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BNL-79415-2007-CP

Ion Sources for Energy Extremes of Ion Implantation

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Presented at the 12th International Conference on Ion Sources (ICIS 2007)
Jeju, Korea
August 26 – 31, 2007

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Abstract. For the past four years a joint research and development effort designed to develop steady state, intense ion sources has been in progress with the ultimate goal to develop ion sources and techniques, which meet the two energy extreme range needs of mega-electron-volt and 100's of electron-volt ion implanters. This endeavor has already resulted in record steady state output currents of high charge state of Antimony and Phosphorous ions: P^{2+} (8.6 pmA), P^{3+} (1.9 pmA), and P^{4+} (0.12 pmA) and 16.2, 7.6, 3.3, and 2.2 pmA of Sb^{3+} Sb^{4+}, Sb^{5+}, and Sb^{6+} respectively. For low energy ion implantation our efforts involve molecular ions and a novel plasmaless/gasless deceleration method. To date, 1 emA of positive Decaborane ions were extracted at 10 keV and smaller currents of negative Decaborane ions were also extracted. Additionally, Boron current fraction of over 70% was extracted from a Bernas-Calutron ion source, which represents a factor of 3.5 improvement over currently employed ion sources.

Keywords: **ion sources for ion implantation**

PACS: 41.75Ak, 41.75Cc, 81.15Jj, 52.77Dq,

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a) Invited paper, published as part of the Proceedings of the 12th International Conference on Ion Sources, Jeju, Korea, August 2007.

I. Introduction

Various types of ions, but mostly B, P, Sb, and As, are implanted, over a wide range of energies into some of the materials used in the construction of semiconductors. These energies range from as low as approximately 100 eV for shallow surface implantations, to as high as multi-MeV for deep implantation into the substrate. State of the art ion sources meet industry needs for the energy range of about 10 keV to about 300 keV. But at the two extremes (100's of eV and at multi-MeV) of the energy range, there is room for improvement due to space charge limitations at the low energy range and due to inefficiency in acceleration at the higher energy range. A joint research and development effort focusing on meeting industry needs for steady state, intense ion sources has been in progress for the past four years, with ion source test facilities at High Current Electronic Institute (HCEI) in Tomsk, Russia, and Institute for Experimental and Theoretical Physics (ITEP) in Moscow, Russia. Originally, the collaboration started to develop enhanced charge states pulsed metal vapor ion sources, with an external electron beam in two ion sources provisionally dubbed E-MEVVA. Lead and Bismuth, which previously achieved doubly charged ions, were ionized to ion charge states of Pb^{+7} & Bi^{+8} with ion currents exceeding 200 mA [1,2]. The natural next step was to adapt charge enhancement techniques to ion sources that generate steady state multi-charged B, P, As, and Sb ions in order to improve upon present day high-energy ion implanters that use rf accelerators [3]. This endeavor has resulted in record steady state output currents of higher charge state Phosphorous and Antimony ions: 8.6 pmA of P^{2+}, 1.9 pmA of P^{3+}, and 0.12 pmA of P^{4+}, as well as, and 16.2, 7.6, 3.3, and 2.2 pmA of Sb^{3+} Sb^{4+}, Sb^{5+}, and Sb^{6+} respectively. However, during the course of the project, it was realized that the

semiconductor industry has greater needs in the area of low energy (100's of eV) ion implantation, where space charge problems associated with lower energy ion beams limit implanter ion currents, thus leading to low production rates. To tackle the space charge problem, two approaches were followed: using molecular ions and ion beam deceleration with space charge compensation. To date, 1 emA of positive Decaborane ions were extracted at 4 keV and a smaller current of negative Decaborane ions was also extracted. Some simulations of a novel gasless/plasmaless ion beam deceleration method were also performed. Finally, a spin-off result of a Bernas-Calutron ion source, from which over 70% of the extracted ion beam consists of singly charged Boron, was achieved (compared to the 20% of current implanters). This paper is a synopsis of an extensive ion source R&D program designed to address industry needs at the energy extremes of ion implantation.

High charge state ion sources are covered in section II. Recent Decaborane ion source results are briefly described in section III, while a novel gasless/plasmaless ion beam deceleration method is also mentioned in this section. Simulations and diagnostics are described in section IV. Finally, an ion source, from which over 70% of the extracted ion beam consists of singly charged boron, is described in section V.

II. High Charge State Ion Sources

Ion beams containing record high charge states of Phosphorous and Antimony have been extracted from ion sources located at HCEI and at ITEP respectively. For some of the higher charge states, the improvement was greater than an order of magnitude over existing technologies.

