

## Ion-beam-induced porosity of GaN

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Wurtzite GaN films bombarded with heavy ions ( $^{197}\text{Au}^+$ ) show anomalous swelling of the implanted region with corresponding volume expansion up to  $\sim 50\%$ . Results show that this phenomenon is due to the formation of a porous layer of *amorphous* GaN. An important implication of this study for the fabrication of GaN-based devices is that amorphization of GaN should be avoided during ion implantation. © 2000 American Institute of Physics. [S0003-6951(00)03136-3]

Very attractive applications of ion beams in the fabrication of GaN-based devices have stimulated considerable research efforts to understand ion beam processes in GaN.<sup>1</sup> It has been shown that, despite very efficient dynamic annealing of radiation defects, GaN can be rendered amorphous by high dose ion implantation.<sup>2-5</sup> However, the properties of GaN amorphized by ion bombardment have not yet been studied in any detail. In this letter, we show that GaN layers amorphized by heavy ion ( $^{197}\text{Au}^+$ ) bombardment are porous. The formation of a porous structure causes large material swelling and increased surface roughness. This observation has significant technological implications, suggesting that amorphization of GaN should be avoided during high dose ion implantation.

The  $\sim 2\text{-}\mu\text{m}$ -thick wurtzite undoped GaN epilayers used in this study were grown on *c*-plane sapphire substrates by metalorganic chemical vapor deposition in a rotating disk reactor at Ledex Corporation. Implantation with 2 MeV  $^{197}\text{Au}^+$  ions was done at liquid nitrogen temperature ( $\text{LN}_2$ ) with a beam flux of  $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$  over the dose range from  $1 \times 10^{14} \text{ cm}^{-2}$  to  $5 \times 10^{16} \text{ cm}^{-2}$  using the ANU 1.7 MV tandem accelerator (NEC, 5SDH). Before implantation, samples were partly masked by a piece of Si. During implantation, samples were tilted by  $\sim 7^\circ$  relative to the incident ion beam to avoid channeling.

After implantation, samples were characterized *ex situ* by Rutherford backscattering/channeling (RBS/C) spectrometry with 1.8 MeV  $^4\text{He}^+$  ions incident along the [0001] direction. Selected samples were studied by cross-sectional transmission electron microscopy (TEM) in a Philips CM12 TEM operating at 120 keV. Cross-sectional TEM specimens were prepared by 3 keV  $\text{Ar}^+$  ion beam thinning using a Gatan precision ion polishing system. The surface morphol-

ogy of implanted samples was studied by tapping mode atomic force microscopy (AFM). The AFM study was performed under ambient conditions with a Nanoscope III scanning probe microscope using commercial single-beam Si cantilevers with force constants of  $30\text{--}120 \text{ N m}^{-1}$ . In addition to AFM, the step height between implanted and unimplanted regions was measured by a Tencor Instruments Alpha-Step 200 stylus profilometer.

An AFM image in Fig. 1 illustrates the border between implanted (on the left) and unimplanted (on the right) areas of a GaN sample bombarded with 2 MeV Au ions at  $\text{LN}_2$  to a dose of  $1 \times 10^{16} \text{ cm}^{-2}$ . As clearly seen, ion implantation has caused pronounced material swelling with a step height as large as  $\sim 1700 \text{ \AA}$ . In addition, the implanted area exhibits large-scale roughness.

