

# Boron Beam Performance and in-situ Cleaning of the ClusterIon<sup>®</sup> Source

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**Abstract:** The implantation of borohydride ions has enabled very high dose rates at low implantation energies. Using the borohydride material B<sub>18</sub>H<sub>22</sub>, an on-wafer equivalent current of 18 mA at 1 keV are readily achieved using a ClusterIon<sup>®</sup> source on a conventional high current implanter. As is frequently the case when running condensables, when borohydrides are introduced into the source in the vapor phase, boron-containing deposits tend to condense and accumulate in and around the ion source over extended periods of operation. In order to achieve production-worthy source lifetimes, we have developed a means of controlling the temperature of those surfaces exposed to the vapor to reduce condensation, and an in-situ cleaning process to efficiently remove deposits from the system. We show beam recovery after periodic cleaning cycles which enable good beam stability and performance. The in-situ cleaning process is also beneficial in reducing potential exposure to toxic fumes during source removal.

**Keywords:** High current implantation; molecular implantation; ion sources

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## INTRODUCTION

The propagation of high currents of very low energy boron and arsenic beams has been an area of intense development for more than a decade. In particular, CMOS device scaling has driven boron implant energies below 1 keV, for example, to form source/drain extensions. The transport of such low energy boron beams is limited by space charge effects as embodied by the Child-Langmuir law. Deceleration techniques have proven successful as a means to increase beam currents in high current (HC) implanters by transporting them at higher energy and abruptly decelerating the beam prior to its reaching the wafer. However, upon deceleration, space charge effects tend to blow up the beam, increasing beam angular divergence and spatial extent. This creates unwanted non-uniformity and resist mask shadowing during the implant; these are negative effects for serial implantation systems, in which implant uniformity is more sensitive to beam quality than in batch systems. Energy purity is also affected by some deceleration techniques due to the partial neutralization of the beam prior to deceleration.

An attractive technique to increase transport energy and reduce space charge is through molecular implantation, using beams of the borohydride ions B<sub>18</sub>H<sub>x</sub><sup>+</sup> or B<sub>10</sub>H<sub>x</sub><sup>+</sup>. The utility of implanting B<sub>18</sub>H<sub>x</sub><sup>+</sup>

ions can be appreciated through the observation that at a given accelerating voltage, the increased mass of the ion reduces the implant energy per boron atom by about twenty-fold, while at the same time producing an eighteen-fold increase in dose rate [1,2,3]. Thus, large conglomerates or “clusters” of like dopant atoms are useful for both ultra-low energy and ultra-high dose applications.

## THE CLUSTERION<sup>®</sup> SOURCE

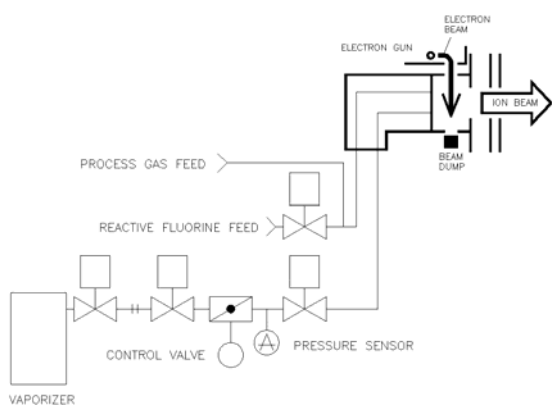
To efficiently produce molecular ions without dissociation, a source using a “soft” ionization method is preferred over a conventional arc discharge source. An electron impact source has been developed [4,5] for this purpose, the ClusterIon<sup>®</sup> source. By using ClusterBoron<sup>®</sup> feed material (a form of octadecaborane, B<sub>18</sub>H<sub>22</sub>), and SemEquip’s integrated vapor delivery and reactive fluorine cleaning modules, molecular implantation can now be performed on implant tools having traditional beam line architectures.

### Source Design

The source uses electron impact to provide the gentle ionization necessary to preserve the integrity of the molecules being ionized. While the source is

designed to provide the best possible beam current performance using ClusterBoron<sup>®</sup> feed material, it also produces several mA of As and P beams (including As<sub>4</sub><sup>+</sup> and P<sub>4</sub><sup>+</sup>) from arsine and phosphine gas, using a traditional gas box and gas feed to the system. The design of the source takes advantage of the remote electron emitter location made possible by the electron injection optics. By placing the emitter as shown in Figure 1, filament wear associated with ion erosion is minimized, helping to ensure long filament life.

