High-temperature high-dose implantation of N\(^+\) and Al\(^+\) ions in 6H–SiC


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A series of experimental and theoretical investigations has been initiated for 6H–SiC samples sequentially implanted with high doses of N\(^+\) (65 keV) + N\(^+\) (120 keV) + Al\(^+\) (100 keV) + Al\(^+\) (160 keV) ions at temperatures between 200 and 800 °C. Nitrogen and carbon distribution profiles are measured by ERD and structural defect distributions are measured by Rutherford backscattering with channeling. A comparison between the experimental data and the results of computer simulation yields a physical model to describe the relaxation processes of the implanted SiC structure, where the entire implanted volume is divided into regions of different depth, having different guiding kinetics mechanisms. © 1997 American Institute of Physics. [S1063-7850(97)01908-3]

INTRODUCTION

Wide-gap semiconductors based on SiC solid solutions have recently attracted considerable interest for the development of new optoelectronic and high-temperature devices. The quasibinary system (SiC)\(_{1-x}\) (AlN)\(_x\) is probably the most promising for these applications at the present time. However, the published data apply mostly to polycrystalline ceramics fabricated by sintering\(^1\) and to epitaxial layers.\(^2\)

EXPERIMENTAL AND CALCULATED DATA

Experimental investigations were made of (SiC)\(_{1-x}\) (AlN)\(_x\) samples fabricated by ion beam synthesis. Wafers of (0001)-oriented n-type 6H–SiC were bombarded with N\(^+\) and Al\(^+\) ions at elevated substrate temperatures using the Danphysik accelerator at the Rossendorf Research Center, Germany. The implantation parameters were selected to obtain buried layers of (SiC)\(_{1-x}\) (AlN)\(_x\) with \(x = 0.2\). Each sample was bombarded in the following order: first with 65 keV nitrogen ions at a dose of 5 × 10\(^{16}\) cm\(^{-2}\), then with 120 keV nitrogen ions at a dose of 1.3 × 10\(^{17}\) cm\(^{-2}\), followed by 100 keV aluminum ions at a dose of 5 × 10\(^{16}\) cm\(^{-2}\) and then 160 keV aluminum ions at a dose of 1.3 × 10\(^{17}\) cm\(^{-2}\). The ion energies were selected so that the distribution profiles of the N\(^+\) and Al\(^+\) ions overlapped under the overall bombardment. During implantation the current ion density was maintained between 0.6 and 1 \(\mu\)A/cm\(^2\) at substrate temperatures of 200, 400, 600, and 800 °C, for which we used an Ohmically heated, temperature-calibrated substrate holder. After implantation, the samples were investigated by Rutherford backscattering in conjunction with channeling (RBS/C) method\(^3\) using a 1.4 MeV He\(^+\) ion beam, and also by the ERD method, to determine the depth distribution of nitrogen and carbon. The RBS spectra were processed using a computer program developed at the Rossendorf Research Center, which yielded depth distributions of structural defects (Fig. 1a).

The TRIRS and DYTRIRS computer codes\(^4\)-\(^6\) were used to calculate the ballistic distributions of the implanted ions and defects, and also to calculate the changes in the density of the SiC components for high-temperature implantation at the corresponding doses. Ballistic distributions of N\(^+\) and Al\(^+\) ions (DETRIRS) (Fig. 1a, curve 1) and total defect distributions (Fig. 1a, curve 2) were obtained. Ballistic distributions of implanted nitrogen (as a result of all four successive bombardments at the doses used experimentally) are plotted in Fig. 1b (DYTRIRS).

A comparison between the ballistic data (see curve 2 in Fig. 1a) and the RBS results for irradiation at 200 °C shows that this at this temperature the modified (“amorphous”) material does not anneal at the deposition depth of the implanted nitrogen and aluminum ions (curve 1).

Assuming, for a rough estimate, that all vacancies and interstitial atoms separated by spontaneous recombination distances (see, for example, Refs. 7 and 8) recombine thermally, the residual intrinsic defects and implanted ions will give an overall profile lying below the RBS experimental data (curve 3). The two limiting cases (only ballistic distributions — curve 2 and allowance for total recombination — curve 3) show substantial differences, and a comparison between these and the experimental data (RBS)\(^3\) reveals the role of diffusion processes in high-temperature implantation in regions of the irradiated SiC of different depth.

At higher irradiation temperatures however, the distribution profiles of the scattering centers change with depth. Since RBS is sensitive to any scattering centers for He\(^+\), including implanted ions, single intrinsic defects (vacancies and interstitial atoms in Si and C sublattices), and clusters (both intrinsic and impurity defects), the experimentally determined\(^3\) different behavior of the scattering center profiles over depth indicates that different annealing mechanisms operate at different depths in the implanted material.

The distribution profiles of N\(^+\) ions (Fig. 1b, ERD) were determined experimentally (ERD) for SiC samples irradiated at different temperatures. A comparison between these pro-
files and the calculated ballistic nitrogen profile for the entire bombardment sequence at the corresponding experimental doses (Fig. 1b, DYTRIRS) shows that at all the temperatures used, the implanted nitrogen undergoes very little diffusion which, reflects the slight change in the overall distribution profiles of the scattering centers for the central regions of the implanted SiC obtained by RBS.

The influence of N⁺ and Al⁺ irradiation can also be seen in a change in the concentration of SiC components. A very common consequence of implantation is the formation of carbon nonuniformity. A comparison between the change in the carbon concentration produced only by the ballistic action of the implanted ions (Fig. 2, DYTRIRS) and the experimentally determined (ERD) depth dependences of the carbon concentrations at various irradiation temperatures (Fig. 2) suggests that an increase in implantation temperature leads to diffusion-induced changes in the structure of the material. However, like the RBS data, these experiments indicate that the structure of the material during high-temperature implantation evolves differently in regions of different depth.

The entire irradiated material may thus be divided into five regions according to depth (regions A, B, C, D, and E in Fig. 1) in which different diffusion reactions may play a dominant role in the kinetics.

**PHYSICAL MODEL**

By comparing the experimental RBS and ERD data with the ballistic calculations, we will now give a qualitative description of the main physical reactions determining the kinetics of the radiation defects in SiC in regions of different depth in order to put forward a physical model to describe the annealing processes in high-temperature implantation.

We shall begin with the most defect-saturated region D (Fig. 1).

**REGION D (BETWEEN 1500 AND 3000 Å)**

This region has the highest concentration of scattering centers (up to 80%). At high irradiation temperatures, between 400 and 800 °C, the structure of the region changes relatively little. It receives the highest concentration of implanted N⁺ and Al⁺ ions (Fig. 1, curve 1) and electron microscopy reveals fairly good long-range order. Since temperatures up to 800 °C have little influence on the number of