At HCEI the ion source is a modified Bernas-Calutron ion source with 1mm x 40mm aperture. The source employs a design similar to that of the Russian ion implanter "Vesuvius" [4] which can generate record high charge states of Phosphorous ion beams. This kind of ion beam generator could be considered as a combination of Bernas ion source [5] and Calutron ion source [6]. A standard Calutron ion source has a filament cathode outside the arc chamber with a collimating slot. The Bernas ion source has a filament inside the arc chamber. In our modification of the ion source, the second filament cathode was removed and replaced by a Ta plate outside the discharge chamber. The anticathode can be electrically coupled to the anode, allowed to float, or connected to the cathode (filament). When the anticathode is electrically floating or connected to the cathode, an electron oscillation discharge occurs. This mode is characterized by high efficiency of multiply charged ion production. This is due to most of the electron energy being expended during ionization [7].

In this ion source the conventional gas delivery system was replaced by an oven. After optimizing all ion source operating parameters: power, magnetic field and oven temperature, record yields of P^{2+} (8.6 pmA), P^{3+} (1.9 pmA), and P^{4+} (0.12 pmA) were extracted from the modified Bernas-Calutron ion source [7] (spectrum is displayed in figure 1a). It is significant to observe that the previous best results [8,9] were P^{2+} (3 pmA), P^{3+} (0.2 pmA), and only a miniscule P^{4+} output. Further details and additional experimental results can be found in reference 7.

Additionally, from this ion source (when operating with Boron), close to 1emA of B^{+2} ions were extracted.

Record enhancement of Antimony charge states were obtained in an ITEP Bernas ion source in which a staggered, oscillating electron beam was generated [10]. Figure 1b shows the spectrum of Antimony extracted from the ITEP Bernas ion source. Current levels reaching a Faraday cup after magnetic separation are 16.2, 7.6, 3.3, and 2.2 pmA of Sb^{3+}, Sb^{4+}, Sb^{5+}, and Sb^{6+} respectively. Additional results as well as a detailed investigation can be found in reference 10. Ion source extraction area is 20 mm^2.

III. Ions for Shallow Implantations

Since the invention of the transistor, the trend has been to miniaturize semiconductor devices. This has resulted in the need to decrease ion implantation energy, since shallow profile implantation is desired. But, due to space charge (intra-ion repulsion) effects, low energy ion beams are characterized by low current. Neutralizing plasmas, utilized in today's implanters, to reduce space charge offer only a partial solution and often result in implanting undesirable impurities. Therefore, low energy ion implanters have low production rates. Consequently, increasing the current of pure, low energy ion beams is of paramount importance to the semiconductor industry.

To mitigate the contamination problem, our collaboration is involved in two projects: molecular ions and beam decelerator that compensates for space charge effects without gas or plasma. The latter is a highly proprietary novel technique for a low energy high current ion beam propagator. This technology produces ion implantations that are contaminant free! The collaborators filed a record of invention.

Decaborane ($B_{10}H_{14}$) was introduced into the ITEP Bernas source and the spectrum shown in figure 2a was obtained [11]. A Decaborane current of 1 emA was extracted from an aperture of 1mm x 20mm for an extraction voltage of under 4 KV. Very similar results were obtained from a Freeman ion source as shown in figure 2b.

Additionally, a 0.2 emA current of negative Decaborane was obtained as well [12,13]. This result has significance in that it opens the possibility of merging negative and positive Decaborane beams, while slowing them down to further reducing the space charge problem. An extremely important ingredient for Decaborane ion generation is proper temperature, of the ions source walls and internal electrodes, to prevent fragmentation or wall deposition of Decaborane molecules. For negative Decaborane generation slow electrons are also needed. Operationally, the main difference between optimal ion source operation for positive and negative Decaborane generation is the absence of discharge in the later (i.e., slow electrons are sprayed unto a chamber with warm walls) [13].

Presently, we think that Decaborane current is limited by bending magnet acceptance. Enlarging source aperture size by a factor of 6 might result in a proportional increase in Decaborane ion beam current.

IV. Simulations and Diagnostics

Aperture size of the ITEP Bernas ion source is only 1mm x 20mm due to small bending magnet acceptance. And, there is an inherent difficulty in transporting various species from Bernas type ion sources, since they contain magnetic fields perpendicular to the extraction direction that bend and separate ion species during extraction. The challenge is to find a transport system where electro-static forces compensate for this effect of the magnetic field. Such a system was successfully set up by adding a focusing element followed by a deflection element (to compensate for source magnetic field bending) and another focusing element (before the bending magnet). Simulation of extraction and transport of a ribbon beam over a wide range of masses from Boron to Decaborane was performed [12, 14]. Some results [15], which can be found in figure 4 of reference 15,

and the latest results [11] with a shorter LEBT, which can be found in figure 2 of reference 11, agree with experimental results.

