One possibility of producing large-current ion beams

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The possibility is discussed of producing large-current ion beams by evaporating and desorbing ions from a metal surface under the influence of a strong electric field.

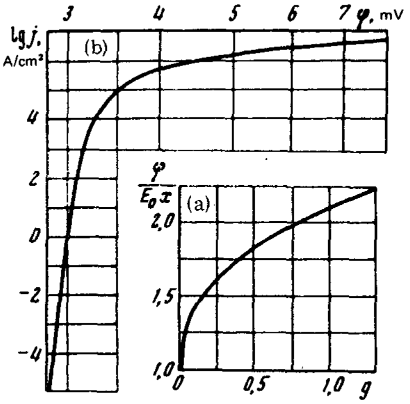
Strong-current ion beams (SIB) with currents $\sim 10^2$–10^3 A have been obtained in[1-3]. A number of pulsed strong-current ion beams were suggested, with currents $\sim 10^3$–10^6 A and energies $\sim 10^6$–10^9 eV.[4-6]

The purpose of this paper is to elucidate one more possibility of obtaining SIB, by evaporation and desorption of ions from a metal surface under the influence of a strong ($\sim 10^8$–10^9 V/cm) electric field. Questions concerning evaporation and desorption by a field are dealt with at microcurrent levels ($I \sim 10^{-10}$–10^{-7} A) in field emission ion microscopy.[7]

We consider the limiting ion current density (j_{lim}) obtained by field evaporation in the space-charge-limited regime. The field needed for evaporation can be produced near a needle-point electrode. Since the ion-current density (j) is maximal near the surface of the needle point, we estimate j_{lim} by using the model of a planar diode.

We obtain the simultaneous solution of the Poisson equation

$$\frac{d^2\phi}{dx^2} = \frac{\mu j}{\sqrt{\phi}}, \tag{1}$$



where

$$\mu = 4\pi\sqrt{\frac{m}{2eZ}}, \quad j = \text{const}\,(x),\ \phi = V_0 - V,\ V_0 = V|_{x=0}$$

with boundary conditions

$$\phi(0) = 0,\ \phi(x) = \phi,\ \frac{d\phi}{dx}(0) = E_0$$

and of the equation that describes evaporation by a field (in the approximation of thermally activated process):

$$j = j_0 \exp f(E_0), \quad f(E_0) = \frac{Ze}{kT}x_c(E_0 - E_c) - \frac{a}{2kT}(E_0^2 - E_c^2), \tag{2}$$

where V is the potential, m and eZ are the mass and charge of the ion, E_0 is the field intensity on the anode surface, E_c is the critical value of E_0, x_c is the critical distance from the anode surface, T is the surface temperature, $\alpha \equiv \alpha_a - \alpha_i$ and $\alpha_a(\alpha_i)$ is the polarizability of the atom (ion).

The solution (1) can be represented in the form of a cubic equation in $\sqrt{\phi}$, from which we get

$$\phi = \frac{E_0 x}{16g}\left[1 + 2\cos\left(\frac{4\pi}{3} + \frac{1}{3}\arccos G\right)\right]^2 \quad \text{at } g \leqslant \frac{1}{3},$$

$$\phi = \frac{E_0 x}{16g}\left(1 + 2\,\mathrm{ch}\frac{1}{3}\mathrm{arc\,ch}\,G\right)^2 \quad \text{at } g \geqslant \frac{1}{3}, \tag{3}$$

where

$$g = \mu^2 j^2 x E_0^{-3} \exp 2f(E_0), \quad G = 1 - 24g + 72g^2.$$

A plot of $\phi(g)$ is shown in Fig. a.

Expressions (2) and (3) determine the current-voltage characteristic (CVC) of an ion field-emission strong-current diode in the field-evaporation regime. It can be constructed by specifying the values of E_0 as a parameter in the interval

$$E_c \leqslant E_0 \leqslant E_B = a^{-1}[Zex_c - (Z^2e^2x_c^2 - 2aA_Z)^{1/2}]$$

[E_B is the upper limit of the applicability of (2), and A_Z is the energy difference between the ionic state at $x = x_c$ and the atomic state at $x_0 d_c$ in the case when $E_0 = 0$], and by obtaining j and from (2) and (3).

In the limiting cases we obtain: at

$$E_0 \approx E_c, \quad g \ll 1 \quad \phi \approx E_0 x\left(1 + \frac{4}{3}\sqrt{g}\right);$$

and at

$$E_0 \approx E_B, \quad g \sim 1, \ G \gg 1 \ \left(j \sim 10^6 \text{ to } 10^7\ \mathrm{A/cm^2}\right)$$

$$j_{\mathrm{lim}} = \frac{4\phi^{3/2}}{9\mu x^2}\left(1 - \frac{27x^2E_0^2}{16\phi^2}\right) \approx \frac{4\phi^{3/2}}{9\mu x^2} \ \text{(“three-halves” law).}$$

For a point with radius r_0 we have

$$E_0 = \frac{U}{\kappa r_0}, \quad \kappa = \frac{1}{2}\ln\frac{2D}{r_0}, \quad x \sim r_0, \quad \phi \sim \frac{U}{\kappa},$$

$$j_{\mathrm{lim}} \sim \frac{4}{9\pi r_0^2}\left(\frac{2eZ}{m}\right)^{1/2}\left(\frac{U}{\kappa}\right)^{3/2}, \quad I_{\mathrm{lim}} \sim \pi r_0^2 j_{\mathrm{lim}}, \tag{4}$$

where U is the applied potential difference and D is the distance between the cathode and the anode.

