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Stabilization of an electrostatic lens for a focused ion beam system

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An electrostatic lens is used as the focusing lens for focused ion beam (FIB) systems. The lens action against charged particles is caused by creating a high-electric field between the electrodes. To improve the stability of the electrostatic lens, it is necessary to raise the withstand voltages of the insulator and the electrodes in the electrostatic lens. We have improved the withstand voltage of the insulator by covering the triple junction with a dielectric and using the conditioning procedure described in this paper. As a result, a stable electrostatic lens system for manufacturing application of FIB has been developed.

I. INTRODUCTION

Focused ion beam (FIB) technology is maturing to a stage where commercial applications are potentially possible. Examples of a number of interesting structures fabricated with FIB have been reported.¹ Stability of the FIB system is a significant factor for its successful application in commercial device production. A second significant factor for FIB to reach production applications is to reduce the pattern size and to improve the throughput of the system. Therefore, it is necessary to form an ion beam with high current and with excellent focusing characteristics.

Since an ion has a much larger mass than an electron, the electrostatic lens, whose lens action depends only on the electric charge of the beam, is used as a focusing lens for the FIB system. It is generally known that the electrostatic lens aberrations can be reduced by creating a higher electric field between the electrodes. This makes it possible to form an ion beam with high current and with excellent focusing characteristics. For this reason, it is necessary to supply high voltage to the electrostatic lens, which brings up the problem of microdischarges in vacuum within the lens. Moreover, owing to the generally large internal resistance of the high voltage generator that supplies high-voltage to the electrostatic lens, microdischarges in the vacuum will be accompanied with lens voltage fluctuations, impairing stable lens action. Therefore, to improve the lens characteristics, microdischarges generated in the electrostatic lens must be minimized and the withstand voltage of the electrostatic lens must be improved. Therefore, to improve the stability and reliability of the FIB system for production applications, the most important requirement is to minimize microdischarges in vacuum.

This paper describes electrostatic lens stability, the electric discharge characteristics of the electrostatic lens, and the relative improvements to be made.

II. MICRODISCHARGES OF ELECTROSTATIC LENS

Figure 1 shows a cross-section of an electrostatic einzel type lens used as the objective lens of an FIB system, we have developed JIBL-100A.² This electrostatic lens consists of three electrodes with a small gap (3 mm) and two insulators

which fix the three electrodes. The top and bottom electrodes are at ground potential and high voltage is supplied to the central electrode. This creates a high-electric field between the electrodes, causing lens action to the charged particles. In the case of the JIBL-100A, an ion beam with 100 kV accelerating voltage focused at the specimen with a lens voltage of about 45 kV. Since such high-dc voltage is used for the electrostatic lens, two types of discharges in the vacuum become a problem. One is microdischarge over the surface of the insulator and the other is microdischarge from the electrode surface.

A. Microdischarge over the insulator surface

Microdischarge over the insulator surface has been studied by many researchers in the past.³ The mechanism of its generation is already fairly clear. The generally accepted theory on this microdischarge is currently typified by the following model.⁴

Unevenness of the electrode surface where the cathode side electrode and the insulator join, results in field electron emission. The electrons thus emitted collide with the insulator surface. Since the secondary electron yield factor (δ) of material used as an insulator such as alumina is $\delta > 1$, secondary electrons are multiply emitted from the insulator surface, and the surface becomes positively charged. Repetition of this process distorts the electric field on the insulator.

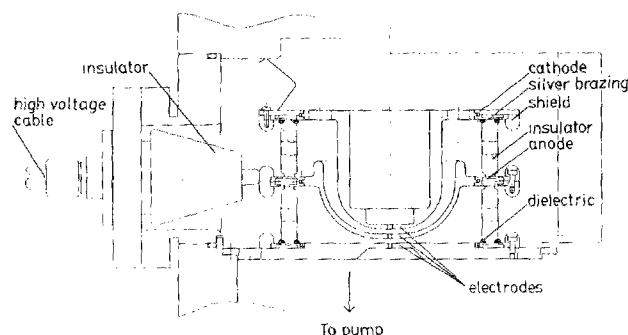


FIG. 1. Schematic diagram of the electrostatic lens that is used as the objective lens of FIB system (JIBL-100A).

As a result, the electric field strength on the cathode surface gradually rises, promoting the increase of field electron emission, and finally microdischarge is generated over the insulator surface. This microdischarge is a pulsed discharge of several tens of milliseconds in duration.⁵ If a small gap exists between the cathode and insulator, the electric field will be concentrated in this gap and microdischarge takes place.⁶ As seen from the above, the place where the cathode and insulator joint (generally called "triple junction" because the vacuum, insulator, and cathode come together) plays an essential role in the microdischarge over the insulator surface.

