BROOKHAVEN
NATIONAL LABORATORY

BNL-76883-2006-CP

# *Ion Sources for High and Low Energy Extremes of Ion Implantation*

**A. Hershcovitch, V.A. Batalin, A.S. Bugaev, V.I. Gushenets, B.M. Johnson, K.A. Kolomiets, G.N. Kropachev, R.P. Kuibeda, T.V. Kulevoy, I.V. Litovko, E.S. Masunov, E.M. Oks, V.I. Pershin, S.V. Petrenko, S.M. Polozov, H.J. Poole, I. Rudskoy, D.N. Seleznev, P.A. Storozhenko, A. Ya. Svarovski, G. Yu Yushkov**

*Presented at the 16th International Conference on Ion Implantation Technology (IIT2006)*
Marseille, France
June 11-16, 2006

**Collider-Accelerator Department, Accelerator Division**

**Brookhaven National Laboratory**
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

# DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed on recycled paper

# Ion Sources for High and Low Energy Extremes of Ion Implantation

A. Hershcovitch[1], V. A. Batalin[2] A. S. Bugaev[3], V. I. Gushenets[3], B. M. Johnson[1], A. A. Kolomiets[2], G.N. Kropachev[2], R. P. Kuibeda[2], T. V. Kulevoy[2], I. V. Litovko[3], E.S.Masunov[4], E. M. Oks[3], V. I. Pershin[2], S. V. Petrenko[2], S.M.Polozov[4], H. J. Poole[5], I. Rudskoy[2], D. N. Seleznev[2], P. A. Storozhenko[6], A. Ya. Svarovski[7], G. Yu. Yushkov[3]

*1-Brookhaven National Laboratory, Upton, New York 11973, USA*
*2-Institute for Theoretical and Experimental Physics, Moscow, Russia*
*3-High Current Electronics Institute Russian Academy of Sciences, Tomsk, 634055 Russia*
*4-Moscow Engineering Physics Institute, Kashirskoe sh. 31, Moscow, 115409, Russia*
*5-PVI, Oxnard, California 93031-5023, USA*
*6-State Research Institute for Chemistry and Technology of Organoelement Compounds 38, sh. Entuziastov, Moscow, 111123, Russia*
*7-Siberian Divisions of Russian National Research Center "A.A. Bochvara Scientific Research Institute for Inorganic Materials," Seversk, 636070 Russia*

**Abstract.** A joint research and development effort focusing on the design of steady state, intense ion sources has been in progress for the past two and a half years. Our ultimate goal is to 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 higher charge state 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 a somewhat smaller current of negative Decaborane ions were also extracted. Initial results also indicate that a Boron fraction of over 70% was extracted from a Bernas-Calutron ion source.

**Keywords**: ion sources for ion implantation
**PACS**: *41.75Ak, 41.75Cc, 81.15Jj, 52.77Dq,*

## INTRODUCTION

Various types of ions 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 a lot of room for improvement due to space charge limitations at the low energy range and due to inefficiency in acceleration at the higher energy range. This paper is a synopsis of an extensive ion source R&D program designed to address industry needs.

Originally, the collaboration started to develop pulsed metal vapor ion sources with enhanced charge states. We utilized 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 these charge enhancement characteristics to ion sources that generate steady state multi-charged B, P, As, and Sb ions. These technical enhancements can be adapted to DC ion implanters [3] in order to improve upon present day high-energy ion implanters that use rf accelerators. Progress in generating higher charge state B, P, and Sb ion beams is reported in section I.

However, we soon realized 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. Recent results from a Decaborane ion source are briefly described in section II; while a novel gasless/plasmaless ion beam deceleration method is also mentioned in this section.

Finally, a spin-off result of an ion source, from which over 70% of the extracted ion beam consists of singly charged boron, is described in section III.

# I. 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 sources we have removed the second filament cathode and placed 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.

In this ion source a 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 1). 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 experimental results can be found in reference 7. Since the ion source contains a magnetic field perpendicular to ion beam extraction, charge state distribution measurements are being repeated with magnetic separation for confirmation.

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

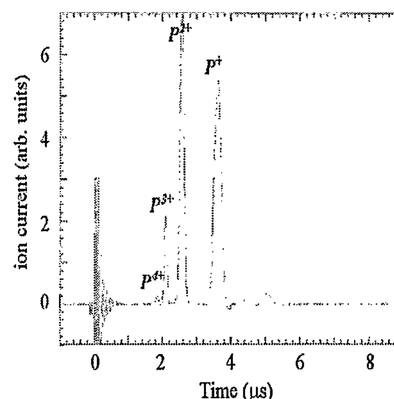


**FIGURE 1.** Phosphorous TOF ion beam spectrum.

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 2 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 $mm^2$.

