Characteristics of the fast electron emission produced during the cleavage of crystals

B P CHANDRA, N L PATEL, S S RAHANGDALE, R P PATEL and V K PATLE

Department of Postgraduate Studies and Research in Physics and Electronics, Rani Durgavati Vishwavidyalaya, Jabalpur 482 001, India

Abstract. The present paper reports the fast electron emission produced during the cleavage of alkali halide crystals and models the dynamics of the process. The mechano-emission arises as a result of the ionization of surface traps at the expense of the energy which is released in the annihilation of the defects which are formed during cleavage. The slow electrons which appear upon the ionization of surface traps are subsequently accelerated in the field of negatively charged segment of the freshly cleaved surface. Considering the basic mechanism of fast electron emission, expressions are derived which are able to explain satisfactorily the temporal, thermal, charge, surface, coloration, water adsorption and other characteristics of the fast electron emission produced during the cleavage of crystals. The decay time of the charges on the newly created surfaces, and the velocity of cracks can be determined from the measurements of fast electron emission produced during the cleavage of crystals. It is shown that two types of diffusing centres are responsible for the charge relaxation and thereby for the emission of fast electrons produced during the cleavage of alkali halide crystals.

1. Introduction

One of the most spectacular non-equilibrium processes which are observed during the breakdown of ionic crystals is the emission of fast electrons. The emission of fast electrons during the mechanical destruction of the solids was first discovered by Karasev *et al* in 1953 [1] who observed this phenomenon during the tearing of polymer films from various substrates, and subsequently by Krotova and Karasev in 1953 [2], who reported the fast electron emission during the destruction of crystals. The emission was detected by the blackening of radiation-sensitive plates. The energy of the electrons was evaluated by Karasev and Krotova in 1954 [3] from the deviation of the electron beam in a magnetic field and by measuring their passage through obstacles. The emission of fast electrons during fracture was subsequently investigated by Deryagin and co-workers [4–8] and by a number of other workers [9–14]. The emission of fast electrons takes place from the freshly formed surface both during the fracture process and after it. Emission is observed during the fracture of many ionic crystals, polymers, mica, ferroelectrics etc. Dickinson and his

co-workers have reported the fast electron emission from several organic and inorganic materials [15–25].

The average energy of the electrons released upon the fracture of alkali halide crystals is usually 10^2–10^3 eV, although individual particles may have energies up to 100 keV. The initial flux intensity is equal to 10^3–10^4 cm^{-2} s^{-1}. After attaining a maximum value, the emission falls off with time, initially at a fast rate and then at a slow rate. Irradiation of a freshly cleaved alkali halide crystals in the F-centre wavelength absorption region leads to a fresh emission of electrons. The emission intensity depends on the temperature of the samples.

The emission of fast electrons produced during the cleavage of alkali halide crystals depends on several parameters in the following way:

Time: When a crystal is cleaved, initially the rate of fast electron emission increases with time, attains a peak value and then decreases with time [13,14,25–28].

Area of newly created surfaces: The rate of fast electron emission increases with the area of newly created surfaces [29].

Surface charge density: The rate of fast electron emission increases with the surface charge density of newly created surfaces of the crystals [5,25,29,30].

Temperature: Initially, the rate of fast electron emission increases with temperature, attains a peak value and then it decreases with further increase of temperature [4,5].

Coloration: The rate of fast electron emission increases with the radiation doses given to the crystals [5,11,26] prior to cleavage.

Luminescence: The crystal having more efficiency for the radiation recombination, i.e., more luminescence exhibit less number of fast electron and vice-versa [4,30].

Dopant: The rate of fast electron emission produced during the cleavage of alkali halide crystals depends on the concentration of dopant in the crystal. The dopant causing enhancement in the luminescence efficiency decrease the rate of fast electron emission and vice-versa [30].

Deformation: The fast electron emission produced during the cleavage of crystals depends on the pre-deformation of the crystals.

Water adsorption: The rate of fast electron emission produced during the cleavage of crystals decreases with the formation of adsorbed film of water during exposure of the crystal to humidity before cleavage. The emission is extinguished for the adsorbed water film on the surface of crystal at 80% humidity [4].

Photo-stimulation: The illumination of the surface of freshly cleaved alkali halide crystals in the F-centre adsorption region leads to a sharp increase in emission intensity.

Crystallographic direction: The rate of fast electron emission produced during the cleavage of alkali halide crystals is different for different directions of cleaving the crystals.

The present paper reports a theory for the dependence of fast electron emission on different parameters for the first time, and then compares the theoretical and experimental results.

