Proposal for Emitter Shape to Obtain Higher Ion Current of Gas Field Ion Source*

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The emitter shape dependence of the ion current from a gas field ion source (GFIS) was examined using numerical simulations. The simulator is constructed by an electric field calculation program and the spread sheets which were developed by authors based on the gas supply model. The gas supply for Ar was examined in this article, and was compared with that for He. As a result, when using the same emitter, it demonstrated that the effective capture area of Ar gas is 6.8-8.0 times larger than that of He. For a gas temperature of 300K, the effective capture area of Ar and He were estimated to be 0.0814 and 0.0107 µm², respectively. It was also estimated that the ion current of Ar was 2-2.3 times larger than that of He. Through an actual experiment, a similar tendency was confirmed. For Ar, the influence of the shank taper angle to the ion current was confirmed and that influence is more effective than He. The emitter of small shank angle is capable of higher ion current. Therefore, it was concluded that the ion current can be increased through optimization of the emitter configuration. [DOI: 10.1380/ejssnt.2010.174]

Keywords: Computer simulations; Field ionization; Ion emission; Field ion microscopy; Adatom gas

I. INTRODUCTION

It is expected that the focused ion beam (FIB) system equipped with a gas field ion source (GFIS) realizes a beam diameter of the sub-nanometer level. Helium GFISs are now employed in scanning ion microscopes [1], but have the disadvantage of a low beam current. In order to increase the beam current of GFIS it is necessary to supply many source gases to the ionization area on the tip apex. For this purpose, the effective capture area of gas molecules around the emitter must be enlarged. The size of the effective capture area depends on emitter shape and size. It was reported that the ion current is proportional to the square of the tip base radius for the emitter with a protrusion on the apex [2]. However, the shank shape of the emitter remains a matter of research for obtaining a higher ion current. The authors studied the effect of a shank taper angle on the ion current for helium [3,4]. In general, high mass gas species are used to improve processing efficiency of the ion beam sputtering. Therefore the gas supply for Ar is examined in this article and compared with that of helium. The gas species dependence and the emitter shape dependence of the ion current are examined using numerical simulations.

II. SIMULATION MODEL

The simulator is constructed by an electric field calculation program and the spread sheets which were developed by authors based on the gas supply model. The gas supply theory was proposed by Southon [5]. However, the application to a specific shank shape is not reported.

The gas molecules have polarization potential energy (PPE) \( (1/2)\alpha F^2 \) in electric field, where \( \alpha \) is the gas molecules polarizability and \( F \) is the field strength. It is assumed that the velocities of the gas molecules defer to Maxwell distribution. The following arguments are performed with mean value. Around the emitter, one of the axes of the local three-dimensional coordinate is defined in direction of electric field. And two other axes are defined on the plane that is perpendicular to direction of the electric field. In the electric field axis, the one-dimensional thermal equilibrium energy (TEE) of gas molecules at temperature \( T \) is \((1/2)kT\), where \( k \) is Boltzmann's constant and is compared with PPE. The TEE components along two other axes do not contain the components that turn the gas molecules toward the emitter surface. The calculation of the gas flux density is performed with mean value of the velocities of the gas molecules. Therefore, we can get mean value of the number of gas molecules that are supplied from gas phase for emitter surface.

The space around the emitter is divided into three parts as shown in Fig. 1. It is well known that the gas molecules...
are attracted into the area around the emitter by polarization force when the condition $PPE > TEE$ is satisfied [5]. The space where the condition $PPE < TEE$ is satisfied does not contribute to gas supply. The area where the condition $PPE = TEE$ is satisfied is the field enhanced incident area of gas molecules. The simulation is performed by computing the following items sequentially; the field enhanced incident area, the capture probability, the effective capture area and the ion current. Please refer to reference [4] for details of the calculation. The simulation model proposed in this article is applicable in the gas supply limit regime.

Not all the gas molecules which are supplied from the field enhanced incident area would be field ionized. The incident gas molecules are cooled down by transferring the kinetic energy to the emitter surface during the hopping motions and accumulate into the high field region above the tip. Moreover, the gas molecules that reached the ionization area at critical surface are field ionized. Therefore, the probability that a supplied gas molecule reaches the ionization area by the hopping process to ionize is defined as the capture probability. The semi-heuristic form of capture probability proposed by Southon [5] is used in this paper. The capture probability $\Pi_c$ is expressed as follows.

$$\Pi_c \sim c_0 \Phi^{1/2} \text{ for } \Phi \leq \Phi_1,$$

$$\Pi_c = 1 \text{ for } \Phi > \Phi_1,$$

$$\Phi = \alpha F^2/(2kT),$$

$$c_0 = 0.46a_0^{1/4},$$

$$\Phi_1 = 1/c_0^2,$$

where $F$ is the emitter surface field and $a_0$ is the thermal accommodation coefficient. The classical expression of $a_0$ is not used here. Because Tsong [6] pointed out that use of experimental values is more appropriate for low impact energy such as FIM, we use the value of $a_0 = 0.026$ for the collision between He and Mo and $a_0 = 0.315$ for the collision between Ar and Mo, respectively [6]. It seems that the capture probability reflects the mass effect. But $a_0$ for the collision between He and W is 0.020. The dependence to emitter materials of $a_0$ is small. It should be noted that since $F$ is a function of the position, the capture probability is also a function of the position. Therefore, the capture probabilities have to be calculated along the surface of the emitter.