Next a new simulation code was developed for simulating the plasma in the ITEP Bernas ion source. Like all other universal plasma models, ours is also based on the Vlasov-Boltzmann equation, which can be used to describe a wide variety of these sources. To solve this equation we used the Monte-Carlo Particle-In-Cell (MCPIC) method also known as Particle-In-Cell method with Monte-Carlo collisions. In reference 15 results of the 2D3V numerical code simulations as applied to Bernas ion sources **PICSIS-2D** through the approach of the MCPIC can be found. The numerical results are compared with experimental data [16].

Originally charge state and species distribution was measured by time-of-flight (TOF) at HCEI and via bending magnet at ITEP. During E-MEVVA experiments [2], ITEP and HCEI results were in excellent agreement. But, the E-MEVVA magnetic field is oriented in the direction of beam extraction, while in both the Bernas and the modified Bernas-Calutron ion sources the magnetic field is perpendicular to direction of extraction. Therefore industry did not accept any results other than whole beam bending magnet measurements, even though our transport systems were designed to compensate for any beam spreading [15]. So the HCEI Phosphorus and Boron results were repeated with bending magnet measurements. Under those conditions, good agreement was observed between the TOF and bending magnet measurements [17].

V. High Fraction Boron yield

Final results to report are that intense beams of boron ions were extracted from the HCEI modified Bernas-Calutron ion source. The anticathode was placed inside a discharge chamber and instead of using the conventional boron-trifluoride (BF_3) gas; a

solid lithium-boron-tetrafluoride ($LiBF_4$) compound was heated to release boron. For optimal ion source parameters, beams of up to 41 mA were extracted. Singly charged boron made up over 70% of the total ion beam [18]. Due to the very limited acceptance of the bending magnet, only about 20% of the beam can reach the collector. To increase beam transparency, source aperture was reduced from 1mm x 40mm to 1mm x 16mm. For this aperture, bending magnet spectrum is displayed in figure 3.

By comparison, no more than 25% of the extracted beam from conventional ion sources is Boron. Additionally, BF_3 is extremely toxic, while $LiBF_4$ is a safe compound. The key to this ion source performance is a somewhat tricky optimization adjustment of the temperature of the oven containing the solid $LiBF_4$ compound, and Fluorine removal before the vapor enters the discharge region. Once steady optimal boron vapor flow into the ion source is achieved, discharge current and voltage is adjusted by increasing hot cathode emission current. More details can be found in reference 18.

VI. Discussion

The main objective of our program has been to develop commercial ion implantation sources for the semiconductor industry. We started to develop high charge state ion sources for high-energy implantation. After achieving record results with P & Sb ions and trying to interest potential clients, we learned that the real interest is in B ions. While shifting emphasis to Boron ions, we realized that low energy ion implantation is what the industry needs, hence, diversion of our efforts to molecular ions.

Ion sources (with modifications of-course) explored during the course of the research were Bernas-Calutron, Freeman, Bernas, and duoPIGatron. Both Freeman and Bernas ion sources proved effective and have shown promise for Decaborane ion beams. The Bernas with an internal electron source and the Bernas-Calutron generated record

current output of high-charge state ions. The later also generated record output of singly charged Boron. Although the duoPIGatron is rugged, with long lifetime cathode and ability to withstand large thermal loads, it has disapprovingly low current output [19]. Hence, the Bernas-Calutron and the Bernas have been our "work-horses." Schematics of the Bernas-Calutron and the Bernas (with internal electron gun) ion sources are shown in figures 4a and 4b respectively.

Over the past four years substantial results were obtain by our collaboration in spite of the fact that many changes in the research program have been introduced during this relatively short period.

Acknowledgments

One of the authors (A.H) is grateful to P. Splinter, M. Sieradzki, V. Benveniste, K. Saadatmand, B. Vanderberg, M. Graf, J. Poate W. DiVeriglio, R. Rathmell, and A. Perel for many stimulating and very useful discussions. Work is supported by research contracts between BNL and HCEI with ITEP under the IPP Trust-2 program and by the U.S. Department of Energy.

