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# ION DAMAGE STUDIES IN $GaAs/Al_{0.6}Ga_{0.4}As/GaAs$ HETEROSTRUCTURES*

B. A. Turkot, D. V. Forbes, H. Xiao, I. M. Robertson, and J. J. Coleman
University of Illinois, Urbana, IL 61801

and

M. A. Kirk, L. E. Rehn, and P. Baldo
Argonne National Laboratory, Argonne, IL 60439

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# ION DAMAGE STUDIES IN $GaAs/Al_{0.6}Ga_{0.4}As/GaAs$ HETEROSTRUCTURES

B.A. TURKOT*, D.V. FORBES**, H. XIAO*, I.M. ROBERTSON*, J.J. COLEMAN**, M.A. KIRK***, L. E. REHN***, and P. BALDO***
*University of Illinois, Department of Materials Science & Engineering, Urbana, IL 61801
**University of Illinois, Materials Research Laboratory, Urbana, IL 61801
***Argonne National Laboratory, Argonne, IL 60439

## ABSTRACT

The development of the damage structure produced in (100) $GaAs/Al_{0.6}Ga_{0.4}As/GaAs$ by 1 MeV $Kr^+$ ion irradiation at 77 and 293 K has been investigated by RBS channeling and cross-sectional high-resolution TEM techniques. Following an implantation to a dose of $10^{14}$ ions $cm^{-2}$ at 77 K, RBS channeling spectra indicate that the $Al_{0.6}Ga_{0.4}As$ layer contained a high defect density and was possibly amorphous. Warming to room temperature resulted in a change in the channeling spectrum, which indicated that the damage in the $Al_{0.6}Ga_{0.4}As$ layer had partially recovered. The degree of recovery was greatest at the $GaAs/Al_{0.6}Ga_{0.4}As$ interface, and decreased with increasing depth. TEM observations show the damage in the $Al_{0.6}Ga_{0.4}As$ to be comprised of planar defects, the density of which increases with depth, and an amorphous layer at the bottom interface. This difference in the damage distribution is consistent with the asymmetry in the channeling spectrum. A model based on the depth variation of cascade density is proposed to account for the observations.

## INTRODUCTION

Investigations of the damage produced by low temperature (77K) ion implantation of the GaAs/AlAs/GaAs system have shown that a greater degree of mixing and damage occurs at the AlAs/GaAs (bottom) interface than at the GaAs/AlAs (top) interface [1-6]. Others have observed (with 77 K implantation of $Si^+$ into GaAs/AlAs/GaAs) that layers of GaAs contiguous to AlAs remained partially crystalline near the boundaries at a dose where the remainder of the GaAs layer had already become amorphous [2,3]. These experiments also showed that the amorphization of the AlAs layer proceeded from the bottom of the layer upward. In these cases no explanation was given for the observed amorphization behavior of either GaAs or AlAs.

The mechanism causing this asymmetric damage distribution is unclear; Bode et al. [4] suggested that an electrostatic field is created across the AlAs layer and this causes implantation-induced defects to migrate to, and accumulate at, the AlAs/GaAs (bottom) interface. Klatt et al. [6] applied this charged defect concept to the interpretation of their RBS intermixing results where greater mixing was determined for the AlAs/GaAs (bottom) than for the GaAs/AlAs (top) interface.

In this paper we report the results of RBS and TEM investigations of the damage produced in a $GaAs/Al_{0.6}Ga_{0.4}As/GaAs$ sample following implantation at 77 K with 1 MeV $Kr^+$ ions. A model based on the depth dependence of the density of events having a recoil energy in a particular range is proposed to explain the experimental observations.

## EXPERIMENT

The samples consisted of a layer of 100nm GaAs on 150 nm of $Al_{0.6}Ga_{0.4}As$, grown by atmospheric pressure metalorganic chemical vapor deposition (MOCVD) [7] in a vertical geometry, rotating disc reactor on a (001) Si-doped GaAs substrate.

