Stable field-induced electron emission from a solidified liquid metal ion source

L. W. Chen and Y. L. Wang
Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 106, Taiwan, Republic of China and Department of Physics, National Taiwan University, Taipei 106, Taiwan, Republic of China

(Received 19 August 1997; accepted for publication 19 November 1997)

Stable field-induced electron emission is derived from a tungsten tip covered by indium which has been solidified from its liquid state during an ion emission process. By choosing different ion emission currents at the beginning of the solidification process, the final geometry of the solidified emitter can be reshaped and the characteristics of the electron emission changed. The Fowler–Nordheim equation is used to infer the geometry of the electron emitter prepared by various solidification processes. The dual ion/electron point source is expected to have high potential applications in focused ion and electron beam technologies. © 1998 American Institute of Physics.

Since the employment of a liquid metal ion source (LMIS) for the formation of focused ion beam (FIB), this microlithographic and microimaging technology has gradually evolved from a pure research curiosity into an industrial reality. In the last few years, this rapidly developing technology has found many important academic and industrial applications. Among them are scanning ion microscopy, high spatial resolution secondary ion mass spectrometry, in situ semiconductor device fabrication, beam-induced selective area material deposition and etching, photolithographic mask repair, and sample preparation for transmission electron microscopy. In many of the applications, it is necessary to conduct in situ inspections of the sample before and after the microsurgical operation. Such inspections can help monitor the progress of the operation and correct the errors in the designed procedure. A FIB, which is similar to a scanning electron microscope (SEM) in many respects, can also be used for the inspection. However, due to the inherently large momentum of ions, a FIB is highly destructive and materials are continuously sputter-removed from the sample surface during the inspection. Details of a microstructure could be eroded away before a meaningful measurement is achieved. Therefore, a system equipped with both SEM and FIB is highly desirable for microsurgical applications. The much less destructive SEM is used for inspection while the FIB is used primarily for sputtering and deposition. For obvious economic reasons and for certain types of applications (e.g., both the ion and electron beams need to incident normally on the sample surface), it is beneficial to design a single optical column capable of delivering both focused ion and electron beams. A key step towards constructing such a dual focused ion/electron beam (FIEB) system is to have a stable dual ion/electron point source. In this letter, we describe the first successful operation of such a dual source based on an indium (In) LMIS.

This experiment was carried out in a vacuum chamber with a base pressure of \(1 \times 10^{-9}\) Torr. A commercial In LMIS (FEI Inc.) was mounted on a system (Fig. 1) designed for measuring both the ion and electron current at different extraction voltages \(V_s\). The total ion \(I_{ti}\) and electron \(I_{te}\) emission currents and their respective fractional currents \(I_{ti}\) and \(I_{te}\) collected by the Faraday cup were used to characterize the emission properties of the dual ion/electron source.

Typical \(I_{ti}\) vs \(V_s\) for various heating currents \(I_h\) are shown in Fig. 2. The threshold voltage is \(\sim 6\) kV and the minimum \(I_h\) needed for stable ion emission is \(\sim 2.3\) A. Larger \(I_h\) and therefore higher source temperatures lead to larger ion emission currents for given \(V_s\). Similar ion emission characteristics have been reported previously. Kang and Swanson suggested that ions are field-evaporated from a conical protrusion on the end of the Taylor cone, which is formed on a LMIS subjected to a critical electric field. According to this so called “jetlike protrusion” model, when the extraction voltage is increased, the field on the protrusion apex remains constant due to the increase of its radius. Since the total area responsible for ion emission increases with the apex radius, the total emission current also increases. The observed temperature dependence of ion emission current (Fig. 2) can be attributed to the change of the field strength needed for the field evaporation. Higher temperature reduces the field required for evaporation, and there-

---

**Fig. 1.** Schematic of the experimental setup. The anode–cathode spacing is 0.1 cm.
fore increases the emission current at a given field strength. Qualitatively, the model is consistent with the experimental results. It also suggests that an emitter’s radius could be frozen to different values by choosing different ion currents during a cooling process.

In order to extract stable electron emission from the dual ion/electron emitter, the source is first operated in the ion emission mode with a desired ion current. This is achieved by choosing adequate \( I_h \) and \( V_s \). The emitter is then quenched to room temperature by turning off \( I_h \) while maintaining \( V_s \). For better ion emission stability, we typically operate the source at \( I_h = 2.9 \, \text{A} \) before the quenching starts. The corresponding temperature of the source assembly is estimated to be \( \approx 300 \, ^\circ\text{C} \). Usually, once \( I_h \) is turned off, the ion emission continues for several seconds before it abruptly drops to zero. The delay time depends on the ion emission current at the beginning of the quenching process and the higher the ion current the longer the delay time. A few minutes after the quenching, the polarity of \( V_s \) is changed to operate the emitter in the electron emission mode. Figure 3 shows typical electron current \( I_{ce} \) vs \( V_s \) for the electron emitters prepared by quenching the LMIS during ion emission at various currents. Within the spatial position and angular resolution of our measurement system, we do not observe any significant shift of the emission point or misalignment of emission axis with respect to the ion beam. However, comparable stability in the position and alignment of the electron beam is not achieved in other LMIS we have studied. (The stable electron emission from the solidified metal is different from the pulse electron emission from a liquid metal reported by Swanson.)

