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Electron Emission Properties of Liquid-Gallium on a Tungsten Field Emitter Tip

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Abstract. For $\langle 110 \rangle$ and $\langle 111 \rangle$ oriented tungsten tips deposited with liquid-gallium, electron emission patterns and emission current characteristics were investigated by field emission microscopy. When the tip voltage was applied for the first time after deposition of gallium, stable liquid-gallium cones were formed on the remolded facets for thicknesses of 1.5 ~ 5nm and DC electron emission occurred. The total emission current obeyed the Child-Langmuir's law. This means that the stabilization mechanism of liquid-gallium cones is the space-charge effect. These experimental results are very similar to those for the liquid-lithium deposited tungsten tips already reported. When the applied voltage was decreased to zero and again increased, weak distorted pattern appeared on the same facets and became bright gradually. The emission current monotonously increased with the applied voltage. In this case, no liquid-gallium cone seems to be formed and the electron emission probably occurs from the liquid droplet, as mentioned by Rao et al.

1. INTRODUCTION

It is well known that a liquid metal droplet forms a Taylor cone [1] when an appropriate positive electric field is applied. Since the electrostatic force which acts on liquid metal has no dependence on the direction of applied field, a liquid metal coated field emitter has the possibility of providing a function of high-brightness ion/electron source. Electron emissions from liquid III-group metals which are important for applications had already been tried by several researchers. Swanson and Schwind had carried out the experiment of extracting field electrons from a liquid Ga-In alloy and observed the periodic pulsed emission [2]. Later, Rao et al. found the DC-mode electron emission from liquid-gallium coated tungsten tips with radii of about 100nm [3], and they reported that no field-stabilized cone is formed and the general field emission occurs. We tried the in situ HV-TEM observation of tungsten tip coated with liquid Ga-In-Sn alloy and found that a field-stabilized small cone is formed provided the liquid-metal is thin [4]. Recently, Driesel et al. performed the HV-TEM in-situ investigations of the tip shape of a gallium liquid metal electron emitter and obtained the result supporting the Rao's model [5]. In these experiments, however, the liquid thickness was not controlled. We have lately clarified that the careful thickness control of liquid-lithium makes the formation of stable lithium cone possible [6,7]. The liquid-metal thickness is the key factor for the stable cone formation and the determination of emission mode (DC or pulse).

In this paper, therefore, the possibility of the stable cone formation as well as the electron emission characteristics were investigated for the tungsten tips deposited with liquid-gallium, by carefully controlling the thickness.

2. EXPERIMENTAL

A gallium-deposited tungsten tip is prepared as follows. A W $\langle 110 \rangle$ poly-crystalline or a W $\langle 111 \rangle$ single-crystal wire was spot-welded to the apex of a tungsten hair-pin filament. The one end of the wire was electrolytically etched to be about a few hundreds nm of the apex radius by 1N NaOH. In an FEM

column (base pressure of 1.3×10^{-8} Pa) [7], the tip was flashed for 30s at 2100K. Subsequently, the (100) plane of W<110> (or the (111) plane of W<111> tip) was remolded for 30s under the conditions of the tip temperature of 1850K (or 2000K) and the field strength of 71.2MV/cm (or 61.7MV/cm). Gallium having melting point of 303K was deposited on the remolded tip from one direction perpendicular to the tip axis by using a chimney-type evaporator. The deposited thickness t was estimated by taking into account the directivity of evaporator to be

$$t = t_m (r + b \tan \alpha) / (r + a \tan \alpha), \quad (1)$$

where t_m is the gallium thickness on the quartz thickness monitor, r the inner radius of chimney, and a and b are the distances from the end of chimney to the tip and to the quartz thickness monitor, respectively and α ($\approx 3^\circ$) the spread half angle of gallium vapor. Setting the temperature of the gallium-deposited tip to about 600K so that the deposited gallium was in a liquid state and applying the negative voltage to the tip, field electrons were extracted. As the vapor pressure of gallium is very low at 600K, only a little of liquid-gallium evaporate. Fig.1a shows the scanning electron microscope (SEM) image of remolded W<110> tip just after deposition of gallium of 3nm thickness. It is found that the gallium atoms are not deposited uniformly but form the droplets (shown by arrows) due to the high surface tension (718 mN/m). Fig.1b shows the SEM image of another gallium deposited tip after extraction of electrons. This suggests that the liquid-gallium is uniformly diffused on the tip surface during operation.

