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W, WSi_x AND Ti/Al LOW RESISTANCE OHMIC CONTACTS TO InGaN, InN AND InAlN

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C.B. Vartuli*, S.J. Pearton*, C.R. Abernathy*, J.D. MacKenzie*, R.J. Shul**, J.C. Zolper**, M.L. Lovejoy**, A.G. Baca** and M. Hagerott-Crawford**
*Department of Materials Science and Engineering University of Florida, Gainesville FL 32611
**Sandia National Laboratories, Albuquerque NM 87185-0603

ABSTRACT

W, $WSi_{0.44}$ and Ti/Al contacts were examined on n^+ $In_{0.65}Ga_{0.35}N$, InN and $In_{0.75}Al_{0.25}N$. W was found to produce low specific contact resistance ($\varrho_c \sim 10^{-7}\ \Omega \cdot cm^2$) ohmic contacts to InGaN, with significant reaction between metal and semiconductor at 900 °C mainly due to out diffusion of In and N. WSi_x showed an as-deposited ϱ_c of $4x10^{-7}\ \Omega \cdot cm^2$ but this degraded significantly with subsequent annealing. Ti/Al contacts were stable to ~ 600 °C ($\varrho_c \sim 4x10^{-7}\ \Omega \cdot cm^2$ at ≤600 °C). The surfaces of these contacts remain smooth to 800 °C for W and WSi_x and 650 °C for Ti/Al. InN contacted with W and Ti/Al produced ohmic contacts with $\varrho_c \sim 10^{-7}\ \Omega \cdot cm^2$ and for WSi_x $\varrho_c \sim 10^{-6}\ \Omega \cdot cm^2$. All remained smooth to ~ 600 °C, but exhibited significant interdiffusion of In, N, W and Ti respectively at higher temperatures. The contact resistances for all three metalization schemes were $\geq 10^{-4}\ \Omega \cdot cm^2$ on InAlN, and degrades with subsequent annealing. The Ti/Al was found to react with the InAlN above 400 °C, causing the contact resistance to increase rapidly. W and WSi_x proved to be more stable with $\varrho_c \sim 10^{-2}$ and $10^{-3}\ \Omega \cdot cm^2$ up to 650 °C and 700 °C respectively.

INTRODUCTION

Recently much progress been made in the processing of the III-V nitrides and their ternary alloys, resulting in nitride-based blue/UV light emitting and electronic devices.[1-8] The III-nitrides pose a problem however in the development of low resistance ohmic contacts because of their wide bandgaps. Most of the work done in this area has been focused on n-type GaN. Au and Al single metal contacts to n^+ GaN and non- alloyed Au/Ti and Al/Ti were found to have contact resistances of ~ 10^{-3} to $10^{-4}\ \Omega \cdot cm^2$.[9-13] Lin et. al.[14] reported the lowest contact resistance to n^+ GaN, with Ti/Al contacts after annealing at 900 °C for 30 sec in a rapid thermal annealer ($\varrho_c = 8x10^{-6}\ \Omega \cdot cm^2$). They suggested the formation of a TiN interface as important in the formation of the low resistance contact. W was found to produce low resistance ohmic contacts to n^+ GaN ($\varrho_c \sim 10^{-4}\ \Omega \cdot cm^2$) with little interaction between the semiconductor and the metal up to 800 °C[15]. WSi_x on n^+ GaN was found to be stable to 800 °C as well, with a contact resistance of ~$10^{-5}\ \Omega \cdot cm^2$.[16] Graded contact layers to GaN have been formed with both InN [17] and InGaN with WSi_x.[16] Ohmic contacts to InN have also been investigated, with non-alloyed Ti/Pt/Au producing specific contact resistance $\varrho_c = 1.8x10^{-7}\ \Omega \cdot cm^2$.[19] Graded

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DISCLAIMER

$In_xGa_{1-x}As/InN$ contacts have also been used on GaAs/AlGaAs heterojunction bipolar transistors, with ϱ_c as low as $5\times10^{-7}\ \Omega\cdot cm^2$.[20] Ohmic contacts to the nitrides have been reviewed previously by Smith and Davis.[21]

For high temperature electronics applications, or for high reliability, we would like to employ refractory metal contacts such as W and WSi_x. Moreover, the contact resistance could be reduced if lower bandgap In-containing alloys (or InN) were used as contact layers on GaN, much as the case with InGaAs on GaAs. However the In-based nitrides are less thermally stable than GaN, and we need to establish the trade off between better contact resistance and poorer temperature stability.

