HIGH TEMPERATURE STABLE WSi_x OHMIC CONTACTS ON GaN

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ABSTRACT: We have sputter-deposited 500-1200Å thick $WSi_{0.45}$ metallization onto n^+ GaN ($n \geq 10^{19} cm^{-3}$) doped either during MOCVD growth or by direct Si^+ ion implantation ($5x10^{15} cm^{-2}$, 100 keV) activated by RTA at 1100°C for 30 secs. In the epi samples R_C values of $\sim 10^{-14} \Omega cm^2$ were obtained, and were stable to ~1000°C. The annealing treatments up to 600°C had little effect on the WSi_x/GaN interface, but the β-W_2N phase formed between 700-800°C, concomitant with a strong reduction (approximately a factor of 2) in near-surface crystalline defects in the GaN. Spiking of the metallization down the threading and misfit dislocations was observed at 800°C, extending >5000Å in some cases. This can create junction shorting in bipolar or thyristor devices, R_C values of $<10^{-6} \Omega cm^2$ were obtained on the implanted samples for 950oC annealing, with values of after 1050°C anneals. The lower R_C values compared to epi samples appear to be a result of the higher peak doping achieved, $\sim 5x10^{20}$ cm^{-3}. We observed wide spreads in R_C values over a wafer surface, with the values on 950°C annealed material ranging from 10^{-7} to $10^{-4} \Omega cm^2$. There appear to be highly non-uniform doping regions in the GaN, perhaps associated with the high defect density ($10^{10} cm^{-2}$) in heteroepitaxial material, and this may contribute to the variations observed. We also believe that near-surface stoichiometry is variable in much of the GaN currently produced due to the relative ease of preferential N_2 loss and the common use of H_2-containing growth (and cool-down) ambients. Finally the ohmic contact behavior of WSi_x on abrupt and graded composition $In_xAl_{1-x}N$ layers has been studied as a function of growth temperature, InN mole fraction x=0.5-1) and post WSi_x deposition annealing treatment. R_C values in the range 10^{-3}-$10^{-5} \Omega cm^2$ are obtained for auto-doped n^+ alloys, with the n-type background being little affected by growth conditions ($n \sim 10^{20} cm^{-3}$). InN is the least temperature-stable alloy (≤700°C), and WSi_x contact morphology is found to depend strongly on the epi growth conditions.

INTRODUCTION

GaN is attracting attention for high temperature, high power switches and microwave amplifiers[1,2]. One of the key requirements for these devices is low resistance, reliable ohmic contacts, capable of withstanding elevated temperatures (~550°C) and high current densities. In the defense arena, control electronics capable of switching 25kV, 2kA is needed for several different applications, while lower powers are attractive for aerospace and automotive applications. A stable metal-GaN system is of paramount importance in achieving high power nitride devices.

In this work, we have examined stability of WSi_x on III-nitrides in three different situations, First, it has been deposited on n^+ GaN epilayers, and the contact and interface properties measured as a function of post-deposition annealing temperature. Second, we have used Si^+ implantation into undoped GaN, followed by high-temperature activation to create n^+ doping, and then examined the thermal stability of WSi_x on this material. This

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process simulates formation of source/drain regions in self-aligned HFETs or MESFETs. Third, we have examined contact properties of WSi_X on InGaN or InAlN epilayers on n-GaN, in an attempt to lower the specific contact resistance.

EXPERIMENTAL

The GaN layers were grown by metalorganic chemical vapor deposition (MOCVD) on (0001) Al_2O_3 substrates. Details of the growth and processing methods have been presented elsewhere[3]. The doping was either $<10^{16}cm^{-3}$ for undoped or $10^{19}cm^{-3}$ for Si-doped. The carrier density was obtained from van der Pauw geometry Hall measurements using alloyed HgIn contacts. The WSi (5:3.9) contact metal layers, 500Å thick, were sputter deposited on the GaN using an MRC 5001 sputtering chamber with an Ar discharge and an acceleration voltage of 90V. Subsequent to metal deposition the samples were rapid thermal annealed in a N_2 ambient for 1 min at temperatures up to 1000°C.

