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IMPLANTATION ACTIVATION ANNEALING OF Si-IMPLANTED GALLIUM NITRIDE AT TEMPERATURES > 1100 °C

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ABSTRACT

The activation annealing of Si-implanted GaN is reported for temperatures from 1100 to 1400 °C. Although previous work has shown that Si-implanted GaN can be activated by a rapid thermal annealing at ~1100 °C, it was also shown that significant damage remained in the crystal. Therefore, both AlN-encapsulated and uncapped Si-implanted GaN samples were annealed in a metal organic chemical vapor deposition system in a N_2/NH_3 ambient to further assess the annealing process. Electrical Hall characterization shows increases in carrier density and mobility for annealing up to 1300 °C before degrading at 1400 °C due to decomposition of the GaN epilayer. Rutherford backscattering spectra show that the high annealing temperatures reduce the implantation induced damage profile but do not completely restore the as-grown crystallinity.

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 particular, recent studies on the thermal stability of implantation-induced defects in GaN suggest that the annealing temperature must be pushed significantly above 1100 °C (5) . In this work, we present structural and electrical data for Si-implanted GaN annealed at temperatures up to 1400 °C. Both electrical and structural data are presented to correlate the effect of the removal of implantation-induced damage to electrical activation of implanted Si donors.

EXPERIMENTAL APPROACH

The GaN layers used in the 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 (10). The

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GaN layers were unintentionally doped, with background n-type carrier concentrations $\leq$ 1×10^{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 graphite heater in the growth reactor.

Two sets of samples were prepared for implantation and annealing. The first set of samples was encapsulated with 120 nm of sputter deposited AlN (11). The AlN was deposited in an Ar-plasma at 300 W using an Al-target and a 10 sccm flow of N_2. The film had an index of 2.1±0.05. Si implantation was performed through the AlN at an energy of 210 keV and a dose of 5×10^{15} cm^{-2}. Monte Carlo TRIM calculations predict that ~7% of the Si-ions come to rest in the AlN film with 4.6×10^{15} cm^{-2} being placed in the GaN (12). The Si peak range from the GaN surface is estimated to be 80 nm. The second set of samples was unencapsulated and implanted with Si at an energy of 100 keV and dose of 5×10^{15} cm^{-2}. This also gives a range from the GaN surface of 80 nm. A sample from each set was annealed under one of four conditions as shown in Table I. The samples annealed in the rapid thermal annealer (RTA) were placed in a SiC coated graphite susceptor and processed in flowing N_2. The remaining samples were annealed in a custom built metal organic chemical vapor deposition (MOCVD) system that employed rf-heating with the samples placed on a molybdenum holder on a SiC coated graphite susceptor. The stated temperatures were measured with a Accufiber Model-10 or a Minolta Cyclota-52 pyrometer which were calibrated by the melting of Ge at 934 °C. The pressure in the MOCVD reactor was 630 Torr with gas flows of 4 slm of N_2 and 3 slm of NH_3. The encapsulated and unencapsulated samples for a given temperature were annealed together.

TABLE I: Summary of annealing conditions.

samples	anneal temperature (°C) /time (s)	reactor	ambient
4,8	1100/15	RTA	N_2
3,7	1100/30	MOCVD	N_2/NH_3
2,6	1300/30	MOCVD	N_2/NH_3
1,5	1400/30	MOCVD	N_2/NH_3

Samples were characterized by channeling Rutherford Backscattering (C-RBS) with a 2 meV ^4He 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 with evaporated Ti/Au contacts deposited on the corners of each sample and annealed at 500 °C for ~15 s. The AlN encapsulated samples were analyzed by C-RBS before having the AlN stripped at ~80 °C in a KOH-based photoresist developer solution (AZ400K) (13,14). This etch has been shown to selectively etch AlN with no measurable GaN etching. The unencapsulated samples had Hall measurements performed prior to C-RBS to avoid any unintentional modification to the electrical characteristics from the He-beam. The surface of the samples was examined by optical and electron microscopy before and after annealing.

RESULTS AND DISCUSSION

Figures 1a and 1b shows the sheet electron concentration and electron Hall mobility versus the annealing conditions for the unencapsulated and AlN encapsulated samples,

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respectively. An unimplanted sample annealed at 1100 C for 15 s in the RTA remained highly resistive with n << $1x10^{15}$ cm^{-2}. The mobility of this undoped film could not be reliably measured with the Hall effect due to the low carrier concentration.

