Ext. Abs. the 5th International Workshop on Junction Technology 2005

# Using Boron Cluster Ion Implantation to Fabricate Ultra-Shallow Junctions

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## 1. Introduction

The use of molecules or clusters to enhance the productivity of low energy ion implantation processes is now well established [1-4]. By operating at higher extraction and transport energy, beam loss effects in ultra-low-energy ion implant are ameliorated. ClusterBoron™ ($B_{18}H_{22}$), a stable, solid material at room temperature is efficiently ionized in SemEquip's ClusterIon® Source, an electron-impact ion source. This allows the implanter to be operated at 20x the process energy, so that, for example, a 500eV $B^+$ process is achieved by operation at 10keV. The use of $B_{18}H_x^+$ implantation enables a conventional high current implanter to operate at high productivity for all low energy boron implants required for the 65nm node and beyond.

Shallow $B_{18}H_x^+$ implants do not require beam deceleration and therefore contain no energy contamination and beam divergence that are associated with deceleration. Importantly, the beam space charge density is only 1/18$^{th}$ that of an equivalent monomer implant, dramatically reducing beam blowup and wafer charging.

Boron cluster ion beams contain many masses due to the binomial distribution of the two naturally occurring isotopes (mass 10 and mass 11) of boron. The broadness of the mass distribution peak in the dispersive plane is further complicated by a plurality of ion states, due to the varying number of hydrogen atoms remaining attached to the borohydride molecule when it is ionized.

The $B_{18}H_x^+$ cluster ion mass spectrum from an electron impact ionization source has been analyzed in detail. Ultra-high resolution mass spectra of natural abundance $B_{18}H_{22}$ and mass 11 isotopically enriched $B_{18}H_{22}$ have used to achieve deconvolution of the binominal distribution from ion states present in the cluster ion beam.

$B_{18}H_x^+$ and $B^+$ ion implantation have been used to fabricate the SDE of pMOSFETs with gate lengths of ~60nm. We will compare results of $B_{18}H_x^+$ and $B^+$ from the viewpoint of transistor performance. The implants were performed at equivalent process energies and doses.

## 2. Source Performance

The ClusterIon® source has been specifically designed to maintain the integrity of the cluster during the ionization process. This allows copious quintiles of beam to be generated without breaking up the molecule. Figure 1 shows the electrical beam current as a function of extraction voltage as well as the effective boron current as a function of equivalent implant energy. The effective implant energy is 1/20 of the extraction energy because the energy is partitioned in proportion to the mass ratios. The effective boron current is 18X the electrical current because there are 18 boron atoms per charge.

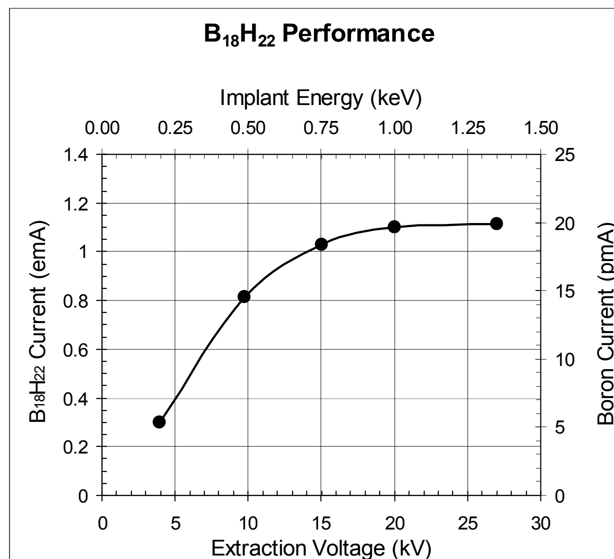


Figure 1. ClusterIon® source performance. $B_{18}H_{22}$ vapor is ionized with an energetic electron beam producing large quintiles of ionized clusters.

