BEHAVIOR OF W AND WSi_x CONTACT METALLIZATION ON n- AND p- TYPE GaN

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Cite this article as: MRS Internet J. Nitride Semicond. Res. 4S1, G6.39(1999)

ABSTRACT

Sputter-deposited W-based contacts on p-GaN (N_A~10^{18} cm^{-3}) display non-ohmic behavior independent of annealing temperature when measured at 25 ^oC. The transition to ohmic behavior occurs above ~250 ^oC as more of the acceptors become ionized. The optimum annealing temperature is ~700 ^oC under these conditions. These contacts are much more thermally stable than the conventional Ni/Au metallization, which shows a severely degraded morphology even at 700 ^oC. W-based contacts may be ohmic as-deposited on very heavily doped n-GaN, and the specific contact resistance improves with annealing up to ~900 ^oC.

INTRODUCTION

One of the limiting factors in GaN device technology are the relatively high ohmic contact resistances. In the search for improved contact characteristics, a wide variety of metallizations have been investigated on p-GaN besides the standard Ni/Au[1-7], including Ni[4,5,8], Au[4,7,9,10], Pd[4], Pd/Au[11,12], Pt/Au[6], Au/Mg/Au[9,13], Au/C/Ni[14], Ni/Cr/Au[12,15] and Pd/Pt/Au[6]. This area has been reviewed recently by Mohney and Lau[16], and by Liu and Lau[17]. Typically Ni, Pd or Pt is the metal in direct contact with the GaN, and the structure is annealed at 400 - 750 °C. This produces contact resistances in the 10^{-1} - 10^{-3} $\Omega\cdot cm^2$ range. For higher temperatures severe degradation in contact morphology is observed, usually resulting from the formation of the metal gallides[16].

For n-type ohmic contacts, the most popular metallization schemes have been those based on Al/Ti/n-GaN, often with overlayers of Au/Ni[16,17]. It is believed that diffusion of Al to the metal/GaN interface is a critical step in forming the lowest specific contact resistance, and that TiN formation produces a high concentration of nitrogen vacancies that lead to n^+ doping level and lower R_c values[17]. We have previously reported that both W and WSi_x on n^+ epi GaN layers (n ~ 10^{19} cm^{-3}) produce reasonable contacts (R_c ~ 8×10^{-5} $\Omega\cdot cm^2$), but extremely stable behavior[18,19] - annealing at 1000 °C led to a shallow reacted region of ≤ 100 Å, and in junction field-effect transistor structures these contacts can withstand implant activation anneals at 1100 °C[20].

In this paper we report on use of ion implantation to increase the doping level in GaN, which would be of particular interest for creating n^+ or p^+ regions in device structures, and also

https://doi.org/10.1557/S1092578300003252 Published online by Cambridge University Press

on the characteristics of W and WSi_x metal contacts on both n- and p-type GaN. The thermal stability of the refractory metal contacts is superior to that of the conventional Ni/Au scheme employed for p-GaN.

EXPERIMENTAL

P-type ($N_A = 10^{18}$ cm^{-3}), Mg-doped GaN layers 1 µm thick were grown on Al_2O_3 substrates by Molecular Beam Epitaxy using solid Ga and rf plasma-activated N_2[21]. Strong cathodoluminescence was observed at ~385 nm, with very little deep level emission. Undoped GaN layers ~3 µm thick were grown on Al_2O_3 by Metal Organic Chemical Vapor Deposition. These samples were implanted with 100 keV Si^+ ions at a dose of 5×10^{15} cm^{-2}, and annealed with AlN caps in place to 1400 °C for 10 secs[22]. This produced a peak n-type doping concentration of ~5×10^{20} cm^{-3}. W or $WSi_{0.45}$ layers ~ 1000 Å thick were deposited using an MRC501 sputtering system. The sample position was biased at 90 V with respect to the Ar discharge. Prior to sputtering, the native oxide was removed in a 20:1 H_2O:NH_4OH solution. Transmission line patterns were defined by dry etching the exposed metal with SF_6/Ar, and forming mesas around the contact pads using BCl_3/N_2 dry etching to confine the current flow. For comparison, on the p-GaN, Au(1000 Å)/Ni(500 Å) was deposited by e-beam evaporation, defined by lift-off and mesas formed by dry etching. Both n- and p-type samples were annealed for 60 secs (in some experiments this was varied from 30 - 300 secs) at 300 - 1000 °C under flowing N_2.

