

METHODOLOGICAL NOTES

Electrification of an ionic crystal upon plastic deformation and fracture

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Three independent electrification effects have been found and studied in crystals of lithium fluoride. Upon cleavage, the parts of the crystal become charged with charges equal in magnitude and opposite in sign. As a result of plastic deformation, the crystal becomes a sort of pyroelectric, and an intrinsic electric field appears in it. When the deformed crystal contacts a conductor, the crystal becomes charged with a sign opposite to that of the intrinsic field at the point of contact. An interpretation of the cited effects is given.

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1. INTRODUCTION

Even Faraday knew that certain crystals become electrified upon deformation and fracture. He wrote in 1833: "By ordinary electricity I understand that which can be obtained from the common machine, or from the atmosphere, or by pressure, or cleavage of crystals..."^[1] The next mentions of this phenomenon appeared 100 years later. In 1930, Obreimoff^[2] noted that mica becomes electrified when cleaved. In 1933, Stepanov^[3] found an electrification of rock salt upon plastic deformation.

Fischbach and Nowick^[4] and Caffyn and Goodfellow^[5] reproduced the Stepanov effect in 1955. It has since been subjected to further study.^[6-13]

These studies have shown that electrification (in ionic crystals) arises with any type of plastic deformation: compression, tension, bending, impact of an indenter, etc.; an electric charge arises in all cases at a metallic electrode cemented or pressed onto the deformed crystal.

The authors of the studies did not deem it necessary to discuss this fact from the standpoint of the law of conservation of charge, and the problem of the source of the charge remained open. Yet the following possibilities are the only ones that do not contradict the conservation law:

- the charge arises from electron flow from the crystal to the electrode (or vice versa);
- the charge of the electrode is an induced charge that arises from an electric field in the crystal.

In turn, there are two possibilities in the latter case:

- the electric field arises from a change in the charge of the crystal, e.g., owing to emission of electrons (or ions) into the surrounding air;
- the electric field arises from polarization of the crystal, i.e., owing to an ordered distortion of its crystal structure.

The experiments to be discussed below permit us to select among these possibilities. Yet first it is useful to discuss certain general problems that pertain to any electrified objects.

2. THE FIELD OF AN ELECTRIFIED OBJECT

We say that a solid object is electrified when it possesses an electric field. The latter arises when either the overall charge of the object or the distance between the "centers of gravity" of the opposite charge components is not zero.

The field can be calculated in both cases. Let us illustrate this with the example of a disk-shaped dielectric object (the calculations are extremely cumbersome for an object of another shape).

Let us denote the radius of the disk by a , its thickness by h , and we shall seek the field intensity at a point lying along the axis of the disk at the distance l from its surface. Let us examine two problems that correspond to the two above-cited types of electrification:

a) Excess charge distributed uniformly with the density ρ throughout the volume of the disk. In this case, owing to the uniform charge distribution, there is practically no polarization of the material of the disk, and an elementary calculation (neglecting polarization) leads to the following expression for the field intensity:

$$E = 2\pi\rho h \left(1 - \frac{z_0 + z}{\sqrt{z_0^2 + 1} + \sqrt{z^2 + 1}} \right), \quad (1)$$

where $z_0 = l/a$, and $z = z_0 + (h/a)$.

Hence we can easily see that infinitesimal deviations from neutrality of the material lead to enormous electric fields. For example, let $h = a = 0.5$ cm, and $\rho = 50$ cgs esu per cm^3 . Then the field near the surface of the disk will be ~ 100 cgs esu, i.e., 30,000 V/cm. Moreover, the stated charged density corresponds to 10^{11} electron charges per cm^3 , which is 10^{12} times smaller than the total number of charges of a given sign per cubic centimeter.

b) The overall charge of the disk is zero. The field is due to displacement of the centers of gravity of the opposite charge components. Above all, certain classes of ionic crystals possess a field of this type: pyroelectrics, in which the centers of gravity of the positive and negative ions are per se displaced with respect to one

another, and piezoelectrics, in which a displacement of the centers of gravity arises under elastic deformation of the crystal.

The dependence of the field intensity on the magnitude of the displacement can be calculated from the formula given above. Let us assume as a hypothetical example that in a lithium fluoride crystal the fluorine lattice has been displaced with respect to the lithium lattice by a segment of length λ along the $\langle 100 \rangle$ direction. Let the crystal here have the shape of a disk whose axis coincides with the stated direction.

