InN-based Ohmic contacts to InAlN

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(Received 27 December 1966; accepted for publication 19 February 1997)

The ability to form low resistance Ohmic contacts to InAlN using refractory metallization on In-containing contact layers has been investigated. The crystal quality as measured by surface roughness and x-ray diffraction was found to be a determining factor in the contact resistance which could be obtained using WSi_x contacts. InN growth conditions which resulted in poorer structural quality, such as the use of GaAs rather than sapphire substrates, low nitrogen flows, and low growth temperatures, resulted in contact resistances of $10^{-4}-10^{-3}$ Ω cm^2, as compared to $\sim 10^{-5}$ cm^2 for InAlN alone. Using optimized conditions, contact resistances to InAlN of $\sim 3.5\times 10^{-6}$ Ω cm^2 were obtained. © *1997 American Institute of Physics*. [S0003-6951(97)00617-7]

III–V nitrides are becoming increasingly important for the development of high temperature electronic and optical devices due to their wide band gaps and high saturation velocities.[1] Before the performance of III-nitride devices can be optimized, however, several key processing issues must be addressed. Among the most important of these is the ability to fabricate low resistance, thermally stable Ohmic contacts to n-type material. Work has been done on Ohmic contacts to GaN starting with Foresi and Moustakas[2] and furthered by others.[3–8] Most contact resistivities to GaN have been reported in the $10^{-3}-10^{-4}$ Ω cm^2 range, however Lin *et al.*[3] were able to obtain values as low as 8×10^{-6} Ω cm^2 by annealing Ti/Al contacts at high temperatures (900 °). Similar studies have not been performed for InAlN, which is a potential replacement for GaN and AlGaN in a number of device structures.

In electronics applications, narrow band gaps and/or high doping levels are usually needed in order to minimize the resistances arising from ohmic contacts. In GaAs-based devices, for example, the high doping and narrow band gap of n-doped InGaAs can be used to reduce parasitic resistances to GaAs, resulting in contact resistances of $\sim 2-6\times 10^{-7}\Omega$ cm^2 vs$\sim 1\times 10^{-6}$ Ω cm^2.[9] Attempts to introduce In-containing layers to GaN device structures have been hampered by the methods typically used to grow InN and the other III-nitride materials. In the past, InN has been deposited primarily using various sputtering[10–15] or electron beam[16] techniques. Since techniques like metal organic chemical vapor deposition (MOCVD) suffer from the need for high growth temperatures, the amount of In which can be incorporated in the III-nitride alloys is limited.[17] The use of plasma sources in techniques like electron cyclotron resonance molecular beam epitaxy (ECRMBE)[18] or electron cyclotron resonance (ECR) metal organic molecular beam epitaxy (ECRMOMBE) removes the temperature limitation making growth of In-containing materials including InN feasible.[19,20] The use of refractory contacts such as those based on W or WSi_x allows thermally stable contact formation. Unfortunately, this type of metallization often produces higher contact resistances than less stable metallization schemes. Thus the use of refractory contacts makes the need for improved contact layer structures even more critical. This letter, presents the first report of improved ohmic contact resistance to InAlN using InN and refractory contacts.

The samples were grown on either (0001) sapphire or semi-insulating (100) GaAs substrates in an Intevac Gas Source Gen II. The group III precursors, dimethylethylamine alane (DMEAA) and trimethylindium (TMI) were transported by a He carrier gas in order to avoid possible hydrogen passivation effects. An electron cyclotron resonance plasma source (Wavemat MPDR 610) operating at 2.45 GHz and 200 W forward power was used to provide the nitrogen flux. N_2 flows of 5 or 20 sccm were used. Growth temperatures for In-containing layers ranged from 500 to 575 °C, while AlN layers were grown at 700 °C. The growth sequence on sapphire consisted of a nitridation step of 5 min at 700 °C, followed by a low temperature (425 °C) 500 Å AlN nucleation layer and finally a 5000 Å AlN buffer layer. Electrical transport properties were obtained from Van der Pauw geometry Hall measurements at 300 K using alloyed (400 °C, 2 min) HgIn Ohmic contacts. The compositions of the calibration samples were determined by electron microprobe analysis using a 6 kV beam, and by powder x-ray diffraction assuming Vegard's law. Surface morphology was examined by scanning electron microscopy (SEM) and atomic force microscopy (AFM). X-ray diffraction (XRD) was used to evaluate the structural quality and to determine that all of the films grown, including those on GaAs, crystallized in the wurtzite phase. Contact resistances were measured using the transmission line method (TLM) on WSi_x contacts fabricated by sputtering. Two types of contact structures were evaluated, those with InN contacting regions (InN/InAlN/AlN/low temperature AlN), and those without (InAlN/AlN/low temperature AlN). A 500 Å graded region between the InAlN and the InN was used to avoid band discontinuities at the InN/InAlN interface.

