Structure and thermal evolution of small clusters found in ultra low energy high dose boron implanted silicon

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To continue scaling down CMOS devices, ultra-shallow and extremely highly doped *p+/n* junctions must be fabricated. In most practical cases, the dopant (boron) is introduced by ion implantation at concentrations which largely exceeds the equilibrium solubility limit of boron in silicon. It is thus not surprising that it cannot be activated in full and instead forms precipitates of the metastable SiB3 or stable SiB6 phase after long and high temperature annealing (1). However, diffusion and activation studies show that, even after ion implantation at lower doses, a large part of the boron atoms is inactive and immobile. These observations have convinced the community that clusters involving both Si and B atoms must be formed when supersaturations of both Si interstitial atoms and boron coexist. There has been much debate in recent years concerning the possible structure of these clusters. Ab initio calculations have been extensively used to study the stability o small clusters containing B and Si atoms in a Si matrix with the result that is now generally admitted that these clusters *should* consist of only few atoms.

Surprisingly our recent investigations show that the injection of Si interstitials into regions containing high concentrations (but still well below the solubility limit) of substitutional B results in the deactivation of the dopant and the formation of "immobile" boron. To study this phenomenon, boron delta doped layers were grown by CVD, implanted with Si ions then annealed. As a routine characterization, TEM was performed on these samples, with the unexpected result that the deep delta layers, far from the implanted region, where a fraction of boron was immobile during annealing, could be *seen* in the TEM under appropriate conditions. While nothing can be detected by classical nor by high resolution imaging, (very) weak beam dark field electron microscopy reveals the presence of small (1-2 nm) objects imaged thanks to the local deformation they create in the Si matrix. Unfortunately, their density was not large enough to allow us to study their structure in detail.

To overcome this difficulty, we have investigated samples implanted with boron at 500 eV, $1x10^{15}$ $cm^{-2}$ and annealed at 650°C. We have found again the same objects using the same imaging conditions but this time in large enough densities so that their structure and kinetic evolution during annealing can be studied. Figure 1 is a typical high resolution image of one of these defects. The original and filtered images show that the defects are circular, have a diameter of about 2 nm and systematically bend the surrounding (100) planes outwards, as expected for interstitial-type defects lying between two successive Si (100) planes. It is crucial to note that such defects in Si have never been reported so far and that they are not

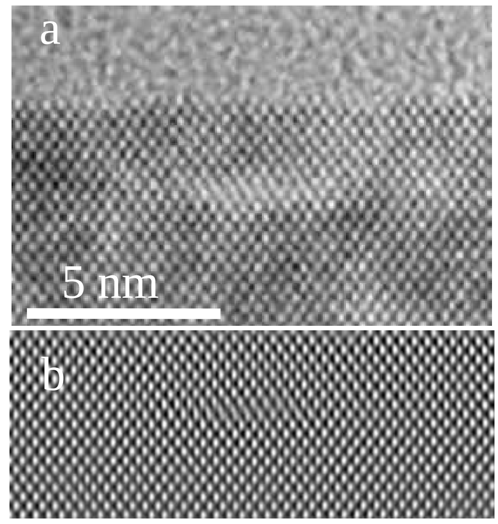


**Figure 1: a-** original HREM image
**b-** IFFT, using {200}, {111},{220}spots

observed in Si implanted samples when boron is not present in large concentration (2).

We have investigated the thermal evolution of these defects upon annealing at low temperature. A typical result is shown in Fig.2. During annealing these defects grow in size and reduce their density following a non-conservative Ostwald ripening process (2). Spike annealing at high temperature makes them dissolve and this shows that they are not the precursors of a stable second phase.

Moreover, annealing the defects under oxidizing ambient, i.e. injecting extra Si atoms in the system, results in the increase of the volume fraction occupied by these defects and a decrease of the substitutional fraction of boron in the matrix.

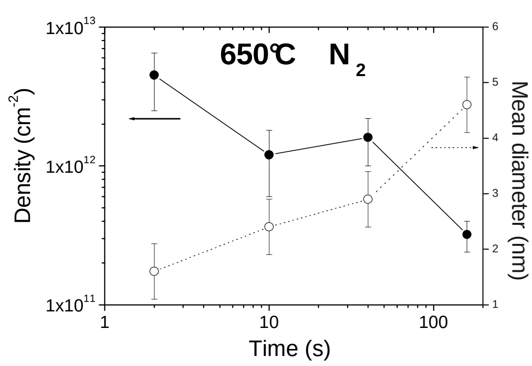


**Figure2:** Thermal evolution of density and mean diameter

These results strongly suggest that the observed clusters are 2 dimensional precipitates involving both B and Si atoms. This may be the very first evidence that boron-interstitial clusters can be imaged by TEM and thus are probably much bigger than generally assumed. They might contain tens or hundreds of atoms.

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References

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