Experimental investigation of the transition sound radiation emitted by dislocations emerging to the surface

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Transition radiation of sound by dislocations is studied experimentally. The movement of a dislocation pile-up inside the crystal is recorded by high-speed motion picture photography as it approaches and crosses the surface. Simultaneously, the sound emitted during the process is measured. It is found that within the experimental errors, pronounced sound emission is observed only after the dislocations reach the crystal surface (transition radiation). Change of sign of the dislocations "bombarding" the crystal surface causes a change in sign of the sound emission. The sign of the sound emission is identical with that of the dislocation flux density, so that it is possible to determine from the data on the sound emission whether the plastic deformation of the crystal increases or decreases as a function of time. The dislocation velocity is estimated from the intensity of the sound signal, and the kinetics of the emergence of the dislocations to the surface are considered.

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1. INTRODUCTION

Starting out from the continuous theory of dislocations and electrodynamics, one can expect that the mechanisms of sound radiation by the dislocations should be analogous to the mechanisms of radiation of electromagnetic waves by moving charges. Natsik[1] has considered one such mechanism—the radiation of the sound by the dislocation upon its emerging to the surface. This radiation is similar to the transition radiation of electromagnetic waves from a charged particle, which appears at the intersection of the boundary of two media with different dielectric constants,[2] and has been called transition radiation by analogy with electrodynamics. It turned out that in this case the fields of the radiation are proportional to the rate of emergence of the dislocation to the surface and to its Burgers vector. It was hoped that the radiation could be observed experimentally in the elastic twinning of calcite. An elastic twin is a plane macroscopic pile-up of twinning dislocations,[3] which can be produced by parallel sections of rectilinear dislocations and can be controlled by a known external stress field.[4]

We have proposed and achieved[5] a method which enables us to observe a sound pulse when an elastic twin emerges from a crystal under the action of the surface tension forces. The presence of a correlation between the character of the signals and the dislocation velocity near the surface, observed earlier,[6] indicated that the radiating component of the field of the moving dislocations was being observed. A comparison was carried out[7] of the sound pulse observed in the experiment with the theoretical value. The latter was computed from the rate of motion of the dislocations, which was determined from the theory of the dynamic behavior of the twin,[8] and the radiation was assumed to be taking place according to a transition mechanism.[1] The agreement of the theoretical and experimental data turned out to be completely satisfactory. This allowed us to propose a method[9] of establishing the absolute values of the rates of motion of the dislocations near the surface from the acoustic emission accompanying the plastic deformation of the crystals. Synchronous recording of the motion of the dislocations and the sound radiation generated by them[10] has shown that the method proposed in Ref. 9 actually allows us to obtain information on the dislocation velocities.

At the same time, it should be noted that in the experiments carried out previously,[5–7, 9, 10] it was not possible to isolate the transition radiation in pure form, since, in the experimental situations employed there, there was nonstationary movement of dislocations inside the crystal at the same time as the emergence of the dislocations to the surface (or their entrance into the crystal), which would lead to transition radiation. These latter would be accompanied by sound radiation similar to the bremsstrahlung of electromagnetic waves by rapidly moving charges. The aim of the present research was to detect, in pure form, transition radiation of sound from dislocations as they emerge to the surface. For this purpose, we proposed and achieved the following experimental technique.

2. EXPERIMENT

As in the experiment on the observation of sound radiation in annihilation of dislocations,[11] the crystal 1 (Fig. 1) was so cut that an elastic twin could be produced in it, consisting of rectilinear sections of twinning screw dislocations when both ends do not emerge to the lateral faces of the crystal. Upon application of a concentrated load 3 to the surface of the crystal, an elastic twin 2 appears in it. Such a twin, according to Ref. 3, consists of dislocations of different signs. If we use the system of coordinates shown in Fig. 1d and the known definition of dislocations (see, for example, Ref. 12), then all the dislocations on the right of the concentrated load 3 are positive, and those on the left are negative. Under the action of the load 3, they move in opposite directions, as shown by the horizontal arrows in Fig. 1a. After the dimensions of the twin become stabilized, a distributed load, shown in Fig. 1b by the vertical ar-

