PROSPECTS OF LIQUID METAL ION THRUSTERS
FOR ELECTRIC PROPULSION

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ABSTRACT

Liquid Metal Ion Sources (LMIS) have a wide range of applications in focused ion beam technology. A special type of LMIS is the liquid metal ion thruster developed at the European Space Research and Technology Centre (ESTEC) for Field Emission Electric Propulsion (FEEP). Combining this technology with the microfabrication methods developed at the Stanford Research Institute (SRI) for microvolcano ion sources, there results the concept of "Miniaturized Liquid Metal Ion Sources (MLIMS)".

Although the use of condensable liquid metal propellants such as cesium has caused reluctance on the part of potential users because of their concern over spacecraft contamination, for the future there appear interesting prospects for electric propulsion using LMIS-thrusters, e.g., spacecraft without solar energy conversion power supplies; that applies especially to prospective spacecraft with nuclear electric propulsion (NEP) systems.
polarity, the free electrons are rejected into the bulk of the liquid metal, while the ions are accelerated and expelled from the emitter by the same electric field which has ionized them. The charged particles leaving the liquid metal surface as an ion beam are replenished by the hydrodynamical flow of the liquid metal. The liquid metal more or less is converted directly into an ion beam without the transitional vapor phase which is common in the technology of other ion sources; therefore ionization operates with high power efficiency.

Because the radius of curvature at the apex of such a cone is of the order of $10^{-7} \text{m}$ or less, for interelectrode spacings of some $10^{-2} \text{m}$ applied voltages of some $10^4 \text{V}$ are sufficient to obtain the required high electric fields. A rough criterion for onset of ion emission is given by the assumption that electrostatical forces and surface tension forces are in balance.

Stable and exceedingly bright ion emission with a rather low energy spread from an extremely small apex region of the liquid metal cone characterizes the ion beam and result in some unique applications which never may be met by other ion sources. Single-site ion emission with currents up to several $10^{-8} \text{A}$ may be obtained with a brightness in excess of $10^8 \text{Acm}^{-2} \text{s}^{-1}$.

For a multiplicity of scientific and technical applications especially devoted to microelectronics technology and surface analysis, LMIS of the needle type and sometimes of the capillary type have been used with a variety of pure metals (e.g., Ag, Au, Bi, Cd, Cs, Ga, Hg, In, K, Li, Na, Pb, Sn, Tl) for nonmetals (e.g., As, B, Be, Ge, Si) or excessively volatile metals, binary or ternary alloy combinations have been used to obtain ions from otherwise unaccessible species.

In LMIS, ion beams can be created from liquid metal wetted needles (or arrays of needles) or from capillaries into which the liquid metal is allowed to flow. As in the case of the slit emitter, the capillary is elongated to a long slit of nearly rectangular cross section, allowing therefore the occurrence of a series of emitting cones, each of them contributing to the ion beam. This different types of ion beam emitters schematically are outlined in Fig.1.

**Fig.1: Schematic diagram of different types of liquid metal ion sources:** (a) pin or needle type; (b) tube or capillary type; (c) elongated slit type. Left: shape of the liquid metal tip without electric field. Right: distortion of the liquid metal tip by an electric field due to a positive emitter potential $+U_e$ and a negative accelerator potential $-U_{acc}$ versus common ground.

**SEMI-MINIATURIZED LIQUID METAL ION SOURCES**

When the European Space Agency (ESA) starts its own development programme on electric space propulsion in 1968, the first activities were devoted to the exploration of a colloid thruster, and the idea of using linear emitter geometries instead of capillary or annular shaped electrodes was advanced.

At the European Space Research and Technology Centre (ESTEC), the slit emitter progressively has been developed and evolved from a single-pin emitter through linear arrays of stacked needles to the presently favored emitter module 1/1. Due to the micron-sized dimensions of both the emitter slit width and the resulting emission site spacing, the slit emitter may be regarded as a semi-miniaturized LMIS.