In this paper we report the results of W, $WSi_{0.44}$ and Ti/Al contacts deposited on n^+ $In_{0.65}Ga_{0.35}N$, n^+ InN and n^- $In_{0.75}Al_{0.25}N$. The electrical, structural and chemical stability of these contacts were examined after anneals up to 900 °C, using Transmission Line Method (TLM) measurements, Scanning Electron Microscopy (SEM) and Auger Electron Spectroscopy (AES). We find that InGaN allows achievement of excellent contact resistances, with stability up to ~ 600 °C for W metalization.

EXPERIMENTAL

The InGaN, InN and InAlN samples were grown using Metal Organic Molecular Beam Epitaxy (MO-MBE) on semi-insulating, (100) GaAs substrates in an Intevac Gen II system as described previously.[22,23] The group-III sources were triethylgallium, trimethylamine alane and trimethylindium, respectively, and the atomic nitrogen was derived from an ECR Wavemat source operating at 200 W forward power. The layers were single crystal with a high density (10^{11} - 10^{12} cm^{-2}) of stacking faults and microtwins. The InAlN and InGaN were found to contain both hexagonal and cubic forms. The InN, $In_{0.65}Ga_{0.35}N$ and $In_{0.75}Al_{0.25}N$ were highly autodoped n-type (~10^{20} cm^{-3}, ~ 10^{19} cm^{-3} and 8×10^{18} cm^{-3} respectively) due to the presence of native defects.

The samples were rinsed in $H_2O:NH_4OH$ (20:1) for 1 min just prior to deposition of the metal to remove native oxides. The metal contacts were sputter deposited to a thickness of 1000Å in the case of W and $WSi_{0.44}$, and then etched in SF_6/Ar in a Plasma Therm reactive ion etcher (RIE) to create TLM patterns. For the Ti/Al contacts, 200Å of Ti and then 1000Å of Al was deposited, and the TLM pattern formed by lift off. The nitride samples were subsequently etched in $Cl_2/CH_4/H_2/Ar$ in an Electron Cyclotron Resonance (ECR) etcher to produce the mesas for the TLM patterns.[24] The samples were annealed at temperatures from 300 to 900 °C for 15 sec under a nitrogen ambient in a RTA system (AG-410). TLM measurements were performed at room temperature, and the results used to calculate the specific contact resistances. SEM was used to examine the surface morphology of the contact both before and after annealing, and AES depth profiles were acquired for selected samples to determine the amount of interdiffusion during annealing.

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RESULTS AND DISCUSSION

The contact resistance for W, WSi_x and Ti/Al ohmic contacts to InGaN as a function of annealing temperature is shown in Figure 1. All contacts had similar contact resistance as deposited, ~ $2\text{-}4\times10^{-7}\ \Omega\cdot cm^2$. After a 600 °C anneal, the W contact improved slightly, while the Ti/Al contact was stable, and the WSi_x contact resistance increased by an order of magnitude. Above 600 °C, the Ti/Al contacts degraded rapidly, and the WSi_x continued to degrade, while ϱ_c for both samples increased up to ~ $10^{-5}\ \Omega\cdot cm^2$ at 900 °C. The W contact resistance increased to the as deposited value at 700 °C, but dropped steadily as the temperature increased. The error in these measurements was estimated to be ±10 % due mainly to placement of the probes. The widths of the TLM pattern spacings varied slightly due to processing, (maximum of ± 5 %) as determined by SEM measurements, which were taken into account when calculating the contact resistances. These results show that W is an attractive choice for low resistance stable contacts on InGaN. The surfaces of the as deposited contact metals were relatively smooth. The W was still quite smooth even after 900°C anneal, while the Ti/Al had significant pitting at the lowest anneal of 500 °C even though the contact resistance did not degrade until ≥ 600 °C.

