ISSN 1063-780X, Plasma Physics Reports, 2011, Vol. 37, No. 4, pp. 366–369. © Pleiades Publishing, Ltd., 2011.
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LOW-TEMPERATURE PLASMAS

Energy of Electrons Emitted as a Result of Separation of Surfaces

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Received October 18, 2010

Abstract—Experiments indicating acceleration of charged particles as a result of separation of solid surfaces are analyzed. As a possible mechanism of such acceleration, generation of surface charge on the separated surfaces of a cleaved ionic crystal is considered. The maximum electric field generated due to the charging of the separated surfaces and the energy of electrons accelerated in such a field are estimated. It is shown that, for the maximum attainable electric field, conditions are created for the generation of runaway electrons that, even at atmospheric pressure, electrons are accelerated to high energies, not experiencing collisions with gas particles.

DOI: 10.1134/S1063780X11040027

1. INTRODUCTION

It is well known (see [1–11] and references therein) that mechanical cleavage of ionic crystals, as well as the peeling of scotch tape from the roll, is accompanied by electric phenomena, such as slight crackling, luminescence of air and the chamber wall, and ionization of the gas surrounding the separated object. The physical reason for these phenomena is the process of charge separation on the cleaved surfaces, which results in the generation of an electric field capable of accelerating charged particles. Another reason for the generation of an electric field near the surface of a solid body is a mechanical shift of the body layers (piezoelectric effect) [12, 13]. The potential of this electric field is high enough for the charged particle emitted from the separated surfaces not only to generate X-rays with photon energies up to several hundred keV [7, 8, 10], but also stimulate fusion reactions (in the presence of deuterium molecules) accompanied by neutron emission [11]. This allows one to utilize these phenomena for creating simple generators of fast particles and hard radiation [10, 14, 15].

Charge separation on the cleaved surfaces is caused by different mechanisms. In the case of mechanical cleavage of an ionic crystal along certain planes, the surfaces turn out to be charged oppositely [4]. In the case of peeling a soft polymer layer (such as an adhesive tape) from a solid surface, a rather complicated physical–chemical mechanism based on different mobilities of oppositely charged ions, as well as on different electron and proton affinities of the radicals present on the surface, comes into play. In spite of vast experimental data, this mechanism still remains obscure and is actively discussed in the scientific literature (see, e.g., [4, 5, 9]). Quantitative estimates of the maximum electric field generated near the separated surfaces are also contradictory. Thus, the authors of [9] suppose that the maximum electric field in a gas is limited by the breakdown strength, which in atmospheric-pressure air is about 30 kV/cm. However, this contradicts the experimental data [7, 8, 10], according to which the energy of X-ray photons emitted during the destruction of an ionic crystal or the peeling of an adhesive tape reaches a few hundred keV. In the present paper, it is shown that, even at atmospheric pressure, a runaway regime can occur for electric fields substantially exceeding the above critical value. In this regime, electrons emitted from the charged surface are accelerated up to energies of about 1 MeV, not experiencing collisions with gas particles. In particular, such high fields are generated during the cleavage of an ionic crystal along a plane corresponding to the maximum possible surface density of the ion charge.

When analyzing these phenomena, the following relationship between the surface charge density σ produced due to the cleavage of surfaces and the electric field E near the surface is usually used [16]:

$$E = 4\pi\sigma. \quad (1)$$

This expression follows from the classical electrostatic approach and is valid for the case of an infinitely large surface. It can be assumed that, for a charged surface

of size d, this relationship is valid at distances of $x \ll d$ from the surface.

The maximum attainable value of σ can be estimated using the structure of a NaCl crystal as an example (see Fig. 1). This structure is a regular cubic lattice consisting of positive (Na^+) and negative (Cl^-) ions, the distance between the neighboring ions being $a = 0.563$ nm. The fresh surfaces produced due to the cleavage of such a crystal may be charged with oppositely charged ions. The value of the surface charge density σ depends on the orientation of the cleave plane. The maximum value of the surface charge density is

$$\sigma_{max} = \frac{|e|}{S_{min}^2}, \quad (2)$$

where $S_{min} = 2^{1/2}a$ is the minimum distance between similar charges and e is the elementary charge. According to Eq. (2), the maximum attainable value of the charge density on the cleaved surface of such a crystal is $\sigma_{max} \approx 1.6 \times 10^{14}\ |e|/\text{cm}^2$. The corresponding maximum attainable value of the electric field near the charged surface is

$$E_{max} = 4\pi\sigma_{max} = \frac{2\pi|e|}{a^2} = 1.45 \times 10^8 \ \text{V/cm}. \quad (3)$$

Note that nearly the same electric field is generated due to the shift of crystal layers, because, in both cases, the electric field is limited by the field of a monolayer of polarized atoms or molecules.

