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Si implant-assisted Ohmic contacts to GaN

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ABSTRACT

The contact resistance, ρ_C, was measured for the traditional Ti/Al/Ni/Au Ohmic contact for samples implanted with Si to >10^{20} cm^{-3} and annealed at 1100, 1150, 1200, or 1250 °C for 2, 5 or 10 min using an AlN annealing cap. These results are compared with those for samples annealed in the same way, but were not implanted. The as-grown samples were doped to 3.56×10^{17} or 6.67×10^{16} cm^{-3} or were unintentionally (UI) doped. In almost all cases, ρ_C for the implanted sample was lower, and a record low $\rho_C = 2.66 \times 10^{-8}$ Ω cm^2 was achieved for the more heavily doped implanted sample annealed at 1200 °C for 10 min. ρ_C decreased with the doping concentration, and for the UI samples, Ohmic contacts could be made only if the samples were implanted. The surface roughness was also measured, and it was found for an as-grown with an RMS roughness of 0.303 nm, the roughness increased from 0.623 after an 1100 °C anneal to 3.197 nm after a 1250 °C anneal for the implanted samples annealed for 10 min, and it increased from 1.280 nm to 5.357 nm under the same conditions for the samples that were not implanted.

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1. Introduction

Reliable, low contact resistance, ρ_C, Ohmic contacts to *n*-GaN can improve the operating characteristics of devices such as Schottky diodes and high power, high frequency, high electron, mobility transistors (HEMTs). For the high power HEMTs ρ_C, can contribute significantly to the on-resistance, and for the high frequency HEMTs it contribute significantly to the channel resistance; in some cases its contribution can be as high as 50%.

One reason ρ_C for these devices is relatively high is because the contacts are made to relatively low doped material. For Schottky diodes used in high power applications, the *n*-GaN is low doped to increase the breakdown voltage, while for the HEMTs, the contacts are made to unintentionally (UI) doped GaN or AlGaN. One can increase the local doping concentration where the contacts are made by selective area diffusion [1] or ion implantation [2–9]. The problem with ion implantation is that the GaN has to be annealed at temperatures above which the rate of the preferential evaporation [10] becomes significant, which creates hexagonal etch pits. Researchers have attempted to deal with this problem by annealing for a short time (30 s) in flowing NH_3 [6,7], placing the samples face-to-face [2,3], under high N_2 pressures [4,5], or with sputtered Si_3N_4 [8,9] or AlN [4,5]. However, face-to-face capping does not hermetically seal the surface, the partial pressure of N_2 greatly exceeds the N_2 over pressures that were used [10], and sputtered Si_3N_4 [11] or AlN [12] does not stick very well and is relatively weak so it can be punctured by the large N_2 vapor pressures at the annealing temperatures that were used.

We have developed an annealing cap composed of a thin (~80 nm) low temperature (~600 °C) deposited AlN adhesion layer grown by metal organic chemical vapor deposition (MOCVD) and a thick (~1 μm) sputtered AlN layer for added strength [12] that can withstand annealing temperatures up to ~1250 °C, which is about the temperature where the yield strength of AlN [13] is equal to the partial pressure of N_2 in equilibrium with GaN. As a result we are able to study the effects of annealing for temperatures up to 1250 °C for various amounts of time on the contact resistance. In this paper we study the effects of annealing both samples that were implanted and were not implanted over the range of temperatures from 1100 to 1250 °C for 2, 5 or 10 min. We also examine how annealing affects the surface roughness of the GaN by measuring the RMS roughness using an atomic force microscope (AFM).

2. Experimental procedure

Three 2 μm thick GaN films were grown at 1100 °C on sapphire substrates by MOCVD using a low temperature (600 °C) GaN buffer layer. They were unintentionally doped or doped with Si using a SiH_4 flow of 1 or 0.25 sccm during the growth of the GaN films. A gold mask was used to create TLM patterns on one half of each of the wafers and totally covered the other half. Si was implanted through the opening where the contact pads were deposited later