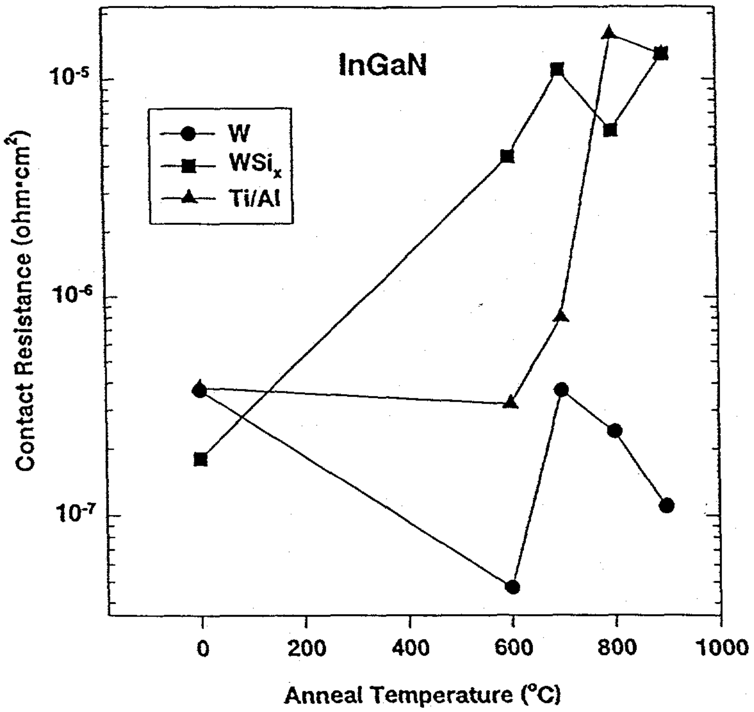

Figure 1. Contact resistance for W, $WSi_{0.44}$ and Ti/Al ohmic contacts to InGaN as a function of annealing temperature.

In Fig. 2 AES depth profiles of InGaN contacted with W before and after a 900 °C anneal are shown. As-deposited samples show some diffusion of W into the sample. After annealing however there was a large out diffusion of In and N. The In has only diffused about 500 Å into the W, showing a sharp peak in concentration at that point. Though much smaller amounts of N have diffused out, it also had a peak in concentration at that

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point. The Ga remained stable, consistent with results that found GaN to be stable with W to high temperatures.[15] There is not significant diffusion of W after annealing emphasizing the excellent thermal stability of these contacts.