By using Eq. (1), in which ρ now denotes the overall charge of the ions of a given sign per cm^3 , let us find separately the fields due to the lithium ions and the fluoride ions. Upon adding these fields and dropping the terms of higher order of smallness, we get

$$E = \pm 2\pi\rho\lambda \left(\frac{x_0}{\sqrt{x_0^2 + 1}} - \frac{x_0}{\sqrt{x_0^2 + 1}} \right). \quad (2)$$

The sign of the field is determined by the sign of the "closer" lattice, and thus it differs on the two sides of the disk.

As before, let us give a numerical example. If we assume as before that $h = a = 0.5 \text{ cm}$, $l \approx 0$, and we set $\rho = \pm 7.5 \times 10^{12} \text{ CGSE units per cm}^3$, we easily see that a field of $\sim 100 \text{ cgs esu}$ arises upon displacing the lattices by only two ten-thousandths of the interionic distance.

In conclusion, we should point out that actually the field of an electrified object seldom reaches 100 cgs esu . A glow discharge is already possible in such fields, and the ions formed in the air are attracted and attached to the surface of the object to partially neutralize it. Moreover, even in small fields, neutralization occurs, owing to the ions that are always present in the atmosphere.

Thus, under ordinary conditions the field does not exceed several tens of cgs esu , and it persists only for several hours, even in good dielectrics.

3. EXCESS ELECTRIC CHARGES [15]

The object of investigation throughout the study has been lithium fluoride crystals. At the outset, in the process of preparing the specimens, it turned out that the crystals become electrified upon cleavage. The study of this phenomenon (already mentioned in the Introduction) is subdivided into two stages.

In the first of these, the specimens were prepared with the apparatus shown schematically in Fig. 1. The crystal is placed on the end of a grounded brass cylinder. The brass tube 2, which bears the steel knife 3, is fitted from above onto the cylinder 1, and easily slides on it. The required position of the knife is attained by rotating the tube about the axis. Then the cap 4 is inserted into the tube. A sharp blow on the cap cleaves the crystal into two parts. One of them is removed and placed on a grounded brass table, and the other part is cleaved further. Then the same is done with the first part, etc. Each specimen obtained thus is brought into the chamber of a measuring apparatus to determine the charge.

Both this manipulation and all the previous ones are done with tweezers having smooth platinum tips; the tweezers are grounded with a thin, flexible conductor.

The apparatus for measuring the charge consists of a chamber directly attached to an electrometer and a grounded shield (Fig. 2). If we denote the capacity of the chamber (together with the electrometer) by C and the

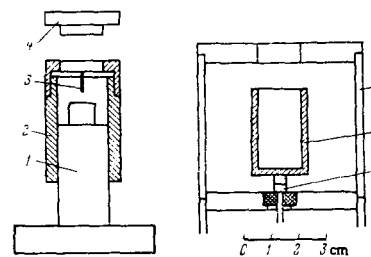


FIG. 1

FIG. 2

FIG. 1. Apparatus for cleaving specimens.

FIG. 2. Apparatus for measuring charge. 1—electrometer input, 2—chamber, 3—shield.

potential of the chamber when the specimen is inside by U , then we can easily find the charge of the specimen:

$$q = \frac{C}{300} U, \quad (3)$$

Here q is expressed in CGSE units, U in V, and C in cm^2 .

The measurements showed that specimens belonging to one given crystal differ from one another, both in absolute magnitude of the charge and in its sign. This circumstance determined the method of processing the experimental data.

Forty specimens were cleaved from one piece of crystal (of the same dimensions insofar as was possible). The charge values found for them were arranged in increasing order: $q_1 < q_2 < q_3 < \dots < q_N$. Then a graph was constructed in which each q on the horizontal axis corresponded to a y value on the vertical axis, as found by using the standard statistical tables from the equation:

$$\frac{t}{N+1} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t/\beta} e^{-x^2/2} dx.$$

Whenever the distribution of the specimens with respect to amount of charge obeys the normal law

$$p(q) = \frac{1}{\beta \sqrt{2\pi}} \exp\left(-\frac{q-\bar{q}}{2\beta^2}\right),$$

the relation between y and q is expressed by a straight line.

Hence, by constructing the stated graph, we can easily test whether the distribution obeys the normal law, and if so, we can directly find \bar{q} and β from the graph. The first of these quantities corresponds to the point of intersection of the straight line with the horizontal axis, and the second one to the tangent of the angle between the straight line and the vertical axis. [16]

Figure 3 shows such a graph for one of the studied crystals. It was subsequently possible to show that redistribution of free electrons between the knife and the crystal during cleavage plays a considerable role in the charge production. In the pertinent experiments, the cleavage was performed with a steel knife that was fastened by means of a Teflon insulator to the brass holder (Fig. 4). One can introduce such a knife into the electrometric chamber through the upper hole in the shield (see Fig. 2).

