Ectons in electric discharges

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There are many ways to concentrate energy up to 10^4 J/g in microscopic volumes of a cathode. These concentrations of energy result in microscopic explosions accompanied by the emission of electrons, a plasma, liquid droplets of metal, and metal vapor. This effect has been called the "ecton" effect. If the current flowing out of a microscopic-explosion region is above a critical value, a self-sustenance of ectons begins. Ectons play a fundamental role in a large number of electric discharges.

During microscopic explosions on a cathode, there is an intense emission of electrons accompanied by the emission of plasma, metal vapor, and microscopic metal droplets.[1-3] This effect has been labeled "explosive electron emission."[3,4] It has been suggested that only one microscopic-explosion mechanism is operating: a heating of microscopic protuberances on the cathode by the field-emission current.[5] It has also been suggested that explosive electron emission plays a fundamental role only in vacuum discharges.[2] In the present letter we wish to show that (first) there are many mechanisms which would give rise to microscopic explosions; field emission is only one of a few possibilities for the triggering of these mechanisms. Second, microscopic explosions at electrodes are a fundamental process for many types of discharges.

Let us review how explosive electron emission arises and evolves. At a current density $j > 10^8$ A/cm^2, microscopic sharp points on the surface of the cathode acquire an energy $\sim 10^4$ J/g and explode over a time t_3, which can be found for many metals from

$$j^2 t_3 \approx 10^9 \ (\mathrm{A/cm^2})^2 \cdot \mathrm{s}\,. \tag{1}$$

After the explosion, a current of explosive electron emission arises, and a microscopic crater forms on the cathode. If the explosive-emission current exceeds a certain critical level i_c (on the order of a few amperes), the current from the first microscopic explosion ceases (over a time on the order of 10^{-9}–10^{-8} s), and one or several new microscopic explosions and microscopic craters form. The process thus becomes self-sustaining. Each new explosion behaves in qualitatively the same way as the secondary electrons which appear on a cathode as a result of the application of ions, photons, electrons, metastable particles, and so forth. This phenomenon has been labeled an "ecton," since the zone in which the explosive electron emission occurs is frequently called an "explosive center" or "emission center" in the literature in this country and in the foreign literature. The word "ecton" is an acronym formed partly from the first letters of these English words.

For a primary ecton to appear, there must accordingly be a sufficiently high concentration of energy in a microscopic volume of the cathode ($\sim 10^4$ J/g). If the primary ecton is to initiate one or several secondary ectons, its current must be above a critical value. These are essentially the two basic conditions for the appearance and self-sustenance of ectons. However, it is not difficult to show that field emission is not necessary in order to satisfy these conditions, nor is a vacuum.

A concentration of energy in a microscopic cathode volume sufficient for an explosion can be achieved with the help of an intense laser beam, an intense plasma stream, an intense ion beam, the impact of a fast microscopic particle, a discharge along the surface of a dielectric where it makes contact with a sharp tip, metal bridges between a cathode and an anode, and so forth. It is not necessary that these processes lead to the microscopic explosion directly. There are accompanying effects which arise at comparatively low energy flux densities and then promote a concentration of energy in microscopic volumes of a cathode. One such effect is the interaction of a cathode surface with a plasma. Such a plasma arises, in particular, upon the evaporation of a microscopic surface area of a cathode or upon the desorption of a gas caused by a high temperature, followed by ionization of the gas and metal vapor by an electric field.

It has been established experimentally that plasma streams initiate microscopic explosions at a cathode.[2] The reason lies in the presence of dielectric films and contaminants on the cathode. If a plasma is incident on such a film, the film becomes charged by the ion current.

In order to reach electric fields $E \geqslant 10^6$ V/cm, at which a film breaks down over a time $t \leqslant 10^{-8}$ s, it is necessary to satisfy the condition

$$nv \geqslant 10^{22}\ \text{cm}^{-2} \cdot \text{s}^{-1}, \tag{2}$$

where v is the ion velocity, and n the density. If $v \gtrsim 10^6$ cm/s, we can expect ectons to form as a result of the incoming plasma at $n \leqslant 10^{16}$ cm^{-3}.