In addition to extraordinary boron currents the source also produces adequate quantities of may other species. Table 1 lists the obtained currents of typically used spices all extracted at the stated voltage.

| | Analyzed Beam | | | |
|---|---|---|---|---|
| Ion | Ext. Voltage (kV) | Current (emA) | Equivalent Energy (keV) | Effective Current (pmA) |
| $B_{18}H_{22}$ | 20 | 1 | 1 | 20 |
| $B_{10}H_{14}$ | 20 | 1.2 | 2 | 12 |
| $B_2H_6$ | 20 | 1.05 | 10 | 2.1 |
| $BF_2$ | 40 | 0.5 | 40 | 0.5 |
| As | 40 | 0.5 | 40 | 0.5 |
| $As_2$ | 20 | 0.25 | 10 | 0.5 |
| $As_4$ | 10 | 0.25 | 2.5 | 1.0 |
| P | 40 | 0.5 | 40 | 0.5 |
| $P_2$ | 40 | 0.5 | 20 | 1.0 |
| $P_4$ | 20 | 0.15 | 5 | 0.6 |
| $N_2$ | 20 | 2.7 | 10 | 5.4 |

Table 1. Beam currents of many species ionized by the ClusterIon® source. All are extracted at energies that represent typical implants for the specific specie. $As_4$ and $B_{18}H_{22}$ are typically used for source/drain extension implants.

## 3. Bare Wafer Implants

*Implant Profiles*

Bare wafers have been implanted with $B_{18}H_{22}^+$ ions or with $B^+$ ions. The $B_{18}H_{22}$ implants were carried out on a

Axcelis GSD100 implanter retrofitted with a Model 320 ClusterIon® source. The wafers were subsequently depth profiled using $O_2$ leak SIMS. The samples were analyzed on the same day in the same load by Evans North East. Figure 2 shows the results of the SIMS analysis. The data clearly shows that the wafers implanted with $B_{18}H_{22}$ exhibit shallower pre-annealing junctions. The junction depth is defined as the depth at which the B concentration is $1X10^{18}$ B/cm$^3$. The cluster generated profiles are about 50Å shallower than those generated by monomer B implants. We believe that this is due to self amorphization of the silicon by the cluster ion beam. Of course the junctions will be deeper after annealing depending on the annealing technique applied. Self amorphization has been demonstrated by implants with $B_{10}H_{14}$ [5]. Certainly if decaborane will amorphize, then octadecaborane will even more effectively amorphize. The abruptness of the junctions is clearly enhanced with the ClusterBoroon™ implants. In fact it increases from ~75 Å/decade to ~50 Å/decade.

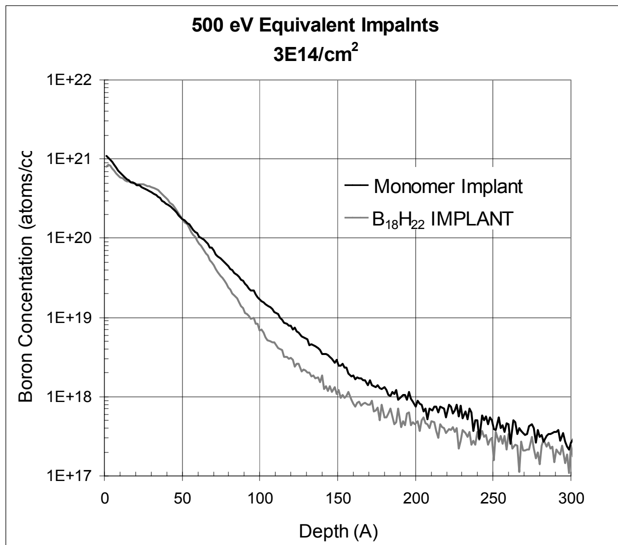


Figure 2. SIMS boron depth profiles of $B_{18}H_{22}$ cluster implants and monomer B implants at the equivalent dose and energy. The cluster implants are both shallower and more abrupt.

*Ultra-High Resolution Mass Spectroscopy*

All of the ClusterBoron™ implants are done with 15 amu of $B_{18}H_x$ peak included in the beam. We have determined the content of this peak and analyzed its effect on the as implanted profiles. Figure 3 is a low resolution mass spectrum of a 20 keV $B_{18}H_{22}$ beam.

Figure 4 is an ultra high resolution mass spectrum from mass 182 to mass 220. This ultra-high mass resolution is usually unavailable to the ion implant community, however our 120 degree mass analyzing magnet and the extremely low emittance of the ion beam extracted from the ClusterIon® source coupled with a variable width beam defining aperture and variable width mass defining slits allow for superior mass resolution.

