Decaborane Ion Source Demonstration*

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***Abstract*-This project demonstrated concept and feasibility of a proprietary high current decaborane ion source suitable for ultra shallow doping. This was motivated by the attractive scaling of decaborane ions for space charge dominated extraction and transport. A highly modified Bernas source was mounted on an NV-10/80 implanter. Using standard extraction and beamline components, 2.3 mA of boron nucleon current was produced in the form of $B_{10}H_x^+$ at 50 kV. Due to under dense plasma, beam current scaled linearly with extraction voltage.**

I. INTRODUCTION

Compared with a boron ion beam, decaborane offers extremely attractive scaling for ultra shallow junction doping. Motivated by the relentless push for shallower junctions, research decaborane beams and processes have been demonstrated [1, 2, 3, 4]. Device characterization with split lots and an analyzed beam has begun [5]. A commercially supplied delivery system is also available [6]. However, commercialization has been hampered by the lack of a suitable high current decaborane ion source. Early attempts to ionize decaborane in Bernas sources had been informally reported as failures, with significant dissociation in the source.

This project demonstrated over 2.3 mA of boron nucleon current in the form of $B_{10}H_x^+$ at 50 kV. An NV-10/80 implanter was used with modifications to the gas box, delivery system, and Bernas ion source. In principle, all of the required changes could be implemented on any standard high current implanter in a manner that is interchangeable with standard sources and processes. With modern extraction optics, commercially attractive boron nucleon current below 1 keV per nucleon is expected.

II. SPACE CHARGE MOLECULAR BEAM SCALING

Low energy boron implantation is a critical process for semiconductor doping today. High current, low energy beam extraction and transport is limited by basic physics. This is illustrated by considering the implications of the Child-Langmuir limits for extraction of space charge dominated beams [6],

$$J = 5.44 \times 10^{-8} (Z/A)^{1/2} V^{3/2}/d^2 \qquad (1)$$

where beam current density, J (Amp/cm2), scales proportional to the square root of charge to mass ratio, $(Z/A)^{1/2}$ and the power of the extraction potential, $V^{3/2}$, but inversely with the square of the gap, d^2 (cm^2). The numerical coefficient is model dependent, but the parametric scaling contains the essential physics. The strong scaling with potential severely limits low energy beam current. In the past, tool vendors have used adjustable extraction gaps to maximize extraction current down a few kV. However, gap reduction is limited by sparking or shorting caused by deposits. Below 10 kV, reduced potential begins to overwhelm the practical limits of reduced gap. Some compensation can be gained by increasing the extraction area, but, for space charge limited beam transport, this translates into a larger area, more expensive beamline and analyzing magnet. Without innovation, standard high current implanter architecture will become an increasingly expensive method for delivering high current dopant below 1 keV.

A simple example illustrates the challenge, and the theoretical advantage of decaborane. Consider a hypothetical ion source/extraction system capable of 10 mA of B_{11}^+ at 10 kV extraction. For convenience, assume the extraction area is 10 cm^2. Using the scaling of Eq. (1), the maximum B_{11}^+ performance of this system with fixed gap would be 0.3 mA at 1 kV. Decaborane benefits from the double advantage of 10 kV extraction, and 10x dopant nucleons per charge. The exact nucleon energy depends on the ion mass spectrum, as discussed in Section V. So, expected performance is illustrated in Table I by assuming one tenth energy for the boron nucleons. With fixed gap, the decaborane current at 10 kV would be 3 mA, which corresponds to 30 mA of boron nucleon current.