2. Theory

The proposal advanced by Deryagin and co-workers [31] concerning the auto-electronic mechanism of mechanico-emission has been a most fruitful working hypothesis which has determined the direction of investigations for over a quarter of a century. It was suggested that mechano-emission arises as the result of the auto-ionization of surface traps in the strong electric field of the charges which arise during cleavage. However, calculations showed that the electric field arising in this way from the charged surfaces (charge density not more than 10^3 e.s.u./cm^2) could not produce any appreciable field emission even for comparatively shallow traps such as surface F-centres. Therefore, another mechanism was suggested by Molotskii [25] in which it was postulated that mechanico-emission arises as the result of the ionization of surface traps at the expense of the energy which is released in the annihilation of the defects which are formed during fracture, i.e., mechanico-emission is a different form of exo-electron emission. The electrons leaving the traps have low energies (< 1 eV). The acceleration of slow electrons in the field of negatively charged surface region leads to the emission of fast particles. This mechanism allows one to account for the main features of mechanico-emission.

According to Molotskii [30], the relaxation of the charges on a fracture takes place by the following chain mechanism. Electrons, which have been accelerated in the field of the fracture, penetrate into the positively charged wall and excite a large number of excitons. The majority of the excitons decay within the crystal but some of them succeed in emerging onto the surface. Since defects can be generated in the cationic sub-lattice of the crystal during the non-radiative decay of excitons, free cations are formed during the decay of the surface excitons. These cations, which are accelerated in the field of the fracture, bombard the negatively charged wall and give rise to secondary ion–electron emission. After this, the chain of processes, including the electronic, excitonic and ionic stages, is repeated.

When a crystal is cleaved, charged surfaces are produced due to processes like piezo-electricity, charged dislocation movement, baro-diffusion of charged defects near the crack tip, presence of defective piezoelectric phase etc. [32–38]. When cleaved in a vacuum, the surface charge can be neutralized by the charge carriers and ions produced during the charge relaxation process.

Strube and Linke [39] have performed the time-resolved crack velocity measurements for alkali halide crystals. They have reported that although initially the crack velocity is low, after a certain length of crack, the crack velocity attains a constant value. The terminal value of the crack velocities of 3800 m s^{-1} and 3000 m s^{-1} were observed for LiF and NaF crystals, respectively. In our theory we ignore this variation and use an average crack velocity v. If a crystal having length L, breadth W and thickness H, is cleaved along the plane parallel to its breadth side, the rate of creation of new surfaces is given by $2Wv$, where v is the average velocity of the separation of cleavage plane. If γ is the charge density of the newly created surface of the crystal, then the rate of generation of surface charge is given by

$$g_s = 2\gamma W v. \tag{1}$$

If α is the rate constant for the relaxation of charges on the newly created surfaces, then we may write the following rate equation:

$$\frac{dQ}{dt} = g_s - \alpha Q \tag{2}$$

where Q is the surface charge at any time t.

As $Q = 0$ at $t = 0$, eq. (2) gives

$$Q = \frac{g_s}{\alpha}[1 - \exp(-\alpha t)]. \tag{3}$$

Let us assume that the rate of generation of excitons during the cleavage of crystals is proportional to the rate of charge relaxation, i.e., αQ. Then, using eq. (3), we may write the following expression for the rate of generation of excitons

$$g = B\alpha Q$$

or

$$g = B \cdot g_s[1 - \exp(-\alpha t)] \tag{4}$$

where B is a factor relating the rate of generation of excitons and the rate of charge relaxation.

If β_1 and β_2 are the rate constants for the radiative and non-radiative decay of excitons, then we may write the following rate equation

$$\frac{dn}{dt} = g - \beta_1 n - \beta_2 n = 2B\gamma Wv[1 - \exp(-\alpha t)] - \beta n \tag{5}$$

where n is the number of excitons at any time t, and $\beta = (\beta_1 + \beta_2)$, and $1/\beta$ is the lifetime of the excitons.

Integrating eq. (5) and taking $n = 0$, at $t = 0$, and $\beta \gg \alpha$, we get

$$n = \frac{2B\gamma Wv}{\beta}[1 - \exp(\alpha t)]. \tag{6}$$

When the charged surfaces are created at cleavage, the electrons ejected from negatively charged surface are accelerated in the field of fracture. The accelerated electrons penetrate into the positively charged wall and consequently excite a large number of excitons. Some of the excitons succeed in emerging into the surface and free cations are formed during the non-radiative decay of surface excitons. Subsequently, these free cations are accelerated in the field of fracture and they bombard the negatively charged wall and give rise to secondary ion–electron emission. Thus, the rate of fast electron emission, J_D, produced during the cleavage of crystal may be assumed to be proportional to the rate of non-radiative decay of excitons and it may be expressed as

$$J_D = D\beta_2 n = \frac{2D\beta_2 B\gamma Wv}{\beta}[1 - \exp(\alpha t)] \tag{7}$$

where D is a constant correlating the rate of the conversion of non-radiative decay of excitons and the rate of fast electron emission.

