RBS LATTICE SITE LOCATION AND DAMAGE RECOVERY STUDIES IN GaN

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Abstract

Erbium was implanted with 160 keV at doses between $5x10^{14}$ and $5x10^{15}$ at/cm^2 into (0001) epitaxial GaN on sapphire and annealed at various temperatures between 600° and 1000° C. The RBS/Channeling technique was used to analyze the damage recovery during different annealing steps and to determine the lattice location of the implanted Er. For a sample implanted with $5x10^{14}$ and annealed for 30 min at 600° C a complete overlap of the Er and Ga angular scans across the <0001> axis was observed, indicating that 100% of Er occupies substitutional sites. Measurements along the $<10\bar{1}1>$ channel show that Er is located on Ga sites. The damage recovery was slightly better for the samples co-implanted with the same dose of Oxygen in an overlapping profile (E=25 keV). However, a complete recovery of the damage caused by the implantation was not achieved. Samples implanted with higher Er and O doses ($5x10^{15}$ at/cm^2) and at the same energies as above were annealed at 600° for 30 min and at 900°, 1000° C for 120 s using a proximity cap. The higher dose caused an almost complete amorphisation of the surface layer. After annealing indications of epitaxial regrowth were observed, however, the substitutional fraction remains substantially lower and the damage recovery is less complete.

Introduction

GaN and other wide gap nitrides are materials with a large potential for high temperature electronics and optoelectronics applications. However, for the integration of GaN into circuits an adequate structuring technique is necessary. At present, the standard technique for selectively doping semiconductors and thus creating device structures is ion implantation. It unavoidably introduces damage to the crystal which has to be annealed in order to achieve electrically or optically active doping. Whereas in standard semiconductors like Si these procedures are well understood the situation in GaN is more complicated. The strong bonding of this material on one

hand ensures a high resistance to lattice damage and amorphisation on the other hand it considerably hampers the epitaxial regrowth on the underlying undamaged crystal lattice after an implantation. It is therefore interesting to study the behavior of impurities after implantation as well as the general recovery of the GaN lattice. In the present study the lattice location of Er implanted in GaN and the possible influence of coimplanted Oxygen on the Er behavior was investigated. Doping of GaN with Er during growth or by implantation has been intensively studied mainly in photoluminescence measurements [1, 2] due to the potential application of this impurity in optoelectronics. The intra 4f shell transitions at a wavelength of 1.54 µm, which coincides with a minimum in loss in silica optical fibers, makes Er an interesting, optically active ion in devices such as lasers, optical amplifiers and optically pumped glass fibers [3].

Experiment

Samples were cut from high quality (0001) GaN epilayers of 4µm thickness grown by the MOCVD technique on sapphire substrates at the University of Florida. In some cases also commercially available material (CREE, 1.5µm) was used. The unintentional n-type background doping was of the order of 10^{16} cm^{-3}. The GaN samples were implanted at room temperature with doses of D = $5x10^{14}$ Er^{+}/cm^{2} and $5x10^{15}$ Er^{+}/cm^{2} at an energy of 160 keV. The measured implantation range (R_p) was about 40 nm in agreement with TRIM95 [4] calculations. Some samples were further implanted with Oxygen with the same doses, respectively. The energy of the O ions was chosen to be 25 keV in order to obtain an overlap of the O and Er profiles. After the implantation all samples were annealed between graphite strips at various temperatures under flowing nitrogen using another GaN sample as a proximity cap.

RBS/channeling studies were performed with a 1 mm diameter collimated beam of 2 MeV He^{+} ions. The backscattered particles were detected at 140^{o} and 180^{o}, with respect to the beam direction, using silicon surface barrier detectors located in the standard IBM geometry and with resolutions of 13 and 16 keV, respectively. The angular scans were carried out using a two-axis goniometer and, in order to avoid radiation effects due to the analyzing beam, a fresh spot for each measurement was used. To reduce the pile-up effect which would degrade the sensitivity for the Er signal, the beam current was kept below 2 nA. Full angular scans of the axial directions were recorded for the <0001> and <$10\bar{1}1$> axes. The experimental results were compared to computer simulations which were carried out using a Monte Carlo code [5]. The wurtzite

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structure, not part of the original code, was incorporated in order to simulate the GaN angular curves.