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with doses of 1.5×10^{15} cm^{-2} at 30 and 60 keV [5]. The peak concentration obtained from a TRIM profile was 5.6×10^{20} cm^{-3} at the depth of 21 nm and was below 10^{20} cm^{-3} for depths >100 nm. After removing the implant mask, 8 × 10 mm samples were cut from the wafers, and an 80 nm MOCVD AlN film was deposited on them at 600 °C followed by the sputter deposition at 500 °C of a 1 μm thick AlN film. One implanted sample was paired with one that was not, and they were annealed together under a nitrogen pressure at 1100, 1150, 1200, or 1250 °C for 2, 5 or 10 min. Following the annealing process, the AlN annealing cap was removed by a warm KOH solution. Then, the annealed samples were examined in an a scanning electron microscope (SEM) to investigate the morphology of the GaN surface to see if there had been any local hexagonal etch pits created by the preferential evaporation of the N, and to also examine the effects of diffusion on the surface. Next, AFM scanning was used for measuring the RMS roughness of GaN after annealing. The RMS roughness was recorded over 5 × 5 or 25 × 25 μm^2 areas on samples that were annealed at 1100, 1150, 1200 or 1250 °C for 10 min.

Before the capping layers were deposited, 8 × 10 mm samples were cut from each wafer for Hall effect and TLM measurements to electrically characterize the as-grown material. Ohmic contacts were fabricated using an alloyed metal stack of Ti/Al/Ni/Au for the contact [14] with thicknesses of 10/100/50/20 nm followed by a 30 s rapid thermal anneal (RTA) at 800 °C under nitrogen pressure. Hall effect measurements were made to measure the carrier concentration, mobility, and sheet resistance of the initial GaN. To create the TLM patterns, a Cr/Ni (30/200 nm) bi-layer mask was used to form the mesas for the individual TLM structures using an RIE etch, the Ohmic metal pads were deposited over the implanted regions, and then the contacts were annealed. Both ρ_C and the sheet resistance, R_{SH} were determined from the *I–V* measurements. TLM measurements were performed on an as-grown sample from each of the three wafers, as well as on annealed samples that were implanted or not implanted.

Table 1
Hall effect measurements.

Doping level (cm^{-3})	Mobility (cm^2/V s)	Sheet resistance (Ω/sq)	Specific contact resistance (Ω cm^2)
3.56×10^{17}	417	3.46×10^{2}	3.90×10^{-6}
6.67×10^{16}	524	1.34×10^{3}	3.96×10^{-5}
Unintentionally doped	Unable to measure	8.4×10^{4} [a]	Unable to measure

[a] Average sheet resistance from TLM measurements of the sheet resistance between the pads.

Table 2
Specific contact resistance of higher and lower doped samples.

T_{Anneal} (°C)	Time (min)	Higher doped wafer ρ_C (Ω cm^2) Not-implanted	Higher doped wafer ρ_C (Ω cm^2) Implanted	Lower doped wafer ρ_C (Ω cm^2) Not-implanted	Lower doped wafer ρ_C (Ω cm^2) Implanted
1100	2	7.87×10^{-6}	1.12×10^{-5}	4.17×10^{-5}	4.15×10^{-4}
	5	5.50×10^{-6}	7.28×10^{-4}	1.19×10^{-5}	1.62×10^{-5}
	10	7.87×10^{-6}	1.19×10^{-6}	3.47×10^{-5}	7.11×10^{-6}
1150	2	1.12×10^{-5}	8.52×10^{-7}	5.75×10^{-6}	2.40×10^{-5}
	5	1.43×10^{-6}	4.57×10^{-7}	2.01×10^{-5}	9.81×10^{-6}
	10	4.20×10^{-7}	1.43×10^{-7}	1.54×10^{-5}	1.05×10^{-5}
1200	2	3.74×10^{-7}	3.25×10^{-7}	1.50×10^{-5}	4.23×10^{-6}
	5	1.01×10^{-6}	6.24×10^{-7}	8.94×10^{-5}	5.56×10^{-6}
	10	1.24×10^{-5}	2.66×10^{-8}	2.56×10^{-3}	1.16×10^{-6}
1250	2	7.25×10^{-6}	8.44×10^{-7}	6.04×10^{-4}	7.47×10^{-6}
	5	2.56×10^{-4}	8.95×10^{-7}	3.54×10^{-3}	2.24×10^{-5}
	10	5.16×10^{-4}	3.38×10^{-6}	1.44×10^{-2}	1.19×10^{-5}