2. ELECTRON ENERGY NEAR A CHARGED SURFACE

Electrons moving in an atmospheric-pressure gas in the electric field with the above strength can be accelerated to high energies, not experiencing collisions with gas particles. This effect, which came to be known as electron runaway [17], is related to a monotonic decrease in the cross section for inelastic electron–molecule collisions at high electron energies. In the case of separation of the cleaved surfaces of an ionic crystal, the source of electrons is the negatively charged surface, which emits electrons due to field emission. The energy ε_e acquired by these electrons in the gas at high electric field strengths E can be estimated from the equation

$$\frac{\partial\varepsilon_e}{\partial x} = eE - N\sigma_{ion}\varepsilon_e. \quad (4)$$

Here, the x axis is directed along the electric field (i.e., along the normal to the charged surface), the coordinate origin $x = 0$ lies on the charged surface, σ_{ion} is the cross section for electron-impact ionization of gas molecules, and N is the number density of gas particles. In deriving Eq. (4), it was assumed that fast electrons lose their energy mainly due to ionization of gas particles and that, in such a collision event, an electron loses almost all its energy. At low emission currents from the surface, the space charge practically does not affect the distribution of the electric potential near the surface; therefore, the distribution of the potential is described by the following simple expression:

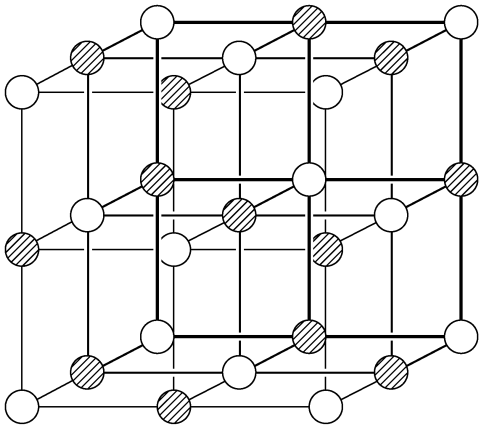

Fig. 1. Structure of a NaCl ion crystal. The closed and open circles show the positive (Na^+) and negative (Cl^-) ions, respectively.

$$U(x) = 4\pi\sigma x. \quad (5)$$

Using this expression, we find that the solution to Eq. (4) with the initial condition $\varepsilon_e(x = 0) = 0$ has the form

$$\varepsilon_e(x) = eE\exp\left[-\int_0^x N\sigma_{ion}(\varepsilon_e)dx\right] \times \int_0^x dx''\exp\left[\int_0^{x''} N\sigma_{ion}(\varepsilon_e)dx'\right]. \quad (6)$$

Note that the solution to Eq. (4) is, to a great extent, determined by the integral

$$I(x) = \int_0^x N\sigma_{ion}(\varepsilon_e)dx'. \quad (7)$$

Under the condition $I(x) \ll 1$, the electrons are accelerated by the electric field practically not experiencing collisions with gas particles and their energy depends on the coordinate x as follows:

$$\varepsilon_e(x) = eEx = 4\pi\sigma x. \quad (8)$$

It can be seen that, in this case, the presence of a gas does not affect the mean electron energy. For $I(x) \geq 1$, the electrons accelerated in the electric field lose a fraction of their energy in inelastic collisions, so their energy depends on the density of gas particles. According to Eq. (5), the value of integral (7) is inversely proportional to the electric field; therefore, depending on the electric field, the integral can be

