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FIELD EMISSION OF ELECTRONS FROM A LIQUID ALLOY SURFACE

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Electrons were extracted from Ga-In-Sn alloy on a liquid metal ion source by reversing polarity of the high electric field. The emission current was kept stable to 2.5 nA/hour in a vacuum of 1x10^{-7} Torr by using a high-impedance stabilizer. The I-V characteristics obey Fowler-Nordheim's law, indicating the field emission mechanism. The size of effective emission area can be of the order of 10^{-2} m. The angular current density and the brightness amounted to 20 to 40 uA/sr and ca. 10^{10} A/cm^{2} sr, respectively. The energy spread of emitted electrons was comparable to that of solid-phase field emission.

1. Introduction

A liquid metal ion source (LMIS) has attracted great attention in the fields of microfabrication, surface microanalysis, and so on because of its prominent feature, very high brightness with a small source size. Liquid metal supplied to the apex region of an emitter is known to form a sharp cone (called the Taylor cone) with the apex radius of the order of 50 to 500 Å in a high electrostatic field. Ions are emitted from such a restricted surface area, yielding a very high brightness (ca. 10^6 A/cm^2 sr). Thus the liquid metal ion source seems to be most suitable for producing submicron ion beams1).

For electron beams, on the other hand, one usually employs a solid-metal field emitter as a bright electron source. The smallest possible radius of the emitter tip, however, is practically limited by individual tip etching techniques to ca. 1000 Å, resulted in the optical source size of several ten Å. Solid emitters sharper than this value are of less practical use because of their shortened lifetime.

Clampitt and Jefferies2) reported that the electron emission took place very readily from the liquid cesium emitters in 1972. Swanson and Schwind3) proposed an idea of extracting electrons from a liquid...
metal by reversing the polarity of applied field. If this technique became established, it would give an excellent source satisfying the following requisites:

a) small source size,  
b) high brightness,  
c) long lifetime, and  
d) wide variety of emitter material.

In this paper we describe experimental results of stable electron emission from a liquid alloy surface. We obtained an evidence of the fact that the current consisted really of electrons tunneling through the surface potential barrier. The current stability, the effective source size and the brightness were deduced.

2. Experimental

Fig. 1 illustrates construction of the LMIS we employed. It is equipped with an up-and-down mechanism to move the tungsten emitter tip from outside of vacuum, through a sleeve containing liquid metal, so as to be easily wetted with it. The LMIS has a means of electron bombardment heating for the tip and the sleeve, but it was left unused during the experiment of electron emission. Diameters of the extractor aperture, the emitter wire and the sleeve hole were 1, 0.5 and 0.8 mm, respectively. The extractor was located 2 mm down from the end of the sleeve and was grounded across a high impedance resistor $R$ as an emission current stabilizer, whose resistance value was variable from 0 to 10 GΩ in 100 MΩ steps.

As the liquid metal material, we used Ga-In-Sn alloy, which is fluid at the room temperature. It flows along the tungsten tip down to its apex. Electron emission is obtained simply by reversing the polarity of acceleration voltage in comparison with the ion emission mode.

3. Results and Discussion

3.1 Current Stability

Electrons were extracted out when the applied voltage to the tip increased above a threshold. The current was kept stable with time even in a medium vacuum condition of $1 \times 10^{-7}$ Torr, as shown in Fig. 2. The stability was better than 2.5 %/hour. The role of high-impedance resistor in stabilizing the current was understood from the fact that the current became to fluctuate when we removed it.

Detailed wave forms of the current traced by an oscilloscope are shown in Fig. 3. The repetition of abrupt increase and slow decay is observed and its frequency looks to be determined by the connected impedance and the stray capacitance. As a cause of the oscillation, Swanson et al proposed the explosion of Taylor cone, taking thermal process of the liquid tip into consideration. In contrast with their
experiments, however, where upward cone formed atop a capillary gave a current of ca. 0.5 mA above a threshold voltage as high as 8 kV, ours did a current not higher than several ten μA above a threshold of ca. 1 kV. Temperature calculated by Swanson et al shows no rise in this current range. Tamura, one of the coauthors, has obtained a SEM image with an emission current below 5 μA in a separate experiment. Through these facts, DC emission may be expected in a low current region.

Fig. 2 Stability of the emission current in 1x10^-7 Torr.

