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HIGH TEMPERATURE STABLE W AND WSi_X OHMIC CONTACTS ON GaN AND InGaN

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ABSTRACT

Conventional III-V metallization schemes such as Au/Ge/Ni, Ti/Pt/Au and Au/Be were found to display poor thermal stability on both GaN and InGaN, with extensive reaction and contact degradation at ≤500°C. By contrast. W was found to produce low contact resistance ($\rho_C \sim 8x10^{-5} \Omega cm^2$) contacts to n^+GaN. Ga outdiffusion to the surface of thin (500Å) W films was found after annealing at 1,100°C. but not at 1000°C. Interfacial abruptness increased by ~300Å after 1,100°C annealing. In the case of WSi_X (x=0.45), Ga outdiffusion was absent even at 1,100°C, but again there was interfacial broadening and some phase changes in the WSi_X. On $In_{0.5}Ga_{0.5}N$ a minimum specific contact resistivity of $1.5x10^{-5}\Omega cm^2$ was obtained for WSi_X annealed at 700°C. These contacts retained a smooth morphology and abrupt interfaces to 800°C. Graded $In_XGa_{1-X}N$ layers have been employed on GaAs/AlGaAs HBTs, replacing conventional $In_XGa_{1-X}As$ layers. R_C values of $5x10^{-7}\Omega cm^2$ were obtained for non-alloyed Ti/Pt/Au on the InGaN, and the morphologies were superior to those of InGaAs contact layers. This proves to have significant advantages for fabrication of sub-micron HBTs. Devices with emitter dimensions of $2x5\mu m^2$ displayed gains of 35 for a base doping level of $7x10^{19}cm^{-3}$ and stable long-term behavior.

INTRODUCTION

Owing to their large band gaps and high dielectric constants, III-V nitrides are very attractive for high temperature electronics and blue and UV optoelectronic device applications. Improved material properties have recently led to a variety of devices being demonstrated.(1) Blue light-emitting devices (LED's)(2,3) and metal-semiconductor field-effect transistors (MESFET's) have been successfully fabricated.(4) However, forming low resistance, thermally stable and uniform ohmic contacts to a wide band gap semiconductor, such as GaN with a band gap about 3.4 eV, constitutes a major obstacle to the furtherment of nitride based devices. These devices provide

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high efficiency and acceptable reliability only if their contacts are stable and have low resistance ohmic characteristics.

In an earlier attempt to achieve ohmic contacts on GaN epilayers, Foresi et al.[5] used Al and Au contacts with 575°C anneal cycle. However, the specific contact resistivity of these contacts was relatively poor ($10^{-3}\Omega cm^2$). Khan et al.[3] used Ti/Au to contact n-type GaN and measured a contact resistance of $7.8x10^{-4}$ Ωcm^2 after annealing at 250°C for 30s. Nakamura et al.[2] have used Au (and later Au/Ni and Al) as p and n-type contacts respectively in their LED structures. While the contact resistances were not reported in their LED structures, an operating voltage of 4V and 20mA forward bias is clear evidence that reasonable contact resistances were obtained. Recently Lin et al.[6] have obtained extremely good ohmic contacts on n-type GaN layers grown on sapphire substrates. Using Ti/Al metallization scheme they were able to obtain specific contact resistivities as low as $8x10^{-6}\Omega cm^2$ after annealing at 900°C for 30s. Lin et al.[7] also demonstrated a novel ohmic contact scheme to GaN using an InN/GaN short-period superlattice (SPS) and an InN cap layer. Ohmic contact resistivities as low as $6x10^{-5}\Omega cm^2$ were achieved even without any post-annealing.

An ohmic contact study of five standard metallization schemes in III-V technology: Ti/Pt/Au, Au/Ge/Ni, W, WSi_X and AuBe/Au, has been undertaken in this work, Also we investigated a novel scheme which had an InGaN layer on top of GaN. The InGaN has a lower bandgap than GaN and should produce lower contact resistance. Ultimately we would like to use such a scheme for improved contact properties on devices, much as InAs is used on GaAs. WSi_X was used for metallization to the InGaN layer. Electrical characterization of the contacts was done using standard transmission line measurements (TLM) and materials characterization included Scanning Electron Microscope (SEM) and Auger electron Spectroscopy (AES).

