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DOPING AND ISOLATION OF GaN, InGaN AND InAlN USING ION IMPLANTATION

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Abstract. Both n- and p-type doping have been achieved in GaN using Si^+ or Mg^+/P^+ implantation, respectively, followed annealing at ≥ 1050°C. Using proximity rapid thermal annealing (10sec) the GaN surface retains both smooth morphology and its original stoichiometry. Variable temperature Hall measurements reveal approximate energy levels of 62meV for the implanted Si and 171meV for the Mg, which are similar to their values in epitaxially grown GaN. Implant isolation of both n- and p-type GaN, and n-type $In_{0.75}Al_{0.25}N$ with multiple energy inert species (e.g. N^+ or F^+) produces high resistivity ($\geq 10^8 \Omega/\square$) after subsequent annealing in the range 600–700°C. Smaller increases in sheet resistance are observed for $In_xGa_{1-x}N$ (x=0.33–0.75) under the same conditions due to the smaller energy bandgaps and the shallower energy levels of the damage-related states controlling the resistivity.

1. Introduction

The recent realization of p-type doping of GaN during Metal Organic Chemical Vapor Deposition using Cp_2Mg has led in a short period to the availability of blue and green light-emitting diodes [1,2]. The processing of these devices could be improved if an implant doping technology was also practical, since one could employ selective area implantation for improved ohmic contact formation and moreover this would make possible a variety of field-effect transistor (FET) structures capable of high-temperature operation. Since ion implantation is a high yield, high throughput process, the availabilty of implant doping and isolation technologies would allow the production of FETs at a much lower cost than is currently possible with epitaxial growth. Junction FETs are for more readily fabricated using ion implantation of both n- and p-type dopants than would be the case with epitaxy, and integration of n-channel and p-channel devices is much simpler [3].

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To date, ion implantation has generally been used to introduce impurities for study of their optical properties [4]. GaN LEDs have been found to emit at 430nm (violet) when implanted with Mg, at 590nm (yellow) when Mg/Zn were co–implanted and in the green when implanted with Zn alone [5]. In all of the cases the implanted impurities behave as color centers. Implanted Er has also been reported to produce 1.54μm emission (from optically excited Er^{3+}) in GaN [6]. In the FET structures reported by Binuri et al.[7,8], implantation with H^+ or He^+ ions was used for device isolation.

2. Experimental

The GaN layers used were grown on c–Al_2O_3 by MOCVD in a multi-wafer rotaing disc reactor at 1040°C with a GaN buffer layer of ~200Å grown at 530°C. Undoped films were n-type (≤ $4x10^{16}cm^{-3}$) and were used for the doping experiments. Other layers were doped using disilane or bis-cyclopentadienyl-magnesium to achieve n– and p–doping, respectively of ≤ $4x10^{18}cm^{-3}$. these samples were used for the implant isolation experiments. The $In_xGa_{1-x}N$ (x=0.33–1) and $In_xAl_{1-x}N$ (x=0.5–0.75) were grown on semi-insulating GaAs by MOMBE between 525–650°C using TEG, TMAAl and TMI for the group III elements and ECR generated nitrogen. The layers were auto-doped n-type (10^{19}–$10^{20}cm^{-3}$). The undoped GaN was implanted with Si^+ ($5x10^{14}cm^{-3}$, 200keV), Mg^+($5x10^{14}cm^{-3}$, 180keV) or Mg^+/P^+($5x10^{12}cm^{-2}$, 180/250keV) and annealed up to 1100°C for 10sec in a graphite susceptor. For isolation experiments, multiple energy (50–250keV) N^+, F^+ or O^+ ions at doses of 2-$50x10^{13}cm^{-2}$ were used to produce uniform damage profiles throughout the nitride layers. Post-implant annealing at 400–900°C was employed to study the thermal stability of the isolation

3. Results and Discussion

Figure 1 shows that above 1050°C, the implanted Si^+ becomes electrically active with an efficiency of ~90% for a dose of $5x10^{14}cm^{-2}$. Mg^+ implantation alone did not produce p-type doping, but when co-implanted with P^+ we obtained a sharp n-to-p conversion of the GaN at 1050°C, with an activation efficiency of ~60% at a dose of $5x10^{14}cm^{-2}$. As in other III-V semiconductors, the role of the P^+ co-implant is to increase the vacancy concentration and promote substitutionality of the Mg upon annealing. Annealing by itself above 1000°C produced a slight increase in n-type conductivity in GaN which may be a result of creation of N_V-related centers.

Variable temperature Hall measurements on the implanted samples showed activation energies of ~62meV for Si (Figure 2) and ~171meV for Mg (Figure 3) similar to their values in epitaxially grown material [9,10]. We note however that these are dependent on the method of plotting the data and if one uses $\rho T^{3/2}$ instead of Ns, then values of 30 and 120meV are obtained.

Both n- and p-type GaN can be converted to high-resistance material ($>10^9\Omega/\Box$) by N^+ implantation and subsequent annealing at ~750°C where hopping conduction is minimized. Activation energies of ~0.90eV for initially n-type, and 0.83eV for initially p-type GaN, were obtained from temperature-dependent resistivity measurements, suggesting the Fermi-level becomes pinned at these energies in isolated material. These values are not at midgap (~1.6eV), which is the most favorable situation for achieving maximum isolation resistances, but are still large enough that the GaN resistivity is well above the minimum necessary for good electronic device isolation, i.e. $>10^6 \Omega/\square$ [11].