Results

A. Damage annealing

Figure 1 shows the random and <0001> aligned RBS spectra of the samples (CREE, 1.5 µm) implanted with $5x10^{14}$ cm^{-2} (Fig. 1a) and $5x10^{15}$ cm^{-2} (Fig. 1b). As can be seen the amount of damage created by the implantation of the higher dose is just enough to produce an overlap of the random and aligned spectra in the whole implanted region (55nm). This result, also observed in other semiconductors, is an indication of the amorphisation of this region. In the present case it allows to conclude that a dose of D = $5x10^{15}$ Er^{+}/cm^{2} at 160 keV is just above the threshold dose for the amorphisation of GaN at 293 K. This is slightly lower than in the case of Si implantation into GaN [6] but, due to the higher mass of Er, not unexpected. Essentially the same features were observed in the samples coimplanted with oxygen.

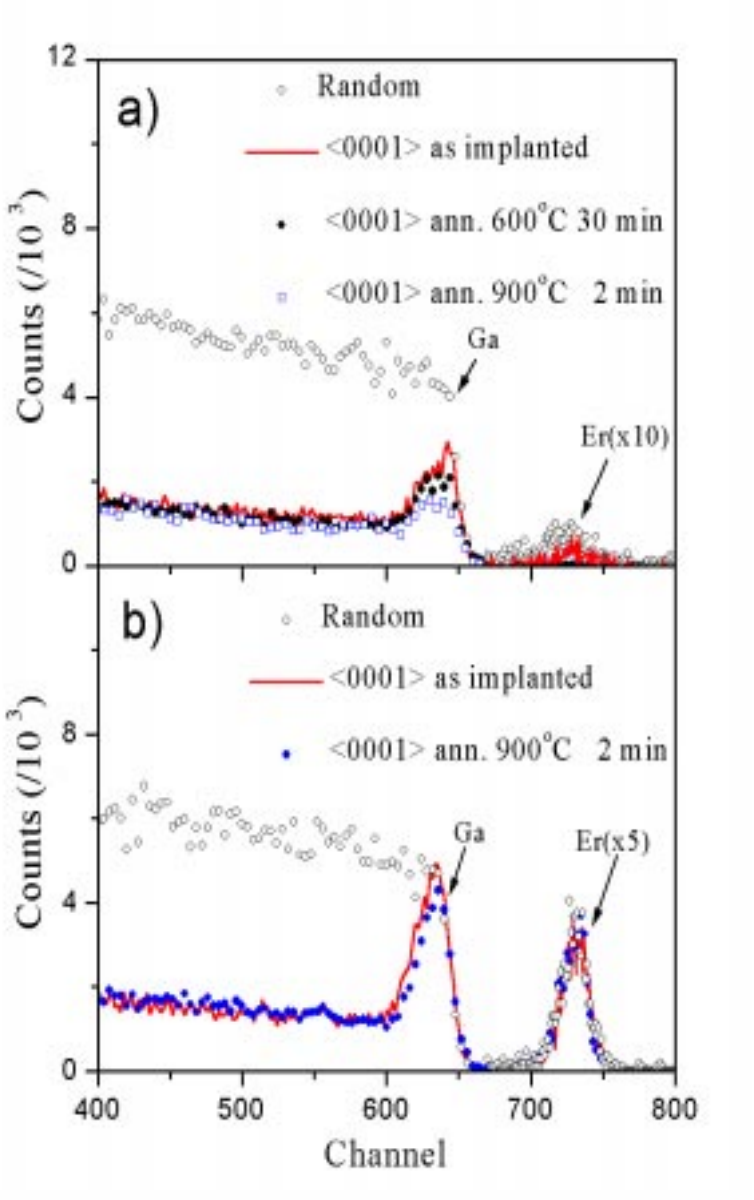

Figure 1: Random and <0001> aligned RBS spectra for GaN samples implanted with two different doses of Er ions after annealing at different temperatures. a) D = $5x10^{14}$ Er^{+}/cm^{2}, b) D = $5x10^{15}$ Er^{+}/cm^{2}

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A mild annealing at 600°C for 30 min reduces the damage in the 4 µm thick sample almost to the virgin level (of χ_{min} = 2%), whereas in the 1.5 µm sample implanted with the lower dose of Er only a slight decrease of the damage is observed (Fig. 1a). The same annealing procedure has little effect on the damage of the samples implanted with $5x10^{15}$ ions/cm^{-2} (Fig. 1b). For both Er doses the results show that the coimplantation of O does not influence the recovery process significantly at this temperature. A further small decrease of the damage peak in all the samples after annealing at 900° C can be observed (Fig. 1b). The small narrowing of the Ga peak in figure 1b indicates that some epitaxial regrowth of the amorphous layer occurs at this temperature. Further regrowth takes place at 1000° C yielding values of χ_{min} = 12% and χ_{min} = 60% for the sample with the lowest and the highest dose, respectively. An extension of the annealing time at 1000° C to 30 min leads to an increase of the Ga surface peak for the samples with the lowest Er and O doses, probably as a consequence of surface decomposition. During the whole annealing program the Er profile in both Er + O implanted samples remained unchanged. A different behavior is observed for the samples implanted with Er only. Here at the highest annealing temperatures the Er peak shows a narrowing towards the surface whereas the damage peak is reduced similarly to the other samples. This can be taken as an indication that the presence of Oxygen in the vicinity of the Er impurity contributes to the stabilization of Er in substitutional positions. Generally the results illustrate the difficulty to anneal the damage completely, even for low implantation doses.

