NEGATIVE ION SOURCES AT KEK

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Abstract

Negative ion sources based on plasma-surface interactions(BLAKE ion source) have been developed at KEK for producing negative heavy ions. The first negative heavy ion source(BLAKE-II) was developed by modifying the ordinary negative hydrogen ion source with converter(BLAKE-I) placed into the plasma. It generates various species of negative heavy ions with intense beam currents. For example, a more than 10mA Au- ion beam was obtained from the ion source. Recently, the large scaled negative heavy ion source(BLAKE-III) has been developed and in the preliminary test experiment, more than 100mA Cu- ion beam has been stably obtained with a10% duty factor in pulsed operation . The BLAKE-II ion source was attached to the BNL 15MV and Tsukuba University TANDEM accelerators and large current negative heavy ion beams were successfully accelerated in pulsed mode operation. In order to examine the negative ion formation process fundamentally, negative ion production probability related on sputtered particle velocity was measured and the results showed exponential dependence of the production probability on particle velocity as Norskov and Lindquist's theory predicted

Introduction

Recently, various new types of negative ion sources which make it possible to generate various species of intense negative ion beams such as H-,C-,Si-,Cu-,Ni-,Au- and so on have been developed at KEK.[1][2][3] In these ion sources, negative ions are produced at the surface of the material which is placed in a hydrogen plasma confined by a cusp magnetic field for producing negative hydrogen ions or a xenon plasma for negative heavy-ions. This type of negative ion source has been originally developed at LBL(Lawrence Berkley Laboratory) for producing an intense negative hydrogen beam for nuclear fusion[4] and then improved for accelerator applications at LANL(Los Alamos National Laboratory)[5] and KEK(National Laboratory for High Energy Physics). Therefore, the ion source has a nickname of BLAKE negative ion source.

The BLAKE-I source was designed as a negative hydrogen ion source. This ion source generates negative hydrogen ion beam of more than 40mA maximum and can be operated stably for more than 2,000 hours with LaB6 filaments. It has been used in the KEK 12-GeV proton synchrotron for more than four years. The BLAKE-II ion source is a modified ion source of BLAKE-I for generating intense negative heavy ions and, for example, it has produced a Au^- ion beam intensity of about 10mA. Recently, a large scaled negative heavy ion source(BLAKE-III) has been developed and more than 100mA of Cu^- ion beam has been obtained with high duty factor(10%).

Recently, demand for acceleration of intense pulsed heavy ion beams in an electrostatic tandem accelerator has been increased more rapidly because a tandem accelerator can be used as an efficient injector for heavy ion synchrotrons [6][7][8] and a pioneer work has been already started at BNL with their 15MV tandem accelerator which was operated as an injector for the AGS synchrotron. Also in the field of nuclear physics, such intense pulsed beams are very attractive for some experiments.[9] The BLAKE-II ion source was attached to the BNL 15MV and Tsukuba University 12MV tandem accelerators to accelerate the intense negative heavy ion beams. Relatively higher beam intensities of 0.2 - 1.4 mA for Au^- and Cu^- were obtained at the exit of the accelerators. However, in order to accelerate more beam current in the tandem accelerators, it was found that beam emittance degradation due to the space charge effect for such large beam intensities should be eliminated.

In order to examine the fundamental process of negative ion formation on the metallic substrate in the BLAKE ion source experimentally, the velocity dependence of the negative ion formation probability was studied by measuring the negative ion formation yields for C^-, Si^-, $Ag^-$and Sn^-ions sputtered by Xe^+ ions. The negative ion formation probability was found to have an exponential dependance on the velocity as predicted by theory and the parameter related the electronic configurations of the negative ion and the metal combination was decided by experimentally.

BLAKE-II Ion Source

Details configuration of the BLAKE negative ion source have already been described in previous papers.[1][2][3] The ion source consists of a cylindrical plasma chamber made of stainless steel, a sputter probe, cesium oven and two sets of filaments. There are eighteen pieces of SmCo permanent magnets surrounding the plasma chamber to make the cusp magnetic field. Two small permanent magnets making a dipole magnetic field of about 100 gauss were also placed at the exit of the anode hole and used to return the extracted electrons back to the anode. The total drain current of the extraction power supply was substantially reduced with these dipole magnets. The sputtering probe was placed at the center of the plasma chamber, which was 12cm from the anode aperture, and biased negatively by a voltage of up to -970V. A quartz glass covered the probe except the surface to the anode hole and helped to prevent the supporting and cooling channel of the probe from sputtering by xenon ions in the plasma.

More than 20 species of the negative-heavy ions have been tested . The beam intensities for most of species are almost 50-100 times larger than those obtained from the ordinary cesium sputtered negative-heavy ion source. Beams from the ion source were very stable and reproducible. The measured mass-spectrum for Au ion beam is shown in Fig.1.

