PRODUCTION OF MULTIPLY CHARGED IONS BY A PULSED PIG SOURCE IN HIMAC

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Abstract

A pulsed PIG heavy ion source (duty factor of 0.05 - 0.5 %) has been developed for the injector (e/m < 1/7) of HIMAC. Peak yields of multiply charged ions are increased by a factor of 3 - 10 compared with DC operation. Present performance are a 120 μA of Ar^{6+} beam with an arc condition of 1.4 kV and 3 A, and a 30 μA of Si^{4+} beam with 920 V and 5A by bombarding a silicon single-crystal with Ar.

Introduction

The HIMAC facility has been presented in some places[1,2] and this conference. Two types of ion sources are provided in HIMAC. One is a PIG source mainly for light ion production and another is an ECR source mainly for heavier ion production than Ar. The results of initial test of our PIG source for lighter ions than Ne are satisfactory. So, the urgent purposes in PIG source development are two : one is to improve the yield of high charge state ions such as Ar^{6+}, and another is to improve the yield of sputtered ions especially with a low sputtering efficiency such as Si. These R&D have been carried out using a PIG ion source test bench since 1987. Source type is an indirectly heated one[3].

The basic characteristics of PIG discharge under DC operation and the performance of pulsed PIG source including sputter source are discussed in this paper.

Characteristics under DC operation.

Gas flow

The yields of Ar^{5+} - Ar^{7+} versus gas-flow (1.4 - 3.0 cc/min) are plotted in Fig.1. Fig. 1 shows that a gas-flow rate of 1.4 cc/min is close to an optimum. As the gas-flow increases, yields of higher charge state ions decrease rapidly. In the lower gas-flow than 1.3 cc/min, the arc plasma becomes unstable and the yield also decreases. In order to measure the depedence of yields only on gas-flow, arc current and arc voltage are kept to be 2 A and 800 V throughout the measurement by careful adjustment of the bombard current.

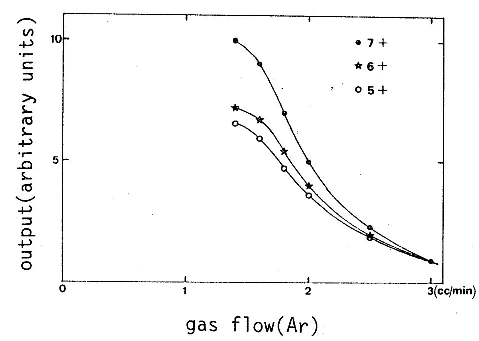

Fig.1. Yields of high charge state Ar ions as a function of gas-flow. All curves are normalized at 3 cc/min. Arc conditions (DC) are fixed to 800 V and 2 A.

Arc current

The yield of Ar^{4+} - Ar^{7+} versus arc current (1 - 7 A) are plotted in Fig.2. Arc voltagre and gas-flow are fixed to 550 V and 1.6 cc/min, respectively. The yield of Ar^{4+} increases nearly in proportion to arc current. The rate of increase for higher charge state ions (5+ - 7+) is larger than that of arc current. Since the arc current is roughly equal to the electron current from hot cathode, a high electron density is effective for the production of multiply charged ions.

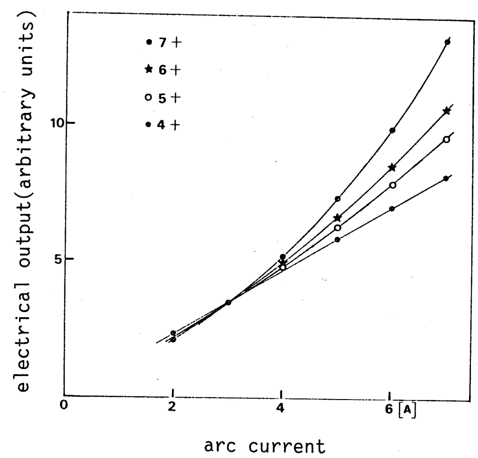

Fig.2. Yields of high charge state Ar ions as a function of arc current. All curves are normalized at 3 A. Arc voltage (DC) and gas-flow are fixed to 550 V and 1.6 cc/min.