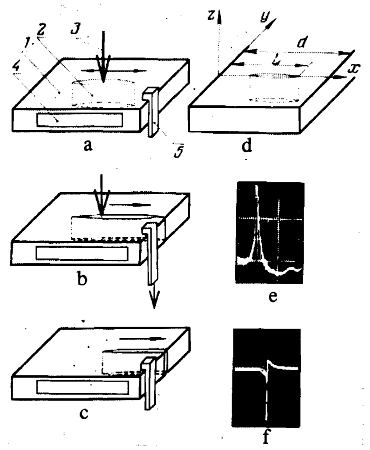

FIG. 1. Scheme of the experiment. a) Formation of an elastic twin under a concentrated load: 1—calcite crystal, 2—elastic twin, 3—concentrated load, 4—piezo-detector, 5—bar for application of distributed loading (attached to an electromagnet). b) Emergence of positive dislocations to the surface under the action of a distributed load. c) Emergence of an elastic twin, formed by negative dislocations, from an unloaded crystal under the action of the surface tension. d) Orientation of the set of coordinates (*d* is the width of the crystal, *L* is the coordinate of the right end of the twin). e) Sound pulse observed at the instant of emergence of the right end of the twin to the surface (scale of the oscillogram: along the abscissa, 10 mV/sec, along the ordinate, 20 millisec/cm). f) Sound pulse observed in the emergence of the elastic twin, formed by negative dislocations, from the unloaded crystal under the action of the surface tension (scale of the oscillogram: along the abscissa, 10 mV/cm, along the ordinate, 100 millisec/cm).

row, is applied to a bar connected with an electromagnet. A high-speed camera SKS-1 for recording the motion of the twin was turned on synchronously with the operation of the electromagnet (in transparent calcite crystals it was possible to illuminate the sample so that the interference color of the twin is clearly seen and the changes of the dimensions of the elastic twin in the course of its motion are readily recorded by high-speed photography). Under the action of the distributed load, the positive dislocations begin to move in the direction of the lateral face of the crystal (their direction of motion is shown by the horizontal arrow in Fig. 1b). At the moment when the twinning dislocations approach the surface of the crystal (the motor of the camera had by that time reaches the optimal speed, which allowed us to photograph at the rate of 3000 frames per second), the synchronizing apparatus triggers the system for recording the sound emission[5] and switches on a flashlamp located near the objective of the camera, which enabled us to record on the motion-picture film the moment of turning on the oscillograph.

The form of the acoustic signal that accompanies the emergence of the positive dislocations to the surface under the action of the distributed load is shown in Fig. 1a. In such an experimental setup, the situation is as close as possible to that considered in the theory of Ref. 1; emergence to the surface of rectilinear (parallel) pieces of screw dislocations takes place, with the direction of the velocity perpendicular to the surface. In contrast to the experiments undertaken earlier,[5–7,9,10] along with the continuous, nonstationary motion of the dislocations inside the crystal, there is clearly established a point on the time axis which separates the period when there is no emergence of the dislocations to the surface from the period when there is such an emergence.

The change in the distance from the tip of the twin to the surface and the oscillogram of the acoustic signal are compared in Fig, 2. These data can be compared against a single time scale with an error which does not exceed several milliseconds. In the limits of this error, significant acoustic radiation takes place only beginning from the moment of arrival of the twinning dislocation at the surface of the crystal, as should be the case for transition radiation. The reproducibility of the experiment is entirely satisfactory.

3. DISCUSSION OF THE RESULTS

In the experiments that have been described, we have succeeded in isolating in pure form the transition radiation of sound by dislocations as they emerge to the surface. The sound radiation of the dislocations which are accelerated inside the crystal has not been isolated. Estimates made earlier[7] show that this radiation is much weaker than the transition radiation. Possibly, therefore, it could not be separated in the given experiments.

