Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 237 (2005) 142–147
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

# Reducing ultra-shallow boron diffusion using carbon and fluorine co-implantation

Aaron Vanderpool *, Mitch Taylor

*Intel corporation, 16681 SW Marcile Ln., Beaverton, OR 97007, United States*

Available online 17 June 2005

**Abstract**

A method to reduce the diffusion of boron in ultra-shallow junctions (USJ) has been found using the co-implantation of fluorine and carbon. In this $2^4$ designed experiment a 40% reduction of B diffusion in the presence of a shallow F and C implant was found over the use of F alone. In addition another 10% reduction of B diffusion can be obtained if a medium dose arsenic implant is preformed before F and B implantation. It has been found that implanting in this order significantly alters the defect structure of the USJ and suggests that F trapped in the lattice after anneal may be tied up in vacancy fluorine clusters which increase B activation.


*Keywords:* Boron; Diffusion; Fluorine; Carbon; Co-implant

## 1. Introduction

Control of boron diffusion is critical in the production of P-type metal oxide semiconductor (PMOS) devices in silicon. In order to produce very large scale integrated (VLSI) transistors boron must be implanted into silicon to create high resolution ultra-shallow junction (USJ) structures. The implantation of boron and other ions in the PMOS process flow creates damage in the silicon lattice that enhances the interstitial diffusion mechanisms of boron. To control the diffusion of boron it is then necessary to interact with these enhanced interstitial mechanisms. Equally important is that boron must remain in solution with the silicon lattice and be electrically active to be useful as an USJ in PMOS devices.

The primary obstacle to the formation of boron USJ's is the transient enhanced diffusion (TED) it experiences due to the release of Si self-interstitials from the implant end of range (EOR) defects [1]. As the interstitials diffuse towards the surface to recombine [2] with the tremendous population of virtual vacancies there they can kick-out the

* Corresponding author. Tel.: +1 971 214 1447.
*E-mail address:* aaron.o.vanderpool@intel.com (A. Vanderpool).

0168-583X/$ - see front matter 
doi:10.1016/j.nimb.2005.04.089

substitutional B or form interstitial complexes with boron [3]. The fast diffusing species that are created increase the diffusion predicted by Fick's Law by several orders of magnitude [1]. Control of this diffusion was first accomplished with $BF_2$ implants and then with F co-implantation [4]. Speculation being that the very reactive F was interacting with the boron or Si self-interstitials reducing diffusion [4–6].

## 2. Theory

Modern PMOS process flows contain other implants besides the boron USJ implant (P-type source drain extension or P tip implant) and the F co-implant that affect the diffusion properties of boron. Most notable is the angled As halo implant used to reduce the depletion regions of the source and drain to prevent punch through below the channel. This implant is usually a medium dose of 70–90 keV As implanted at 30–45° in the same area as the B USJ implant. This implant can add significant damage to the Si lattice. If preformed after the B USJ implant it is conceivable that B atoms could be spread deeper into the substrate via a knock-on effect. Jacques et al. [7] believed that she was observing a knock-on effect like this when she toggled the implant order of a B USJ implant (500 eV $B^+$ at a dose of $1 \times 10^{15}$ ions/cm$^2$) and the F co-implant (6 keV $F^+$ at a dose of $2 \times 10^{15}$ ions/cm$^2$). Fig. 1 contains B secondary ion mass spectrometry (SIMS) profiles of B with F co-implants into amorphized Si where the order of the implants is switched for various anneal times. There is another explanation for these profiles. When F is implanted first it interacts with some of the existing point defects in the Si before the B can. This prevents B from interacting with them to some extent magnifying fluorine's diffusion reduction mechanism.

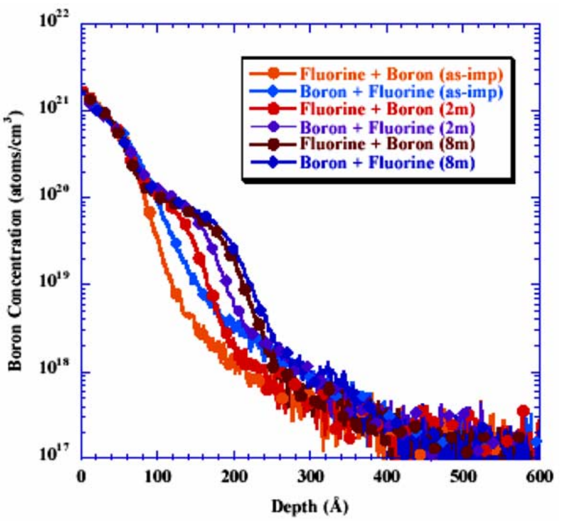


Fig. 1. Boron SIMS profiles as a annealing time that at 600 °C (as-implemented to 8 min) – Jacques et al. [7].

Besides the boron dopant and the Si self-interstitials it is possible that the point defect F interacts with is the implant generated vacancies near the surface. Diebel et al. [8,9], Dunham [10] and Shano et al. [11] have all proposed that the most stable cluster F can form in this region is a fluorine-vacancy cluster ($F_nV_m$). They calculate that this cluster is immobile but will be annihilated by interstitials at high temperature. More convincingly Pi [12] has shown using positron annihilation spectroscopy (PAS) that a very large concentration of vacancies exist when F is present. His data indicates that the as-implanted vacancy concentration with F present extends well into the EOR and that $F_nV_m$ clusters near the surface are initially vacancy rich but become F rich after several hours at 700 °C.

## 3. Experiment

A $2^4$ full factorial design of experiment (DOE) was built to more fully characterize the PMOS process flow around the boron USJ implant. The four factors of this DOE were a carbon co-implant, a fluorine co-implant, the order of the As halo and B USJ implant and the activation anneal. The processing steps in the DOE are illustrated in Table 1 where the halo first order uses the As halo implant to damage the lattice before the B and F implants. The P tip first order places the As halo implant damage after the B and F implants.

The As halo implant is a 90 keV $As^+$ implant with a dose of about $2 \times 10^{13}$ ions/cm$^2$ at a 30° tilt.