For the InGaN and InAlN epilayers, growth was performed by Metal Organic Molecular Beam Epitaxy (MOMBE)[4]. A typical structure was 500Å of $In_{0.5}Ga_{0.5}N$ ($n\sim10^{20}cm^{-3}$) or $In_{0.5}Al_{0.5}N$ ($n\sim10^{19}cm^{-3}$) on top of n-GaN. In some cases the InAlN was graded up to InN to examine the effects on contact stability.

RESULTS AND DISCUSSION

(a) WSi on n^+ GaN

Our previous data on W or GaN showed excellent stability up to 1000°C, with W_2N forming at the interface at <800°C[3]. In the present case of WSi_X, x-ray diffraction showed no interfacial reactions up to ~600°C[5]. For higher temperatures, a cubic β-W_2N phase was observed forming at the interface.

Figure 1 displays the AES depth profiles for the 600 and 800°C annealed WSi/GaN samples. The 800°C sample shows a slight broadening with respect to the unreacted (600°C) sample. Auger Electron Spectroscopy (AES) surface scans are shown for these samples in Figure 2. There is no detectable Ga outdiffusion, even at 800°C, suggesting the β-W_2N is an efficient diffusion barrier for this element.

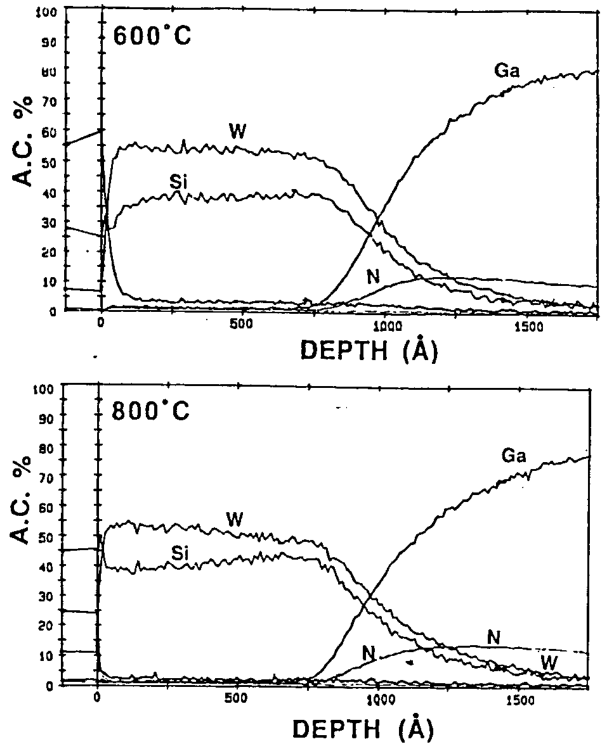

Figure 1. AES depth profiles for the (a, top) unreacted 600°C and (b, bottom) reacted 800°C annealed WSi to GaN samples.