EXPERIMENTAL

The nominally undoped GaN and $In_{0.5}Ga_{0.5}N$ was grown on GaAs at 800°C using $(CH_3)_3Ga$ and an Electron Cyclotron Resonance plasma generated N_2 flux in a Metal Organic Molecular Beam Epitaxy system.[8] The samples predominantly consisted of the cubic phase, with typical x-ray FWHM of 300-500arc·sec. The n-type doping level in the ternary was $\sim10^{19}cm^{-3}$, while the GaN was typically $\leq10^{17}cm^{-3}$ due to the presence of native shallow donors. At this point it has been impossible to grow p-type InGaN at InN mole fractions above 0.07.

Five different metallization schemes common in III-V technology were investigated, i.e. Ti/Pt/Au, Au/Ge/Ni, AuBe, W and WSi_X. The purpose of this was to establish their relative thermal stabilities on GaN. Once this was established, we wanted to use the most stable on InGaN, which as mentioned earlier is our intended final structure for device applications. The contact metals were deposited using two techniques, namely, electron beam evaporation for the first three and sputtering for the latter two. The contact metal was deposited onto square openings (100 x $100\mu m^2$) linearly spaced (with intervals of 2 to 16µm) in a photoresist layer. Subsequently, InGaN mesas were etched to give the required one-dimensional current flow.

RESULTS AND DISCUSSION

The Au/Ge/Ni sample showed a smooth, stable morphology to 500°C (Figure 1, left), but, above this temperature there was severe reaction with the GaN forming many small pits at 700°C (Figure 1, right). Similar results were obtained for Ti/Pt/Au, where at 700°C the metal had formed isolated islands. The stability of Au/Be was even poorer, with extensive reaction already at 400°C, so we did not pursue this metallization scheme further.

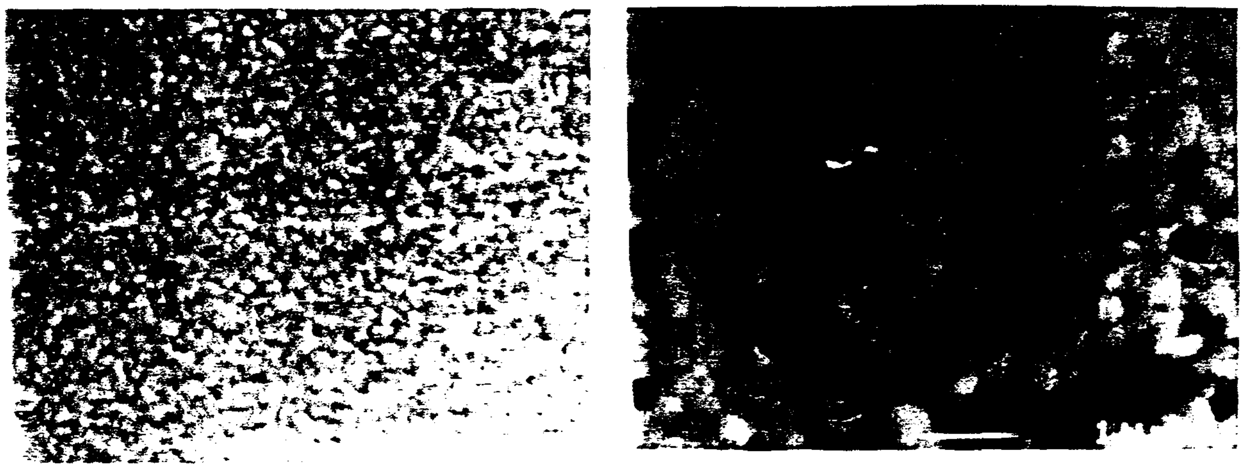

Figure 1. Surface morphology of Au/Ge/Ni/GaN contacts (magnification x10,000), after annealing at 500°C (left) or 700°C (right).

WSi_X/GaN structures (x~0.45) suppressed outdiffusion of the Ga, and it could not be detected on the surface even after annealing at 1,100°C for 15 secs. These was little interfacial broadening, but the W and Si began to form new phases at this temperature (Figure 4). Both W and WSi_X contacts showed smooth morphology at 1100°C.

The inference drawn from the analysis of the SEM and AES results of the different metallization schemes was that the WSi_X contact was more thermally stable compared to the other schemes and hence this metallization scheme was employed on $In_{0.5}Ga_{0.5}N$ to study lower band gap contacts.. The samples were annealed in the temperature range of 400-900°C.

