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PROPERTIES OF DC MODE FIELD EMISSION OF ELECTRONS FROM LIQUID LITHIUM CATHODE

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Abstract - By reversing the polarity of extraction voltage for a liquid metal ion source, we measured I-V characteristics and observed emission patterns of field-emitted electrons. The Fowler-Nordheim plot of emissions from cleaned liquid surface did not fit a straight line. Emission patterns showed stable protrusions formed on the emitter tip. In order to study application feasibility of this electron source, further experiment was made by measuring the angular current density $dI/dQ$ and detecting SEM images.

1. Introduction

The liquid metal ion source (LMIS) has been investigated by many researchers for applications to microelectronic fabrication, microsurface analysis and the like. Because of its advantage, point source with a very high brightness, a sub-micron beam is easily obtained from LMIS in combination with the focused ion beam technique.

Since the LMIS has a construction very similar to the field emission (FE) electron gun, one can expect its potential to work as an electron source. Only the difference in construction between LMIS and conventional FE gun is whether the phase of emitter metal is in liquid or solid. If the FE phenomenon takes place with a metal in liquid phase, the application of LMIS is certainly expanded to provide a novel probe which performs complementary functions of ion and electron sources with a single gun assembly.

Swanson and Schwind first noticed this potential of LMIS. They made experiments of FE from Ga-In liquid alloy, and observed periodic pulsed emissions. In our recent study with Ga-In-Sn alloy, however, a DC mode FE was obtained under the condition of smallness in the liquid volume at the tip surface, or apex radius of the tip. As for the shape of liquid apex at the cathode tip, however, a clear explanation was still difficult. In this paper, we propose an elucidation from emission patterns. Scanning electron microscope (SEM) images were also taken as an attempt for application of the liquid metal electron gun.

2. Experimental

Experiment was made by means of a home-made vacuum column with an einzel lens and a set of parallel deflectors as shown in figure 1. A quadrant extractor and a disc anode were employed to measure angular current density $dI/dQ$ and observe SEM images.

In the ion emission mode of LMIS, it is reported that the emission easily goes off-axis with a sharp tungsten tip. In order to obtain DC mode electron emission from LMIS, the tip radius should be smaller than 1 µm. Under this condition, however, the off-axis emission often took place, much the same as the ion emission mode. Thus we added a self-aligning function to the extractor by connecting a high resistor of 2 GΩ between each piece of quadrant electrodes and the high voltage supply. Electrons are extracted with an axially asymmetric field due to voltage drops generated by individual currents across the high resistors. The anode potential determines the final acceleration voltage for the electron beam.
In the measurement of emission patterns and I-V characteristics, a grounded disc extractor was used instead of the quadrant and the anode, because the quadrant gives an axially asymmetric lens effect which warps the emission pattern. A fluorescent screen was placed 55 mm down from the extractor to observe the emission pattern, which we looked at through a window with a dip of 20°.

The LMIS we used is of needle type and equipped with a reservoir entwined by a coil heater. A tungsten needle with diameter of 0.5 mm and apex radius of ca. 0.2 μm can be put in and out through a hole at the bottom center of the reservoir easily with a micrometer knob from outside of vacuum. This mechanism allows one to adjust the distance between the tip and the extractor, and also to change the volume of liquid metal adhered on to the tip even during emission. In this experiment, we chose Li as the source metal, which is suited as cathode material due to its low work function of 2.9 eV (5) and low vapor pressure of ca. 1 x 10⁻¹⁰ Torr (6) at the melting point of 180.5°C. Moreover, Li looks adequate for use with tungsten tip in view of adhesion through a past experiment of ion beam extraction. Throughout the experiment, the base pressure was 1 x 10⁻⁹ Torr.

3. Results and Discussion

3.1 Field Emission Patterns

When emission patterns are observed, a special attention should be paid to purity of the liquid metal surface. We compared emission patterns of the Li emitter before and after the cleaning. Figure 2 shows the emission patterns (a)
before and (b) after cleaned by field evaporation of Li with the ion current below 1 mA. Two different patterns are obviously found: one (a) comprising small bright spots with neither symmetry nor reproducibility and the other (b) with no structure. The pattern with small bright spots may be caused by adsorption of residual gas molecules or exposure of the surface of tungsten substrate due to poor wetting with the liquid metal. Not pursuing the cause of structured patterns, we paid attention to those without structure. Smooth coverage of W tip with Li was confirmed by the optical microscope observation after patterns (b) were obtained.