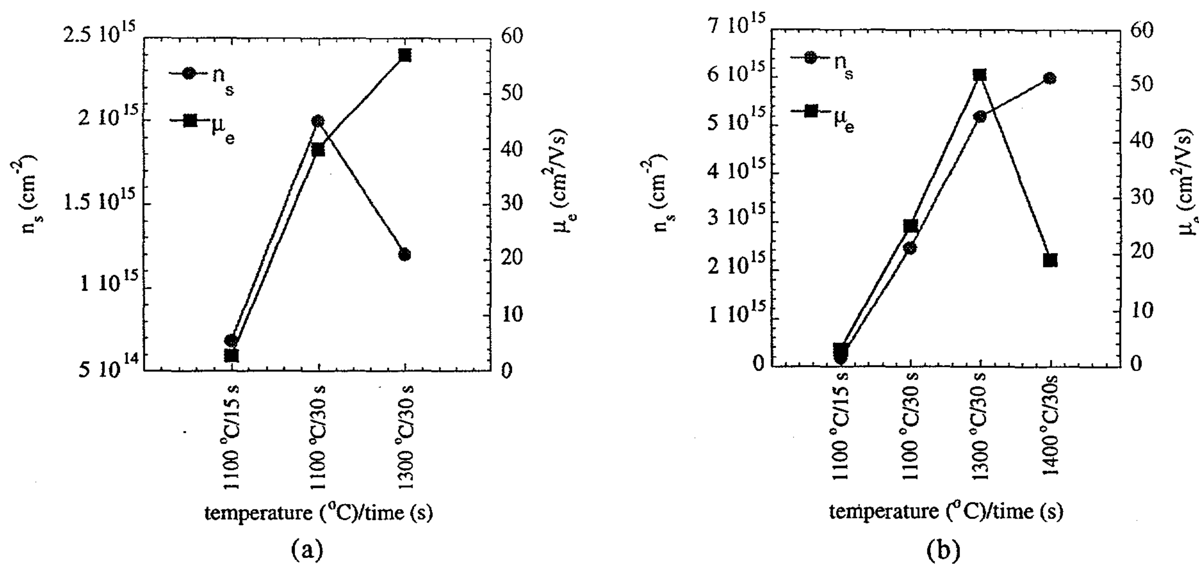

Figure 1. Sheet electron concentration and electron Hall mobility versus annealing treatment for a) unencapsulated and b) AlN encapsulated Si-implanted GaN.

First looking at the data for the unencapsulated samples (Fig 1a), the sample annealed at 1100 °C for 15 s in the RTA has a sheet electron concentration of $6.8x10^{14}$ cm^{-2} or 13.6 % of the implanted dose. This activation percentage is in the range reported for earlier Si-implanted GaN samples annealed in this way (7,8). After the 1100 °C, 30 s MOCVD anneal the number of free electrons goes up to 40% of the implanted dose before decreasing to 24% for the 1300 °C anneal. The decrease for the 1300 °C sample was accompanied by a degradation of the surface of the sample as determined by observation under an optical microscope. (This point will be revisited when discussing the C-RBS spectra later, but it is suspected that the GaN layer has started to decompose during this anneal.) Therefore, the reduction in the electron concentration may be due to loss of material. The Hall mobility increased with increasing thermal treatment and is suggestive of improved crystalline quality. No data is given in Fig. 1a for the unencapsulated sample annealed at 1400 °C since the GaN film completely sublimed or evaporated during this anneal. This was confirmed by C-RBS data for this sample that showed only the substrate Al and O peaks with a slight Ga surface peak.

Now turning to the data for the AlN encapsulated samples (Fig 1b). There is increasing sheet electron density with increasing thermal treatments for the encapsulated samples including the highest temperature anneal. The RTA sample has a lower activity than the comparable unencapsulated sample (3.6% versus 13.6%), however, all the other AlN encapsulated samples have higher electron concentrations than the comparable unencapsulated sample. The 1300 °C sample has a sheet electron concentration of $5.2x10^{15}$ cm^{-2} that is 113% of the Si dose that should have been retained in the GaN layer ($4.6x10^{15}$ cm^{-2}). This may be due to indiffusion of the Si from the AlN encapsulant into the GaN substrate or to the activation of other native donor defects in the GaN layer such as N-vacancies. The sample annealed at 1400 °C has a still higher free electron concentration ($6x10^{15}$ cm^{-2}) that may also be partly due to activation of native defects. This sample had

visible failures in the AlN layer (cracks and voids) that allowed some degree of decomposition of the GaN layer. This was confirmed by scanning electron microscope (SEM) images that show regions of GaN loss. Therefore, the formation of N-vacancies in this sample is very likely and may contribute to the electron concentration.

