ORNL/CP-94748

CONF-971207--

BORON-ENHANCED-DIFFUSION OF BORON: THE LIMITING FACTOR FOR ULTRA-SHALLOW JUNCTIONS

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Abstract

Reducing implant energy is an effective way to eliminate transient enhanced diffusion (TED) due to excess interstitials from the implant. It is shown that TED from a fixed Si dose implanted at energies from 0.5 to 20 keV into boron doping-superlattices decreases linearly with decreasing Si ion range, virtually disappearing at sub-keV energies. However, for sub-keV B implants diffusion remains enhanced and x_j is limited to ≥100 nm at 1050°C. We term this enhancement, which arises in the presence of B atomic concentrations at the surface of ≈6%, *Boron-Enhanced-Diffusion (BED).*

Introduction

It is currently projected that 0.07 μm technology will require junction depths, x_j, ≈ 30 nm. This places severe restrictions on the amount of transient enhanced diffusion (TED) which can be tolerated. If dopants are to be introduced by implantation, TED is inevitable due to the excess interstitials from the implant. However, it is hoped that TED can be reduced by reducing the implantation energy, thus placing the dopant and the implantation-induced excess interstitials closer to the surface which is a sink for interstitials. Consequently, ultra-low energy implantation is being widely pursued for shallow junctions for future device technologies (1), and a new generation of ultra-low energy commercial implanters is being designed. In this work, we show that reducing implant energy is an effective way to eliminate TED due to interstitials from the implant. However, for sub-keV B implants diffusion remains enhanced and x_j is limited to ≥100 nm at 1050°C. This enhancement is also observed from evaporated B layers arising in the presence of B atomic concentrations at the surface of ≈6%.

TED from low-energy Si^+ implants

We have quantified the reduction in TED with reduced implant energy using implantation of Si into boron-doping superlattices (B-DSL) containing B marker layers grown by molecular beam epitaxy (MBE) (2). Diffusion of the B marker layers (e.g. Fig.1) is profiled using SIMS and the diffusivity enhancement (ratio of observed diffusivity to equilibrium diffusivity) is extracted for each marker layer using the process simulator PROPHET (3), which takes into account the standard concentration-dependence of B diffusion.

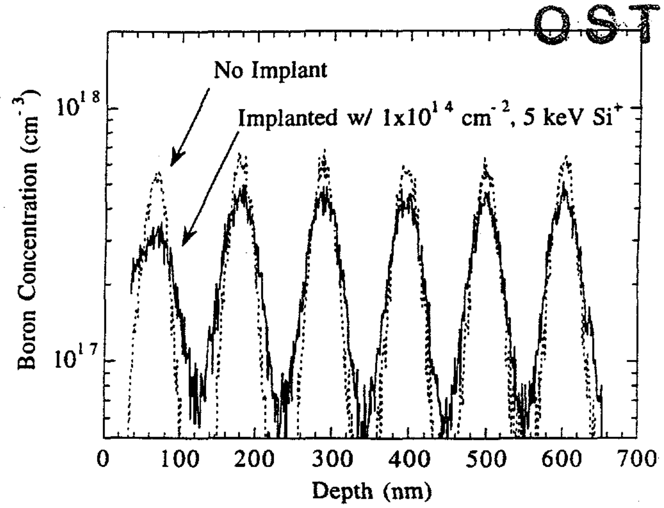

Fig.1 SIMS profiles comparing diffusion of B spikes during 600 s at 810°C in unimplanted and 5 keV Si^+ implanted B-DSL's. The Si^+ dose was 1×10^{14} cm^{-2}.

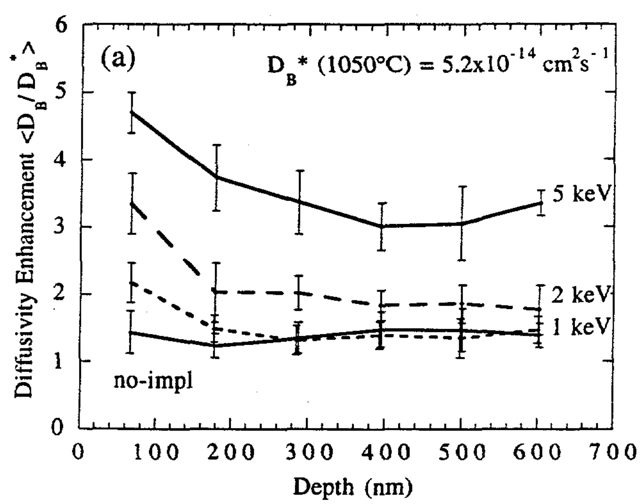

Fig.2(a) Diffusivity enhancement of B markers from a 1×10^{14} cm^{-2} Si^+ implant at 1-, 2-, and 5-keV, following 1050°C, 10 s annealing, as a function of marker layer depth.

