# Development of Intense Pulsed Heavey Ion Beam Diode Using Gas Puff Plasma Gun as Ion Source

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Abstract

A magnetically insulated ion diode with an active ion source of a gas puff plasma gun has been developed in order to generate a high-intensity pulsed heavy ion beam for the implantation process of semiconductors and the surface modification of materials. The nitrogen plasma produced by the plasma gun is injected into the acceleration gap of the diode with the external magnetic field system. The ion diode is operated at diode voltage $\approx$ 200 kV, diode current $\approx$ 2 kA and pulse duration $\approx$ 150 ns. A new acceleration gap configuration for focusing ion beam has been designed in order to enhance the ion current density. The experimental results show that the ion current density is enhanced by a factor of 2 and the ion beam has the ion current density of 27 A/cm$^2$. In addition, the coaxial type Marx generator with voltage 200 kV and current 15 kA has been developed and installed in the focus type ion diode. The ion beam of ion current density $\approx$ 54 A/cm$^2$ is obtained. To produce metallic ion beams, an ion source by aluminum wire discharge has been developed and the aluminum plasma of ion current density $\sim$ 70 A/cm$^2$ is measured.

## 1. Introduction

High-intensity pulsed heavy ion beam (PHIB) technology has been developed over the last two decades primarily for nuclear fusion and high energy density physics research [1]. One of most interesting topics is the application of PHIB to develop a unique pulsed energy source as a tool for the surface modification of materials [2,3]. Compared with conventional ion implantation, the PHIB process possesses high power density and short pulse width to rapidly melt, evaporate, or ablate a thin surface layer of treated materials at high heating and cooling rate of $10^8 - 10^{11}$ K/s. Due to the characteristics of PHIB technology, its application for the surface engineering currently focuses on two aspects, i.e. PHIB irradiation to modify the surface of materials [4–6] and PHIB ablation to deposit the thin film [7]. Especially for the implantation process, PHIB technique has received extensive attention as a new type of ion implantation technology, since the ion implantation and the surface heat treatment or the surface annealing can be completed in the same time [8].

The pulsed ion beams usually are generated in conventional magnetically insulated ion diodes (MID) with transverse magnetic field in the acceleration gap to suppress the electron flow and enhance the ion flow. The conventional MID, however, has the fault that the producible ion species is limited to the material of electrode and that the beam usually contains much quantity of impurity ions [9,10], since the surface flashover ion source is used. Therefore, the conventional pulsed ion diode is not suitable for the implantaton process. We have developed a new type of By type MID with an active ion source of a gas puff plasma gun in order to produce the PHIB with acceptable purity. The nitrogen ion beam with ion current density $\sim$ 13 A/cm$^2$ and the purity of the beam $\sim$ 85 % has been obtained at 55 mm downstream from the anode [11]. The ion current density, however, is not intense enough to apply PHIB to the implatation process.

A new electrode of ion diode for focusing ion beams has been designed and installed in MID to enhance the ion current density. We also have developed the coaxial type Marx generator with voltage 200 kV and current 15 kA as the pulsed power generator of ion diode. The generator has power energy enough to generate the high-intensity PHIB for the implantation process. In this paper, we report experimental results on the generation of nitrogen ion beam. In addition, the preliminary results of the experiment on the pulsed metallic ion source by a wire discharge are described.

## 2. Experimental Setup

A schematic configuration of the intense pulsed heavy ion diode system is displayed in Fig.1. The system consists of a high voltage pulsed power generator, a gas puff plasma gun, a $B_y$ type magnetically insulated ion acceleration gap (diode), and a stainless-steel vacuum chamber with a diffusion pump package. The vacuum chamber is evacuated to $5 \times 10^{-3}$ Pa. The pulsed power generator used in the experiment consists of a fast capacitor bank and a multi-turn step up transformer using magnetic cores of amorphous metal. The capacitor bank of maximum charging voltage 50 kV produces a high power pulse of pulse duration about 150 ns (FWHM) and the pulse voltage is magnified by the step up transformer with winding ratio 1:9. The output parameter of the generator is voltage 200 kV, current 2 kA and pulse duration 150 ns, which is applied to the anode of the ion diode.

