Aluminum Ion Implantation Using a Variable Energy RFQ Implanter

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Abstract

High energy aluminum ion implantation has been studied for power semiconductor device fabrications. A new MeV ion implanter system using a variable energy RFQ linac is developed and tested for pulse mode operation. The RFQ linac is driven by an r.f. resonance circuit having an external variable inductance coil and it is tuned so that the acceleration energy of aluminum ions is 0.9 MeV. The ions are implanted into 6-inch silicon wafers and the depth profile and dose uniformity are measured. Results show that this implanter can be operated stably for more than eight hours, and the depth and dose non-uniformity are 1.35 μm and 0.7 %, respectively. This system is useful for fabrication of semiconductor devices.

1 INTRODUCTION

A milliampere class MeV ion implanter has been studied for high dose implantation in the MeV energy range. This implanter contains a four-rod radio frequency quadrupole (RFQ) as an additional accelerator. Since the RFQ can accelerate ions of several tens of milliamperes, it is suitable for a high current MeV ion implanter. A new type of RFQ acclerator with an external variable inductance was developed because the output ion energy of the RFQ must be changed in various applications.

High energy ion implantation is one of the most important fabrication processes of ultra-large scale integrated circuits (ULSIs) [1-3]. In low voltage devices, required depth of implanted ions is several micrometers. On the other hand, high voltage semiconductor devices such as thyristors require a junction depth of over 50 μm. Since the diffusion coefficient of aluminum in silicon is about ten times larger than that of boron in silicon, aluminum ions are very useful for p-type dopants in high voltage devices.

So far, we have developed a new microwave multiply charged ion source [4], a high current ion injector to the RFQs [5], and a variable energy RFQ linac [6]. We were able to accelerate 1.0 MeV P^+ ions of 1.2 mA and 0.64 MeV B^+ ions of 0.24 mA [7] using this implanter.

In this paper, we describe the pulse beam acceleration using a variable energy RFQ linac. We also present the depth profile and dose uniformity results for an aluminum-implanted silicon wafer when pulse mode operation is operated.

2 EXPERIMENT

2.1 Experimental Apparatus

A schematic diagram of the high current MeV ion implanter is shown in Figure 1. This implanter is divided into three parts: a low energy beam transport, an RFQ linac, and a target chamber (end station).

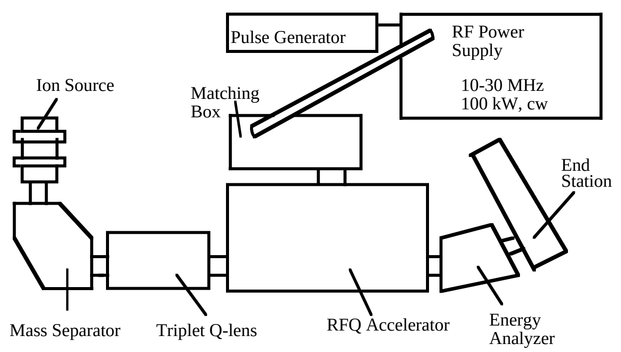

Fig.1 High current MeV ion implanter using a variable energy RFQ linac

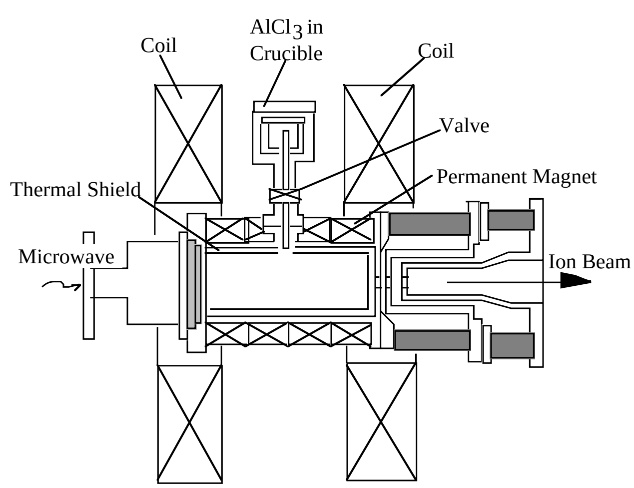

Fig.2 Schematic diagram of microwave ion source

(1) Low energy beam transport

The ion source is a microwave multiply charged ion source, which can extract a ten to twenty milliampere class of doubly charged ions [4]. A schematic diagram of the ion source is shown in Figure 2. It has a cylindrical plasma chamber (90 mm diameter) with a mirror and octopole magnetic fields. To introduce gases from solid materials into the plasma chamber, a crucible is connected with the ion source. A continuous 2.45 GHz microwave is introduced into the chamber along the axial direction. The ion beam is extracted from a multi-aperture electrode (7 holes, each 4 mm in diameter) with an extracted voltage of 12.0 kV.

The mass separator is a sector type mass analyzer. The deflection angle and beam transporting gap are 90^o and 60 mm, respectively. After mass separation, the beam is focused at the entrance of the RFQ electrodes by adjusting the lens strength of the magnetic quadrupole triplet. The beam injection system can focus a high current doubly charged ion beam of several milliamperes with a diameter of 10 mm [5].

