RECENT PROGRESS IN IMPLANTATION AND ANNEALING OF GaN AND AlGaN

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ABSTRACT

Heterostructure modulation doped transistors (MODFETs) based on AlGaN/GaN structures have demonstrated impressive DC and microwave performance often despite high transistor access resistance. One approach to reducing the access resistance is to use selective area Si-implantation. While several reports exist on Si-implantation in GaN, little work has been done on implantation in AlGaN. In addition, more information on the annealing of implantation damage in GaN is needed to optimize its use in FETs and thyristors.

We report the electrical and structural properties of Si-implanted $Al_{0.15}Ga_{0.85}N$ based on Hall measurements and Rutherford Backscattering (RBS) spectra, respectively. $Al_{0.15}Ga_{0.85}N$ shows less damage accumulation than GaN for a room temperature Si-implant dose of $5x10^{15}$ cm^{-2} based on the minimum channeling yield (26% for AlGaN as compared to 34% for GaN), however, as with GaN, this damage is difficult to remove by thermal annealing at ~1100 °C.

We also report on high pressure (up to 15 kbar) and high temperature (up to 1500 °C) annealing for Si-implanted GaN. At 1250 °C ~50% electrical activation is achieved which increases to ~90% at 1500 °C. The photoluminescence of these samples is also restored, or even enhanced, by the high temperature treatments. Furthermore, RBS demonstrates that complete removal of the implantation induced damage is achieved for the 1500 °C anneal.

INTRODUCTION

With the development of GaN-based electronics for high-power and high-temperature operation the reduction of the transistor access resistance becomes a more critical issue (1-4). The two approaches taken to reduce this resistance in other III-V semiconductor transistors are recessed gate designs and self-aligned implanted structures (5). Structures based on selective area implantation may be the preferred approach for GaN-based transistors due to the present difficulty in controllable wet etching of GaN (6).

Although implantation doping of GaN has already been demonstrated, more work is needed to optimize the implant activation annealing process (7-9). In addition little work has been reported on the implantation doping and annealing of AlGaN. AlGaN layers will be employed in heterostructure transistors to realize a two dimensional electron gas (2-DEG) and to increase the transistor breakdown voltage. One would anticipate that the addition of Al to the GaN matrix will increase the damage threshold as is the case for AlGaAs as compared to GaAs (10), but this has not been studied prior to this work. In addition, it was recently reported that annealing implantation induced damage in GaN starts to occur between 1100 and 1300 °C, however, significant sample decomposition can also occur in this temperature range (11). Therefore, to study the fundamental limitation on implantation damage removal

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in GaN, high pressure (up to 15 kbar) and high temperature (up to 1500 °C) annealing was performed of Si-implanted GaN. Under such high pressure conditions the decomposition of GaN is completely suppressed to allow the uncompromised study of the damage annealing process.

EXPERIMENTAL APPROACH

The AlGaN layer used for the implantation study was nominally 1.0 µm thick grown on a c-plane sapphire substrate. The Al-composition was estimated to be 15% based on x-ray and photoluminescence measurements. The as-grown minimum backscattering yield measured by channeling Rutherford Backscattering was 2.0% and is comparable to a high quality GaN layer.

The GaN layers used in the high-pressure/high-temperature experiments were ~1.0 µm thick grown on c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD) in a multiwafer rotating disk reactor at 1040 °C with a ~20 nm GaN buffer layer grown at 530 °C (12). The GaN layers were unintentionally doped, with background n-type carrier concentrations $\leq 1\text{x}10^{16}$ cm^{-3} as determined by room temperature Hall measurements. When annealed at 1100 °C for 15 s the material maintained its high resistivity. The as-grown layers had featureless surfaces and were transparent with a bandedge luminescence at 356 nm at 4 K. Additional luminescence peaks were observed near 378 and 388 nm. We speculate that these second peaks are due to carbon contamination in the film from the heater in the growth reactor or from the metalorganic precursors.

