Development of Bipolar Pulse Accelerator for Intense Pulsed Heavy Ion Beam

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A new type of a pulsed ion beam accelerator named “bipolar pulse accelerator (BPA) ”has been proposed to improve the purity of the intense pulsed ion beam. In order to confirm the principle of the BPA, we have developed a bipolar pulse generator and a prototype of the accelerator. When the bipolar pulse generator was operated at 70 % of the full charge condition, the bipolar pulse with the first (-138 kV, 72 ns) and the second pulse (+130 kV, 70 ns) was successfully obtained. The BPA system utilizes B_y type magnetically insulated acceleration gap and is operated with the bipolar pulse. When the bipolar pulse with voltage of about ± 100 kV and pulse duration of about 70 ns was applied to the drift tube, the ions were successfully accelerated from the grounded anode to the drift tube in the 1st gap by the negative pulse of the bipolar pulse and the pulsed ion beam with current density of 40 A/cm^2 and pulse duration of 30 ns was obtained at 50 mm downstream from the anode surface. In addition, part of the ion beam was again accelerated toward the grounded cathode in the 2nd gap by the positive pulse of the bipolar pulse. The pulsed ion beam with the peak ion current density of 2.1 A/cm^2 and the beam pulse duration of 30 ns was obtained at 30 mm downstream from the cathode surface.

Keywords: bipolar pulse accelerator, pulsed heavy ion beam, pulsed power technology

1. Introduction

An intense pulsed ion beam (IPIB), which has an ion energy of several 100 keV, a high ion current density of several 100 A/cm^2, and a short pulse duration of $< 1\mu$s, has been widely used for materials surface properties modification by the methods of ion implantation, ion plasma coatings deposition, and high energy ion beam energetic impact [1-3]. Compared with the traditional ion implantation method, the IPIB irradiation into materials enables the accumulation of energy in very short time into the near surface region while it maintains a low substrate temperature. The annealing by IPIB is expected to be novel annealing techniques, which do not require high temperature, for crystal damage recovering and electrically activating the dopants. Therefore, IPIB has received extensive attention as a tool for a new ion implantation technology named “pulsed ion beam implantation ”to semiconductor materials such as silicon carbide, since the ion implantation and the surface annealing can be completed simultaneously.

In order to meet the requirements of research and industrial application, a number of IPIB sources have been developed so far for different applications of IPIBs [4, 5]. The magnetically insulated ion diode (MID) is one of the most sophisticated one. The purity of the IPIB, however, is usually deteriorated by absorbed matter on the anode (flashboard) surface and residual gas molecules in the diode chamber, since the anode plasma is produced by a high-voltage flashover and an electron bombardment to the anode surface. For example, the pulsed heavy ion beam produced in a point pinch ion diode contains many kinds of ions including protons, multiply ionized carbons, and organic ions [6]. Thus, the conventional ion diode is not suitable for the application to the ion implantation.

To improve the purity of the intense pulsed ion beam, we have proposed a new type of pulsed ion beam accelerator named “bipolar pulse accelerator (BPA)” [7]. We have developed a bipolar pulse generator and a prototype of the accelerator to carry out proof of principle experiments on the BPA. The bipolar pulse generator consists of a Marx generator and a pulse forming line (PFL) with a rail gap switch on its end. The BPA employs a magnetically insulated ion diode with an ion source of a coaxial gas puff plasma gun. In this paper, we present the experimental results of the bipolar pulse generator and preliminary results of the ion beam acceleration by the BPA.

