W AND WSi_x OHMIC CONTACTS ON p- AND n-TYPE GaN

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ABSTRACT

W and WSi_x 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^{-5} Ω-cm² range are obtained for WSi_x on Si-implanted GaN with a peak doping concentration of $\sim 5 \times 10^{20}$ 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} Ω-cm² 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-W₂N interfacial phases appear to be important in determining the contact quality.

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I. INTRODUCTION

One of the life-limiting factors in GaN laser diodes to date has been the p-ohmic contact.⁽¹⁾ Due to the relatively poor specific contact resistances(R_c) achievable, the metallization will heat-up as current flows across the p-n junction, leading to metal migration down threading dislocations and eventual shorting of the junction.⁽¹⁾ Removal of the dislocations, such as in epitaxial lateral overgrowth structures, will greatly extend the device lifetime.⁽¹⁾ There are a number of contributing factors to the high R_c values for contacts on p-GaN, including:

- (i) The absence of a metal with a sufficiently high work function (the bandgap of GaN is 3.4 eV, and the electron affinity is 4.1 eV, but metal work functions are typically ≤ 5 eV).
- (ii) The relatively low hole concentrations in p-GaN due to the deep ionization level of the Mg acceptor (~ 170 meV).
- (iii) The tendency for the preferential loss of nitrogen from the GaN surface during processing, which may produce surface conversion to n-type conductivity.

In the search for improved contact characteristics, a wide variety of metallizations have been investigated on p-GaN besides the standard Ni/Au,⁽²⁻⁷⁾ 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 Mohny 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} $\Omega\text{-cm}^2$ 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 ($n \sim 10^{19} \text{ cm}^{-3}$) produce reasonable contacts ($R_c \sim 8 \times 10^{-5} \Omega\text{-cm}^2$), but extremely stable behavior^(18,19) - annealing at 1000 °C led to a shallow reacted region of $\leq 100 \text{ \AA}$, and in junction field-effect transistor structures these contacts can withstand implant activation anneals at 1100 °C.⁽²⁰⁾

In this paper we report an investigation of W and WSi_x contacts on p-GaN, and of W on Si-implanted, n^+ GaN. The annealing temperature dependence of the current - voltage (I-V) characteristics and contact morphology have been examined over the temperature range 300 - 1000 °C.

II. EXPERIMENTAL

P-type ($N_A = 10^{18} \text{ cm}^{-3}$), 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 $\sim 385 \text{ nm}$, with very little deep level emission. Undoped GaN layers $\sim 3 \mu\text{m}$ 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 $5 \times 10^{15} \text{ cm}^{-2}$, and annealed with AlN caps in place to 1400 °C for 10 secs.⁽²²⁾ This produced a peak n-type doping concentration of $\sim 5 \times 10^{20} \text{ cm}^{-3}$. W or $WSi_{0.45}$ layers $\sim 1000 \text{ \AA}$ 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 H₂O:NH₄OH solution. Transmission line patterns were defined by dry etching the exposed metal with SF₆/Ar, and forming mesas around the contact pads using BCl₃/N₂ 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 N₂.

III. RESULTS AND DISCUSSION

A. p-GaN

From Fermi - Dirac statistics we can calculate the Fermi level position E_F for p-GaN containing 10^{18} acceptors · cm⁻³ as a function of absolute temperature T , from

$$N_A \frac{1}{1 + 2 \exp((E_a - E_F)/kT)} = N_V \exp(-(E_F - E_V)/kT)$$

where N_A is the acceptor concentration, $E_a = 171$ meV for Mg in GaN and N_V is the valence band density of states. Using this relation, we calculated the ionization efficiency for Mg as a function of sample temperature, as shown in Figure 1. Since the hole concentration in the p-GaN will increase rapidly with temperature, we would expect better ohmic contact properties.

Figure 2 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.

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 3. For the latter metallization, islanding is quite severe after 700 °C annealing due to reaction of the Ni with the GaN.⁽²³⁻²⁵⁾

From the earlier discussion, we would expect the contact properties to improve at elevated temperatures because of the increased hole density and more efficient thermionic hole emission across the metal - GaN interface. Figure 4 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. Table I shows the R_c values at 300 °C are $9.2 \times 10^{-2} \Omega\text{-cm}^2$ (Ni/Au), $6.8 \times 10^{-2} \Omega\text{-cm}^2$ (W) and $2.6 \times 10^{-2} \Omega\text{-cm}^2$ (WSi). The TLM measurements showed that the substrate sheet resistance is reduced from $1.39 \times 10^4 \Omega/\square$ at 200 °C, to 8470 $\Omega/\square$ at 250 °C and 4600 $\Omega/\square$ at 300 °C, indicating that the increased hole concentration plays a major role in decreasing R_c .

There was not a strong dependence of the room temperature I-V characteristics on annealing time. An example is shown in Figure 5 for W/p-GaN, annealed at 700 °C. There is little change in the characteristics for 30 - 120 secs, but the contacts become more rectifying for longer times.

B. n-GaN

Figure 6 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 -W₂N interfacial phase is formed. Cole et al. 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 -W₂N 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 is shown in the SEM micrographs of Figure 7, where a sharp interface is retained after 750 °C annealing.

IV. SUMMARY AND CONCLUSIONS

One of the emerging applications for GaN is in ultra-high power electronic switches, where thermal stability of the contact metallization will be of paramount importance. Tungsten-based contacts on both n- and p-type GaN offer superior thermal stability to the standard metalization used in photonic devices, Ti/Al and Ni/Au, respectively.

