Development of low energy ion beam system for space charge compensation experiments[a)]

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A low energy ion beam system for space charge compensation (SCC) experiments was developed and evaluated. This system was designed for observation of SCC of a positive ion beam with an electron beam. The system consisted of the ion source chamber and the SCC experiment chamber. The ion source chamber was equipped with the compact microwave ion source for low voltage extraction. Ion current at initial position of the analysis chamber was 84 μA at extraction voltage of 500 V, and satisfied a condition to observe the SCC effect clearly. In order to evaluate the SCC, we measured the arrival ion current by supplying thermionic electrons, which were extracted from a tungsten filament driven by ac voltage. As the electron supply, the arrival ion current increased from 40 to 68 μA at the potential of filament of +3 eV which produced the thermionic electron with extremely low energy extracted by space charge of the ion beam. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2801549]

I. INTRODUCTION

As integrated circuits are becoming smaller, beam energy is becoming lower in ion implantation process, which is the essential technique to introduce impurity atoms in semiconductor devices. According to the International Technology Roadmap for Semiconductors (ITRS), the implantation energy of boron ions will become less than 200 eV for a high current implanter, which corresponds to junction depth of source/drain extensions after the 32 nm technology node.[1,2] Transportation of a high current ion beam with low energy results in the divergence of the ion beam due to its huge space charge.[3] Space charge compensation (SCC) of the positive ion beam by supplying with well-controlled electrons is necessary. We have proposed that the field emission arrays made of silicon (Si-FEA) will be a possible candidate for the SCC device, because they are free from metal contamination and have less outgas.[4] However, SCC experiments for detailed discussion of such extremely low energy ion beam using a electron emitter are few, even those using a thermionic electron source. In order to realize the SCC device, it is necessary to develop a system in which the details of the SCC process can be analyzed. In this study, we developed a low energy ion beam system which is suitable for use in the SCC experiments, and preliminary measurements investigating the properties of charge-compensated ion beam were performed. Moreover, compensation of the ion beam by using a thermionic electron source has been also demonstrated.

II. DESIGN OF SCC SYSTEM

In order to observe SCC of ion beam with low energy in several hundreds eV, two specific conditions are inevitably required. One is the formation of the parallel beam before the charge compensation. The ion beam is required to have a large current as its space charge rules its behavior. The other is high vacuum which makes it possible to observe the SCC effect without electrons produced by charge change between the ions and the residual gas. The high vacuum is also necessary for ion implantation to evaluate a precise dose because charge loss resulting from charge exchange due to particle collision is prevented in such a high vacuum. A typical commercially available ion implanter has a field-free space with the length of about 500 mm, which is the distance from a collimator magnet to a wafer target. As we intend to transport parallel ion beam with low energy in the ion implanter, the SCC experiment system must have a vacuum chamber with the length of at least 500 mm, in which some electron sources and analyzing device are installed.

Figure 1 shows the schematic diagram of the low energy ion beam system for the SCC experiment developed in this study. This system consists of two chambers, which are an ion source chamber (IC) and an analysis chamber (AC). The IC is electrically floated to accelerate the low energy ion

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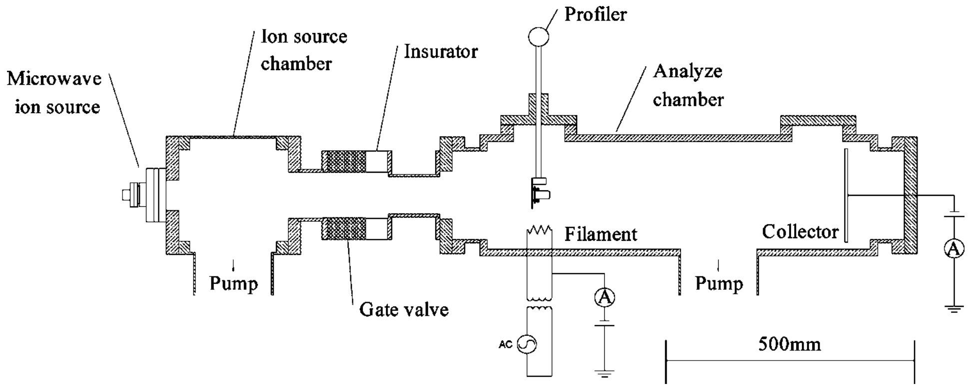