Now, on the basis of eq. (7), we shall discuss the characteristics of the fast electron emission produced during the cleavage of alkali halide crystals.

(i) *Temporal characteristics of the fast electron emission*

Case A. For short time duration: For short time duration, eq. (7) may be written as

$$J_D = 2\eta DB\gamma W \alpha v t \tag{8}$$

where $\eta = \beta_2/\beta$ is the probability of non-radiative decay of excitons.

Equation (8) shows that for short time duration the rate of fast electron emission should increase linearly with time t. The physical concept related to this fact may be understood in the following way: The value of J_D depends linearly on the rate of charge relaxation which depends linearly on the instantaneous value of the surface charge. Since in the beginning the surface charge increases linearly with time, a linear increase of J_D with t takes place. The factor α in eq. (8) takes account of the charge relaxation process.

Case B. For long time duration: After the completion of the cleavage of the crystal, at $t = t_{\mathrm{m}}, v$ becomes zero and hence $g_s = 0$, at $t = t_{\mathrm{m}}$. Thus, from eq. (2), we get

$$\frac{dQ}{dt} = -\alpha Q. \tag{9}$$

For $Q = Q_0$ at $t = t_{\mathrm{m}}$, the solution of eq. (9) gives

$$Q = Q_0 \exp[-\alpha(t - t_{\mathrm{m}})]. \tag{10}$$

From eq. (3), Q_0 may be expressed as

$$Q_0 = \frac{g_s}{\alpha}[1 - \exp(-\alpha t_{\mathrm{m}})] = \frac{2\gamma w v}{\alpha}[1 - \exp(-\alpha t_{\mathrm{m}})]. \tag{11}$$

As $\alpha \sim 0.1\ \mathrm{s}^{-1}$ (see §3) and $t_{\mathrm{m}} = 10\ \mu\mathrm{s}$ (for a crystal of 1 cm height for which the crack velocity is of the order of 10^5 cm/s), $\alpha t_{\mathrm{m}} \ll 1$ and eq. (11) may be expressed as

$$Q_0 = 2\gamma W v t_{\mathrm{m}} = 2\gamma W H \tag{12}$$

where $t_{\mathrm{m}} = H/v$ is the time taken for the cleavage of the crystal.

Equation (12) indicates that as the rate of charge relaxation is a slow process and the cleavage takes place in a very short duration, the charges relaxed up to the time t_{m} may be negligible.

From eqs (10) and (12), we get

$$Q = 2\gamma W H \exp[-\alpha(t - t_{\mathrm{m}})]. \tag{13}$$

Thus, the rate of generation of excitons after the cleavage is given by

$$g_{PD} = B\alpha Q = 2B\gamma W H \alpha \exp[-\alpha(t - t_{\mathrm{m}})]. \tag{14}$$

In this case, the rate equation may be written as

$$\frac{dn}{dt} = 2B\gamma W H \alpha \exp[-\alpha(t - t_{\mathrm{m}})] - \beta n. \tag{15}$$

In equilibrium, the above equation gives

$$n = \frac{2B\gamma W H\alpha}{\beta} \exp[-\alpha(t - t_{\mathrm{m}})]. \tag{16}$$

Using eq. (16) the rate of fast electron emission after the cleavage of crystals may be expressed as

$$J_{PD} = 2\eta DB\gamma W H\alpha \, \exp[-\alpha(t - t_{\mathrm{m}})]. \tag{17}$$

Equation (17) shows the exponential decay of fast electron emission after the cleavage of crystals, where the decay time will be controlled by the rate constant for the relaxation of surface charges, or, by the decay time of the surface charges.

(ii) *Maximum emission rate characteristics of the fast electron emission*

As the time up to which the creation of new surfaces takes place is $t_{\mathrm{m}} = H/v$, from eq. (8), the maximum value of J_D may be expressed as

$$J_{\mathrm{m}} = 2\eta DB\gamma W H\alpha = \eta DB\gamma\alpha A \tag{18}$$

where $A = 2WH$ is the area of newly created surfaces of the crystal.

It is seen from eq. (18) that the maximum rate of fast electron emission should increase directly with the area of newly created surfaces as well as with the charge density of the newly created surfaces.