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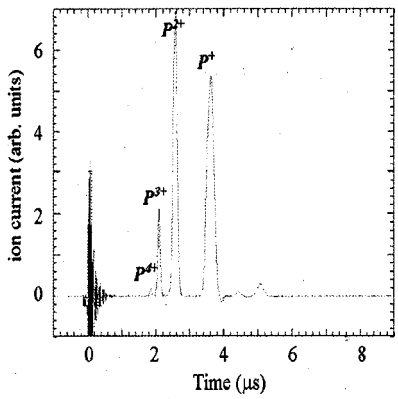
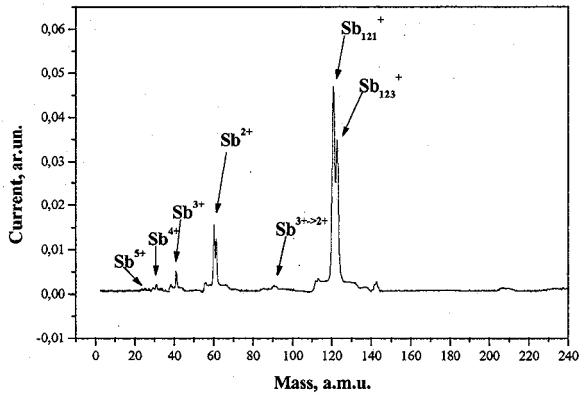
Figure Captions

1. Spectra of (a) Phosphorous extracted from the HCEI modified Bernas-Calutron ion source, and (b) the spectrum of Antimony extracted from the ITEP Bernas ion source.
2. Spectrum of Decaborane ion beam from ITEP (a) Bernas, and (b) Freeman ion sources.
3. Ion beam charge state distribution, as measured by a bending magnet, for beam extracted from the Bernas-Calutron ion source (small magnet acceptance; reduced aperture ion source).
4. Schematics of the Bernas-Calutron (a) and the Bernas (b) ion sources.


ion current (arb. units)
Time (μs)
P4+
P3+
P2+
P+

(a)


Current, ar.un.
Mass, a.m.u.
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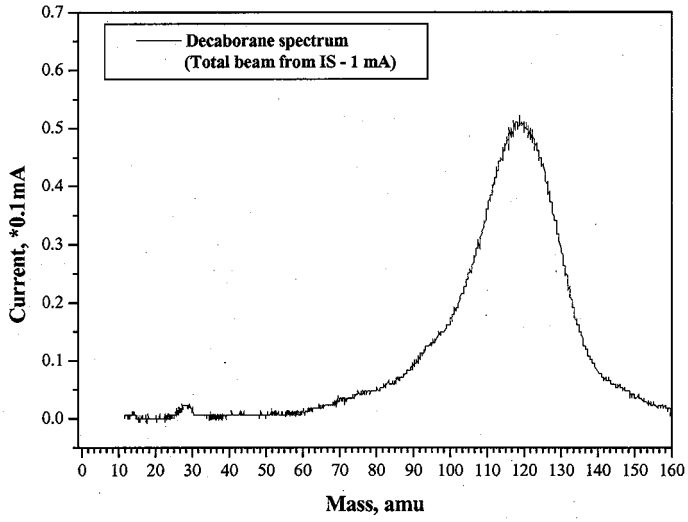
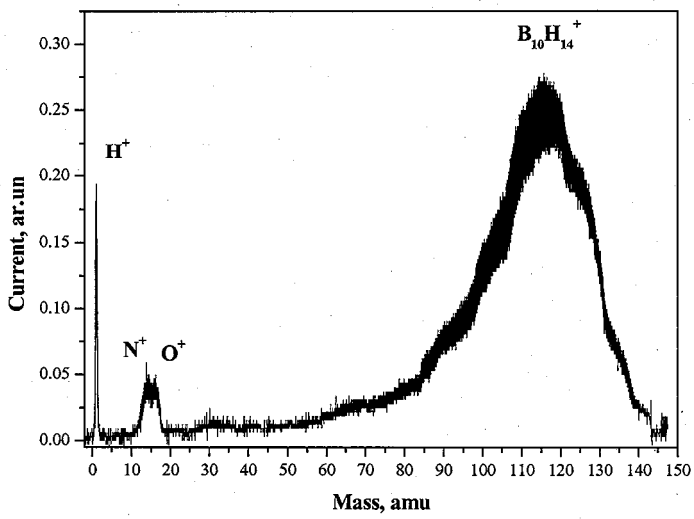
Sb4+
Sb3+
Sb2+
Sb3+->2+
Sb121+
Sb123+

(b)

