

# Universal Ion Source™ for Cluster and Monomer Implantation

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**Abstract.** Energetic cluster and molecular ion beams have become useful for performing high dose implants at very low implantation energies. The ClusterIon® source, when installed on a conventional beam line implanter, can routinely produce >1 mA of electrical  $B_{18}H_x^+$  ion current on the wafer, enabling boron dose rates in excess of 18 mA at an effective implant energy of 1 keV per boron atom implanted. However, this very important application represents only a fraction of the implant processes required for leading edge device fabrication. For example, both p-type and n-type source/drain structures, as well as halo, punch through, poly gate, and threshold adjust implants are required. To address this need for a true multi-species capability, a new ion source has been developed. The source is a novel dual-mode design which operates in a cluster formation mode and a monomer formation mode, such that the cluster formation mode is mediated by electron impact ionization and the monomer formation mode by an arc discharge.

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

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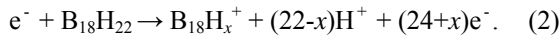
## INTRODUCTION

Ion sources, for example sources of the Bernas type [1], use an arc discharge to efficiently dissociate molecular feed gases into their constituent elements, enabling dopant monomer ions to be generated, *e.g.*,



Here,  $B^+$  is the dopant ion of interest. There are, however, also important applications for the implantation of molecular ions which require the preservation of the parent molecule during ionization. To efficiently produce molecular ions without dissociation, a “soft” ionization method is preferred over the arc discharge method. An electron impact source has been developed [2, 3] for this purpose, the ClusterIon® source, which can produce a beam of several milliamperes of molecular ions. As is typical with electron impact ionization sources, the ion temperature and ion density are low, producing a quiet, low-emittance ion beam which lends itself to ready inclusion in conventional medium-current (MC) and high-current (HC) implanter platforms.

A boron-containing material of interest is the large borohydride molecule *octadecaborane* ( $B_{18}H_{22}$ ), which can be ionized according to the reaction:



In eq. (2),  $x$  is an even integer [4], and  $x \leq 22$ . The utility of implanting beams of  $B_{18}H_x^+$  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 [5,6,7]. Thus, large conglomerates or “clusters” of like dopant atoms are useful for both ultra-low energy and ultra-high dose applications. For example, the p+ drain extension implant for 45nm CMOS devices requires a 300eV boron implant at a dose of about  $1E15 \text{ cm}^{-2}$ , which can be achieved at high throughput in drift mode with a conventional beam line implanter by substituting a 6 keV  $B_{18}H_x^+$  implant at a dose of  $5.6E13 \text{ cm}^{-2}$  [8,9]. In addition to increased throughput, it has been reported [8,9] that  $B_{18}H_x^+$  implantation provides other important advantages, such as: *i)* obviating the need for a pre-amorphization implant to reduce channeling, *ii)* reducing or eliminating end-of-range defects and reducing the device leakage currents they cause, *iii)* enabling improved dopant activation, *iv)* eliminating energy contamination, and the high-energy tail which is a characteristic of deceleration-mode implantation, *v)* dramatically improving low-energy beam quality (reduced angular divergence, and increased angular and spatial uniformity) on wafer, and *vi)* achieving ultra-shallow junctions with conventional spike anneal

technologies. These results have been described in detail elsewhere [5–10].

In addition to borohydride vapors, the ClusterIon<sup>®</sup> source runs conventional feed gases such as AsH<sub>3</sub> and PH<sub>3</sub> to produce several milliamps of AsH<sub>x</sub><sup>+</sup> or PH<sub>x</sub><sup>+</sup> ions, and indeed can produce molecular beams of any gaseous or vapor feed materials which can be ionized by electron impact. Multiply-charged currents are small, however, as this is a “soft” ionization source.