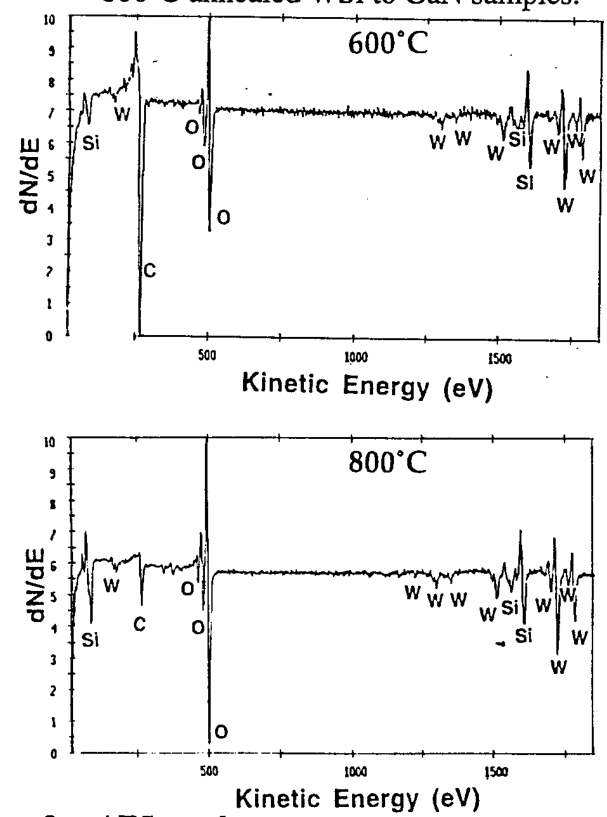

Figure 2. AES surface surveys for the (a, top) unreacted 600°C and (b, bottom) reacted 800°C annealed WSi to GaN samples.

Cross-sectional transmission electron nicroscopy showed that interfacial regions devoid of the β-W_2N phase had extensive contact metal rotrusions into the GaN[5]. The area of interfacial rotrusion was found to diminish with elevated nnealing temperature due to the increased orizontal extent of the β-W_2N interfacial phase. In nost cases the protrusions extend >5000Å down lislocations, and this would be a major issue for levice shorting. The β-W_2N phase is also mportant for contact properties, since N ccumulation to form this species leaves N_V defects which are shallow donors and lower the surface esistivity. R_C values $\leq 10^{-4}\Omega cm^2$ were obtained for WSi_X and W on n^+ GaN.

(b) WSi_X on Si-implanted GaN

Zolper et.al.[6] reported that ultra-high emperature (≥1400°C) annealing of Si-implanted GaN produces extremely high n-type carrier lensities in the mid $10^{20}cm^{-3}$ range. We have subsequently deposited W or WSi_X on these sample, and measured R_C as a function of post-metallization annealing temperature. Figure 3 shows that a minimum in the R_C values occurs at ~950°C, producing extremely low contact resistance, ~10^{-6} ohm·cm^2. We assume that two mechanisms may lead to the improved contact resistance with increasing annealing temperature - firstly, damage to the near-surface region during the sputtered W deposition needs to be removed, and secondly, formation of the β-W_2N phase may be beneficial to producing superior ohmic characteristics. At annealing temperatures above ~950°C, dissociation of the GaN may lead to degraded contact properties.

At temperatures up to 900°C there was no detectable reaction of the refractory metal with the implanted GaN. Figure 4 shows a cross-sectional SEM micrograph of W/GaN after 750°C annealing, showing the excellent thermal stability of this system. AES on the same samples also showed no detectable interdiffusion. We also performed Secondary Ion Mass Spectrometry measurements on the implanted Si profile before and after annealing - there was no detectable Si motion even at 1400°C, indicating that $D_{Si} \leq 10^{-13}cm^2 \cdot sec^{-1}$. We also observed quite wide spreads in R_C values on the implanted material. This is being reported more

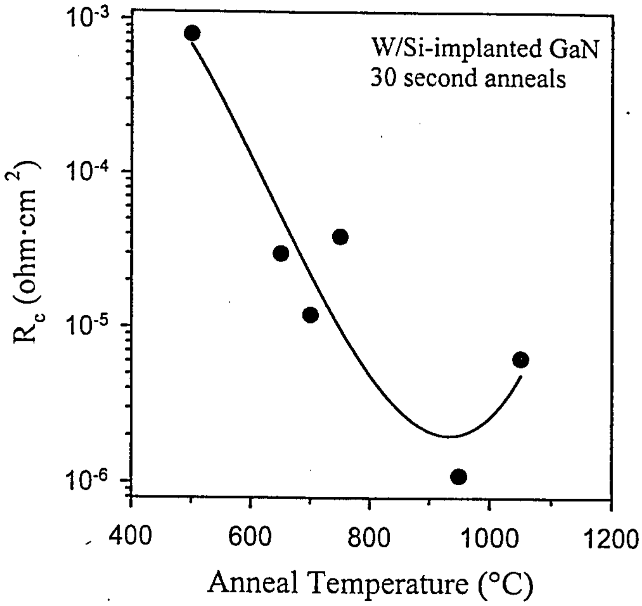

Figure 3. Contact resistance for W on Si-implanted GaN, as a function of post-metallization annealing temperature.