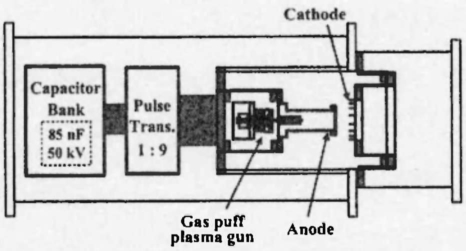



**Fig.1 Schematic of the Ion Diode System.**

Figure 2 shows the detail of the ion diode. The diode consists of a cylindrical anode of 115 mm length by 60 mm diameter at the top and a cathode of grid structure. The top of the anode is a copper plate, in which 37 holes of 5 mm diameter are drilled at the central area of anode in order to allow the source plasma to inject into the acceleration gap. The cathode has a grid structure to pass through the accelerated ions. The cathode also acts as a multi-turn magnetic field coil in order to generate a transverse magnetic field in the acceleration gap to insulate the electron flow and enhance the ion flow. Thus, as shown in Fig. 2, the cathode (coil) has a shape like 8-character and is made of phosphor bronze strip of 10 mm width and 1 mm thickness. The coil is powered by a capacitor bank of 250 $\mu$F and charging voltage 5 kV. By applying a pulse current of 10 kA with rise-time 50 $\mu$s, a uniform magnetic field of 0.8 T is produced in the gap.

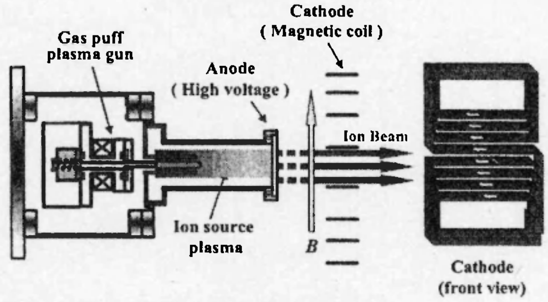



**Fig.2 Cross-sctional view of $B_y$ type MID.**

The gas puff plasma gun is used as the ion source in order to produce the pulsed ion beam with high purity and is installed inside the anode. The plasma gun consists of a coaxial plasma gun and a high-speed gas puff valve. The plasma gun has a pair of coaxial electrodes, i.e. an inner electrode of 80 mm length by 6 mm outer diameter and an outer electrode of 18 mm inner diameter. The inner electrode has six gas nozzles of 1 mm diameter. The gas puff valve consists of a nylon vessel, an aluminum valve and a driver coil. The vessel is pre-filled with $N_2$ gas up to 1.4 atm. By discharging the capacitor bank of 20 $\mu$F and charging voltage 5.5 kV, a pulsed strong magnetic field is produced in the driver coil, which pushes the valve. As a result, the valve opens quickly in the time order of 100 $\mu$s and the gas expands with a supersonic velocity and is injected into the plasma gun via the nozzles on the inner electrode. After the injection of the gas, the ion source plasma is produced by discharging the capacitor bank of the plasma gun with the optimal delay time, since it takes $\sim$ 150 $\mu$s to open the valve and several tens $\mu$s for $N_2$ gas to reach the gas nozzle on the inner electrode of the plasma gun. The ion current density of the plasma produced by the plasma gun is estimated to be 28 A/cm$^2$ by a biased ion collector (BIC) placed at $z$ = 90 mm downstream from the top of the plasma gun where the anode is placed in the acceleration experiment. The capacitor bank 3.3 $\mu$F for the plasma gun is charged up to 17 kV.

Figure 3 shows a schematic drawing of the focus type diode. The ion diode is basically same as the diode shown in Fig.2 but both the anode and the cathode have a spherical configuration to achieve geometrical focusing of the PHIB. The radii of curvature of the anode and cathode are 80 mm and 70 mm, respectively. In the experiment the acceleration gap length $d_{A-K}$ is adjusted to 10 mm. The diode voltage ($V_d$) and diode current ($I_d$) are measured by the capacitive voltage divider and Rogowski coil, respectively. The values of diode voltage and diode current is calculated by the ratio factor of the voltage divider 136000 and the coefficient of the Rogowski coil 27 kA/V. For the measurement of the ion current density BIC is used.

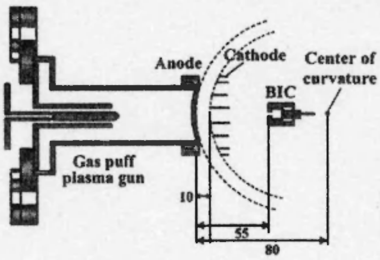
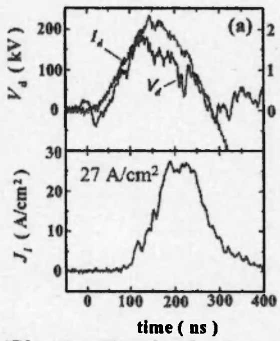