There has been considerable interest in incorporating borohydride and other molecular implantation capabilities in conventional beam line implantation platforms to enable a wider range of both N- and P-type implants, *i.e.*, a “hybrid” of HC and MC applications [7]. Given the industry-wide move to serial wafer processing for HC as well as the traditionally serial MC systems, it is clearly advantageous to cover the applications spaces of both generic platforms within one serial hybrid implanter. Such hybridization is greatly simplified by the incorporation of an ion source which delivers molecular ions and ionized clusters, in addition to conventional ion species.

## ION SOURCE DESCRIPTION

The Universal Source<sup>™</sup> is based on the ClusterIon<sup>®</sup> source [3], but is designed to support a broader range of applications. While the electron impact source has the great utility of providing high currents of molecular ions and ionized clusters, its monomer currents are suitable for medium-current implants only. High currents of N-type dopants, increased currents of As and P clusters, and the formation of multiply-charged ions are features of the Universal source. Its guiding operating principle is that it is “dual mode”, that is, it can operate in either an electron impact mode (to produce clusters and molecular ions), or in an arc discharge mode (to produce high currents of monomers and multiply-charged ions). This is accomplished by incorporating a separate electron gun and an arc emitter in the source; for cluster operation, only the electron gun is used; to produce monomers and multiply-charged ions during arc operation, the arc emitter is energized, striking a plasma discharge, as in a Bernas-type source. As shown in Fig. 1, the source incorporates an externally-mounted electron gun and an indirectly-heated cathode (IHC). Although not shown in Fig. 1, the source incorporates both vaporizer and process gas inlets.

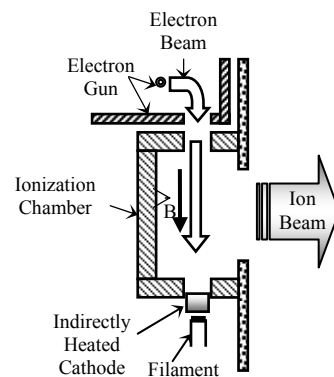


FIGURE 1. Ion Source Schematic.

## Electron Impact Operation

Referring again to Fig. 1, we describe the electron impact mode of operation. An externally generated electron beam creates a stream of ions just behind the long rectangular slot from which ions are extracted by the implanter optics.

The electron gun creates an energetic electron beam of between 1 mA and 100 mA, which is then deflected through 90 degrees by a magnetic dipole field. Since the electron gun is remote from the ionization chamber and has no line-of sight to the process gas, it resides in the high vacuum environment of the implanter’s source housing, resulting in a long emitter lifetime. The deflected electron beam enters the source ionization chamber through a small entrance aperture. Once within the ionization chamber, the electron beam is guided along a path parallel to and directly behind the ion extraction slot by a uniform axial magnetic field of about 100 Gauss produced by a permanent magnetic yoke surrounding the ionization chamber. Ions are thus created along the electron beam path and adjacent to the extraction slot. This serves to provide good extraction efficiency of the ions, such that an ion current density of up to 1 mA/cm<sup>2</sup> can be extracted from the source. The beam current dynamic range thus achieved is comparable to other sources; by varying emission current and also the flow of feed material into the source, a stable on-wafer electrical beam current of between 5 μA and 2 mA is achieved. Fig. 2 below shows the dependence of extraction and wafer current on the rate of vapor flow into the ionization chamber, as measured by the inlet pressure to the ion source. B<sub>18</sub>H<sub>22</sub> or B<sub>10</sub>H<sub>14</sub> vapor is typically introduced into the source from an externally mounted vaporizer, through a pressure control device which regulates the flow of vapor into the source ionization chamber [11,12].

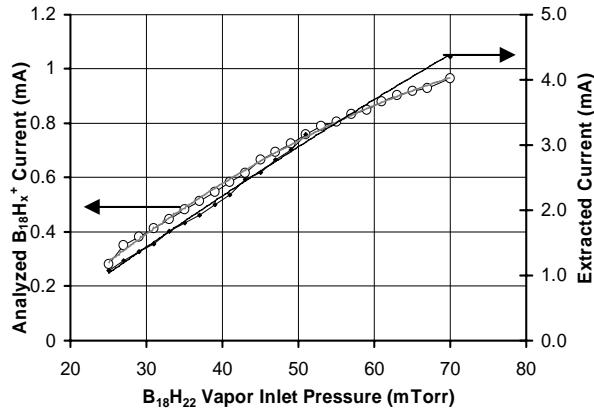


FIGURE 2. Current versus vapor inlet pressure. Solid Line: extracted current. Open circles: analyzed current.