2. Principle of bipolar pulse accelerator

Figure 1 shows the conceptual diagram of the bipolar pulse accelerator. The BPA consists of an ion source, a drift tube and a grounded cathode. As seen in Fig.1, the BPA is an electrostatic two-stage accelerator. In the system, a bipolar pulse of voltage $\pm V_0$, duration τ_p each is applied to the drift tube. At first the negative voltage pulse of duration τ_p is applied and ions produced in the ion source are accelerated in the 1st gap toward the drift tube. The polarity of the pulse is reversed at $t = t_1$ and the positive voltage pulse of duration τ_p is applied to the drift tube. As a result, the ions are again accelerated in the 2nd gap toward the grounded cathode. The condition for the

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most effective acceleration is that the pulse duration τ_p is adjusted to the time of flight delay of the ion to pass through the drift tube, i.e., $\tau_p = L/v_i$, where v_i is the ion velocity in the drift tube and L is the length of the drift tube. This condition can be satisfied by adjusting the parameter of the bipolar pulse and the length of the drift tube. In addition, the merit of the BPA is that the ion source can be installed on the grounded anode, which extremely enhances the accessibility to the anode, while in the conventional PIB diode, the ion source is placed on the anode where the high voltage pulse is applied.

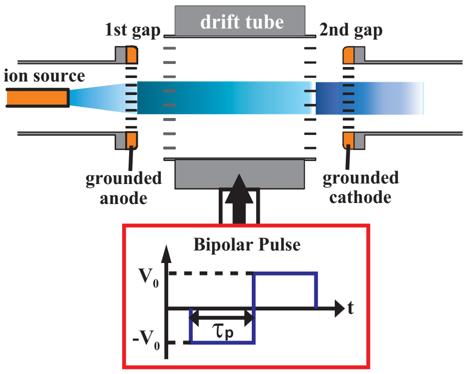

Fig. 1 Schematic view of bipolar pulse accelerator.

Figure 2 illustrates the principle of the improvement of the purity of the ion beam. Let us now consider the acceleration of ions in the case that the ion beam produced in the ion source consists of N^+ ion and impurity of H^+ ion. Each ion of N^+ and H^+ is accelerated in the 1st gap toward the drift tube when the negative voltage is applied, where N^+ and H^+ ion beams are schematically described in Fig. 2. As seen in Fig. 2, the length of H^+ beam is much longer than that of N^+ beam due to the difference of the velocity. We assume that the length of the drift tube is designed to be same as the beam length of N^+ beam with a beam pulse duration τ_p at an acceleration voltage V_0. It is, for example, calculated to be 11.6 cm when $V_0 = 200$ kV and $\tau_p = 70$ ns. On the other hand, the length of H^+ beam at $V_0 = 200$ kV and $\tau_p = 70$ ns is 43.3 cm. When the voltage is reversed and the positive voltage is applied to the drift tube ($t = t_1$),

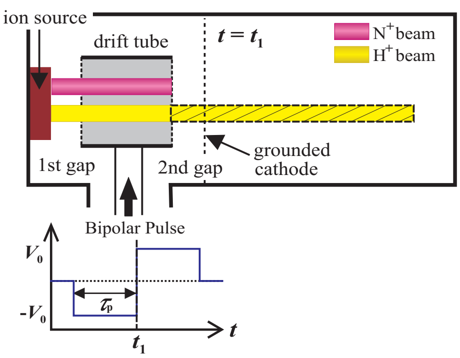

Fig. 2 Principle of the improvement of the purity of the ion beam.

N^+ beam with the length of 11.6 cm in the drift tube is accelerated in the 2nd gap. In contrast, 73 % of the beam is out of the drift tube and decelerated in the 2nd gap by the first pulse (negative voltage pulse). Hence 73 % of H^+ beam is not accelerated in the 2nd gap by the positive voltage pulse of the bipolar pulse and is removed in the bipolar pulse accelerator. As a result, the purity of the ion beam is improved.

Figure 3 shows in detail the acceleration gap design of the BPA. It consists of a grounded anode, drift tube and a grounded cathode. To produce insulating magnetic fields in both acceleration gaps, a magnetic field coil of grating structure is used, which produces a uniform magnetic field in longitudinal direction.