(2) Variable energy RFQ linac

Figure 3 shows a variable energy RFQ linac with an external tunable one-turn coil. The RFQ electrodes are made of oxygen-free copper and are water-cooled along the center axis. The electrodes are supported by twelve ceramic blocks. RFQ electrodes designed for high current acceleration are used in the experiments. Their principal design parameters are summarized in Table 1.

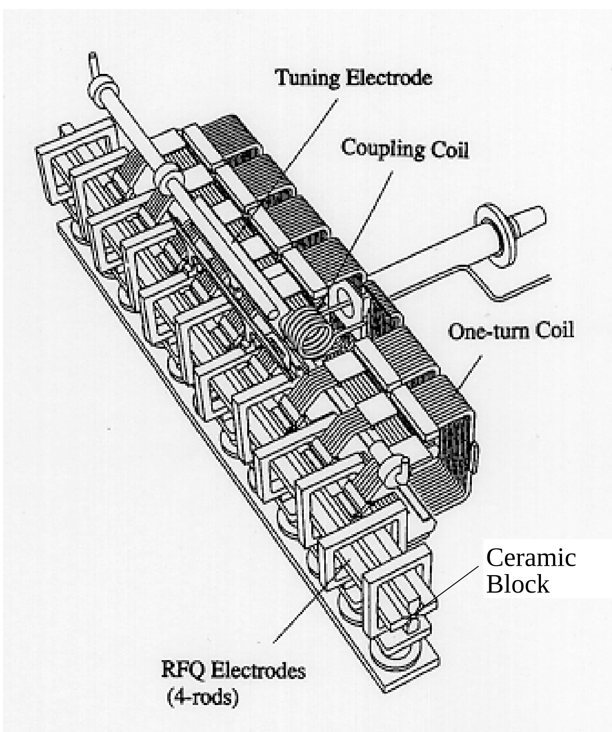

Fig.3 Variable energy RFQ linac using an external tunable one-turn coil

Table 1 Design parameters of the RFQ electrodes.

Frequency: f	21 MHz
Charge to mass ratio: q/A	1/31
Input energy: W_{in}	30 keV
Output energy: W_{out}	1103 keV
Normalized acceptance: ε_n	0.05 π cm mrad
RFQ vane length: L	230.96 cm
Number of cells: N	120
Intervane voltage: V_P	80.0 kV

RFQs have a capacitance of about 500 pF. For aluminum doubly charged ions (Al^{2+}), acceleration conditions at a drive frequency of 20.1 MHz are an intervane voltage (V_P) of 32.1 kV and acceleration energy of 0.9 MeV. Resonance frequency is tuned by changing the cross-sectional area or the length of the coils. The variable resonance frequency range is from 9.6 to 39 MHz. This value corresponds to an energy variation of 16 times.

An radio frequency (r.f.) power is introduced through a coupling coil (120 mm diameter) set at the center axis of the one-turn coil. Duty of the power supply can be varied from 10 to 100 %. Figure 4 shows an example of fluctuations in the main plate voltage of the power supply. In this measurement, rising and falling times of the pulse modulator are both set at 10 ms. The plate voltage jumps up at the falling time of the madurator due to an induced current. Since the maximun value of the plate voltage is 14.5 kV, rising and falling time must be larger than 10 ms. Repetition and pulse width of the beam are set at 1 Hz and 500 ms, respectively (50 % duty).

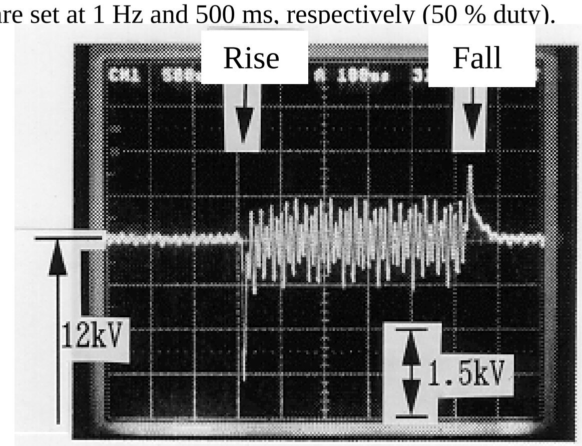

Fig.4 Fluctuations in main plate voltage of the r.f. power supply

(3) End station

The target chamber is set after a final 10^o bending magnet that can remove both low energy ion beams and charge exchanged neutral beams. Ten 6-inch wafers are held on the rotating disk. During implantation, the disk rotates at 560 rpm, while it is being simultaneously scanned in about 30 seconds in the vertical direction.