The specific contact resistivity (ρ_c) is calculated from a measurement of the effective contact resistance (R_c), the contact width (W) and the transfer length (L_T):

$$\rho_c = R_c W L_T$$

The specific contact resistance dropped from $5.95\times10^{-5}\,\Omega cm^2$ on the as-deposited sample to $3.92\times10^{-5}\,\Omega cm^2$ after annealing at 400°C, and reached a minimum value of $1.48\times10^{-5}\,\Omega cm^2$ after annealing at 700°C (Figure 5) The trends are similar to those of WSi_X on InGaAs.[(10)]

By contrast, the W was essentially stable to ~1,000°C. At 1,100°C, Ga had diffused out through the grain boundaries in the W, and was detectable by AES on the surface (Figure 2). The interfacial reaction region was broadened by ~300Å by this annealing (Figure 3). X-ray diffraction measurements showed formation of a β-W_2N phase at ≥1,100°C.[(9)]

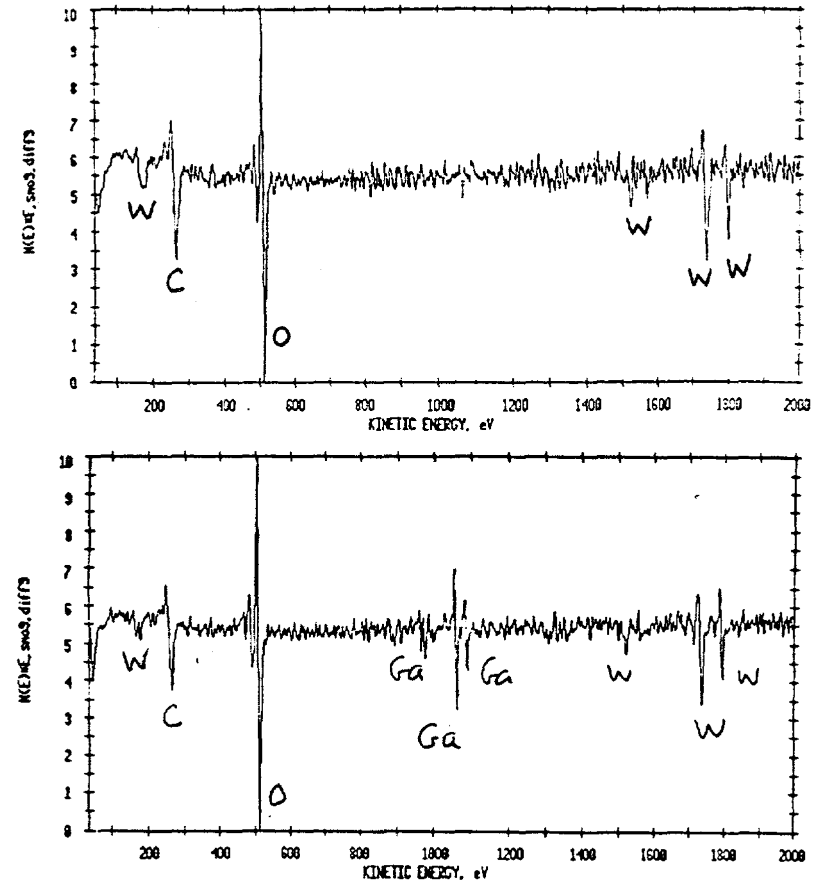

Figure 2. AES surface profiles of 500Å thick W on GaN before (left) and after (right) annealing at 1,100°C.