(iii) *Total emission characteristics*

The total number of fast electrons emitted may be given by the area below the rate of fast electron emission vs. time curve, and it may be expressed as

$$J_{\mathrm{T}} = \int_0^{t_{\mathrm{m}}} J_D \, \mathrm{d}t + \int_{t_{\mathrm{m}}}^{\infty} J_{PD} \, \mathrm{d}t. \tag{19}$$

From eqs (8), (17) and (18), J_{T} may be expressed as

$$
\begin{aligned}
J_{\mathrm{T}} &= \int_0^{t_{\mathrm{m}}} 2\eta DB\gamma W \alpha vt \, \mathrm{d}t + \int_{t_{\mathrm{m}}}^{\infty} 2\eta DB\gamma W H\alpha \exp[-\alpha(t - t_{\mathrm{m}})]\mathrm{d}t \\
&= 2\eta DB\gamma W \alpha \left[\frac{vt_{\mathrm{m}}^2}{2} + \frac{H}{\alpha} \right] \\
&= 2\eta DB\gamma W \alpha \left[\frac{H^2}{2v} + \frac{H}{\alpha} \right].
\end{aligned}
\tag{20}
$$

As $H/\alpha \gg H^2/2v$, eq. (20) may be expressed as

$$J_{\mathrm{T}} = \eta DB\gamma A. \tag{21}$$

It is evident from eq. (21) that the total number of fast electrons emitted should increase directly with the area of newly created surface as well as with the surface charge density of the newly created surfaces.

(iv) *Surface characteristics of the fast electron emission*

Equations (18) and (21) show that both the maximum rate of fast electron emission and the total number of fast electrons emitted increase linearly with the area of newly created surface of the crystals.

(v) *Charge characteristics of the fast electron emission*

It is evident from eqs (18) and (21) that both the rate of fast electron emission and the total number of fast electrons emitted should increase directly with the charge density of the newly created surfaces. This means the crystals having higher surface charge density should exhibit higher emission of the fast electrons.

(vi) *Thermal characteristics of the fast electron emission*

Equations (18) and (21) show that both J_m and J_T should depend on the probability of non-radiative decay η of excitons and also on the surface charge density γ. At low temperature, the probability of non-radiative decay of excitons decreases and, therefore, both J_m and J_T should decrease with decreasing temperature of the crystals. As the surface charge density decreases with increasing temperature of the crystals, in the high temperature range, the values of both J_m and J_T should decrease with the increasing temperature of the crystals. As a matter of fact, both J_m and J_T should attain optimum values for a particular temperature of the crystals. For the crystals whose luminescence efficiency becomes constant at low temperature, both J_m and J_T should become independent of temperature in the low temperature range, and in the high temperature range, it should decrease with increasing temperature of the crystals.

(vii) *Coloration characteristics of the fast electron emission*

When the crystals are colored by X or γ-irradiation, then color centres will be produced. In this case, the value of B, a factor correlating the rate of generation of excitons and the rate of charge relaxation, may increase and consequently, as evident from eqs (18) and (21), the values of J_m and J_T may increase with increasing coloration of the crystals.

(viii) *Luminescence characteristics of the fast electron emission*

The exciton decay recombination produced during the cleavage of crystals, which leads to the excitation of mechanico-electrons must also be accompanied by luminescence. If larger number of recombinations will take place radiatively causing luminescence, then less number of recombinations will occur non-radiatively, and consequently less number of fast electrons will be produced. Therefore, when the luminescence intensity produced during cleavage will be more, the mechano-electron emission will be less and vice-versa.

(ix) *Dopant characteristics of the fast electron emission*

The introduction of Tl^+, Ag^+, Pb^{2+} and other impurity ions, which enhance the luminescence of alkali halide crystals, must reduce the mechano-emission. Introduction of homologous anion impurities and H^+ ions enhancing the formation of defects in the course of non-radiative decay of excitons should enhance the intensity of mechano-electron emission.

(x) *Energy characteristics of the fast electron emission*

The number of fast electrons emitted during the cleavage of crystals decreases with increasing electron energy. This may be due to the existence of several forms of charge mosaic on the cleavage surface which differ in the magnitude of the period and maximum density. The existence of a small number of mechano-electrons with energies of tens of keV can be explained by the existence of local centres with a high charge density.

(xi) *Deformation characteristics of the fast electron emission*

Since the pre-deformation of crystals may change the charge density of the newly created surfaces, probability of non-radiative decay of excitons etc., the emission of fast electrons produced during the cleavage of crystals may depend on the pre-deformation of the crystals.