**Fig.3 Schematic drawing of focus type ion diode and experimental setup.**

## 3. Experimental Results

### 3.1 Focus type ion diode

In the acceleration experiment the high voltage pulsed power generator is fired at a delay time $\tau_d$ after the rise of the discharge current of the plasma gun. Figure 4(a) shows typical waveforms of the diode voltage ($V_d$), the diode current ($I_d$) and the ion current density of the accelerated beam ($J_i$) obtained with the focus type ion diode system. Here, the pulse power system is triggered at $\tau_d$=9.4 $\mu$s and $J_i$ is measured by the BIC placed on the axis at $z$ = 55 mm downstream from the surface of the anode. As seen in the Fig.4(a), $V_d$ rises in 100 ns and has a peak of 190 kV. On the other hand, $I_d$ rises with $V_d$ and have a peak of 2.2 kA at $t$ = 120 ns and after that decreases. It is observed from Fig.4(a) that the ion beam with $J_i$ of 27 A/cm$^2$ and pulse duration of 120 ns in FWHM is obtained at 160 ns after the rise of $V_d$. Considering the time of flight delay, the ion beam corresponding the peak of $J_i$ seems to be accelerated around the peak of $V_d$. For comparison, the experimental results obtained with conventional ion diode is shown in Fig.4(b), where $\tau_d$=12 $\mu$s. In case of conventional ion diode, the ion diode is operated at $V_d$=220 kV, $I_d$=2 kA and $J_i$ of 13 A/cm$^2$ is obtained, as seen in Fig.4(b). It is evident from comparison of Fig.4(a) and (b) that by using the spherical electrode, the ion current density is enhanced by a factor of 2.



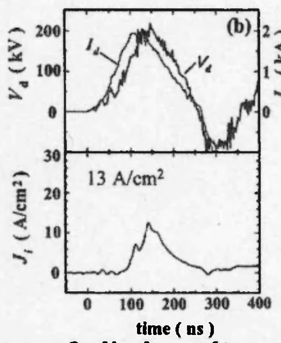




**Fig.4 Typical waveform of diode voltage $V_d$, diode current $I_d$ and ion current density $J_i$ obtained with (a) Focus type MID and (b) conventional MID, respectively**

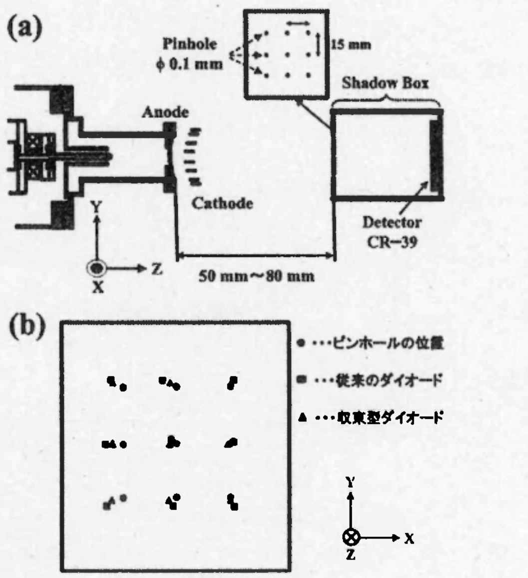



**Fig.5 (a) A schematic view of shadow box setup and (b) typical pinhole image of the ion beam obtained at $z$ = 50 mm.**

Figure 5 shows an arrangement of shadow box measurement and an example of shadow box image obtained at $z = 55$ mm. As seen in Fig.5(a), the shadow box consists of a multi-pinhole plate and an ion track detecting plastic of CR-39 placed at 10 mm behind of the pinhole plate. The pinhole plate consists of 9 pinholes of diameter 0.1 mm each at the interval of 15 mm as shown in Fig.5(a) Position of each pinhole and pinhole image obtained with the conventional MID are shown in the figure as the reference. We can see from Fig.5(b) that the divergence angle of the focus type MID is small compared with that of the conventional MID. Therefore, the enhancement of the ion current density is due to the effect of geometrical focusing of the PHIB by using the spherical electrode.

### 3.2 Ion diode installed coaxial type Marx generator

The ion current density is enhanced by using the focus type ion diode with the spherical electrode. The ion current density, however, is not enough for the material processes. Since the step up transformer is used to magnify the pulse voltage, the diode current is limited. Thus, the coaxial type Marx generator, which can supply both high voltage and large current, has been developed and installed in the intense pulsed heavy ion diode system in order to achieve ion current density enough for the material process. Both schematic view and circuit diagram of coaxial type Marx generator are shown in Fig.6. The circuit component of the Marx generator is shown in Fig.6(b). The generator has