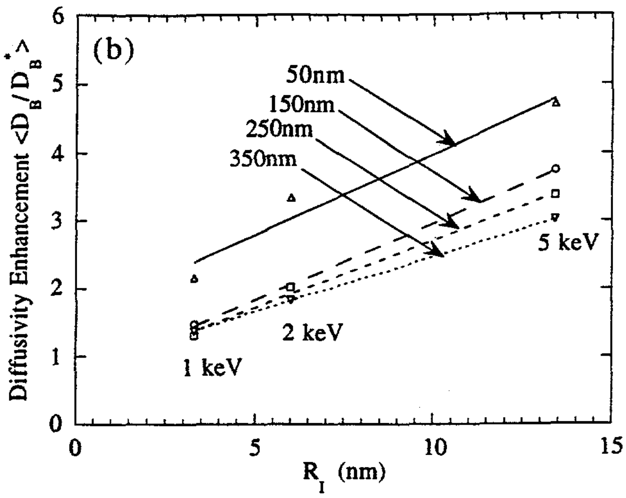

Fig.2(b) Boron diffusivity enhancement data from Fig.2(a), at 1050°C as a function of R_I, implant range (depth of excess interstitials).

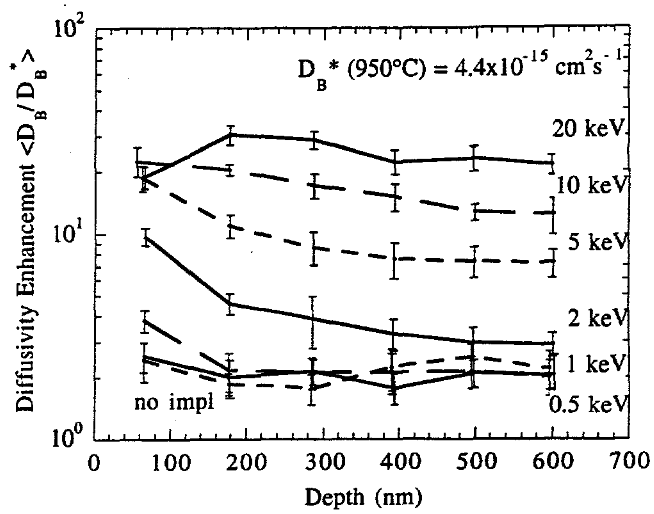

Fig.3 Diffusivity enhancement of B markers from a 1×10^{14} cm^{-2} Si^+ at 0.5-, 1-, 2-, 5-, 10-, or 20-keV, following 950°C, 10 s annealing, as a function of marker layer depth.

The diffusivity enhancements from 1-, 2-, and 5-keV Si^+ implanted and unimplanted B-DSL's are compared in Fig.2(a) as a function of marker layer depth. The enhancement decreases linearly with implant depth (i.e., the distance of the interstitials from the surface), as shown in Fig.2(b). The enhancement decreases from ~5× for 5 keV implantation energy to ~2× for 1 keV, and extrapolates to ~1× for zero keV. This is consistent with our expectation that at zero implantation energy (deposition), there would be no excess interstitials from the self-ion implantation and hence no TED. The same energy-dependent trend is observed at a lower temperature of 950°C, and over nearly two orders of magnitude of energy (Fig.3). The reduction in TED with reduced self-ion implantation energy is due to increased interstitial annihilation at the surface which behaves as a perfect sink for interstitials (4). These Si-implant results demonstrate that in the range of annealing temperatures of interest for p-n junction formation TED is virtually eliminated at sub-keV implantation energies.

Ultra-shallow n-type junctions

Results from these types of experiments can be directly extended for design of ultra-shallow n^+ junctions (5). By implanting As and P at energies as low as 2 and 1 keV, respectively, TED can be minimized. Fig.4(a) and (b) show diffused dopant profiles for 2 keV As^+ and 1 keV P^+. with junction depths of 200 and 550Å, respectively. Relatively high solid solubilities of As and P result in sheet resistance values of 600 and 450 Ω/sq, respectively. In each case, the sheet resistance can be reduced further by increasing the implantation dose.

