Variable Energy RFQ for MeV Ion Implantation[1]

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Abstract

To obtain mA-class MeV heavy ion beams for ion implantation, a new variable energy RFQ system driven by an external LC-resonance circuit has been developed. Beam energy variation and high-current acceleration were demonstrated in a feasibility study. On the basis of the results, RFQ parameters to meet the final goal are discussed.

1. INTRODUCTION

MeV ion implantation has recently been applied to fabrication of ULSI memory devices such as 16-64Megabit DRAMs[1]. In addition, surface modification of materials due to MeV ion implantation is recognized as a very useful technique to improve erosion resistance or wear resistance.

Heavy ion beam acceleration using the conventional cavity-type RFQ accelerator has been reported[2]. However, the beam current obtained is usually limited to less than 0.4 mA and the acceleration energy cannot be continuously varied because of the constant operation frequency. Therefore, several attempts to vary the frequency have been reported[3,4].

In order to realize mA-class MeV implantation since 1987, we have been developing a variable energy RFQ driven by an external LC-resonance circuit[5,6]. Specifications of our final goal, to be met by March 1994, are listed in Table 1.

In this report, results to date on the development work on our variable energy RFQ are described. The RFQ parameters to meet the final goal are also discussed.

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Table 1 Specification of the final goal in our variable energy RFQ development.

(1) P ions(using P^{+}, P^{2+}, P^{3+})		
	Energy	0.5-4 MeV, Variable
	Current(average)	≥ 1 mA (2 MeV)
		≥ 0.25 mA(4 MeV)
(2) Ion species		
	Current(average)	
	P, As	≥ 1 mA (2 MeV)
	N, O, F, Al	≥ 0.5 mA (2 MeV)
	B, Ti, Mo, Ta	≥ 0.1 mA (2 MeV)

2. ACCELERATOR EXPERIMENTS

2.1. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig.1. The beam injection system consists of an

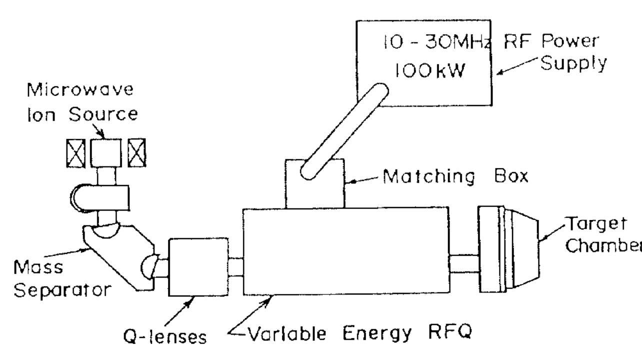


Fig.1 Schematic diagram of experimental apparatus.

Table 2 Principal parameters of the RFQ electrodes for the feasibility study.

Vane length	2.3 m
Frequency	15 MHz
Ion	N^+
Incident energy	35 keV
Output energy	541 keV
Intervane voltage	45 kV
Normalized emittance	0.05 πcm mrad
Min. bore radius	0.55 cm
Max. modulation	2.5
Focusing strength	- 0.45
Final synchronus phase	- 36.5
Transmission	
0 mA	81 %
3 mA	82 %
5 mA	77 %

ion source, mass separator and three-stage magnetic quadrupole lenses. The ion source is the new microwave ion source using a 2.45 GHz microwave discharge[7,8]. Mirror and octupole magnetic fields are superimposed onto the ion source plasma chamber. The source is designed to provide rather lower-charge-state, multiply charged ions. Ar^{2+}/Ar^+ ratio is about 1. In addition, the ion beams extracted from the source contain Ar^{2+} ions of about 10 mA in the range of 20 to 40 kV[7]. Metal ions are generated by connecting a vaporizer to the plasma chamber. In this microwave ion source, metal-halide materials are utilized as vaporized sample.

Three-stage magnetic quadrupole lenses are installed to adjust the beam emittance of the multiply charged ions. The RFQ accelerator contains water-cooled, 4-vane RFQ electrodes and an LC-resonance circuit. The principal parameters of the RFQ electrodes used in this experiments are listed in Table 2.

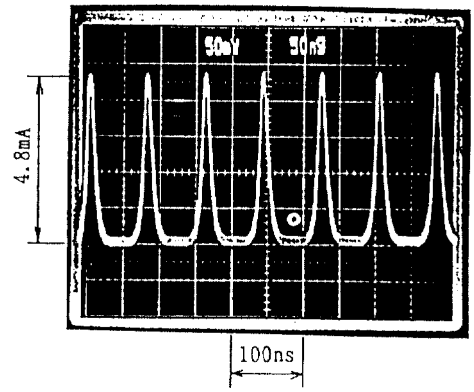
Two types of LC-resonance circuit have been developed to vary the frequency. One consists of a vacuum-capacitor (50-200 pF) and a one-turn copper coil. As a result, the total capacitance of the circuit equals the sum of the RFQ electrode and the vacuum-capacitor capacitance. The frequency can be continuously varied by adjusting the vacuum capacitor. Typical shunt-impedance of the circuit was 30 to 70 kilo-ohm[6], depending on the circuit structure.

The other circuit consists only of a variable inductance coil. The resonance frequency is determined from the coil inductance and RFQ electrode capacitance. In this circuit, the inductance is varied by changing the coil area mechanically.

The rf power from a 100 kW power supply is introduced into the LC-resonance circuit through a matching box. The frequency of the power supply can also be continuously varied from 10 to 30 MHz. Thus, the LC-resonance circuit generates an intervane voltage higher than 60 kV at 30-50 kW rf power.

