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## LMIS ENERGY BROADENING INTERPRETATION SUPPORTED BY HV-TEM OBSERVATIONS

G. Ben Assayag and P. Sudraud

*Laboratoire de Physique des Solides, 91405 Orsay, France*Résumé

Les largeurs énergétiques des faisceaux d'ions émis par LMIS de métaux nobles ont été mesurées. Une interprétation concernant la dispersion énergétique des ions simples est proposée à partir de l'effet Boersch et des résultats obtenus en microscopie électronique haute tension in-situ de LMIS.

Abstract

We give the values of energy spread for noble metal LMIS. An interpretation for simple ions is given using Boersch effect and results obtained in HV-TEM of Ga LMIS.

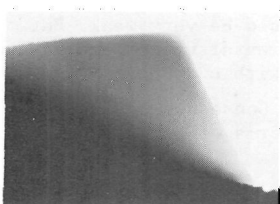
I. INTRODUCTION

Concerning the physical mechanism of LMIS emitters, the first theoretical treatments based on the conical-shape assumption (R. Gomer, 1) present some discrepancies with experimental results. The difficulty in interpretation comes from a poor knowledge of the exact shape of the emissive zone. Our recent HV-TEM observations clearly proved that the shape of liquid tip on a LMIS is not exactly a cone (2). The shank of the pseudo-cone is curved and a fine protusion exists at the apex. Radius of the protusion is about 3 nm for an ionic emission of 9  $\mu\text{A}$ .

As a consequence of the very small apex radius the density of emitted particles is locally very high, so that the coulombian forces can be important. The present paper investigates this possibility to explain energy spread of LMIS, more particularly in the case of simple ions. For this purpose, we have combined Kingham and Swanson model (3) which have the advantage to give values of the apex shape and radius rather compatible with experimental TEM observations, with Knauer's theory based on Boersch effect.

II. EXPERIMENTAL CONSIDERATIONS*II.1) TEM observations.*

For these observations we used the 3 MeV TEM of Toulouse with a special specimen holder allowing in-situ working with LMIS. Fig. 1 presents the aspect of the liquid meniscus under increasing electric field. We denote three regimes : onset regime, stable emission, high current emission with hydrodynamical instabilities.



*Onset regime. (Fig. 1a) - It is well known that the "Taylor cone" and ionic emission appear for a critical voltage  $V_c$  when surface and electrostatic stresses are equal. Initially, the liquid meniscus is spheroidal. During the voltage increasing, liquid takes an ellipsoidal aspect, then for  $V$  very close to  $V_c$  liquid oscillation appears between ellipsoidal and the future conical shape. The frequency of these oscillations increases with  $V$  and for  $V = V_c$  the oscillations stop and "Taylor cone" stays stable with about 1  $\mu\text{A}$  emission.*

*Fig. 1a -  $V=4,63$  kV  
 $I < 1 \mu\text{A}$*

*Intermediate current (Fig. 1b.c)* - If the famous conical aspect described by Taylor represents rather well the general shape of the phenomenon, a more detailed study shows some differences between LMIS hydrodynamic structure and a perfect cone. When the current increases, the "cone" walls become more and more concave and apex seems more and more pulled by field. Liquid has a cuspidal rather than a conical shape. A fine jet-like protusion which diameter is equal or less than 3 nm for 10  $\mu$ A emission is clearly visible for current  $I > 9 \mu$ A.

*High current regime (Fig. 1d)* - For an emission current more than 70-80  $\mu$ A, the "pseudo-cone" becomes unstable with apex bursting. Particle emission spreads over a large area of the cone walls; this high current regime is accompanied by an intense heating coming from secondary electron bombardment arriving from bombarding extracting plate.

