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The Role of AlN Encapsulation of GaN During Implant Activation Annealing

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With the demonstration of implant doping of GaN and the resulting need to perform the activation anneal at ~1100 °C, the details of the thermal stability of the surface of GaN needs to be understood. In this work we report on the use of a sputtered AlN encapsulant to preserve the surface of GaN during such an annealing process. The surface was characterized by the formation of Pt/Au Schottky contacts and by Auger Electron Spectroscopy (AES). Schottky contacts deposited an GaN annealed with the AlN encapsulant displayed good rectification properties while those formed on GaN annealed uncapped approached ohmic behavior. AES analysis supports the hypothesis that the uncapped sample has lost N from the very near surface which creates N-vacancies that act as donors and thereby form an n^+-surface layer.

INTRODUCTION

Ion implantation doping and isolation has played a critical role in the realization of high performance photonic and electronic devices in all mature semiconductor material systems. This is also expected to be the case for the binary III-Nitride materials (InN, GaN, and AlN) and their alloys as the epitaxial material quality improves and more advanced device structures are fabricated. To fully apply ion implantation technology to GaN-based electronics, both Schottky and ohmic contacts must be readily fabricated on the semiconductor following the implantation and activation process. For example, for an all ion implanted GaN MESFET to be achieved a Schottky gate contact must be formed on the implanted channel region after the activation anneal. Since the activation anneal for GaN has been shown to be in the range of 1100 °C [1,2], we studied the formation of a Pt/Au Schottky contact on n-type GaN after such a high temperature anneal. We show that the Pt/Au contacts deposited on GaN annealed at 1100 °C without an AlN cap resulted in very poor reverse bias characteristics. Since it is the reverse characteristic that is involved in the modulation of the channel of a MESFET, an improved annealing process is needed. To this end, we demonstrate that reactively sputtered AlN is an effective encapsulant for GaN at an annealing temperature of 1100 °C [3].

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EXPERIMENTAL PROCEDURE

Two sets of GaN samples were processed into Pt/Au Schottky contacts following a 1100 °C, 15 s rapid thermal anneal. One set of samples was n-type as-grown (n ~ 1×10^{17} cm^{-3}) while the second was initially semi-insulating and was implanted with Si-ions at an energy of 100 keV and a dose of 5×10^{13} cm^{-2} to simulate a MESFET channel implant. One sample from each set was encapsulated with 120 nm of reactively sputtered AlN prior to annealing. Following annealing, the AlN was removed in a selective KOH-based etch (AZ400K developer) at 60-70 °C [4]. This etch has been shown to etch AlN at rates of 60 to 10,000 Å/min, depending on the film quality, while under the same conditions no measurable etching of GaN was observed [5]. The etch rate of the sputter deposited AlN film was found to increase as a function of post-deposition annealing temperature as shown in Fig 1 [6]. Ti/Al ohmic contacts were deposited and defined by conventional lift-off techniques on all samples and annealed at 500 °C for 15 s. Pt/Au Schottky contacts were deposited and defined by lift-off within a circular opening in the ohmic metal. Electrical characterization was performed on a HP4145 at room temperature on 48 µm diameter diodes. Samples prepared in the same way, except without any metallization, were analyzed with Auger Electron Spectrometry (AES) surface and depth profiles. The surface morphology was also characterized by atomic force microscopy (AFM) before and after annealing.

