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Sources and Transport Systems for Low Energy Extreme of Ion Implantation*

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Abstract. For the past seven years a joint research and development effort focusing on the design of steady state, intense ion sources has been in progress with the ultimate goal being to meet the two, energy extreme range needs of mega-electron-volt and 100's of electron-volt ion implanters. However, since the last Fortier is low energy ion implantation, focus of the endeavor has shifted to low energy ion implantation. For boron cluster source development, we started with molecular ions of decaborane ($B_{10}H_{14}$), octadecaborane ($B_{18}H_{22}$), and presently our focus is on carborane ($C_2B_{10}H_{12}$) ions developing methods for mitigating graphite deposition. Simultaneously, we are developing a pure boron ion source (without a working gas) that can form the basis for a novel, more efficient, plasma immersion source. Our Calutron-Berna ion source was converted into a universal source capable of switching between generating molecular phosphorous P_4^+, high charge state ions, as well as other types of ions. Additionally, we have developed transport systems capable of transporting a very large variety of ion species, and simulations of a novel gasless/plasmaless ion beam deceleration method were also performed.

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INTRODUCTION

Since the invention of the transistor, the trend has been to miniaturize semiconductor devices. Consequently, the technology has been focused on the formation of shallower junctions, and thus lower energy implants. The continuing need to reduce implantation energies creates significant challenges for the designers of advanced implanters. Current density limitation associated with extracting and transporting low energy ion beams result in lower beam currents that in turn adversely affects the process throughput. A joint research and development effort whose ultimate goal is to develop steady state intense ion sources to meet the two-energy extremes needs of mega-electron-volt and of 100's of electron-volt ion implanters has been in progress for the past eight years. Our R&D effort has been on boron cluster source development. We started with molecular ions of decaborane ($B_{10}H_{14}$), octadecaborane ($B_{18}H_{22}$), and presently our focus is on carborane ($C_2B_{10}H_{12}$) ions. Simultaneously,
we developed a pure boron ion source (without a working gas) that can form the basis for a novel, more efficient, plasma immersion source. And our Berna-Calutron ion source, which in the past produced record currents of steady state high charge phosphorous [P^{2+} (8.6 pmA), P^{3+} (1.9 pmA), and P^{4+} (0.12 pmA)] has been generating molecular phosphorous P_4^+. Our plans are to convert the Berna-Calutron into a universal source capable of switching between generating molecular phosphorous P_4^+, high charge state ions, as well as other types of ions. Additionally, we have developed transport systems capable of transporting a very large variety of ion species, and simulations of a novel gasless/plasmaless ion beam deceleration method were also performed. Various results will be presented at the conference.

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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 briefly 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 carborane and molecular phosphorous ion sources are described in section II; additionally a novel gasless/plasmaless ion beam deceleration method is also mentioned in this section.

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

I. OLD RESULTS FROM 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]. 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]. 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.

Record enhancement of Antimony charge states were obtained in an ITEP Bernas ion source in which a staggered, oscillating electron beam was generated [10]. 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.

II. MOLECULAR BEAMS ION SOURCS

Since shallow profile implantation is desired, there is a need to decrease ion implantation energy. 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. Decaborane ($B_{10}H_{14}$) was introduced into the ITEP Bernas source and 3 emA of decaborane were extracted from a 1.5mmx20mm slit at 14 kV.[11] Discharge current was only 85 mA. Later 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.

Presently, our focus is on carborane ions, which are much more stable than either decaborane or octadecaborane. But, carborane discharges leave graphite residue, which when deposited on grids results is unacceptable "shadow" on wafers during implantation. Consequently, our preset work is focused mitigating this problem.