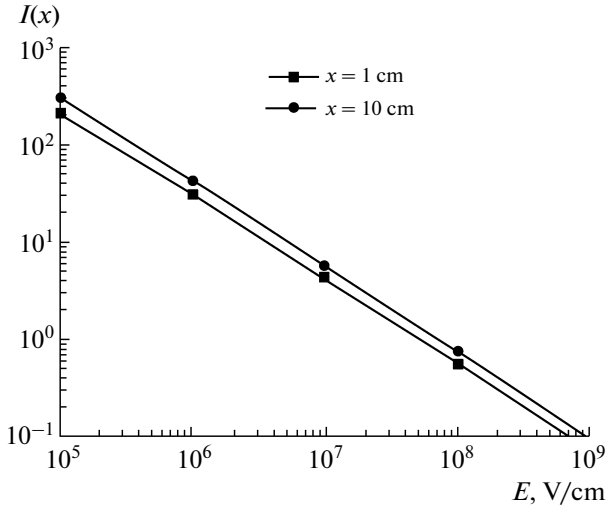

Fig. 2. Dependence of integral (7) on the electric field, calculated for an electron moving in atmospheric-pressure molecular nitrogen for two distances from the charged surface, $x = 1$ and 10 cm.

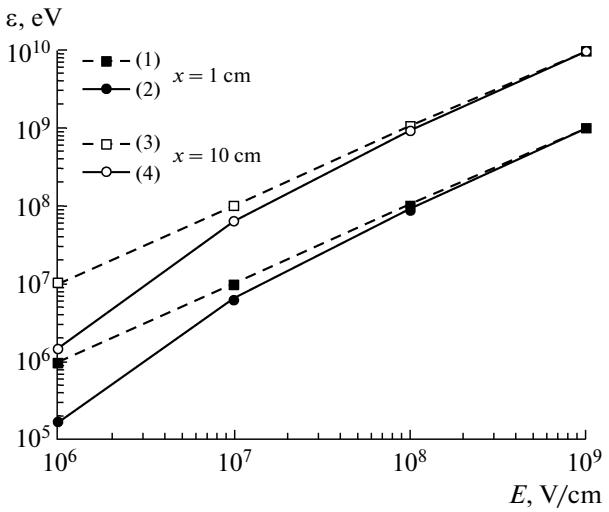

Fig. 3. Dependence of the electron energy ε_e on the electric field E for different distances x from the charged surface: (*1*, *3*) linear dependence (8) and (*2*, *4*) dependence calculated using expression (6).

either larger or smaller than unity. The dependences of integral (7) on the electric field for two distances from the surface, $x = 1$ and 10 cm, are shown in Fig. 2. The dependences were calculated for N_2 at atmospheric pressure. The dependence of the cross section for electron-impact ionization of N_2 was taken from [18] and extrapolated using the Born approximation into the energy range $\varepsilon_e > 10^3$ eV, for which this cross section was not measured.

It can be seen from Fig. 2 that, for a molecular gas at atmospheric pressure, the electron runaway conditions are satisfied for fields $E > 10^7$ V/cm. This corresponds to surface charge densities of $\sigma > 10^{13}\,|e|/\text{cm}^2$. However, in lower fields, the electrons accelerated near a charged surface can also acquire considerable energy. This can be seen in Fig. 3, which shows the dependences of the electron energy on the electric field at distances of 1 and 10 cm from the surface. These dependences were calculated using solution (6) to Eq. (4). Note that according to Eq. (3), the electric fields $E = 10^4$, 10^5, 10^6, 10^7, and 10^8 V/cm nearly correspond to distances $a \approx 10$, 3, 1, 0.3, and 0.1 nm between neighboring uncompensated charges on the plane, respectively.