In the scheme of experiment described above, the effect of the sign of the dislocations emerging to the surface on the character of the radiation could also be verified. Since, according to Natsik,[11] the field of the radiation is proportional to the Burgers vector, it follows that upon emergence of the dislocation to the surface the sign of the radiation field should be determined by the sign of its Burgers vector. After all the positive dislocations emerge to the surface of the crystal, the elastic twin will consist only of twinning dislocations of one sign (in the given case, negative) and takes the form of a thin wedge (Fig. 1c), as in all the experiments car-

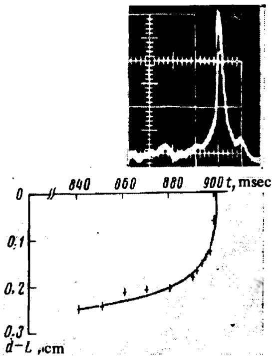

FIG. 2. Graph of the time dependence of the distance from the end of the twin to the surface of the crystal (obtained from data of high-speed filming), superposed with the oscillogram of the sound pulse recorded in parallel (for the time origin, we take the instant of switching on the high-speed camera; the scale of the oscillogram: along the abscissa, 10 mV/cm, along the ordinate, 20 millisec/cm.

ried out earlier with an elastic twin. If now we unload the crystal, then the elastic twin begins to emerge from the crystal under the action of the surface tension forces (the direction of motion is shown in Fig. 1c by the horizontal arrow). The possibility now appears of recording the sound radiation arising upon bombardment of this portion of the crystal surface by dislocations of opposite sign. The corresponding acoustic pulse is shown in Fig. 1f.[1] Comparison of Figs. 1e and 1f shows that under conditions in which the direction of the velocity of the dislocation relative to the surface do not change and only the sign of the dislocation changes, the sign of the radiation field also changes.

It was shown earlier[9] that if the sign of the Burgers vector of the dislocation is preserved but the direction of the velocity of its motion relative to the surface changes, the sign of the radiation field also changes. Thus, one can determine the sign of the product $\mathbf{b}\cdot\mathbf{V}$ from acoustic emission data, but the sign of this product determines also the sign of the component of the tensor of flux density of the dislocations j_{ik} (for more detail, see the review of Ref. 14), which is connected with the plastic deformation tensor ε_{ik}^{pl} by the following relation:

$$\partial\varepsilon_{ik}^{pl}/\partial t=-J_{ik},$$

where J_{ik} is the symmetric part of the tensor j_{ik}.

Thus, the possibility appears of measuring the acoustic emission and obtaining information on the sign of the derivative $\partial\varepsilon_{ik}^{pl}/\partial t$, i.e., of determining whether the plastic deformation increases or decreases with time. In the case shown in Fig. 1b, the tensor j_{ik} has only a single component different from zero, $j_{yz}=-NbV$ (N is the number of dislocations arriving on a unit area of surface perpendicular to the dislocation), i.e., in this case $j_{yz}<0$. Then $\partial\varepsilon_{ik}^{pl}/\partial t>0$. Actually, the emergence of the right end of the twin at the surface increases the plastic deformation. It can be shown that in the case of emergence of the plastic twin from the crystal under the action of surface tension forces (Fig. 1c), $j_{yz}>0$. Then $\partial\varepsilon_{ik}^{pl}/\partial t<0$ and the plastic deformation should decrease with time after emergence of the elastic twin from the crystal; the lattice completely recovers its original shape which it had before the beginning of the plastic deformation by elastic twinning. The formation of the twin under loading[9] produced acoustic emission the opposite sign relative to the emission in the successive emergence of the elastic twin from the unloaded crystal, which serves as one more confirmation of the conclusion reached above. In light of the confirmation indicated above, it becomes clear that the sign of the field of the radiation in the annihilation of dislocations is identical with such for the case of emergence of the twin from the crystal under the action of surface tension forces.

We now use the method for the determination of the rate of motion of the dislocations according to acoustic emission data[9] and compare the velocity of the dislocations obtained in such a way with the velocities of motion of the tip of the twin at the moment of its arrival at the surface of the crystal. For twin No. 1, the values of these velocities are 190 and 100 cm/sec, for twin No. 2, they are 225 and 75 cm/sec, respectively, for twin No. 3, 260 and 55 cm/sec. We turn our attention to the fact that the data of the fast filming makes it possible only to estimate the lower bound for the velocities of emergence of the dislocations to the surface, since the minimum distance which separates the twin from the surface amounts to 0.04 cm in the case of the speed of filming used (on the next frame, the twin already touches the surface).