2.2 Implantation Tests

To evaluate dose uniformity and depth profile of the implanted aluminum ions, Al^{2+} implantation is carried out at an energy of 0.9 MeV ($1x10^{14}$ cm^{-2}) and 1.0 MeV ($1x10^{16}$ cm^{-2}), respectively. The dose uniformity is measured by sampling sheet resistance values after furnace annealing at 1000^oC for 30 min. A pulsed beam (0.9 MeV) is used to investigate effects on the uniformity. The depth profile is measured by SIMS (Secondary Ion Mass Spectroscopy). The profile is compared with the projected range (Rp=1.4 μm) predicted by the Monte Carlo simulation program TRIM [8] and with a profile calculated by assuming a Gaussian profile.

3 RESULTS AND DISCUSSION

3.1 Pulse Acceleration

Characteristics of the accelerated N^+ (0.53 MeV) beam are shown in Figure 5. The upper line (CH1) denotes the generated wave form of the pulse generator, and the lower line (CH2) denotes the N^+ beam current at Faraday cup set after the RFQ electrodes. The horizontal line is time (200 ms/Div.) and vertical line is voltage (CH1:500mV/Div., CH2:10mV/Div.). In the CH2 signal, the vertical line denotes the accelerated beam current (0.2mA/Div.), so the N^+ beam is calculated as 500 μA. The maximum N^+ beam obtained is 750 μA.

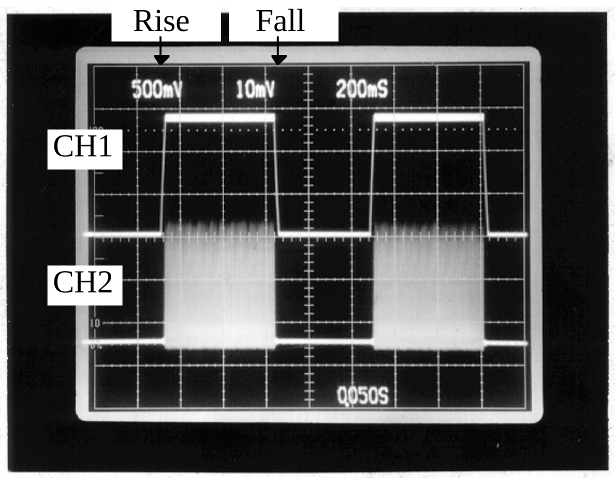

Fig. 5 Pulsed acceleration beam current wave forms of N^+ (0.54 MeV)

In this figure, it is obvious that the pulsed acceleration beam (CH2) is stable during the acceleration. The beam is accelerated when the acceleration voltage (CH1) just reaches the maximum, and the beam current is stable within 500 ms. Results of a long time operation test show that this implanter system can be operated stably for more than eight hours.

3.2 Depth Profile and Dose Uniformity

Figure 6 shows the depth profile obtained by SIMS. The measured Rp is 1.35 μm which is in good agreement with the predicted value, 1.4 μm. The profile tail is slightly spread compared with the calculated one. This is thought to be caused by the presence of a channeled component of the beam.

From the measurement of sheet resistance value, the dose non-uniformity is calculated as 0.7 %. It is comparable to that obtained using conventional implanters (<1 %). Thus, The machine can be used as a commercial implanter.

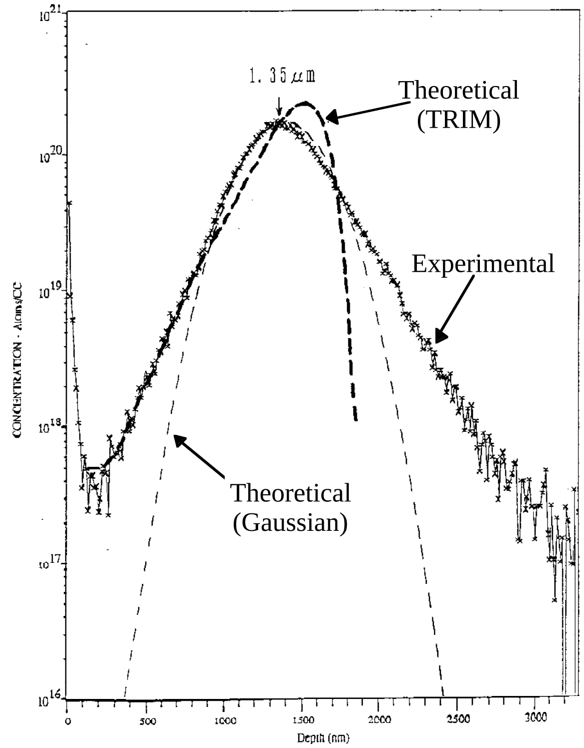

Fig. 6 SIMS profile of Al^{2+} (1.0 MeV) in Si.

4 CONCLUSIONS

The pulse mode acceleration of a MeV ion implantation was demonstrated using a variable energy RFQ linac. The result showed that the beam was stably accelerated for more than eight hours. From SIMS measurements, it was found that the depth profile had good agreement with the projected range (1.35 μm). The dose non-uniformity was 0.7 % with the dose of 1×10^{14} cm^{-2}.

It was concluded this high energy ion implanter using a variable energy RFQ linac should be very useful for fabrication of high power semiconductor devices.

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