Forty cleavages were carried out. After each of them, the potential of the chamber was determined after the knife had been introduced into it. The difference between the preceding and the following values of the potential characterizes the amount of charge that has been trans-

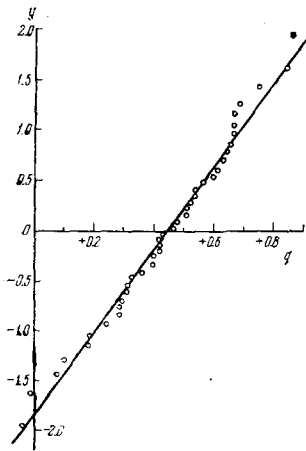


FIG. 3. Graph of $y(q)$: charges of specimens cleaved with a grounded steel knife (in cgs esu).

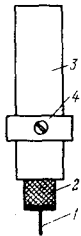


FIG. 4

FIG. 4. Steel knife on an insulator. 1—knife, 2—teflon insulator, 3—holder, 4—detent ring.

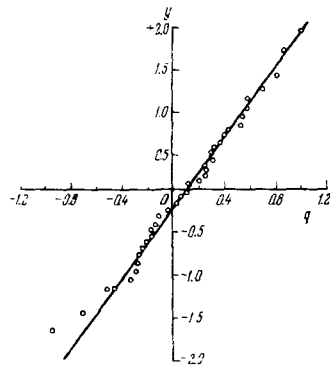


FIG. 5

FIG. 5. Graph of $y(q)$: charges on the knife arising upon cleavage (in cgs esu).

ferred from the knife to the crystal in the given cleavage. The graph of Fig. 5, which was drawn on the basis of the numbers thus obtained, is close in all respects to the graph of Fig. 3.

This implies quite definitely that the excess charges at least partially originate from redistribution of electrons between the knife and the crystal. It was found out later what causes this process and why it leads to such widely divergent results in different specimens, in spite of strict regulation of the experimental procedure. It turned out that the specimen is somewhat deformed upon cleavage, and consequently it acquires unusual contact properties (see Sec. 6).

Evidently, one should cleave the crystal with a dielectric knife in order to rule out this "extraneous" mechanism of charge formation.

4. ELECTRIFICATION UPON FRACTURE^[17]

A sapphire knife was used in the subsequent experiments. In contrast to the steel knife, it does not acquire a charge upon cleavage.

Figure 6 shows the corresponding apparatus. The crystal 1, which stands on the polished sapphire³⁾ plate 2, is cleaved by the sapphire knife 3. Owing to the presence of the detaining ring 4, the displacement of the knife during the stroke does not exceed 1–2 mm. The parts of the cleaved specimen remain in the quartz tube 5.

TABLE I. Change in the total charge of specimens upon cleavage (in CGSE units)

No.	Before	After	Difference	No.	Before	After	Difference
1	+0.04	+0.72	+0.68	11	-0.03	+1.02	+1.00
2	+0.18	+1.15	+0.97	12	+0.39	+0.88	+0.49
3	+0.07	+0.31	+0.24	13	+0.21	+0.97	+0.76
4	+0.36	+0.76	+0.40	14	+0.21	+2.10	+1.89
5	+1.10	+1.24	+0.14	15	+0.07	+0.51	+0.44
6	+0.60	+0.92	+0.32	16	+0.09	+0.67	+0.58
7	-0.10	-0.11	0	17	+0.07	+1.05	+0.98
8	+0.35	+0.66	+0.31	18	0	+1.25	+1.25
9	+0.21	+1.80	+1.59	19	+0.18	+0.87	+0.69
10	0	+1.20	+1.20	20	+0.35	+0.24	-0.11

TABLE II. Charges of the parts of a cleaved specimen (in CGSE units)

No.	I	II	No.	I	II	No.	I	II
1	-1.20	+1.92	8	+0.54	+0.12	15	+0.42	+0.09
2	+1.65	-0.50	9	-3.30	+5.10	16	-2.40	-1.74
3	+3.30	-3.00	10	+4.65	-3.45	17	+1.42	-0.36
4	+1.60	-0.90	11	-1.80	+2.82	18	-0.57	+0.69
5	-2.40	+1.15	12	-0.87	+1.75	19	-2.70	-1.83
6	+0.99	-0.07	13	+1.50	-0.53	20	-2.40	-2.16
7	+2.25	-2.13	14	-1.95	+4.05			

Subsequent manipulations with them are made by using sapphire-tipped tweezers.