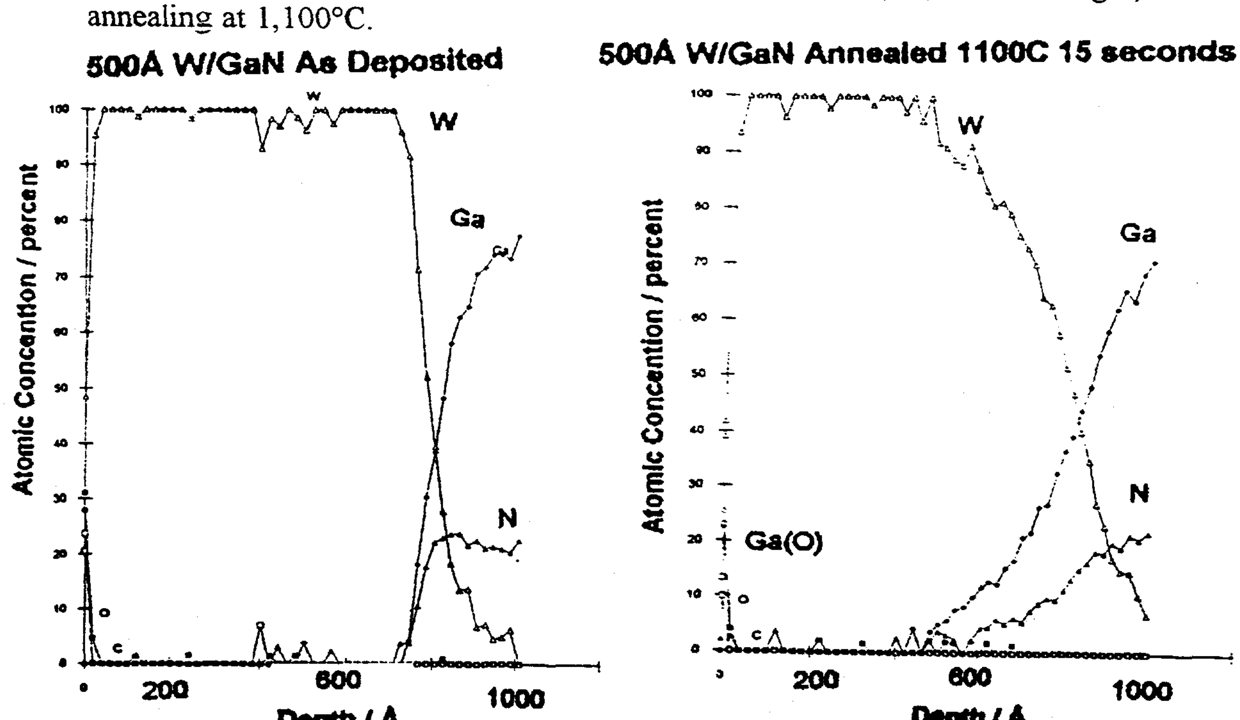

Figure 3. AES depth profiles of 500Å thick W on GaN before (left) and after (right) annealing at 1,100°C.