In the current JIBL-100A objective lens, the gap is eliminated by metalizing the small gap between the cathode and insulator, and the electric field concentration on the triple junction is alleviated by inserting shield electrodes, as shown in Fig. 1. In the present study, we have tried covering the triple junction with a dielectric in order to further alleviate electric field concentration at the triple junction and hold down electron emission.

The insulator used in our experiment was cylindrical alumina 115 mm in inner diameter, 135 mm in outer diameter, and 36 mm in height. The specific resistance and relative dielectric constant of this insulator are more than $10^{14} \Omega \text{ cm}$ and 9 (1 kHz), respectively. For a dielectric to cover the triple junction, we used a ceramic bonding material with a relative dielectric constant of 6.1 and a specific resistance of $3.52 \times 10^{14} \Omega \text{ cm}$. The chamber was evacuated to below 10^{-6} Torr.

Discharges were periodically repeated one to three times per 20 min beginning 2 h after the start of voltage application (60 kV), when the triple junction was not covered with dielectric. Judging from this periodicity, it is believed that discharges on this insulator are caused by its charging up. On the other hand, when the triple junction is covered with dielectric, no microdischarges are observed after 1 h from voltage application (60 kV). This is because the covering of the triple junction with a dielectric alleviated the electric field at the junction and curbed field electron emission from this surface.

Residual gas absorbed on the insulator surface reduces the withstand voltage on the insulator surface.⁷ One method to remove this absorbed gas is degassing by baking at an elevated temperature. In the present research, the method called "conditioning" was used to remove the absorbed gas on the insulator surface. The procedure is to apply high voltage to both ends of the insulator, causing discharge or microdischarge over the insulator surface for degassing. In principle, degassing is thus carried out and the withstand voltage at the insulator is increased. Figure 2 shows the conditioning effect on this insulator. In the experiment, an insulator with its triple junction covered with a dielectric was employed. The abscissa represents the elapsed time and the ordinate the number of discharges occurring per hour. Conditioning was carried out at 55 and 70 kV and 50 kV was then applied to both ends of the insulator.

When conditioning was carried out with 70 kV, no discharges were ascertained during 24 h, indicating that degassing was successful, raising the withstand voltage on the insu-

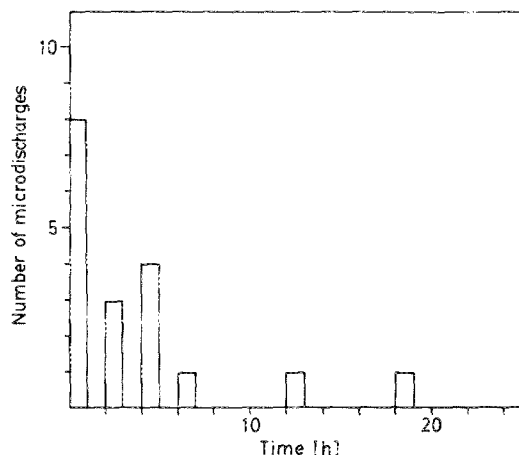


FIG. 2. Conditioning effect on each insulator at supplied voltage 50 kV after conditioning; when conditioning voltage was 70 kV, no microdischarges were ascertained for over 24 h.

lator surface. Furthermore, we investigated the withstand voltage over an insulator which had a triple junction covered with a dielectric.

After conditioning was fully carried out with 70, 90, and 110 kV, respectively, 50, 65, and 80 kV were applied to both ends of the insulator to investigate its stability for 24 h. The results are shown in Fig. 3. This figure shows that no discharges were observed at a voltage of 65 kV, making possible the application of high voltage.

B. Microdischarge between lens electrodes

The field electron emission from a metal surface is influenced by the work function of the metal. In a substance with a small work function, field emission takes place at a lower electric field. Therefore, considering that the same may be true of microdischarges from electrodes, we investigated this point with respect to three types of electrodes having different work functions—SiC (4.85 eV),⁸ titanium (4.1 eV), and stainless steel (4.4 eV).

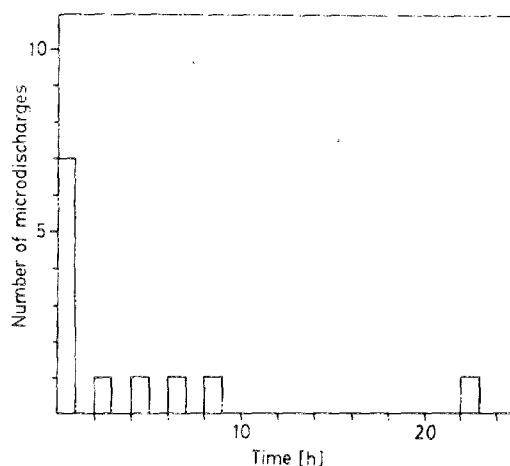


FIG. 3. Time distribution of microdischarges over the insulator; when supplied voltages were 50 and 65 kV, no microdischarges were ascertained for over 24 h.