The specimens were of dimensions $5 \times 5 \times 20$ mm. First the specimen is introduced into the electrometric chamber to determine its initial charge. Then it is set vertically under the knife and is cleaved longitudinally into two approximately equal parts. First one of them is introduced into the chamber to measure its charge. Then the second one is added to it, and the total charge of the two halves together is measured. Tables I and II give the results of the measurements.

Table I shows for each specimen: the initial charge before cleavage, the total charge of both parts after cleavage, and the difference between these values. We see from the table that cleavage causes the specimen to acquire a positive charge that is equal on the average to $+0.6 \pm 0.4$ CGSE units.

We can attribute this fact to emission of electrons from the newly formed surfaces. However, more likely, the charge arises from partial loss of adsorbed ions that compensate the intrinsic charge of the specimen.

Table II gives for each specimen the charges individually of its two parts. The numbers in the table were processed by the method presented above, and they are shown in Fig. 7. All of them fit one common straight line. If we subtract from these numbers the constant component found above of $+0.6$ cgs esu, then the straight line is shifted toward the left to pass through the origin. This implies that, apart from the constant component, one of the parts of the crystal upon cleavage acquires a positive charge, and the other one acquires exactly the same negative charge.

It is hard to believe that each time during cleavage the knife strikes a separation boundary of oppositely charged regions of the crystal (even if such regions exist). Hence we have to conclude that the charges arise in the cleavage process, owing to redistribution of electrons or ions between the walls of the running crack.

We can explain the charge separation in terms of imperfection of the crystal. For example, let us assume that the cleavage crack has encountered a structural defect and has deviated from the cleavage plane $\{100\}$ to uncover a small region of the crystallographic plane $\{111\}$. Then a "spot" will appear on one wall of the

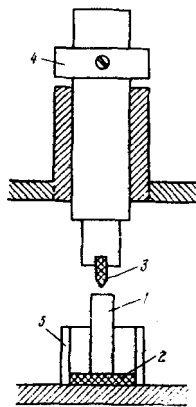


FIG. 6

FIG. 6. Apparatus for cleaving crystals with a sapphire knife.

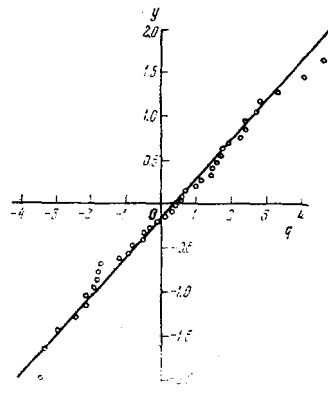


FIG. 7

FIG. 7. Graph of $y(q)$: charges of the parts of cleaved specimens (in cgs esu).

crack that consists of metal ions, and on the other wall, the same sort of spot consisting of halide ions (layers of metal alternate with halide layers in the $\{111\}$ plane). Hence fresh cleavages will be strewn with charged centers of both signs, and if by chance an excess of positive charges appears on one of the fragments, then an excess of negative charges will appear on the other fragment.

With this mechanism of electrification of the surface, the charge distribution on one fragment must be a mirror image of that on the other fragment. A corresponding experiment was set up to test this idea.

A probe was attached to the electrometer instead of the chamber. The probe was a rod 0.6 mm in diameter, to the bottom end of which was cemented perpendicularly a thin nickel plate of dimensions 6×1.5 mm.⁴⁾ The plate is set ~ 0.5 mm from the surface of the specimen, as is shown in Fig. 8. The table on which the specimen rests can be displaced (in the plane of the drawing) at a rate of 4 mm/min. Thus the specimen is "scanned" under the probe from one end to the other. The electrometer readings are recorded here on a strip-chart recorder.

The charge density σ on the lower surface of the "head" of the probe is related to the electric field intensity E of the specimen by the relation $\mp\sigma = \pm ES/2\pi$, where S is the area of the head. Hence the result of measuring the field intensity has the form

$$E = 2\pi \frac{C}{S} \frac{U}{300}; \quad (4)$$

Here U is the electrometer reading (the potential of the probe) in volts, C is the capacity of the electrometer plus the probe in cm,⁵⁾ and E is the field intensity in units of the cgs esu system.