FIG. 1. Schematic diagram of the low energy ion beam system for space charge compensation experiments.

beam and is also designed with a space sufficient to install an electrostatic lens. A compact microwave ion source designed for low voltage extraction was selected as the ion source.[5] This ion source is suitable for the SCC experiment because it can extract a high current ion beam at desired voltage by adjusting the gap and the extraction electrodes. Details of the ion source is described elsewhere.[5,6] The IC is separated from the AC to achieve the operating pressure as low as possible to evaluate the SCC. The IC and the AC are evacuated individually by 500 l/s turbomolecular pumps and are connected with a long tube for differential pumping. In order to use the Si-FEA for SCC in the future, the operating pressure must at least be less than half of 10^{-3} Pa. It is possible to maintain the operating pressure of the AC by using various tubes with desired vacuum conductance. When a tube with 20 mm diameter and 200 mm length was used, the pressure achieved was 2.0×10^{-4} Pa. The tube is connected to the IC and can be isolated from the ground potential in order to transport ion beam efficiently with high energy and decelerate at the AC. The size of AC is designed as 770 mm long and 230 mm height and width.

Our purpose is to investigate the SCC phenomena with field emitted electrons. However, in this study, preliminary experiments were done with a conventional thermionic electrons. A tungsten filament with a diameter of 0.4 mm is used for an electron source for the SCC experiment. The filament current is controlled by using a variable autotransformer connected with 60 Hz ac power supply.

Before the SCC experiment, it is necessary to estimate how much ion current is needed to cause beam divergent by space charge. Trajectory equation of cylindrical ion beam with space charge is given by Gauss's law, as shown below,[3]

$$\frac{d^2r}{dz^2} = \frac{1}{2r}\frac{I_0}{V_0^{3/2}2^{3/2}\pi\epsilon_0}\sqrt{\frac{m}{q}}, \tag{1}$$

where r is the beam radius, I_0 is the beam current, V_0 is the acceleration voltage, ϵ_0 is the vacuum permittivity, m is the ion mass, and q is the charge. According to the estimation in Ref. 3 which is based on Eq. (1), space charge effect has the dominant influence on beam shape when the beam current is 10 μA class under the following conditions: ion specie consisting of only Ne^+, beam energy of 500 eV, and initial radius of 40 mm.

III. ION BEAM CHARACTERISTICS

Ion beam characteristics were measured with neon gas. The SCC system was evacuated by turbomolecular pumps to 1×10^{-5} Pa. It is unnecessary for the thermionic electron source to operate in vacuum as high as what field emitters need. Also, a convergent lens was not installed due to simplification of the SCC system. Thus, a diameter of the differential pumping tube was maintained of 80 mm in order to keep the current as large as possible. A 2.45 GHz microwave generated by a magnetron was supplied to the ion source. Extracted ion current was measured by a large collector plate with a 200×200 mm^2 at the IC ($L=150$ mm) and at the initial position of the AC ($L=660$ mm).

Figure 2 shows the relationship between the collector current and the extraction voltage. In this figure, the total extracted currents are also illustrated. The microwave input power was 30 W. The flow rate of neon gas was maintained at 2.0 CCM (CCM denotes cubic centimeter per minute). The pressure was 7.4×10^{-3} Pa at IC and 2.1×10^{-3} Pa. In this figure, open circles show the characteristics for the extracted ion current, and solid circles show ion current that reached the AC through the differential pumping tube with 80 mm diameter. We obtained the ion current of 84 μA at the AC at the extraction voltage of 500 V. The above mentioned current is sufficient to perform the SCC experiment. It

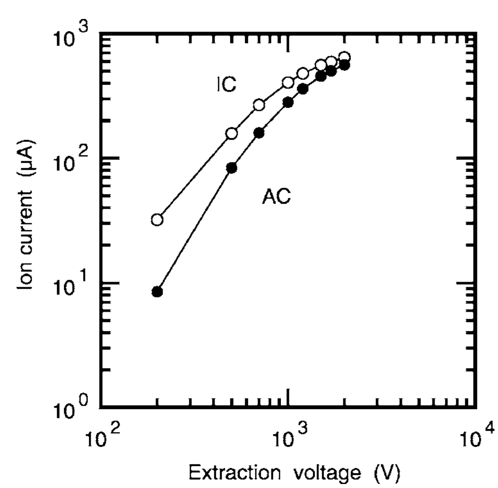

FIG. 2. Emission ion current and arrival ion current as a function of extraction voltage.