In addition, implantation of S, Se and Te for creation of n-type doping and of Mg, Be and C for p-type doping was examined in undoped MOCVD-grown GaN. Annealing was performed up to 1500 °C, using AlN cap layers for surface protection.

RESULTS AND DISCUSSION

(a) Implantation

Secondary Ion Mass Spectrometry(SIMS) did not detect any measurable redistribution for S, Se, Te, Mg or C at 1450 °C, implying effective diffusivities of $\leq 2\times10^{-13}$ $cm^2 \cdot sec^{-1}$ for each of these dopants at this temperature. The exception was Be, which displayed an apparent damage-assisted diffusion at 900 °C, but did not move at higher annealing temperatures. It appears that in GaN, the intersitial as-implanted Be undergoes a type of transient enhanced diffusion until excess point defects created by the nuclear stopping process of the implanted ions are removed by annealing, at which stage the Be is basically immobile.

While Si^+ implantation produced n-type doping levels up to 5×10^{20} cm^{-3}, the other donors were less effective. The maximum doping achieved with S^+ implantation was ~5×10^{18} cm^{-3}, while with Te^+ it was ~1.6×10^{18} cm^{-3}.

It is difficult to create p-type doping by implantation in GaN because of the large ionization levels of acceptor species and n-type character of residual lattice damage. We did not achieve p-type conductivity by implanting C^+, while a maximum doping level of 10^{17} cm^{-3} was obtained with Mg^+ under the same conditions.

(b) Contact Properties

(i) p-GaN

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Figure 1 shows annealing temperature dependence of the I-V characteristics of the Ni/Au, W and WSi on p-GaN, with the measurements made at 25 °C in all cases. Note that for the optimum anneal temperatures (700 °C for Ni/Au and W, and 800 °C for WSi_x), the contacts are not ohmic, but are more accurately described as leaky Schottky diodes. In the case of W and WSi, we assume that annealing above the optimum temperature produces loss of N_2 and poorer contact properties.

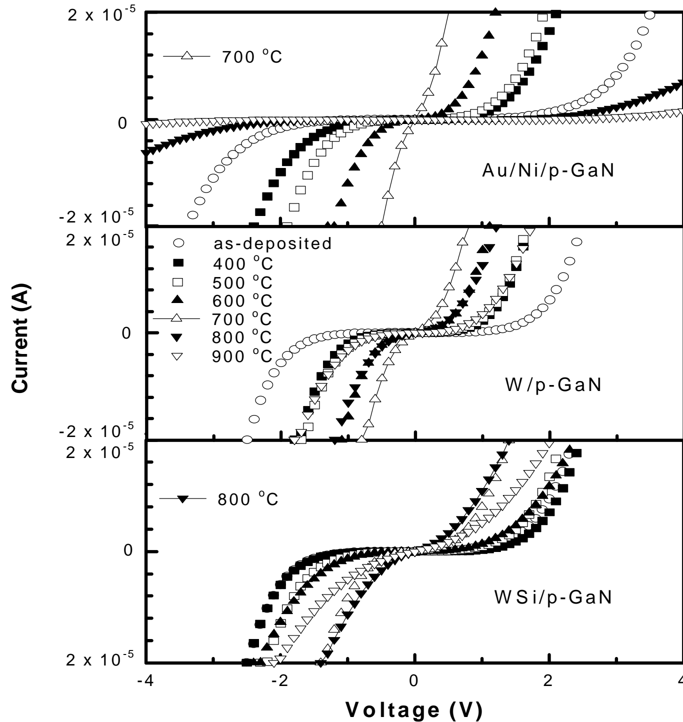

Fig. 1. Annealing temperature dependence of I-V characteristics of WSi, W and Ni/Au contacts on p-GaN(60 sec anneal times).

The contact morphology on the W and WSi metallization remained featureless to the highest temperature we investigated. This is in sharp contrast to the case of Ni/Au, as shown in Figure 2. For the latter metallization, islanding is quite severe after 700 °C annealing due to reaction of the Ni with the GaN[21-23].