Shown in Fig. 2 is the dose dependence of the step

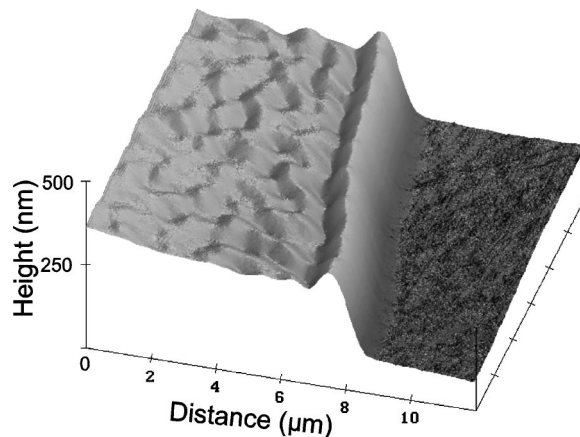


FIG. 1. Tapping mode AFM image illustrating the border between implanted (on the left) and unimplanted (on the right) areas of a GaN sample bombarded with 2 MeV Au ions at  $\text{LN}_2$  to a dose of  $1 \times 10^{16} \text{ cm}^{-2}$  with a beam flux of  $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ .

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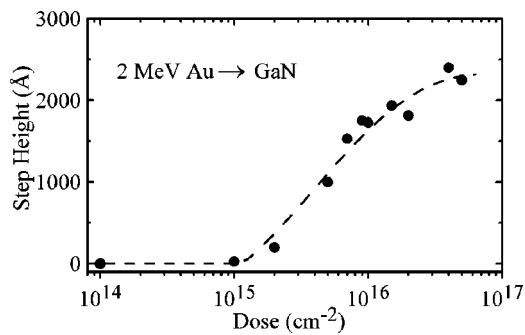


FIG. 2. Dose dependence of the step height between implanted and unimplanted regions of GaN films bombarded with 2 MeV Au ions at LN<sub>2</sub> with a beam flux of  $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ .

height between implanted and unimplanted regions of 2 MeV Au ion bombarded GaN. It is seen that rapid step height increase occurs for ion doses above  $\sim 3 \times 10^{15} \text{ cm}^{-2}$ . Figure 3(a) shows a cross-sectional (low magnification) TEM image of the GaN film bombarded with 2 MeV ions at LN<sub>2</sub> to a dose of  $1 \times 10^{16} \text{ cm}^{-2}$ . This TEM image illustrates a  $\sim 5500$ -Å-thick, completely amorphous surface layer bounded by a  $\sim 1000$ -Å-thick band of defect complexes and planar defects, which has been confirmed by detailed TEM and electron diffraction measurements. An enlarged image of the near-surface part of the same sample is shown in Fig. 3(b). It is seen that the amorphous GaN layer has voids or gas bubbles which are close to spherical in shape. The average radius of the voids/bubbles depends on the depth and seems to scale with the nuclear energy loss profile of Au ions.

A combination of RBS/C, TEM, and AFM data shows that the onset of the large step height, with increasing ion dose, coincides with the nucleation of a buried amorphous layer in the region of the maximum nuclear energy loss. Moreover, rapid step height increase in the dose range from  $\sim 3 \times 10^{15} \text{ cm}^{-2}$  to  $\sim 7 \times 10^{15} \text{ cm}^{-2}$  (see Fig. 2) corresponds to the dose interval in which buried and surface amorphous layers extend until they meet, resulting in a thick continuous layer of amorphous material. These results indicate that ion-beam-induced porosity and concomitant material swelling are the effects observed in *amorphous* GaN. Relatively small material expansion (see Fig. 2) for ion doses before those required for amorphization in the GaN bulk may be partly attributed to the swelling caused by the formation of a thin surface amorphous layer. The origin of this thin surface amorphous layer, observed by TEM and RBS/C, has been previously attributed to the trapping of migrating point defects by the GaN surface or amorphous/crystalline interface.<sup>4,5</sup>

It should be noted that similar porous structures have also been observed in GaN films amorphized by 300 keV Au ion bombardment. However, in this latter case of kilo-electron-volt heavy ion bombardment, the ion penetration depth is significantly smaller than that in the case of mega-electron-volt ion irradiation, which makes the material swelling less pronounced. A combination of TEM, RBS/C, and AFM data shows that ion-beam-induced volume expansion of amorphous GaN is close to 50%.

The effects of ion-beam-induced porosity and concomitant material expansion reported here are, in fact, not new.