TABLE I
CHILD-LANGMUIR SCALING FOR A 10 kV, 10 mA BEAM

Ion	mass	E, keV	J, mA/cm2	I, mA
B	11	10	1	10
	11	1	0.03	0.3
B10 Hx	117	10	0.3	3
(B, nucleon)	11	1	3	30

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For given dopant energy, both nucleon current and extraction potential scale proportional to the number of nucleons in a molecule. So, Eq. (1) implies surprisingly high leverage for molecular beams. For example, let the molecular mass be expressed as, $A_{mole} = N_d A_d + N_{nd} A_{nd}$, where N_d denotes the number of dopant nuclei per molecule, and *"nd"* denotes the average for non-dopant species. If the desired dopant energy is E_d and charge state one is assumed, the extraction potential must be $V_{mole} = A_{mole} E_d / A_d$. Taking the ratio of molecular dopant nucleon current to corresponding dopant ion current, the theoretical extraction limited dopant nucleon current gain for molecules is,

$$G_{molecule} = N_d \, (N_d + N_{nd} \, A_{nd}/A_d). \qquad (2)$$

Note that gain in Eq. (2) is independent of extraction potential. For decaborane, $N_{boron} = 10$, $N_{nd} = 14$ and $m_{nd}/m_{boron} = 1/11$. So, the space charge limited current gain is, $G_{decaborane} = 113$. This remarkable result draws attention to the fact that no existing ion source comes close to the theoretical extraction limits for decaborane or similar heavy molecule.

III. EXPERIMENTAL

A proprietary, modified Bernas ion source was designed for a 1980's vintage NV-10/80 implanter. The decaborane vaporizer was mounted in the gas box, in place of a bottle. Modest heating was required for the delivery system and gas line on the atmospheric side to maintain temperatures above 20°C for decaborane evaporation and transport. The standard utility capabilities of the gas box were sufficient for the modest heating requirements of decaborane. On the vacuum side, the gas line was below 300°C, so most of the decaborane reached the ion source intact. Opto-isolated controls and sensors were installed on top of the existing control system. This outdated tool was much easier to modify than a modern, computerized implanter.

The extraction system and beamline were standard. Before decaborane testing began, the tool was qualified using a standard Bernas source. At the conclusion of testing, the standard Bernas was re-installed, and the tool was qualified for standard production implants. Due to various equipment failures, extraction current could only be read occasionally. Analyzed beam current was measured with the Faraday. The transfer ratio of the total $B_{10}H_x^+$ current was less than one percent, probably because the extraction optics were poorly matched to decaborane. The target wheel was not functional during our tests, but was made operational afterwards.

The decaborane and delivery system were provided by ATMI [5]. The only difficulty with the delivery system was our homemade digital controller, which lacked sufficient resolution. So, the vaporizer temperature routinely drifted by 1° or 2° C during the five to ten minutes needed to manually scan the spectrum from 130 to 1 amu. The nominal mass of decaborane is 124, but neither the boron nor the hydrogen constituents were isotopically pure. Micro-Amps of beam at masses above 124 were seen under some operating conditions. These are probably molecular isomers, but were not investigated. The long time required to take a full spectrum made it impractical to routinely scan from mass 130 to 1. To minimize the effects of thermal variation, partial spectra were typically taken at the masses of most interest, especially around $B_{10}H_x^+$.

IV. HEALTH AND SAFETY

Decaborane is a toxic solid, with low vapor pressure at room temperatures and a distinctive, unpleasant odor. Toxicity is lower than many other process materials. At room temperature, the vapor pressure is at the threshold limit value. So, decaborane vapor has the advantageous characteristic of being detectable by its unpleasant odor before dangerous levels are reached. One danger is that the vapor pressure rises rapidly above room temperature. Also, decaborane can have explosive chemical interaction with oxidizing agents routinely found in fabs. It dissolves latex rubber, so butyl nitrile gloves are required. Decborane itself dissolves readily in alcohol. This makes cleanup easy, but excellent splash protection is required, because skin absorption is also dangerous. A full face shield breathing apparatus is recommended.

Refractory temperature ion source components reduce decaborane into its constituent elements. Elemental boron is difficult to clean, but safe. The source was removed after approximately 20 hours of operation. A hydride sniffer was used, but no detectable vapor pressure was found in the source enclosure. In our view, the primary risk for dangerous tool contamination would be an event where the deca delivery system (vaporizer and gas line) is energized with the arc OFF. Then, significant evaporation into the source would occur, with the likelihood of some evaporation into the source enclosure.