The electron emission characteristics appear to depend on the ion emission current at the beginning of the solidification process. In order to further quantify the size of the electron emitter, we resort to the Fowler–Nordheim theory of field-induced electron emission. According to the theory, the current density \( J \) (A/cm\(^2\)) as a function of the field strength \( E \) (V/cm) and the work function \( \phi \) (eV) can be expressed as

\[
J = \frac{1.55 \times 10^{-6} E^2}{\phi} \exp \left( -\frac{6.86 \times 10^7 \phi^{3/2}}{E} \right) \times v(y),
\]

where \( v(y) \) is Nordheim’s elliptic function of variable \( y = 3.62 \times 10^{-4} E^{1/2}/\phi \). By assuming \( E = V_s/V_s' \), where \( \beta \) is a constant depending on the geometry of the emitter, we can convert the equation to one of \( \log(I_{ce}/V_s^2) \) vs \( 1/V_s \), so that it can be used to fit our experimental data. The characteristic of an emitter is usually described by its slope \( \alpha \) in a Fowler–Nordheim plot, which is denoted by

\[
\alpha = \frac{-3 \times 10^7 \phi^{3/2} s(y)}{\beta}.
\]

Since we are interested in the relative size variation of the emitters, only the relative slopes in the Fowler-Nordheim plot are of concern. Substituting \( \phi = 3.8 \, \text{eV} \) for In and \( s(y) = 1 \), \( \alpha \) can be related to the radius of the emitter because \( \beta \) is estimated to \( 1/5r \), where \( r \) is the radius of emitter. Based on the above assumptions, the radii of the emitters prepared under different ion–emission currents appear to change by a factor of 2 (Fig. 4). The corresponding absolute sizes of the emitters are estimated to be between 100 and 200 nm. Quenching while emitting a larger ion current indeed leads to the formation of a blunter emitter. Qualitatively, we could try to understand the mechanism of the change in the emitter radius as follows. After turning off \( I_h \), the ion emission does not terminate until the temperature approaches the melting point of the LMIS. Therefore, the radius and shape of the emitter in the electron emission mode depend on the ion emission current during the quenching process. An immediate implication of this observation is that one can reshape the emitter and change its electron emission characteristics by setting the ion emission current at certain desired value before starting the quenching process.

For most practical applications, both the ion and electron emission currents from the dual ion/electron point source have to be stable within a time frame of at least a few hours. Since the stability of ion emission from In LMIS is well known, we have concentrated only on the long-term stability of the electron emission from a solidified In dual ion/electron emitter. The source presents excellent stability in the low current (\(< 100 \, \text{nA}\) emission region. Typically, the current exhibits an initial decay to \( \approx 80\% \) of its initial value in the first hour of operation. Then it remains at this level with
less than 5% fluctuation during a course of more than 5 h. Even for a high emission (> ≈ 1 μA) mode, the source exhibits good stability as shown in Fig. 5. During a course of more than 5 h, current fluctuation is maintained at less than ~10% after the initial phase of decay.

We would also like to point out that the stability of the electron emission depends on the quenching process of the liquid In. Quenching under a higher ion emission current leads to the formation of a blunter emitter whose electron emission characteristics also appear to be less stable. It is plausible to imagine that a blunter emitter, which has been quenched under larger ion emission, could also contain more wrinkles or micro-protrusions on its surface. Field-induced evaporation of the atoms or adsorbates from the surface of these microstructures could lead to a change in their geometry or work functions. Such changes could certainly result in a change of the electron emission characteristics, reducing the stability of the source. Therefore, we believe that the stability of the electron source can be further improved by reducing the chamber pressure and fine tuning the solidification process.

In conclusion, we have demonstrated the first operation of a dual ion/electron point source derived, respectively, from liquid and solidified In on a sharp W tip. For ion emission, the source is operated as a well-known liquid metal ion source. For electron emission, the emitter is first prepared by quenching the liquid metal during ion emission and then subjected to an extraction field of the opposite polarity. The electron emission characteristics can be manipulated by changing the quenching procedure and stable electron current from a well-prepared emitter can be maintained for a long period of time. Such an electron source can also be rejuvenated by temporarily operating the source in the ion emission mode and then switching back to the electron emission mode. Demonstration of this dual ion/electron point source is an important step toward the fabrication of a dual focused ion/electron beam column.

This work was supported partly by the National Science Council (Contract No. 86-2112-M-001-015), and United Microelectronics Corp. Taiwan, Republic of China.

References