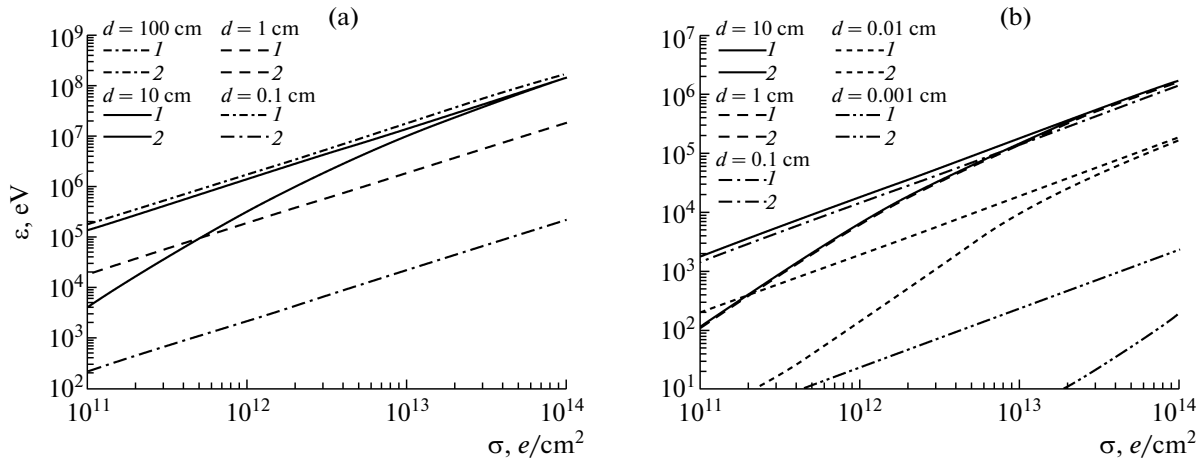

Fig. 4. Dependence of the electron energy ε_e on the surface charge density σ in nitrogen, calculated for circular charged surfaces of different radii ($d = 0.1$–100 cm) at two distances from the surface, $x =$ (a) 1 and (b) 0.01 cm: (*1*) dependence calculated using expression (6) and (*2*) linear dependence (8).

3. LIMITED-SIZE SURFACE

The results presented above refer to a cleaved crystal surface with a relatively large area. As was mentioned above, relationships (1) and (3) are valid for $x \ll d$, where d is the characteristic size of the cleaved surface. At larger distances from the surface, $x \geq d$, the electric field decreases with increasing distance x. Therefore, the potential of a charged surface with respect to the ambient space is limited to the value $U_{\max} < Ed \sim 4\pi\sigma d$, which determines the maximum electron energy. These qualitative considerations are confirmed by the results of model calculations of the energy acquired by the electrons emitted from a charged surface as a function of the surface charge density σ. The emitting surface was modeled by a circle of diameter d. In this case, the dependence of the electric field along the symmetry axis of the system on the distance x from the surface is described by the expression

$$E_D(x,\sigma) = 4\pi\sigma x\left(\frac{1}{x} - \frac{1}{\sqrt{(d/2)^2 + x^2}}\right), \qquad (9)$$

which turns into the dependences $E = q/x^2$ (where q is the total charge of the surface) or (1) in the limiting cases $x \gg d$ and $x \ll d$, respectively. The calculated dependence of the electron energy in atmospheric-pressure nitrogen on the surface charge density σ for different values of the surface diameter d and different distances x from the surface are shown in Fig. 4. It can be seen that, even for a relatively small ionic crystal, the emitted electrons can be accelerated in atmospheric-pressure gases to energies of about tens of keV or more. Even higher electron energies can be achieved in vacuum (see dependences *2* in Fig. 4).

Comparison of the results of calculations performed for a limited-size charged surface with the experimentally determined maximum energy of X-ray photons observed during the cleavage of an ionic crystal ($\hbar\omega \sim 200$–500 keV) allows us to estimate the characteristic transverse size of the charged surface in the above experiments. Assuming that the surface charge density is equal to its maximum attainable value $\sigma \sim 10^{14}|e|/\text{cm}^2$ and using the above qualitative analysis, we obtain the following estimate: $d \sim e\hbar\omega/(4\pi\sigma|e|) \sim 0.3$ mm. Note that the increase in the size of the charged surface by improving the crystal structure can result in the generation of even harder X-rays.

4. CONCLUSIONS

It is shown using a simple model that the electric field generated as a result of the cleavage of an ionic crystal can reach a value of about 10^8 V/cm. The energy of electrons emitted from the cleaved surface due to field emission can reach relativistic values even at atmospheric pressure. This explains the detection of X-rays during the cleavage of a mica crystal [1] and peeling of an adhesive tape [10]. Although the mechanisms of charging of the surfaces of an adhesive tape and a cleaved ionic crystal are different (the former having a more complicated chemical nature [9]), both phenomena lead to the generation of intense electric fields and fast electrons, accompanied by bursts of optical and X-ray emission. Note that our calculations indicate that, for fields as high as $E \sim 10^8$ V/cm, the electrons in atmospheric-pressure gases are accelerated to relativistic energies, practically not experiencing collisions with gas particles.

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Translated by E.V. Voronova