alloyed RTA measured from the HP-4156 system.

935 °C (sample D), and 1000 °C (sample E). They were put in a nitrogen ambient furnace for 2 h and sample A was the standard GaN sample, without the diffusion process. After the thermal diffusion process, a chemical solution consisting of HF, HNO₃, and CH₃COOH at a ratio of 6:20:7 was used to remove the metal and cap layers. These Si-diffused GaN films were rinsed in deionized water, so that the ohmic contact property on the diffused GaN films could be studied in this experiment.

Through reactive ion etching (RIE), the mesa region of the GaN films was defined for the use of the transmission line measurement method (TLM). BCl₃ gas was used to etch the GaN films at an etching rate of 600 Å/min with a 2 μm etching depth. The flow rate, the rf power, and the pressure were fixed at 5 sccm, 120 W, and 24 mTorr, respectively. The dimensions of the metal contact pads were 200 μm wide and 100 μm long. The gaps between the two contact pads ranged from 20 to 120 μm with 20 μm increments. The Si-diffusion depth in the GaN films was 0.15 μm at a 1000 °C annealing temperature, observed from secondary ion mass spectrometry (SIMS) profiles. The Ni/Al/Ti (300 Å/1200 Å/150 Å) metal pads were deposited by using the e-beam evaporator. These metal contact pads were defined on the mesa region by using a photoresist lift-off technique. The specimens were treated in a RIE system for the second time to etch the Si-diffused layer between the two contact pads. The thin Ni metal layer was used as a RIE metal mask to protect the metal layer during the RIE treatment. After the treatments, the specimens were alloyed by rapid thermal annealing at 800 °C for 30 s.

The current–voltage (I – V) characteristics of the metal contacts to the Si-diffused GaN films before and after thermal alloying are shown in Fig. 2. These three curves show the contact properties of sample A without RTA, sample E without RTA, and sample E with alloyed RTA, using Ni/Al/Ti (300 Å/1200 Å/150 Å) layers as the ohmic contact metals, respectively. Sample A without the alloyed RTA exhibited nonlinear I – V characteristics, which were probably due to the formation of a Schottky contact. Sample E without the alloyed RTA, in the linear I – V curve, showed ohmic

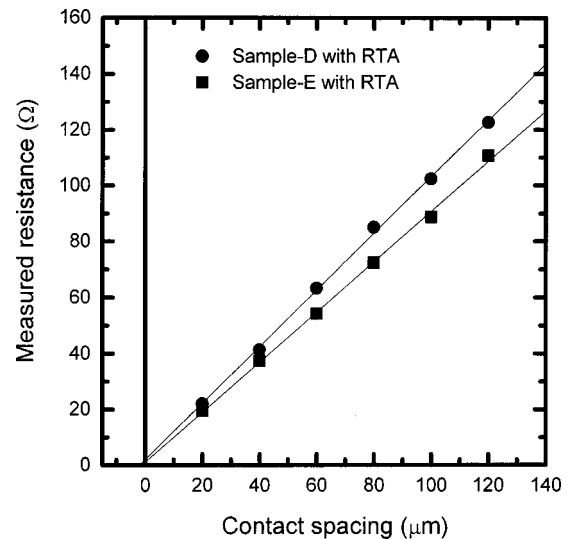


FIG. 3. Total contact resistance as a function of the Ni/Al/Ti metal pad spacing of samples D and E. All contacts were RTA alloyed at 800 °C for 30 s.

behavior on the Si-diffused GaN film. In this experiment with the metal contact on Si-diffused GaN films, we got a ρ_c value of $1.6 \times 10^{-3} \Omega \text{ cm}^2$, even for the nonalloyed Ni/Al/Ti ohmic contacts. This implied that the Si atoms had been diffused and activated during the high-temperature diffusion process. The heavy n -type GaN layers from the Si-diffusion treatment provided the current tunneling through the barrier height at the metal/GaN interface. During the high-temperature diffusion process, there is a probable mechanism that lets the nitrogen atoms escape from the GaN leaving vacancies⁶ to form the donor sites for the Si atoms. The third I – V curve for sample E with the alloyed RTA exhibited a sharp linear I – V curve and lower overall contact resistance characteristics.