### Arc Discharge Operation

In arc discharge mode, the electron gun is not used. Instead, the IHC is energized, creating a plasma column along the magnetic field direction, which provides plasma confinement. Fig. 3 and Fig. 4 show arsine and phosphine spectra, respectively, from the Universal source operating in arc discharge mode. As further indicated in Fig. 5, up to 12 mA of  $P^+$  and  $As^+$  current were delivered to the wafer position at an arc current of less than 0.5A. These values were achieved at an arc voltage of 70V and 80V, respectively. SDS gas flows of 4.3sccm of  $PH_3$  and 5.8sccm of  $AsH_3$  were used to generate the currents shown in Figs. 3—5. The relatively high gas flows are due to the large area of the ion extraction aperture (arc slit), which was 48mm tall by 8mm wide, *i.e.*, an extraction area of about  $4\text{ cm}^2$ .

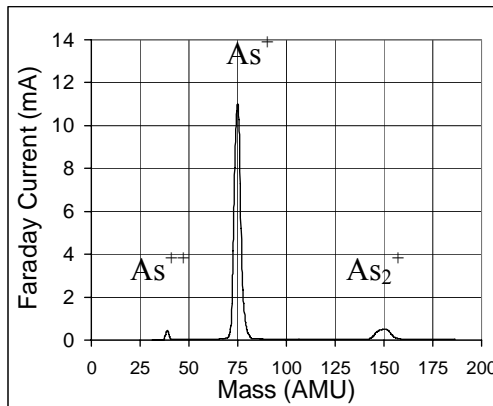


FIGURE 3. Arsine spectrum in arc discharge mode.

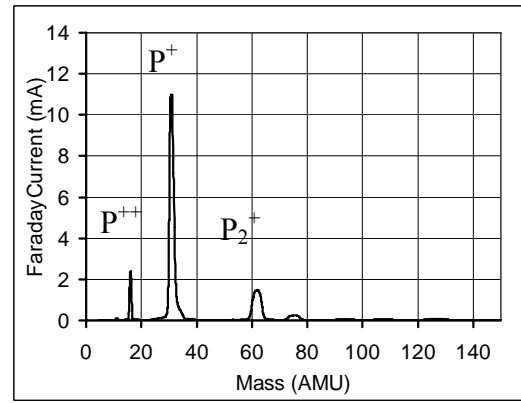


FIGURE 4. Phosphine spectrum in arc discharge mode.

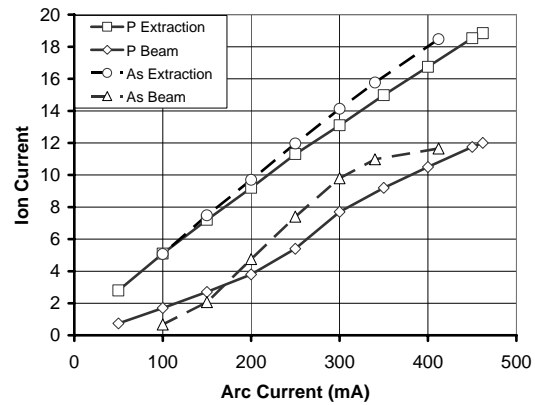
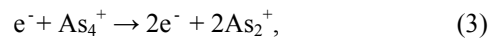


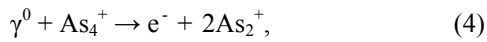
FIGURE 5. Extraction and post-analysis As (dotted line) and P (solid line) currents versus IHC arc current.