Figure 1


Decaborane spectrum
(Total beam from IS - 1 mA)
Current, *0.1mA
Mass, amu

(a)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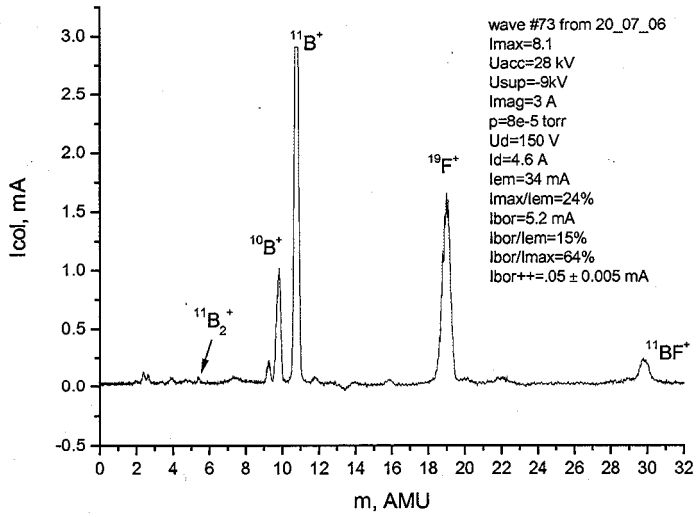
H^+
N^+
O^+
Current, ar.un
Mass, amu

(b)

Figure 2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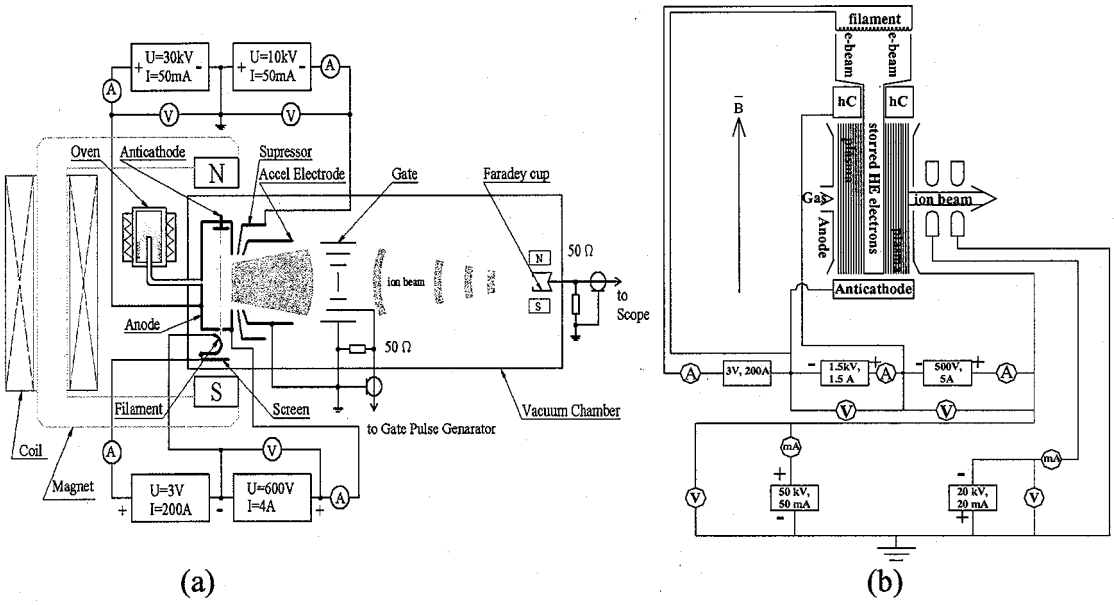
Uacc=28 kV
Usup=-9kV
Imag=3 A
p=8e-5 torr
Ud=150 V
Id=4.6 A
Iem=34 mA
Imax/Iem=24%
Ibor=5.2 mA
Ibor/Iem=15%
Ibor/Imax=64%
Ibor++=.05 ± 0.005 mA
$^{11}B^+$
$^{19}F^+$
$^{10}B^+$
$^{11}B_2^+$
$^{11}BF^+$
Icol, mA
m, AMU

Figure 3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I=50mA
U=10kV
I=50mA
Oven
Anticathode
N
Supressor
Accel Electrode
Gate
Faraday cup
50 Ω
to
Scope
ion beam
Anode
50 Ω
S
Filament
Screen
to Gate Pulse Genarator
Vacuum Chamber
Coil
Magnet
U=3V
I=200A
U=600V
I=4A
(a)
filament
e-beam
e-beam
hC
hC
B
Gas
Anode
stored HE electrons
plasma
ion beam
Anticathode
3V, 200A
1.5kV,
1.5 A
500V,
5A
50 kV,
50 mA
20 kV,
20 mA
(b)

Figure 4