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Electrical and structural analysis of high-dose Si implantation in GaN

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For the development of ion implantation processes for GaN to advanced devices, it is important to understand the dose dependence of impurity activation along with implantation-induced damage generation and removal. We find that Si implantation in GaN can achieve 50% activation at a dose of 1×10^{16} cm^{-2}, despite significant residual damage after the 1100 °C activation anneal. The possibility that the generated free carriers are due to implantation damage alone and not Si-donor activation is ruled out by comparing the Si results to those for implantation of the neutral species Ar. Ion channeling and cross-sectional transmission electron microscopy are used to characterize the implantation-induced damage both as implanted and after a 1100 °C anneal. Both techniques confirm that significant damage remains after the anneal, which suggests that activation of implanted Si donors in GaN doses not require complete damage removal. However, an improved annealing process may be needed to further optimize the transport properties of implanted regions in GaN. © *1997 American Institute of Physics.* [S0003-6951(97)02320-6]

Research on the group-III–nitride semiconductors has resulted in remarkable advances in material quality and device performance. The materials improvements were largely the result of the discovery of the utility of a low-temperature (~500 °C) GaN or AlN buffer layer grown on sapphire prior to the high-temperature (~1050 °C) growth of active device layers.[1,2] The further realization that activation of hydrogen-passivated Mg acceptors by thermal annealing could produce *p*-type GaN opened the door for many device demonstrations including light-emitting diodes, laser, detectors, and transistors.[3–10] While further advances in material quality will lead to additional device improvements, many advanced device structures will require improvements in device processing technology as well. One area of processing technology that should play an enabling role, particularly for electronic devices, is ion implantation, which can be used to produce selective area doping or compensation. While *n*- and *p*-type implantation doping of GaN has already been reported with the use of Si and O for *n* type and Mg and Ca for *p* type, further work is needed to optimize the implantation and annealing process.[11,12] In particular, the limits on achievable doping levels via ion implantation, the removal of implantation-induced damage, and the impact of this damage on impurity activation are of interest. Along these lines, the dose dependence of damage formation in Si-implanted GaN at 90 keV and 77 K has recently been reported.[13] In that study, GaN was shown to have a Si-dose threshold for amorphization at 77 K of $\sim2\times10^{16}$ cm^{-2} that is much larger than the amorphization dose for GaAs (4×10^{13} cm^{-2}) but closer to the level for AlAs ($\sim8\times10^{15}$ cm^{-2}) at this temperature. Since, for other compound semiconductors, the upper limit on the practical implantation dose is generally determined by the onset of amorphization and the impurity solubility level, this result suggests that very high implantation doses, and therefore, high doping levels, may be possible via implantation in GaN.

We have studied the structural and electrical properties of Si-implanted GaN up to doses of 1×10^{16} cm^{-2} to ascertain the dose dependence of electrical activation and damage removal. Implantation of Ar, which should be a neutral impurity in GaN, is also studied to better understand the electrical nature of the implantation-induced damage. The impact of the implant activation annealing sequence on the defect concentration is also examined by channeling Rutherford backscattering (C-RBS) and cross-sectional transmission electron microscopy (XTEM).

The GaN layers used in the experiments were 1.5–2.0 μm thick grown on *c*-plane sapphire substrates by metalorganic chemical vapor deposition in a multiwafer rotating disk reactor at 1040 °C with a 20 nm GaN buffer layer grown at 530 °C.[14] The GaN layers were unintentionally doped, with background *n*-type carrier concentrations

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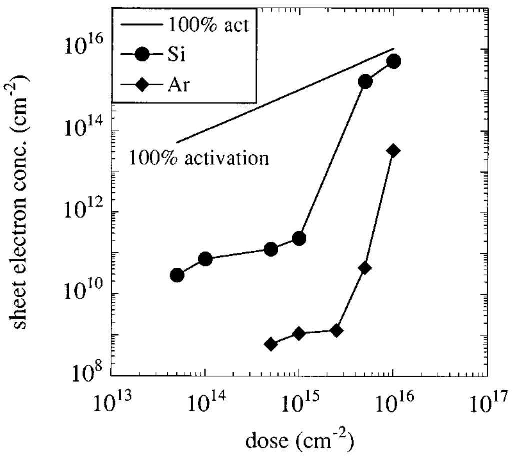

FIG. 1. Sheet electron density vs implantation dose of each ion for Si- and Ar-implanted GaN annealed at 1100 °C for 15 s. The top line represents 100% activation of the implanted dose assuming full ionization.

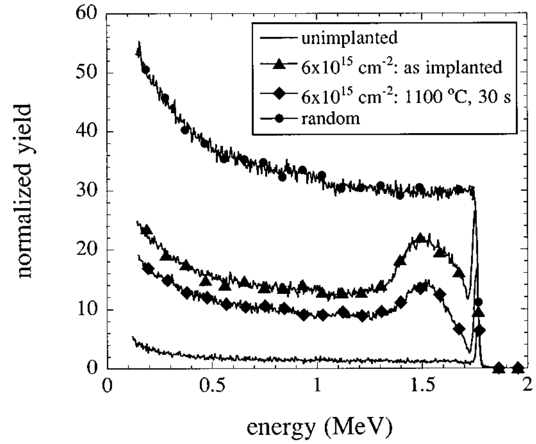

FIG. 2. Channeling Rutherford backscattering (C-RBS) spectra for as-grown (random and aligned, unimplanted) and Si-implanted (90 keV, 6×10^{15} cm^{-2}) GaN (as implanted and after a 1100 °C, 30 s anneal). The implants were performed at room temperature.