This formula ignores the presence of the rod in the probe. Yet the rod, which lies in the field of the specimen just as the head does, makes a certain contribution to the electrometer readings. We can estimate this contribution by repeating the measurements twice: once with a normal probe, and the second time with a probe lacking a head. The pertinent correction depends on the dimensions and shape of the specimen. For the specimens that we shall discuss below, the correction amounts to as much as 20%. Therefore all the results of calculating the field by using Eq. (4) will henceforth be diminished by 20%.

The experiments were conducted as follows. Marks

FIG. 8. Movable table. 1—specimen, 2—glass plates, 3—supports, 4—probe.

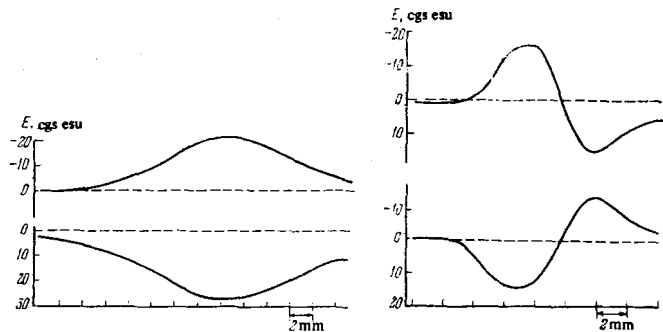
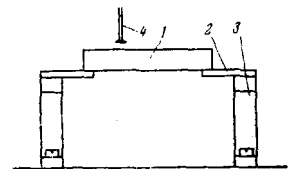


FIG. 9

FIG. 10

FIG. 9. Field distribution (field intensity) in the two halves of a cleaved specimen. The dotted lines correspond to zero field.

FIG. 10. The same as Fig. 9 (rare case).

(scratches) were made near one of the ends of the specimen on the two opposite faces. After this, the specimen is set up with the marks underneath in the apparatus of Fig. 6, and it is cleaved into two approximately equal parts in such a way that each has its own mark.

Then one half is first put on the table with the fresh cleavage up and the mark below, and it is scanned with the probe. Then the same is done with the second half. The experiment as repeated on several tens of specimens confirmed the expectation: the recordings of the field distribution of the two halves of the cleaved specimen match one another as mirror images, as in Figs. 9 and 10 (as a rule, the sign of the field does not change within the confines of a fragment; sign constancy was violated in only one case). Thus the studied mechanism of origin of the excess charges agrees with the experimental data.

5. ELECTRIFICATION UPON PLASTIC DEFORMATION^[18]

The experiments were conducted on specimens of lithium fluoride of dimensions $15 \times 5 \times 5$ mm. The specimens were cleaved in series of 10–15 pieces each from neighboring regions of the crystal. The deformation was carried out by compressing the specimen along the long axis. A micrometer having freely rotating tips was used as the press.⁶⁾ In order to prevent rotation of the specimen during compression, the tip on the stationary end of the micrometer was pinned. Polished sapphire disks cemented to the end surfaces of the tips ensured the electric isolation of the specimen.

The micrometer screw was rotated by means of a reducing gear with a Warren motor. The rate of compression was 0.1 mm/min. The micrometer and the motor with the reducing gear were set up on an optical bench. The electric field of the specimen that arose during deformation was measured by a probe method. The electrometer was set up on the same optical bench, and its probe was set above the upper surface of the specimen at a distance of ~ 1 mm from it (Fig. 11).

The electrometer could be displaced along the bench at a rate of 4 mm/min by means of a push rod driven by a motor. Here the probe passed over the specimen from one end to the other, and the electrometer readings were recorded on a strip-chart recorder.

The experimental setup permits one to measure the relationship between the field intensity and the degree of deformation (with a fixed position of the probe) and the relationship between the field intensity and the probe position (at a fixed degree of deformation).

Figures 12 and 13 show three characteristic types of relationships of the field intensity to the degree of deformation (with the probe over the middle of the specimen), while Figs. 14 and 15 show the relation of the field intensity to the probe position for different specimens and at different degrees of deformation.

Apparently the variegated and unpredictable variations in the two relationships are due to the inhomogeneity of the specimens and to unavoidable bending during compression in the press.

Further studies had the aim of finding whether the field of the deformed specimen changes when the load is removed. After the record had been completed, the press containing the specimen was removed from the bench, and a sapphire table was put under the probe in place of it. The specimen was released from the press and laid on this table by using sapphire-tipped tweezers. The electrometer was then set into motion, and its readings were recorded again with the recorder. Comparison of this recording with the original one shows that the field of the specimen does not change when the load is removed.