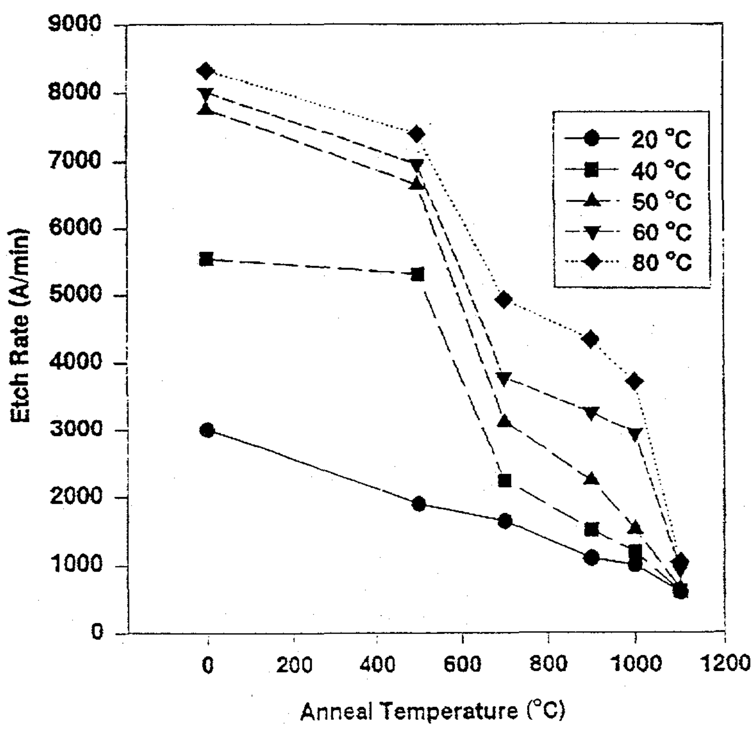


Fig 1. Etch rate versus annealing temperature for sputter deposited AlN as a function of etch solution temperature.

RESULTS AND DISCUSSION

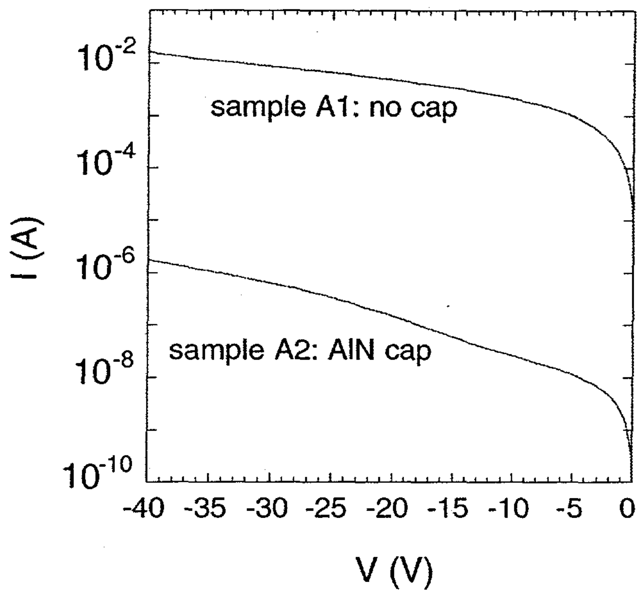


Fig 2. Reverse current/voltage characteristics for 48 μm diameter Pt/Au Schottky contacts on GaN annealed at 1100 °C, 15 s with (sample A2) and without (sample A1) an AlN cap.

Figure 2 shows the reverse current/voltage characteristics of 48 μm diameter Pt/Au Schottky diodes on the initially n-type samples. The sample annealed without the AlN cap has over 3 orders-of-magnitude higher reverse leakage current than the capped sample. The reason for the difference in reverse bias characteristics is discussed below.

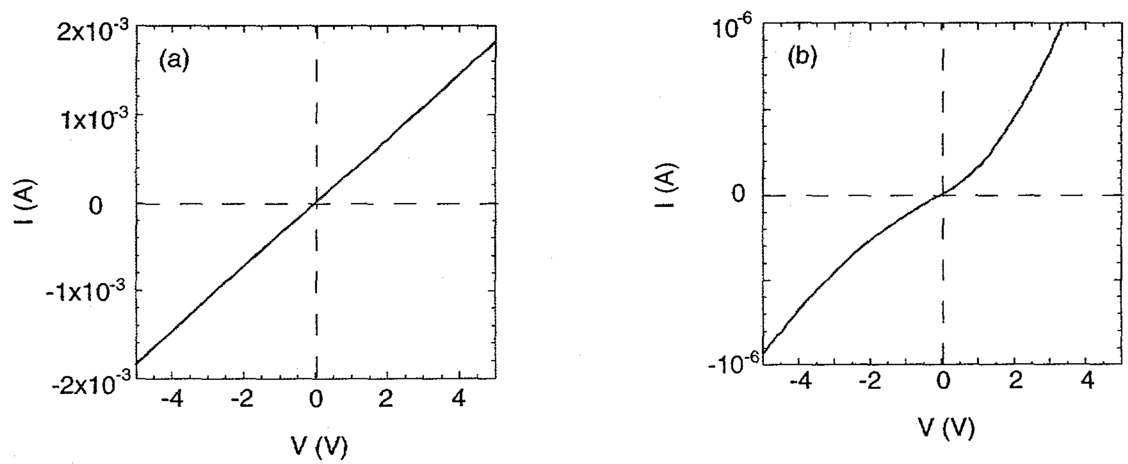
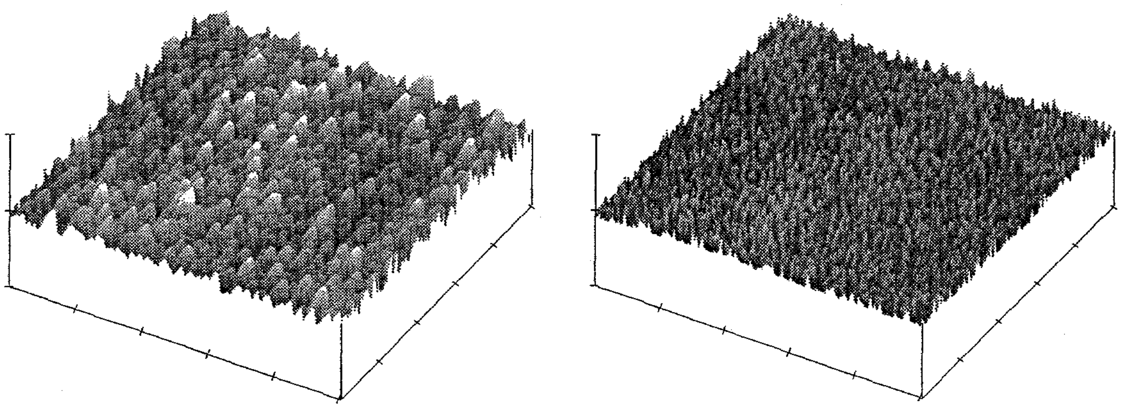