3. Results and discussion

As shown in Table 1, Hall effect measurements show that the carrier concentration for the film doped with a 1 sccm flow of dilute SiH_4 is 3.56×10^{17} cm^{-3}, and it is 6.67×10^{16} cm^{-3} when the flow rate is 0.25 sccm. The corresponding mobilities are 417 and 524 cm^2/V s, which is about what is expected for GaN films containing dislocation concentrations in the low 10^9 cm^{-2} [15], which is typical for our films. We were unable to form Ohmic contacts to the UI doped material. However, we can estimate its carrier concentration from R_{SH} that was determined from our TLM measurements. It was 84,000 Ω/□ compared to 346 and 1340 Ω/□ for the doped samples suggesting the net carrier concentration in the UI doped sample was ∼10^{15} cm^{-3}. We did not make Hall measurements on the annealed samples, but we noted that the average sheet resistance for the low doped sample was only 2.3% lower than it was for the sample that was not annealed, and it was only 1.8% lower for the higher doped sample. This suggests that processes that could profoundly affect the electrical properties, such as the formation of N vacancies through the preferential evaporation of N, was held in check.

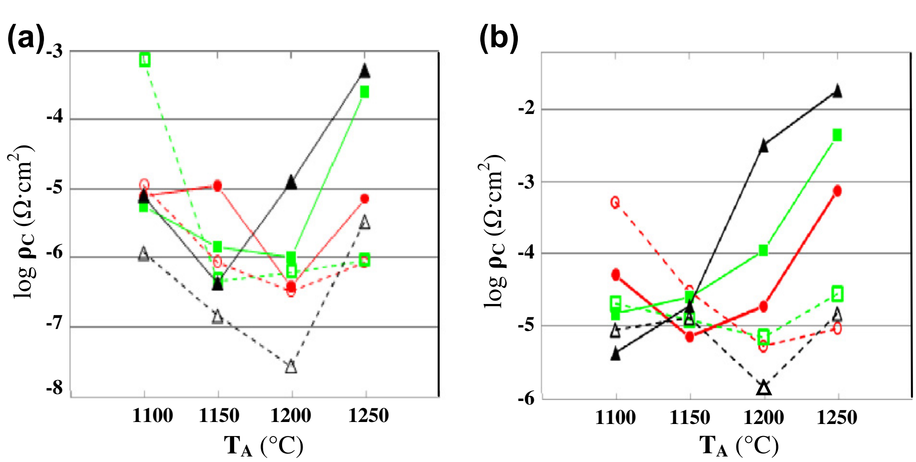

Fig. 1. Specific contact resistance for samples that were implanted with doses of 1.5×10^{15} cm^{-2} at both 30 and 60 keV (- -) or not implanted (—), and were annealed for 2 (●), 5 (■), or 10 (▲) min for the sample doped to the (a) heavier, and (b) lighter doped samples.

Table 3
Specific contact resistance UI doped samples.

T_{Anneal} (°C)	Time (min)	Unintentionally doped	
		ρ_C (Ω cm^2) Not-implanted	ρ_C (Ω cm^2) Implanted
1100	2	Not Ohmic	Not Ohmic
	5	Not Ohmic	1.47×10^{-1}
	10	Not Ohmic	9.13×10^{-2}
1150	2	Not Ohmic	3.01×10^{-1}
	5	Not Ohmic	4.8×10^{-1}
	10	Not Ohmic	5.62×10^{-2}
1200	2	Not Ohmic	2.08×10^{-4}
	5	Not Ohmic	1.08×10^{-1}
	10	Not Ohmic	3.0×10^{-2}
1250	2	Not Ohmic	4.0×10^{-2}
	5	Not Ohmic	8.9×10^{-4}
	10	Not Ohmic	1.37×10^{-2}

The contact resistance to the more heavily doped sample was $3.90 \times 10^{-6}\ \Omega$ cm^2, which is similar to what others [14] have obtained. As seen in Fig. 1a and Table 2, annealing the implanted sample for a time, t_A = 10 min, has the most significant effect on reducing ρ_C, and the largest reduction is achieved when the annealing temperature, T_A, is 1200 °C, where we achieved a record low value for this carrier concentration of $2.66 \times 10^{-8}\ \Omega$ cm^2. The previous record was $3.6 \times 10^{-8}\ \Omega$ cm^2 [3] and most of the other values for implanted contacts were in the low 10^{-6} range. ρ_C decreases with T_A from 1150 to 1250 °C for all three values of t_A, suggesting that increasing T_A and/or t_A increases the percent of the implants that have become electrically activated. For all three annealing times ρ_C is larger when T_A = 1250 °C than it is at 1200 °C, and the samples that were not implanted show the same behavior. It is also not likely this increase is due to the preferential evaporation of N because N vacancies are donors [16]. We will show that it is unlikely that much N escaped because our annealing cap remained intact. Rather, it seems likely this increase in ρ_C was due the effects of greater solid state diffusion at the higher T_A.