If there are no dielectric films or contaminants, ectons arise because of the increase in the current density at microscopic protuberances. Let us assume that a microscopic protuberance has a surface area s and that it joins the cathode in a circular area of radius r. The ion current $j_p s$ which is incident on the surface of the protuberance then has a density $j_p s/\pi r^2$ where the protuberance joins the cathode. In other words, the amplification of the current density is

$$\beta_j = s/\pi r^2. \tag{3}$$

For a cylinder on a plane, for example, this amplification would be $2h/r$, where h is the height of the cylinder. For a cone it would be l/r, where l is the length of the generatrix of the cone. For a sphere it would be $4R^2/r^2$, where R is the radius of the sphere. The value of h/r for a cylindrical microscopic protuberance can be measured well, since it also characterizes the amplification of the electric field and typically has a value of 10^2 or more.[6] For a spherical microscopic protuberance, β_j can be 10^3 or more. This effect amplifies the flux density of plasma ions directed toward the cathode, which could give rise to the appearance of ectons. This effect apparently occurred in Ref. 7.

We will use the example of explosive emission to show why an ecton survives for a short time ($\sim 10^{-9}$–10^{-8} s) and then disappears, giving rise to new ectons. The reason is that a crater which forms as the result of Joule heating of a cathode by the explosive-emission current increases in radius, evaporates atoms, and ejects heated liquid metal. As a result, the crater cools down, and the emission stops. Two types of ectons are observed experimentally:[3] (1) ectons for which the craters do not geometrically touch each other and (2) ectons for which secondary craters arise at the positions of, or at the periphery of, the primary craters. The ectons of the first type result from the propagation of plasma along the surface of the cathode, the charging of dielectric films and contaminants, and their breakdown, as outlined above. The ectons of the second type result from a concentration of energy at the cathode as the liquid metal interacts with the plasma.[2] In our opinion, the most effective mechanism for the appearance of secondary ectons may be the explosion of a neck of liquid metal or the breakoff of a droplet. In this case the ion current density to a spherical droplet can reach $> 10^6$ A/cm^2. Since we have[8] $\beta_j = 4R^2/r^2 \geqslant 10^3$ in this case, the explosion of the neck occurs over a time $t_2 < 10^{-9}$ s according to (1). In vacuum arcs[9] and explosive electron emission,[3] the number of microscopic droplets is $j = (1\text{–}5) \times 10^7$ C^{-1} for various metals. Under the assumption that the critical current (i_c) required for self-sustenance of ectons is equal to the current at which at least one droplet arises over the cycle time τ_μ, we find the condition for self-sustenance of ectons:

$$\gamma \tau_u i_c \geqslant 1. \tag{4}$$

At the given value of γ and with[10] $\tau_u \approx 10^{-8}$ s, the current i_c would have to be several amperes. This conclusion agrees with experiments on explosive emission[3] and vacuum arcs.[11]

Ectons thus arise because of a high power density concentrated at a metal surface. However, one of the most common methods for arranging this state is Joule heating of microscopic regions of a cathode. The amount of metal carried off from the cathode in this case is 10^{-11}–10^{12} g, the typical crater size is $< 10^{-4}$ cm, and the specific mass loss is 10^{-5}–10^{-4} g/C (Ref. 2). The amount of energy required for a microscopic explosion is thus no more than 10^{-8}–10^{-7} J.

Some electric discharges in which ectons may exist are the explosive emission of electrons, vacuum discharges, vacuum arcs, certain types of arcs in gases, discharges in microscopic gaps in gases, discharges on the far left and far right branches of the Paschen curve, pseudosparks, unipolar arcs, certain types of discharges in liquids, the transition from a glow discharge to an arc, the contraction of a discharge in a high-pressure gas laser, electric contacts, and electric-spark processing of metals (there are others yet). Ectons are thus not some exotic effect but one of the most common electric-discharge effects.

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