First approach to mitigating the problem of carbon deposition was to use fluorinated carborane. Synthesizing fluorinated carborane is a significant accomplishment, since it was not done before and since according to Varian personnel, their carborane suppliers claim that it cannot be done. In fluorinated carborane, one of the hydrogen was replaced with a fluorine atom. Some encouraging, though not completely conclusive were obtained. But, the ion source still had some graphite residue. Next a new a highly proprietary carborane-like compound was synthesized with spectacular results as it can be seen from figures 1-3, which are self explanatory.

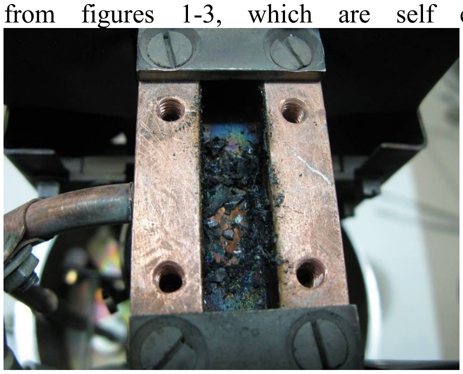

FIGURE 1 Ion source after carborane operation

FIGURE 2 same discharge chambers after novel compound operation.

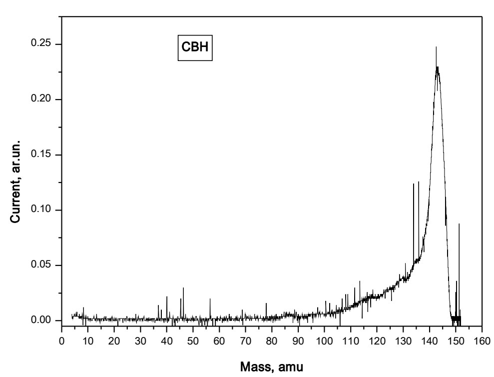

FIGURE 3 Carborane beam spectrum

Ion source has an extraction aperture of 1x20 mm^2, from which a beam current of 0.3 mA was extracted. This ion source has an aperture, which is at least a factor 6 smaller than most operating ion sources. At HCEI the modified Bernas-Calutron ion source is being converted to a truly universal ion source by generating molecular phosphorous P_4^+. The extract current density was somewhat above 1 mA/cm^2, which matches peak previous results. It's the same ion source, from which 41 mA were extracted, of which singly charged boron made up over 70% of the total ion beam [14].

Presently, the effort to generating molecular phosphorous P_4^+, or high charge phosphorous, is being channeled towards converting the ion source from being oven fed to a purely gas fed ion source.

III. MOLECULAR BEAM TRANSPORT AND DECELERATION

A novel LEBT is being developed to provide better molecular beam transmission through a bending magnet, and to facilitate beam slowing down. An electrostatic focusing system with long focus length was developed and tested for improved beam transmission through the separating magnet. And, after the bending magnet, an electrostatic undulator is being developed as a transport channel for total carborane beam transmission to the target. Additionally, target installation at the potential of last undulator electrode enables energy regulation of implanted ion beam, i.e. beam slow down without space charge blow-up.

Simulations have shown that a 10 kV carborane beam can be slowed down to 2 kV at implantation. Experimental verification is about to commence. Given the track record of agreement between previous simulations and experiments [15,16], it's possible that indeed gasless plasmaless beam deceleration can be achieved.

DISCUSSION

Currently our program is focused on four topics: molecular boron using complex molecules containing carborane resulting in carborane ions with no graphite residue in ion sources; plasmaless gasless deceleration of ion beams; gas fed phosphorous molecular ion sources; and pure boron plasma immersion. The latter is based on our success in generating pure boron plasmas[17].

Some additional details can be found in papers by Vizir et al, and by Kulevoy et al in these proceedings.

Much of the work is highly proprietary due to the fact that our capabilities are limited to small aperture ion sources, since we do not have large bending magnets. Additionally, we do not have the ability to fabricate full implanters and mark them. Nevertheless, substantial results were obtained by our collaboration during a few years in spite of the fact that many changes in the research program have been introduced during this relatively short period.

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