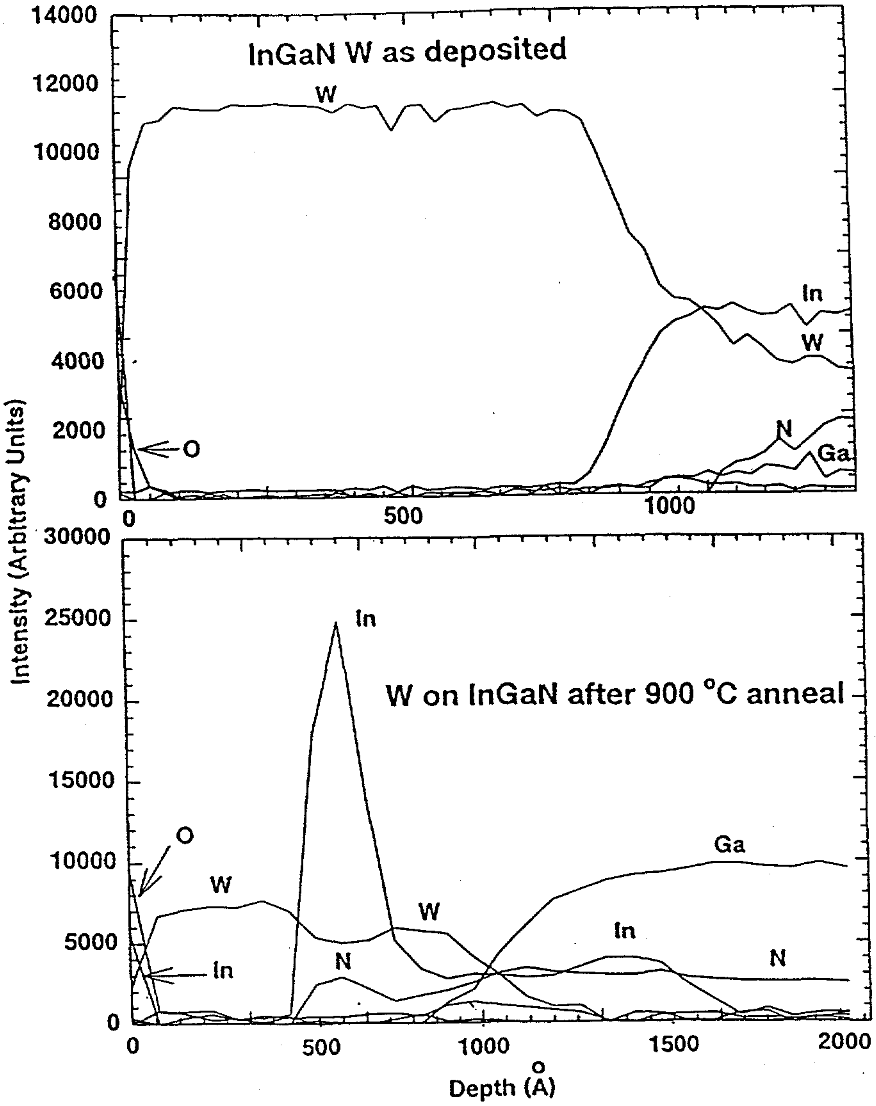

Figure 2. AES depth profiles of InGaN contacted with W before (top) and after a 900 °C anneal (bottom).

The contact resistance for ohmic contacts of W, WSi_x and Ti/Al to InN as a function of annealing temperature is shown in Fig. 3. Because of the lower thermal stability of InN, these contacts were annealed between 300 °C and 500 °C. As deposited samples again had similar contact resistances, ~ $2x10^{-7}\ \Omega \cdot cm^2$. WSi_x contacts showed the most degradation at low temperature, with the resistance rising a factor of 5 after 300 °C annealing and then remaining constant. Ti/Al deviated little from initial values, although there was severe pitting on samples annealed at 500 °C while W resistance began to degrade at 500 °C.

In Fig. 4 the contact resistance is shown for W, WSi_x and Ti/Al ohmic contacts to InAlN as a function of annealing temperature. As-deposited Ti/Al had the lowest contact resistance on this material, ρ_c ~$1x10^{-4}\ \Omega \cdot cm^2$. The contact resistance rose to ~ $2x10^{-2}\ \Omega \cdot cm^2$ after a 500 °C anneal, and continued rising with annealing temperature. WSi_x was

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stable at 500 °C at ~ $1\times10^{-3}\ \Omega\cdot\mathrm{cm}^2$, but degraded rapidly above that. W had the highest initial contact resistance, ($\varrho_c \sim 1\times10^{-2}\ \Omega\cdot\mathrm{cm}^2$) but the resistance remained relatively constant until the 900 °C anneal where it began rising. The W on InAlN remained smooth until 800 °C, and then begins to form hillocks, as did the WSi_x contact at 700 °C. The Ti/Al began pitting at 400 °C. As will be seen in subsequent figures, the pitting in the