At $3.96 \times 10^{-5}\ \Omega$ cm^2, ρ_C for the more lightly doped sample was 10X larger, but the implanted samples followed the same trends as those for the implanted more heavily doped sample. That is, ρ_C decreased with T_A up to 1200 °C, and then it increased for the 1250 °C anneal. However, it was one to two orders of magnitude larger for comparably annealed samples. Again, the lowest ρ_C was achieved after the 10 min anneal at 1200 °C, with the value being $1.16 \times 10^{-6}\ \Omega$ cm^2. The trend is different for the samples that were annealed, but were not implanted; ρ_C essentially increased with both T_A and t_A with the exception of 1150 °C annealing case. One possible explanation is that the annealing reduces the dislocation concentration, and it is more difficult to make a contact to a sample that has fewer dislocations that act as diffusion pipes. Although Ohmic contacts could not be made to the as-grown UI samples, they could be made to the implanted UI samples for all but the sample annealed for 2 min at 1100 °C, as is shown in Table 3. The Ohmic contact could probably not be made because the implants had not been sufficiently activated. However, ρ_C is much larger than it is for the doped samples with values being in the 10^{-2}–$10^{-1}\ \Omega$ cm^2 range with only the samples annealed at

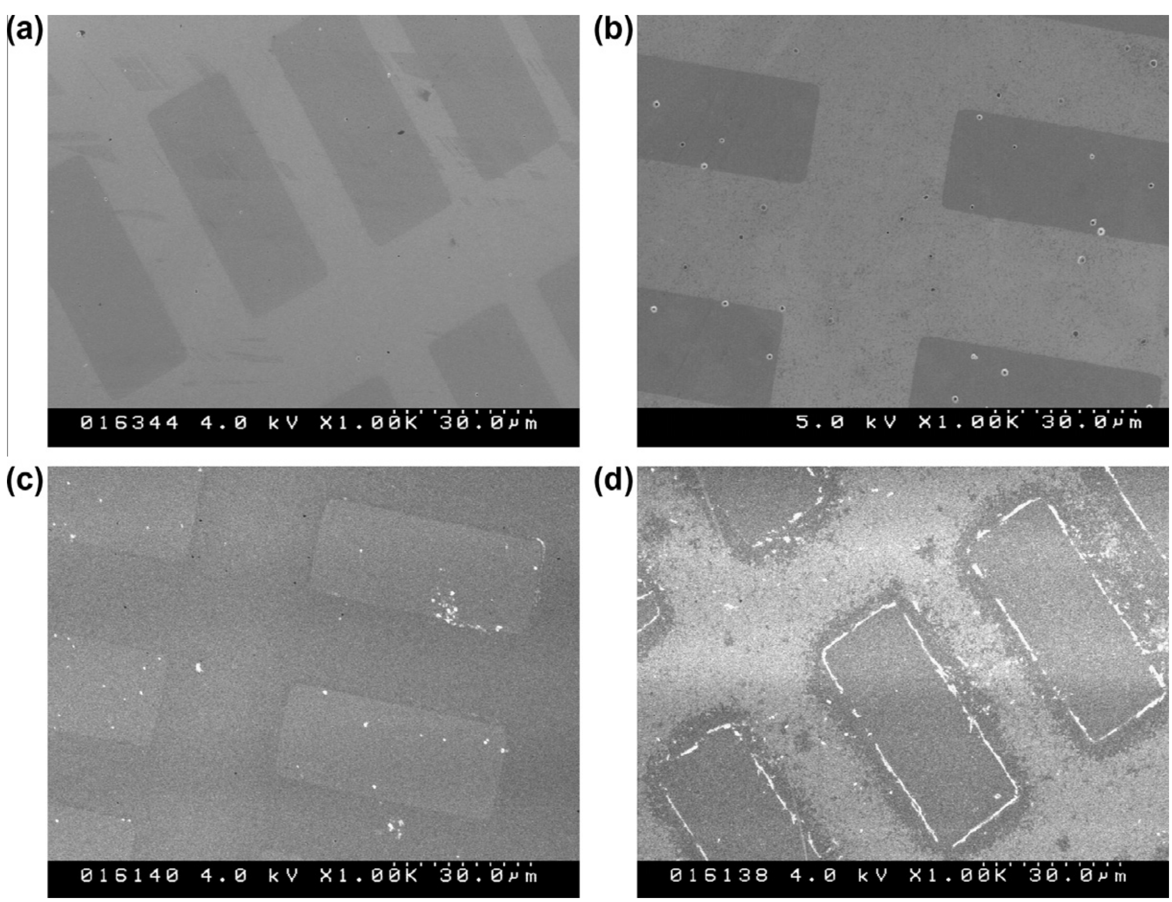

Fig. 2. SEM micrographs of the implanted regions under the TLM pads of the heavier doped sample that was annealed for 10 min at: (a) 1100 °C, (b) 1150 °C, (c) 1200 °C, and (d) 1250 °C.

