Structural Defects Formed in Al Implanted and Annealed 4H-SiC

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Abstract. Using RBS/channeling, TEM, and HREM, we show that the degree of irreversible structural damage of samples implanted to 10¹⁹ cm⁻³ is much less than that measured in samples implanted to 10²⁰ cm⁻³. The RBS/channeling χₘᵢₙ is 4.95 for the samples annealed at 1400, 1500, and 1600°C, and it drops to 2.0 for the 1700°C anneal. TEM shows that small extended defects are present in all cases, but there are fewer of them at the higher annealing temperatures, although they are larger, and they are concentrated closer to the surface. HREM shows the extended defects are structural, and they appear to be stacking faults or dislocations.

Introduction

Bluet et al. [1] have shown that Al implanted to 10²⁰ cm⁻³ is only about 37% activated after an anneal at 1670°C for 12 min. Others [2] have obtained similar results, and they showed that the lower activation was due, in part, to acceptors being trapped out by structurally induced defects – possibly the deep donors associated with the D_I defect [3]. Further, the annealed samples contain a large number of stacking faults as determined by transmission electron microscopy (TEM) and high resolution electron microscopy (HREM). In addition, χₘᵢₙ, the parameter used as a measure of structural quality in Rutherford backscattering spectroscopy (RBS)/channeling experiments, drops initially with the annealing temperature, but then increases at the higher annealing temperatures implying that the structural defects increase in number. This suggests that the damage is irreversible. The smaller mobility in implanted layers when compared with epitaxial layers doped to the same high level [2] can also be attributed to permanent damage. The damage does not appear to be nearly so severe for lower doping concentrations, as Saxe et al.[4] determined that for material implanted to concentrations of ~10¹⁷ cm⁻³ the activation was 77% after an anneal at 1600°C for only a five minutes.

To determine if these differences can be attributed to differences in the amount of residual implant damage, we examined the structural damage in samples implanted to 10¹⁹ cm⁻³ with aluminum using RBS/channeling, TEM, and HREM. This was done by annealing the samples with a (BN)AlN annealing cap [5] and examining their structure.

Procedure

A wafer purchased from Cree with an n⁺ epitaxial layer doped to 8.2 x 10¹⁵ cm⁻³ grown on it was implanted with Al at 600°C with one tenth the doses used to implant the Al to 10²⁰ cm⁻³ to a depth of ~0.3 µm according to TRIM calculations [2]. They were coated with ~200 nm thick AlN film using pulsed laser deposition (PLD), and then were annealed in Ar for 30 min at 1400, 1500, 1600, and 1700 °C. The 1700 °C sample also had a BN cap deposited on the AlN cap using PLD to prevent the AlN, itself, from evaporating [5]. The BN cap was ion milled off after the anneal had been completed, and it, along with the other samples had their AlN caps removed in a warm KOH solution. The RBS measurements in combination with channeling were made using a 2.0 MeV He beam. The scattering angle was 165° with an overall energy resolution of 20 keV. The channeling analyses were done along the [0 0 0 1] axes. A JEOL 2010 TEM operated at 200 kV was used to examine the structure of cross sections of the films and to look for possible reaction products.
Samples were prepared using the standard "sandwich" procedure, including grinding, polishing, dimpling, and ion milling at the final stage.

Results and Discussion

For the as-implanted sample almost uniform damage extending to a depth of about 400 nm was observed, and there was a slight hump at about 200 nm. The channeling yield near to the surface was 12%. Annealing at 1400, 1500 and 1600°C yielded similar spectra in the channeling condition with minimum yields of 4.95%. The hump had now disappeared. The spectra clearly indicate recovery of the damaged zone. For good quality SiC the minimum yield should be less than 2%. This indicates that some damage in the form of point defects, stacking faults, and/or dislocations was still present. For the sample annealed at 1700°C, the recovery is better. As seen in Fig. 1, the axial angular scan showed a minimum yield of 3%, and the random and aligned spectra showed a slightly higher aligned yield. There is long background tail that could be caused by impurities. The background is very small, but if it is subtracted out the minimum yield would go down to 2% or lower. This is opposite to what was found for the samples implanted to $10^{20}$ cm$^{-3}$ where the minimum yield increased at the higher annealing temperatures suggesting that at these high annealing temperatures, more of the damage can be annealed out as opposed to enhancing the growth of these flawed regions.

![Graph showing RBS/channeling spectrum for SiC implanted with Al and annealed at 1700°C](image-url)

**Fig. 1.** The RBS/channeling spectrum for the sample annealed at 1700°C.
That there is extended damage in the implanted material is shown in Fig. 2 where the (1 1 2 0) TEM micrographs of the annealed samples are displayed. The damage is present as localized strain fields represented by spots in the micrograph. They are greater in number, but are smaller in size, for the samples annealed at the lower temperatures. The densities are 12, 7.8, 2.1, and $1.3 \times 10^{11}$ /cm$^2$ for samples annealed respectively at 1400, 1500, 1600 and 1700°C. We have also observed that the strain fields appear to move towards the surface at the higher temperatures suggesting they are upwardly mobile. The fact that there are fewer of them, but they are larger in size suggests that some of the transformed regions grow at the expense of others, but few, if any, new nuclei are formed. One interpretation is that essentially all of the excess point defects generated by the implantation process have coalesced to form extended defects or have been annihilated by the annealing process, and that some of the extended defects grow at the expense of others, but they are not annihilated. This can explain why $\chi_{\text{min}}$ is relatively constant and $>2$ for the samples annealed at 1400, 1500, and 1600°C, but it is difficult to explain why $\chi_{\text{min}}$ is smaller after the 1700°C anneal.

Fig. 2. (a) TEM micrograph of as-implanted sample.

Fig. 2. (b) TEM micrograph of sample annealed at 1600°C.

Fig. 2. (c) TEM micrograph of sample annealed at 1500°C.

Fig. 2. (d) TEM micrograph of sample annealed at 1700°C.
It is possible that the SiC was beginning to heal itself, but we did not see that in the HREM micrographs.

The HREM micrographs shown in Fig. 3 do show that the extended defects are confined to a small region in the sample implanted to $10^{19} \text{cm}^{-3}$, and they could be the localized double stacking fault observed by others in heavily N-doped samples [6]. This is very different from the extensive amount of residual damage in samples implanted to $10^{20} \text{cm}^{-3}$, as is shown in Fig. 3b where the damage is much more severe and spread out. The fact that the difference in the extent of the damage as determined both by TEM and RBS/channeling is so large suggests there is a critical implant dose above which the residual damage is extensive and can expand significantly as the annealing temperature is raised. Below this critical implant dose, the extended defects can grow, but they grow at the expense of others so there is no net gain, and at 1700°C there might even be a net diminution of the total amount of residual damage.

That there are small extended defects present in samples implanted with the smaller dose supports our assertion that the D₁ defect must be an extended defect because it is so temperature stable, and the intensity of the L₁ spectral lines associated with it either increases in intensity with temperature or remains the same [2]. As with the D₁ defect, the extended defects we observed are very stable and they do grow as the annealing temperature is increased.

Fig. 3. (a) HREM micrograph of a sample implanted with $10^{19} \text{cm}^{-3}$ of Al and annealed at 1600°C for 30 min.  

Fig. 3. (b) HREM micrograph of a sample implanted with $10^{20} \text{cm}^{-3}$ of Al and Si and annealed at 1600°C for 30 min.

References
Summary

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