In the next series of experiments, the field distribution was recorded in an analogous way along all four long

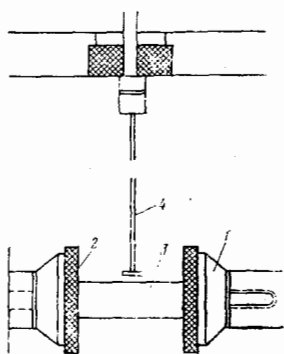


FIG. 11. Elements of the experimental apparatus. 1—micrometer tip, 2—sapphire disk, 3—specimen, 4—probe.

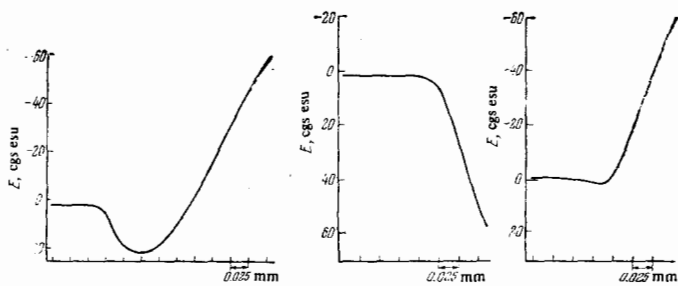


FIG. 12

FIG. 13

FIG. 12. Relation of the field intensity to the degree of deformation of the specimen. One division on the axis of abscissas corresponds to displacement of the micrometer screw by 0.025 mm.

FIG. 13. The same as Fig. 12—two extreme cases.

faces of the deformed specimen. Figure 16 shows as an example such a set of recordings: the curves pertaining to the opposite faces are juxtaposed. We see from the curves that the field of the deformed specimen near certain regions of the surface is positive, and near others it is negative, whereas the overall field is close to zero. Hence we should conclude that the overall charge of the specimen does not change upon plastic deformation.

The experiments to be discussed below were undertaken to test this conclusion. The ends of a thin kapron filament (20 cm long) were cemented to the original undeformed specimen at a little distance from its ends. The specimen is lowered on this filament by using a special support into the electrometric chamber in order to measure the initial charge. Then the specimen is carefully removed from the chamber, and is suspended between the sapphire disks of the micrometer. Here the desired degree of deformation is imparted to the specimen, whereupon it is again lowered into the chamber for

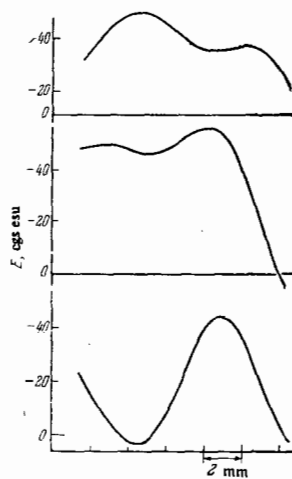


FIG. 14

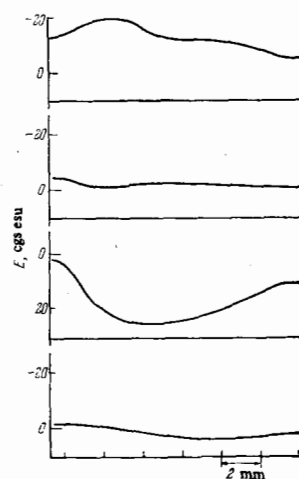


FIG. 15

FIG. 14. Field distribution in three deformed specimens. Degree of deformation (top to bottom): 0.037, 0.25, and 0.35 mm of compression.

FIG. 15. Field distribution in a deformed specimen. The first recording pertains to the initial state; the second, third, and fourth recordings to successive stages of deformation.

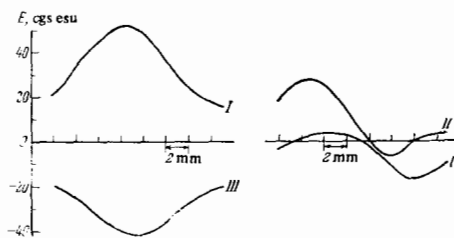


FIG. 16. Field distribution along the four long faces of a deformed specimen.