$\leqslant 1\times10^{16}$ cm^{-3} as determined by room-temperature Hall measurements. The material maintained its high resistivity when annealed at 1100 °C for 15 s. The as-grown layers had featureless surfaces and were transparent with a strong band-edge luminescence at 356 nm at 4 K. Other strong luminescence peaks were observed near 378 and 388 nm. We speculate that these additional features are due to carbon contamination in the film from the graphite heater in the growth reactor. Si ions were implanted at about 100 keV at doses from 5×10^{13} to 1×10^{16} cm^{-2}. Ar ions were implanted at 140 keV and over the same dose range to place its peak range at the equivalent position as the Si. All samples were annealed at 1100 °C for 15 s in flowing N_2 with the samples in a SiC-coated graphite susceptor. This annealing sequence has previously been shown to activate implanted dopants in GaN.[11,12] Following annealing, the samples were electrically characterized at room temperature by the Hall technique with evaporated Ti/Au Ohmic contacts at the corners of each sample. Structural analysis of selected Si-implanted GaN samples was performed with C-RBS and XTEM.

Figure 1 shows the room-temperature sheet carrier concentrations versus implant dose for the Si- and Ar-implanted samples after the 1100 °C anneal. For the Si-implanted samples, there appears to be no significant donor activation until a dose of 5×10^{15} cm^{-2} is achieved. This is in contrast to earlier results at a dose of 5×10^{14} cm^{-2}, where roughly 10% of the implanted Si ions were ionized at room temperature, corresponding to 94% of the implanted Si forming active donors on the Ga sublattice assuming a Si-donor ionization energy of 62 meV.[11] The absence of free electrons for the lower-dose Si-implanted samples in this study may be due to compensation by background carbon in the as-grown GaN, as was postulated to exist based on the photoluminescence. For the two highest-dose Si-implanted samples, 5 and 10×10^{15} cm^{-2}, 35% and 50%, respectively, of the implanted Si ions created ionized donors at room temperature. The possibility that implant damage alone is generating the free electrons can be ruled out by comparing the Ar-implanted samples at the same dose with the Si-implanted samples, which have over a factor of 100 times more free electrons. If the implantation damage were responsible for the carrier generation or for enhanced conduction by a hopping mechanism, then the Ar-implanted samples, which will have more damage than the Si-implanted samples as a result of Ar's heavier mass, would demonstrate at least as high a concentration of free electrons as the Si-implanted samples. Since this is not the case, implant damage cannot be the cause of the enhanced conduction and the implanted Si must be activated as donors. The significant activation of the implanted Si in the high-doses samples and not the lower-dose samples is explained by the need for the Si concentration to exceed the background carbon concentration that is thought to be compensating the lower-dose Si samples.

Figure 2 shows the C-RBS spectra for as-implanted (Si: 90 keV, 6×10^{15} cm^{-2}) and annealed (1100 °C, 30 s) GaN implanted at room temperature. Figure 3 shows XTEM images of two similarly treated samples. Figures 2 and 3 demonstrate that the sample is not amorphized under these conditions and show the difficulty in removing the implantation-induced damage from the GaN layer. Similar results were obtained at a dose of 1×10^{16} cm^{-2} while at 2.4×10^{16} cm^{-2} an amorphous region occurred near the surface. Although the C-RBS spectra in Fig. 2 displays improved channeling after annealing, as seen by the decrease in the backscattered signal, when changes in dechanneling due to the reduced surface peak are accounted for, no significant change in the buried defect concentration is evident.[15] This is confirmed by the XTEM images of Fig. 3, where the annealed sample still has significant damage apparently consisting of clusters, loops, and planar defects. The fact that significant damage remains for an implantation and annealing sequence that produces significant electrical activation of Si donors, as seen in Fig. 1, suggests that complete defect removal is not required to activate implanted Si donors in GaN. This is in stark contrast to the case of Si-implanted GaAs, where damage removal and dopant activation are sequential processes.[16] However, since the defects in GaN will most likely act as scattering centers and degrade transport properties of the implanted layers, it will be desirable to