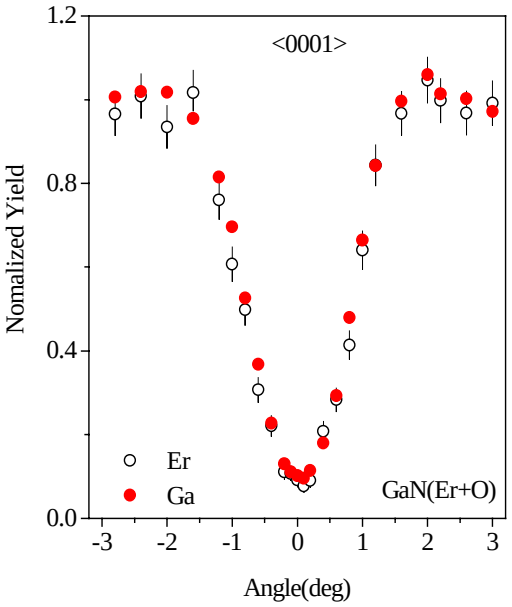

Figure 2: Angular scan through the <0001> axis of the GaN wurtzite lattice for a sample (Univ. Florida) implanted with Er and O at a dose of $5x10^{14}$ cm^{-2} each and annealed at 600° C for 30 min.

B. Lattice location

Angular scans through the <0001> axis immediately after the lower dose implantations show minimum yield values of 40% for the samples implanted with Er and Er + O. For these

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measurements the Ga window was set from 20 to 80 nm, incorporating all the Er implanted depth region. The corresponding Er scans show a complete overlap with the Ga scans indicating that Erbium is subjected to exactly the same disorder caused by the implantation as the Ga sublattice. In figure 2 a detailed angular scan through the <0001> axis for the sample grown at Florida University implanted with $5x10^{14}cm^{-2}$ Er + O after implantation and a mild annealing for 30 min at 600°C is shown. The temperature was chosen because it is easily reached with conventional annealing set-ups. A minimum yield of χ_{min} = 10% is derived which can be compared to the minimum yield of a virgin sample of χ_{min} = 2%. Again the Er and Ga curves fully overlap which is an indication that Er is occupying a Ga site. The large fraction of Er in substitutional sites after the 600° C annealing step agrees well with a hyperfine interaction study on the incorporation of the transition metal Hf into GaN after implantation [7]. Also there it was observed that the implantation damage around the Hf impurity was annealed to a large extent at 600° C. This effect was attributed mainly to the restoration of the N sublattice.

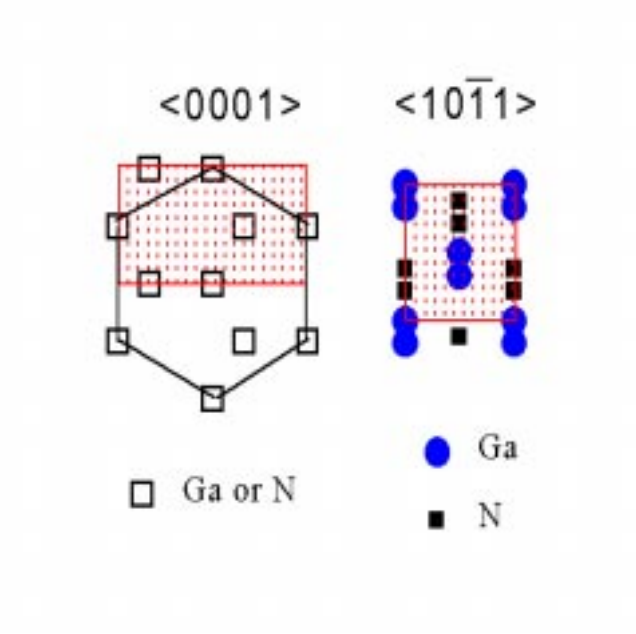

Figure 3: Projections of the atomic position of Ga and N in the GaN wurtzite lattice as seen along the <0001> and the <10$\bar{1}$1> axes.