Both the AlGaN and GaN samples were implanted with Si at room temperature at an energy of 100 keV. The AlGaN samples were given one of two doses, 1 or $5\text{x}10^{15}$ cm^{-2}, while the GaN samples were implanted only with the higher dose. The higher Si-dose has previously been shown not to amorphize GaN and produce an as-implanted channeling yield of 34% (13).

Samples were characterized by channeling Rutherford Backscattering (C-RBS) with a 2 meV ^{4}He beam with a spot size of 1 mm^2 at an incident angle of 155°. Aligned spectra are taken with the beam parallel to the c-axis of the GaN film. Random spectra are the average of five off-axis, off-planar orientations. Electrical characterization was done by the Hall technique at room temperature.

RESULTS AND DISCUSSION

AlGaN-Implantation:

Figures 1 shows the sheet electron concentration and electron Hall mobility versus the annealing temperature for the Si-implanted AlGaN samples. Data for an unimplanted sample is included as a control. First of all, it is clear the implanted samples have significant donors produced by the annealing process alone. This may be due to the activation of unintentional impurities, such as Si or O, in the film. O may be a particular suspect due to the tendency of O to incorporate in Al-containing material. At the highest temperature, the high dose Si-implanted sample has four times higher free electron concentration ($1.7\text{x}10^{15}$ cm^{-2}) than the unimplanted sample. This corresponds to 34% activation of the implanted Si.

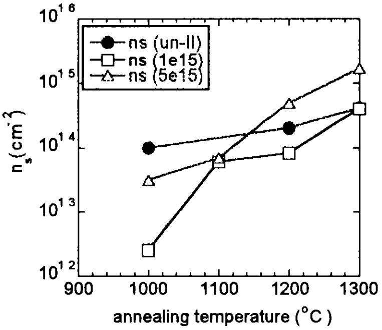

Figure 1. Sheet electron concentration for unimplanted and Si-implanted (100 keV) AlGaN (15% AlN) at the doses shown versus annealing temperature.

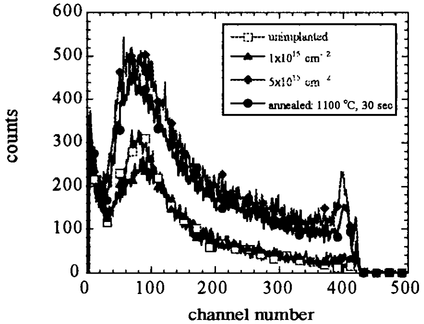

Figure 2: Channeling Rutherford Backscattering (C-RBS) spectra for as-grown, unimplanted, Si-implanted (100 keV, 1 or $5x10^{15}$ cm^{-2}), and implanted (100 keV, $5x10^{15}$ cm^{-2}) annealed AlGaN.

Figure 2 shows aligned C-RBS spectra for 15% Al in AlGaN either as-grown (unimplanted), after Si-implantation at a dose of 1 or 5 $x10^{15}$ cm^{-2}, and for the higher dose samples after annealing. As was the case for GaN, the $1x10^{15}$ cm^{-2} sample shows limited dechanneling while the higher dose sample shows a marked damage peak. The minimum channeling yield for the high dose sample was 26.67% which is lower than that seen for GaN which showed χ_{min} between 34 and 38% implanted under the same conditions. This means the addition of 15% aluminum to the GaN matrix increases its damage threshold as is the case for Al-additions to GaAs to form AlGaAs (10). The spectra for the annealed sample shows limited damage removal, again consistent with that seen for GaN at this temperature (14). There is evidence, however, of improvement in the near surface as seen by the reduction in the first surface peak. This peak has been suggested to be due to preferential sputtering of nitrogen from the film surface (15). The reduction of this peak via annealing suggests the surface stiochiometry is restored during the anneal. Further study is needed to better understand this effect.

