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Ion implantation in 4H–SiC

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Abstract

Silicon carbide offers unique applications as a wide bandgap semiconductor. This paper reviews various aspects of ion implantation in 4H–SiC studied with a view to optimise ion implantation in silicon carbide. Al, P and Si ions with keV energies were used. Channelling effects were studied in both *a*-axis and *c*-axis crystals as a function of tilts along major orthogonal planes and off the major orthogonal planes. Major axes such as [0 0 0 1] and the $[1 1 \bar{2} 0]$ and minor axis like the $[1 1 \bar{2} 3]$ showed long channelling tails and optimum tilts for minimising channelling are recommended. TEM analyses of the samples showed the formation of (0 0 0 1) prismatic loops and the $(1 1 \bar{2} 0)$ loops as well,in both a and *c*-cut crystals. We also note the presence of voids only in P implanted samples implanted with amorphising doses. The competing process between damage accumulation and dynamic annealing was studied by determining the critical temperature for the transition between crystalline and amorphous SiC and an activation energy of 1.3 eV is extracted.

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Keywords: Ion implantation; Silicon carbide; Channelling; Extended defects; Dynamic annealing; Damage accumulation

1. Introduction

Silicon carbide is a promising wide bandgap semiconductor and has unique properties for specific device applications as already observed by Shockley in the 1950's. It has a wide range of applications for high temperature, high power and high frequency devices. For instance, silicon carbide devices can operate at 600 °C while current silicon devices will not operate at temperatures higher than 350 °C. Another unique property of SiC is its ability to exist in several crystal forms known as polytypes [1] which have different bandgaps. Ion implantation is the most viable process to achieve both lateral and in depth control over dopant incorporation. Defects are an important by-product of ion implantation and it is crucial to understand defect formation and the nature of the defects in order to cater for the needs of the devices. A major hurdle for the SiC devices was the propagation of stacking faults to the surface under forward bias leading to device failure [2–4]. Several groups showed a polytypic transformation resulting from two Shockley partials gliding on neighbouring basal planes [3,5,6] creating a 3C SiC lamellae in between. These 3C–SiC lamellae behave like quantum wells in 4H–SiC crystals because of the different bandgaps associated with the different polytypes. In this paper, we review selected results from our work. In the first part of the paper, we will show the effect of channelling on Al distribution in both *a*-cut and *c*-cut 4H–SiC and we will recommend optimum tilt orientation for these crystal to minimise channelling. The second

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part of the paper concentrates on the transmission electron microscopy (TEM) studies of P implanted 4H–SiC. The third part of the paper addresses the issue of dynamic annealing in silicon carbide during ion implantation with a view to understand which defects are responsible for defect annihilation during ion implantation.

2. Channelling in *a*-cut and *c*-cut 4H–SiC

For doping, the junction depth is determined by the implant depth which is predominantly varied with the implant energy. However, because of the difference in the channelled and random stopping power of ions in a crystal, the depth of the junction will also depend on the extent of channelling of the implant ions. In the Si microelectronics industry, a 7° tilt of the substrate is commonly used to avoid channelling of the implanted ions in (100)Si. There is very little literature to recommend the optimum tilt in hexagonal crystals to minimise channelling. Channelling in *c*-cut crystal could be even more complicated, considering the fact that there are six intersecting major planes to the *c*-direction, namely the $\{11\bar{2}0\}$ and the $\{1\bar{1}00\}$ planes. In addition, the miscut necessary for growing epitaxial *c*-cut 4H–SiC needs to be taken into account when determining optimum implant orientation as different suppliers of silicon carbide offer wafers with miscut in different planes.

