

# Chicane Deceleration – An Innovative Energy Contamination Control Technique in Low Energy Ion Implantation

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**Abstract.** High current beams suitable for USJ implantation were generated by ‘Chicane Deceleration’ involving an s-bend to block contaminants. Implanted wafers were analyzed with 200eV O<sub>2</sub><sup>+</sup> beams at 45° to resolve the sources of dopant profile variation in fine detail. Energy contamination is essentially eliminated, but for B<sup>+</sup> channeling remains important. Unannealed X<sub>j</sub> values from 5 to 7 nm are reported for different implant species.

**Keywords:** Ion implantation; SIMS; Boron; USJ; Energy Contamination; Deceleration.

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## INTRODUCTION

The ITRS identifies the need for sub-40nm S/D junction depths. In the case of P-MOS devices, implant process requires very shallow implants, probably optimized to control damage mechanisms, to minimize phenomena such as transient-enhanced and boron-enhanced diffusion during the anneal. Ultra-shallow dopant placement (<< 10 nm) is desirable.<sup>1</sup> Alternatives to conventional boron implants have been developed, including implantation of decaborane<sup>2</sup> and octadecaborane<sup>3</sup> molecular ions, true gas cluster doping<sup>4</sup>, and plasma doping.

This paper describes a) a deceleration technique to deliver high current beams of boron or BF<sub>2</sub> at pure ultra-low energies, and b) SIMS data taken under conditions which optimize resolution of the ultra-shallow dopant profiles produced with the new technique. We explore a number of effects on the resulting measured dopant profile, including the effects of SIMS parameters. We quantify energy contamination and channeling (which could lead to deep tails in the dopant profile), as well as dose and species-related effects which can modify the as-implanted profile. At this stage, annealing was not investigated.

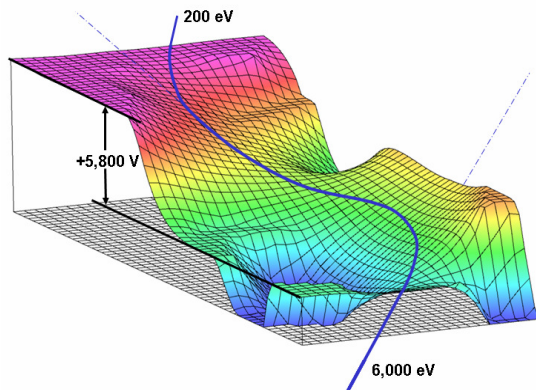


Figure 1. Chicane Deceleration. Ions are retarded by a potential field which deflects left and right around obstacles.

## EXPERIMENTAL DETAILS

Deceleration a short distance before the implantation station of an implanter is desirable to increase the available beam current, but in most commercially available ion implanters, results in energy contamination.<sup>5,6</sup>

We have developed an apparatus and technique for decelerating ion beams to small fractions of their original energy (from 1/3 to 1/30) while preserving a high percentage of the beam current and eliminating these high-energy contaminants. Fig. 1 shows how this technique works. Because of the obvious resemblance, it is named a ‘Deceleration Chicane’ after chicanes used in motor racing. The beam is deflected through

an s-bend by an electric field which contains a strong component of deceleration.<sup>7</sup> Boron ion beams were decelerated from energies in the range of 4 to 10 keV down to final energies of 200eV to 1 keV.

The beam of a relatively conventional beamline is first steered off axis by 5° to direct it into the chicane. In the chicane electric fields bend it 45° left, then 40° right. Ions which do not at all times have the correct energy-to-charge ratio cannot be transmitted around this chicane, and they leave the beam path to the left or right, where they are carefully intercepted by beam stops angled to block forward transmission of any unwanted emitted particles, neutral or charged. Neutral atoms formed within the beam leave the beam at the first bend. Additionally, ions which are neutralized within the chicane are also blocked.

Although space-charge forces are strong, they are controlled well, because the electrostatic bends are strongly focusing<sup>9</sup>, and the focusing and defocusing forces can be balanced. Data is presented in the next section to confirm this balance.

Beam currents were measured in a magnetically suppressed Faraday cup, whose field had been modeled and calculated to permit 100% transmission of 200eV boron. Dosimetry was largely manual; the desired mechanical velocity was hand-calculated and programmed. Since we are considering channeling, we also measured the angular divergence of the beam under several conditions.