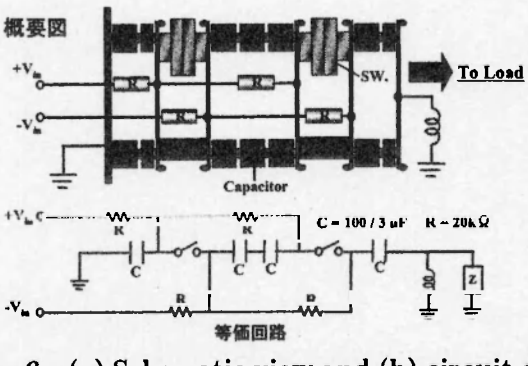



**Fig.6 (a) Schematic view and (b) circuit diagram of coaxial type Marx generator.**

basic characteristics of voltage 200 kV, current 15 kA and pulse duration 100 ns and is about 8 times higher output power than conventional one.

Figure 7 shows typical waveforms of diode voltage ($V_d$), diode current ($I_d$) and the ion current density ($J_i$) where the delay time $\tau_d$ between the plasma gun and the pulse power system is $\tau_d$=10 $\mu$s. Both ion diode system and measurement setup are the same as the focus type ion diode shown in Fig.3 except that the Marx generator is employed as the pulsed power generator. As seen in the Fig.7(a), $V_d$ rises in 75 ns and has a peak of 190 kV, whereas $I_d$ rises with $V_d$ and have a peak of 16 kA at $t$ = 80 ns and after that decreases. We can see from Fig.7(b) that the ion beam with current density of $J_i$ = 54 A/cm$^2$ and pulse duration of 80 ns(FWHM) is obtained at 30 ns after the peak of $V_d$. Considering the time of flight delay, the ion beam corresponding the peak of $J_i$ seems to be accelerated around the peak of $V_d$. It turns out from comparison of Fig.4 and Fig.7 that $I_d$ increases by 8 times, whereas $J_i$ is about 2 times as large as that of the focus type MID. Further investigations on optimal conditions are now undertaken.

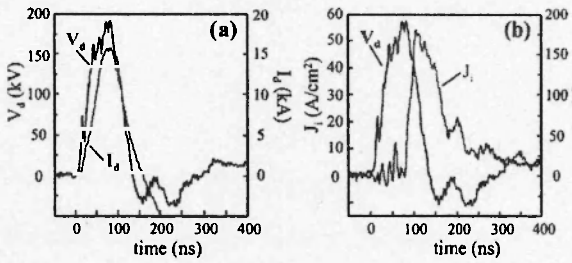



**Fig.7 Typical waveforms of (a) $V_d$, $I_d$ and (b) $J_i$.**

### 3.3 Development of wire discharge metallic ion source

Pulsed metallic ion beams has received extensive attention for the material processes, however they cannot be obtained yet. We have developed the vacuum discharge ion source as an intense pulsed metallic ion source [11,12]. The vacuum discharge ion source, however, cannot produce the stable metallic ion beam. For the purpose of obtaining the stable ion beam we are doing experiments on the wire discharge metallic ion source.

Figure 8 shows the experimental setup to evaluate the characteristics of the wire discharge ion source. An aluminum wire of 30 mm length by 0.1 mm diameter is stretched between two electrodes. Electrodes are connected to a capacitor bank through a gap switch. The capacitor bank of capacitance 1 $\mu$F is charged at 30 kV. The wire is melted, evaporated and ionized by the Joule heating to produce the ion source plasma. For the measurement of the ion current density and of the spatial distribution three BIC's are placed at 150 mm apart from the wire, as shown in Fig.8. The experiment is done in the vacuum of $5 \times 10^{-3}$ Pa.

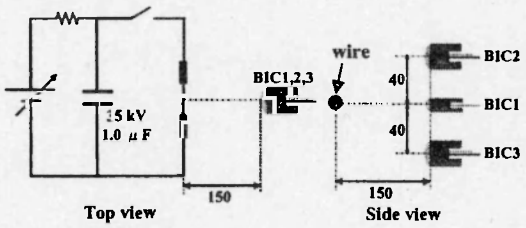



**Fig.8 Experimental setup of aluminum wire discharge ion source.**

Figure 9 shows the typical waveforms of discharge current ($I_a$) and ion current density ($J_i$) measured by BIC1 placed on the central axis. As seen in Fig.9, the discharge current $I_a$ has a sinusoidal waveform of peak current 11 kA and quarter cycle 2 $\mu$s. The ion beam of the peak current density $J_i$=65 A/cm$^2$ and pulse duration of 2 $\mu$s is observed at about $\tau_p$ = 6.5 $\mu$s after the rise of $I_a$.