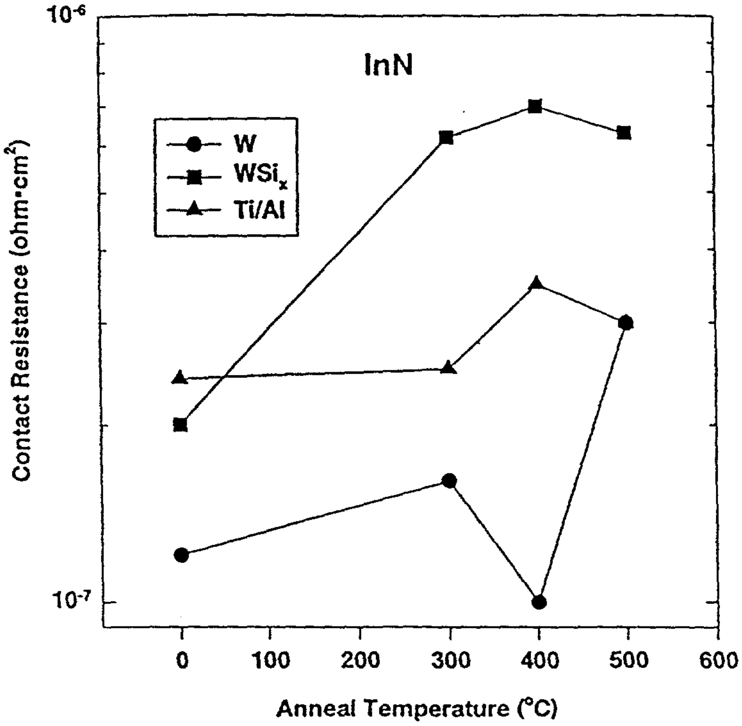

Figure 3. Contact resistance for ohmic contacts of W, WSi_x and Ti/Al to InN as a function of annealing temperature.

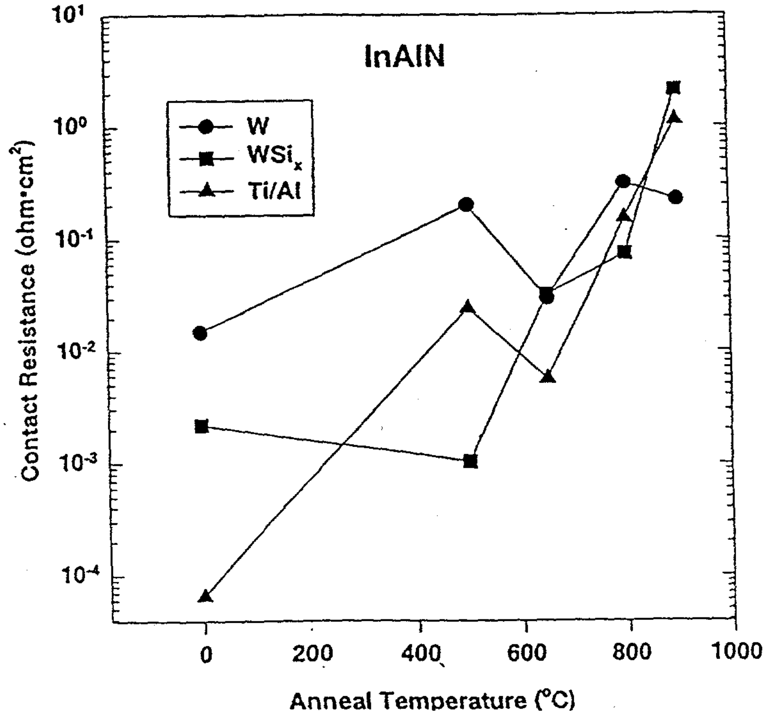

Figure 4. Contact resistance for W, WSi_x and Ti/Al ohmic contacts to InAlN as a function of annealing temperature.

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Ti/Al contacts was due to diffusion of the Al through the Ti into the sample. Hillocks appear to be formed from diffusion of In from the nitride sample into the contact layer.