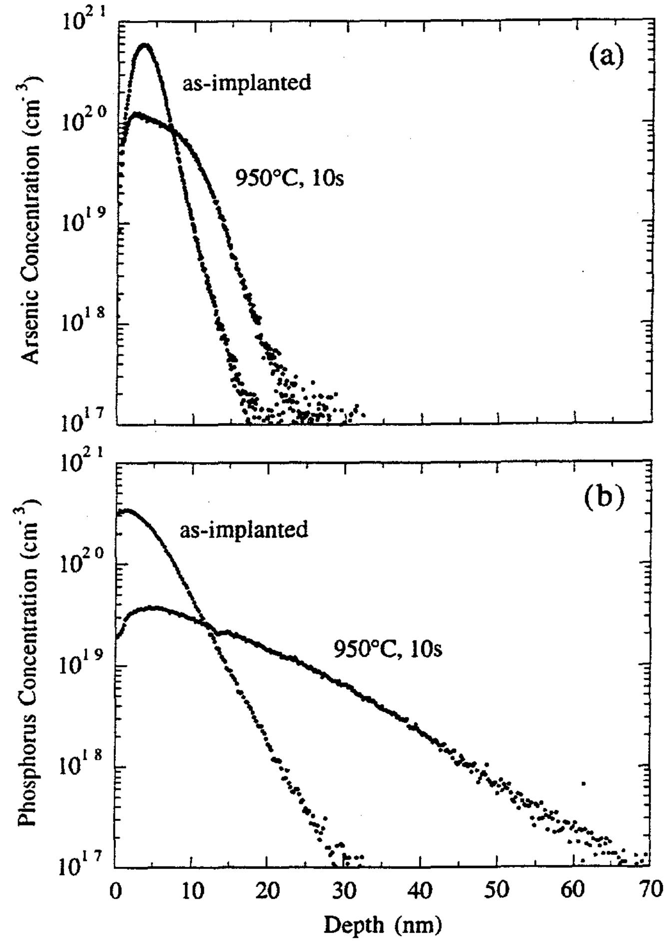

Fig.4 SIMS data comparing as-implanted and annealed depth profiles from (a) 3×10^{14} cm^{-2}, 2 keV As^+, and (b) 3×10^{14} cm^{-2}, 1 keV P^+. Annealing conditions were 950°C for 10 s.

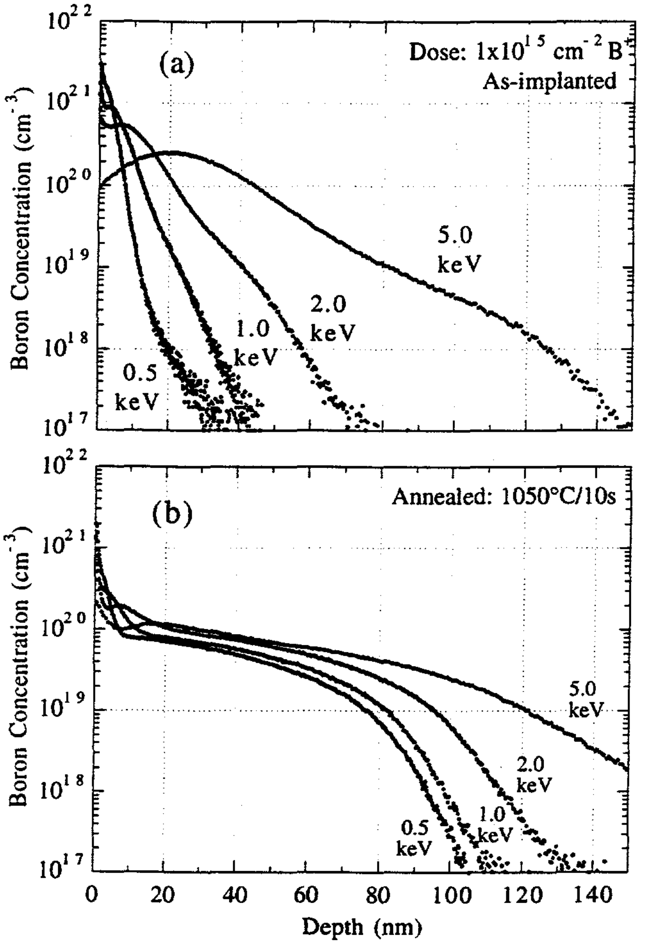

Fig.5 SIMS depth profiles of 1×10^{15} cm^{-2} B implanted at 0.5-, 1-, 2-, and 5-keV (a) as implanted, and (b) after annealing at 1050°C for 10s.