This type of liquid metal ion source represents an ultimate development in precision mechanics, demonstrated by actual numerical values of about $10^{-4} \text{m}$ for both the emitter slit width and the round-off radius of the emitter slit edges. Nevertheless, due to the rather large interelectrode spacing of about $10^{-3} \text{m}$, the operating voltage of the device is above $10^4 \text{V}$ for an emission current of $5.10^{-4} \text{A}$.

The slit emitter module in principle consists of two symmetrical highly polished metal plates. In one or both of the emitter halves there is milled a recess to be used as a reservoir of the liquid metal supplied to the emitter module either by an open funnel or a feeding capillary tube. On certain regions of one of the emitter faces (i.e., on the circumference of the reservoir despite the area adjacent to the emitter edge), there is sputter deposited a layer of nickel with a thickness of the order of $10^{-6} \text{m}$. When the two halves are tightly clamped together, they are separated by the thickness of this layer, thus forming a narrow slit of width $w$ and depth $d$ through which the liquid metal can flow and be transported to the edges of the slit by the action of capillary forces. Until now, a number of emitter modules with slit lengths of 1, 3, 5, and 8 cm have been produced. Although in principle every liquid
metal or alloy may be used in LMIS, the slit emitter generally has been operated with cesium.

The electrode configuration widely used to create the proper electric field at the emitter slit edge region is shown in Fig.2. A plane accelerator electrode with an aperture of width $2b$ is mounted in a distance $a$ of the emitter slit edge. Emitter and accelerator are kept at voltages $+U_s$ and $-U_{AC}$, respectively, versus ground potential in order to create the electric field necessary to produce and accelerate the ion beam. Typical data for the emitter-accelerator geometry according Fig.2 are as follows: $a=1.10^{-4}m$, $2b=4.10^{-3}m$, $d=5.10^{-3}m$, $N=1,2.10^{-4}$.

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**MINIATURIZATION OF LIQUID METAL ION SOURCES**

**State-of-the-Art Technology**

Compared with former constructions, the slit emitter is a semi-miniaturized LMIS due to its emitter slit width of about $10^{-6}m$, which results in an even micron-scaled emission site spacing. However, complete miniaturization of a LMIS requires the reduction of all dimensions to a micrometer scale too. Generally, the principal types of LMIS outlined in Fig.1 are capable of miniaturization. In any case, the crucial problem is the development of fabrication methods which allow to produce such micron-sized structures of metals and insulators. Therefore, methods adopted from semiconductor microelectronics technology as well as from vacuum microelectronics shall improve this situation.

More than ten years ago, using unique electron beam processing and fabrication techniques, it was demonstrated at the Stanford Research Institute (SRI) that individual metal field emitter array (FEA) elements ("Spindt Cathodes") and arrays of these elements could be fabricated with dimensions as small as solid state devices /8/.

At SRI, this technology has been adapted to fabricate micro field-ionizers of the shape of miniature volcanos (Fig.3) for mass spectroscopy of gas samples /9/. This volcano ionizer has been further miniaturized into a microvolcano structure having a volcano orifice with a diameter of about $1.10^{-4}m$, and an integrated counter electrode with an aperture diameter of about $1.5.10^{-4}m /10\%$. Furthermore, the microvolcano can be fabricated in arrays with packing densities of the order of $10^4cm^{-2}$, corresponding to a center-to-center spacing of $1.10^{-4}m$, as is shown in Fig.4. This is a very recent development, but preliminary results have shown that gaseous ions can be formed with the microvolcano with applied voltages of less than 100V.��耗
In Fig. 5 there is outlined the cross section of such a microvolcano field ionizer, showing the metal-insulator-metal sandwich structure with an undercut cylindrical cavity in the oxide layer and containing a metal microvolcano with an extremely sharp rim, surrounded by the gate electrode with an aperture diameter of about 1.5·10⁻⁴m.