(xii) *Water adsorption characteristics of the fast electron emission*

Krotova *et al* [4] have measured the emission of fast electrons during the cleavage of NaCl and LiF crystals in high vacuum (10^{-6} torr). They have found that the formation of an adsorbed film of water on the surface of the crystal at 80% humidity extinguishes the emission due to a change in the surface conductivity. The emission is observed only in specimens of alkali halide crystals specially dehydrated by exposure to P_2O_5. It follows that the surface charges which leak away when there is adosrbed water on the specimen are responsible for the emission. It seems that the adsorbed film of water on the crystal surface does not get destroyed even in high vacuum.

(xiii) *Photo-stimulation characteristics of the fast electron emission*

The illumination of the surface of freshly cleaved alkali halide crystals in the F-centres wavelength absorption region leads to the fresh emission of electrons, i.e., the sudden increase in the emission intensity.

(xiv) *Direction characteristics of the fast electron emission*

As the surface charge density is different for different planes of the crystals, the direction of cleavage of the crystals may change the rate of fast electron emission produced during the cleavage of crystals.

(xv) *Sample characteristics of the fast electron emission*

As indicated by eqs (18) and (21), the rate of fast electrons may be different for different crystals because of the different values of D, η, β, γ and α.

3. Comparison with experimental results

It is seen from figures 1 and 2 that when NaCl and LiF crystals are cleaved, initially, the rate of fast electron emission increases with time, attains a peak value and then it decreases with time. This is in accordance with the fact discussed in the temporal characteristics of

the fast electron emission. It is to be noted that the rise of electron flux density is very fast, so that it is difficult to show in the time scale used for the measurement. Figure 3 shows that initially the rate of fast electron emission decreases at a faster rate and then it decays at slower rate. This fact shows that the charge on the newly created surfaces decay with two rate constants. It seems that initially the charge carriers lying close to the
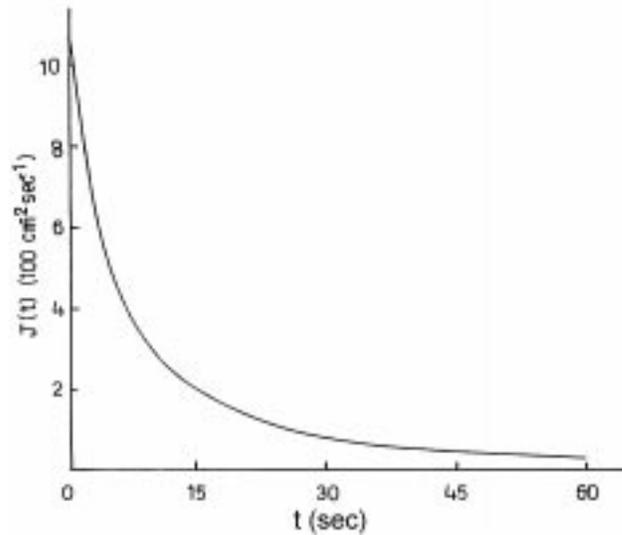

Figure 1. Dependence of the electron flux density on time produced during the cleavage of NaCl crystal (after Khrustalev [7]).
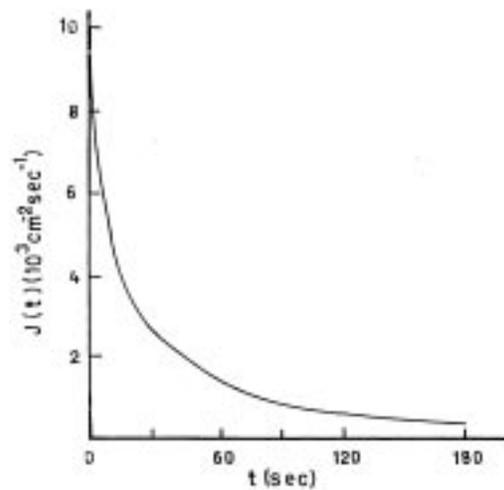