AES depth profiles of Ti/Al contact on InAlN as-grown and after a 550 °C and 900 °C anneal are shown in Fig. 5. In the as grown, a small out diffusion of In through the Ti/Al contact and onto the surface was detected. The interfaces were still well defined. After anneal the In had diffused out significantly, with a peak in concentration again at about 500 Å from the surface. N and Al also diffused to a large extent and were lost from the surface, though it is not clear to what extent the Al diffused from the contact or the nitride sample. Ti was redistributed as well, both into the nitride sample and into the Al contact. After the 900 °C anneal the Ti has diffused throughout the sample. The In and N have migrated completely through the contact layer, and a large amount of Al has been lost from the surface.

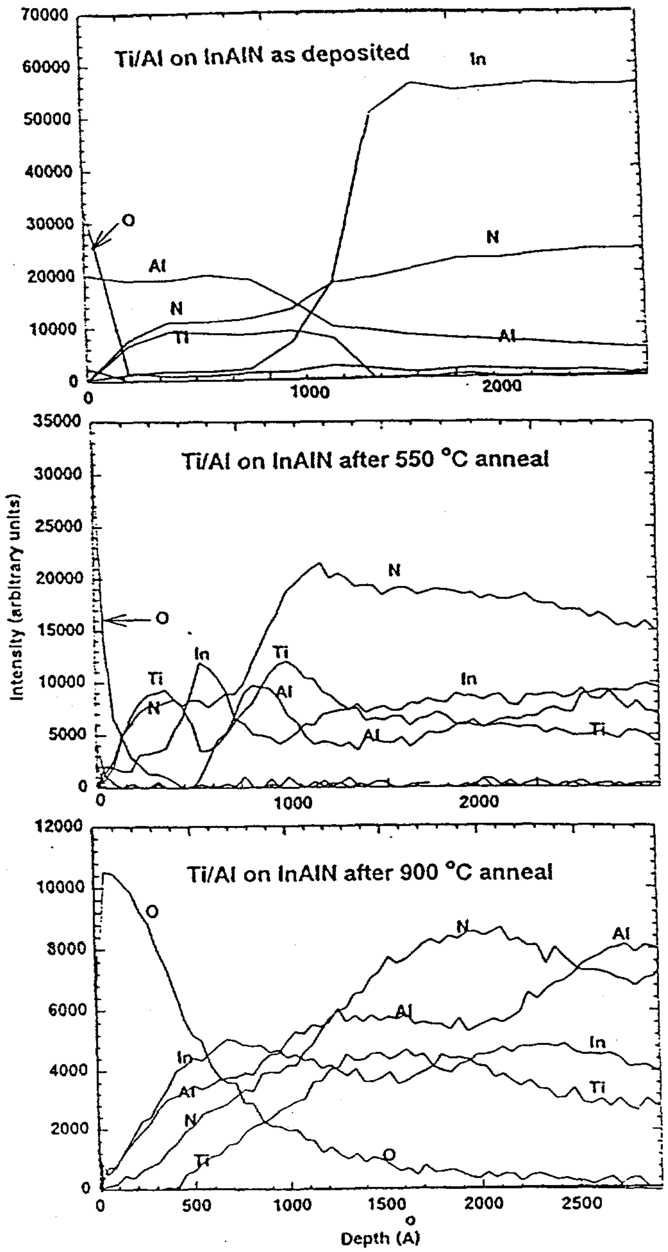

Figure 5. AES depth profile of Ti/Al contact on InAlN before (top) and after a 550 °C (middle) and 900 °C anneal (bottom).

Figure 6 shows AES depth profiles of InAlN contacted with WSi_x, as-grown and after 550 °C anneal. As-deposited, the interface was about 200 Å wide, with minimal interdiffusion of all components. After anneal W and Si were found throughout the nitride sample, with the N reaching approximately 500 Å in the contact layer, and In diffused into the contact layer with a peak concentration approximately 500 Å from the surface.