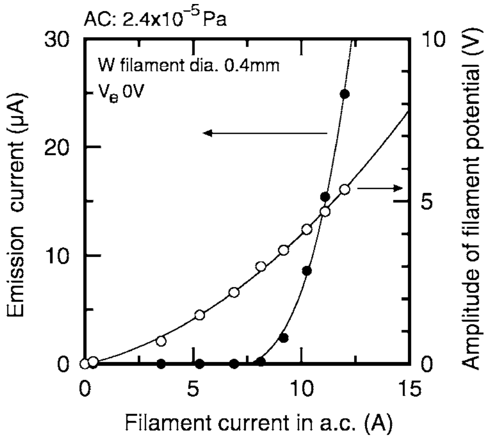

FIG. 3. Averaged emission current and amplitude of filament potential as a function of filament current driven by ac power supply.

is thus expected that the arrival ion current will increase if thermionic electron compensates the space charge of ion beam.

IV. SCC EXPERIMENTS

Figure 3 shows the electron emission current and the amplitude of filament potential as a function of filament current. In this study, the electron emission current was measured as an averaged value because the electron is extracted during negative potential of the filament as if the current was rectified. This was also actually checked by the measurement with an oscilloscope. These data were measured in the AC without an ion beam. Since the electron current was controlled by changing an ac voltage, the energy of emission electron increased with increasing electron current.

Figure 4 shows the wave form of arrival ion current and the filament potential. Here, the filament current was maintained of 10.2 A. Solid lines show a case of thermionic electrons supplied, and dashed lines show a case of without supply. A slight oscillation of 60 Hz in the arrival current was observed when without electron supply. This is due to the noise from commercial electricity. The electron current with ion beam was larger than that without ion beam, as shown in Fig. 3 and the difference was about 23 μA. When the thermionic electron was supplied, the arrival ion current increased from 40 to 68 μA maximum instantaneously and the maximum was observed at the filament potential of about +3 V. In contrast, a slight increase of arrival ion current was shown at minus filament potential.

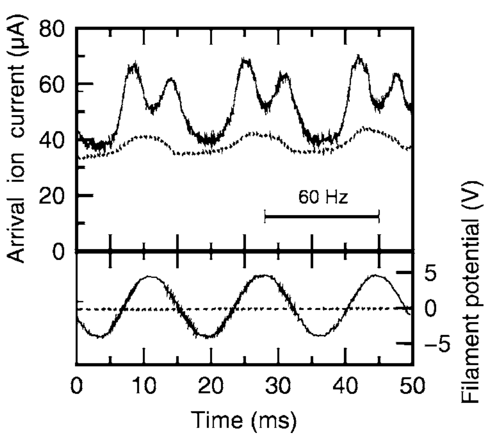

FIG. 4. Wave form of arrival ion current (upper graph) and filament potential with supplying thermionic electron (bottom graph). Solid lines and dashed line represent a case of without electron supplied and case of with electron supplied, respectively. The filament current was 10.2 A in the latter case.

V. DISCUSSION

The difference between the electron currents of ions in Figs. 3 and 4 was probably came from the existence of positive space charge. The positive space charge of ion beam can extract low energy electrons, even if the filament voltage was slightly positive. In Fig. 4, we observed the maximum instantaneous arrival ion current at the filament potential of +3 V. Generally, the space charge of electron Q is described as $Q=I_e/\sqrt{2eV_0/m_e}$. This indicates that SCC effect is most enhanced when there is large electron current and low energy. It seems that the ion beam was compensated by the large negative space charge related to the filament potential of +3 V. As a result, it is considered that the increase of arrival ion current by the effect of SCC was observed. From this result, it was found that we have developed a low energy ion beam system to do the SCC experiment.

VI. SUMMARY

A low energy ion beam system for space charge compensation experiments was developed and the performance was evaluated. We obtained the ion current at the start of the AC to be satisfied in order to observe the SCC effect clearly. From the SCC experiment, by using a thermionic electron, increases of arrival ion current caused by the effect of SCC were observed. The results indicate that the low energy ion beam system we developed has a good performance to be able to do SCC experiment.

ACKNOWLEDGMENT

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