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CHANGE IN THE SURFACE TENSION COEFFICIENT OF METALS IN AN ELECTRIC FIELD

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Because of the development of electrohydrodynamic ion sources the question of change in surface tension coefficient of liquid metals in a strong electric field has taken on practical importance. The present work is an attempt to evaluate this effect. It is shown that in limitingly strong fields the change in γ does not exceed 10-20%.

The question of the change in surface tension coefficient of a liquid metal in a strong electric field is of practical importance in studies of electrohydrodynamic (EHD) ion sources [1, 2]. In such sources field evaporation of ions occurs from the curved surface of a liquid metal located in an electric field of intensity $E_0 \sim 10^8$ V/cm. Surface equilibrium is insured by equality of the capillary and electrical pressures:

$$E_0^2/8\pi = 2\gamma/r. \qquad (1)$$

Knowing E_0 and the surface tension coefficient γ, Eq. (1) can be used to calculate the radius of curvature of the emission zone r [3], which is an extremely important characteristic determining the parameters of the EHD-emitter.

However it cannot be excluded that in an electric field the value of γ decreases. In the fields usually achieved such changes are obviously small, and the authors have found no study which considers this question. However EHD-emitters produce the highest field intensity which can be applied to a surface (at higher intensities ion emission increases intensely so that the ionic space charge screens the field), so that the change in the surface tension coefficient can in principle be significant.

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TABLE 1

Metal	δ, 10^{-8} cm	ε	E_0, 10^8 V/cm	γ_0, erg/cm^2	$\Delta\gamma$, erg/cm^2
Li	0,63	1,02	1,44	398	29
Na	0,86	1,5	1,06	190	33
K	1,2	1,2	0,67	114	15
Rb	1,3	1,2	0,56	77	11

The liquid surface energy can change as a result of ion emission and penetration of the electric field into the depths of the metal. Upon ion emission "holes" are formed in the surface layer of atoms, as a result of which the surface area increases. For gallium the atomic surface density $\sigma \sim 10^{15}$ cm^{-2}, which at the minimum stable emission current density $j = 5 \cdot 10^7$ A/cm^2 [4] corresponds to a mean surface atom lifetime $\tau_0 \sim 3 \cdot 10^{-12}$ sec. If we consider that a "hole" heals over the time of an atom's oscillation in the lattice $\tau \sim 2 \cdot 10^{-13}$ sec, then the "holes" will cover approximately 10% of the surface area, which should lead to an approximate 10% increase in γ. Meanwhile it is obvious that if the field intensity is decreased slightly (so that emission disappears) this effect will cease completely.

Another effect is change in surface energy because of electric field penetration into the depths of the metal. The field intensity E depends on the penetration depth x as

$$E(x) = E_0 \exp(-x/\delta), \tag{2}$$

where $\delta = \sqrt{\varepsilon_F/(6\pi n_0 e^2)} \sim 0.5 \cdot 10^{-8}$ cm; E_0 is the field at the surface; $\varepsilon_F \approx 5$ eV is the Fermi energy; n_0 is the free electron concentration [5]. Thus, the field surface energy in the metal

$$W_{in} = S \int_0^{\infty} \frac{\varepsilon E^2(x)}{8\pi} dx = S \frac{\varepsilon}{8} \frac{E_0^2}{\pi} \frac{\delta}{2}$$

(where ε is the dielectric permittivity of the ion core). In order to evaluate ε, we make use of the known values of metal ion polarizability χ [6]:

$$\varepsilon = 1 + 4\pi\chi n \tag{3}$$

(where n is the ion density). It is to be understood that these calculations are not completely correct, since due to electron shell deformation the ion polarizability changes. However if we calculate the dielectric permittivity of sulfur, silicon, and phosphorus in this manner, we obtain values of $\varepsilon = 2.4$, 4.4, and 3.1, respectively, while in fact we have $\varepsilon = 3.8$, 12.5, and 3.9. Thus the divergences are not too great. They are related to deformation of the outer electron shells, while in the ion core the outer electrons are collectivized and the inner shells are deformed much less severely. Therefore it can be expected that estimates of ε made with Eq. (3) (see Table 1) are reasonable.

In order to estimate the change in γ in an electric field we will consider a small segment of the spherical liquid surface of radius R. We will calculate the change in energy upon displacement of this segment of area S by a small distance ξ, with the motion occurring with constant charge, such that the new surface coincides with one of the "old" equipotentials and the electric field distribution outside the liquid remains as before.

The change in energy of the electric field in the volume occupied by the displaced liquid is

$$\Delta W_E = -E_0^2 S\xi/8\pi.$$

The change in liquid surface energy is

$$\Delta W_\gamma = \gamma_0 \Delta S = 2\gamma_0 S\xi/R$$

(γ_0 is the surface tension coefficient in the absence of an electric field).

The change in electric field energy within the metal is

$$\Delta W_{in} = W_{in}(\Delta S/S + 2\Delta E_0/E_0).$$

For constant charge

$$\Delta E_0 = -E_0 \Delta S/S, \quad \Delta W_{in} = -W_{in} \Delta S/S = -\frac{\varepsilon E_0^2}{8\pi} \delta S \frac{\xi}{R}.$$

In equilibrium the total change in energy upon displacement of the liquid surface will equal zero, i.e.,

$$-E_0^2 S\xi/8\pi + 2\gamma_0 S\xi/R - \frac{\varepsilon E_0^2}{8\pi} \delta S \frac{\xi}{R} = 0$$

or

$$2(\gamma_0 - \Delta\gamma)/R = E_0^2/8\pi \ \ (\Delta\gamma = \varepsilon\delta E_0^2/16\pi).$$

Values of $\Delta\gamma$ for various metals are shown in Table 1, while δ was calculated from Eq. (2) and E_0 from expressions presented in [7].

Thus, in an electric field γ decreases insignificantly (by 10-20% in limitingly high fields), while because of uncertainty in ε the value of $\Delta\gamma$ determined is not very accurate. However the author hopes that publications will appear in which this problem will be considered in greater detail.

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