Arc voltage

The yield of Ar^{5+} - Ar^{7+} versus arc voltage (300 - 1150 V) are plotted in Fig.3. Arc current and gas-flow are fixed to 2 A and 1.5 cc/min. Fig.3 shows that yields depend strongly on arc voltage. High energy

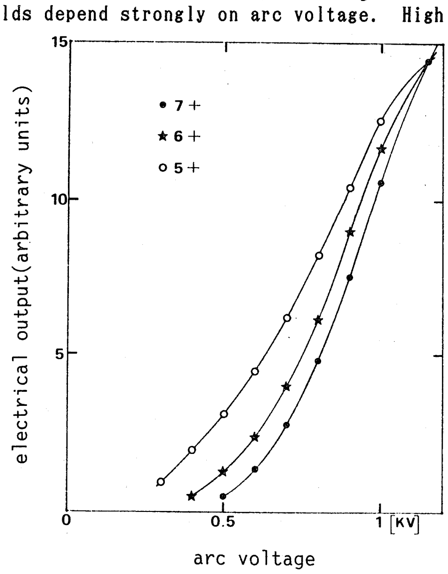

Fig.3. Yields of high charge state Ar ions as a function of arc voltage. All curves are normalized at 1150 V. Arc current (DC) and gas-flow are fixed to 2 A and 1.5 cc/min.

electrons can go through the discharge column many times untill they are trapped in plasma. High electron energy is important not only for ionizing the high charge state ions but also for increasing the effective electron density which results in many interactions with ions. The effective number of higher energy electrons increases rapidly as the arc voltage increases. Thus, the high electron energy is essential for the production of multiply charged ions.

Electrons

An average electron temparature in PIG-plasma is too low (to be lower than 15 eV[4]) to ionize the ions up to a high chatge state through step-by-step process. Therefore, only primary electrons contribute to the production of multiply charged ions. The required electron energy for $Ar^{5+} \rightarrow Ar^{6+}$ is more than 200 eV from the cross section[6]. We did not observe Ar^{6+} ions at arc voltage lower than 300 V (see Fig.3).

Primary electrons are accelerated by arc voltage when they across the thin sheath just before come into plasma. As soon as electrons enter the plasma, their energy has a plateau-shaped distribution between the temparature of plasma electrons and the intial energy of primary electrons by relaxation in plasma[4]. When the energy of electrons is as low as a few hundreds eV, this relaxation is completed before they reach the anti-cathode in their first travel, and there are very few higher energy electrons than 300 eV.

There must be a threshold voltage of around 300 V as can be seen in fig.3. When arc voltage is V_a and this threshold voltage V_i, experimental curves in Fig.3 fit well with the expression, $A_i\ (1-V_i/V_a)^i$, at V_a lower than 1 kV[5]. A_i is the constant depending on charge state, i.

We can roughly assume the ionization process for high charge state ion production as follows : The electron which encounters a neutral atom and loses its energy has no high energy to produce any ions more. The electrons have to survive without collisions with neutral atoms until the multiply charged ions are produced. Thus, low gas pressure is necessary to maintain a high electron density with high energy. On the other hand, a certain gas pressure is required for the production of plasma. An existence of the optimum gas-flow can be explained in this way. When the neutral atom density is N, experimental curves in Fig.1 fit well with the expression, $B_i\ N \exp(-N/N_i)$[5]. B_i and N_i are the constant depending on charge state.

Simulation of gas pressure

Calculation of gas pressure in the discharge column has been made by using a simplified model of the source and vacuum of the magnet chamber as shown in Fig.4. In low-duty pulsed operation, outgasing and sputtering by ions must be negligible, because the temparature of anode is not so high and the drift of ions is small. The magnet chamber is evacuated by a 1500 l/s TMP directly and a 400 l/s TMP through a beam duct 0.5 m in length and 100 mm ϕ. Gas-flow, conductance of the source and outgas from the surface of magnet chamber are taken into the calculation. When the Ar gas-flow is 1.5 cc/min, the pressure around the hot cathode is 2×10^{-3} torr and the pressure in the center of the discharge column is 0.9×10^{-3} torr which corresponds to a neutral atom density of $3 \times 10^{13}/cm^3$. Mean-free-path of electron with an energy of a few hundreds eV is evaluated to be about 100 cm in this pressure.