The electron beam generated by the electron gun is deflected through 90 degrees by a magnetic dipole field. Once deflected, the beam is then injected into the ionization chamber where it is magnetically confined. The magnetic confinement is optimized to maximize the ionization efficiency of the injected electron beam.



**FIGURE 1.** Schematic layout of the ClusterIon<sup>®</sup> source and associated vapor and cleaning gas delivery systems.

### Temperature Control of the ClusterBoron Delivery System

The ClusterIon<sup>®</sup> system has been designed with the requirements of low temperature vaporization in mind. The vapor delivery system is designed to provide the thermal management necessary to avoid condensation and deposition by methods which include the creation of a positive temperature gradient along the vapor delivery path.

#### *Thermal Management and Borohydride residues*

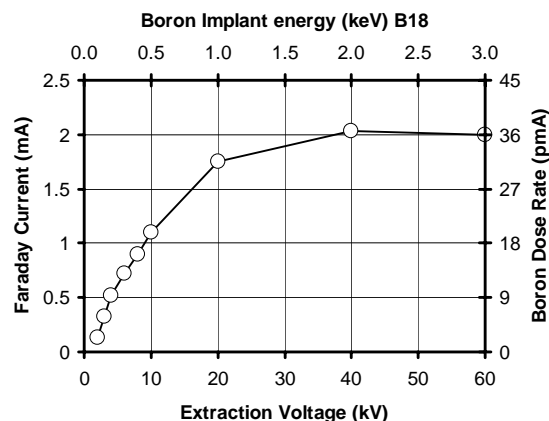
In addition to controlling the wetted surface temperatures in the delivery system, it is desirable to control the temperature of the source exit aperture and the extraction electrode to minimize the condensation and deposition of borohydride residues. Experience suggests that while it is important to keep surfaces which come into contact with the material warm enough to avoid material deposition by cooling from

the vapor phase, it is also necessary to avoid high temperature, which can lead to thermal disassociation of the vapor phase material. The disassociation yields lower order borohydride compounds, which then condense, creating deposits in the source region. Hence, active thermal management is provided for all the component surfaces in the ClusterIon<sup>®</sup> system.

## SOURCE PERFORMANCE

### Beam Current

The source produces high effective boron currents over a wide range of extraction energies. The data presented here are given in boron atomic ion equivalent beam currents which are eighteen fold greater than the B<sub>18</sub>H<sub>x</sub><sup>+</sup> molecular-ion beam current, and boron atomic ion equivalent extraction energy which are twenty fold lower than the B<sub>18</sub>H<sub>x</sub><sup>+</sup> molecular-ion extraction energy; thus, a 2 mA B<sub>18</sub>H<sub>x</sub><sup>+</sup> extracted at 40 kV has dose rate and extraction energy equivalent to a 36 mA B<sup>+</sup> beam extracted at 2kV.



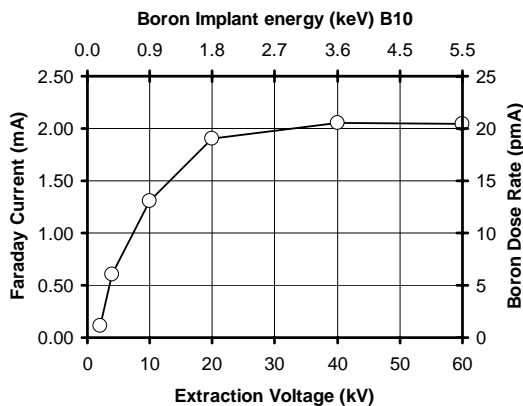
**FIGURE 2.** Octadecaborane boron equivalent dose rate versus equivalent implant energy.

Figure 2 plots octadecaborane electrical current and equivalent boron dose rate), versus extraction voltage (and equivalent boron implant energy) from 4 kV to 60 kV. These data were collected using a model 350 ClusterIon<sup>®</sup> source with a post-analysis Faraday, and operated in drift mode.

