Microstructural evolution in H ion induced splitting of freestanding GaN


1Max Planck Institute of Microstructure Physics, Weinberg 2, D 06120 Halle, Germany
2Département de Physique, Université de Montréal, Succursale Centre Ville, Montréal, Québec, H3T 1J4, Canada
3Department of Physics, Martin-Luther-University Halle-Wittenberg, Friedemann-Bach-Platz 6, D 06108 Halle, Germany

(Received 24 April 2008; accepted 12 June 2008; published online 25 July 2008)

We investigated the microstructural transformations during hydrogen ion-induced splitting of GaN thin layers. Cross-sectional transmission electron microscopy and positron annihilation spectroscopy data show that the implanted region is decorated with a high density of 1–2 nm bubbles resulting from vacancy clustering during implantation. These nanobubbles persist up to 450 °C. Ion channeling data show a strong dechanneling enhancement in this temperature range tentatively attributed to strain-induced lattice distortion. The dechanneling level decreases following the formation of plateletlike structures at 475 °C. Extended internal surfaces develop around 550 °C leading to the exfoliation of GaN thin layer. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2955832]

GaN is attracting a great deal of attention as a promising semiconductor for environmentally compatible solid-state lightning and advanced optoelectronics. The emerging technologies still face major challenges due to the limited quality of the heteroepitaxial structures and to the high price of freestanding (fs) GaN wafers. The ion-cut process holds promise for overcoming these obstacles in an analogous scheme as for the mature technology of silicon on insulator. In this process, implanted H and/or He ions act as an atomic scalpel which allows the transfer of bulk quality thin layers onto different host materials accomplishing a wide variety of heterostructures frequently unattainable by epitaxy. The ion-cut process has been applied to various semiconductor materials such as Ge, InP, and GaAs. Independently of the material, the interaction of the implanted species with the radiation damage seems to play the key role in the splitting process. Apart from Si which was intensively investigated, only few studies were devoted to investigate the atomic processes involved in the splitting of other semiconductors. GaN exfoliation induced by H implantation was reported by Kucheyev et al. However, detailed studies on the mechanisms of ion slicing of GaN are still missing. Understanding these fundamental aspects is vital in order to control and optimize the ion-cut process. This letter sheds some light on structural details of H-implanted fs-GaN and critical transformations leading to thin layer exfoliation.

≈300-μm-thick 2 in. double side polished undoped fs-GaN wafers were used in this study. The wafers were subject to room temperature H implantation at 50 keV with a fluence of 2.6 × 10^{17} atom/cm². A number of samples, as implanted or annealed at different temperatures, were analyzed using cross-sectional transmission electron microscopy (XTEM), high resolution x-ray diffraction, Rutherford backscattering in channeling mode (RBS/C), elastic recoil detection (ERD), and positron annihilation spectroscopy (PAS). The annealing time was ≈1–2 min.

Several atomic processes take place during the implantation of energetic H ions generating defects from both sub-

![Image](329x114 to 545x318)

FIG. 1. (Color online) (a) XTEM image of damage induced in GaN by H ion implantation at 50 keV with a fluence of 2.6 × 10^{17} atom/cm². (b) S parameter depth profile measured before (triangles) and after (squares) H implantation. (c) H concentration/10^{22} cm⁻³ depth profile (circles) and implantation damage profile (line) as deduced from ERD and ion channeling, respectively. (d) X-ray θ/2θ scans of (0002) GaN before and after H implantation.
stands for dynamic annealing cannot explain the unusually high fluence required for the splitting of GaN. The nature of H-defect complexes and their thermal evolution may play the most important role in the annealing process. X-ray diffraction experiments indicate that open volume defects such as nanobubbles, point defect clusters, dislocations, and H-defect complexes can also induce a strong localized lattice deformation leading to an increase of the dechanneling yield [see Ref. 12 and references therein]. The particular influence of each defect or complex was elegantly treated by Feldman et al.13 It is important to note that no lattice disorder is observed near the surface.

Annealed samples were also analyzed using XTEM. In Fig. 3, we show a representative set of XTEM images. We note that annealing up to 450 °C does not trigger any significant morphological changes in the damage band [Fig. 3(a)]. Similarly to the as-implanted sample, the implanted zone remains decorated with nanobubbles. A small increase in temperature above 450 °C leads to the formation of nanoscopic cracks or platelets parallel to the surface [Fig. 3(b)]. Further increase in the annealing temperature induces large cracks leading to a complete exfoliation of a ~340-nm-thick layer. Our detailed XTEM data show that structural transitions from nanobubbles to platelets and from platelets to microcracks occur within temperature windows as narrow as 25 and 50 °C, respectively. 450 °C is identified as the critical temperature at which transformation processes commence. Interestingly, at this temperature, the dechanneling enhancement in RBS/C yield attains its maximum (Fig. 2). To characterize the evolution of this enhancement, we introduce the factor $F_{\text{decch}}$, which can be associated to lattice disorder: $F_{\text{decch}}(E_{BS})=\ln[(1-\chi_D)/(1-\chi_C)]$, where $\chi_D$ is the dechannelling yield divided by the random yield, and $\chi_C$ is the corresponding quantity for the virgin substrate at the same backscattered energy $E_{BS}$. The inset of Fig. 2

