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AN INTENSE PULSED BARIUM ION SOURCE†

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Abstract

A magnetically insulated diode has been used to produce 30 A/cm^2, 250 keV, Ba^+ion pulses for 170-200 nsec, using BaF_2 as the ion source material. Other operating conditions yield pulse of $Ba^+$and F^+ ions at 300 keV and Ba^{+2} ions at 600 keV. The beam is diagnosed with time-of-flight analysis, Secondary Ion Mass Spectroscopy, and Rutherford backscattering of 2.3 MeV helium ions.

Advances in the production of intense pulsed ion beams have suggested the use of these beams as drivers for Inertial Confinement Fusion (ICF),[1] and for annealing semiconductors.[2] For ICF, 10 MeV protons are appropriate but even 200 keV protons have a range of 2 μm in silicon,[3] which is much greater than the typical 0.2 μm depth of microelectronic structures. By contrast, 250 keV barium ions have a range of 0.1 μm in silicon, and these ions would also be suitable for injection into the first stage of an accelerator system designed to achieve the GeV energy level needed for heavy ion beam-driven ICF. In this paper we report the achievement of 30 A/cm^2 of 200-300 keV Ba^+ions and a comparable current of Ba^{+2} ions at twice that energy in a 170-200 ns pulse using a magnetically insulated ion diode.

The barium beam is produced using the LYNX machine, which consists of a small magnetically insulated ion diode powered directly from a Marx bank. 10 cm^2 of 1.5 mm thick BaF_2 is used as the plasma source on the anode of the beam diode. An array of 0.6 mm diameter holes are drilled into the BaF_2. When the high voltage is applied to the diode, electric field stress at the edges of the holes causes a surface flashover which spreads plasma across the BaF_2 surface from which the beam ions can be drawn. Electrons are inhibited from crossing the 0.4 cm diode gap by the 10 kG transverse magnetic field (see Fig. 1). The ions are extracted through slots in the cathode, which is also a portion of the single turn coil for the magnetic field. This machine has been used previously to produce beams of hydrogen, lithium, boron, and carbon ions.[4]

The ions produced from this source are analyzed with a variety of diagnostics. Magnetically insulated, biased Faraday cups are used to measure the ion beam current density as well as for time-of-flight analysis. In addition, the ion beam is deposited into a silicon crystal, and then analyzed with Secondary Ion Mass Spectroscopy (SIMS) and Rutherford Backscattering (RBS) of 2.3 MeV He ions from the sample. Time-of-flight analysis of the ions suggests the presence F^+, Ba^+, and Ba^{+2} ions. The ions start to be emitted during the 50 ns rise of the voltage pulse. Figure 2 shows the diode voltage and Faraday cup (ion current) traces for a 340 kV peak voltage shot. Times appropriate for arrival of 340 keV F^+ and Ba^+, and 680 keV Ba^{+2} ions at the location of the Faraday cup are indicated. Shots at voltages of 250 kV or less do not show the Ba^{+2} peak. Shots taken with a new anode show almost pure Ba^+as shown in Fig. 3. Current densities of 30 A/cm^2 and pulse durations of 170-200 nsec FWHM are obtained. The barium pulse terminates before the end of the voltage pulse at a time which seems to be correlated with the end of a high frequency oscillation of the diode voltage (Fig. 3).

After the anode has been used (for several shots) the beam becomes a mixture of F^+, Ba^+, and Ba^{+2} ions and the ion pulses last for the duration of the diode voltage pulse. Current densities of each species are estimated by the step size in the time-of-flight ion current density, such as those in Fig. 2. In that case they were 14 A/cm^2 F^+, 18 A/cm^2 Ba^+, and 17 A/cm^2 Ba^{+2}. Some shots with a used anode show total ion current densities in the range 70-100 A/cm^2. When the aperture of the Faraday cup is covered with a 2 μm mylar foil, protons having energies over 200 keV could be collected, but none of the heavier ion species can penetrate the foil at the energies of this experiment. No protons are seen from this anode. This is in contrast to previous experiments in which some protons were always seen.[4] Evidently this is because the oil diffusion vacuum pump used earlier has been eliminated in favor of a turbomolecular pump, and the diode high voltage insulator is being run without a protective coating of diffusion pump oil.

The analysis with SIMS and RBS is complicated by the power deposited in the silicon crystal by the ion beam. The silicon is melted with a power input in the range 0.5-1 J/cm^2. Since the ion beam power density exceeds this figure, the barium ions tend to concentrate near the surface because they cannot remain in solution with the molten silicon. Figure 4 shows the SIMS results for an arsenic-implanted silicon target before and after the barium beam is implanted. The arsenic was implemented at 150 keV at a depth of 2500 Å into the silicon and used as a tracer. The arsenic is redistributed to a depth of over 5000 Å by the beam pulse. Barium ions reach a depth of 1000 Å but are concentrated at the surface. The SIMS analysis shows no implanted fluorine, but the SIMS sample was exposed to the beam from a new anode, and the time-of-flight data also showed no fluorine. RBS confirmed that the barium is concentrated at the surface of the sample.