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References

1. See for example, S. Nakamura, in GaN and Related Materials II, ed. S. J. Pearton (Gordon and Breach, NY 1998).
2. S. Nakamura, T. Mukai and M. Senoh, Appl. Phys. Lett. 64 1687 (1994).
3. M. Schauler, C. Kirchner, M. Mayer, A. Pelzmann, F. Eberhard, M. Kamp, P. Unger and K. J. Ebeling, MRS Internet J. Nitride Semicond. Res. 2 44 (1997).
4. H. Ishikawa, S. Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike and M. Murakami, J. Appl. Phys. 81 1315 (1997).
5. K. V. Vassilevski, M. G. Rastegaeva, A. I. Babanin, I. P. Nikitina and V. A. Dmitriev, MRS Internet J. Nitride Semicond. Res. 1 38 (1996).
6. D. J. King, L. Zhang, J. C. Ramer, S. D. Hersee and L. F. Lester, Mat. Res. Soc. Symp. Proc. 468 421 (1997).
7. L. F. Lester, D. J. King, L. Zhang, J. C. Ramer, S. D. Hersee and J. C. Zolper, Mat. Res. Soc. Symp. Proc. 97-1 171 (1997).
8. I. Akasaki, H. Amano, S. Sota, H. Sakai, T. Tanaka and M. Koike, Jap. J. Appl. Phys. 34 L1517 (1995).
9. L. L. Smith, R. F. Davis, M. J. Kim, R. W. Carpenter and Y. Huang, J. Mater. Res. 12 2249 (1997).
10. T. Mori, T. Kozawa, T. Ohwaki, Y. Taga, S. Nagai, S. Yamasaki, S. Asami, N. Shibata and M. Koike, Appl. Phys. Lett. 69 3537 (1996).
11. T. Kim, J. Khim, S. Chae and T. Kim, Mat. Res. Soc. Symp. Proc. 468 427 (1997).
12. J. T. Trexler, S. J. Pearton, P. H. Holloway, H. G. Mier, K. R. Evans and R. F. Karlicek, Mat. Res. Soc. Symp. Proc. 449 1091 (1997).
13. L. L. Smith, M. D. Bremser, E. P. Carlson, T. W. Weeks, Jr., Y. Huang, M. J. Kim, R. W. Carpenter and R. F. Davis, Mat. Res. Soc. Symp. Proc. 395 861 (1996).

14. J. T. Trexler, S. J. Miller, P. H. Holloway and M. A. Khan, Mat. Res. Soc. Symp. Proc. 395 819 (1996).
15. T. Kim, M. C. Yoo and T. Kim, Mat. Res. Soc. Symp. Proc. 449 1061 (1997).
16. S. E. Mohny and S. S. Lau, in GaN and Related Materials II, ed. S. J. Pearton (Gordon and Breach, NY 1998).
17. Q. Z. Liu and S. S. Lau, Solid -State Electron. (in press).
18. M. W. Cole, F. Ren and S. J. Pearton, J. Electron. Soc. 144 L275 (1997); Appl. Phys. Lett. 71 3004 (1997).
19. M. W. Cole, D. W. Eckart, W. Y. Han, R. L. Pfeffer, and T. Monahan, F. Ren, C. Yuan and R. A. Stall, S. J. Pearton, Y. Li and Y. Lu, J. App. Phys. 80 278 (1996).
20. J. C. Zolper and R. J. Shul, MRS Bulletin 22 36 (1997).
21. J. M. Van Hove, P. P. Chow, J. J. Klaasen, R. Hickman, A. M. Wowchak, D. R. Croswell and C. Polley, Mat. Res. Soc. Symp. Proc. 468 51 (1997).
22. J. C. Zolper, R. J. Shul, A. G. Baca, R. G. Wilson, S. J. Pearton and R. A. Stall, Appl. Phys. Lett. 68 2273 (1996).
23. H. S. Venugopalan, S. E. Mohny, B. P. Luther, J. M. DeLucca, S. D. Wolter, J. M. Redwing and G. E. Bulman, Mat. Res. Soc. Symp. Proc. 468 431 (1997).
24. V. M. Bermudez, R. Kaplan, M. A. Khan and J. N. Kuznia, Phys. Rev. B 48 2436 (1993).
25. S. E. Mohony, B. P. Luther and T. N. Jackson, Mat. Res. Soc. Symp. Proc. 395 843 (1996).

Figure Captions

Figure 1. Ionization efficiency of Mg acceptors in GaN, and Fermi level position for GaN containing 10^{18} cm^{-3} Mg acceptors, as a function of temperature.

Figure 2. Annealing temperature dependence of I-V characteristics of WSi, W and Ni/Au contacts on p-GaN(60 sec anneal times).

Figure 3. 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).

Figure 4. Measurement temperature dependence of I-V characteristics of Ni/Au, W or WSi_x contacts on p-GaN.

Figure 5. Annealing time dependence at 700 °C of I-V characteristics from W contacts on p-GaN.

Figure 6. Annealing temperature dependence of R_c for W contacts on Si-implanted GaN.

Figure 7. SEM micrographs of W contacts on Si-implanted GaN after annealing at 750 °C.

Table I. Temperature-dependent contact data for p-GaN.

Contact	Measurement temperature (°C)	Specific contact resistance ($\Omega\text{-cm}^2$)	Contact resistivity ($\Omega\text{-mm}$)
Ni/Au	200	0.125	415.7
Ni/Au	250	0.121	319.5
Ni/Au	300	0.092	205.9
W	300	0.682	758.4
WSi	300	0.026	1728.3