In Fig. 2, normalized RBS/C spectra from H-implanted GaN samples are displayed, either at RT, or after annealing at the indicated temperatures. The ratio between the virgin and random data is found to be much smaller than the case of GaN layers grown on sapphire.11 This is due to the high crystalline quality of fs-GaN substrates used in this study. With a density of dislocations in the order of $10^7$ cm$^{-2}$, these substrates are more suitable to investigate impurity-defect interactions. H implantation creates a peak in the ion channeling yield centered at ~1.32 MeV. Its classic interpretation would be the direct scattering on displaced atoms in lattice channels. However, under ion-cut conditions, implantation-induced structures such as nanobubbles, point defect clusters, dislocations, and H-defect complexes can also induce a strong localized lattice deformation leading to an increase of the dechanneling yield [see Ref. 12 and references therein]. The particular influence of each defect or complex was elegantly treated by Feldman et al.13 It is important to note that no lattice disorder is observed near the surface.
displays the evolution of \( F_{\text{dech}} \) as a function of annealing temperature. The calculations were performed at \( E_{\text{RS}} = 1.52 \text{ MeV} \) near the surface. The corresponding morphologies are also indicated. We note that \( F_{\text{dech}} \) saturates at 450 °C and monotonically decreases above this temperature. It is noteworthy that \( F_{\text{dech}} \), calculated for backscattered energies at the damage peak and beyond the implanted region are found to behave qualitatively similar to the data reported in Fig. 2 (inset). This suggests that the same kind of defects or complexes gives rise to all features observed in postannealing RBS/C spectra (Fig. 2). Since thermal annealing cannot create self-interstitials, dechanneling enhancement indicates that other structural defects are involved. This enhancement is different from what was observed in H-induced Si blistering where the relative increase in backscattering yield was found to be much more pronounced near the surface than beyond the damage layer.\(^2\)\(^1\)\(^4\) This irreversible effect was attributed to the macroscopic deformation of blisters.\(^1\)\(^4\)

Our atomic force microscopy analysis shows that GaN surface remains unchanged up to 550 °C in agreement with detailed blistering studies reported earlier.\(^1\)\(^5\) It is also worth to mention that the macroscopic swelling and surface elevation of ion implanted GaN is always accompanied by the formation of very large cavities.\(^1\)\(^0\) Remember, however, that annealing up to 450 °C does not induce any significant change in nanobubbles size [Fig. 3(a)]. Also, the decrease in \( F_{\text{dech}} \) above 450 °C indicates that the phenomenon behind dechanneling enhancement is reversible in contrast to the case of surface deformation.\(^1\)\(^4\) This drives us to suggest that strain-induced lattice distortions could be at the origin of this unexpected thermoevolution of RBS/C spectra during nanobubbles regime. A possible origin of lattice distortion would be \( H_2 \) molecules trapping in nanobubbles leading to the buildup of internal pressure. However, highly pressurized nanobubbles alone cannot explain the observed dechanneling since their stress field can hardly reach the surface. Since damage layer contain also other defect complexes such as self-interstitial clusters, one can suppose that their combined influence with hydrogen-induced internal pressure can increase the in-plane compressive strain causing a strong lattice distortion. This process will ultimately lead to a weakening of the atomic bonding. The system attains the criticality around 450 °C. \( F_{\text{dech}} \) decreases above this temperature suggestive of a partial relief of the internal strain following the formation of platelets parallel to the surface. These platelets define the fracture paths for the exfoliation. Interestingly, Doppler broadening measurements for samples annealed at \( T \leq 450 \) °C were found to be identical to as-implanted state [Fig. 1(b)]. The absence of vacancy clustering in this temperature range indicates that the necessary void for splitting assemblies dynamically during the implantation process. This behavior differs completely from the evolution observed in Si where an important increase of voidlike defects was found to proceed the exfoliation.\(^1\)\(^2\) \(^3\)\(^4\) In a recent model,\(^1\)\(^7\) damage-induced in-plane compressive strain was suggested as the driving force for vacancy agglomeration leading to platelets formation in Si. The same description was also used to explain H-induced InP exfoliation.\(^1\)\(^8\) However, the remarkable difference in vacancylike defects thermal behavior observed between GaN and Si suggests that a general and predictive microscopic model of ion-cut process has to consider the intrinsic properties of the material, the nature of H-defect complexes, and point defects diffusivity. These aspects are still poorly understood for GaN. Additional systematic experimental studies and calculations would be highly valuable. Finally, despite that \( H_2 \) is believed to play a crucial role, probing and understanding its exact thermal behavior in GaN under ion-cut conditions will remain an open challenge as it is still for Si. The only available data from first-principles calculations demonstrate that \( H_2 \) in GaN requires unfavorably high formation energy (\( \approx 2.4 \text{eV} \) in vacuum) compared to Si.\(^1\)\(^9\) This could explain in part the high fluence needed for GaN ion cutting.

In summary, we investigated the critical structural transformations involved in splitting of GaN by H implantation and subsequent annealing. We found that vacancy clustering during the implantation process leads to assembly of 1–2 nm nanobubbles. Temperatures of 300–450 °C give rise to a strong enhancement of dechanneling tentatively attributed to strain-induced lattice distortion. At higher temperature, the dechanneling is partially reduced following the formation of platelets indicative of a partial relief of the strain. These platelets define the fracture path for the exfoliation. Extended internal surfaces develop around 550 °C leading to splitting of \( \approx 340 \)-nm-thick layer. Our result is a first step toward understanding the basic mechanisms of GaN ion cutting.

The CrysGaN project funded by the German Federal Ministry of Education and Research (BMBF) partially contributed to this work.

---