The initial experiments have been conducted on InAlN structures, using WSi_x contacts. As shown in Fig. 1, the GaAs substrates produce InAlN surface morphologies comparable to those obtained on sapphire, in spite of the larger

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TABLE I. Contact resistance and rms surface roughness of structures grown using various nitrogen flows and growth temperatures.

Structure	Contact resistance (Ω cm^2)	AFM rms roughness (nm)	N_2 flow during InN growth (sccm)	InN growth temp.(°C)
InAlN/AlN/Sapphire	1.9×10^{-5}	1.4	5	525
InAlN/AlN/GaAs	1.4×10^{-3}	1.6	5	525
InN/InAlN/AlN/Sapphire	4.8×10^{-4}	68.7	5	525
InN/InAlN/AlN/GaAs	$8-9\times10^{-4}$	7.0	5	525
InN/InAlN/AlN/Sapphire	3.6×10^{-5}	20.5	20	525
InN/InAlN/AlN/Sapphire	3.5×10^{-6}	54.7	20	575

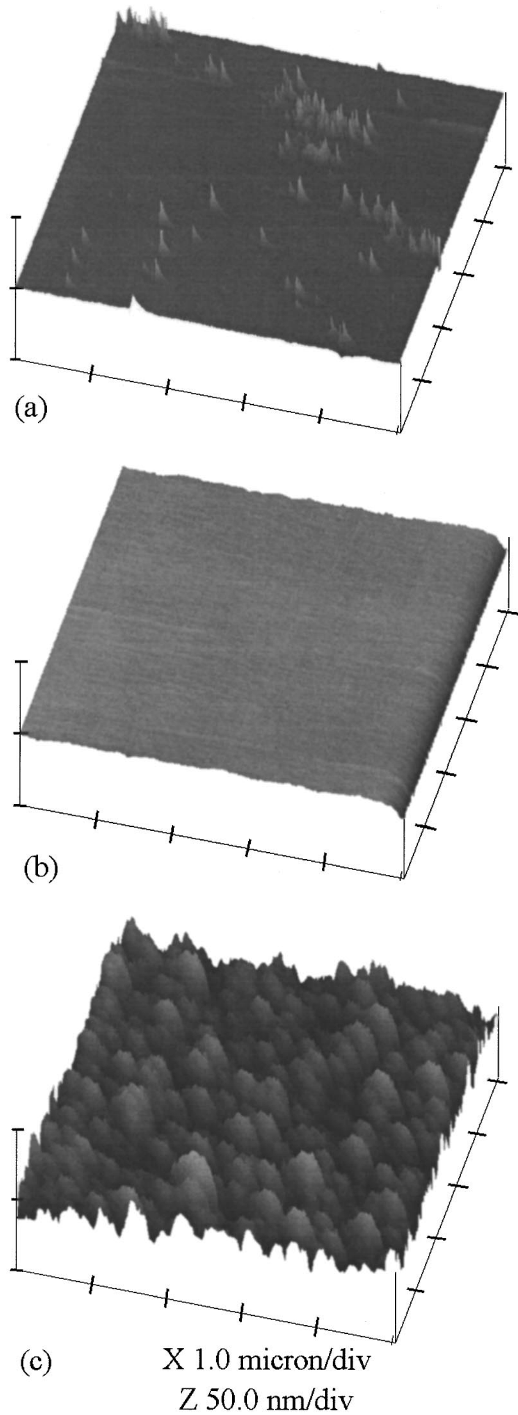

FIG. 1. AFM scans of InAlN on either GaAs (top) or sapphire (middle), and the InN/InAlN contact structure on GaAs (bottom).

lattice mismatch between the GaAs and the epilayer. As expected, the addition of the graded region and the InN contact layer roughens the surface considerably, particularly for the structures grown on sapphire. This is also observed for InAs growth on GaAs-based structures and is due in part to the tendency of In materials to island on non-In containing surfaces. This roughening typically becomes worse with increasing In-containing layer thickness, thus limiting the thickness of the contacting layer which can be used. For this reason, the InN layers used in this study were limited to 500 Å thicknesses. In order to evaluate the electrical properties of the materials, Hall measurements were performed on 0.3–0.5 micron layers grown under the same conditions as those used for the contact structures. This analysis gave mobilities of $\sim$5–15 cm^2/V s for InAlN and $\sim$25–50 cm^2/V s for InN, and electron concentrations of $\sim 1-3\times10^{19}$ cm^{-3} for InAlN films and $\sim 1-3\times10^{20}$ cm^{-3} for InN layers. Such high backgrounds have been observed in In-containing nitrides grown by other methods as well, and have been attributed to a variety of sources including C and native point defects.[12]

Given the similarity in electrical behavior and surface morphology, it was expected that the contact resistances would also be similar in structures grown on the two substrates. However, as shown in Table I, the structures grown on sapphire produce significantly lower contact resistances. This difference does not appear to be related to doping level as the sheet resistances of the InN cap layers were found to be independent of substrate. It is more likely that the poorer contact behavior is due to the poorer structural quality obtained on GaAs relative to sapphire. XRD analysis of both In- and Al-containing materials shows an approximately two-fold increase in full width at half-maximum (FWHM) when layers are grown on GaAs rather than sapphire. Similar behavior has been reported for GaN as well.[21–26] Thus it appears that from the point of view of parasitic resistances, electronic devices fabricated on sapphire will most likely provide superior performance.