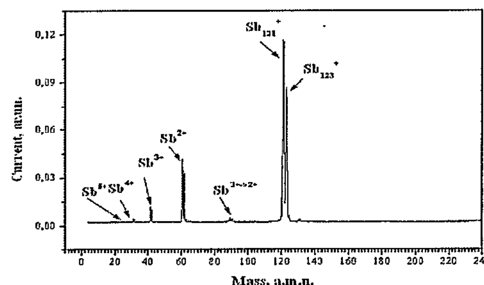

Figure 2. Antimony ion beam spectrum.

# II. 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! A record of invention has been filed by the collaborators.

Decaborane ($B_{10}H_{14}$) was introduced into the ITEP Bernas source and the spectrum shown in figure 3 was obtained [11]. A Decaborane current of 1 emA was extracted. Very recently, a somewhat smaller current of negative Decaborane was also obtained [12]. This significance result opens the possibility of merging negative and positive Decaborane beams, while slowing them down to further reducing the space charge problem.

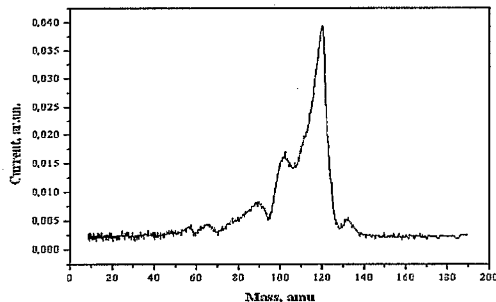


Figure 3. Spectrum of Decaborane ion beam.

Aperture size of the ITEP Bernas ion source is only 1mm x 20mm due to small bending magnet acceptance, which is located 1m from source extractor. There is an inherent difficulty in transporting various species from Bernas type ion sources (for even less than 1m), 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 [13]. The latest results [12] are displayed in figure 4.

Simulations were performed with a modified (ITEP) version of KOBRA. Initial results (very preliminary) indicate that this transport system functions experimentally as well (at least for Decaborane).

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.

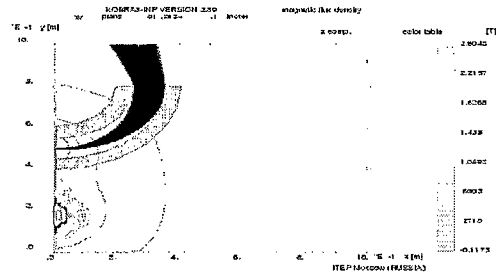

**FIGURE 4.** Simulation results of sector cylindrical electrostatic deflector for Decaborane beam indicating that the whole beam is being transported.

# III. 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 [14]. "Optimal" extracted ion spectrum is shown in figure 5.

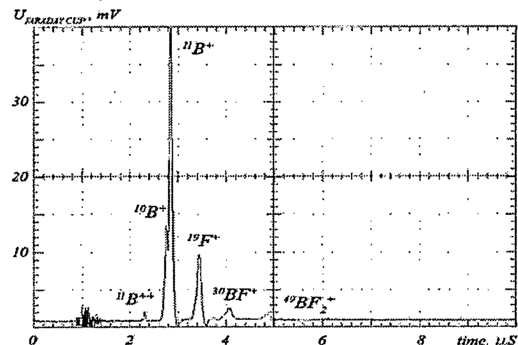


**FIGURE 5.** Ion beam charge state distribution for beam extracted from the Bernas-Calutron ion source for ion source discharge current of 4 A and a corresponding discharge voltage of 110 V.

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.

Ion source performance is optimized by adjusting the temperature of the oven containing the solid $LiBF_4$ compound. Once steady optimal boron vapor flow into the ion source is achieved, discharge current and voltage is adjusted by increasing hot cathode emission current. Table 1 shows source performance (from low

top row, to high, bottom row). More details can be found in reference 14.

**TABLE 1.** Boron charge-state fractions for some operating parameters of the Bernas-Calutron ion source.

| Source Current & Voltage | Total Extracted Ion Beam | $^{11}B^{+}$ Fraction | $^{11}B^{+}$ Fraction |
|---|---|---|---|
| 2 Amp, 250 Volt | 25 mA | 72 % | - |
| 3.6 Amp, 190 Volt | 34 mA | 71 % | 0.6 % |
| 2 Amp, 250 Volt | 41 mA | 68 % | 1.1% |

## 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.

Over the past two and a half 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. A major obstacle to development of a commercial source has been reluctance of potential clients in the ion implantation industry to reveal their true needs out of fear that the competition may find out anything about their R&D plans. Therefore, in addition to tackling technical and scientific challenges, one needs to guess what a secretive market wants.