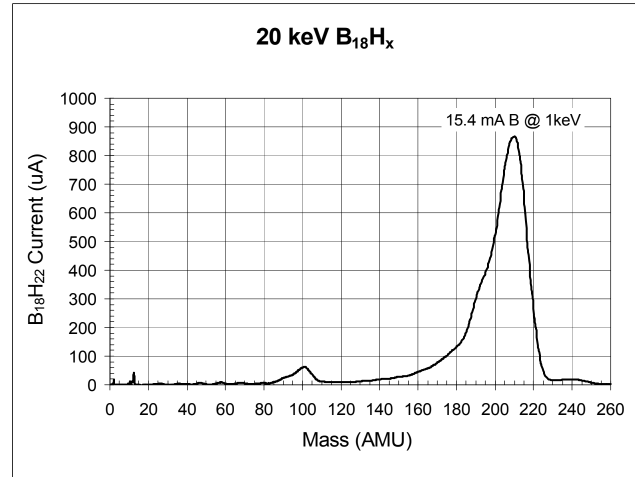


Figure 3. Low resolution mass spectrum of a 20 keV $B_{18}H_x^+$ ion beam. The peak at mass 103 is doubly ionized $B_{18}H_x$. The peak at mass 210 is $B_{18}H_x^+$. The magnitude of all low order clusters is very small.

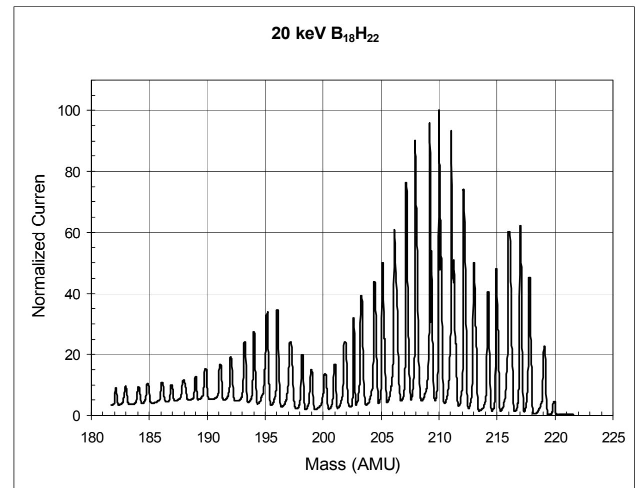


Figure 4. Ultra high resolution mass spectrum of 20 keV $B_{18}H_x^+$ ion beam. The peak at mass 197 is from $B_{17}H_x$ and the bimodal peak at mass 210 is $B_{18}H_x$.

The binomial distribution from 18 atoms 20% mass 10 and 80% mass 11 is insufficient to account for the width of the $B_{18}H_x$ spectrum. There are varying numbers of hydrogen atoms remaining attached to the molecule after ionization. This we have called the hydrogen distribution function. The use of isotopically pure $B_{18}H_{22}$ in the source eliminates the binomial distribution and the mass spectrum is the hydrogen distribution function. Figure 5 is a spectrum obtained with pure mass 11 boron atoms comprising the ClusterBoron™ molecule. There are three important features; 1) there are only even numbers of hydrogen, 2) the distribution is bimodal, and 3) more than 90% of the beam is in 6 hydrogen states, $H_{22}$, $H_{18}$, $H_{16}$, $H_{14}$, $H_{12}$, and $H_{10}$.

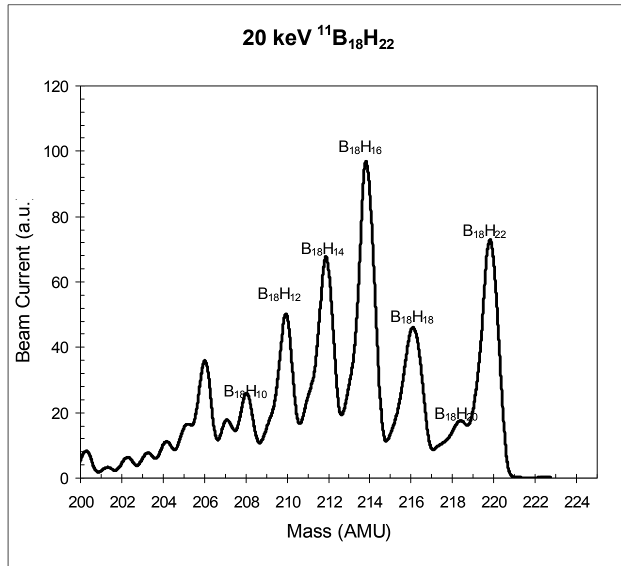


Figure 5. High resolution isotopically pure $B_{18}H_x^+$ spectrum. This is the hydrogen distribution function.