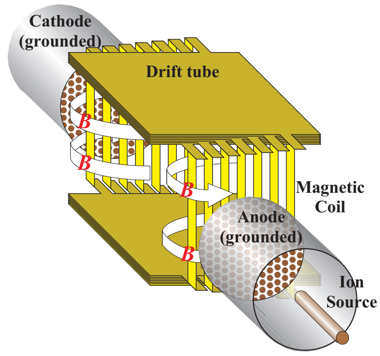

Fig. 3 Conceptual drawing of magnetically insulated gap of bipolar pulse accelerator.

3. Experimental Setup

Figure 4 shows the system of the bipolar pulse accelerator. The system consists of a grounded anode, a drift tube, a grounded cathode and a magnetically insulated acceleration gap (MIG). The anode and the cathode are the copper electrodes of diameter 78 mm, thickness 5 mm. The electrodes are uniformly drilled with apertures of diameter 4 mm, giving beam transmission efficiency of 58 %. The drift tube is connected to a high voltage terminal of a bipolar pulse generator. The magnetic coil of the MIG is installed on the rectangular drift tube and produces the uniform magnetic field of y-direction with strength of 0.3-0.4 T in the acceleration gap of gap length $d_{A-K} = 10$ mm. To obtain higher transmission efficiency of the ion beam, right and left sides of the coil (facing the anode or cathode) consist of 8 blades each and have a grating structure. Each of the blades (10 mm^W x 118 mm^L x 1 mm^T) is connected in series and works as an 8-turn coil. Since the high voltage pulse is applied to the drift tube, the pulsed current produced by the capacitor bank (500 μF, 5 kV) is applied to the coil through an inductively isolated current feeder (IC). The IC is a helically winded coaxial cable and the outer conductor of the IC is connecting the grounded vacuum chamber and the drift tube with inductance of 12.4 μH.

A gas puff plasma gun was used as the ion source in order to produce the pulsed ion beam with high

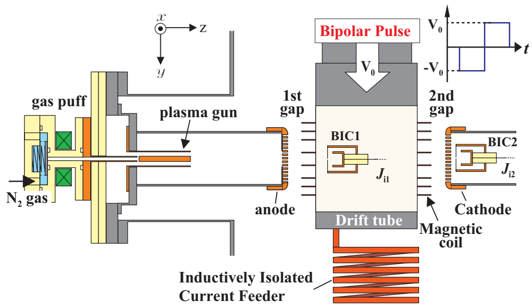

Fig. 4 Experimental setup of bipolar pulse accelerator.

purity and is installed inside the anode. It 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 2 atm. By applying a pulse current to the drive coil, a magnetic stress produced by the pulsed magnetic field presses the aluminum valve to open. As a result, the valve opens quickly in the time order of 100 μs 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 of τ_{PG} around 270-310 μs, since it takes about a hundred μs to open the valve and several tens μs for N_2 gas to reach the gas nozzle on the inner electrode of the plasma gun. To apply the pulsed current to the gas puff coil and the plasma gun, capacitor banks of 5 μF and 1.5 μF are used, respectively. Each capacitor is usually charged up to 6.5 kV and 20 kV, respectively.

Figure 5(a) shows the waveforms of the discharge current of the plasma gun (I_{PG}) and the ion current density (J_{ip}) of the plasma gun at the condition of τ_{PG}=292 μs. Here, the ion current density is measured by a biased ion collector (BIC) placed at 130 mm downstream from the top of the plasma gun where the anode is placed in the acceleration experiment. As seen in Fig. 5(a), the discharge current I_{p} has a sinusoidal waveform of peak current 6.5 kA and quarter cycle 2.6 μs. The ion beam with a peak current density J_{ip}=25 A/cm^2 and a pulse duration of 2 μs is observed at about τ_{p} = 7.5 μs after the rise of I_{p}. The result suggests that it takes 7.5 μs after the rise of the discharge current of the plasma gun (I_{PG}) for the ion beam produced in the plasma gun to reach the acceleration gap. Figure 5(b) shows the dependence of J_{ip} on the delay time of the discharge current rise from the rise of the gas puff current (τ_{PG}). As seen in Fig. 5(b), J_{ip} rises at $\tau_{\mathrm{PG}} \approx$ 270 μs and has a peak around 290 μs, and after that decreased. The result suggests that it takes 270 μs after the rise of the gas puff coil for the gas to reach the nozzles.