Compared with pulsed-mode operation, dc-mode operation requires substantially higher cesium flow rates because the cesium coverage on the sputtering.[10] Therefore, a new cesium oven, cesium valve and cesium transport line for feeding more cesium vapor into the ion source were designed. The diameter of the feed line was increased from 6 to 10cm. The distance between the oven and ion source was decreased from 50 to 15cm. The optimum temperature of the new cesium oven for pulsed-mode operation was decreased by about 50oC compared with the previous oven.

In the preliminary experiment of dc-mode operation, a spherical geometry copper sputter probe was used. At a sputter probe voltage of -610V, the total drain current to the sputter probe was typically 90mA at an arc current of 2A.

The cesium vapor density for an oven temperature of 258oC was estimated to be ~30 times higher than that for pulsed-mode operation(~160oC). Measured total beam intensity as a function of sputter probe current is displayed in Fig.2. The beam intensity is estimated to increase almost linearly with sputter probe current. By linear extrapolation of this data, the beam intensity would reach the

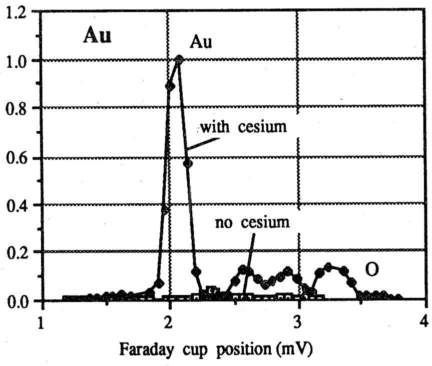

Fig.1 Mass-spectrum of Au⁻ ion beam

same level observed during pulsed-mode operation provided that the arc current could be increased to 15-20A.

BLAKE-III Ion Source

A large scaled BLAKE ion source(BLAKE-III) aiming to obtain a relative large current of more than 100mA with a large duty factor has been developed recently. This ion source has a relatively large rectangular shape sputter probe(5cm x 20 cm) and the extracted beam shape is not round but rectangular. In Fig. 3, the waveform of the extracted Cu- ion beam is shown. The negative ion beam was well focused in the plasma by the concave shape of the sputter probe and this means that the space charge neutralization due to the plasma ions works quite nicely.

Acceleration Test of Heavy Ion Beams in the BNL 15MV and Tsukuba University 12MV Tandem Accelerators

Intense negative gold and silicon ion beams generated by the cusp negative heavy-ion source in pulsed mode operation, were preliminary accelerated by the BNL 15MV tandem accelerator. The cusp negative ion source was attached to the ordinary injector of the BNL 15MV tandem accelerator. The pulse width and the repetition rate of the beam was about 150μsec and 7Hz, respectively, and the peak intensity of more than 3mA was extracted from the ion source for each ion species. The injected beam currents to the tandem accelerator , which were measured at the entrance of the tandem accelerator, were 0.4mA and 0.7mA for the gold and silicon ion beams, respectively and the total accelerated beam current was 1.4mA at the exit of the accelerator. It was understood by computing the beam optics including the non-linear space charge effect of the beam that the poor beam transmission from the ion source to the tandem accelerator was caused by the strong space charge forces in the beams due to the relatively low beam energy in the injection beam line.

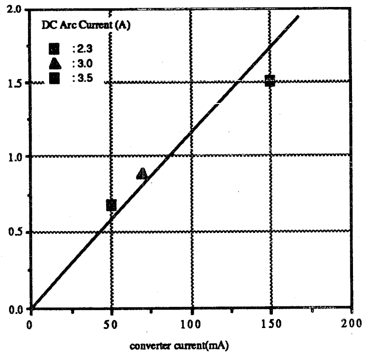

Fig.2 Total beam intenisity as a function of sputter probe current

Intense pulsed heavy ion beams of silicon and copper beams generated by the cusp negative heavy-ion source have been successfully accelerated by the 12MV tandem accelerator at Tsukuba Univ. The peak intensity of the accelerated pulsed beam was almost 100 times larger than that of the ordinary DC beam. No deteriorating effect on the acceleration for the intense pulsed beams, such as sparking or heavy beam loading, has been observed. Remarkably, a slit control system for regulating the column voltage of the tandem accelerator worked quite nicely for such a low duty pulsed beam and the beam energy stability of less than 10-4 was easily obtained.

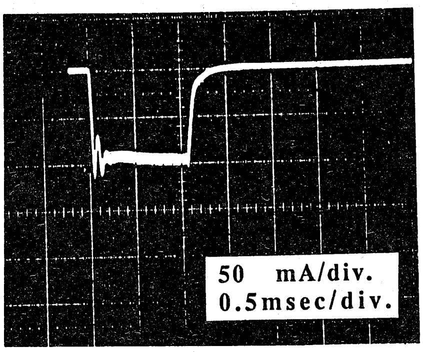

Fig.3 Waveform of Cu⁻ ion beam.(V:50mA/div. H:0.5msec/div.)