At U (pulsed) $\approx 10^7$ V, $E_0 \approx 7\times10^8$ V/cm, $r_0 \approx 5\times10^{-3}$ cm, and $\kappa = 3$ we have $j_{\mathrm{lim}} \sim 10^7\sqrt{Z/A}\,(\mathrm{A/cm^2})$ and $I_{\mathrm{lim}} \sim 10^3\sqrt{Z/A}$ (amp) (A is the atomic weight of the ion). We see from these estimates that the proposed method for obtaining SIB can be of sufficient interest. Figure b shows the CVC calculated from formulas (2) and (3) (using the experimental data of[7] in the region $g \ll 1$) for a tungsten emitter (W^{3+} ions, $\phi = U/\kappa$, $r_0 = x = 5\times10^{-3}$ cm, $T = 77$ °K, $E_c = 5.7\times10^8$ V/cm, $j_0 = 4.8\times10^{-6}$ A/cm², $x_c = 0.55$ Å, $a = 3.44$ Å³, $A_Z = 5.67$ eV, and $E_B = 6.75\times10^8$ V/cm). It should be noted that in[7], at small values of the voltage and current ($U \approx 10^4$ V, $I \sim 10^{-7}$ A, $r_0 \sim 10^{-5}$ cm) they observed an appreciable rate of field evaporation of W^{3+}, viz., $K \sim 10^7$ atomic layers per second (reaching 10^9 layers/sec for W^{4+}). The space-charge effects were still small in this case ($g \ll 1$).

It follows from (4) that to obtain currents $\sim 10^5$–10^6 A it is necessary to use an appreciable number of points, $N \sim 10^3$–10^4. If the distance between the point anode and the flat cathode is $D \gg r_0$, then the limiting current is determined by the “three-halves” law for a flat diode. At $U \approx 10^7$ V, $D \approx 3$ cm, and a cathode area $\sim 10^4$ cm² we get $I \sim 10^6\sqrt{Z/A}$ (amp).

The foregoing estimates are suitable both for evaporation of the point material and for field desorption of atoms specially deposited on the point surface (e.g., D_2, Li, and others). The total desorbed-ion current is $I_g \sim 10^{-4}\,nZ\,\pi r_0^2 N\tau^{-1}$ ampere, where n is the number of deposited atomic layers, and τ is the desorption time. At $n \sim 10^2$, $\tau \sim 10^{-8}$ sec, $r_0 \approx 5\times10^{-3}$ cm and $N \sim 10^4$ we have $I_g \sim 10^6 Z$ amp.

Let us examine certain questions that concern the stability of the emitters. 1) At $j \sim 10^6$ A/cm² and $\tau \sim 10^{-7}$ sec we can neglect the Joule heating of the points. 2) The attainable number of “shots” without changing points is $W \sim 10^3 Z r_0 (j\tau)^{-1}$; at $r_0 \approx 5\times10^{-3}$ cm, $j \sim 10^6$ A/cm², and

$\tau \sim 10^{-7}$ sec we have $W \sim 10^2$. 3) The mechanical stress produced by the electric field is $\sigma \sim E_0^2/8\pi \sim 10^3$ kgf/mm^2. For the point to be stable it suffices to limit the voltage-pulse duration to $\tau < \tau^* = l/s$, where l is the height of the point and s is the speed of sound in the metal ($\tau^* \sim 10^{-7}$ sec at $l \approx 5 \times 10^{-2}$ cm). 4) The damage to the points by the secondary-emission current from the cathode, and the breakdown of the diode gap, can be limited by applying a transverse magnetic field.

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[1] A. A. Plyutto *et al.*, ZhETF Pis. Red. **6**, 540 (1967) [JETP Lett. **6**, 61 (1967)].

[2] A. I. Morozov, A. Ya. Kislov, I. P. Zubkov, *ibid*. **7**, 224 (1968) [**7**, 172 (1968)].

[3] S. Graybill and J. Uglum, J. Appl. Phys. **41**, 236 (1970).

[4] A. A. Kolomenskiĭ and V. P. Sarantsev, Proc. 3rd All-Union Conf. on Accelerators (in Russian), M., 1, 107 (1973).

[5] F. Winterberg, Phys. Rev. 174, 212 (1968).

[6] R. N. Sudan and R. V. Lovelas, Phys. Rev. Lett. 31, 1174 (1973); M. L. Sloan and W. E. Drummond, *ibid*. 31, 1234 (1973).

[7] E. W. Muller and T. T. Tzong, Field Ion Microscopy, Elsevier, 1969; T. T. Tzong and E. W. Muller, Phys. Stat. Sol. 1, 513 (1970).