For liquid-gallium deposited W<110> and W<111> tips, the variations of the electron emission patterns with the applied voltage and the electron emission characteristics were studied.

Figure 1: SEM images of the remolded W<110> tips deposited with gallium of 3nm thickness. (a) Just after deposition of gallium and (b) after extraction of electrons.

3. RESULTS AND DISCUSSIONS

3.1 Liquid-gallium thickness for stable cone formation

Electron emission patterns from tungsten tips deposited with various thicknesses of liquid-gallium were observed to investigate whether stable liquid-gallium cones are formed or not. For the thicknesses of 1.5 ~ 5nm, stable liquid-gallium cones were formed and DC mode electron emission occurred. For thicknesses more than 5nm, however, no stable cone was obtained and only explosive pulsed electron emission resulted. The deposition thickness for forming stable cones is one order of magnitude smaller than that for lithium[6]. This implies the necessity of precise control for deposition of gallium.

3.2 Cone formation sites

3.2.1 W<110> tip

Figs.2a and 2b show electron emission patterns from a W<110> tip just after flashing and after remolding of (100) facets, respectively. Figs.2c-2f show the emission patterns from the remolded tip deposited with liquid-gallium of 2.5nm thickness. When the applied voltage was negatively increased from zero just

after deposition, gallium droplets migrated from the shank to the remolded (100) facets by surface diffusion (2c and 2d). At the critical voltage of -3.19kV , a liquid-gallium cone was formed on the remolded facet (2e). When the voltage was further increased, a new cone was formed on another remolded facet (2f).

Figure 2: Electron emission patterns from the $W<110>$ tip (a,b) and the tip deposited with liquid-gallium of 2.5nm thickness (c-f). (a) after flashing, applied voltage $V = -3.55\text{kV}$, total emission current $I = 1.05\text{ }\mu\text{A}$; (b) after (100)-remolding, $V = -3.19\text{kV}$, $I = 5.51\text{ }\mu\text{A}$; (c) $V = -2.85\text{kV}$, $I = 0.35\text{ }\mu\text{A}$; (d) $V = -3.04\text{kV}$, $I = 1.56\text{ }\mu\text{A}$; (e) $V = -3.19\text{kV}$, $I = 125\text{ }\mu\text{A}$; (f) $V = -3.36\text{kV}$, $I = 259\text{ }\mu\text{A}$.

3.2.2 $W<111>$ tip

The electron emission patterns from a $W<111>$ tip just after flashing and after remolding of (111) facets are shown in Figs.3a and 3b, respectively. The emission patterns from the remolded tip deposited with liquid-gallium of 2.5nm thickness are shown in Figs.3c-3e. When the applied voltage was negatively increased from zero just after deposition, a liquid cone was suddenly formed on the remolded (111) facet

at the critical voltage of -3.36 kV (3c). When the applied voltage was decreased to zero after cone formation and was again increased, a weak small pattern appeared on the same remolded facet (3d) and became bright gradually with the voltage (3e). It should be noted that these patterns are not circular, but distorted. The similar phenomena were also observed for the $W\langle 110 \rangle$ tip.

Figure 3: Electron emission patterns from the $W\langle 111 \rangle$ tip (a,b) and from the tip deposited with liquid-gallium of 2.5 nm thickness (c - e). (a) just after flashing, $V = -4.35\text{ kV}$, $I = 3.15\text{ }\mu\text{A}$; (b) after (111)-remolding, $V = -3.48\text{ kV}$, $I = 2.32\text{ }\mu\text{A}$; (c) $V = -3.36\text{ kV}$, $I = 134\text{ }\mu\text{A}$; (d) $V = -2.08\text{ kV}$, $I = 0.42\text{ }\mu\text{A}$; (e) $V = -3.56\text{ kV}$, $I = 81.4\text{ }\mu\text{A}$.