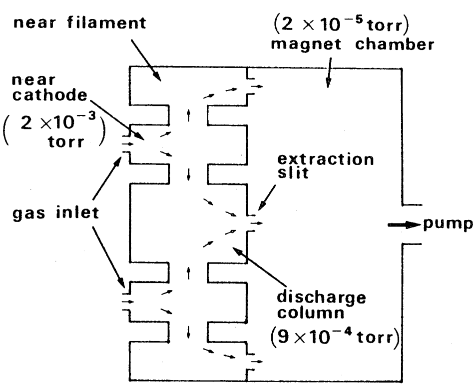

Fig.4. Model and results in the gas pressure simulation at Ar gas-flow of 1.5 cc/min.

Arc impedance

Arc impedance under DC operation becomes high as the gas pressure is lowered as shown in Fig.5. Polarity of arc impedance is positive at the lower arc current than 2 - 3 A, and negative at the higher current. In the range of 2 - 3 A, the plasma becomes slightly unstable. Under the DC operation of indirectly heated PIG source, high arc voltage and high arc current are not obtained simultaneously due to the low arc impedance (50 - 400 ohm). The arc voltage is normally 300 - 800 V.

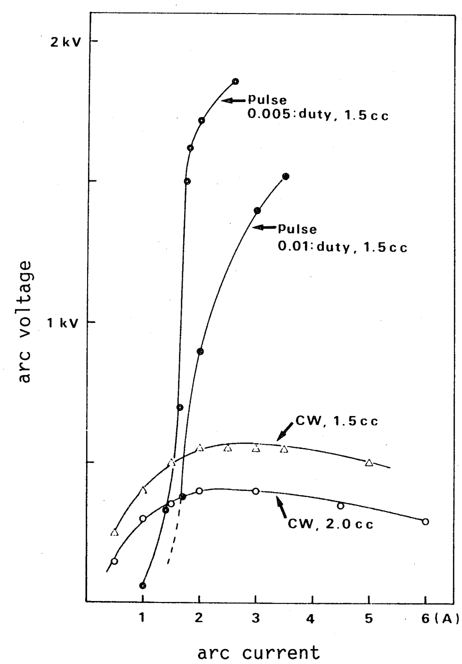

Fig.5. Arc impedances under DC and pulsed operations. Arc impedance is changeable in some degree by adjusting the bombard current.

Arc impendance under pulsed operation is positive and high (200 - 1000 ohm) depending on gas-flow and duty factor. High arc impedance allows the arc voltage to be high (1 - 2 kV), which is very effective for the production of multiply charged ions.

Results of pulsed operation

The photograph of pulsed beam waveform for Ar^{6+} is given in Fig.6. Peak yield is increased by a factor of 3 - 8 compared with DC operation. Such a high amplification can not be seen in the production of lower charge state ions than Ar^{3+}. During the first 200 μs, most of high charge state ions don't reach the wall yet and the wall recombination is little. This can be explained by the following fact. High bombard current, about 1.5 times higher than that with DC operation, is necessary to maintain the pulsed arc stably. In such a short time, the secondary electron emission by ion bombarding is little due to the small drift of ions. Since a definite electron density is required for stable plasma, an additional bombard power has to fill up this lack of emission. Therefore, we guess that the ion temperature is still low and the plasma is not sufficienty heated yet in the first 200 μs. Moreover, the ions can't move much more freely to the anode (wall) than to the cathodes[7], especially the high charge state ions can't do so. This will be a main reason for the high yield in pulsed operation.

From Fig.6, the ionization time is evaluated to be shorter than 100 μs. When the ionization process is ideally step-by-step, the ionization time, τ_i, is defined as follows by using a well-known expression.

$$\tau_i = \Sigma\ 1/\sigma_{i-1,i}\ n\ v \qquad (1)$$

Where, $\sigma_{i-1,i}$ is the cross section from charge state i-1 to i and n is the effective electron density and v the electron velocity. Mean-free-path of electron with an average energy of 700 eV (after relaxation) is estimated to be about 300 cm. The number of electron flight in the discharge column is 30 in this case. Since the electron current density, J_e(e n v), is to be 15 A/cm^2 at an arc current of 3 A, the real J_e reaches effectively 450 A/cm^2 in this case. $\tau_{5,6}$ is calculated to be 60 μs from the $\sigma_{5,6}$ of 5 x 10^{-18} cm^2. $\tau_{4,5}$ and $\tau_{3,4}$ are calculated to be 30 and 15 μs in the same way. $\tau_{2,3}$ and $\tau_{1,2}$ and $\tau_{0,1}$ will be negligibly short compared with these value, because the cross sections are large by one or two order and the real Je also becomes large by taking the plasma electrons into consideration. Thus, we can obtain τ_6 of about 100μs.