To implant an MeV ion beam into 6" -diameter Si wafers, a target chamber for industrial use is installed. The chamber contains a rotating disk (720 rpm). Ten wafers can be mounted on the disk at the same time. Uniform implantation is accomplished by moving the disk along the radial direction while the beam remains stationary.

When the waveform of the acceleration current is measured, a 50-ohm impedance Faraday cup is installed instead of the target chamber.



Operation frequency	10.4MHz
Ion species	N^+
Output energy	0.4MeV
Average current	0.95mA

Fig.2 Waveform of accelerated N^+ beam current.

2.2 Results

In variable energy RFQ, the frequency and the intervane voltage are adjusted so as to satisfy the following equation:

$$(qV/M)^{1/2} f^{-1} = \text{constant}, \qquad (1)$$

where q, M, V, f are ion charge number, ion mass number, intervane voltage and operation frequency, respectively[5]. The acceleration energy is proportional to qV.

Energy variation experiments of N^+ and Ar^{2+} ions were carried out as a function of rf frequency. In this experiment, an RFQ electrodes 1.3m long were used. The N^+ and Ar^{2+} energies were continuously varied from 170 to 300 keV and from 500 to 740 keV in agreement with the calculated one, as reported before[6]. However, the acceleration current was less than 0.1 mA because of mismatching between the injected beam emittance and the designed RFQ acceptance. Thus, in anticipation of a current increase, acceleration experiments with 2.3 m RFQ electrodes (Table 2) were carried out.

The waveform of the bunched beam current was measured with a 50-ohm Faraday cup. A typical waveform for accelerated N^+ ions is shown in Fig.2. The accelerated beams were well bunched and peak current of the pulse beam is 4.8 mA. In Fig.2, average current indicates the effective value of the current and the value reaches about 1 mA. The data and Eq.(1) suggested that N^+ ions of mA current would be effectively accelerated to the MeV range when the frequency and the resulting intervane voltage were set at about 21 MHz and 90 kV, respectively.

In Fig.2, the experiment was carried out at 10.4 MHz, which differed from the designed frequency. This was because the LC-resonance circuit containing the vacuum-capacitor had an unexpected high inductance due to long feed lines. Replacement with a variable inductance circuit is now in progress.

In addition to N^+ ion acceleration, an Ar^{2+} beam acceleration test was also carried out. Ar^{2+} beams were accelerated to 0.74 MeV and the current reached 0.6 emA (in electric mA). The acceleration characteristics obtained to date are summarized in Table 3. The variable energy RFQ system driven by an

Table 3 Summary of beam acceleration results to date.

Beam energy	
Kr^{4+}	1.6 MeV
Ar^{2+}	0.5 - 0.74 MeV(variable)
P^{+}	0.56 MeV
N^{+}	0.1 - 0.3 MeV(variable), 0.4 MeV
Beam current (effective value)	
Ar^{2+}	0.6 emA(0.74 MeV)
P^{+}	0.45 mA(0.56 MeV)
N^{+}	0.98 mA(0.4 MeV)

external LC-resonance circuit has good potential for mA-class MeV ion implantation.

3. RFQ DESIGN FOR FINAL GOAL

In our RFQ development, beam energy variation from 0.5 to 4 MeV will be accomplished by using P^{+}, P^{2+} and P^{3+} ions in the range of 10 to 30 MHz. Since the acceleration energy is proportional to qV(i.e. Mf^2), RFQ electrodes for the final goal should be designed so that P^{3+} ions are accelerated to 4 MeV under conditions of both maximum intervane voltage and maximum operation frequency. This means that P^{+} ions must be accelerated to 1.33 MeV at 17.3 MHz under the same maximum intervane voltage. On the basis of these considerations, new RFQ electrodes for the final goal were designed having the principal parameters listed in Table 4.

By using the new RFQ electrodes, many kinds of ions can be accelerated to the MeV range. Fig.3 relates ion species and the operation frequency as a parameter of acceleration energy. All ions other than Ta can be accelerated to 2 MeV in the range of 10 to 30 MHz.

The new RFQ electrodes and a variable inductance LC-resonance circuit have been installed in the accelerator chamber and beam acceleration tests are now in progress.

Table 4 Principal parameters of the new RFQ electrodes for the final goal.

Vane length	2.3 m
Frequency	17.3 MHz
Ion	P^{+}
Incident energy	34 keV
Output energy	1,345 keV
Kilpatrick factor	1.951
Intervane voltage	90 kV
Normalized emittance	0.05 πcm mrad
Min. bore radius	0.55 cm
Max. defocusing strength	- 0.44
Final synchronous phase	- 30.1
Transmission (500 particles simulated)	
2 mA input	93.2 %(1.9 mA output)
5 mA input	86.4 %(4.3 mA output)
10 mA input	59.6 %(6.0 mA output)

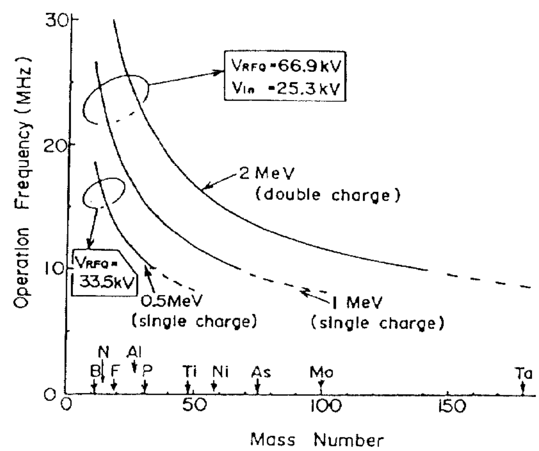


Fig.3 Operation conditions for ion acceleration using the new RFQ. V_{rfq} and V_{in} are intervane voltage and beam extraction voltage from ion source.

4. ACKNOWLEDGEMENTS

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