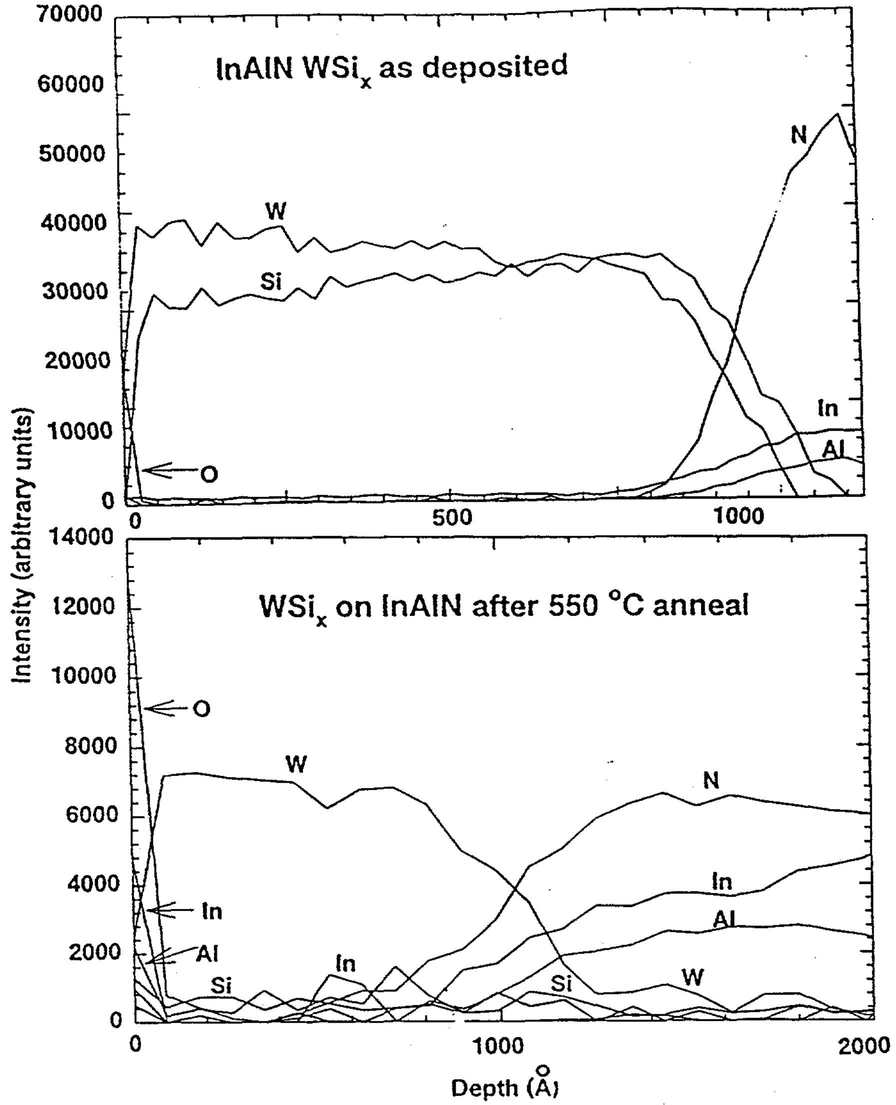

Figure 6. AES depth profiles of InAlN contacted with WSi_x before (top) and after a 900 °C anneal (bottom).

CONCLUSION\

W, WSi_x and Ti/Al were found to produce low resistance ohmic contacts on n^+ InGaN and InN. W contacts proved to be the most stable, and also gave the lowest resistance to InGaN and InN, $\varrho_c < 10^{-7}\ \Omega\cdot\text{cm}^2$ after 600 °C anneal, and $1\times10^{-7}\ \Omega\cdot\text{cm}^2$ after 300 °C anneal, respectively. Significant diffusion of In, N and Al, as well as Ti and W were found after anneal. The contact resistance stability varies for each material and degraded at temperatures > 400 °C on InN, ≥ 500 °C on InAlN and ≥ 600 °C on InGaN. W contacts remained smooth at the highest anneal temperatures. We are currently measuring the conduction mechanism in these contact structures in order to further elucidate their properties.