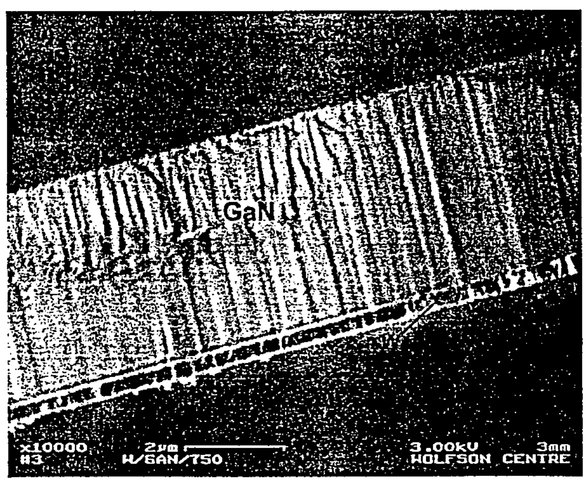

Figure 4. Cross-sectional SEM of W on Si-implanted GaN, after post-metallization annealing at 750°C.

frequently for ohmic contacts on GaN, but the obvious reasons (non-uniform surface contamination, residual oxides) have typically been ruled out. We expect that the columnar nature of the heteroepitaxial GaN plays a role, in that the doping and stoichiometry may vary greatly from grain-to-grain.

(c) WSi_x on In-based Epitaxial Layers

1. WSi_x on InGaN

The unintentional doping levels of MOMBE grown $In_xGa_{1-x}N$ and $In_xAl_{1-x}N$ are very dependent on the In composition[7]. For the case of $In_xGa_{1-x}N$, the doping level of $In_xGa_{1-x}N$ is as high as $10^{20}cm^{-3}$ for a wide range with x (In ratio) larger than 0.37. For $In_{xx}Ga_{1-x}N$ with such high doping level, nonalloyed ohmic contacts can be achieved. With the increase of In concentration in $In_xGa_{1-x}N$, it will also lower the bandgap in InGaN which will further reduce the contact resistance This $In_xGa_{1-x}N$ was proposed as an ohmic contact layer on GaN and specific contact resistivities as a function of annealing temperature are shown in Figure 5. The contact resistance of as-deposited sample is realized as low as $7x10^{-6}\Omega$-cm^2.

Processing of implanted devices involves a high temperature annealing step for implant activation, typically >700°C. The stability of the WSi_x/InGaN contacts are essential to allow the high temperature process for dopant activation. The contact degradation at higher annealing temperature was related to the increase in the sheet resistance which results from the degradation of the metal-semiconductor interface.

From SEM studies, the as deposited sample exhibited a very smooth surface and there was no change in the surface morphology of samples annealed at temperatures of 400 and 700°C[8]. The surface morphology of the samples annealed at 900°C showed only a small amount of surface roughness. The maximum annealing temperature to obtain good surface morphology WSi_x contacts on InGaN samples would therefore be in the range of 700-800°C. The AES studies generally confirmed the SEM observation regarding the inert nature of the metal-semiconductor interface, but indicated interdiffusion of various elements as a result of RTA at temperature of 900°C.

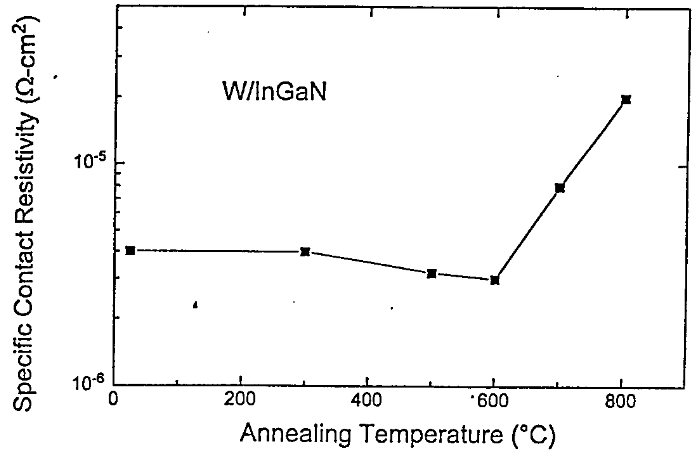

Figure 5. The specific contact resistivity of W/InGaN as a function of annealing temperature.