Fowler-Nordheim (FN) plots for these patterns are shown in figure 3, denoting ○ and ● for patterns with (a) and without (b) structure of the bright spots, respectively. At first sight, the latter (b) without structure does not obey the FN law in contrast that the former (a) does. This implies that the emitter shape and
the emission area depend on the field strength. In other words, in the FN equation given by

$$I = 1.54 \times 10^{-8} \frac{\phi^2 V^2 A}{\phi t^2} \exp\left(-6.83 \times 10^7 \frac{\phi^2}{BV} f\right),$$

where $\phi$ is the work function, $A$ the electron emitting area, $t$ and $f$, functions with nearly constant values close to unity, $\beta$ a geometrical factor defined by

$$E = \beta V,$$

where $E$ is the field strength at the emitter apex, $A$ and $\beta$ are implicit functions of $E$ for the liquid emitter.

Figure 4 shows I-V characteristics of the Li ions and electrons extracted from the same liquid emitter. It is found that the threshold voltages are 3.9 and 1.3 kV for emissions of ions and electrons, respectively. Since the field strength at the emitter tip during field emission of electrons is only a fraction of that for field evaporation, the non-structured patterns are not caused by the Taylor cone which is believed as the emission source for the ion extraction. However, considering the FN plot in figure 3 which may represent a deformation effect due to the electric field as well as the fact that brightness of the non-structured pattern is stable at voltages ranging 1 to 2 kV, it is supposed that one or more protrusions stabilized by the electric field is formed at the apex of the liquid cathode.

Our speculation on this point is as follows: In the field strength range of the steady field emission, micro-protrusions smaller than the so-called Taylor cone are formed at several sites on the tip surface. As the field strength goes higher, these micro-protrusions grow not only in the number but also in the size supplied by the material flowing down to the apex, causing an increase of the liquid volume. When the field exceeds the strength for the steady emission mode, the pulsed emission starts.

Bell, et al.(4) observed ion emission patterns from Ga LMIS in a low current range. At extraction voltages below 3 kV, they obtained non-structured patterns which likely correspond to very small Taylor cones. According to them, the number of bright spots increases with the ion current, or the extraction voltage. This also supports our idea.

3.2 Angular Current Density

We formerly reported that field emitted electrons from a liquid alloy gave $dI/d\Omega$ of several $\mu$A/sr.(2) This low value was probably caused by off-axis emission. In this experiment, therefore, a quadrant extractor was employed, instead
of the conventional apertured disc, to give self-aligning function by restricting the solid angle of the whole probe. An aperture with the half angle of 0.9 mrad was additionally used. The $\frac{dI}{d\Omega}$ was calculated from the measured current divided by the solid angle of the additional aperture. Figure 5 shows these results, $\frac{dI}{d\Omega}$ vs. total current, for both electron and ion beams. The total current of 10 $\mu$A gave about 40 $\mu$A/sr for both electron and ion beams. The increased value of $\frac{dI}{d\Omega}$ is caused not only by a high emission current density but also by the quadrant extractor which provides a lens action as well as the aligning function. Due to axial asymmetry of this extractor, however, asymmetric aberrations ought to appear. Further investigations will thus be needed for practical applications.

3.3 SEM and SIM Images

Fig. 6 (a) SEM image with 10 keV electron probe of 1 nA and (b) SIM image with 10 keV ion probe of 240 pA.
For application of the liquid metal electron gun, an attempt was made by in-situ observation of both SEM and SIM images taken under the same beam energy of 10 keV. Figure 6 shows these images of the identical area on the same specimen, a Cu net with 200 meshes: (a) is an SEM image and (b) an SIM image by means of Li ion beam. The latter (b) was taken immediately after the former (a) by reversing the polarity of applied voltage.

These images do not show a clear difference in the resolution, and the SEM image (a) looks rather noisy compared with the SIM (b). Image quality in the former (a) is limited by the coma aberration due to insufficient alignment of optics in the experiment. Using an improved optics eliminating the coma aberration, we should have obtained a better resolution in SEM than SIM, because of the chromatic aberration for FE electrons far less than EHD ions. Since a flicker noise appears in FE electrons (7), lower vacuum pressure will be required to stabilize the beam current.

Real-time switching between SEM and SIM modes was difficult in this experiment because we had to readjust the extraction voltage and the amplifier gain for different I-V characteristics in electron and ion modes, and also realign the cheap optics mechanically.

4. Summary

FE patterns with no structure were observed with a liquid Li cathode sufficiently cleaned. When these patterns are obtained, the FN plot deviates from a straight line and it implies a deformation of liquid metal by the electric field. This means that field stabilized cones are formed on top of the cathode. It is not certain if these cones are the Taylor's.

The angular current density \( \frac{dI}{d\Omega} \) was measured both for electron and ion beams extracted from liquid Li; both of these values were ca. 40 \( \mu A/sr \) at the total current of 10 \( \mu A \).

SEM and SIM images were observed in-situ though the resolution in both cases was limited to several \( \mu m \) by misalignment of the electrostatic optics. From this, however, we may expect that the microelectronic fabrication by an ion beam can be achieved in combination with the position assignment through in-situ observation of the target by an electron beam.

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6. References