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REFERENCES

1. S. Nakamura, M. Senoh, and T. Mukai, Jpn. J. Appl. Phys. **30**, L1708 (1991).

2. S.C. Binari, L.B. Rowland, W. Kruppa, G. Kelner, K. Doverspike, and D.K. Gaskill, Electron. Lett. **30**, 1248 (1994).

3. M.A. Khan, M.S. Shur, and Q. Chen, Electron. Lett. **31**, 2130 (1995).

4. M.A. Khan, J.N. Kuznia, A.R. Bhattarai, and D.T. Olson, Appl. Phys. Lett. **62**, 1248 (1993).

5. S. Nakamura, M. Senoh, and T. Mukai, Appl. Phys. Lett. **62** 2390 (1993).

6. I. Akasaki, H. Amano, M. Kito, and K. Kiramatsu, J. Lumin. **48/49**, 666 (1991).

7. S. Nakamura, M. Senoh, N. Iwasa, and S. Nagahama, Appl. Phys. Lett. **67**, 1868 (1995).

8. J.C. Zolper, A.G. Baca, R.J. Shul, R.G. Wilson, S.J. Pearton and R.A. Stall, Appl. Phys. Lett. **68**, 166 (1996).

9. J.S. Forsei and T.D. Moustakas, Appl. Phys. Lett. **62** 2859 (1993).

10. M.A. Khan, T.N. Kuznia, A.R. Bhattaraia and D.T. Olson, Appl. Phys. Lett. **62** 1786 (1993).

11. S. Nakamura, T. Mukai and M. Senoh, Jpn. J. Appl. Phys. **30** L1998 (1991).

12. S.C. Binari, L.B. Rowland, W. Kruppa, G. Kelner, K. Doverspike and D.K Gaskill, Electron. Lett. **30** 1248 (1994).

13. S. Nakamura, M. Senoh and T. Mukai, Appl. Phys. Lett. **62** 2390 (1993).

14. M.E. Lin, Z. Ma, F.Y. Huang, Z.F. Fan, L.A. Allen and H. Morkoe, Appl. Phys. Lett. **64** 1003 (1994).

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15. M.W. Cole, D.W. Eckart, T. Monahan, R.L. Pfeffer, W.Y. Han, F. Ren, C.Yuan, R.A. Stall, S.J. Pearton, Y. Li and Y. Lu, J. Appl. Phys. (in press).

16 A. Durbha, "Study of Ohmic Contacts on Gallium Nitride Thin Films" Master thesis.

17. M.E. Lin, F.Y. Huang and . Morkoc, Appl. Phys. Lett. 64 2557 (1994).

18. F. Ren, C.R. Abernathy, S.N.G. Chu, J.R. Lothian and S.J. Pearton, Appl. Phys. Lett. 66 1503 (1995).

19. F. Ren, C.R. Abernathy, S.J. Pearton and P.W. Wisk, Appl. Phys. Lett. 64 1508 (1994).

20. F. Ren, C.R. Abernathy, S.N.G. Chu, J.R. Lothian and S.J. Pearton, Appl. Phys. Lett 66 1503 (1995).

21. L.L. Smith and R.F. Davis, in Properties of Group III Nitrides, ed. J.H. Edgar, EMIS Datareview (INSPEC, London 1994).

22. C.R. Abernathy, J. Vac. Sci. Technol. A 11 869 (1993).

23. C.R. Abernathy, Mat. Sci. Eng. Rep. 14, 203 (1995).

24. R.J. Shul, S.P. Kilcoyne, M. Hagerott-Crawford, J.E. Parmeter, C.B. Vartuli, C.R. Abernathy and S.J. Pearton, Appl. Phys. Lett. 66 1761 (1995).

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