From the shape of the acoustic emission signal, we can decide on the change in the emergence of the dislocations to the surface with time. If, upon emergence of the elastic twin at the surface under the action of surface tension forces (Fig. 1c), the signal increases continuously with time (Fig. 1f; for more detail see also Ref. 6), then upon emergence of the dislocations to the surface (see Fig. 1b), the signal has another shape. These facts can be explained in the following way: when the twin emerges under the action of surface tension forces, a constant force acts on the dislocation, as a result of which a continuous growth of the rate of emergence of the dislocations to the surface takes place. In the case of the emergence of the dislocations at the surface, shown in Fig. 1b, the rate of approach of the tip of the twin to the surface and the emergence of it to the surface are restrained by the surface tension, which in this case slows the motion of the dislocations. After the tip of the twin touches the surface, the dislocations begin to emerge at the surface without hindrance and the rate of their emergence increases. But the quantity of positive dislocations inside the crystal, accelerating the emerging dislocations by their own elastic fields, exhaust themselves in time, which leads to a gradual decrease in the rate of emergence of the dislocations to the surface.

In conclusion, we take this opportunity to thank V. D. Natsik for interest in the research and discussion of the results.

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Theory of nonequilibrium phase transitions

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The character of phase transitions occurring on excitation of quasi-particles in the ordered phase by an external field is investigated for three models: an ordinary superconductor, an excitonic insulator (or structural transitions of the Peierls-transition type) and a superconductor with electron–electron repulsion. The structure of the ordered phase depends essentially on the form of the distribution function $n(\epsilon)$ of the nonequilibrium quasi-particles. If the magnitude of the gap Δ in the single-particle excitation spectrum is less than the energy of the Debye phonons, the distribution function $n(\epsilon)$ differs strongly from the quasi-Fermi function. For this reason, the uniform state of superconductors with pumping can be stable. In the opposite case of a large gap Δ, a quasi-Fermi distribution of the nonequilibrium excitations, with a nonzero chemical potential, is possible. If the ordered phase in this case is a consequence of attractive interaction, the uniform state in the ordered phase is unstable. For the example of an excitonic insulator the dependence of the period of the nonuniform state on the pumping intensity is found. But if the ordered phase is a consequence of repulsive interaction, so that its existence is possible only in conditions of pumping, for a quasi-Fermi (inverted) distribution of the excitations the uniform state is stable.

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1. INTRODUCTION

Great interest has recently developed in the study of the character of the phase transitions in systems situated in the field of an external source. Particular interest in this problem has arisen in connection with the search for possibilities of raising the critical temperature of the superconducting transition.

Most types of phase transition are connected with collective effects. As the temperature is raised, excitations (quasi-particles) appear, leading to a decrease of the degree of order (because of the collective character of the latter) and to the existence of a critical temperature.

The action of an external source can be reduced to an increase of the number of quasi-particles as compared with the equilibrium number, and to a change in the character of their energy distribution. The magnitude of the order parameter in nonequilibrium conditions can be determined by the equation for the equilibrium case, in which, in place of the equilibrium quasi-particle distribution function, we must substitute the solution of the kinetic equation.[1a] Usually, the electron-collision times over which the quasi-particle distribution function changes are long compared with the characteristic times of the variation of the order parameter.

In the kinetic equation the time dependence of the order parameter must be neglected, it being assumed that it has time to reach its stationary value for the particular quasi-particle distribution function $n(\varepsilon)$ at the given moment of time. The form of the function $n(\varepsilon)$ depends essentially on the magnitude of the order parameter Δ. The diagram technique of Keldysh[1b] turns out to be convenient for the description of such systems.

The properties of the system in the ordered phase turn out to be very sensitive to the form of the function $n(\varepsilon)$. For example, if $n(\varepsilon) > \frac{1}{2}$ in a certain energy interval, a superconducting state is found to be possible for a repulsive electron-electron interaction.[2] Instead of perfect diamagnetism, a system in a superconducting nonequilibrium state can possess perfect paramagnetism. In systems of the excitonic-insulator type,[3] in which the dielectric gap arises as a consequence of collective effects, magnetic ordering is possible on pumping.[4]

In the present paper we shall investigate the possibility of the appearance of nonuniform states on pumping, for three models: a normal superconductor (Sec. 2), an excitonic insulator (Sec. 3), and a superconductor with repulsive electron-electron interaction (Sec. 4). Similar problems have been investigated for a num-