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Deep levels in KOH etched and MOCVD regrown GaN p-n junctions

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Threading dislocations continue to challenge the functionality and reliability of GaN based devices. This work investigates the selective etching of threading dislocations in a GaN template grown by metalorganic chemical vapor deposition (MOCVD), and subsequent regrowth as a method to reduce the dislocation density. A 2.0 μm template layer was grown first, followed by either 2 second or 30 second etching of the GaN in KOH, followed by regrowth of 2 μm of GaN and 0.2 μm of p-type GaN. Atomic force microscopy (AFM) images showed that hexagonal pits were opened up by the KOH etch. Deep level transient spectroscopy (DLTS) measurements showed several traps present, including a dominant electron trap at 0.585 eV, with capture cross section of 1.0×10^{-15} cm^2 and concentration of 10^{16}/cm^3. Another electron trap was also measured in the same range (0.536 eV, 5.7×10^{-16} cm^2) with an order of magnitude lower concentration. From the DLTS measurements, the KOH dislocation etching did not significantly reduce the concentration of defects, or eliminate any specific traps.

1 Introduction

GaN is being developed for ultraviolet light emitters and detectors. Also, modulation doped field effect transistors are expected to have a sizeable impact on 1.8 to 2.1 GHz, and higher frequency communications. The difficulty in achieving these goals is presented by the lack of native substrates, resulting in high density of dislocations in epitaxial GaN, typically measured at about 10^9-10^{10}/cm^2. Sapphire is frequently used as a substrate in spite of its mismatch of 16.1% in the *a*-direction, and 19.7% in the *c*-direction. Dislocations accommodate lattice mismatch between the substrate and the epitaxial layer. Misfit dislocations are seen parallel to the interface. Threading dislocations propagate perpendicular to the interface. The various types of dislocations include edge, screw, and mixed. The density of dislocations and the ratio of each type depend on the substrate/buffer template, the growth method, and the growth stoichiometry. Whether or not the screw dislocations have an open or closed core is also thought to be dependent on the growth stoichiometry and method used to grow, and change the leakage and scattering properties of the dislocation.

Previous work has indicated that pure screw dislocations are the main culprits in providing unwanted current paths, rather than pure edge or mixed type dislocations [1]. Parasitic current paths decrease the gain and increase the noise in electronic devices, increase the threshold current and decrease the slope efficiency of lasers, and reduce the responsivity of detectors. Propagation of threading edge dislocations through active layers of electronic devices has also been reported to limit mobility by providing charged scattering centers [2].

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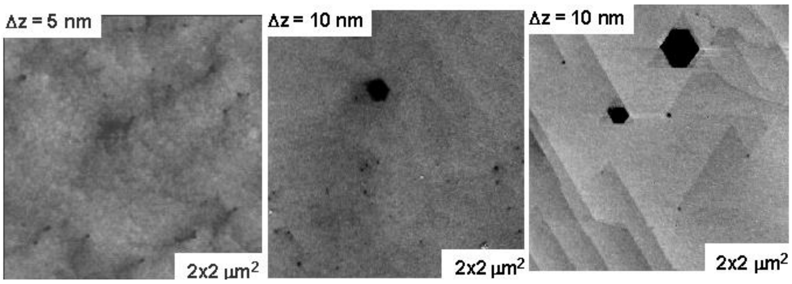
The search for methods to reduce the density of dislocations has resulted in a number of innovative procedures, including lateral epitaxial overgrowth and the pendeo-epitaxy variant. In molecular beam epitaxy, growth is performed under gallium rich conditions where possible, since excess gallium on the surface increases the surface mobility of the nitrogen, or with surfactants such as magnesium [3] and antimony [4].

Another approach is to selectively etch the dislocation defects and deposit an overlayer that will decrease the threading dislocation density if the defective regions no longer provide a nucleation surface and growth takes place laterally from the etch pits. This work presents initial results of selective etching of the defective regions *ex-situ* with KOH, and regrowth on the etched templates. Investigations have shown that KOH preferentially etches the mixed dislocations to form hexagonal pits [5, 6]. It also creates a bimodal distribution of etch pit sizes, although the reasons for this are unknown at this time.



(a) (b) (c)

Fig. 1 AFM images of the templates for regrowth of GaN by MOCVD: (a) the sample without etching; (b) etched for 2 seconds in KOH, and; (c) etched for 30 seconds in KOH, respectively. Etching for 2 seconds starts to open up pits. Longer KOH etching enlarges the pits and results in a layered structure.