The *c*-cut crystals used for this work have a 8.5° miscut equivalent to a 8.5° tilt in the $(1\bar{1}00)$ plane whereas the *a*-cut crystals were on-axis. These crystals were aligned using a 1.46 MeV H^+ beam for Rutherford Backscattering Spectrometry and channelling (RBS-C) and implanted with 60 keV Al^- to a nominal dose of 5×10^{13} cm^{-2} with an unscanned beam and the samples were analysed by secondary ion mass spectrometry (SIMS). Fig. 1 shows the Al profiles measured by SIMS in the *c*-cut crystals. The Al profile implanted on-axis shows a tail of about 0.6 μm compared to the 0.4 μm implant profile obtained from a sample tilted by 8° in a plane halfway between a $\{1\bar{1}00\}$ type plane and a $\{11\bar{2}0\}$ type plane to minimise planar channelling. Interestingly, the sample with a 9° tilt in the $\{1\bar{1}00\}$ plane shows very little channelling and this is similar in orientation to implanting normal to the wafer surface because of the wafer miscut. The most surprising result is the long channelling tail of 1.8 μm observed in the $[11\bar{2}3]$ axis implanted sample. The long channelling tail is even larger than the one observed for the on-axis [0001] implant which is a major axis in contrast to $[11\bar{2}3]$.

Fig. 2 summarises the implants carried out for the *a*-cut crystals. It is interesting to note that the on-axis *a*-cut implanted samples showed an even longer tail of 3 μm than observed for on axis *c*-cut crystals. The sample tilted 10° in a plane 55° from $(1\bar{1}00)$ plane is considered to be the direction with minimum channelling and it is interesting that the sample with a 10° tilt along the $(1\bar{1}00)$ plane showed very little channelling as well [7]. In contrast, a 10° tilt in the (0001) plane showed a 1 μm tail in the profile.

3. TEM study of P implanted samples

There are two main structural defects widely reported in SiC, namely the interstitial loops on the (0001) habit plane, the prismatic (0001) loops [8] and the Shockley partials gliding on the basal plane of type $1/3\langle 1\bar{1}00\rangle$ [9]. Our studies on 4H–SiC implanted with 400 keV P^+ showed that at a low dose of 4×10^{14} cm^{-2} at room temperature, there is no amorphisation and little swelling resulting from the implant (≈ 6% volume increase) whereas the higher dose of 1×10^{15} cm^{-2} showed a buried amorphous region at a depth of 1600–4200 Å independent of orientation. The swelling measured in the latter sample is equivalent to an increase in volume of 17%. Burgers vector analysis was carried out using the standard $\mathbf{g}.\mathbf{b} = 0$ and $\mathbf{g}.\mathbf{b} \wedge \mathbf{u} = 0$ invisibility criteria where **g** is the diffraction vector, **b** is the

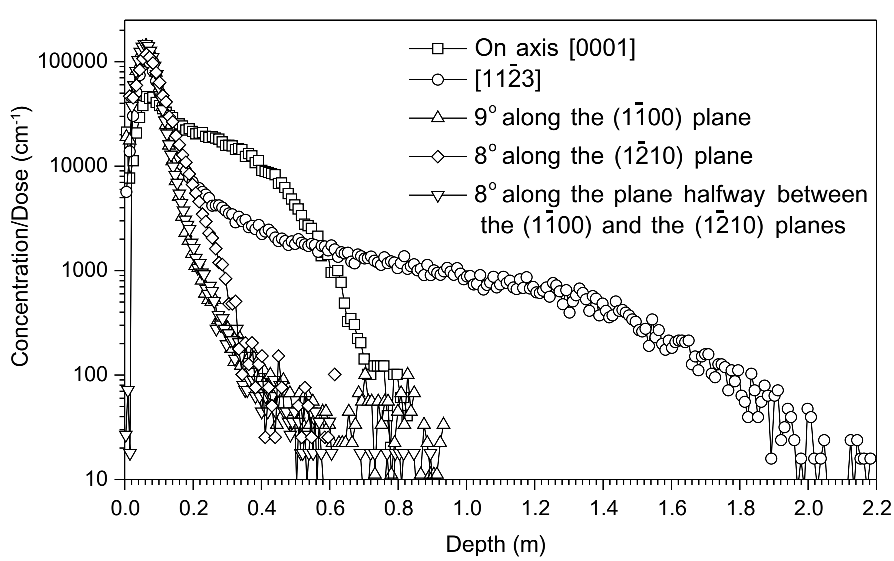

Fig. 1. SIMS profiles of Al implanted in 4H–SiC along various tilts close to the *c*-axis.