A better knowledge of the apex structure is the most interesting result of this experimentation. For currents ranging about 10 microamperes a fine protusion exists. The shapes and size observed increase with the current according to K-S theory. Curve 2 gives protusion radius from K-S calculation of Ga LMIS. Apex size observed agreed well enough with this calculation. If we admit a K-S like model, the existence of the protusion near onset can reasonably be postulated. Following this assumption, it is clear that the maximum resolution ( $\sim 15 \text{ \AA}$ ) of our HV-TEM experiments does not allow the observation of such a thin structure (some angstroms) near onset.

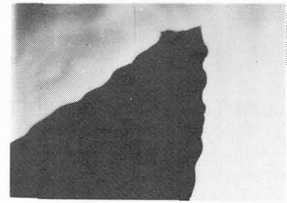


Fig. 1b -  $V = 4 \text{ kV}$   
 $I = 10 \mu\text{A}$ .

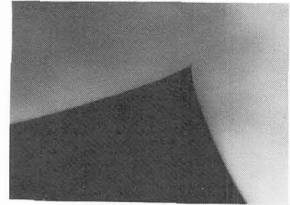


Fig. 1c -  $V = 5,5 \text{ kV}$   
 $I = 30 \mu\text{A}$ .

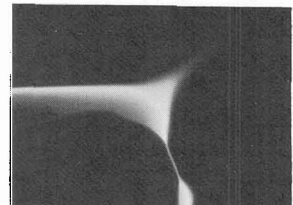
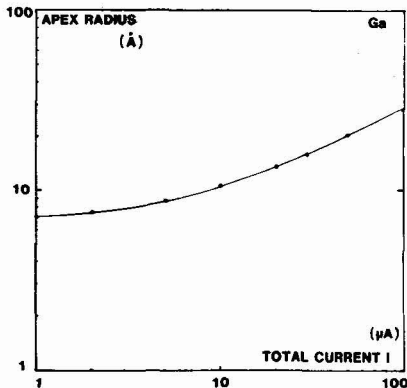


Fig. 1d -  $V = 5,4 \text{ kV}$   
 $I = 100 \mu\text{A}$ .



Curve 2

of the order of several eV at the onset and increase quickly with current.

These values do not agree with a field evaporation process. Consequently, we have searched for an interpretation of this energy broadening in terms of Boersch effect, taking into account KS LMIS model.

### III. THEORETICAL CONSIDERATIONS

Boersch effect is well-known from intense electron beam users. It concerns a various kind of phenomena in which energetic width increases with the total emitted current.

#### II.2) Energy broadening.

A modified double focusing spectrometer is used to record energy spectra of ions. With such a system (4,5), it is possible to obtain the energy spread of each species present in the ionic beam. Next table (3) shows the results obtained for Cu and Ag (6) (we include measurements we have got for Au (7) and for Sn and Ga (4,5)).

Recent calculations of Kingham and Swanson (3) about LMIS emission mechanisms seem to prove that the field evaporation is preponderant in ion production. If so energy spread of ions would be very weak. But the published experimental values are always

Some authors mathematically treated this problem such as Loeffler (8) and Zimmermann (9). Recently, Knauer (10) has adapted those descriptions to ion beams. From Knauer, the expression of the velocity redistribution is given by :

$$\overline{\Delta E} = 5,8\pi \frac{e}{4\pi\epsilon_0} \left(\frac{m}{V_0}\right)^{1/3} R_s J_s^{2/3} \quad (1)$$

where :  $R_s$  = effective source radius ;  $J_s$  = current density ;  $m$  = particle mass ;  
 $\Delta E$  = energy width ;  $V_0$  = applied voltage.