2 Experiment GaN epilayers were grown in a metalorganic chemical vapor deposition (MOCVD) system at a pressure of 200 Torr, using c-plane sapphire (α-Al_2O_3) as a substrate. Trimethylgallium (TMG) and ammonia (NH_3) were used as sources of Ga and N, respectively. The substrate was pre-heated in a stream of H_2 at 1030 ºC for 3 min, on which a 30 nm-thick GaN buffer layer was grown at 550 ºC. This was followed by the growth of 2 µm of undoped GaN at 1010 ºC. The flow rates of the TMG, NH_3, and H_2 used in the growth of GaN were 78.58 µmol/min, 316 mmol/min, and 286 mmol/min, respectively. Parts of these samples were treated with molten KOH at 210 °C, one for 2 seconds and one for 30 seconds. Overgrowth of 2 µm of GaN on the KOH etched and non-etched control GaN template was done at 1020 ºC. Finally, a Mg-doped layer 200 nm thick was grown to form a *p-n* junction.

Conventional photolithography was used to pattern the samples prior to deposition of the Ti/Al/Ti/Au (300Å/1000Å/300Å/150Å) metalization in a background vacuum of better than $4x10^{-7}$ Torr. The contacts were annealed at 900 ºC for 1 min by rapid thermal annealing in nitrogen ambient. Schottky diodes were fabricated with circular Ni/Au (300Å /750Å) contacts 200 µm in diameter.

Structural and optical characterization did not reveal any significant differences in the material properties. X-ray diffraction full width at half maximum (FWHM) was 4.7-4.8 arcmin for the (002) line, with negligible difference between the etched and regrown, and non-etched and regrown layers. The (102) line was 6.9, 7.5, and 6.8 arcmin for the non-etched sample, the sample etched for 2 sec, and the sample etched for 30 sec, respectively. Photoluminescence spectra showed very similar characteristics for all samples, with no distinguishing differences. The FWHM of the exciton peaks at 15 K ranged from 4.6 to 7 meV. Structural characterization was also done with AFM. The effect on the etched surface is seen in Fig. 1. KOH etching for 2 sec etches small pits in the surface. KOH etching for 30 sec opens up the pits to larger hexagonal shapes.

Electrical measurements were also performed. Current versus voltage (I-V) measurements showed similar leakage currents for all of the treatments. An annealing effect was seen for all of the samples, where the leakage current at –5 to –10 volts increased by nearly a factor of ten after the first DLTS scan up to 700K. Typical leakage currents were 1-2 x 10^{-5} amps at –10 V.

Deep level transient spectroscopy (DLTS) was used to measure the defect concentration for each of the treatments, as well as the defect energies and capture cross sections. The DLTS setup is based on a SULA system, with added digitization of the transients for multi-exponential component fitting. Transients recorded at each temperature step were obtained by averaging ~2000 transients together, taking ~600 points at 0.1 msec sampling intervals. The filling pulse width was 10 msec. The temperature was varied in 4 K steps from 80 K to 700 K.

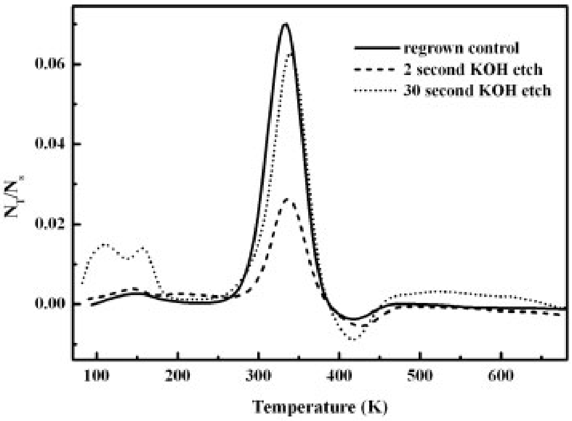


Fig. 2 DLTS ratewindow spectra for MOCVD grown GaN p-n junctions, comparing the non-etched regrown control sample, to GaN etched for 2 and 30 seconds in KOH prior to regrowth. The measurement conditions were: 3 V filling pulse, –1 V measurement bias, 10 msec filling pulse width. The ratewindow is 228/sec.

3 Results The ratewindow plot for the control sample, and the samples etched in KOH for 2 and 30 seconds in Fig. 2 shows several traps. From this ratewindow plot, it appears that the 2 second etch in KOH was most effective at reducing the most prominent trap at 340 K. A comparison of the ratewindow plots for several scans from diodes processed identically revealed that the variation in the concentration of traps was nearly as large as those seen in Fig. 2. However, the trap concentration at 340 K was consistently lower for the material etched for 2 seconds compared to the control sample, or the sample etched for 30 seconds. Etching for 30 seconds produced some of the highest concentration traps at low temperature, below 200 K. None of the etching treatments eliminated any specific traps. The Arrhenius plot is given in Fig. 3, showing the energy for the electron and hole traps. Table 1 presents the characteristics of each trap. The hole trap at 75 meV, the peak of which can be partially seen at the lowest temperatures of Fig. 2. By fitting the transients, the peak at 300-350 K is determined to be composed of two traps with energies of 0.536 eV and 0.585 eV.