The test specimens used were cylindrical ones 10 mm in diameter and 100 mm in length. Two electrodes of the same material were arranged orthogonally at a gap length of 0.25 mm, and after applying a dc voltage between the electrodes, a dark current from the electrodes was measured. The chamber is evacuated to below 10^{-6} Torr.

Figure 4 shows the test results. The ordinate represents the dark current from the electrodes and the abscissa the macroscopic field strengths at the surface of the electrodes.

The stainless-steel electrodes and titanium electrodes show nearly the same tendency. For a field of 70 kV/mm, the dark current rises sharply, clearly indicating that it was a discharge due to cold cathode electron emission resulting from an electric field. As compared with this result, dark current of 5–6 μA was emitted at 62 kV/mm with the dark currents of 0.1 and 0.3 μA , respectively, from stainless steel and titanium electrodes at the same field strength of 62 kV/mm. The work function of SiC, 4.85 eV, is larger than the 4.1 eV of titanium and 4.5 eV of stainless steel, yet SiC showed the largest dark current of all. Figure 5 shows SEM micrographs of the surfaces of the different electrodes. The micrographs show many microprotrusions and stainless-steel electrodes have a very smooth surface. It should also be noted that the surfaces of the titanium and stainless-steel electrodes were smoothed by the effect of conditioning, while the surface condition of SiC was not improved by employing conditioning because it has a high-melting point. As a result, many microprotrusions remain on the surface of the SiC electrode even after conditioning, which presumably results in large dark currents. The dark current from the surface of a metal presently used for electrode of an electrostatic lens is governed by the field electron emission that depend on the radius of curvature and number of microprotrusions rather than by the electron emission efficiency determined by the work function. In the present experiment, the relationship between electrode material and work function could not be investigated clearly.

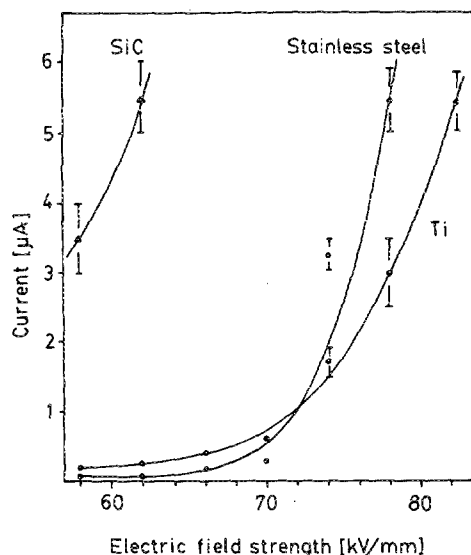


FIG. 4. Correlation between macroscopic electric field strength and dark current of different electrode materials.

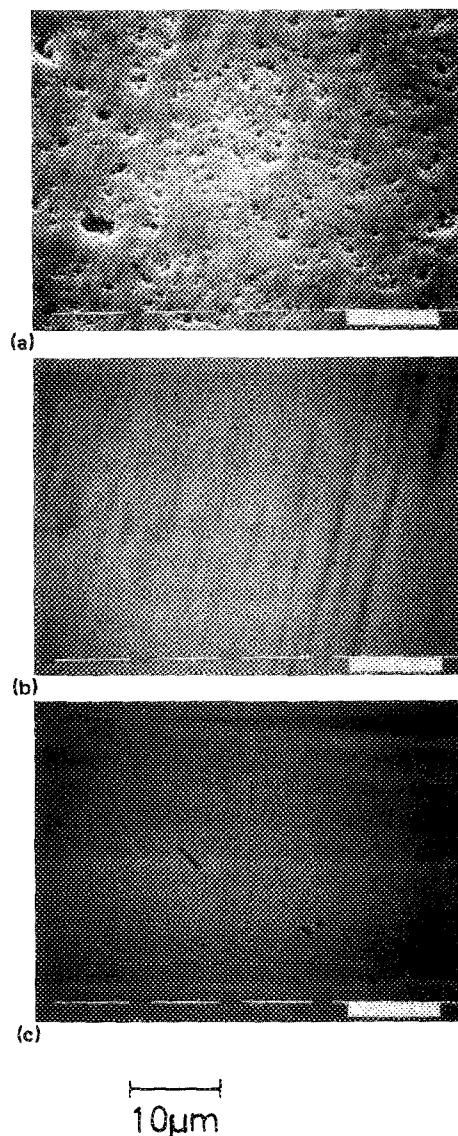


FIG. 5. SEM micrographs of the surface of the different cathode electrodes. (a) SiC, (b) Ti, and (c) stainless steel.