Fig. 3 Measurement of current waveform. (a): Circuit. (b) to (d): Oscillograms obtained with R = 0.4, 1.4 and 2.4 GΩ, respectively. Scales: vertical 20 mV/div. and horizontal 10 ms/div.
3.2 I-V Characteristics

The mean emission current \( I \), defined as the arithmetic mean of peak-to-peak amplitude above zero in the waveform, increased with the acceleration voltage \( V_{acc} \) applied to the liquid tip above its threshold \( V_{th} \) of ca. 1 kV, as shown in Fig. 4. Majority of electrons flow into the extractor electrode and hence raise its potential which is the product of the current \( I \) and the stabilizer impedance \( R \). The effective extraction voltage \( V_{eff} \) is expressed as

\[
V_{eff} = V_{acc} - I \cdot R.
\]  

(1)

The current is replotted against the voltage \( V_{eff} \) in Fig. 5 according to Fowler and Nordheim. In the region A where the current is relatively low, measured values well fit the straight line with the slope \( m = -0.23 \) and the intersection with the vertical axis, \( q = -10.65 \). The linear relationship between \( \log(I/V^{2}) \) and \( 1/V \) means that electrons are emitted by tunneling through the surface potential, that is, the normal field emission mechanism. From the slope \( m \) with the intersection \( q \), we estimated the effective surface area \( S \) of the emission to be of the order of \( 10^{-2} \) A\(^2\). The field strength at the cone apex of the liquid metal is approximated to be about 1.1 V/A at the threshold voltage. This value seems rather high compared to that in the case of conventional solid field emitters (\(<1\) V/A), for which field strength in the vicinity of the cone apex is approximated by

\[
F = V / 5r,
\]  

(2)

where \( V \) and \( r \) are applied voltage and radius of curvature at the apex, respectively. Using \( F = 4 \times 10^{7} \) V/cm typically and \( V = 1 \) kV, our deduction gives \( r = 500 \) Å. Since the discrepancy can hardly be explained at present, authors intend to observe the actual shape of the cone apex in operation.

Fig. 4 Total emission current vs. applied voltage for various stabilizer R's.

Fig. 5 Fowler-Nordheim plot at \( R = 200 \) MΩ.
3.3 Energy Distribution

A filter-lens type energy analyzer was set up on the beam axis. Differentiating current through the filter with retarding field, energy distribution of emitted electrons was obtained as shown in Fig. 6. The full width at half maximum was 0.46 eV at $I = 17 \mu A$. As the analyzer resolution is estimated to be ca. 0.4 eV, the energy spread of electrons is $\Delta E \leq 0.3$ eV. This value is comparable to or slightly larger than that for the solid-phase field emission. Very high intensity of electrons in the present field emission may cause additional energy spread either by Coulomb repulsion in the beam or by a temperature rise near the cone apex.

3.4 Brightness

In order to get the angular current density $dI/d\Omega$, we probed a current toward a restricted solid angle by using an aperture with the half angle of 2.3 mrad. The ratio of the probe current to the total one was nearly constant, as shown in Fig. 7. This means that the microgeometry in the vicinity of the cone apex including the emission area does not change essentially at the current up to several ten $\mu A$. The angular current density was deduced from Fig. 7 to be ca. 1 $\mu A$/sr at the total current of 18 $\mu A$, but it fairly varied by tilting the tip assembly against the aperture. This implies inhomogeneous angular distribution of the density. The maximum $dI/d\Omega$ value so far obtained is 20 to 40 $\mu A$/sr. Brightness $B$ is defined as the ratio $(dI/d\Omega)/S$, where $S$ is the emission area, because it is too small to imagine the optical source size separately. We then obtain $B$ of $10^{10}$ A/cm$^2$sr,
much higher than that of an ordinary solid field emitter. With \( r \) obtained from eq.(2), on the other hand, \( B \) is defined as \( (dI/dQ)/S_o \) with \( S_o = \pi r_o^2 \) and \( r_o = \sqrt{\Delta E/E_a} \), where \( E_a, \Delta E \) and \( r_o \) are acceleration voltage, energy spread and optical source radius, respectively. Even with \( E_a \) of 10 kV typically used in conventional SEM, \( B \) gives the same value as above.

4. Conclusion
Under development is a liquid metal electron source with very small emission area and very high brightness. It endures a long term operation even in a conventional vacuum. This is fairly important in view of practical application. Some problems such as oscillation in the current wave form still remain unsettled. These may also depend on properties of source material employed as the liquid-phase emitter.

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Reference
6) Private communication.