From the experimental results described above, the formation sites of liquid-gallium cone were found to correspond exactly to the remolded facets. This is the same result as that for liquid-lithium cone[8]. When the applied voltage was decreased to zero and was again increased, the results were different from those of liquid-lithium. Because stable liquid-lithium cones are reproductively formed.

3.3 Electron emission current characteristics

Typical total emission currents for the (100)-remolded W<110> tip deposited with liquid-gallium of 2.5nm thickness are plotted against the applied voltage in Fig.4. The closed (●) and open (○) symbols indicate the currents when the tip voltage was applied for the first time after deposition, and the currents when the applied voltage was decreased to zero and then again increased, respectively. In the former case, the emission current jumped from 3.7 μA to 190 μA at the applied voltage of - 2.84kV and simultaneously the emission pattern changed. As the work function of liquid-gallium is constant, the current jump suggests the sharpening of liquid shape and therefore the cone formation. In the latter case, on the other hand, the emission current monotonously increased with the applied voltage and had no jump. This result is very similar to that of Rao et al. [3]. No liquid-gallium cone is formed in this case. In the former case, the emission current after the cone formation suddenly decreased at the lower voltage than -2.84kV when the applied voltage was decreased. In other words, the current showed the hysteresis. For the fixed applied voltages, the emission current decreased linearly with time, as in the case of liquid-

Figure 4: Typical total emission characteristics for the liquid-gallium deposited W<110> tip, ●: when the tip voltage was applied for the first time after deposition and ○: when the applied voltage was decreased to zero and then again increased. △: (100)-remolded tip without deposition and its vertical axis is shown on the right.

Figure 5: Total emission current characteristics in Fig.4, represented using the log scale.

lithium deposited tip [6]. This decrease may be caused by the thermal evaporation of gallium due to the Joule's heating. In the figure, for reference, the currents for the (100)-remolded tip without deposition are shown by the symbol (Δ). It is found that the deposition of liquid-gallium makes the emission current about two order of magnitude larger.

Fig.5 shows the emission characteristics in Fig.4, represented using the log scale. When the tip voltage was applied for the first time after deposition($\bullet$), the increase rate of the emission current changed drastically at -2.84kV where a gallium-cone was formed. The increase rate after the cone formation was 1.64. Therefore it is reasonable to consider that the emission current after the cone formation obeys the Child-Langmuir's law, namely,

$$I = PV^{3/2}, \quad (2)$$

with perveance P of $3.40 \times 10^{-10} \text{A/V}^{3/2}$. In other words, the stabilization mechanism of liquid-gallium cones is the space charge effect as well as in liquid-lithium cones [9]. When the applied voltage was decreased to zero and then again increased($\circ$), on the other hand, the increase rate of the emission current was about 11 and hence the current doesn't obey the Child-Langmuir's law.

4. CONCLUSIONS

For $\langle 110 \rangle$ and $\langle 111 \rangle$ oriented tungsten tips deposited with liquid-gallium, electron emission patterns and electron emission characteristics were studied by field emission microscopy. When the tip voltage was applied for the first time after deposition of gallium, stable liquid-gallium cones were formed on the remolded facets for the thicknesses of $1.5 \sim 5\text{nm}$ and DC electron emission occurred. The total emission current obeyed the Child-Langmuir's law. Therefore the stabilization mechanism of liquid-gallium cones is the space-charge effect. When the applied voltage was decreased to zero after cone formation and again increased, liquid cones were not formed. In this case, the electron emission from the liquid-gallium droplets probably occurs. The cone formation process of liquid-gallium isn't recursive in contrast with that of liquid-lithium. For thickness more than 5nm , no stable cone was obtained and only explosive pulsed emission resulted. The emission patterns of Figs.2a and 3a differed from those for clean tungsten tips because of the insufficient flashing. The investigations with clean tungsten tips are now in progress.

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