SIMS analyses were initially performed on pilot samples under a variety of implant and analysis conditions. The effect of using different O<sub>2</sub><sup>+</sup> energies was explored, and was compared with data obtained by others. For the pilot implants we used argon preamorphization, and saw variability in the dopant background between about 1e17 and 1e18 per cc. However, RBS analysis confirmed that the material had been fully amorphous, eliminating channeling as a potential cause.

The present implant matrix was designed to remove uncertainty about the background, and to be sure to resolve any deep tails present in the dopant profiles. Prime n-type wafers were used. Most wafers were given a pre-amorphization implant (PAI) of 100keV of Ge at 2E15. The high energy and dose were designed to ensure that any higher energy beam components remained in amorphous silicon, to aid interpretation. It also ensured that any end-of-range damage existing beyond the fully amorphous layer was beyond the region of interest in these measurements. Some wafers were left crystalline and were implanted at 0° to permit axial channeling. Some implants used photoresist over 50% of the implanted surface. The effect upon the dopant profile of implanting to different doses was explored, since there was interest in observing saturation effects.

## RESULTS

### Metrology

Figure 2 shows two overlaid measurements of the same sample implanted with BF<sub>2</sub><sup>+</sup> at 981eV (equivalent to 200eV B), using different probe beams. Both use O<sub>2</sub><sup>+</sup> at 45°, but the energies are 200 and 750 eV. The normal velocity of the oxygen atoms is lowered by the use of molecular ions and by the 45 degree incidence, giving them a normal velocity equivalent to energies *per atom* of 70.7 and 265 eV respectively. Figure 2 shows that the result of analyzing these profiles with 750eV O<sub>2</sub> is an overestimate of depth of ~ 2 nm. We have based our conclusions on the 200eV O<sub>2</sub> 45° results, estimating the uncertainty in depth at 0.6nm. The data has an internal consistency of better than 0.1 nm.

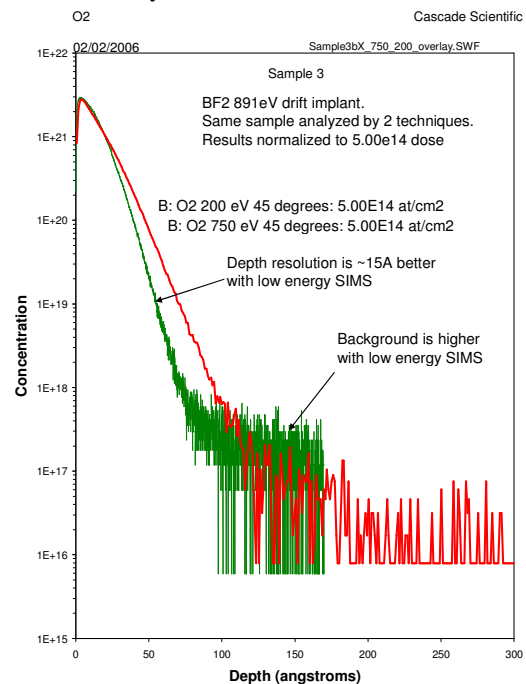
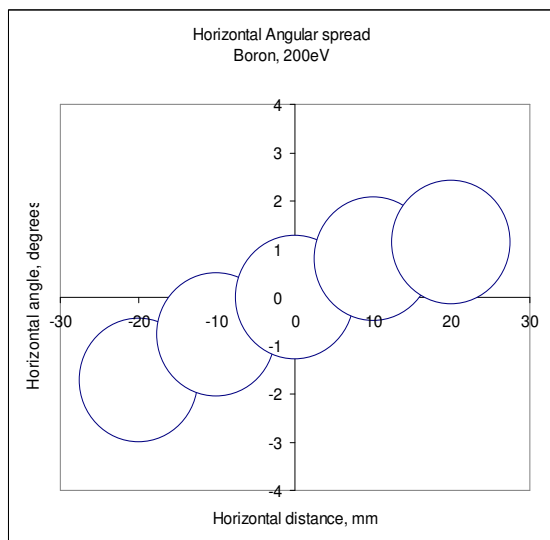


FIGURE 2. Effect of SIMS energy.