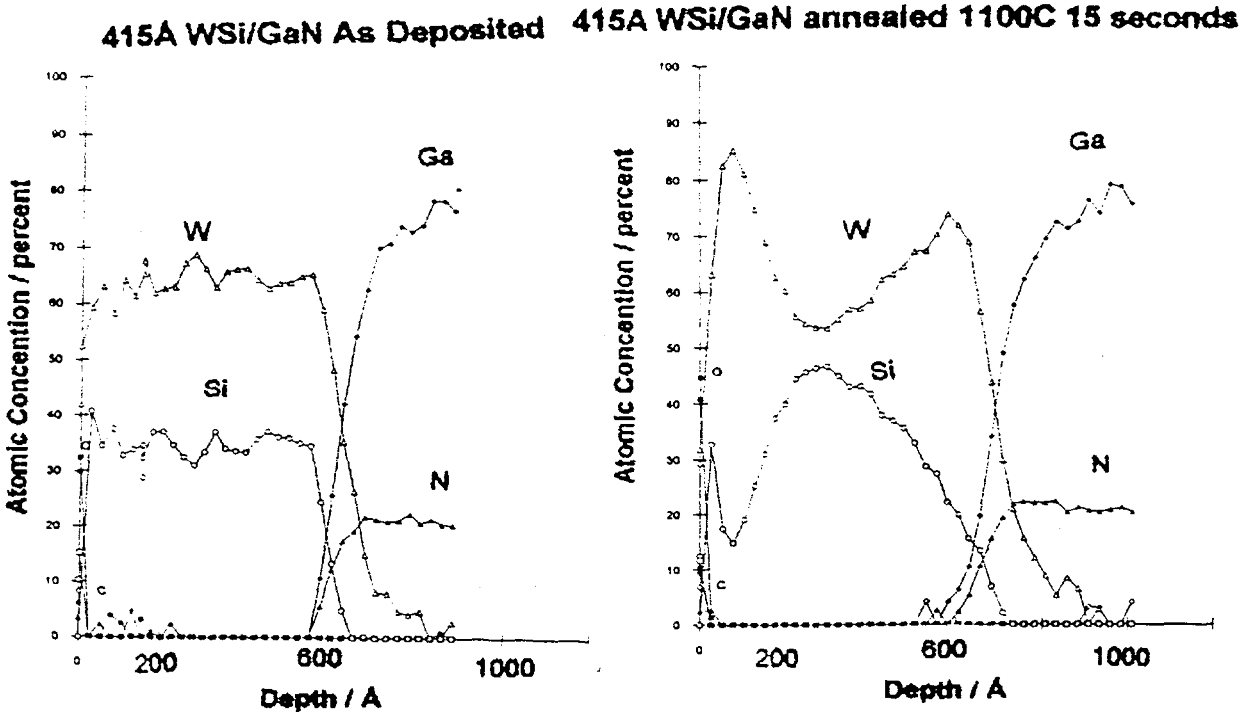

Figure 4. AES depth profiles of 500Å WSi_X on GaN before (left) and after (right) annealing at 1,100°C.

The lowest contact resistance would be obtained for pure InN on GaN, which preferably would be graded through $In_XGa_{1-X}N$ ($x=0\rightarrow1$). We grew InN emitter contact layers on top of GaAs/AlGaAs heterojunction bipolar transistor structures. containing a p^{-}GaAs(C) base with doping level $p=7x10^{19}cm^{-3}$.[10] TiPtAu non-alloyed contacts were patterned on the InN. TLM measurements showed $R_C \sim 5x10^{-7}\Omega cm^2$ as deposited, but even heating at 360°C completely degraded both the morphology and contact resistance.[11] The HBT showed excellent dc performance, with a gain of 35 at emitter current density of $\sim 5x10^4 A\cdot cm^{-2}$.[10] The morphology of the InN contact layer was superior to that of more conventional $In_XGa_{1-X}As$/GaAs structures used as emitter contacts on both GaAs/AlGaAs and GaAs/InGaP HBTs.

CONCLUSION

It was evident from the microstructural and interdiffusion studies of the as-deposited and annealed samples of all these metallization schemes that the WSi_X contacts exhibited the best thermal stability and retained good structural properties at annealing temperatures as high as 800°C on GaN. Processing of FET devices involve a high temperature annealing step for implant activation, typically ≥900°C.

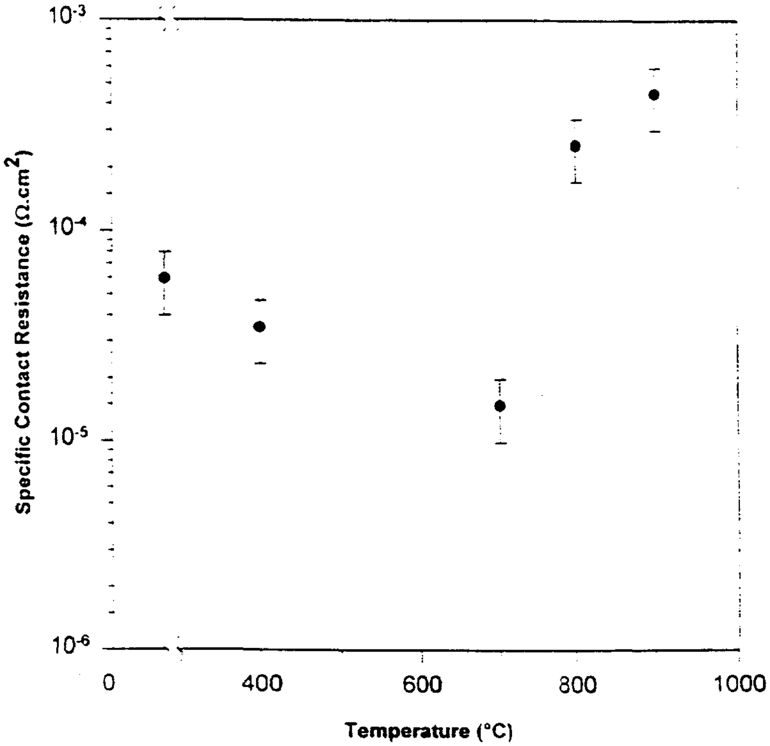

Figure 5. WSi_x specific contact resistivity on $In_{0.5}Ga_{0.5}N$ versus annealing temperature.

Acknowledgments

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