On the fabricated TLM patterns, the R_T valves (total resistance) were measured using the four-point-probe method. The dimensions of the contact pads and the contact spacing were measured by a scanning electron microscope. The R_T data for samples D and E with the alloyed RTA were plotted as functions of the distance for the separated contact pads, as shown in Fig. 3. The contact resistance was determined from the intercepts of the least-squares linear fitting line in the resistance versus distance plot. The total contact resistance for the alloyed RTA at 800 °C was measured and the specific contact resistivities ρ_c were calculated from the TLM method. The specific contact resistivities ρ_c were reduced by increasing the diffusion temperatures. The total resistance of samples D and E with the alloyed RTA at 800 °C varied with the contact pad spacing, as shown in Fig. 3. The specific contact resistivities ρ_c of samples D and E are calculated as 1.9×10^{-6} and $5.6 \times 10^{-7} \Omega \text{ cm}^2$ according to the TLM method. The as-deposited Ni/Al/Ti contact on sample A, without RTA, had a non-ohmic property because of a lower carrier concentration of $1.8 \times 10^{17} \text{ cm}^{-3}$ and a higher barrier of Ti metal.⁷ However, the as-deposited Ni/Al/Ti contact had an ohmic property on the Si-diffused GaN film at 1000 °C (sample E) and the specific contact resistivity ρ_c was measured as $1.6 \times 10^{-3} \Omega \text{ cm}^2$. The reason is the same as in past reports about the results of contact on heavy Si-

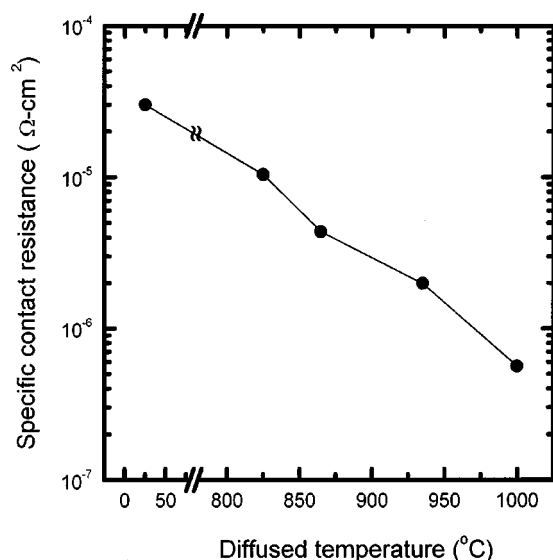


FIG. 4. Specific contact resistivities ρ_c on Si-diffused GaN films with alloyed RTA as functions of diffusion temperatures in the N_2 ambient.

doped and Si-implanted GaN films. The Si-diffused process forms a high surface density of donors to provide the tunneling process at the metal/GaN interface.

Ni/Al/Ti metal on Si-diffused GaN films was RTA alloyed at 800 °C for 30 s in N_2 ambient and the total resistance R_T was measured as the function of the metal pad spacing to calculate its ρ_c value. The specific contact resistivities ρ_c as functions of Si-diffused temperatures on GaN films are shown in Fig. 4. The specific contact resistivity ρ_c decreases with increasing Si-diffused temperatures. From observation of SIMS depth profiles of Si-diffused GaN films, the number of Si atoms increased when the diffused temperatures were raised from 825 to 1000 °C. Large amounts of Si atoms were diffused near the surface to form the heavy Si-doped n^+ -GaN layer of sample E. This Si-diffused process caused the contact resistance to decrease, specifically the ρ_c values observed decreased from 3.0×10^{-5} to $5.6 \times 10^{-7} \Omega \text{ cm}^2$. Ti is the most important metal in the Al/Ti contact because it reduces the gallium oxide, so that the Al

can diffuse through the Ti to reach the GaN surface. The Al-Ti intermetallic phase has a lower work function¹ (lower than 0.07 eV),² and the Al also has the same properties to help reduce contact resistivity. In addition to the lower metal work function, Si-diffused n^+ -GaN surfaces also provide the tunneling process for the electrons. These two important parameters have a strong influence on the specific contact resistivity ρ_c of GaN epitaxial films. Our experiment has shown another way to form heavy Si doping on the GaN surface to help reduce contact resistance.

In conclusion, Si was successfully diffused into GaN films using $\text{SiO}_x/\text{Si}/\text{GaN}/\text{Al}_2\text{O}_3$ structures. SIMS analyzed the diffusion profiles of Si, and large quantities of Si atoms were diffused into the GaN surfaces to form highly doped n^+ -type GaN layers. This Si-diffused process caused the ohmic contact resistance to clearly decrease. The specific contact resistivity ρ_c values were reduced from 3.0×10^{-5} to $5.6 \times 10^{-7} \Omega \text{ cm}^2$ for the Ni/Al/Ti metal contact, and the diffusion temperature increased from 825 to 1000 °C. This technique to form diffused n^+ -type GaN thin layers can be used to fabricate GaN-based devices with good ohmic contact.

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