Miniature and microvolcanos have been used successfully as ion sources for quadrupole mass spectrometers and Wien-filter spectrometers as non-fragmenting field ionizers for gas samples /9/. Clearly, a logical extension of the ionization of gas samples is the use of liquid sample material, especially liquid metals.

Forthcoming Concepts

If one compares the electrode geometries of the slit emitter (Fig. 2) and of the microvolcano (Fig. 5), the striking parallelism is evident. Although the accelerator dimensions, the interelectrode spacing and the emitter body extensions are of a macroscopic scale between 10⁻¹⁻¹ and 10⁻³m, it is obvious to transform the semi-miniatu- rized slit emitter LMIS to a completely miniaturized and integrated LMIS, therefore utilizing the acronym MILMIS in its original sense.

The technology of FEA's and microvolcanos in principle even allows the fabrication of miniaturized, lateral-extended, wedge-shaped cathodes and slit emitters with cross sections corresponding to those shown in Fig. 5. If one adds a proper liquid metal reservoir to such an elongated microvolcano, the device represents a fully miniaturized and integrated slit emitter module, with much lower operating voltages to be anticipated than that of the original model.

However, heating of the whole device above the melting temperature of the liquid metal even has to be performed by miniaturized and integrated heater elements. Conforming technologies recently have been developed for vacuum microelectronics applications, resulting in either thermionic integrated circuits which operate at 800°C /11/ or in fine heating elements operating at about 1000°C /12/. In any case, high temperature resistant materials were used which are compatible with the fabrication technology of FEA's and microvolcanos.

An important requirement is the selection of a proper combination of both the emitter electrode material and the intended liquid metal which allows capillary feeding to the emitter slit orifice. The emitter material has to be wetted easily by the liquid metal and the material properties of the latter have to be sufficient to make the liquid metal flow feasible within a micron sized capillary and to allow a meniscus to occur at the slit orifice.

Combining the basic schemes of LMIS shown in Fig. 1 and the state-of-the-art fabrication technologies, in principle MILMIS may be produced in a large variety, e.g., single site microvolcanos and linear or two-dimensional arrays of microvolcanos as well as slit emitters or parallel arrays of slit emitters. Furthermore, it appears feasible to convert the Spindt cathode into a single tip or a tip array of MILMIS of the pin or needle type. In this case, one has to care for a liquid metal supply by wetting the metal cones only, covering the latter with a thin liquid metal film.

Finally, even a substrate with an array of cones or wedges covered by a liquid metal film and opposed to a planar counter-electrode is of considerable interest, as such a device complies with a recent theoretical study on large-area Lis /13/. In this case, the originally planar liquid metal surface which is thought to be distorted into a sharply peaked structure by hydrodynamically driven instabilities, will be superseded by the array structure covered with liquid metal with the apices of the cones or wedges as preferential emission sites.

A similar concept formerly has been applied to electron emission from liquid mercury pool cathodes, inserting a solid metal anchor wetted by mercury /14/, /15/. High current density field emission emanating from an intrinsically microstructured solid substrate of molybdenum with a diameter of 5mm covered by a thin Hg-film ("Film cathode") and capable of supplying pulsed currents of more than 10mA with an average current density of about 5·10⁴Acm⁻² has been demonstrated /16/, /17/.

CONCLUSIONS AND OUTLOOK

Due to the advanced progress in vacuum microelectronics technology, the fabrication of large-area arrays of microstructures (e.g., microvolcanos, wedges, and tips) for high current LMIS appears feasible.

As far as the main disadvantage of LMIS thrusters, i.e. the danger of spacecraft contamination by the metallic propellant, is of minor importance (e.g., for interplanetary space missions with solar energy power supplies using nuclear electric propulsion), the benefits of FEEP (e.g., a considerable mass saving compared to xenon ion thrusters) offer an interesting alternative.

REFERENCES