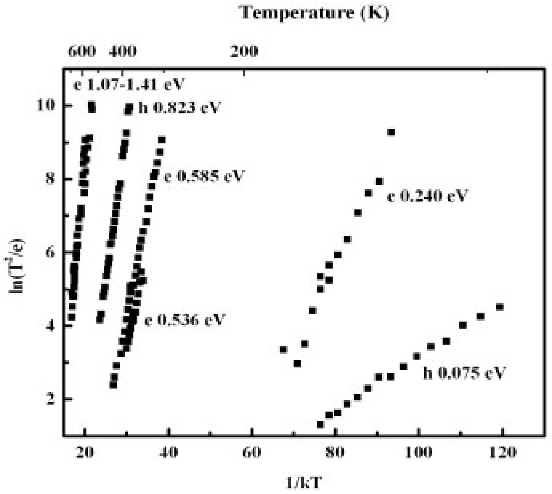


Fig. 3 DLTS Arrhenius plot for the spectra in Fig. 2. Traps at 0.24 eV and 0.585 eV are commonly seen in n-GaN grown by different methods. The hole trap at 75 meV has not been reported previously.

The capture kinetics were also studied as a means to discriminate between point defects and linear defects, such as dislocations. Capacitance transient amplitudes from dislocations have been shown to have a logarithmic dependence on filling pulse width [7]. Increasing the filling pulse from 1 msec to 200 msec for the trap at 340 K resulted in a linear increased in amplitude when plotted versus the log of the filling pulse width, indicating that the trap is related to dislocations. The trap at 160 K showed a change in emission amplitude when varying the filling pulse width from 1 msec to 200 msec, but the response was complicated by the metastable nature of the trap, which is discussed next.

The concentration of traps measured at

temperatures below room temperature depended on the conditions during cooling. The deep level spectra in Fig. 4 for the sample etched for 30 sec were collected under various conditions during cooling to 80 K, including 0 V, 150 μA forward current, and –10 V. This shows that the configuration of defect structure depends on the presence of electrons, being electrically active when the traps are initially filled, similar to the study by Wu, et al. [8]. There is also a thermal annealing effect as seen previously [9], shown by the fact that the spectra taken after cooling with –10 V applied is higher than the spectra taken previously with 0 V cooling. As a result of this observation, all of the spectra in Fig. 2 were recorded after heating to 700 K, and with 150 μA applied during cooling to the starting temperature of 80 K.

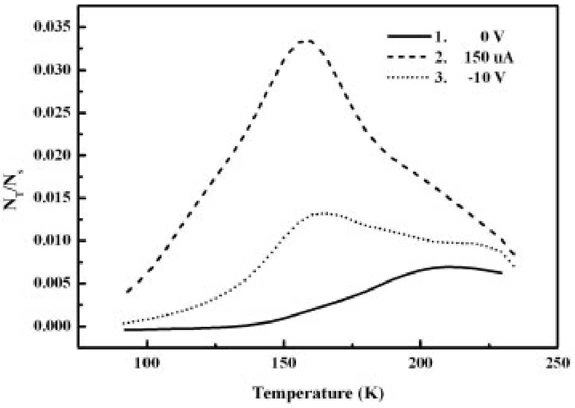


Fig. 4 The concentration of deep levels at 160 K depended on the conditions during cooling, indicating a metastable configuration. Also, there is a thermal annealing effect, since the spectra taken at –10 V should be lower than the spectra taken at 0 V. The order in which the spectra were taken is (1) 0 V, (2) 150 μA, 3) –10 V.

Table 1 Summary of trap energies and capture cross sections for the MOCVD GaN. The traps are common to all of the samples, regardless of KOH etching.

E_T (eV)	E_v + 0.075	E_c – 0.240	E_c – 0.536	E_c – 0.585	E_v + 0.823	E_c – 1.07	Ec – 1.41
σ (cm^2)	$1.2x10^{-19}$	$1.2x10^{-15}$	$5.7x10^{-16}$	$1.0x10^{-15}$	$8.6x10^{-15}$	$1.1x10^{-15}$	$4.7x10^{-13}$
Peak T	<80 K	160 K	340 K	340K	420 K	500-600 K	500-600 K

4 Conclusions This work shows that a defect selective etch such as KOH does not have a significant effect on the defect concentration in subsequently grown GaN. Either the dislocations that are etched can still provide the same strained arrangement of nucleation sites, or the defects characterized by DLTS are not related entirely to the dislocations. A new, low energy hole trap was detected at 0.075 eV, and the trap that is dominant in most DLTS spectra for various growth methods and conditions was decomposed to two traps, one at 0.536 eV and one at 0.585 eV with a higher concentration.

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