Ion implantation and subsequent RBS analysis were performed at Argonne National Laboratory using a 2 MeV NEC Pelletron accelerator with a duoplasmitron ion source in the high voltage terminal. In order to analyze the damage state of the layer as a function of both implantation dose and temperature, RBS spectra were acquired in both random and [001] axial-channeling orientations. Backscattered $He^+$ ions were energy analyzed using a Si surface barrier detector with a scattering angle of 138°. The total $He^+$ ion flux of approximately $10^{16}$ ions $cm^{-2}$ caused negligible amorphization. To determine if room-temperature recovery processes were occurring, channeling yields for samples implanted at 77 K were collected at 77 K, and again after the sample had warmed to room temperature.

Cross-sectional specimens suitable for both diffraction contrast and high-resolution TEM were prepared by cleaving the wafer and then gluing the pieces with their faces together. These samples were then thinned mechanically to a thickness of approximately 50 micrometers. This process involved a temperature excursion of ~100°C for a few minutes. Finally, the samples were mounted on copper grids and ion milled (at liquid nitrogen temperature) to electron transparency with 4 keV $Ar^+$ ions. Once prepared, the samples were examined in a Philips CM12 operating at 120 kV or in a Hitachi 9000 high- resolution microscope operating at 300 kV.

## EXPERIMENTAL RESULTS

Ion channeling spectra gathered at 77 K and 293 K from a sample implanted at 77 K with 1 MeV $Kr^+$ ions to a dose of $10^{14}$ ions $cm^{-2}$ are shown, along with pre-implantation channeled and random spectra, in Figure 1. The 77 K channeled spectrum resembles the random spectrum, implying that the $Al_{0.6}Ga_{0.4}As$ layer is highly disordered. Channeled spectra obtained after the sample had warmed to room temperature show a distinct difference from those obtained at low temperature. The yield from the upper interface (i.e. $GaAs/Al_{0.6}Ga_{0.4}As$ ) has dropped from the random spectrum toward the unirradiated channeled spectrum. This effect indicates that the damage state near this interface has partially recovered during the warm-up process. No change occurs in the channeled yield corresponding to the bottom interface, indicating that the damage at this interface is thermally stable. From other studies it is known that on warming the sample to room temperature, the ion damage recovers unless a fully amorphous state is reached [8]. This asymmetry in the room temperature spectra suggests that the

