Ohmic contacts to Si-implanted and un-implanted n-type GaN

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ABSTRACT

We report on ohmic contacts to Si-implanted and un-implanted n-type GaN on sapphire. A ring shaped contact design avoids the need to isolate the contact structures by additional implantation or etching. Metal layers of Al and Ti/Al were investigated. On un-implanted GaN, post metalization annealing was performed in an RTA for 30 seconds in N_2 at temperatures of 700, 800, and 900°C. A minimum specific contact resistance (r_c) of $1.4 \times 10^{-5} \Omega\text{-cm}^2$ was measured for Ti/Al at an annealing temperature of 800°C. Although these values are reasonably low, variations of 95% in specific contact resistance were measured within a 500 μm distance on the wafer. These results are most likely caused by the presence of compensating hydrogen. Specific contact resistance variation was reduced from 95% to 10% by annealing at 900°C prior to metalization. On Si-implanted GaN, un-annealed ohmic contacts were formed with Ti/Al metalization. The implant activation anneal of 1120°C generates nitrogen vacancies that leave the surface heavily n-type, which makes un-annealed ohmic contacts with low contact resistivity possible.

INTRODUCTION

Obtaining stable, low resistance ohmic contacts is essential for the fabrication of most practical semiconductor devices. For GaN and other highly ionic semiconductors, evidence suggests that contact barrier heights depend directly on the difference between the work function of the metal and the electron affinity of the semiconductor [1]. Consequently, of the common metals used in semiconductor processing, we expect Al and Ti to form ohmic contacts to n-type GaN fairly easily due to their relatively small work functions [2,3]. The quality of ohmic contacts, however, will be greatly influenced by the condition of the semiconductor surface prior to metalization as well as heat treatment of the material after the contacts have been formed. In this paper we present the results of our investigations of the formation of ohmic contacts to Si-implanted and un-implanted n-type GaN. Surface preparation, pre-metalization and post-metalization treatments are discussed.

EXPERIMENT

Annealed Ohmic Contacts to Undoped GaN

Metal was deposited by evaporation at 5×10^{-7} - 10^{-6} Torr. Ring shaped contacts were then formed using a photolithography and liftoff process. The ring shaped contact design avoids the need to isolate the contact structures by additional implantation or etching. For a large ring to gap-spacing ratio, the ring contact geometry reduces to the standard transmission line model (TLM) structure [4]. For practical ring radii (200 μm) and spacings (5-45 μm), though, small, geometrical correction factors are necessary to compensate for the difference between the TLM and ring layouts.

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Our studies indicate that, while Al forms an ohmic contact to undoped n-type GaN, the specific contact resistance for this metalization is very high. This is probably due to the presence of an oxide layer on the GaN surface which reacts with the Al to form insulating Al_2O_3 . Furthermore, Al on GaN 'balls' or forms into puddles when annealed at temperatures above the melting point of Al (660°C) requiring the presence of either a 'wetting' metalization below or a 'capping' metalization above the Al. Consequently, contacts of Al only to GaN are undesirable.

Metal layers of Ti/Al deposited on $4\text{ }\mu\text{m}$ thick undoped, n-type GaN [5] were also investigated with Ti thicknesses of 150, 300, and 500 Å covered with 2000 Å of Al. Ohmic contacts to undoped n-type GaN are obtained with each of the above Ti/Al metalizations after rapid thermal annealing (RTA). As-deposited metal contacts exhibited Schottky behavior or extremely large contact resistance. Heat treatment was performed in a RTA system for 30 seconds in N_2 at temperatures of 700, 800, and 900°C . Lower temperatures were investigated, but gave r_c results that were generally inferior. The specific contact resistance varies with annealing temperature as indicated in Fig. 1 below. A minimum specific contact resistance of $1.4 \times 10^{-5}\text{ }\Omega\text{-cm}^2$ is reached with the 300 Å Ti metalization at an annealing temperature of 800°C . From our study, the optimum titanium thickness is 300 Å. We do not observe any significant alloying of the annealed Ti/Al metalization into the GaN as measured by surface profilometry after stripping of the metalization in HF and H_2SO_4 .