## ACKNOWLEDGMENTS

One of the authors (A.H) is grateful to 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.

Notice: This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH1-886 with the US Department of Energy. The Untied States Government retains, and the publisher, by accepting the article for publication, acknowledges, a world-wide license to publish or reproduce the published form of this manuscript, or others to do so, for the United States Government purposes.

## REFERENCES

1. A.S. Bugaev, V.I Gushenets, E.M. Oks, G.Yu Yushkov, T.V. Kulevoy, A. Hershcovitch and B.M Johnson, Appl. Phys. Lett., **79,** 919 (2001).
2. V.A. Batalin, A.S. Bugaev, V.I. Gushenets, A. Hershcovitch, B.M. Johnson, A.A. Kolomiets, R.P. Kuibeda, T.V. Kulevoy, E.M. Oks, V.I. Pershin, S.V. Petrenko, D.N. Seleznev, and G.Yu. Yushkov, Journal of Applied Physics, **92,** 2884 (2002).
3. V.A. Batalin, A.S. Bugaev, V.I. Gushenets, A. Hershcovitch, B.M. Johnson, A.A. Kolomiets, R.P. Kuibeda, B.K. Kondratiev, T.V. Kulevoy, I.V. Litovko, E.M. Oks, V.I. Pershin, H.J. Poole, S.V. Petrenko, D.N. Seleznev, A. Ya. Svarovski, V.I. Turchin, and G.Yu. Yushkov, Rev. Sci. Instrum. **75**, 1900 (2004).
4. V.V. Simonov, L.A. Kornilov, A.V. Shashelev, E.V. Shokin, *Ion Implantation Equipment* (Radio i Svjaz', Moscow, 1988, in Russian).
5. I. Chavet and R. Bernas, Nucl. Instrum. Methods 51, 7 (1967).
6. H. Rassel and H. Glawischnig, Eds., *Ion Implantation Techniques* (Springer, New York, 1982), p.39.
7. V.I. Gushenets, A.S. Bugaev, E.M. Oks, A. Hershcovitch, B.M. Johnson, T.V. Kulevoy, H.J. Poole, and A.Ya. Svarovski, Rev. Sci. Instrum. **76**, 083301 (2005).
8. T.N. Horsky, Rev. Sci. Instrum. 69, 840 (1998).
9. K. Saadatmand, Rev. Sci. Instrum. 69, 859 (1998).
10. T.V. Kulevoy, R.P. Kuibeda, S.V. Petrenko, V.A. Batalin, V.I. Pershin, N. Kropachev, A. Hershcovitch and B.M. Johnson, V.I. Gushenets and E.M. Oks, and H.J. Poole, Rev. Sci. Instrum. **77**, 03C110 (2006).
11. T.V. Kulevoy, S.V. Petrenko, R.P. Kuibeda, V.A. Batalin, V.I. Pershin, A.V. Koslov, and Yu. B. Stasevich, A. Hershcovitch and B.M. Johnson, E.M. Oks and V.I. Gushenets, H.J. Poole, P.A. Storozhenko, E.L. Gurkova, and O.V. Alexeyenko, Rev. Sci. Instrum. **77**, 03C102 (2006).
12. A. Hershcovitch, V. A. Batalin' A. S. Bugaev, V. I. Gushenets, B. M. Johnson, A. A. Kolomiets, G.N. Kropachev, R. P. Kuibeda, T. V. Kulevoy, I. V. Litovko, E.S.Masunov, E. M. Oks, V. I. Pershin, S. V. Petrenko, S.M.Polozov, H. J. Poole, I. Rudskoy, D. N. Seleznev, P. A. Storozhenko, A. Ya. Svarovski, G. Yu. Yushkov, Rev. Sci. Instrum. **77**, 03B510 (2006).
13. S.V. Petrenko, G.N. Kropachev, R.P. Kuibeda, T.V. Kulevoy, and V.I. Pershin, E.S. Masunov and S.M. Polozov, A. Hershcovitch and B.M. Johnson, H.J. Poole, Rev. Sci. Instrum. **77**, 03C112 (2006).
14. V.I. Gushenets, A.S. Bugaev and E.M. Oks, Ady Hershcovitch and B.M. Johnson, T.V. Kulevoy, H.J. Poole, A. Ya. Svarovski, Rev. Sci. Instrum. **77**, 03C109 (2006).