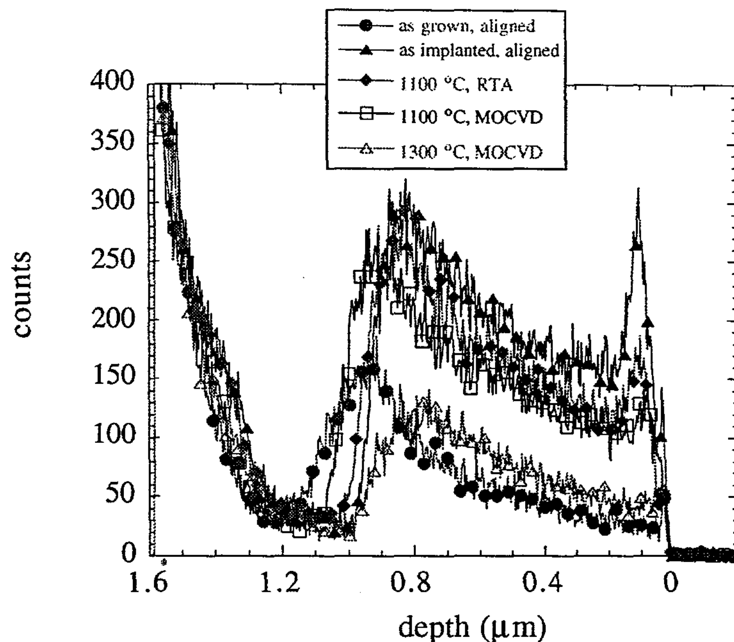

Figure 2: Channeling Rutherford Backscattering (C-RBS) spectra for Si-implanted (100 keV, $5x10^{15}$ cm^{-2}) GaN either as-implanted or annealed as shown in the legend.

Figure 2 shows a compilation of the C-RBS spectra for the unencapsulated samples along with the aligned spectrum for a unimplanted sample. The as-implanted sample shows the damage peak near 100 nm with an additional peak at the surface. The surface peak may be due to preferential sputtering of the surface during Si-implantation and has been reported in earlier implantation studies (15,16). The sample annealed in the RTA has improved channeling and an apparent reduction in the implant damage. It should be noted, however, that the surface peak is also diminished in the RTA sample and it has previously been reported that the change in the surface peak can account for the apparent reduction in the implantation damage peak (16). Upon annealing at higher temperatures or longer times in the MOCVD reactor the channeling continues to improve and approaches, but does not reach, the unimplanted aligned spectra. The 1300 °C sample, however, appeared to show evidence of material loss as demonstrated by the change in position and abruptness of the substrate signal as well as the observation of surface roughing. Therefore, the reduction in the implantation damage peak in this sample may be due to sublimation or evaporation of the implanted region and not recovery of the original crystal structure. The loss of at least part of the Si-implanted region is consistent will the reduction in the free electron concentration in this sample shown in Fig 1a.

Figure 3 shows a compilation of the C-RBS spectra for the AlN encapsulated samples. The as-implanted sample has a damage peak at ~80 nm with no additional surface peak as seen in the unencapsulated sample. The lack of a surface peak in this sample supports the hypothesis that this peak on the unencapsulated sample is due to preferential sputtering since the GaN surface of the encapsulated sample is protected from sputter loss during implantation. A significant reduction in the implantation-induced damage peak occurs after the RTA anneal with a further reduction with increasing thermal processing. The value for the minimum channeling yield (χ_{min}) for the GaN layer on an AlN encapsulated, unimplanted sample was estimated to be 2.5% while the 1400 °C annealed, implanted sample had a χ_{min} value of

12.6%. The as-implanted samples had χ_{min} values of 38.6% (AlN encapsulated) and 34.1% (unencapsulated). Therefore, the 1400 °C annealed sample demonstrates significant damage recovery but not complete damage removal to the virgin, unimplanted level.

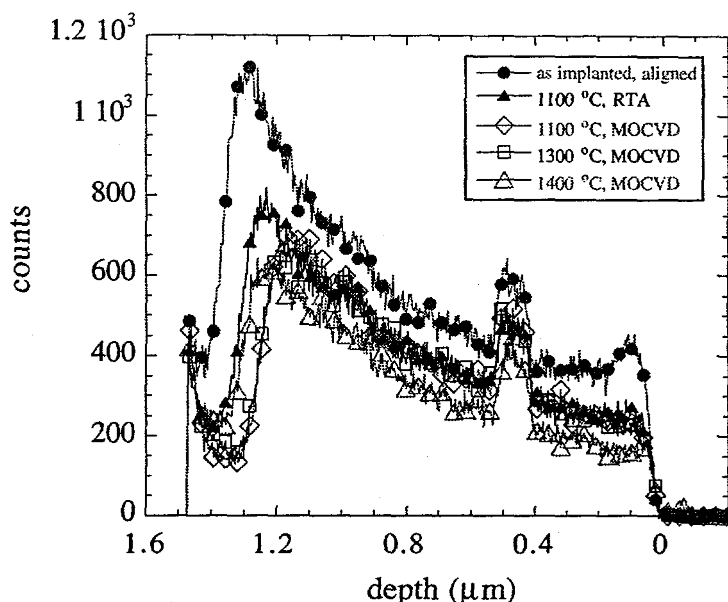

Figure 3: Channeling Rutherford Backscattering (C-RBS) spectra for Si-implanted (210 keV, $5x10^{15}$ cm^{-2}), GaN encapsulated with 120 nm of AlN either as-implanted or annealed as shown in the legend.

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. Electrical data demonstrates that annealing up to 1400 °C increases electrical activity of Si-implanted GaN if the sample can be protected with an AlN encapsulation layer. C-RBS spectra also show that implantation-induced damage can be significantly reduced by using annealing temperatures up to 1400 °C. Further work is needed to improve the thermal stability of the AlN encapsulation; however, once this is accomplished, ion implantation doping of GaN should be a viable technology for high-power and high-temperature electronic devices.

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