High-Pressure, High-Temperature Implantation Annealing of GaN

High pressure, high-temperature annealing was used to study the fundamental limits of implantation induced damage removal in GaN. By employing high N-overpressures (up to 15 kbar) sample decomposition is suppressed and the damage removal can be uncompromisingly examined. Figure 3 shows aligned C-RBS spectra for GaN implanted with 100 keV Si at a dose of $5\text{x}10^{15}$ cm^{-2} and annealed under the conditions shown in the legend. Included in the legend in parenthesis is the minimum channeling yield (χ_{min}) for each sample. An as implanted sample (spectra not shown) had a χ_{min} of ~34%, therefore significant damage removal has occurred for the 1250 °C (χ_{min} = 14.28%) sample with continuing improvement with increased temperature. The 1500 °C sample has a channeling yield equivalent to an unimplanted sample and demonstrated no macroscopic surface decomposition. This result suggests that implantation damage can in fact be removed in GaN given high enough annealing temperature. The next step will be to find alternative ways, besides the extremely high N-overpressure, to maintain the sample stoichiometry. The two approaches under development are the use of encapsulating films and reduced thermal budget with a rapid thermal annealing approach.

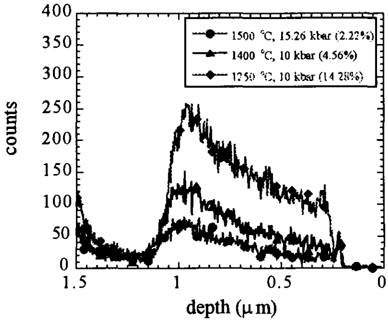

Figure 3. Aligned C-RBS spectra for Si-implanted (100 keV, $5\text{x}10^{15}$ cm^{-2}) GaN annealed for 15 min under the conditions shown. In parenthesis is the minimum channeling yield (χ_{min}) for each sample.

The samples of Fig 3 were also characterized by the Hall technique, by photoluminescence, and by secondary ion mass spectroscopy (SIMS). Hall data suggests 46% electric activity of the implanted Si at 1250 °C with increasing activity to 88% at 1500 °C. However, the SIMS data shows high levels of oxygen in the samples, therefore, the free donor concentration may also have a component due to O-donors. The Hall mobility of the 1250 °C was ~100 cm^2/Vs and is very respectable for such a high donor level (on the order of 10^{20} cm^{-3}). The mobility was roughly constant for the higher annealing temperatures.

The photoluminescence spectra of these samples was also studied. The as-implanted samples had no appreciable luminescence while the annealed samples had both near bandedge and donor/acceptor-like emission peaks. The luminescence increased in intensity with increasing annealing temperature. In fact, the 1500 °C annealed sample had a stronger bandedge luminescence intensity than the as-grown material by a factor of three. The exact nature of this enhancement is under study, but we suspect an enhanced donor/acceptor recombination associated with the Si-doping along with removal of nonradiative centers during the annealing process.

CONCLUSION

The application of ion implantation to GaN-based electronics can be expected to significantly reduced the device access resistance and associated power loss. To optimize the implantation process the activation annealing sequence must be well understood both for GaN and AlGaN. In this paper, it was shown that the addition of 15% Al to AlGaN decreases the damage created by a set Si-implantation dose as compared to GaN. It was also shown that removal of implant damage in AlGaN will required temperatures in excess of 1100 °C.

High temperature and high pressure annealing of GaN was also reported to be effective to completely restore, based on C-RBS measurements, the as-grown crystal quality of Si-implanted GaN. This high temperature annealing also enhanced the photoluminescence of the implanted samples and produced high electron mobilities (100 cm^2/Vs for $n = 1x10^{20}$ cm^{-3}). This work suggests that developing a technology to maintain the GaN stoichiometry while achieving temperatures of up to 1500 °C will be required to fully realize the utility of implantation doping of this material.

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