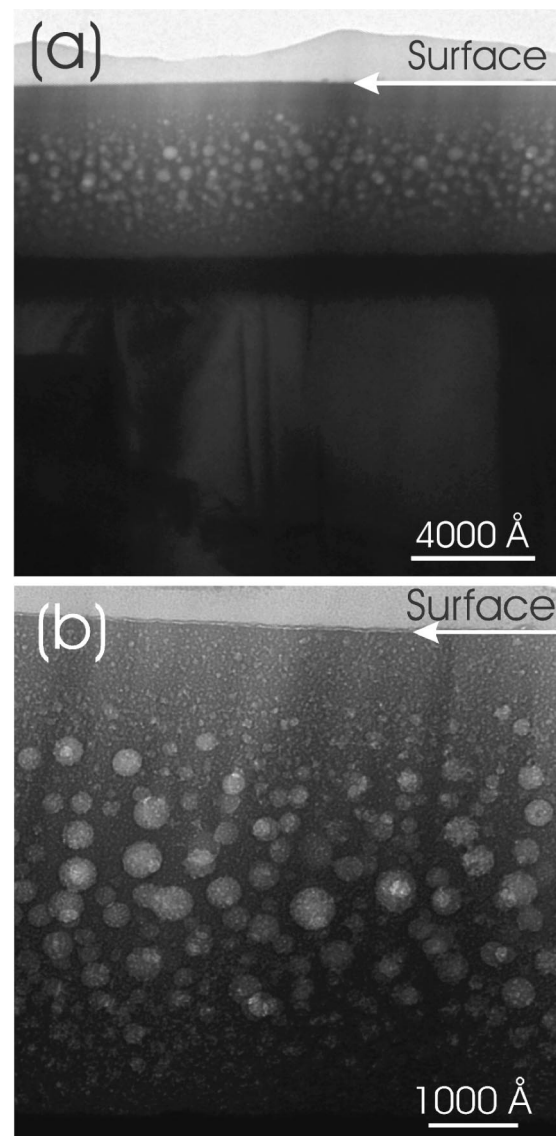


FIG. 3. Cross-sectional bright-field TEM images of the GaN epilayer bombarded with 2 MeV Au ions at LN<sub>2</sub> to a dose of  $1 \times 10^{16} \text{ cm}^{-2}$  with a beam flux of  $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ . Images (a) and (b) have been taken using different magnification.

Similar effects have been observed in some other semiconductors, such as Ge,<sup>6,7</sup> InSb,<sup>8</sup> and GaSb.<sup>9</sup> In general, amorphousness is not necessarily the final state of a semiconductor exposed to ion bombardment. Although studied in some detail (particularly in the case of Ge),<sup>7</sup> ion-beam-induced formation and evolution of porous structures in amorphous materials are not well understood. One of the possible explanations for this effect is energetically favorable agglomeration of vacancy-like defects, generated by an ion beam in an amorphous matrix, resulting in the formation of voids.<sup>6,7,10</sup> In addition, in the case of GaN, the porosity reported here may be also stimulated by ion-beam-induced material decomposition with the formation of N<sub>2</sub> gas bubbles in a Ga-rich matrix, a process which has been discussed elsewhere.<sup>5</sup>

In conclusion, anomalous swelling of GaN films bombarded with heavy ions has been observed. A combination of RBS/C, TEM, and AFM studies indicates that such an anomalous material expansion (with the volume expansion up to  $\sim 50\%$ ) is attributed to ion-beam-induced porosity of *amorphous* GaN. The phenomenon deserves particular atten-

tion since it may affect impurity incorporation when a sample is exposed to air as well as post-implantation annealing. Further studies of ion-beam-induced porosity of amorphous GaN are in progress.

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<sup>1</sup>See, for example, a recent review S. J. Pearton, J. C. Zolper, R. J. Shul, and F. Ren, *J. Appl. Phys.* **86**, 1 (1999), and references therein.

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