V. RESULTS

The goal of this project was to demonstrate concept and feasibility of a prototype high current decaborane ion source suitable for commercial processing. To focus on the source, the extraction potential was usually set at 50 kV, which is comfortable for the extraction optics of the NV-10/80. The dominant part of the spectrum was $B_{10}H_x^+$, which appeared to blend with the $B_9H_x^+$ peaks, as illustrated in Fig. 1. The total current in the $B_{10}H_x^+$ peaks was over 2.3 mA. The most

important control parameter is the vaporizer temperature, indicated by the process value set point, e.g., pv38 means 38 °C.

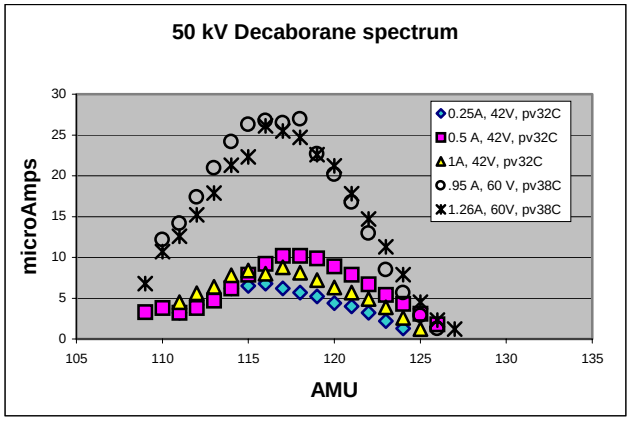

Fig. 1. Decaborane ion spectrum, $B_{10}H_x^+$ and $B_9H_x^+$ at 50 kV. The effect of arc parameters and vaporizer temperature are shown. The second high point at mass 118 in the 0.95 A, 60V data was taken after the rest of the spectrum was scanned, implying that vaporizer temperature had drifted higher.

Decaborane extraction scaling is illustrated by plotting the total $B_{10}H_x^+$ current from 10 kV to 50 kV. This summed molecular current scaled linearly with extraction voltage, rather than following the usual $V^{3/2}$, as illustrated in Fig. 2. Data with two temperature set points are shown, pv 38C for the upper data and pv32C for the lower data set. Curves scaled by $V^{3/2}$ from the maximum 50 kV point are shown for comparison. The roll off from 40 to 50 kV in the pv32C data set is probably due to low vapor pressure being too low. The pv38C current scales linearly with extraction potential over a factor of five range.

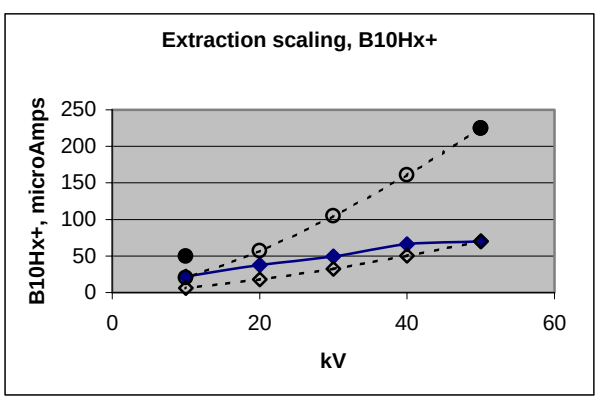

Fig. 2. Total $B_{10}H_x^+$ current scaled linearly with extraction potential at pv32C and pv38C. Solid symbols represent data points; open symbols represent $V^{3/2}$ scaling.

The performance demonstrated here, > 2.3 mA boron nucleon current at 50 kV, should be significantly improved, at lower extraction potential for commercialization. Usable beam current will be determined by the number of total number of process compatible molecular ion peaks. This will require opening up the analyzing aperture, which decreases mass resolving power. Cross contamination with heavy metals, such as antimony (122) and indium (118), was not an issue on this dedicated implanter, but must be addressed for production.

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