The even only phenomenon is not understood. It is believed to be a symmetry of the molecule issue. The bimodal nature of the distribution gives rise to the bimodal mass spectrum and is caused by the molecular structure of the material. There are six bridge hydrogen bonds in $B_{18}H_{22}$. These bonds are very weak because they have only one electron shared by two boron atoms and one hydrogen atom. These weak bonds are first to break and are much more likely to break. Figure 6 is a ball and stick model of the octadecaborane molecule. The six bridge hydrogen bonds are marked with arrows.

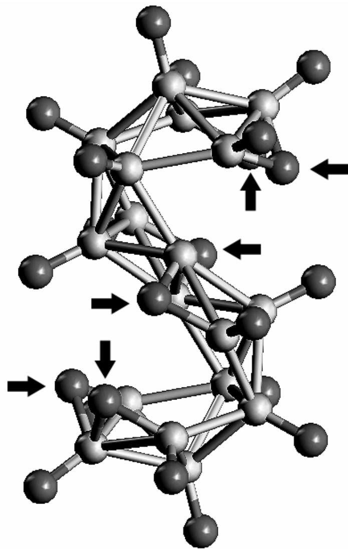

Figure 6. Octadecaborane molecule ball and stick model. The dark spheres represent hydrogen atoms and the light spheres represent boron atoms. The bridge hydrogen bonded hydrogen atoms are indicated by arrows.

Implants are carried out with a 15 amu mass resolving aperture. This allows about 90% of the $B_{18}H_x^+$ ions to pass and eliminates the $B_{17}H_x^+$ ions from the implant. The $B_{17}H_x^+$ ions would lead to a dose error as well as to energy contamination.

*Energy Contamination*

From the results of the high resolution mass spectroscopy it has been ascertained that there are 30 distinct mass-energy products in the 15 amu wide peak. It also yields the probability of each mass-energy product occurring. SRIM has been utilized to model the 30 distributions from these 30 beamlets that comprise the beam. Those thirty profiles are then summed and compared to a monomer SRIM profile. Figure 7 shows the sum and the monomer result. The difference is only two angstroms difference in junction depth. This clearly indicates that the multiple-mass, multiple-energy nature of the beam has no adverse affect on the B depth profiles. Further more, the junction depth as measured by SIMS is nearly exactly where the SRIM calculations predicted it would be. This also indicates that there is very little channeling of the energetic boron ions in cluster implanted silicon. This is due to the increased damage profiles that result from this large cluster ion implantation [5].

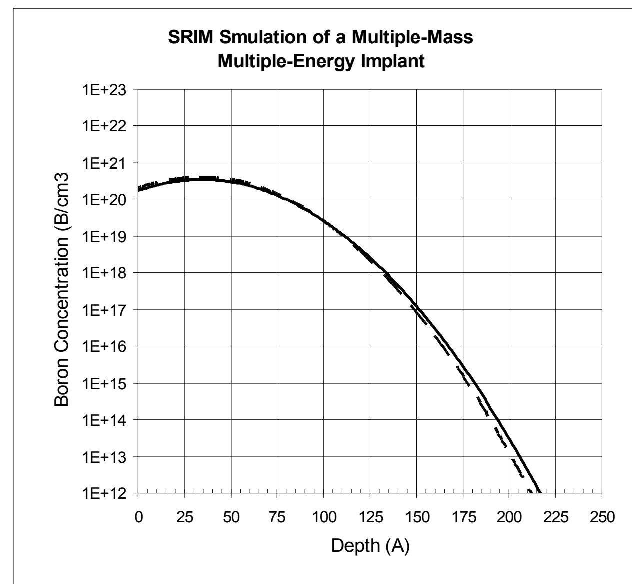


Figure 7. Simulation of an implant with 30 discreet energies and a mono-energetic monomer implant. The solid line is the sum of 30 beam components and the dashed line is the monomer implant simulation.