Since the hole concentration in p-GaN will increase rapidly with temperature due to the higher ionization efficiency for the Mg acceptors, we would expect an improvement in contact properties at elevated temperatures. For example, from calculating the Fermi level position as a function of temperature, we find the ionization efficiency improves from ~10% at 25 °C to ~56% at 300 °C. Figure 3 shows the I-V characteristics for the 700 °C (Ni/Au and W) or 800 °C(WSi) annealed samples, as a function of the measurement temperature(25 - 300 °C). For the Ni/Au, the contacts become ohmic at ≥ 200 °C, while for W and WSi_x this occurs at 300 °C. The R_c values at 300 °C are 9.2×10^{-2} $\Omega\cdot cm^2$ (Ni/Au), 6.8×10^{-1} $\Omega\cdot cm^2$ (W) and 2.6×10^{-2} $\Omega\cdot cm^2$ (WSi). The TLM measurements showed that the substrate sheet resistance is reduced from 1.39×10^4 Ω/☐ at 200 °C, to 8470 Ω/☐at 250 °C and 4600 Ω/☐at 300 °C, indicating that the increased hole concentration plays a major role in decreasing R_c.

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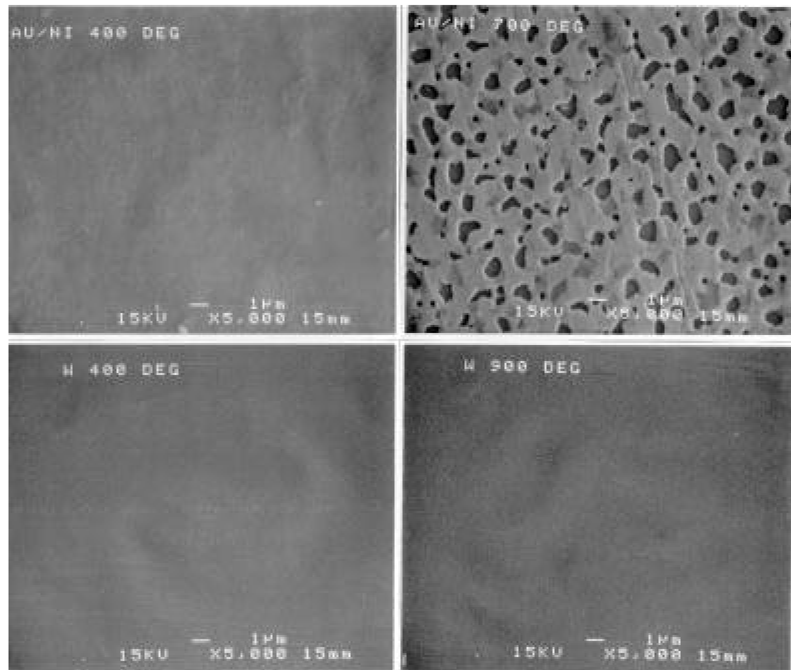

Fig. 2. SEM micrographs of Ni/Au contacts on p-GaN after 60 secs anneals at either 400 °C (top left) or 700 °C (top right), or W contacts after similar annealing at 400 °C (bottom left) or 900 °C (bottom right).