Figure 1. Specific Contact Resistance, r_c , vs. Anneal Temp for three different Ti thicknesses in a Ti/Al metalization on GaN. The Al thickness is 2000 Å. The optimum Ti thickness is 300 Å and the optimum anneal temperature is 800°C .

Variation in specific contact resistance across samples is observed for all of the metalizations examined. Typical TLM data that we obtained is shown in Fig. 2. In this figure, the data denoted by circles was taken from a site adjacent to the site designated by squares. The sheet resistances (R_{sh}), which are found from the slopes of the lines through the data, are the same for both sites, but the contact resistances, which are found from the intercepts, differ significantly. The contact resistance is indicative of properties of the surface, whereas the sheet resistance is a characteristic of the bulk semiconductor. Although it is not immediately obvious why the surface electrical properties should vary so dramatically, any variation at the surface will probably not be reflected by sheet resistance measurements due to the thick GaN layer ($4\text{ }\mu\text{m}$). Donor-compensating hydrogen in the GaN [6] and inadequate pre-metalization surface treatment are two conditions that could have an adverse effect on the GaN surface. Since improvement in the

contact resistance is observed using a $\text{NH}_4\text{OH}:\text{DI}$ pre-metalization dip, our surface treatment is probably sufficient. This fact leaves hydrogen as the probable cause of the non-uniformity; a conclusion supported by the noticeable drop in sheet resistance after further annealing at 800°C . In his studies of p-type GaN grown by MOCVD, Nakamura [7] found that 20 min. anneals in nitrogen at temperatures above 500°C were effective in driving out H_2 and improving the conductivity (sheet resistance) of GaN. It is reasonable to assume that since the annealing time used in our work is only 30 sec. that a higher temperature would be needed to drive out the hydrogen.

The reason for the drop in contact resistance as the anneal temperature is increased from 700 to 800°C is not certain. Titanium, which is known to getter hydrogen [8], could be acting as a catalyst in the removal of H_2 , which would in turn increase the electron concentration at the surface and reduce the contact resistance. Alternatively, r_c could be decreasing due to a deeper alloy of the Ti/Al metalization into the semiconductor.

Figure 2. Resistance between ring-shaped contacts as a function of the gap between contacts. Variation in the contact resistance can be seen from the y-axis intercepts and slopes of the fitted lines, respectively.

Figure 3. The resistance between contacts vs. the spacing for GaN sample pre-annealed at 900°C for 30 sec. before Ti/Al metalization. The improvement in uniformity can be seen by the fact that the various gap spacings fall on the same line.

Due to the belief that hydrogen is present in the material, we decided to investigate the influence of high temperature annealing of the wafer prior to metal evaporation. At the very least, this technique should liberate hydrogen near the surface and increase the conductivity in that region. Without the anneal, it is possible that the contact metalization itself may trap the hydrogen in the GaN. The results of our pre-metalizations anneal study are shown in Fig. 3. Both the uniformity of the specific contact resistance across the sample and the curve fit to the data are significantly improved by pre-annealing the GaN piece at 900°C in flowing nitrogen. This supports our theory that hydrogen compensation can influence ohmic contact formation in undoped GaN. Secondary ion mass spectroscopy (SIMS) analysis of our GaN material was performed to determine the hydrogen concentration. However, the hydrogen concentration that we expect to be present in the material (about 10^{17} cm^{-3} or lower) is extremely difficult to detect by this or any other technique and the results were inconclusive.

In subsequent Ti/Al contact experiments on other GaN wafers, we have found that high temperature annealing does not always prevent sheet resistance or contact resistance non-uniformities in undoped GaN. Variations in the material thickness or defect concentration could also be affecting the ohmic contact results. Nevertheless, we treat the pre-anneal as a preliminary step to eliminate unwanted hydrogen given the good chance that it is present in MOCVD-grown GaN.

Non-Annealed Ohmic Contacts to Si Implanted GaN

To obtain more control over the electronic properties of GaN, as opposed to relying on the reproducibility of unintentionally doped GaN, silicon donor implantation has also been studied. In addition, the implant increases the electron concentration at the near surface, therefore improving the tunneling process involved in forming an ohmic contact to n-type GaN. A two-step implant was performed with doses of $5 \times 10^{14} \text{ cm}^{-3}$ and $7.5 \times 10^{14} \text{ cm}^{-3}$ and energies of 40 and 100 keV, respectively on 4 μm thick GaN grown on both a-plane and c-plane sapphire. This double implant is intended to give approximately $3 \times 10^{19} \text{ cm}^{-3}$ donor atom concentration through the first 3500 Å of the material. We expect about 10% activation of the Si donors given previous results on implanted EMCORE material. The implant activation anneal employed a temperature of 1120°C for 15 sec in flowing N_2 .