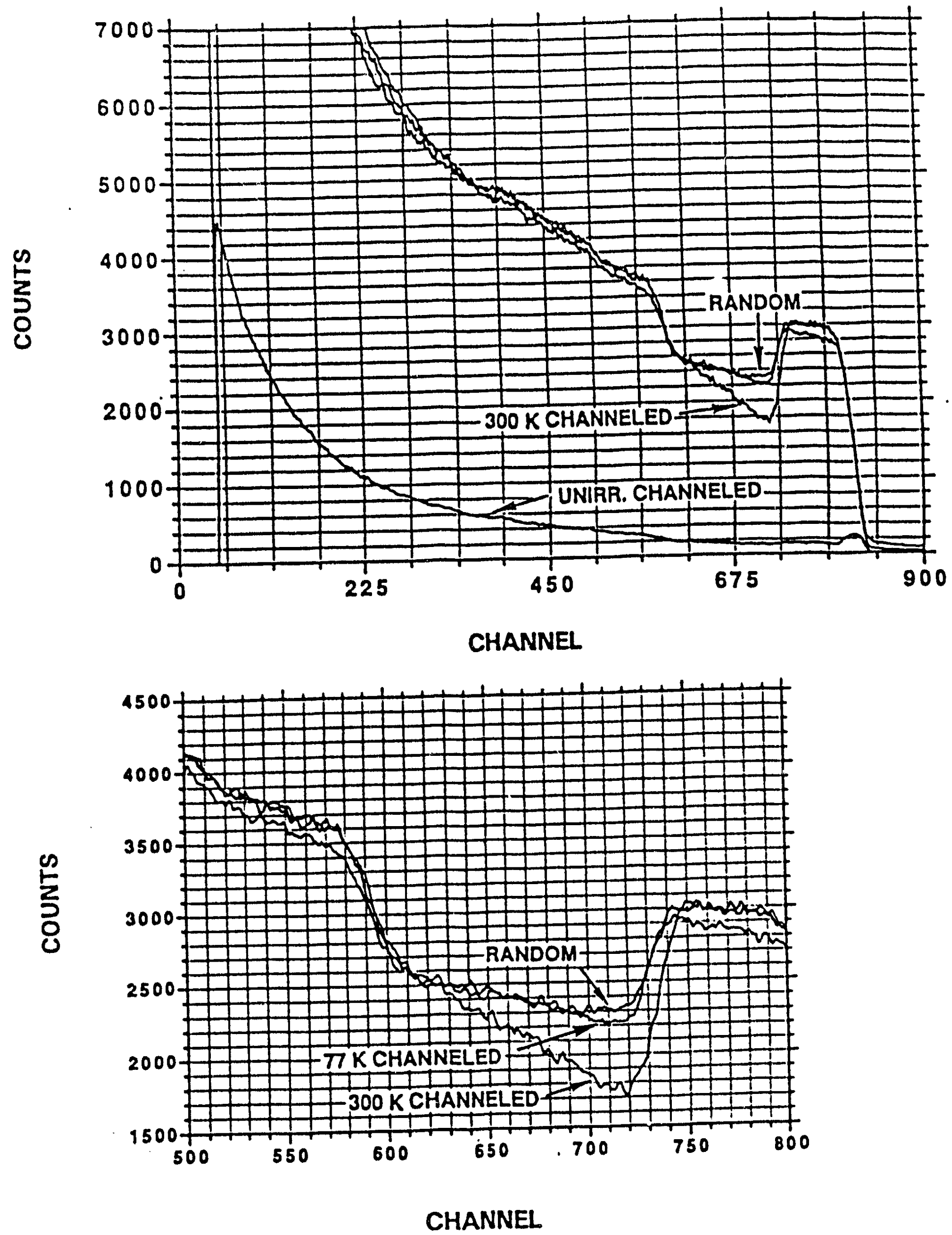


Figure 1. (a) Ion channeling spectra acquired before and after irradiation at 77K. (b) Enlarged view of the spectra across the $Al_{0.6}Ga_{0.4}As$ layer.

damage is inhomogeneous throughout the layer, and increases with sample depth. These same samples were examined after an additional 15 hours at room temperature, with no change in the channeled RBS spectra being detected. This is an important observation in that it gives confidence that the short-term storage and preparation of TEM samples at room temperature does not affect the damage state.

High-resolution TEM examination of as-grown material revealed no interfacial defects at either interface. The damage structure produced in the sample implanted at 77 K to an ion dose of $10^{14}$ ions $cm^{-2}$ is shown in Figure 2. Fig 2a shows the top interface; the GaAs cap is amorphous and the $Al_{0.6}Ga_{0.4}As$ is