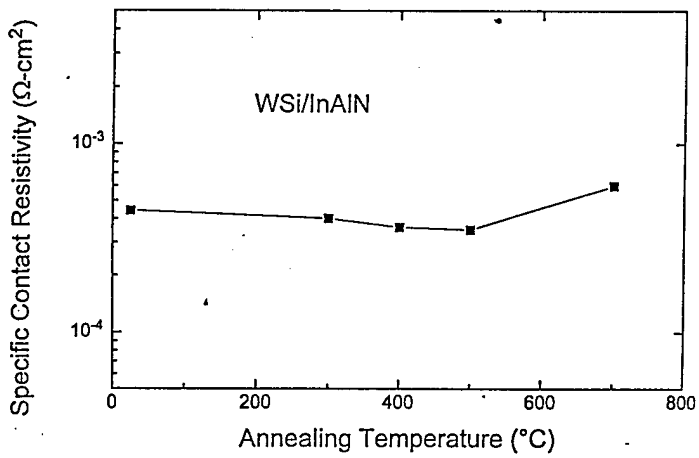

Figure 6. The specific contact resistivity of WSi/InAlN as a function of annealing temperature.

2. W on InAlN and InN/Graded-InAlN/InAlN

As shown in Figure 6 the specific contact resistivities of as-deposited W on $In_{0.6}Al_{0.4}N$ in which the unintentional doping level is $10^{18}cm^{-3}$ is in the high $10^{-4}\Omega$-cm^2 range[9]. Although the contact resistance reduces to $7x10^{-4}\Omega$-cm^2 after annealing up to 500°C, it is still quite high for device applications. Since the unintentional doping level of InN is two orders of magnitude higher than that of $In_{0.6}Al_{0.4}N$, InN with a graded $In_xAl_{1-x}N$ layer can be used as a contact layer for InAlN devices. As illustrated in Figure 7, the contact resistance of W/InN/graded-$In_xAl_{1-x}N$/InAlN is half of that for W/InAlN, and the thermal stability is also improved. The contact morphology and resistance show no degradation up to 500°C, while the AES depth profiles of W/InN/graded-$In_xAl_{1-x}N$/InAlN showed only slight differences between as deposited and 500°C annealed samples. The nitrogen diffused out into W and formed the interfacial WN_2 phase which resulted in lower contact resistance. Further annealing at higher temperatures, caused both morphology and contact resistance to degrade.

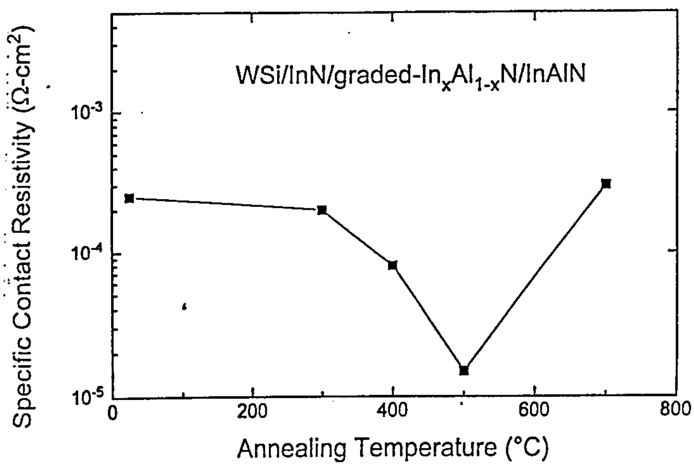

Figure 7. The specific contact resistivity of the annealed WSi/InN/graded-$In_xAl_{1-x}N$/InAlN as a function of annealing temperature.

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