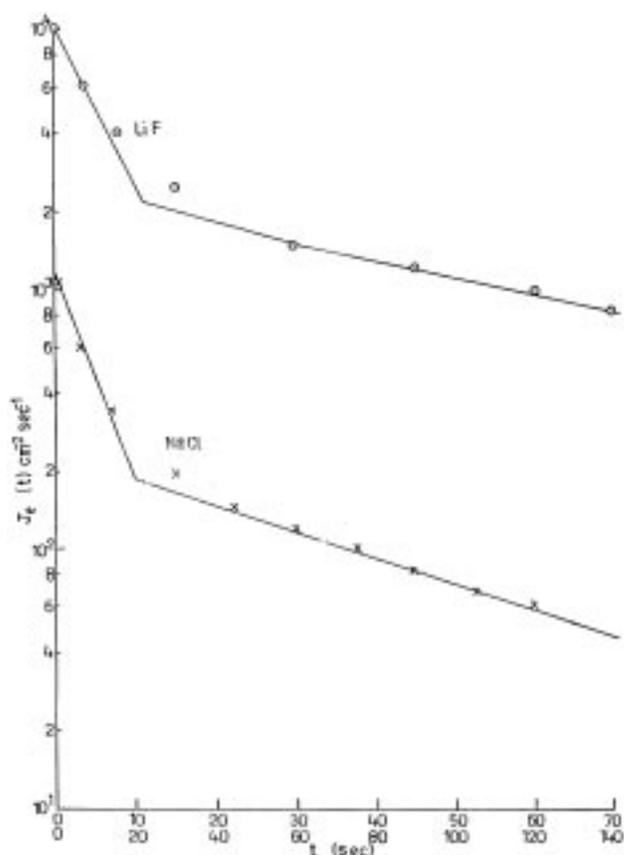**Figure 2.** Time dependence of the electron flux density produced during the cleavage of LiF (after Yanova [28]).

Figure 3. Plot of log (J) vs. t for LiF and NaCl crystals (upper time scale is for NaCl and the lower time scale is for LiF).

Table 1. Values of t_m, γ, α and decay time of charge.

			α (s^{-1})		Decay time ($= 1/\alpha$) (s)	
Crystal	t_m (μs)	γ (100 erg/cm^2)	Fast decay	Slow decay	Fast decay	Slow decay
NaCl	3.12	310	0.19	0.020	5.26	50
LiF	2.63	374	0.073	0.003	13.69	125

newly created surfaces diffuses towards the surfaces and later on the charge carriers lying at relatively longer distances diffuse towards the surfaces, which in turn, cause the faster decay of surface charges in the beginning and slow decay of surface charge later on. Thus, two types of diffusing centres are responsible for the charge relaxation and thereby for the emission of fast electrons produced during the cleavage of alkali halide crystals.

The values of rate constant α and decay time determined from the slope of figure 3 are shown in table 1 for the initial and longer portion of decay, for NaCl and LiF crystals.

Krotova *et al* [4] have shown that the charges on the newly created surfaces of the alkali halide crystals cleaved in vacuum remain for very long duration. Dickinson *et al* [15] have also reported that the surface charges of insulators have long decay times of several minutes to hours in a vacuum. In certain materials, the emission of fast electrons decays rapidly within a time duration of a few microseconds to milliseconds. The rapid decay observed implies that it is a measure of the supply of excited species rather than due to the charge leakage.

Wollbrandt *et al* [5,11], Molotskii [30] and Molotskii and Malyugin [29] have found that the rate of fast electron emission increases with the increasing value of the surface charge density of the crystals. Molotskii and Malyugin [28] have reported that the rate of fast electron emission depends on the area of newly created surfaces of the crystals. All these results matches with the results of the proposed theory.

Wollbrandt *et al* [5,11] have reported that at low temperature, the rate of fast electron emission decreases with decreasing temperature. Krotova *et al* [4] have reported that in the high temperature range, the rate of fast electron emission decreases with increasing temperature of the crystals. Molotskii *et al* [5,11] have shown that the rate of fast electron emission increases with the increasing density of color centres in the crystals. Krotova *et al* [4] have reported that the rate of fast electron emission decreases with increasing humidity. Molotskii [30] has shown that the rate of fast electron emission depends on the dopants in the crystals. All these experimental results are also in accordance with the theoretical results of the present investigation.

Figure 4 shows the energy spectrum of the fast electrons produced during destruction of LiF and NaF crystals. The maximum energy corresponds to 77 and 126 keV for LiF and NaF crystals, respectively. At energies less than 20 keV, there is a decrease in intensity due to the low energy threshold of the scintillation counter. The energy spectrum of the electrons which are emitted during cleavage depends on the surface charge distribution. Hence, the study of the distribution function of the emitted particles enables one, in principle, to obtain information regarding the charge structure of the crystal which is fractured. The existence of a small number of mechano-electrons with energies of tens of keV can be explained by the existence of local centres with a high-charge density. An analysis of the experiments of Wollbrandt *et al* [5,11], carried out by Molotskii and Malyugin [28] showed that the centres with a radius of 2.4×10^{-2} cm and a maximum charge density $\sigma_e \sim 10^4$ cgs e.s.u./cm^2, satisfy the requirements for the emission of fast electrons with a limiting energy of 85 keV during the cleavage of LiF.