## 4. Device Wafer Results

Device wafers have been processed at Renesas and a gamut of electrical measurements performed on the devices. Sixty nanometer test devices were prepared utilizing Renesas' standard process flow [7]. The wafer lot was split at the p-type source/drain extension implant step. Half of the wafers stayed at Renesas and received their standard

boron monomer implant using an AMAT Quantum Leap implanter. The second half of the split was shipped to SemEquip where they were implanted with $B_{18}H_{22}$ using an Axcelis GSD100 ion implanter retrofitted with the SemEquip ClusterIon® Source. All wafers were implanted to equivalent doses and energies. After implantation of the source/drain extensions the lot was reunited at Renesas where the balance of the processing was completed and the wafers were probed. Figure 8 is SIMS data showing the boron profiles before and after a 1050C spike anneal. The junction is shallower and more abrupt both before and after annealing.

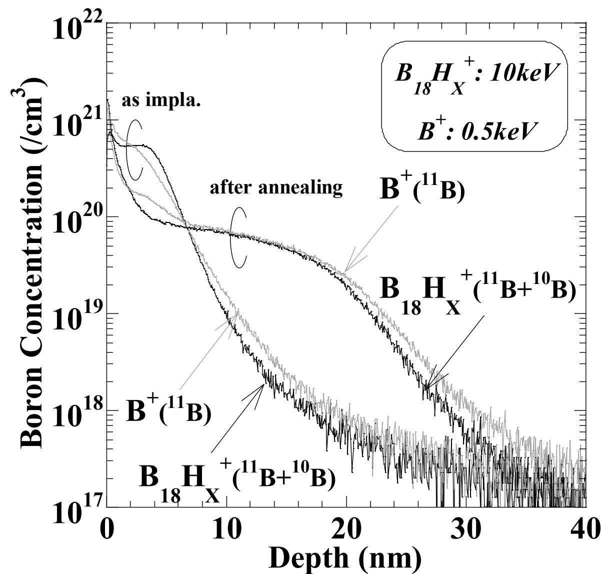


Figure 8. SIMS B depth profiles before and after a 1050C spike anneal showing shallower and more abrupt junctions for the $B_{18}H_{22}$ implants.

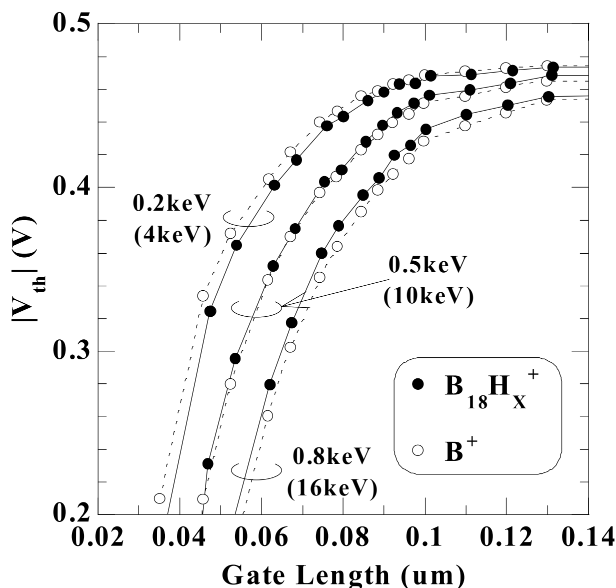


Figure 9. Threshold voltage vs. gate length.

Device performance results were virtually identical in the two splits. Figure 9 illustrates this by featuring threshold voltage data. It is easily observed that there is essentially no device performance difference between the two processes.

## 5. Conclusions

It has been shown that $B_{18}H_{22}$ implantation greatly increases the throughput of low energy boron implants while delivering uncompromised device performance. It can save pre-amorphizing process steps thus increasing the profit margin for the chip maker. The science of $B_{18}H_{22}$ implantation is well understood and the process is now ready for adoption by chip makers.

## Acknowledgements

We wish to thank Yoji Kawasaki of Renesas for the monomer B implants, the device processing and for so willingly sharing his device data with us.

Also we would like to thank Nariaki Hamamoto of Nissin Ion Implant Company for sharing his self-amorphizing data with us.

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