### N-Type Dopant Clusters

The N-type dopants As and P are important for doping silicon to form NMOS transistors. Substantial increases in effective ultra-low energy beam current for these species can be achieved by implanting the dopant clusters consisting of the dimer ( $As_2^+$ ,  $P_2^+$ ) [13] and tetramer ( $As_4^+$ ,  $P_4^+$ ). In general, the implantation of a cluster of  $n$  dopant atoms can provide dose rates (in atoms/s) a factor of  $n^2$  higher than the implantation of single atomic ions. This follows from the Child-Langmuir law, and so assumes a condition in which the transport of the monomer ion beam is fully space charge-limited, a condition often satisfied when implanting ultra-low energy ions such as 1 or 2 keV As, for example, for creating source/drain extensions. The tetramers  $As_4^+$  and  $P_4^+$  do not typically survive as ions in plasma discharges since they readily dissociate via the reactions:



and



Where  $\gamma^0$  is an ultraviolet (uv) photon, for example. Since the ions produced within the ionization chamber are also shielded from the uv radiation produced by the electron emitter filament, the tetramer ion is largely preserved, as can be seen in the As and P spectra of Fig. 6 and Fig. 7. Note how large the tetramers peaks are, containing fully half of the As and P atoms of the overall spectra. These spectra were produced in electron impact mode.

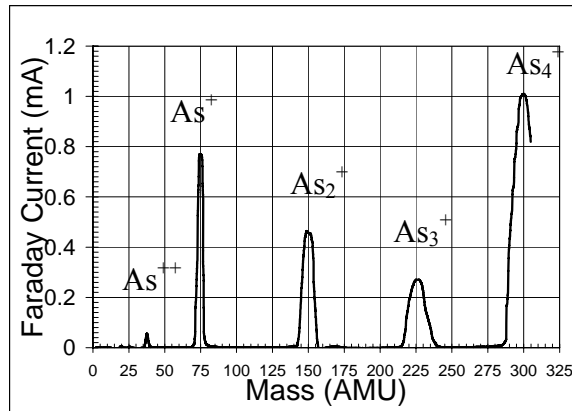


FIGURE 6. As spectrum generated in electron impact mode. Note that half of the As atoms are in the  $\text{As}_4^+$  peak.

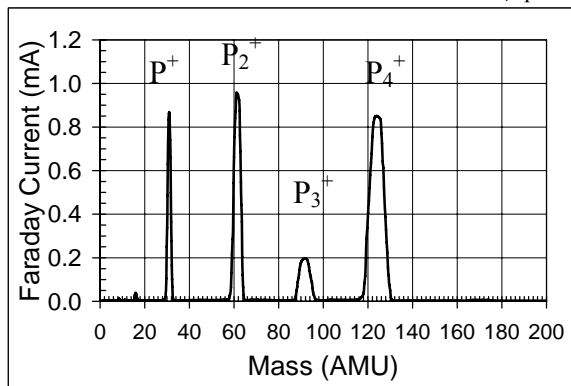


FIGURE 7. P Spectrum generated by electron impact.

## SUMMARY & DISCUSSION

A new multi-species ion source has been developed which has two discrete modes of operation: an arc discharge mode (mediated by an indirectly-heated cathode) for the production of monomer and multiply-charged species, and an electron impact mode (mediated by an electron beam) for producing molecular ions. In addition to  $\text{B}_{18}\text{H}_x^+$  ions, the electron impact formation of significant currents of the

N-type tetramers  $\text{As}_4^+$  and  $\text{P}_4^+$  have not, to my knowledge, been previously observed. These species are immediately useful for creating ultra-shallow source/drain extensions, and also for PMOS halo implants. It is expected that, just as has been demonstrated for  $\text{B}_{18}\text{H}_x^+$  and  $\text{B}_{10}\text{H}_x^+$  implantation, the large mass of these tetramers provide self-amorphization, resulting in reduced channeling [13].

## ACKNOWLEDGMENTS

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