Figure 5 shows the spectral dependence of photo-stimulated emission after stimulation of light of various wavelengths. The curves show a selective form of the photo-stimulated emission as a function of the stimulating light and there is a shift of red edge of the photoeffect (2.5 eV instead of 4.3 eV) [38]. It seems that the emission centres are the energy levels of the forbidden band. The maximum of all the curves in figure 5 corresponds to $\lambda = 490$ nm, i.e., the emission is always associated with one or the other defects which may be the color centres of alkali halide crystals.

It is evident from the relation, $v = H/t_m$, that the average velocity of the crack propagation can be measured by measuring t_m for a given thickness of the crystals. Although there are experimental results related to the occurrence of t_m, it has not been measured accurately to date on fast time scale.

The emission of fast electrons produced during cleavage of alkali halide crystals should be accompanied by the diffusion-controlled recombination mechanoluminescence or ex-

citon mechanoluminescence, in which, the time dependence of the mechanoluminescence should be similar to that of the fast electron emission. In fact, when an alkali halide crystal is cleaved in vacuum, the intensity of the mechanoluminescence produced due to the transient recombination or tunneling is so intense that the intensity of diffusion-controlled recombination mechanoluminescence or exciton mechanoluminescence becomes negligible. The study of diffusion-controlled long-lived recombination mechanoluminescence or exciton mechanoluminescence may be interesting.
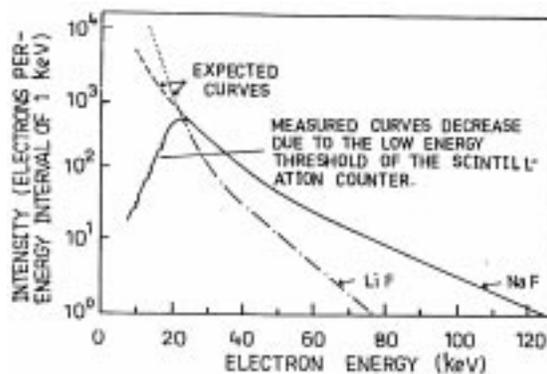

Figure 4. Energy spectra of electrons emitted during mechanical treatment of LiF and NaF crystals. The dashed curves denote the assumed spectrum of the electrons. The solid curve falls to the left because of a drop in the sensitivity of the counter (after Wollbrandt *et al* [5]).
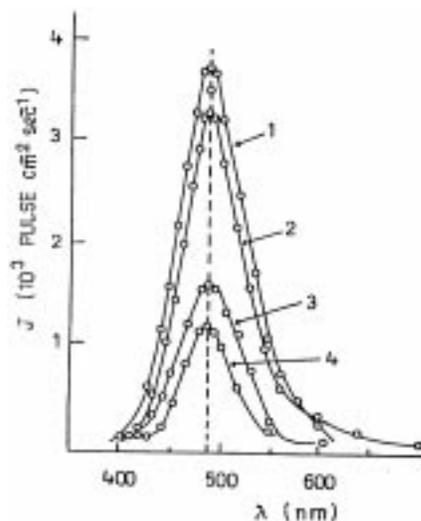

Figure 5. Dependence of photostimulated emission from a fresh NaCl surface several minutes after excavation on the wavelength of the stimulating light. (1) 8 min; (2) 12 min; (3) 22 min; (4) 33 min (after Krotova *et al* [4]).

4. Conclusions

The important conclusions drawn from the present investigations are as given below:

  (i) When a crystal is cleaved, initially, the rate of fast electron emission increases linearly with time, attains a peak value at the time t_m corresponding to completion of the cleavage of the crystal, and then it decays exponentially with time. The decay time of the rate of fast electron emission gives the decay of the charges on the newly created surfaces of the crystals.

  (ii) The maximum rate of fast electron emission, and the total number of fast electrons emitted may be given by the following expressions, respectively

$$J_m = \eta DB\gamma\alpha A$$

and

$$J_T = \eta DB\gamma A.$$

It is evident that both J_m and J_T should increase linearly with the area of newly created surfaces of the crystals as well as with the charge density of the newly created surfaces.

  (iii) The expressions derived explain the several observed characteristics of the fast electron emission produced during the cleavage of crystals.

  (iv) The emission of fast electrons produced during the cleavage of alkali halide crystals should be accompanied by diffusion-controlled long-lived recombination mechanoluminescence or exciton mechanoluminescence, in which, the time dependence of mechanoluminescence intensity should be similar to that of the rate of fast electron emission.

  (v) From the measurement of the fast electron emission, the velocity of crack propagation in a crystal can be determined by using the relation $v = H/t_m$.