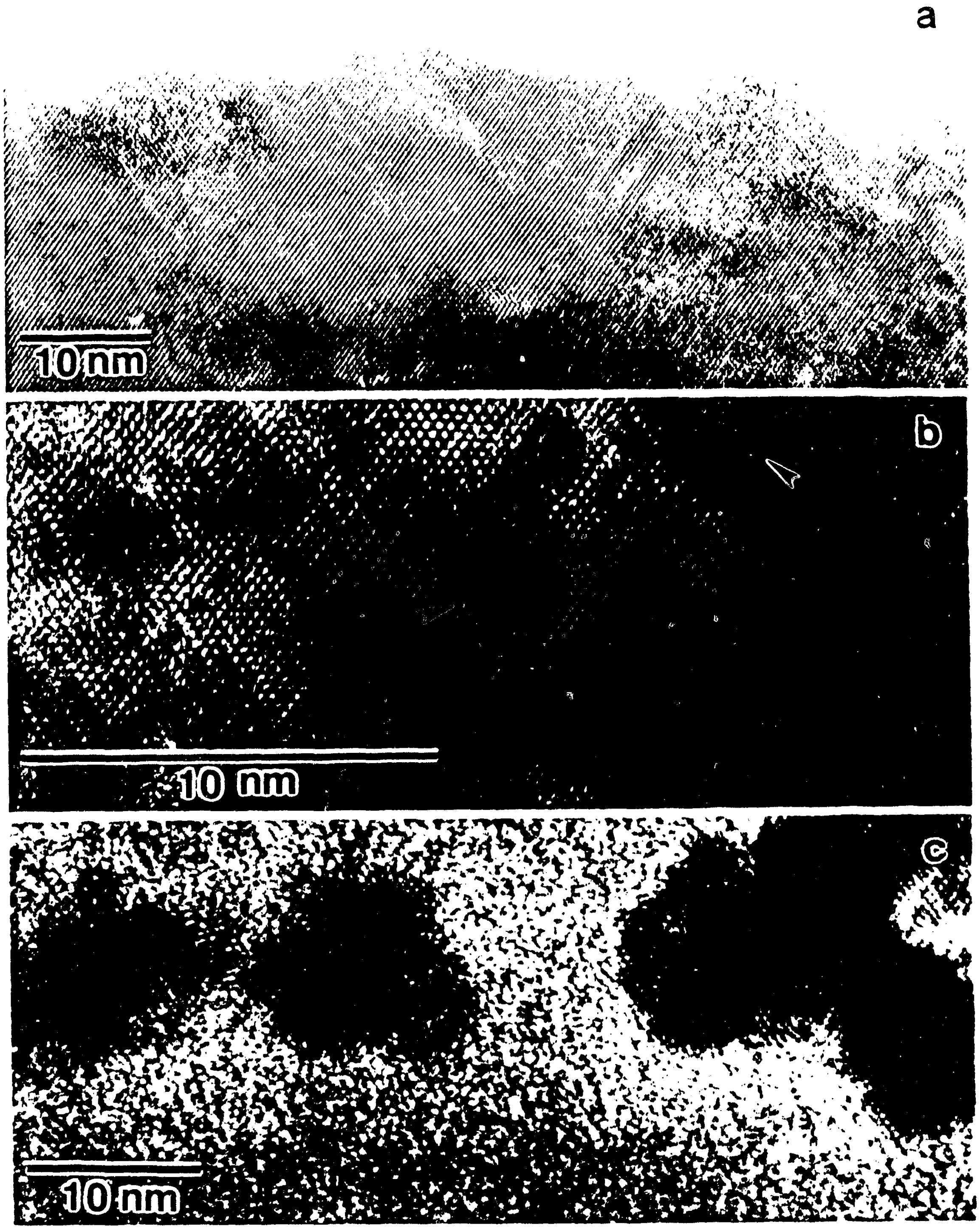


Figure 2. High-resolution TEM images showing (a) GaAs/$Al_{0.6}Ga_{0.4}As$ interface, (b) an area from the center of the $Al_{0.6}Ga_{0.4}As$ layer and (c) the $Al_{0.6}Ga_{0.4}As$/GaAs interface.

crystalline with planar defects now present. The density of these planar defects increases with depth, as evident from fig 2b which is of the central portion of the $Al_{0.6}Ga_{0.4}As$ layer. The bottom of the $Al_{0.6}Ga_{0.4}As$ layer, near the interface with the

GaAs substrate, has been rendered amorphous, see Fig 2c. In this micrograph, the actual position of the interface between the amorphous $Al_{0.6}Ga_{0.4}As$ and GaAs is difficult to discern; it is visible as a slight change in image contrast (indicated by arrows in the micrograph). Within the amorphous $Al_{0.6}Ga_{0.4}As$ small crystallites (marked by arrowheads) exist, the density of which increases as the crystalline $Al_{0.6}Ga_{0.4}As$ layer is approached. Planar defects are also evident within the crystallites.