This expression rewritten in terms of total emission current  $I$ , angular density  $I_\Omega$  and half-angle beam aperture  $\alpha$  is :

$$\overline{\Delta E} = \frac{5,8\pi e}{4\pi\epsilon_0} \left(\frac{m}{V_0}\right)^{1/3} R_s^{-1/3} \left(\frac{I}{2\pi(1 - \cos \alpha)}\right)^{2/3} \quad (2)$$

$$\overline{\Delta E} = \frac{5,8\pi e}{4\pi\epsilon_0} \left(\frac{m}{V_0}\right)^{1/3} R_s^{-1/3} I_\Omega^{2/3} \quad (3)$$

It would be very interesting to use experimental values of all parameters involved in the above formula to evaluate directly  $\Delta E$ , but the accuracy of a few measurements remains too restricted to make use of the Knauer's relation. Therefore, the radius  $R_s$  can be calculated with Kingham's relation (3) :

$$F_e = 4,472 \times 10^{47} \text{ m}^2 I^2 / \rho R_s^4 + 2,259 \times 10^{11} \gamma / R_s$$

with  $F_e$  = evaporation field of the material ;  $\rho$  = volumic mass of the liquid ;  
 $\gamma$  = surface tension.

$\Delta E$  is known to be about 5 eV for  $I = 1 \mu\text{A}$ . With these values one can estimate the alpha angle at the apex to be 33 degrees from the equation (2). That angle value is consistent with the angular distributions recorded for Au, Ag and Cu (6).

Fig. (4) gives the observed FWHM of the energy distributions for Ga and Sn sources (stars) as a function of the emitted current. The continuous curves correspond to the calculated values from expression (2), keeping the alpha value estimated in the above emission conditions and using Kingham-Swanson relation to evaluate  $R_s$  (I).

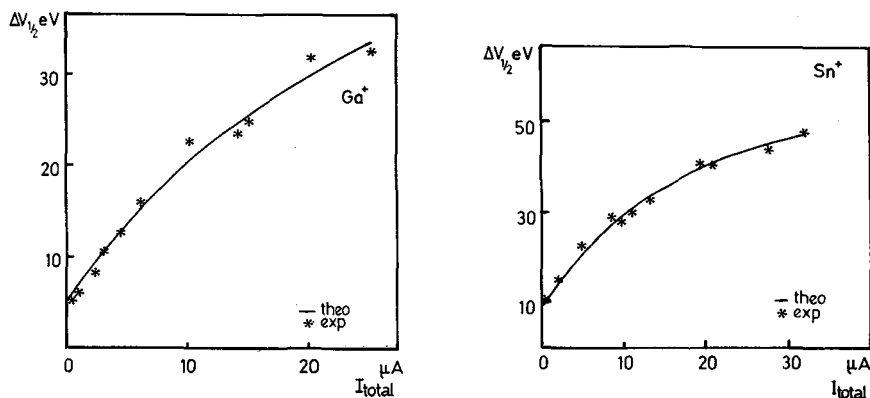


Figure 4

Following tables (3) give experimental and theoretical values of the energy FWHM for noble metals at various emission currents.

	Ag <sup>+</sup>		Cu <sup>+</sup>		Au <sup>+</sup>		
	1 $\mu$ A	6 $\mu$ A	5 $\mu$ A	10 $\mu$ A	18 $\mu$ A	1 $\mu$ A	100 $\mu$ A
exp.	7 eV	20 eV	16 eV	23 eV	27 eV	10 eV	60 eV
the.	6,8 eV	19 eV	15,5 eV	22,9 eV	29,7 eV	10,4 eV	79 eV

TABLE 3

This interpretation seems to agree rather well with experiment. We notice that such a calculation applied to clusters remains very doubtful actually. Indeed, the clusters density is much smaller and the coulombian interactions within beam are weak.

The other point which remains questionable is the constant angle value  $\alpha$  we kept in this calculation. However if one takes into account the curvature of trajectories near the emitter, the variations of this parameter can be considered as weak in the studied currents domain.

#### IV. CONCLUSION

By combining Kingham-Swanson and Knauer models we conclude that Boersch effect seems to be responsible of the energy broadening observed in LMIS for simple ions. This conclusion allow to reconcile a field evaporation process with simple ions broadening values. The interest of such interpretation is also to give indications to develop new LMIS with narrow energy width ; it would be possible using a high extraction voltage for low current or light weight and low evaporation field metals like lithium.

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