TABLE III. Change in the charges of specimens upon deformation

No.	Compression, mm	q, cgs esu			No.	Compression, mm	q, cgs esu		
		Before	After	Difference			Before	After	Difference
1	0.10	+0.06	+0.37	+0.31	6	0.20	+0.37	+0.57	+0.20
2	0.15	+0.57	+0.72	+0.15	7	0.25	+0.16	+0.98	+0.82
3	0.15	+1.05	+1.9	+0.85	8	0.20	+0.28	+0.75	+0.47
4	0.15	-0.30	+0.72	+0.42	9	0.30	+0.23	+0.67	+0.44
5	0.20	+0.41	+0.40	-0.01	10	0.20	+0.30	+0.60	+0.30

measuring the final charge. Table III shows the obtained results.

The calculations show that the field of the specimen is related to its charge (uniformly distributed over the volume or the surface) by the relationship $E \approx 3q$. Hence, by using the data of the last column of the table, we can easily see that the field arising from the acquired charge does not exceed 2–3 cgs esu. Moreover, the observed fields are 10–20 times greater. The discrepancy indicates that the crystal is polarized by the plastic deformation, or an electric field appears in it while its charge remains unchanged and close to zero.

This fact has a simple explanation. The plastically deformed crystal is permeated with dislocations. The nuclei of the dislocations, and also the elastic lattice distortions in the intervals between them, unavoidably perturb the local compensation of charges of the ions of opposite types. Consequently, corresponding electric fields arise at certain sites. Since the dislocations are oriented in a certain way in the crystal, these fields have a preferential orientation, and their superposition gives rise to the electric field of the crystal as a whole.

Chapter 2 implies that such a field (in magnitude) can be obtained by displacing the lattices of the ions of opposite types by a ten-thousandth of the interionic spacing. The displacements of the ions in the distorted lattice of a plastically deformed crystal on the average are of the same order of magnitude. Thus there is every reason to consider a deformed crystal to be a sort of pyroelectric. We note here that several regions differing in direction of displacement of the lattices can arise in the crystal during deformation, owing to the existence of equivalent slip systems. Thereby, a deformed crystal is as a rule a polydomain pyroelectric whose domain structure depends very greatly on the conditions of deformation. This circumstance complicates the pattern of the electric field of the crystal, and gives it an unpredictable character.

We shall further point out that any pyroelectric is simultaneously also a piezoelectric.⁷⁾ Thus a plastically deformed crystal must possess piezoelectric properties: to be deformed by the action of an electric field, and to be electrified upon deformation (in the elastic region!). There are a number of experimental studies in which both effects have been directly observed (see, e.g., [12, 20, 21]).

6. CONTACT PHENOMENA [18,22]

Owing to the existence of an intrinsic field, a plastically deformed crystal possesses unusual contact properties. If one approaches the surface of a specimen with an electrometer probe, one sometimes observes electrical breakdown of the air gap. The ions that arise here are attracted to the surface, and they change the charge of the specimen when they deposit on it. Contact with the probe changes the charge of the specimen, even at lesser fields—in the absence of a spark.

This effect has been subjected to more thorough study by using the same methodology.

The same deformed specimens were studied as in the previous experiments. The specimen was placed on the sapphire table in the same way, and scanned under the electrometer probe.

However, in this case a contact probe was used. In

TABLE IV. Charges acquired by the specimen upon contact (in CGSE units)

-0.11	-3.1	+0.79	+0.75
-3.4	+2.2	+2.6	+0.37
+0.4	-0.64		

The deformation of the specimens is 0.2–0.3 mm of compression; each specimen was tested once; the duration of contact was 10 sec; measurements in which electric breakdown occurred are not cited.

contrast to the probe that had been used before, it has an elastic loop of platinum wire (wire diameter 0.1 mm) instead of the usual head. At the beginning of the measurement, the table is gently raised until the loop contacts the surface of the specimen. After some time of contact has elapsed, the table is lowered, and the specimen is removed. Two electrometer readings are taken during this procedure: directly before contact of the specimen with the probe, and after complete removal of the specimen. The first reading gives information on the sign of the field, and roughly on its magnitude—since the probe is not designed for field measurements. The second reading permits one to determine the sign and magnitude of the residual charge of the electrometer. This charge (with the sign reversed) equals the charge acquired by the specimen upon contact. Numerous measurements showed that in all cases the sign of the acquired charge is opposite to the sign of the field, and as a rule, its magnitude is proportional to the field intensity. Hence, in a region of the surface that corresponds to a positive sign of the field, free electrons are attracted into the crystal; in a region corresponding to a negative sign of the field, they are repelled from it. Table IV gives a picture of the numerical values of the acquired charge.