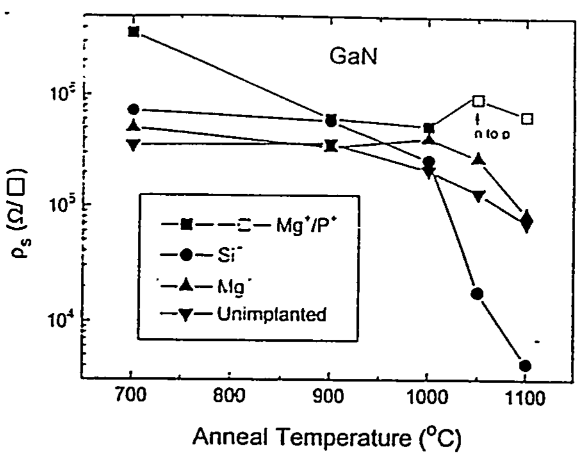

Figure 1. Sheet resistance of nominally undoped GaN either unimplanted. or implanted with a dose of $5x10^{14}cm^{-2}$ Si^+, Mg^+ or Si^+, Mg^+, as a function of annealing temperature.

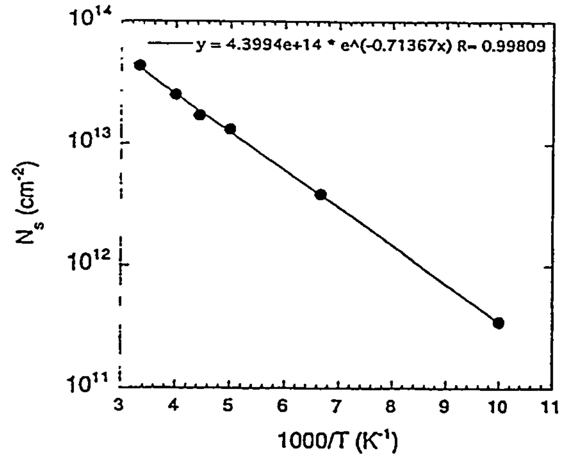

Figure 2. Arrhenius plot of carrier density in Si^+ implanted GaN.

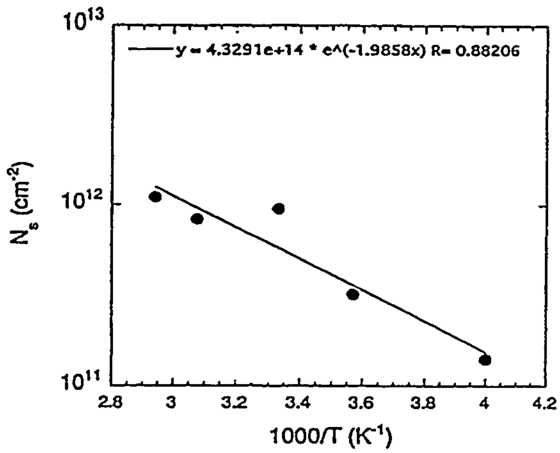

Figure 3. Arrhenius plot of carrier density in Mg^+/p^+ implanted GaN.

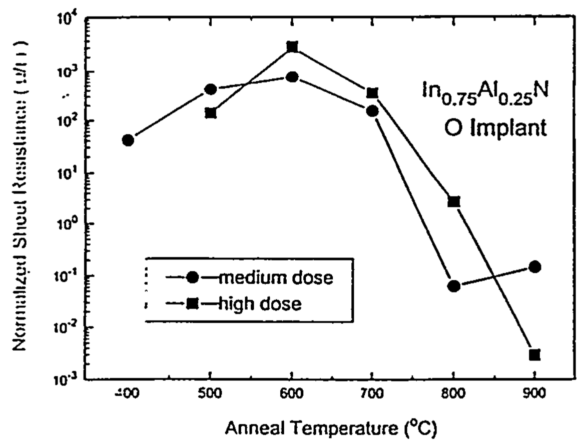

Figure 4. Normalized sheet resistance (relative to the unimplanted values) versus anneal temperature for $In_{0.75}Al_{0.25}N$ implanted with various doses of 0^+.

For the ternary compounds, increases in sheet resistance of up to a factor of $\sim10^4$ were achieved in $In_{0.75}Al_{0.25}N$ after implantation at high doses ($\sim10^{14}cm^{-2}$) of the isolating species, followed by annealing at 600–700°C (Figure 4). Slightly lower increases were obtained for mediums ($\sim10^{13}cm^{-2}$) or low ($\sim10^{12}cm^{-2}$) doses. The behavior for $In_xGa_{1-x}N$ followed the same general trends, with somewhat lower increases in sheet resistance $In_{0.75}Al_{0.25}N$ the Fermi level appears to pin at E_C–0.54eV for high N^+ doses and E_C–0.19eV for low doses, whereas in $In_{0.33}Ga_{0.67}N$ optimized annealing conditions produce a dominant activation energy of only 0.40eV, and above an annealing temperature of

~800°C the energy level reverts to E_C–0.025eV (the same as in the as-grown material). There was no evidence for a high density of chemical deep levels associated with the implanted N^+, F^+ or O^+. The implant isolation behavior of n-type InGaN and InAlN appears analogous to that of InP and InGaAs in that only moderate resistivities are obtainable in initially n-type material.

4. Summary

For electronic device isolation it appears that $In_xAl_{1-x}N$ can be made sufficiently resistive by implantation, whereas the initial conductivity of $In_xGa_{1-x}N$ will determine whether or not implantation will be successful for isolation. For photonic devices, the requirements are less demanding and implantation should work well for current guiding. In GaN implant isolation works quite well in both n- and p-type material. We have achieved good implant activation by the simple expedient of using a high annealing temperature and high quality starting material.

Acknowledgments

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