Velocity Dependence of the Negative Ion Formation Probabilities of Sputtered Atoms

In the formation process of negative ions sputtered out from the surface of the substrate, the velocity dependence of the negative ion formation probability has been well understood theoretically by considering the time-varying potential experienced by the sputtered particle leaving the surface, and Norskov and Lundquist[11] calculated the ionization probability P of negative ions.

According to the theory developed by Norskov and Lundquist, the negative ion formation probability P can be obtained in the following equation.

$$P = 2/\pi \ \exp[-C1\pi(\phi-A)/h\gamma v] \ \exp[-C2\pi/h\gamma v] , \qquad (1)$$

where ϕ and A are the workfunction of the substrate and the electron affinity of sputtered atom, respectively and v is a velocity of atom leaving from the surface of the substrate. Parameters C1 and C2 are related the effective energy difference between the electron affinity and the Fermi energy when the atom goes out of the substrate, γ is a characteristic distance beyond which no further electron exchange between atom and the substrate takes place and v is the perpendicular component of the particle velocity.

In the experimental approach to study the velocity dependence, several experimentss have been done so far. Among them , Yu measured in his excellent work[12] the negative ion formation probability of oxygen ions sputtered out from the chemisorbed oxygen layers on vanadium and niobium by argon ions as a function of the perpendicular component of the velocity emitted from the substrate. He showed clearly a linear velocity dependance of the negative ion formation probability of oxygen ion as predicted by theory and obtained that the coefficient $C_1\pi/h\gamma$ in the exponent of eq.(1) was $4x10^{-5}$ eV m^{-1}sec in the system of the negative oxygen ion.

When an atom or molecule is sputtered out from the substrate, the most probable energy is almost equal to its sublimation energy E_s

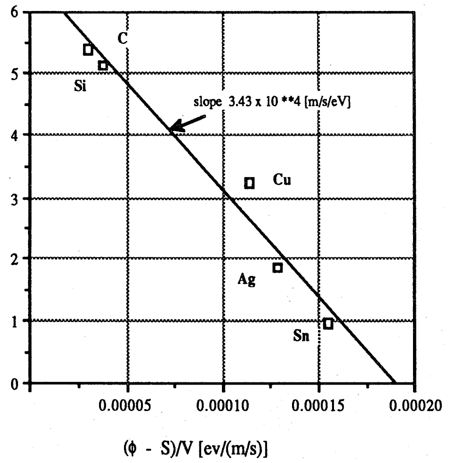

Fig.4 Measured negative ion formation probability

according to the theory of sputtering. Therefore, the negative ion formation probability on the cesiated substrate can be re-written as,

$$P = 2/\pi \ \exp[-C_1\pi(\phi-A)/h\gamma\, v], \qquad (2)$$

where $v=(2E/m)^{1/2}$ and m is the mass of the particle. According to eq.(2), the negative-ion formation probability for various species of atoms and molecules can be be estimated with the electron affinity and the sublimation energy for various species of atoms and molecules. This is very useful to predict the negative ion beam current from the sputtered type of negative ion sources.

In order to check the validity of eq.(2) experimentally, we made a measurement of negative ion formation probabilities for carbon, silicon, copper,tin and silver atoms and the coefficient $C_1\pi/h\gamma$ obtained in the present experiment was compared with the value taken by Yu.

Measurement of the negative ion formation probabilities for carbon, silicon, copper, tin and silver were made using the cusp negative heavy-ion source which has been developed at KEK recently.

The substrate used in the experiment consisted of carbon , silicon,copper, tin and silver plates of 0.5mm in thickness and it was attached on a mollibudenum metallic base. For such massive ions as tin and silver, the measured mass peak for each one was not well resolved because the resolving power of the analyzer became poor for heavy mass ions. Therefore, in order to estimate the relative intensities for tin and silver negative ions, the beam intensities data, which were previously measured for pure tin and silver sputtering probes at the same experimental condition[4], were used. The intensity ratio between tin and silver, ISn/IAg, measured in that experiment was 0.33.

In order to examine the velocity dependence of the negative ion formation probability indicated in eq.(2), the relative intensity for each species has to be normalized by the sputtering rate of each substrate atom.

Figure 4 shows the measured negative ion formation probability as a function of the particle velocity(v=(2E/m)1/2). This shows an exponential dependence of negative ion formation probability on the particle velocity as predicted by the theory. The gradient obtained from this figure shows that $C_1\pi/h\gamma = 3.4 \times 10^{-5}$eV m^{-1}sec and this value agrees well with the value measured by Yu for O^-ion.

CONCLUSION

Characteristics and performance of the newly developed negative ion sources have been described. More than 20 species of negative heavy-ion beams have been obtained so far at the ion source test stand and the beam intensities from the ion source were found to be almost 50-100 times larger than those from the ordinary cesium sputtered negative ion source. Beam emittance was also measured for a Ni beam and the 90% normalized emittance was about 37π mm.mrad.(MeV)1/2.

This ion source might be useful not only for nuclear experiments with a tandem accelerator but also for ion beam applications such as ion implantation.

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