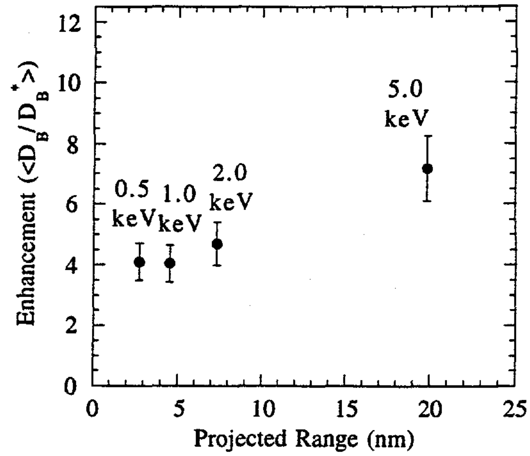

Fig.6 Diffusivity enhancements extracted from data in Fig.5(b) as a function of the B projected range.

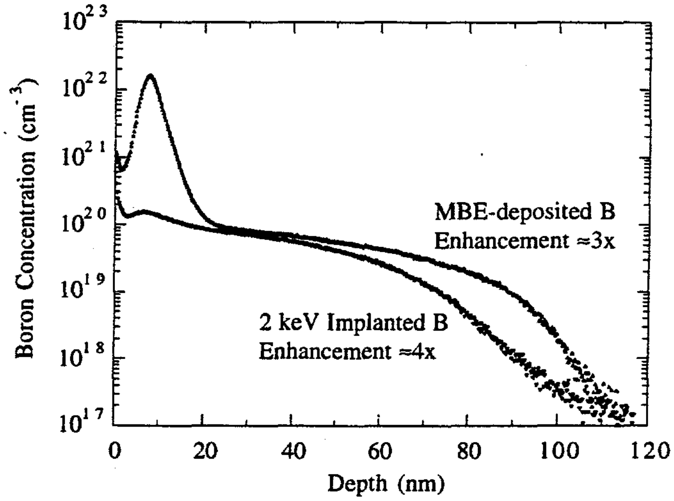

Fig.7 SIMS depth profiles comparing enhanced diffusion from MBE-deposited B and 1×10^{15} cm^{-2} B+ implant at 2 keV, after annealing at 1050°C for 10 s.

Not-so-ultra-shallow p-type junctions

In the case of B implantation, however, we observe a saturation in the decrease in TED, and hence in x_j, with reduction in implantation energy. Figs.5(a) and (b) show depth profiles of 1×10^{15} cm^{-2} B+ implanted at 0.5-, 1-, 2-, and 5-keV, before and after annealing at 1050°C for 10s. The diffusivity enhancements for the data in Fig.5(b) are plotted in Fig.6 as a function of the boron ion projected range. The reduction in enhancement saturates at ~4× when the implantation energy is reduced to 1 and 0.5 keV. Since the Si implantation results (Figs.2 and 3) demonstrate that TED can be effectively reduced by reducing implantation energy, this observation suggests that in the case of boron implantation there is some additional effect which leads to enhanced diffusivity. We call this effect *Boron-Enhanced-Diffusion* (BED). The BED effect is larger than that which can be accounted for by variation due to temperature control. Since TED is driven by excess interstitials there are two possible explanations for these findings; either the implantation-induced excess interstitials are not being annihilated at the surface for shallow B implants (in contrast to the results from Si implants), or a greater number of excess interstitials are being generated from the shallower implanted B layer than from the deeper implants.

Deposited boron

To test the effect of surface B, we have measured the diffusivity enhancement from a B layer deposited onto Si by MBE. This represents the ultimate limit of ultra-low energy implantation since the B atoms arrive at the surface at ≈0.0001 keV. Fig.7 compares diffusion from the evaporated B layer with that from a 2 keV B+ implant. Diffusivity from the MBE-deposited B layer is enhanced by a factor of ~3×. Since there are no excess interstitials in the case of MBE-deposited boron and yet enhanced diffusion is observed, it seems likely that interstitials injected from the B layer are responsible for the observed BED.