### III. RESULTS AND DISCUSSIONS

Figure 3 shows the calculation results of the field enhanced incident area of He and Ar. The portions projected brightly (blue color) show the space satisfying the condition $PPE > TEE$. In the case of Ar, it is confirmed that the field enhanced incident areas are affected by the taper angle, same as He. But the extent of the incident area of Ar is larger than that of He. Because $\alpha$ of Ar is large. The value of $\alpha$ for Ar and He is 1.14 and 0.143 meV (nm/V)$^2$, respectively [7].

Figure 4 shows the calculation results of the capture probability of He and Ar. The capture probability in the shank part is low (0.12 for He, 0.25 for Ar) but becomes higher (0.26 for He, 0.75 for Ar) in the cap part and sharply increases at the protrusion on the apex. The capture probability of Ar is higher than He. Because $\alpha$ and $a_0$ of Ar are large.
FIG. 3: The field enhanced incident area around the emitter. (a) For He gas, $\theta = 2^\circ$, field of view: 1 $\mu$m. (b) For Ar gas, $\theta = 2^\circ$, field of view: 1 $\mu$m. (c) For He gas, $\theta = 15^\circ$, field of view: 1 $\mu$m. (d) For Ar gas, $\theta = 15^\circ$, field of view: 1 $\mu$m.

FIG. 4: Capture probability for He and Ar.

Figure 5 shows the dependence of the effective capture area on the shank taper angle for He and Ar. It is confirmed that the effective capture area of Ar is more easily affected by the taper angle than He. In the case of a taper half angle of 2$^\circ$, the effective capture area of Ar and He were estimated to be 0.0814 and 0.0107 $\mu$m$^2$, respectively. In the case of a taper half angle of 15$^\circ$, the effective capture area of Ar and He were estimated to be 0.0531 and 0.0078 $\mu$m$^2$, respectively. Therefore the effective capture area of Ar is 6.8-8.0 times larger than He.

FIG. 5: Dependence of the effective capture area on the shank taper angle.

FIG. 6: Dependence of ion current on gas pressure.

For the taper half angle of 15$^\circ$, the ion current of Ar and He were estimated to be 10.3 and 4.8 pA respectively at gas pressure of 0.05 Pa. Therefore the ion current of Ar is 2-2.3 times larger than He. For Ar, the influence of the shank taper angle to the ion current was confirmed and that influence is more effective than He.

Figure 7 shows the experimental result of the dependence of ion current on gas pressure in a gas supply regime. Please refer to ref. [3] for details of experimental system. In the FIM (field ion microscope) experiment, the protrusion, which was terminated with a trimer, was observed. The emitter was cooled at 20K for He and 90K for Ar. The measurement of the ion current was performed using He gas at room temperature and Ar gas at room temperature alternately. Applied voltage was adjusted so that the electric field strength at critical surface was consistent with the best image field, i.e., 44 V/nm for He and 22 V/nm for Ar, respectively [6]. The ion current of Ar and He were measured to be 6.61 and 4.27 pA respectively at a gas pressure of 0.05 Pa. The ion current of Ar is 1.54 times larger than that of He. The real tip with trimer termination is a threefold symmetry form. However, the simulation model adopts a rotational symmetry (i.e., conical) shape. This difference causes the small influence on the field strength of a shank part, but a large influence on the field strength of a tip apex. Therefore, it is pre-
dicted that this affects the accuracy of the calculation of the ion current. Anyway, the calculation agreed with the experiment qualitatively.

IV. CONCLUSIONS

In this article, the emitter shape dependence of the ion current from a GFIS was examined using numerical simulations. When using the same emitter, it was estimated that the ion current of Ar was 2-2.3 times larger than that of He. A similar result was achieved in the experiment. For Ar, the influence of the shank shape to the ion current was confirmed and that influence is more effective than that of He. The emitter of a small shank angle is capable of a higher ion current. Therefore, it was concluded that the ion current can be increased through optimization of the tip configuration.

Moreover, it is expected that the improvement of the ion current emitted from GFIS will be achieved by optimization of the emitter size and source gas temperature.

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