Contrary to what has been observed for GaN, where even relatively low In mole fractions ($X_{\mathrm{In}}\sim0.25$) produce significant improvements in contact resistance,[27] it was found that InAlN contact layers produce unacceptably high contact resistances even at low aluminum concentrations ($X_{\mathrm{Al}}\sim0.25$). Therefore while GaN containing structures may only require fairly low In concentrations for improved performance, structures with InAlN layers will most likely require pure InN. However, simply adding an InN layer to the growth sequence does not guarantee improved contact performance, as shown in Table I. While the addition of InN cap layers did reduce the resistance in structures grown on GaAs structures, it actually degraded the performance for structures on sapphire. This may be due to the rougher surface morphologies which occur from the islanding behavior of InN. It was found that by increasing the nitrogen flow from 5 to 20 sccm through the ECR plasma source during growth of the InN the surface roughness could be reduced to values closer to those of InAlN alone, as listed in Table I. The higher flow also produced significant improvement in the XRD patterns

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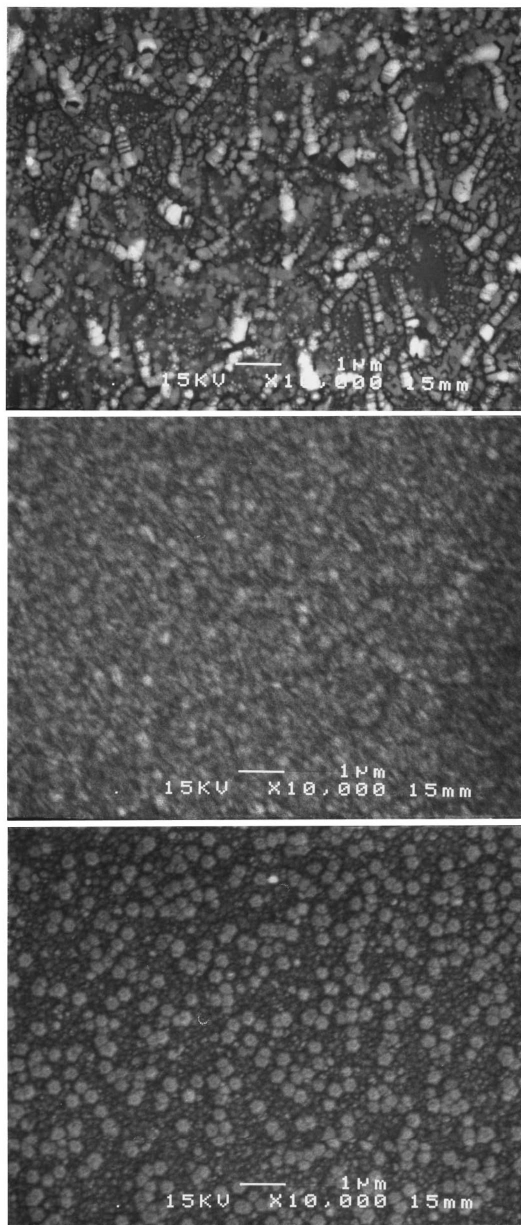

FIG. 2. SEM micrographs of contact structure grown on sapphire at 525 °C and 5 sccm N_2 (top), 525 °C and 20 sccm N_2 (middle), and 575 °C at 20 sccm N_2 (bottom). Samples grown at lower nitrogen flow or higher temperature show enhanced tendency toward islanding.

as well, indicating an improvement in the crystal quality. The rough surface and poor structural quality at low nitrogen flow may indicate that growth has occurred under nitrogen deficient conditions, leading to the formation of In-rich regions in which 2D growth does not occur, see Fig. 2. Such behavior is also observed in other In-containing materials such as InAs. Given the improvement in structural quality and morphology, it is not surprising that increasing the nitrogen flow produced a (∼10X) reduction in the contact resistance as well.

Further improvement in the contact resistance was obtained by increasing the growth temperature from 525 to 575 °C. While this actually degraded the surface roughness slightly, increasing the growth temperature reduced the as-deposited resistance by an order of magnitude. Using these optimized growth conditions, contact resistances as low as 3.5×10^{-6} Ω cm^2 were achieved, making these structures suitable for use in either digital or analog applications.

The ability to realize the potential of wide band gap III–V nitrides for high performance electronic and optical devices lies partly with the formation of useful ohmic contacts. This letter has shown that the use of InN contacting layers can help to achieve this goal, providing that the material quality and morphology are optimized. Contact resistances as low as 3.5×10^{-6} Ω cm^2 were achieved using this approach in combination with WSi_x contacts.

This work was partially supported by Grant No. ECS-9522887 from the National Science Foundation.

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