Decaborane (B<sub>10</sub>H<sub>x</sub><sup>+</sup>) also provides the advantages of molecular implantation, the difference being each B<sub>10</sub>H<sub>x</sub><sup>+</sup> molecular-ion contains ten boron atoms and has mass approximately eleven fold greater than that of a single boron atom. Figure 3 shows decaborane beam current versus implant energy for extraction voltages from 2 kV to 60 kV. The equivalent boron

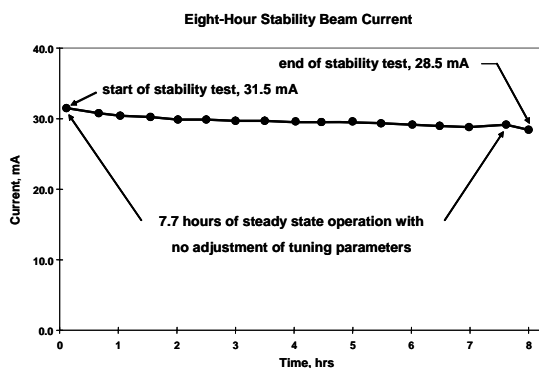
current rises rapidly from 1.2 mA at 200 eV to 19 mA at 2 keV, rising slowly to 20.5 mA at 6 keV. These data were collected in the same system used to generate the data of Figure 2.

**FIGURE 3.** Decaborane boron equivalent beam current versus equivalent implant energy



### Beam Stability and Glitch Rate

Beam stability and glitch rate are important metrics for ion implantation. The ClusterIon® source model 350 has been operated for periods of over seven hours without adjustment of any source tuning parameters. Only the emission current of the electron gun was stabilized through closed-loop control; no other automatic tuning was used. With manual or automatic tuning, the beam current can be stabilized for longer periods of operation.



**FIGURE 4.** Eight hour stability run, without source tuning.

Figure 4 shows eight hours of continuous operation including a period of 7.7 hours during which no adjustment of source tuning was made. During this period the beam current fell from 31.5 mA to 28.5 mA or about 9.7% which equals a drift rate of about 1.3% per hour. Manual or automated beam tuning can be used to keep drift close to zero for a similar period.

Electric discharge across the extraction gap (*i.e.*, glitching) can affect implant dose uniformity and should be minimized. Typical glitch rates for ion implanters may be greater than five glitches per hour. During the entire eight hour period displayed in Figure 4, there were four glitches recorded.

## Material Deposition & In Situ Cleaning

### Cleaning Methodology

The ClusterIon® source, like other ion sources, tends to accumulate residual material in the ionization chamber and on other components, which will eventually cause a reduction in beam current. By introducing reactive fluorine gas into the ionization chamber these residues are converted to high vapor pressure compounds and pumped away. By adjusting fluorine flow, source housing pressure, and component temperatures, deposits are effectively removed from the ionization chamber, extraction electrode and source housing.

Cleaning recipe and schedules should be tuned to provide the highest degree of implanter availability, and generally accepts recovery time of the ion beam current to its spec level (including cleaning time, recovery, and beam restart). As of this writing, we routinely see one hour beam to beam performance with full beam current recovery.

The fluorine cleaning chemistry is highly reactive. While the focus of current development is on cleaning borohydride residues, preliminary testing indicates that the *in situ* clean is also effective on other typical implant chemistries.

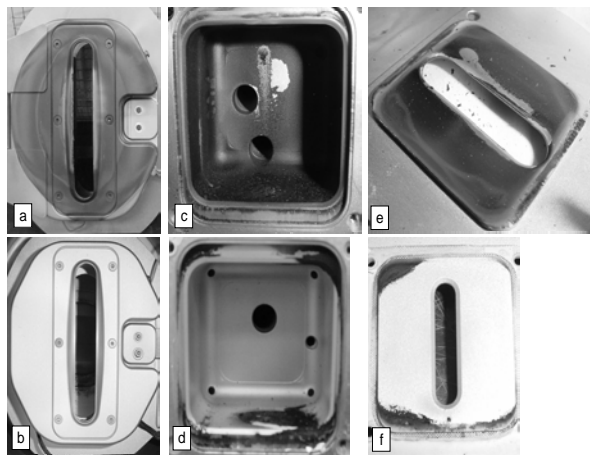
### In Situ Cleaning Simplifies Manual Cleaning