The background level is a source of concern and uncertainty. It can be seen from Fig. 2 that the background is higher in the case of 200eV analysis than of 750eV analysis. BF<sub>2</sub><sup>+</sup> produces a profile differing from the equivalent boron profile both in a substantially lower background (at about 1/3) and in a deeper peak concentration; further the amount of self-sputtering dose loss is greater. (These features are visible in fig. 4, further discussed below). The reason for the lower background is not clear, and is the subject of further study. The difference is not caused

by the presence of energy contaminants or by channeling; these mechanisms have been eliminated by careful use of controls, and will be further discussed below. The use of  $\text{BF}_2^+$  implants at 891 eV as a reference standard for 200eV boron implants is therefore invalid.

The angular distribution of the boron ion beam was measured by passing the beam through a set of holes in a plate, and allowing the resulting beam to mark a target 150mm behind the holes. In this manner we confirmed that the centroid of the incident ion beam was normal to the wafer surface within about  $0.3^\circ$ . The beam contained a distribution of angles about this centroid, 90% of the ions lying within about  $\pm 2.5^\circ$  of the centroid. There was no discernible variation of incident angle across the surface of the wafer using this method.



**FIGURE 3.** The angular divergence of the 200eV beams measured by passing the beam through five 3mm dia. holes, drifting 150mm, and recording the beam burns on paper.

## Analysis

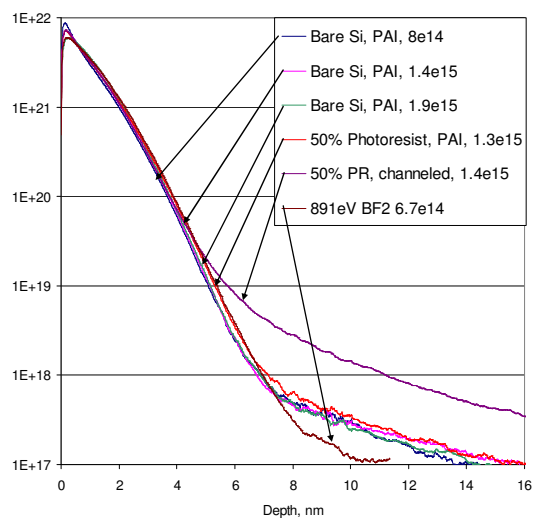
### Key observations

The profile of each peak is well resolved. No measurement artifacts are apparent at the surface. Surface oxide was approx 1.3nm based on elapsed time since pre-amorphization, except for the channeled wafers, where oxide thickness was unknown.

We can see differences in Fig. 4 in the position of the maximum concentration as a function of dose, presumably because of knock-on during implantation. For 200eV B at  $8.0 \times 10^{14}$  per  $\text{cm}^2$ , the peak concentration occurs at 0.11nm deep. At  $1.9 \times 10^{15}$  this increases to 0.21

nm. The peak position of a  $5.8 \times 10^{14}$   $\text{BF}_2$  891eV implant is deeper than that of the same dose of 200eV B, although the ion velocities are the same, but matches that of the  $1.9 \times 10^{15}$  boron profile. This can be accounted for by assuming that one effect of the co-implanted fluorine atoms in the lower dose  $\text{BF}_2^+$  implant is to knock on previously implanted boron at a similar rate to primary boron ions.

Above 3nm the effect of photoresist-induced pressure changes can be resolved. Above 4nm the effects of channeling can be resolved. Whereas the channeling leads to a very noticeable tail about 4nm deeper than the PAI implants, the effect of pressure dependence cannot be resolved above 10nm deep.



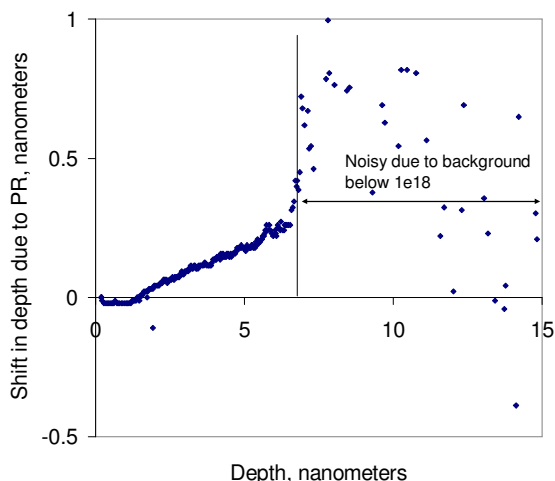
**FIGURE 4.** All profiles 200eV  $\text{B}^+$  using chicane deceleration from 6 keV, except 891eV  $\text{BF}_2$  from 8 keV for reference. All normalized to  $8.0 \times 10^{14}$  for comparison. Data is smoothed by a rolling average to reduce noise, width varying from 0.01 to 0.1 nm with depth. SIMS  $\text{O}_2^+$  200eV  $45^\circ$ . Boron currents 2.1 to 2.5 mA.  $\text{BF}_2$  3.6 mA. Preamorphization Ge 100 keV  $2 \times 10^{15}$  except where noted.