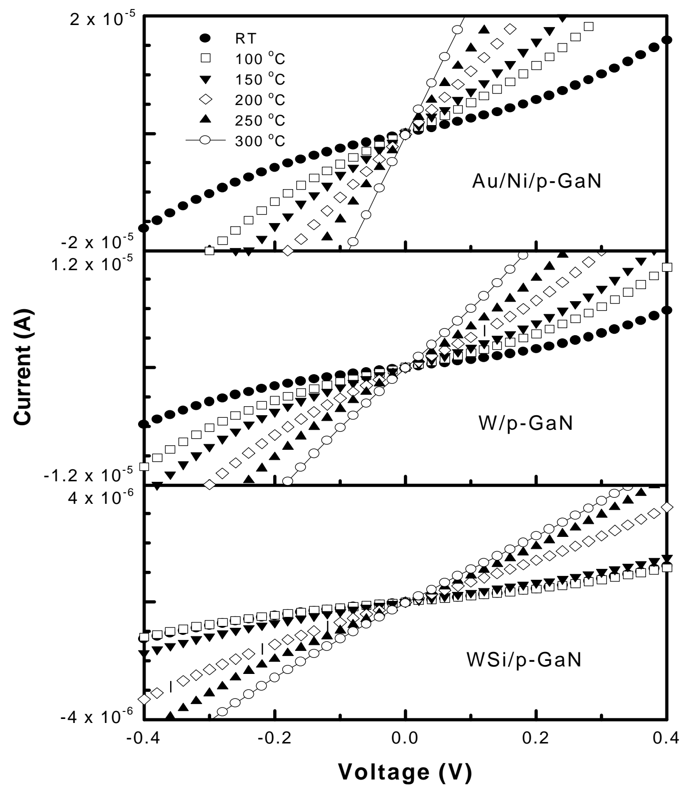

Fig. 3. Measurement temperature dependence of I-V characteristics of Ni/Au, W or WSi_x contacts on p-GaN.

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(ii) n-GaN

Figure 4 shows the annealing temperature dependence of R_c for W contacts on Si-implanted GaN. The specific contact resistance improves with annealing up to ~950 °C, which appears to correspond to the region where the β-W_2N interfacial phase is formed. Cole et al[19]. reported that W and WSi contacts on GaN annealed in the range 750-850 °C showed the minimum degree of metal protrusion in the interfacial regions devoid of the β-W_2N phase, whereas at lower annealing temperatures the horizontal spatial extent of this phase was smaller and allowed more protrusions to develop. The excellent structural stability of the W on GaN was clear from both AES and SEM data on annealed samples.

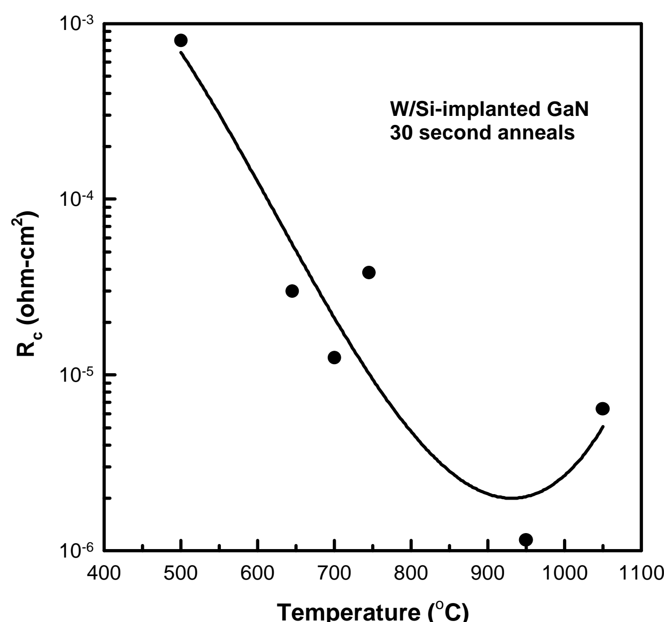

Fig. 4. Annealing temperature dependence of R_c for W contacts on Si-implanted GaN.

SUMMARY AND CONCLUSIONS

W and WSi ohmic contacts on both p- and n-type GaN have been annealed at temperatures from 300 - 1000 °C. There is minimal reaction (≤ 100 Å broadening of the metal/GaN interface) even at 1000 °C. Specific contact resistances in the 10^{-6} $\Omega \cdot cm^2$ range are obtained for W on Si-implanted GaN with a peak doping concentration of ~ 5×10^{20} cm^{-3}, after annealing at 950 °C. On p-GaN, leaky Schottky diode behavior is observed for W, WSi_x and Ni/Au contacts at room temperature, but true ohmic characteristics are obtained at 250 - 300 °C, where the specific contact resistances are typically in the 10^{-2} $\Omega \cdot cm^2$ range. The best contacts for W and WSi_x are obtained after 700 °C annealing for periods of 30 - 120 secs. The formation of β-W_2N interfacial phases appear to be important in determining the contact quality.

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ACKNOWLEDGEMENTS

The work at UF is partially supported by a DARPA/EPRI grant (D. Radack/J. Melcher) and by an NSF grant (DMR-9732865) monitored by L. D. Hess. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin company, for the US Department of Energy under contract No. DEAC04-94AL85000.

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