Furthermore, we investigated the effect of the conditioning procedure to eliminate the protrusions on the cathode surface that cause field electron emission.

Figure 6 shows the effect of the conditioning procedure for electrodes on the field current characteristics. After carrying out the conditioning procedure with 27 and 33 kV/mm, a dc high voltage was applied to plot the dark current value at that time. The abscissa represents the macroscopic field strength on the electrode surface. For the experiment an electrostatic lens used as the objective lens for the JIBL-100A was tested. Each electrode has a gap length of 3 mm and is made of stainless steel. The insulators to support the electrodes were made of alumina whose triple junction was covered with a dielectric, like those used in the above-mentioned experiment on surface microdischarges. The chamber is evacuated to below 10^{-6} Torr.

The dark current was 8–9 μA at 25 kV/mm prior to using the conditioning procedure. The dark current then fell to 1.2 μA after conditioning at 33 kV/mm. Conduction current of

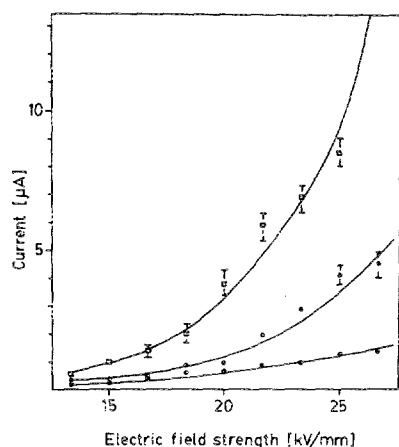


FIG. 6. Correlation between macroscopic electric field strength and dark current. (□) Before conditioning; (○) before conditioning 27 kV/mm; (●) after conditioning 33 kV/mm.

the insulator is calculated to be $< 0.01 \mu\text{A}$ under this applied voltage for the given lens geometry. On the other hand, the lens electrodes, except for the lens gap area, have large gap lengths near the insulator as shown in Fig. 1. This means that a sufficiently high-electric field for the conditioning procedure does not affect the electrode area surfaces. Therefore, small protrusions are not eliminated, and the dark current caused by electron field emission remains. Also, as compared with the limit field strength obtained in the experiment on discharges between cylindrical electrodes, it for the actual lenses was markedly reduced. This was probably due to the area effect of the cathode surface.

III. STABILITY ESTIMATION

We have so far examined discharges within the lenses. As for discharges between electrodes, it was ascertained that the dark current can be reduced by carefully carrying out the conditioning procedure described in this paper. With the presently available JIBL-100A, the lens voltage is $\sim 45 \text{ kV}$ when the accelerating voltage is 100 kV . Since the gap length between the surfaces of electrodes is 3 mm , the macroscopic field strength at the electrodes is 15 kV/mm . As seen in Fig. 6, even when the macroscopic field between the electrodes is 25 kV/mm , the dark current is $\sim 1 \mu\text{A}$. Under this condition, the calculated voltage fluctuation of a high-voltage generator with reduced internal resistance was $< 0.3 \text{ V}$. Furthermore, since there is almost no time fluctuation in this dark current, its influence upon the stability of the electrostatic lens can be ignored. The withstand voltage between the electrodes can be increased up to an application voltage of $\sim 80 \text{ kV}$ by carrying out the conditioning procedure.

Figure 3 shows the measurement results for only 24 h; however, even if the insulator is conditioned with 110 kV , it is ascertained that one discharge takes place every 8 h over its surface within a measurement time of 48 h. These discharges can cause fluctuations that can impair stable lens operation. However, when 65 kV (conditioning voltage is 90 kV) is applied, no discharges were observed within the measurement time. It was thus ascertained that if 24 h is regarded as a criterion for stability, the withstand voltage over the surface of this insulator is nearly 65 kV .

From the above discussion, it was ascertained that the withstand voltage of the electrostatic lens presently used in our instrument (JIBL-100A) is governed by the withstand voltage over the insulator surface, and that its value is 65 kV .

IV. CONCLUSION

The stability of the electrostatic lens, which is indispensable for the focusing of the ion beam, was described.

The discharges in the electrostatic lens are classified into two types: those occurring between the electrodes and those occurring over the surface of the insulators supporting the electrodes.

As for discharges between the electrodes, it was ascertained that the withstand voltage is improved by sufficiently polishing their surfaces and carrying out the conditioning procedure described above. As for discharges over insulator surfaces, the withstand voltage is improved by covering the triple junction (which is a substantial cause of discharges) with a dielectric.

As a result, it was ascertained that the electrostatic lens of the recently developed FIB equipment has high-enough reliability, judging from the fact that it is operated with $\sim 70\%$ of the limit value for stable operation.

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