In addition to extending the time between mechanical source maintenance, *in situ* cleaning also simplifies maintenance. When it is necessary to remove the source for servicing, a cleaning recipe optimized for source housing cleaning reduces or eliminates the need for mechanical cleaning of the source housing and extraction electrode. This not only reduces the total time required for manual maintenance of the source but also improves the vacuum recovery of the system, reducing the pump down time associated with a source exchange. It is also beneficial in reducing personnel exposure to toxics.

### Efficacy of the In Situ Clean

Figure 5 illustrates the efficacy of the *in situ* cleaning process. Photographs a, c, and e show typical

borohydride deposition in a Model 320 ClusterIon<sup>®</sup> source and its associated extraction electrode. Photographs b, d, and f are of another Model 320 source with a similar operation history and a 30 minute *in situ* clean. These photographs illustrate that the cleaning process is very effective at removing deposited boron residues from the ionization chamber and extraction electrode. In fact, an optimized cleaning recipe maximizes source availability and beam current over the mechanical life of the source.



**FIGURE 5.** Model 320 ClusterIon<sup>®</sup> source, before and after *in situ* clean.

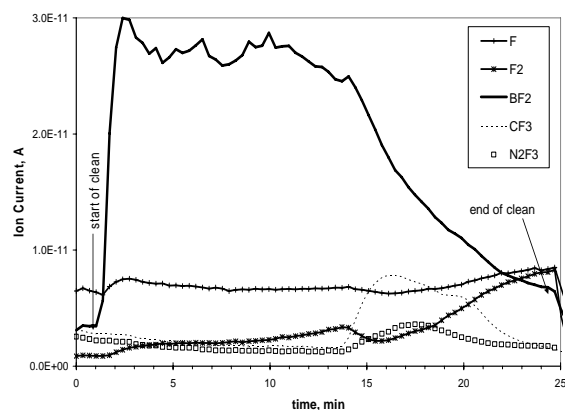
#### Material Evolution During *in situ* Cleaning

During the process of cleaning recipe development, a quadrupole residual gas analyzer was used to study material evolution during the cleaning process. Mass spectra were collected continuously, resulting in trend partial pressure plots (ion current over time) for multiple evolved gas phase species.

Figure 6 shows trend plots for: F\*, F<sub>2</sub>, BF<sub>2</sub>, and N<sub>2</sub>F<sub>3</sub> as well as the beginning and end of F\* injection. The partial pressure of BF<sub>2</sub>, P<sub>BF<sub>2</sub></sub>, is of particular interest because it can be used to evaluate the reaction rate and end point of the F\*-B<sub>x</sub>H<sub>y</sub> reaction, and hence the effectiveness of the cleaning process. When the F\* flow is switched on, P<sub>BF<sub>2</sub></sub> rises quickly and levels off, indicating a constant reaction rate, for about 12 minutes. The falling P<sub>BF<sub>2</sub></sub> indicates that most of the B<sub>x</sub>H<sub>y</sub> has been consumed, *i.e.*, the reaction rate is decreasing and the end point has been reached. While P<sub>BF<sub>2</sub></sub> is falling we see a rise in P<sub>F\*</sub>, P<sub>F<sub>2</sub></sub> and P<sub>N<sub>2</sub>F<sub>3</sub></sub> which is consistent with the absence of B<sub>x</sub>H<sub>y</sub> and the recombination of reactive species.

While RGA data is useful for cleaning process development it is not required for regular operation. For any given source operation regimen and cleaning recipe, the repeatability of the cleaning signature

indicates that simple time-based control should work well.



**FIGURE 6.** Typical RGA plot showing time varying ion currents for several species of interest.

## CONCLUSIONS

The SemEquip ClusterIon<sup>®</sup> source is an effective tool for achieving high equivalent boron ion currents at low delivered implant energies in traditional beam line implanters. It provides for high throughput operation and eliminates the need for deceleration techniques. *In situ* cleaning ensures that a high level of source performance and availability can be maintained over the mechanical life of the source.

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