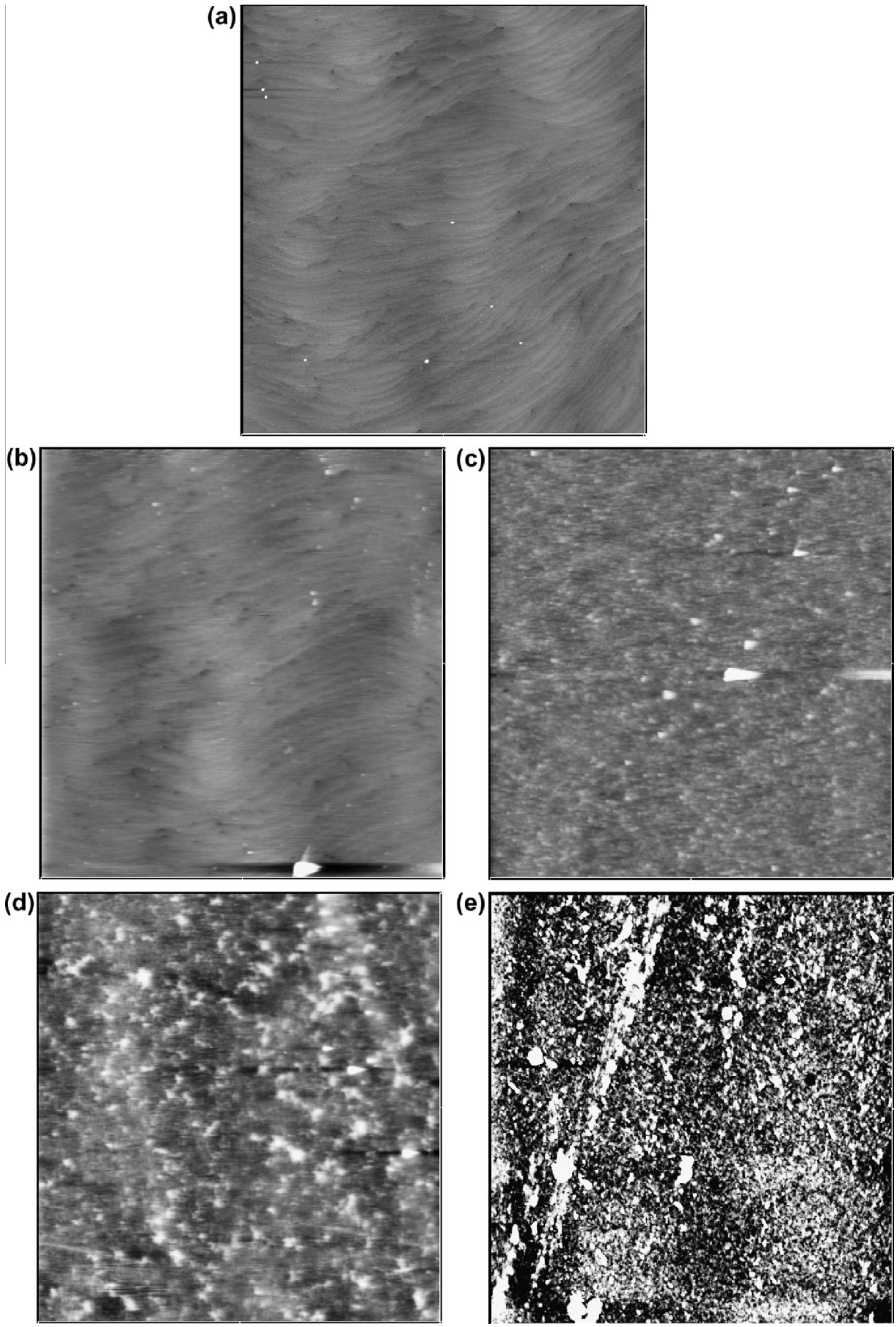

Fig. 3. AFM micrographs of the (a) as-grown sample, and for the implanted sample annealed for 10 min at, (b) 1100 °C, (c) 1150 °C, (d) 1200 °C, and (e) 1250 °C.

1200 °C for 2 min (2.08×10^{-4}) and 1250 °C for 5 min (8.9×10^{-4}) being in the 10^{-4} Ω cm^2 range.

The SEM micrographs of the GaN surface with the AlN annealing cap etched off in Fig. 2 for the more heavily doped, implanted samples annealed for 10 min show that the annealing cap can withstand the stresses produced by the N_2 vapor pressure, but the stress increases with T_A. There are virtually no hexagonal etch pits typical of specimens annealed at these temperatures without a cap. However, as shown in the AFM micrographs in Fig. 3, the surfaces do become rougher as T_A increases. The RMS surface roughness increases from 0.623, to 0.685, to 1.086, to 3.196 nm in a 5×5 μm^2 area as T_A is increased from 1100, to 1150, to 1200, to 1250 °C. The RMS roughness for the as-grown sample was 0.303 nm. For the comparable samples that were implanted, the RMS roughness was 1.280 nm for the sample annealed at 1100 °C, and it was 5.357 for the sample annealed at 1250 °C. This information suggests that even though the N_2 does not appear to be able to escape, the surface can be roughened by surface and/or solid state diffusion that can occur at these elevated temperatures.

4. Conclusions

When properly annealed, ρ_C for doped samples implanted with Si to $>10^{20}$ cm^{-3} near the surface can be reduced one to two orders of magnitude as compared to the doped samples that are not implanted, but annealed in the same way. ρ_C can also be reduced more than two orders of magnitude as compared to the as-grown film. We obtained a $\rho_C = 2.66 \times 10^{-8}$ Ω cm^2 for a sample doped to 3.56×10^{17} cm^{-3} and annealed for 10 min at 1200 °C. For the as-grown sample, $\rho_C = 3.90 \times 10^{-6}$ Ω cm^2. For the samples doped to 6.67×10^{16} cm^{-3}, ρ_C was 10–100 times larger for the comparably annealed more lightly doped samples. Ohmic contacts could not be made to the UI samples, which we estimate to have a carrier concentration of $\sim 10^{15}$ from our sheet resistance measurements, and ρ_C was large ($\sim 10^{-2}$–10^{-1} Ω cm^2) for the implanted samples.