### Energy contamination

It was deemed impractical to obtain a valid reference sample of silicon implanted with drift-mode Boron at 200eV. The least ambiguous way to determine the level of energy contamination is to compare results from a bare wafer and from one with a 50% covering of photoresist (PR). Measurement of the actual pressure close to the wafer has little meaning since the outgassing hydrogen is a directed stream, and effective pressure in the beam is far higher than gauges will record. Dose control was based on measured beam current before the implant; the dose received by the wafer with photoresist was found to be 5% lower than the bare wafer. This can be explained

if the pressure rise in the beamline upstream of the chicane structure was high enough to increase beam neutralization by 5%. It is thus estimated that the flux of 6keV neutral boron atoms was at least 5% of the delivered 200eV boron. The projected range of 6 keV boron is 27 nm with 13 nm straggle, and the SIMS data shows no sign of such a contaminant.

But Fig. 4 shows a slight shift in the profile with the photoresist present. By normalizing the two profiles to the same total dose, and subtracting the bare wafer's profile from the photoresist profile, we can look at this difference in detail. This difference is plotted in Fig. 5. We have a high quality signal extending to 6.5 nm. Beyond this depth, the noise-swamped signal changes sign several times, and no clear evidence can be extracted from it. The data indicates that the profile depth at 6.5 nm is increased by 0.25nm (i.e. to 6.75nm), by the presence of photoresist. At this depth the concentration is around  $1E18$  per  $cm^3$ .

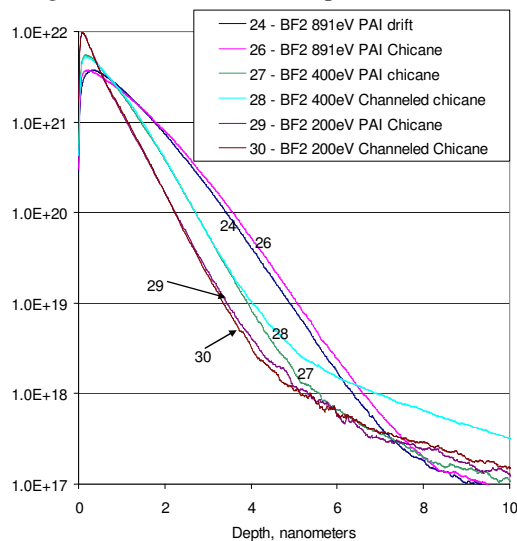


**FIGURE 5.** Effect of photoresist is to increase profile depth by up to 0.25nm. This is the limit of any energy contamination.

Fig. 6 shows two 891eV  $BF_2$  implants, number 24 being a drift-mode beam and number 26 using chicane deceleration from 8 keV. There is a shift in profile depth of about 0.25 nm. The background in both  $BF_2^+$  implants is 1/3 that of the 200eV  $B^+$  implants.

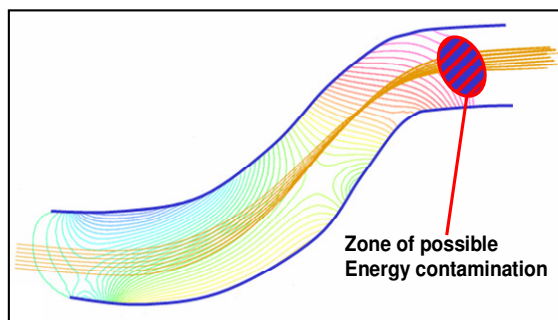
The highest contaminant energy present is clearly very small, being only tens of volts greater than the 200eV present. The mechanism by which it is formed is shown in Fig. 7. Any high-energy contaminant which can reach the wafer must be formed right at the exit of the chicane in the final region of electric field. We can estimate the magnitude. For 200eV boron, we can estimate that raising the energy by 22 eV on a bare wafer would give a profile which would fall within the observed PR profile. For 891eV  $BF_2$ , raising the drift-

mode energy by about 98eV would give a profile falling within the chicane decel profile.