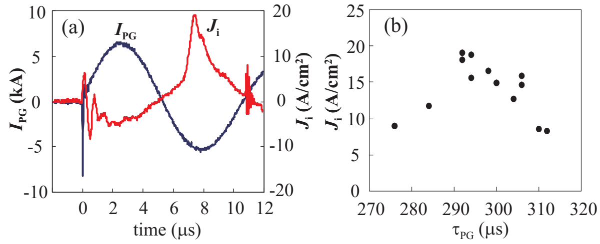

Fig. 5 (a) Typical waveforms of I_{PG} and J_{ip} and (b) Dependence of J_{i} on τ_{PG}.

Figure 6 illustrates the experimental setup of the bipolar pulse generator, which consists of basically a Marx generator, a PFL, a transmission line (TL) and a dummy load ($CuSO_4$ water solution). The designed output of the bipolar pulse generator is the negative and positive pulses of voltage ± 200 kV with pulse duration of 70 ns each. The line consists of three coaxial cylinders with a rail gap switch on the end of the line, which is connected between the intermediate and outer conductors. The PFL is filled with the deionized water as a dielectric and charged positively by the low inductance Marx generator with maximum output voltage of 300 kV through the intermediate conductor. The waveform of the bipolar pulse is very sensitive to the performance of the rail gap switch, that is, the rise time and the time to reverse the polarity are dependent on the system's inductance including the inductance of the output switch. In order to realize the bipolar pulse with the fast rising and reversing time, the multichannel rail gap switch is used as the output switch of low inductance. The rail gap switch is filled with pure SF_6 gas.

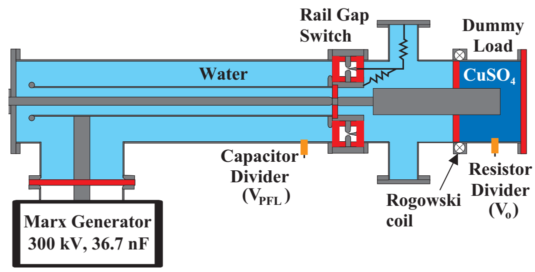

Fig. 6 Cross-sectional view of bipolar pulse generator.

Figure 7 shows the typical waveforms of the charging voltage of the PFL (V_{PFL}) and bipolar pulse output (V_0) at the charging voltage of 40 kV for the Marx generator. Here the filling pressure of the rail gap switch is 4.0 atm and the impedance of the dummy load is set at Z_L=7.5 Ω, which is almost same as the characteristic impedance of the line between the inner and intermediate conductors. As seen in Fig. 7, when the charging voltage of the PFL reaches the peak of 280 kV, the rail gap switch is self-broken at $t \approx 225$ ns and the square bipolar pulse, which consists of the first pulse with a voltage of -138 kV and a pulse duration of 72 ns (FWHM) and the second pulse with a voltage of +130 kV and a pulse duration of 70 ns (FWHM), is successfully obtained. The peak voltage of the first pulse is almost equal to the half of the maximum charging voltage of the PFL. In contrast the voltage of the second pulse is smaller. The reduction of the voltage in the second pulse seems to be due to the resistance of the rail gap switch.

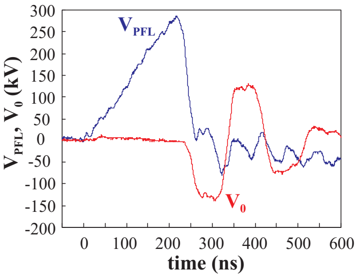

Fig. 7 Typical waveforms of V_{PFL} and V_0.

