Interstitial related defect of $^{12}\text{B}$ implanted into n- and p-type silicon


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$^{13}$-radiation detected nuclear magnetic resonance ($^{13}$-NMR) measurements of $^{12}\text{B}$ occupying sites with noncubic surroundings after implantation into Si have been extended from p-type to moderately doped n-type material. The quadrupole split signals observed in both materials indicate the existence of the same interstitial related boron defect but with lower thermal stability in n-type Si.

1. Introduction

The B interstitial related defect $\text{Bi}$ has been the object of extensive electron paramagnetic resonance (EPR) and deep-level transient spectroscopy (DLTS) experiments in electron-irradiated boron-doped silicon [1-3]. Three charge states $\text{Bi}^+$, $\text{Bi}^0$, $\text{Bi}^-$ were found with negative $-U$ ordering of their energy levels in the gap. Depending on the position of the Fermi level the diamagnetic states $\text{Bi}^+$ and $\text{Bi}^-$ are thermodynamically stable in p- or n-type material, respectively, whereas the EPR-active neutral state $\text{Bi}^0$ is metastable and only seen after photogeneration. For the three charge states of $\text{Bi}$ different microscopic models have been suggested [1,2,4]. A recent theoretical calculation yielded for $\text{Bi}^+$ not the simple B interstitial but rather a B substitutional combined with a Si interstitial with axial $\langle 111 \rangle$ symmetry. For $\text{Bi}^0$ and $\text{Bi}^-$ defect structures with lower, similar symmetries were calculated [4].

Interstitial related boron $\text{Bi}$ clearly also is to be expected if boron is implanted into silicon. In two recent $^{13}$-NMR studies on $^{12}\text{B}$ ($\tau_\beta = 29$ ms, $I = 1$) implanted into variously doped Si samples it turned out that only at high temperatures above 600 to 900 K nearly all boron defects anneal to normal substitutional sites $^{12}\text{B}_s$, where the annealing temperature increases in going from n- to p-type material [5,6]. In a subsequent $^{13}$-NMR study on $^{12}\text{B}$ implanted into a moderately doped p-type Si sample at $T = 320$ K it was further found that about 30% of the species $^{12}\text{B}_n$ occupying sites with noncubic surroundings represent indeed an interstitial related defect showing properties in accordance with $\text{Bi}^+$ deduced from EPR and DLTS measurements in electron-irradiated Si : B [7]. In the present study extensions both to n-type Si and to other temperatures will be reported.

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2. Measurements and results

Spin polarized $^{12}$B nuclei, created by the nuclear reaction $^{11}$B(d, p)$^{12}$B in a thin target foil, were implanted into crystalline Si with recoil energies distributed between 0 and 450 keV. Their asymmetric $\beta$ radiation was used to detect the NMR signals. Details of the $\beta$-NMR method are given in another contribution to this conference [8].

$\beta$-NMR signals at the Larmor frequency $\nu_L$ correspond to $^{12}$B$_s$, whereas $^{12}$B$_i$ gives rise to quadrupole split spectra due to the nonvanishing electric field gradient (efg) at sites with noncubic surroundings [6,8]. Since under our experimental conditions the relative Zeeman populations are 4 : 3 : 3 for $m = -1, 0, +1$, respectively [9,10], only the transition $-1 \leftrightarrow 0$ produces a NMR signal. In strong magnetic field $B$ its frequency is given for the case of an axially symmetric efg [11] by

$$
\nu_i = \nu_L + \frac{3}{8h} e^2 Q (3 \cos^2 \phi_i - 1) \\
+ \frac{3}{16 \nu_L \hbar^2} (e^2 Q)^2 \left[ \frac{3}{2} \cos^2 \phi_i (1 - \cos^2 \phi_i) + \frac{3}{8} (1 - \cos^2 \phi_i)^2 \right].
$$

(1)

Fig. 1. Quadrupole split $\beta$-NMR signals of $^{12}$B$_i^+$ in n-type Si for five crystal orientations. The baselines of all resonance curves are shifted to 10% to correct for different instrumental asymmetries. The sample was rotated about the [100] axis; $\alpha = \angle (B, [001])$. In spectrum d) additionally the Larmor signal of $^{12}$B$_s$ is registered. In spectrum e) quadrupole shifted and Larmor signals collapse. $T = 240$ K, $B = 400.6$ mT, rf induction $B_{1\text{rot}} = 150$ $\mu$T, rf modulation $\pm 1$ kHz.