## DISCUSSION

In the previous section it was shown that the implantation of 1 MeV $Kr^+$ at 77 K into $Al_{0.6}Ga_{0.4}As$ to a dose of $10^{14}$ ions $cm^{-2}$ produced significant damage (Figure 1). Ion channeling spectra suggest that the $Al_{0.6}Ga_{0.4}As$ layer is in a highly disordered state at 77K, and that some recovery of the damage occurs when the sample warms to 293 K. The degree of damage recovery decreases with increasing depth, suggesting that the initial damage state increased with depth. This depth dependence of the recovered damage state is consistent with previous observations where the damage was analyzed at room temperature, but created at low temperature. [1-6,9]. TEM examination confirmed that the degree of damage surviving the warm-up is indeed depth dependent, with the crystalline defect density increasing with depth and the lower interface region remaining in an amorphous state, Fig. 2. It is envisioned that the initial damage state consists of a high defect density throughout the $Al_{0.6}Ga_{0.4}As$ layer, ending in an amorphous layer at the $Al_{0.6}Ga_{0.4}As$/GaAs interface.

Previous work demonstrated that $Al_xGa_{1-x}As$ is more resistant to amorphization than GaAs, and that this resistance increases as the fraction of Al increases [1-6,9,10]. Jencic et al. [10] demonstrated that the amorphization dose at 30 K in $Al_{0.85}Ga_{0.15}As$ is one to two orders of magnitude higher than that in GaAs. The reason for this observed Al-dependence of the amorphization dose is not well understood. However, it is consistent with the observation that, with the exception of the bottom interface region, most of the $Al_{0.6}Ga_{0.4}As$ remains crystalline, albeit highly defective, whereas the GaAs layer is rendered amorphous.

Bode et al. [4] and later Klatt et al. [5], [6] attributed the difference in ion mixing at the two interfaces to interfacial electrostatic effects. The observations presented earlier in this report cannot exclude the possibility of electrostatic effects; however, one would not expect warming the sample to room temperature to have such a marked effect on an electrostatic response.

The results described above indicate that the initial damage state varies with sample depth. From the viewpoint of the damage process, this depth dependence of the damage may reflect that of either the total damage energy or the number of recoil events within a particular energy range. TRIM [11] calculations show that the variation of the recoil energy over the layer thickness is negligible, and cannot account for the observation. Preliminary TRIM calculations show that the number of recoil events with an energy >30 keV is greater (by at least a factor of two) at the bottom than at the top interface. This increase in the density of cascade-producing events with sample depth might explain the observed damage distribution.

The formation of planar defects extending from the crystalline region toward the remaining amorphous material is a characteristic feature of solid-phase epitaxial regrowth of an amorphous layer [2,12]. It is believed that the extended defects observed throughout much of the $Al_{0.6}Ga_{0.4}As$ layer result from such recovery of the damage. The small crystallites throughout the amorphous $Al_{0.6}Ga_{0.4}As$ layer could serve as nucleation sites for recrystallization.

## CONCLUSIONS

1. The asymmetry observed in the ion channeling spectra recorded at room temperature reflects the thermal instability of the damage produced by the low temperature implantation. Unless the implantation dose renders the entire layer amorphous, a similar recovery of the damage is expected for AlAs layers implanted at 77K and warmed to room temperature.
2. The depth dependence of the initial state of damage appears to follow that of the number of recoil events having an energy > 30 keV.
3. The formation of planar defects is a consequence of the recovery of the damage.

## ACKNOWLEDGMENTS

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