4. Experimental Results

In order to confirm the principle of the BPA, the bipolar pulse was applied to the drift tube. First, BIC was installed inside the drift tube to observe the ion beam accelerated in the 1st gap by the first pulse of the bipolar pulse, as seen in Fig. 4 The system was operated at 70 % of the full charge condition of the PFL. The plasma gun was operated at the condition of $\tau_{\mathrm{PG}} \approx 270$ μs and the PFL was fired at 5-10 μs after the rise of the I_{PG}. Figure 8(a) shows the typical waveforms of the output voltage (V_0), the output current (I_0) and the ion current density (J_{i}) accelerated in the 1st gap, where J_{i} was measured at 50 mm downstream from the anode surface. As seen in the Fig. 8(a), the first pulse of V_0 reaches the peak of 130 kV in 40 ns and the pulse duration is $\approx$ 65 ns. I_0 rises in 25 ns after V_0 is initiated, and reaches its peak of 9.5 kA within about 65 ns, whereas the ion beam with a current density of $J_{\mathrm{i}} = 40$ A/cm^2 and a pulse duration of 30 ns(FWHM) is obtained at 45 ns after the peak of the first voltage pulse. Considering the time of flight delay, the peak current density of 40 A/cm^2 corresponds to nitrogen ion (N^+, N^{2+}) and the ion beam corresponding the peak of J_{i} seems to be accelerated around the peak of the first pulse.

Next, BIC was placed at 30 mm downstream from the grounded cathode to measure the ion beam accelerated by the bipolar pulse. The experimental result is shown in Fig. 8(b). The peak value of the second pulse is 90 kV with a pulse width of about 60 ns, and the current I_0 rises about 35 ns after the second voltage pulse starts, to a maximum value of 3 kA. It can be seen from Fig. 8(b) that the ion beam with a current density of $J_{\mathrm{i}} \approx 2$ A/cm^2 and a pulse duration of 30 ns is obtained at 14 ns after the peak of the diode voltage. In the system, the length of the drift tube is designed to be same as the beam length of N^+ beam of duration 70 ns at acceleration voltage 200 kV. On the other hand, in the experiments the peak value of the accelerating pulse is $\approx$ 100 kV as seen in Fig. 8(b). When the polarity of the bipolar pulse is reversed, singly ionized nitrogen ions do not reach the 2nd gap. Thus, N^+ are not accelerated by the 2nd pulse of the bipolar pulse. Considering the time of flight delay, doubly ionized nitrogen ions and/or charge-exchange singly ionized nitrogen ions seem to be again accelerated in the 2nd gap.

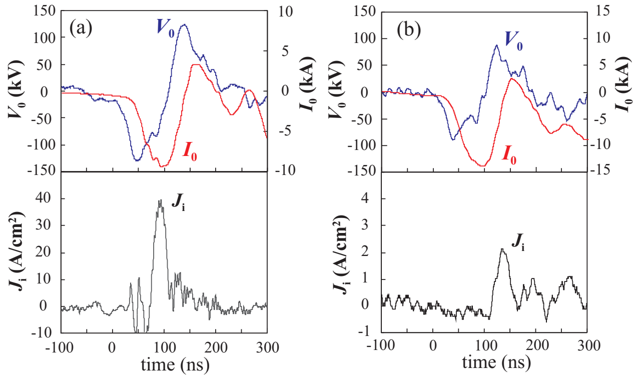

Fig. 8 Typical waveforms of output voltage (V_0), output current (I_0) and current density (J_{i}) observed in (a) 1-stage acceleration and (b) 2-stage acceleration.

5. Conclusion

We have developed a bipolar pulse generator and a prototype of the accelerator to perform proof of principle experiments on the BPA. The bipolar pulse with fast rise time and sharp reversing time was confirmed experimentally. When the bipolar pulse was applied to the drift tube, the ions were successfully accelerated in each 1st and 2nd acceleration gap by the bipolar pulse. To confirm the principle of the BPA, we are planning to evaluate the ion species and the energy spectrum of the ion beam in detail.

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