**FIGURE 6.**  $BF_2$  implant profiles, all doses normalized to  $5e14$  for comparison and smoothed by a rolling average increasing from 0.01 to 0.1nm with depth

The chicane is highly effective in eliminating energy contamination. The excess energy is much lower than that produced by Einzel lenses and electron suppression schemes in some systems claiming to deliver 'drift' beams. Evaluation of a percentage energy contamination is almost impossible when the increase in energy is very slight, and has no practical value. Stating the effective maximum energy is more useful.



**FIGURE 7.** Source of residual contamination.

#### Profile Shape.

We implanted 200eV boron at several doses under otherwise identical conditions, and analyzed them in one batch under identical conditions.

For bare wafers, with PAI and 1.3nm oxide, we observed that the peak concentration occurred at a depth of 0.11 nm for a SIMS dose of  $8.5e14$ , but increased to 0.22 at a dose of  $1.9e15$ . Comparison of

the implanted doses and SIMS doses indicates loss of dopant at higher doses, reaching a relative 25% loss of dose by self-sputtering at  $1.9 \times 10^{15}$ .

It appears that as the dose is increased, the boron is redistributed by the collision cascades of the implanted ions. Dose retention would be seriously compromised at doses above  $4 \times 10^{15}$ , but up to  $2 \times 10^{15}$  is acceptable. The same mechanism that removes part of the dose pushes the peak concentration deeper.

891 eV  $\text{BF}_2^+$  implantation produces a profile similar to a 200eV  $\text{B}^+$  implant *at three times the dose*, as can be seen in the figures. Presumably fluorine atoms in the molecule also displace previously implanted atoms at a similar rate to boron ions.

#### *Channeling.*

For 200 keV  $\text{B}^+$  implants at  $0^\circ$ , Fig. 4 shows that failure to pre-amorphize the substrate caused the 'as-implanted  $X_j$ ' depth of dopant at a concentration of  $1 \times 10^{18}$  to increase by 4 nm. More than 1% of the implant channeled to a small extent, about 0.1% contributed to this deep tail. It has been reported elsewhere<sup>8</sup> that tilting the substrate is ineffective at low energies in reducing channeling.

For  $\text{BF}_2^+$  implants, the situation was different. We compared channeled and PAI implants at 400 and 200eV. In analyzing the results shown in Fig. 6, one should bear in mind that the effective boron energy is 90 and 45 eV respectively, while the oxygen effective energy in the SIMS is 71 eV. Therefore the resolution of the depth profile of these implants is compromised because the SIMS energy is not low enough.

At 400eV the implant doses were  $5 \times 10^{14}$ . Channeling did produce a significant effect at this energy, probably disqualifying this energy for use without PAI.

At 200 eV the implant doses were  $3 \times 10^{14}$ . It is striking that there is no discernible difference between the PAI and the crystalline substrates. The depth at which the concentration reaches  $1 \times 10^{18}$  is about 4.6 nm. The beam current for these implants was 1.0mA, which is sufficient for 33 300mm wafers per hour using reasonable generic handling times. With no requirement for PAI this is a throughput worth consideration for production use.

## CONCLUSIONS

We presented the Chicane deceleration technique for generating high-current ion beams (several mA) of various ions at low energies, and we present data in the

range from 200eV to 1 keV. The technique produces beams with very low angular spread, dominated by the thermal physics of ion production. It virtually eliminates high-energy contaminants from the ion beam.

We showed the need to use very low energy  $\text{O}_2$  beams in the SIMS analysis, in order to avoid significant distortion of the results. We further discussed issues of control and background. We performed SIMS analyses of a number of implants using this technique, to quantify the monochromaticity of the ion beam, and elucidate the effects of channeling and saturation.

We demonstrated that USJ implants using  $\text{B}^+$  ions can be performed *with only ~22eV energy contamination* at 200eV and 2.5 mA, sufficient for >60 wph. However PAI is required. We further showed that 200eV  $\text{BF}_2^+$  implantation can give still shallower junctions, and does not require PAI implants.

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