In samples obtained from CREE the 600° C annealing step produces a decrease of 10% in the number of atoms in substitutional sites for the sample containing only Er while for the sample coimplanted with O no changes were observed. The annealing at 900°C leads to a further reduction of the substitutional fraction and a narrowing on the bottom of the angular curve of Er for the Er implanted sample while for the sample coimplanted with O Er remains in the Ga site. The observed narrowing could be due to the association of Er with defects, which lead to a slight displacement of the Er atoms from the ideal substitutional positions.

The assumption made above that Er is located on the Ga sites could be proven by a scan across the <10$\bar{1}$1> axis. Contrary to the <0001> axis, where we have mixed rows of Ga and N, in the <10$\bar{1}$1> direction we have pure Ga and N rows as depicted in figure 3. The different atomic numbers of Ga and N result in different steering potentials for the respective rows leading in turn

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to angular scans with very different widths as can be seen from the simulated curves shown in figure 4. Simulations or the <0001> axis with an average potential of the mixed Ga + N rows yield just one width. By varying the fraction of Er atoms in Ga and random sites it was tried to reproduce the experimental data. The best agreement was obtained (continuous curve in Fig. 4) by assuming that 70% of the Er atoms are in regular Ga sites of the lattice with the rest at random positions. The random fraction takes into account the still damaged or not perfectly regrown regions of the lattice. A comparison of the O co-implanted to the samples implanted only with Er but subjected to the same annealing procedures indicate that the presence of O stabilizes the Er in the Ga sites probably through the formation of Er-O complexes similar to the ones observed in Si and GaAs co-doped with Er and O[8, 9].

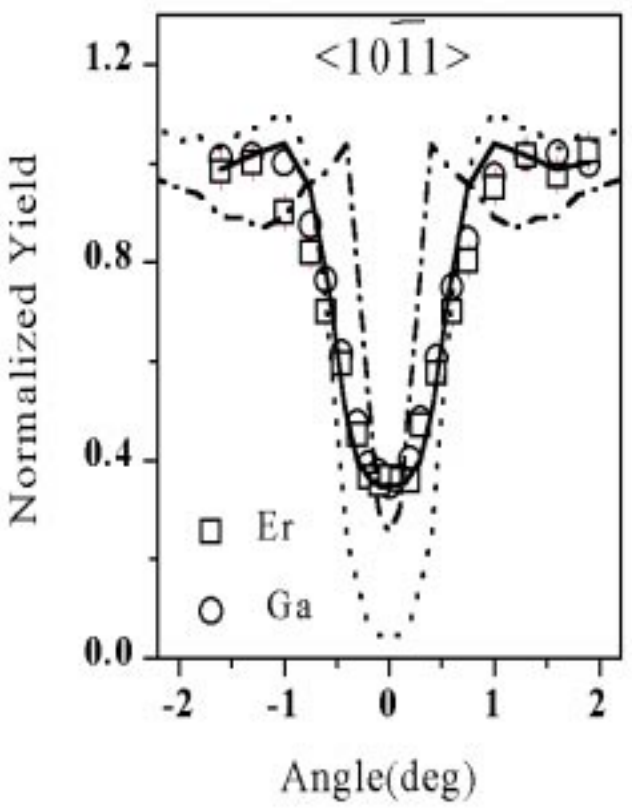

Figure 4: Angular scan through the <10$\bar{1}$1> axis for the sample implanted with $5x10^{14}$ cm^{-2} Er+O after annealing at 900°C. The dotted and the dash-dotted curve are the angular scans expected for Ga and N, respectively. The symbols are the data points obtained for Er and Ga and the solid line represents the result of a simulation assuming 70% of the Er impurities in substitutional Ga positions.

Conclusions

After implantation into epitaxial GaN and annealing Er is incorporated to more than 70% into substitutional Ga sites. The threshold dose for the amorphisation of the GaN films studied is close to $5x10^{15}$ Er^{+}/cm^{2}, a relatively high value compared with other III-V compounds. The implantation damage in lightly damaged samples ($D = 5x10^{14}$ cm^{-2}) starts to anneal at 600°C. However, an increase of the annealing temperature up to 900°C is not enough to remove the damage completely. At this temperature the thickness of the amorphous layer is reduced, indicating the occurrence of some epitaxial regrowth. The presence of low doses of O in the implanted layer does not influence the annealing process significantly but increases the amount of Er in Ga sites after the annealing at 900°C. At the highest annealing temperatures the presence of O seems to stabilize the Er in substitutional lattice position.

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