References

[1] V V Karasev, N A Krotova and B V Deryagin, *Dokl. Akad. Nauk. SSSR* **88**, 777 (1953)
[2] N A Krotova and V V Karasev, *Dokl. Akad. Nauk. SSSR* **92**, 607 (1953)
[3] V V Karasev and N A Krotova, *Dokl. Akad. Nauk. SSSR* **99**, 715 (1954)
[4] N A Krotova, E Linke, Yu A Khrustalev, I Wollbrandt and V I Shipovskii, *Dokl. Akad. Nauk. SSSR* **208**, 138 (1973)
[5] I Wollbrandt, Yu A Khrustalev, E Linke, N A Krotova and B V Deryagin, *Dokl. Akad. Nauk. SSSR* **225**, 342 (1975)
[6] Yu A Khrustalev and N A Krotova, *Krist. und Techn.* **13**, 1077 (1976)
[7] Yu A Khrustalev, Thesis Inst. Fiz. Khimii Akad Nauk. SSSR, Moscow (1978)
[8] B V Deryagin, N A Krotova and V P Smilga, *The adhesion of solids* (Adgeziya Tverdykh tel, Moscow, 1973) (in Russian)
[9] K Hoffman and E Linke, *Krist. und Techn.* **11**, 835 (1976)
[10] K Hoffman and E Linke, *Krist und Techn.* **12**, 495 (1977)
[11] J Wollbrandt, E Linke and K Mayer, *Phys. Status Solidi* (a) **27**, 53 (1975)

[12] I V Krylova, *Materials of the Vth All-Union Symposium on the Mechanico-emission and Mechanico Chemistry of Solids* (in Russian), Tallin, **1**, 49 (1977)

[13] I Wollbrandt, U Bruckner and E Linke, *Phys. Status Solidi* **A78**, 163 (1983)

[14] V N Rudkovskii, V I Zametin and U Ya Nikiforov, *Fiz. Tverd. Tela* (Leningrad) **26**, 3709 (1984)

[15] J T Dickinson, E E Donaldson and M K Park, *J. Mater. Sci.* **16**, 2897 (1981)

[16] J T Dickinson, M K Park, E E Donaldson and L C Jensen, *J. Vac. Sci. Technol.* **20**, 436 (1982)

[17] J T Dickinson, L B Brix and L C Jensen, *J. Phys. Chem.* **88**, 1698 (1984)

[18] J T Dickinson, L C Jensen and W D Williams, *J. Am. Ceram. Soc.* **68**, 235 (1985)

[19] J T Dickinson and E E Donaldson, *J. Adhesion* **24**, 199 (1987)

[20] J T Dickinson, S C Langford and L C Jensen, *J. Mater. Res.* **8**, 2921 (1993)

[21] J T Dickinson, L C Jensen and R P Dion, *J. Appl. Phys.* **73**, 3047 (1993)

[22] J T Dickinson and E E Donaldson, *J. Adhesion* **24**, 199 (1987)

[23] S C Langford, J T Dickinson and L C Jensen, *J. Appl. Phys.* **62**, 1437 (1987)

[24] Yi Ma Zhen and J T Dickinson, *J. Appl. Phys.* **70**, 4797 (1991)

[25] M I Molotskii, *Dokl. Akad. Nauk SSSR* **243**, 1438 (1978)

[26] M I Molotskii, *Pis'ma Zh. Tekh. Fiz.* **6**, 1523 (1980)

[27] V V Surkov, *Zh. Tekh. Fiz.* **56**, 1818 (1986)

[28] L P Yanova, *Proc. Fifth All-Union Symposium on Mechano-emission and Mechano-chemistry of Solids*, Tallin (in Russian) **2**, 90 (1977)

[29] M I Molotskii and V B Malyugin, *Fiz. Tverd. Tela* (Leningrad) **25**, 2892 (1983)

[30] M I Molotskii, *Fiz. Tverd. Tela* (Leningrad) **19**, 642 (1977)

[31] V V Karasev, N A Krotova and B V Deryagin, *Dokl. Akad. Nauk. SSSR* **89**, 109 (1953)

[32] B P Chandra and J I Zink, *Phys. Rev.* **B12**, 816 (1980)

[33] B P Chandra and J I Zink, *J. Chem. Phys.* **73**, 5933 (1980)

[34] M I Molotskii, *Sov. Sci. Rev. B, Chem. Rev.* **13**, 1 (1989)

[35] B P Chandra, *Nuclear Traks* **10**, 825 (1985)

[36] A T Walton, *Adv. Phys.* **26**, 887 (1977)

[37] D V Alekseev, *Sov. Phys. Solid State* **34**, 1085 (1992)

[38] V S Fomenko, *Emission properties of elements and chemical properties* (in Russian), Kiev, (1964), p.62

[39] W Strube and E Linke, *Crystal Res. Technol.* **19**, 965 (1984)