We see from the table that the effect is large, and it should be taken into account in all cases in which a deformed or deformable crystal comes into contact with metallic objects, with a knife, with tweezers, electrodes, etc.

¹⁾See also the more complete review of Urusovskaya. [14]

²⁾The design of the electrometer and the dimensions of the chamber were changed during the course of the study. Correspondingly, the capacity in different experiments varied from 4 to 5 cm.

³⁾This refers to single-crystal leucosapphire.

⁴⁾In other experiments, a disk 3.2 mm in diameter.

⁵⁾In this case, $C \approx 5.5$ cm.

⁶⁾This type of micrometer is used to measure the thickness of paper.

⁷⁾Yet a piezoelectric need not be a pyroelectric. [19]

¹⁾M. Faraday, *Experimental Researches in Electricity*, Vol. 1, Sec. 284, E. P. Dutton, New York, 1940; Dover, New York, 1965 (Russ. Transl., Izd-vo AN SSSR, M., 1947).

²⁾I. W. Obreimoff, *Proc. Roy. Soc.* A127, 290 (1930).

³⁾A. W. Stepanov, *Zs. Phys.* 81, 560 (1933).

⁴⁾D. B. Fischbach and A. S. Nowick, *Phys. Rev.* 98, 1543, 99, 1333 (1955).

⁵⁾J. E. Caffyn and T. L. Goodfellow, *Nature* 176, 878 (1955).

⁶⁾D. B. Fischbach and A. S. Nowick, *J. Phys. Chem. Sol.* 5, 302 (1958).

⁷⁾F. Rueda and W. Dekeyser, *Phil. Mag.* 6, 359 (1961); *J. Appl. Phys.* 32, 1799 (1961).

⁸⁾J. E. Caffyn and T. L. Goodfellow, *Proc. Phys. Soc.* A79, 1285 (1962); *Philos. Mag.* 7, 1257 (1962).

- ⁹ F. Rueda and W. Dekeyser, *Acta Met.* **11**, 35 (1963).
- ¹⁰ I. Kiss, *Kristallografiya* **10**, 890 (1965) [*Sov. Phys.-Cryst.* **10**, 740 (1966)].
- ¹¹ F. Rueda and W. Dekeyser, *Phys. Stat. Sol.* **17**, 739 (1966).
- ¹² R. DeBatist, E. Van Dingenen, Yu. N. Martyshev, I. M. Sil'vestrova, and A. A. Urusovskaya, *Kristallografiya* **12**, 1012 (1967) [*Sov. Phys.-Cryst.* **12**, 881 (1968)].
- ¹³ C. N. Ahlquist and L. Carlsson, *Scripta Met.* **6**, 1129 (1972).
- ¹⁴ A. A. Urusovskaya, *Usp. Fiz. Nauk* **96**, 39 (1968) [*Sov. Phys.-Uspekhi* **11**, 631 (1969)].
- ¹⁵ M. I. Kornfel'd, *Fiz. Tverd. Tela* **10**, 2422 (1968); **12**, 318 (1970) [*Sov. Phys.-Solid State* **10**, 1904 (1969); **12**, 263 (1970)].
- ¹⁶ D. Hudson, *Statistics for Physicists*, (Russ. Transl. "Mir", M., 1970).
- ¹⁷ M. I. Kornfel'd, *Fiz. Tverd. Tela* **13**, 474 (1971); **16**, 3385 (1974) [*Sov. Phys.-Solid State* **13**, 381 (1971); **16**, 2193 (1975)].
- ¹⁸ M. I. Kornfel'd, *Fiz. Tverd. Tela* **15**, 3014 (1973); **16**, 180 (1974) [*Sov. Phys.-Solid State* **15**, 2008 (1974); **16**, 107 (1974)].
- ¹⁹ L. D. Landau and E. M. Lifshitz, *Élektrodinamika sploshnykh sred* (Electrodynamics of Continuous Media), Gostekhizdat, M., 1957 (Engl. Transl., Pergamon Press, Oxford, 1960).
- ²⁰ R. L. Sproull, *Phil. Mag.* **5**, 815 (1960).
- ²¹ B. K. Kardashev, S. P. Nikanorov, and O. A. Voinova, *Fiz. Tverd. Tela* **16**, 1068 (1974) [*Sov. Phys.-Solid State* **16**, 687 (1974)].
- ²² M. I. Kornfel'd, *Fiz. Tverd. Tela* **16**, 311 (1974) [*Sov. Phys.-Solid State* **16**, 311 (1974)].

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