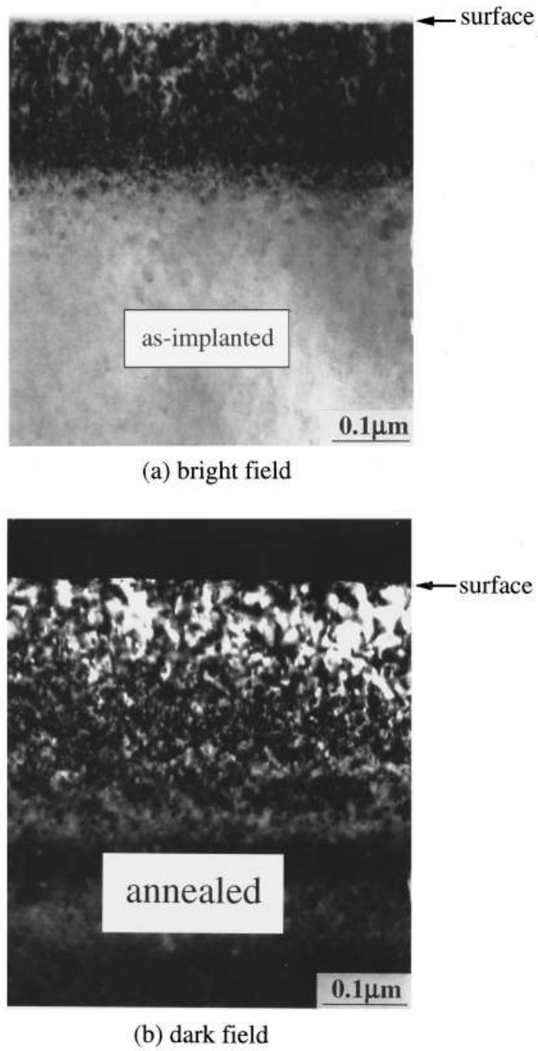

FIG. 3. Cross-sectional transmission electron micrograph (XTEM) of Si-implanted GaN (90 keV, 6×10^{15} cm^{-2}) as implanted and after a 1100 °C, 30 s anneal. The implants were performed at room temperature.

develop an annealing procedure that more effectively restores the initial crystal quality. This will most likely require using a higher annealing temperature.

In conclusion, the dose dependence of Si implantation in GaN has been reported. Although low-dose samples do not show Si activation, possibly due to a background carbon level in the sample, a Si dose of 1×10^{16} cm^{-2} demonstrates 50% activation. The possibility that implantation damage alone is responsible for the enhanced conductivity is discounted by comparing the Si-implanted samples to Ar-implanted samples. Finally, C-RBS and XTEM show that, for these high doses, significant damage remains even after the 1100 °C activation anneal. Therefore, complete removal of implant damage in GaN is not required to achieve activation of implanted Si donors. However, improved annealing may be desirable to optimize the transport properties of implanted regions in GaN.

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[1] H. Amano, M. Kitah, K. Hiramatsu, and I. Akasaki, J. Electrochem. Soc. **137**, 1639 (1990).
[2] S. Nakamura, M. Senoh, and T. Mukai, Jpn. J. Appl. Phys. 1 **30**, L1708 (1991).
[3] H. Amano, M. Kito, K. Hiramatsu, and I. Akasaki, Jpn. J. Appl. Phys. 1 **28**, L2112 (1989).
[4] S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, Jpn. J. Appl. Phys. 1 **31**, L139 (1992).
[5] I. Akasaki, H. Amano, M. Kito, and K. Hiramatsu, J. Lumin. **48/49**, 666 (1991).
[6] S. Nakamura, T. Mukai, and M. Senoh, Appl. Phys. Lett. **64**, 1687 (1994).
[7] M. A. Khan, J. N. Kuznia, A. R. Bhattarai, and D. T. Olson, Appl. Phys. Lett. **62**, 1786 (1993).
[8] S. C. Binari, L. B. Rowland, W. Kruppa, G. Kelner, K. Doverspike, and D. K. Gaskill, Electron. Lett. **30**, 1248 (1994).
[9] M. A. Khan, A. Bhattarai, J. N. Kuznia, and D. T. Olson, Appl. Phys. Lett. **63**, 1214 (1993).
[10] J. C. Zolper, R. J. Shul, A. G. Baca, R. W. Wilson, S. J. Pearton, and R. A. Stall, Appl. Phys. Lett. **68**, 2273 (1996).
[11] S. J. Pearton, C. B. Vartuli, J. C. Zolper, C. Yuan, and R. A. Stall, Appl. Phys. Lett. **67**, 1435 (1995).
[12] J. C. Zolper, R. G. Wilson, S. J. Pearton, and R. A. Stall, Appl. Phys. Lett. **68**, 1945 (1996).
[13] H. H. Tan, J. S. Williams, J. Zou, D. J. H. Cockayne, S. J. Pearton, and R. A. Stall, Appl. Phys. Lett. **69**, 2364 (1996).
[14] C. Yuan, T. Salagaj, A. Gurary, P. Zawadzki, C. S. Chern, W. Kroll, R. A. Stall, Y. Li, M. Schurman, C.-Y. Hwang, W. E. Mayo, Y. Lu, S. J. Pearton, S. Krishnankutty, and R. M. Kolbas, J. Electrochem. Soc. **142**, L163 (1995).
[15] H. H. Tan, J. S. Williams, J. Zou, D. J. H. Cockayne, S. J. Pearton, and C. Yuan, Proceedings of the 1st Symposium on III–V Nitride Materials and Processes, Electrochemical Society, Vol. 96–11, 142 (1996).
[16] *Ion Implantation and Beam Processing*, edited by J. S. Williams and J. M. Poate (Academic, Sydney, 1984).