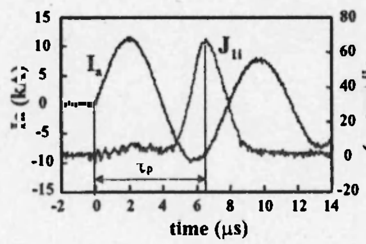



**Fig.9 Typical waveforms of discharge current ($I_a$) and ion current density ($J_i$).**

Figure 10 shows the dependence of the peak current density ($J_{ipeak}$) and the delay time ($\tau_p$) of $J_{ipeak}$ from the rise time of $I_a$. As seen in Fig.10, each $J_{ipeak}$ measured by BIC1, 2 and 3 has a scattering. Taking the result measured by BIC1 as an example, the average value of $J_{ipeak}$ in the 10 shots is calculated to be 67 A/cm$^2$, whereas the standard deviation is evaluated to be 14 A/cm$^2$.

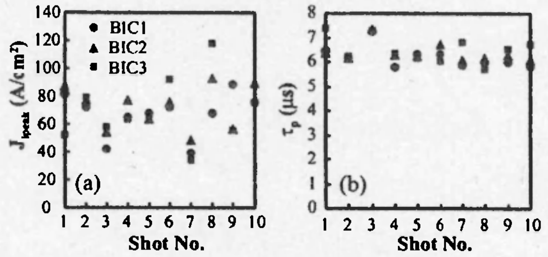



**Fig.10 Dependence of (a) $J_{ipeak}$ and (b) $\tau_p$ on shot number.**

On the other hand, $\tau_p$ is relatively stable and the average value of $\tau_p$ in the 10 shots is 6.2 $\mu$s. Each average value of $J_{ipeak}$ and $\tau_p$ and the standard deviation(SD) of $J_{ipeak}$ are summarized in Table.1. Those values of the vacuum arc discharge ion source are also shown as the reference. We can see from Table.1 that the SD of $J_i$ is 1 order of magnitude smaller than the vacuum arc ion source. The average current density decreases by a factor of 3 but is enough for the ion source. The experimental results also indicate that the ion beam has an almost uniform spatial distribution of the ion current density. This device is expected to be employed as the ion source for the intense pulsed metallic ion beam system.

**Table 1 Experimental results**

| | $J_i$ (A/cm$^2$) | $\tau_p$ ($\mu$s) | SD of $J_i$ |
|---|---|---|---|
| BIC1 | 67 | 6.2 | 14 |
| BIC2 | 72 | 6.4 | 15 |
| BIC3 | 69 | 6.5 | 22 |
| Vac. arc | 181 | 6 | 161 |

In order to evaluate the drift velocity of the plasma by a time of flight method (TOF), two BIC's are placed at 77 and 155 mm downstream from the discharge gap, respectively. The TOF delay time between of two BIC signals is 4 $\mu$s, which gives the drift velocity of $1.96 \times 10^4$ m/s. Assuming aluminum ions it corresponds to the ion energy of 54 eV.

## 4. Summary

We have develop the intense pulsed heavy ion beam diode with ion current density as large as ~50 A/cm$^2$ in order to apply PHIB to material processes For the purpose, two approaches to the enhancement of ion current density have been employed, i.e. the focus type ion diode and development of the coaxial Marx generator. When the plasma produced by the plasma gun is injected into the acceleration gap of the focus type ion diode, the ion diode is successfully operated at diode voltage $V_d \approx 190$ kV, diode current $I_d \approx 2.2$ kA and pulse duration $\approx 150$ ns (FWHM). The ion beam of ion current density $J_i = 27$ A/cm$^2$ is obtained at 55 mm downstream from the anode. By using the spherical electrode for focusing ion beam, the ion current density is enhanced by a factor of 2. When the coaxial Marx generator is employed as the power supply for the ion diode, the ion diode is operated at diode voltage $V_d \approx 200$ kV, diode current $I_d \approx 16$ kA, pulse duration $\approx 100$ ns and the ion beam of $J_i = 54$ A/cm$^2$ is obtained. We find that $I_d$ and $J_i$ increases by about 8 and 2 times compared to those of the focus type MID, respectively. We are currently investigating the optimal conditions to generate the ion beam with the expected ion current density.

We are developing the wire discharge metallic ion source in order to produce the intense pulsed metallic ion beam. The characteristics of the ion source are evaluated and the source plasma of current density $\sim 70$ A/cm$^2$ with the plasma drift velocity $1.96 \times 10^4$ m/s is obtained. The ion source is expected to be applied to the intense pulsed metallic ion beam system. There seems to be some room for making improvements including the electrode structure.

## Acknowledgement

This work is supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan.

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