The sheet resistance of the GaN does not change appreciably after the implant due to the thickness of the epilayer as compared to the implant depth. This ratio is about 10:1. Typical sheet resistances of the a- and c-plane material are about 1500-2000 Ω/square and 6000-7000 Ω/square , respectively.

Our experiments on Si-implanted material show that un-annealed Ti/Al ohmic contacts with low specific contact resistances are possible. The lowest r_c that we obtained for un-annealed contacts is $1.0 \times 10^{-5} \Omega\text{-cm}^2$. This same metalization deposited on un-implanted material yields Schottky or rectifying characteristics when annealing is not used. This result implies that the implantation and/or activation anneal process leaves the top surface of the GaN very heavily n-type. To determine whether the Si donors or the 1120°C anneal are responsible for the high electron concentration at the surface, we compared the contact resistance of a Ti/Al contact on an un-annealed, un-implanted GaN wafer and an 1120°C annealed, but un-implanted sample. The non-alloyed contact on the un-annealed sample was Schottky as usual, but the non-alloyed contact on the 1120°C wafer was ohmic with a contact resistance of $1.3 \times 10^{-3} \Omega\text{-cm}^2$ (see Fig. 6, wafer 110A result). Clearly, the annealing increases the electron concentration at the surface. The most probable mechanism is through desorption of nitrogen [9] from the GaN at high temperature leaving nitrogen vacancies that behave as donors in GaN [10].

After the 1120°C anneal for 15 sec. in N_2 , we do not observe Ga puddled on the surface either optically or in a scanning electron microscope (SEM). If any Ga were left on the surface, however, the contact resistance should be very sensitive to the surface chemical treatment used before metal deposition. A wafer clean that uses a corrosive 1:1 $\text{H}_2\text{SO}_4\text{:H}_2\text{O}_2$ acid etch intended to remove Ga left on the surface after the high temperature anneal does not appear to change the quality of the ohmic contact significantly as shown in Figs. 4 and 5. The r_c results shown in Fig. 4 and 5 also indicate that any potential oxide left by the anneal is better removed by NH_4OH than by HCl .

Figure 4. The specific contact resistance of Ti/Al non-alloyed contacts to Si-implanted GaN grown on a-plane sapphire (wafer 184a) as a function of wafer clean (acid-etch or no etch) and the surface treatment (NH_4OH or HCl) just prior to placing the material in the metal evaporator.

Figure 5. The specific contact resistance of Ti/Al non-alloyed contacts to Si-implanted GaN grown on c-plane sapphire (wafer 184c) as a function of wafer clean (acid-etch or no etch) and the surface treatment (NH_4OH or HCl) just prior to placing the material in the metal evaporator.

Figure 6. The specific contact resistance data contained in Figs 4 and 5 compared to two other samples. 110A is un-implanted and annealed at 1120°C prior to metalization and 168c is Si implanted and annealed at 1120°C .

CONCLUSIONS

Specific contact resistances of $1.4 \times 10^{-5} \Omega\text{-cm}^2$ have been obtained for a 300 Å Ti/2000 Å Al metalization annealed at 800°C for 30 seconds in N₂. We have observed that pre-annealing of undoped, n-type GaN at 900°C for 30 seconds improves the uniformity of the specific contact resistance across the material. We attribute this result to release of compensating hydrogen during the high temperature pre-processing anneal. For both Si-implanted and un-implanted GaN, annealing at 1120°C in flowing N₂ for 15 seconds prior to processing yields ohmic contacts for as-deposited (un-annealed) Ti/Al metalizations. This result is explained by the creation of nitrogen vacancies, which are known to behave as donors, at the surface of the GaN. For p-type MOCVD grown III-N's where a high temperature anneal is commonly used to drive out compensating hydrogen, a capping film may be necessary to avoid compensation of acceptors due to nitrogen vacancies at the near surface.

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