Fig 3. Current/voltage characteristics between two adjacent Ti/Al ohmic contacts on GaN annealed at 1100 °C, 15 s (a) without and (b) with an AlN cap. Note the change in current scale for the two samples.

Figure 3 shows the current/voltage characteristics between two adjacent Ti/Al ohmic contacts on the same two samples as in Fig 2. Here the sample annealed without the AlN cap displays dramatically lower resistance than the AlN-capped sample. This is consistent with the Schottky characteristics and suggests the creation of an n^+-surface is formed on the sample annealed without the AlN encapsulant.



(a) RMS = 4.02 nm (b) RMS = 2.51 nm

Fig 4. Atomic force microscope images of GaN after an 1100 °C, 15 s anneal either a) uncapped or b) capped with reactively sputtered AlN. The AlN film was removed in a selective KOH-based etch (AZ400K developer) at 60 - 70 °C. On both images, the vertical scale is 50 nm per division and the horizontal scale is 2 µm per division.

Further evidence of the difference between the two anneal processes is seen in the atomic force microscopy images shown in Fig 4. The sample annealed without the AlN cap is markedly rougher than the capped sample, again suggesting some degree of surface decomposition. In an attempt to quantify the change in the GaN surface resulting from annealing with and without the AlN cap, AES surface and depth profiles were performed an annealed samples (capped and uncapped) after removal of the AlN encapsulant. Unfortunately, since carbon is often a surface contaminant in AES analysis and N can also be adsorbed at the surface, it is difficult to compare the absolute Ga and N concentrations from the AES data. However, when comparing the Ga/N ratio for each case we do see an increase for the sample annealed without the AlN cap (Ga/N ratio = 2.34) as compared to the as-grown sample (Ga/N ratio = 1.73). This can be understood by N-loss from the GaN during the annealing process [7]. For the sample annealed with the AlN cap, the AES spectrum had a strong signal from C contamination at the surface that masked the absolute N-concentration. AES depth profiles of the uncapped and annealed sample suggests that the N-loss is occurring in the very near surface region (~ 50 Å).

N-loss and the formation of N-vacancies during the high-temperature anneal is proposed as the key mechanism involved in changing the electrical properties of the Schottky and ohmic contacts. Since N-vacancies are thought to contribute to the background n-type conductivity in GaN, an excess of N-vacancies at the surface should result in a n^+-region (possibly a degenerate region) at the surface [8]. This region would then contribute to tunneling under reverse bias for the Schottky diode and explain the increase in the reverse leakage current in the uncapped samples. Similarly, a n^+-region at the surface would improve the ohmic contact behavior as seen for the uncapped samples [9]. The effectiveness of the AlN cap during the anneal to suppress N-loss is readily understood by the inert nature of AlN and its extreme thermal stability thereby acting as an effective diffusion barrier for N from the GaN substrate.

CONCLUSION

In conclusion, we have demonstrated the viability of using reactively sputtered AlN films as an encapsulating layer for GaN during high-temperature (1100 °C) annealing. Schottky diodes with good rectification properties were demonstrated on the sample annealed with the AlN encapsulation while these contacts where nearly ohmic on the sample annealed uncapped. Experiments are underway to employ AlN encapsulation to fabricate all ion implanted GaN MESFETs.

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