For the more heavily doped samples ρ_C decreased with the annealing temperature, T_A, from 1150 to 1250 °C, but the decrease of ρ_C after the 1250 °C anneal for the implanted samples is minimal, while ρ_C increased for the samples that were not implanted. It also tended to decrease with the annealing time, t_A, for a given T_A for t_A = 2, 5 or 10 min for the implanted samples, but tended to increase with t_A for the samples that were not implanted. For the more lightly doped samples the trends for ρ_C were similar to those for the more heavily doped samples for both the implanted samples and the samples that were not implanted. However, ρ_C tended to increase with T_A, as well as t_A. This could be due to the reduction in the dislocation concentration during the anneal, which would reduce the number of diffusion pipes for the Ohmic metal.

The changes in ρ_C are more likely to be due to diffusion in the bulk and on the surface, as opposed to the preferential evaporation of N because an AlN cap was used during the annealing process. The evidence that the cap was effective was the lack of hexagonal etch pits formed by the preferential evaporation of N when a cap is not used. In addition to changes in ρ_C evidence that there was considerable diffusion is reflected in the increase of the RMS surface roughness from 0.623 to 3.196 nm when T_A was increased from 1100 to 1250 °C for the annealing time of 10 min for the more heavily doped sample that was implanted, and an increase from 1.280 to 5.357 nm over the same temperature range for the same time for the more heavily doped sample that was not implanted. The surface roughness of the as-grown sample was 0.303 nm.

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