These results are consistent with our expectations for the BaF_2 anode. The first and second ionization energies of barium are 5.21 eV and 10.0 eV, while the first ionization energy of fluorine is 17.4 eV. Thus, barium should be the dominant positive ion in the anode plasma. On the other hand, fluorine is more easily accelerated, since it is lighter. This is reflected in the Child-Langmuir current densities for fluorine and barium at 300 kV and a 4 mm diode gap, which are 13 A/cm^2 and 4.8 A/cm^2 ($m^{-1/2}$ mass dependence), respectively. Thus, we are seeing barium current densities exceeding the Child-Langmuir value by a factor of 10, while the fluorine current density is on the order of the Child-Langmuir value. This suggests that the F^+ ion concentration in the anode plasma is small compared to the $Ba^+$and Ba^{+2} concentrations, consistent with fluorine's extremely large ionization potential.

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We have demonstrated the use of a BaF_2 anode in a magnetically insulated diode to generate pulses of Ba^+ ions at 200-300 keV and 30 A/cm^2 for 200 nsec, with a total barium current of 300 A. Operation of the diode with a used anode surface generates an ion beam that is a combination of 200-300 keV F^+ and Ba^+, and 400-600 keV Ba^{+2} with a total ion current of up to 1 kA. The total current is limited by the area of BaF_2 on the anode and, in principle, can be increased to any desired value by increasing the active anode area. The ion species that can be generated by this technique are probably limited only by the availability of dielectric materials in which the desired ion is the most easily ionized. Fluoride compounds have performed well, and magnetic separation of a small fluorine component from much heavier ions like barium or uranium should not be impractical.

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References

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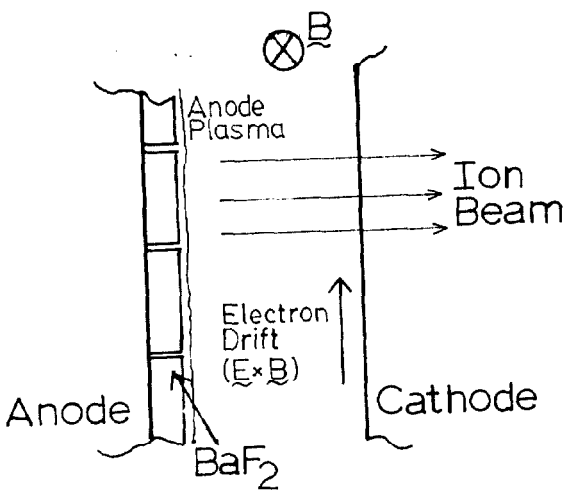

Fig. 1 Cross sectional view of diode gap.

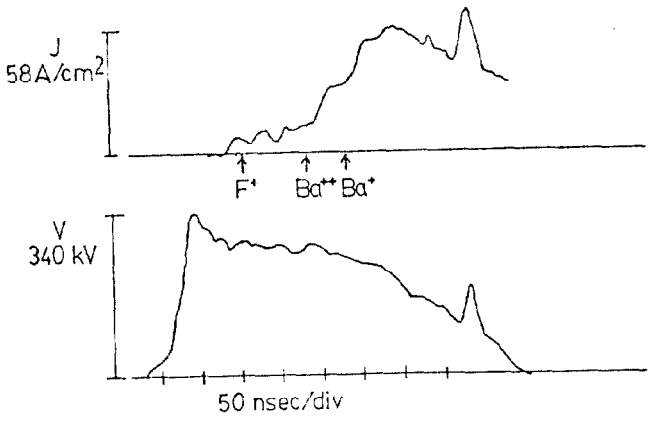

Fig. 2 Diode voltage and time-of-flight ion current for used anode.

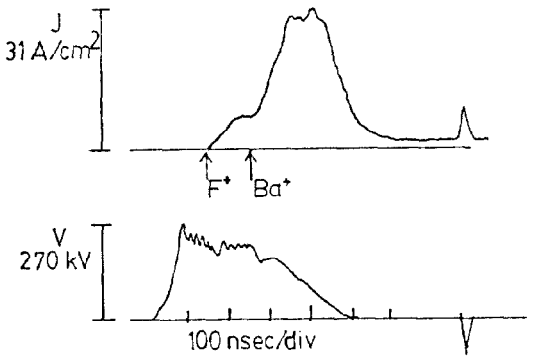

Fig. 3 Diode voltage and time-of-flight ion current for new anode.

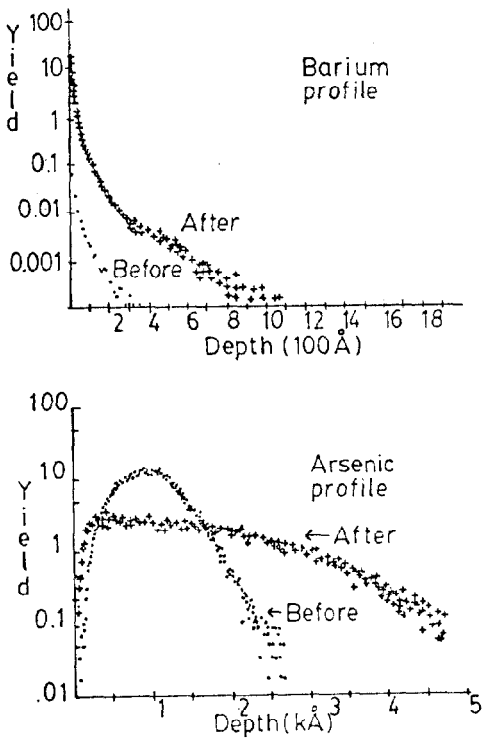

Fig. 4 SIMS analysis of arsenic implanted silicon crystal before and after treatment with barium beam.