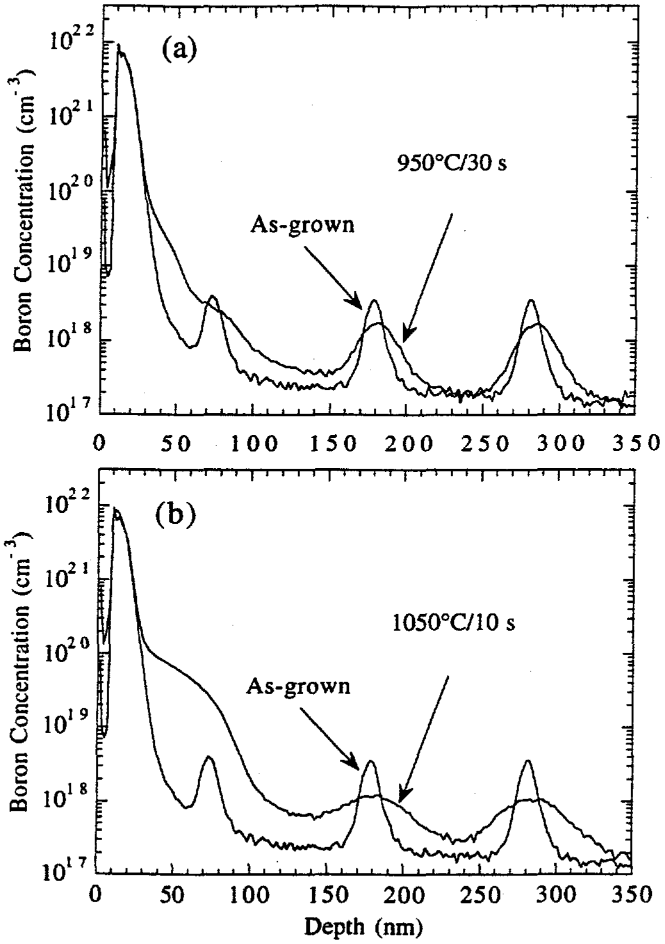

Fig.8 SIMS depth profiles comparing as grown and annealed MBE-grown B-DSL's containing an elemental B layer, annealed at (a) 950°C, 30 s, and (b) 1050°C, 10 s.

SiB_4 phase transformation and interstitial injection

Electron diffraction analysis of samples with MBE-deposited B or high dose implanted layers reveals the presence of an amorphous layer even after annealing. Based on comparison with published X-ray diffraction data we have indexed the diffraction pattern as SiB_4 (6). It thus appears that when the B concentration in the implanted layer exceeds a certain threshold, a separate silicon boride phase can be formed. It is possible that formation of this phase injects interstitials into the bulk. We have used specially designed B-DSL's, consisting of three B marker layers, buried beneath a layer of evaporated B, to check for interstitial injection from the silicon boride layer via enhanced marker layer diffusion. Figs.8(a) and (b) compare as grown and diffused B profiles after annealing at 950°C/30s and 1050°C/10s, respectively; diffusion of the buried markers is enhanced by factors of 1.5× and 3.2×, respectively. These experiments indicate that interstitial injection is indeed occurring from the high concentration boron layers. We assume that the <50Å thin B layer is not giving rise to a significant temperature difference because the optical properties of the wafer at 1050°C are dominated by free carriers. Based on minimum doses for SiB_4 phase formation from 2 and 10 keV B implants, we estimate the threshold atomic B concentration to be between 6 and 10%. BED becomes important for ultra-shallow implants because the concentration of B increases rapidly as the energy is reduced.

Summary

We have investigated ultra-shallow junction formation using very low energy ion implantation. Using 0.5 to 20 keV Si implants into boron doping-superlattices it has been shown that transient enhanced diffusion, driven by implantation-induced excess interstitials, decreases linearly with the implant depth and virtually disappears at sub-keV energies. However, for sub-keV B implants diffusion remains enhanced, limiting junction depths to >100 nm following 1050°C/10s annealing. This enhancement, which we call BED (boron-enhanced-diffusion), is also observed in several experiments involving boron layers deposited by molecular beam epitaxy where there is no implantation damage. BED correlates with the presence of high atomic concentration boron and is an additional effect to the standard concentration-dependence of boron diffusivity. Electron diffraction analysis has revealed formation of a silicon boride phase (SiB_4) when the boron concentration exceeds 6% and there is evidence that silicon boride phase formation leads to interstitial injection.

References

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