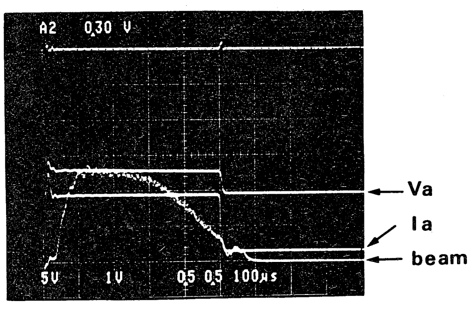

Fig.6. Pulsed beam waveform of Ar^{6+}. Peak intensity is 120 μA under duty factor : 1 %, arc voltage : 1.4 kV, arc current: 3 A and gas-flow : 1.5 cc/min.

Pulsed sputter source

Two kinds of support gas, Ar and Xe, have been tested to check their sputtering efficiency for Al, Cu and Si ions. There is no clear difference between them. A photograph of the pulsed beam waveform for Si^{4+} is shown in Fig.7. The ratio of the yield of Si^{4+} under pulsed operation to the DC case reaches about 10. A peak intensity of 30 μA of Si^{4+} has been obtained by bombarding a silicon single-crystal with Ar. Although the ionization time is estimated to be about 100 μs in Fig.7, it is complicated to explain its process.

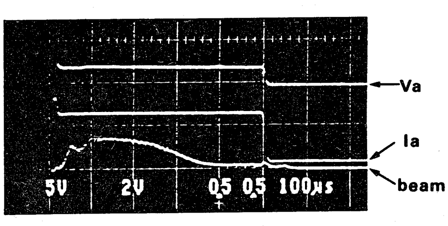

Fig.7. Pulsed beam waveform of sputtered Si^{4+} ions. Peak intensity is 30 μA under duty factor : 1 %, arc voltage : 920 V, arc current : 5 A and support gas (Ar) flow : 1.5 cc/min.

Near the sputter electrode, a sputtered atom density, N_s, is expressed as follows.

$$N_s = Sj_s/\varepsilon e(2E_s/m_s)^{1/2} \qquad (2)$$

Where, S is the efficiency of sputtering, j_s is the sputter current density, ε is the mean charge state of Ar ions, E_s is the bombard energy and m_s the mass of bombard particle. As a material of sputter electrode, we have used a silicon single-crystal with a conductivity of 450 ohm cm and an impurity density (mainly Boron) of 10^{12}/cm^3 . The size is 9 mm in wide, 50 mm in height and 20 mm in depth. Sputter current is 0.5 A which corresponds to J_s of 0.1 A from the surface area of 5 cm^2. When S is 0.5[8], m_s is 40, ε is 3 and E_s 900 eV, N_s is 1.6 x 10^{12}/cm^3.

The main evacuation from discharge column will be through the slit (6 cc/ms) and adsorption at the wall. These volumes per 200 μs are very small compared with that of column, 10 cc. The diffusion rate of sputtered atoms with a temperature of 3 eV is to be the order of a few tens μs in the column. In early stage of the pulse, a Si atom density will be uniform in the column and close to N_s, the order of 10^{12}/cm^3.

Conclusion

Characteristics of the low-duty pulsed operation of PIG plasma is distinctly different from that of DC one. Some features are 1) high arc impedance and 2) easy operation at a positive arc impedance region.

Only in first 200 μs after ionization time, we can obtain a 120 μA of Ar^{6+} and a 30 μA of Si^{4+} in sputter source. These intensities are higher than the obtainable under DC operation by a factor of 3 - 10. Beam pulse width of 200 μs is satisfactorily long compared with the injection time (150 μs) of synchrotron in HIMAC.

Acknowledgement

The authors wish to thank Dr. Y. Miyazawa(RIKEN) for useful discussions and the staff of NIRS cyclotron for their help during the measurement.

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