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ATHERMAL DISLOCATIONAL ANOMALIES IN MICROCONTACT SPECTRA OF ZINC SINGLE CRYSTALS

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Regularities in the behavior of athermal dislocational anomalies of microcontact spectra of zinc single crystals are established. It is shown that they arise due to emission of terahertz waves by dislocations. In this case hexagons of basis dislocations surrounding the microcontact generate in most cases monochromatic high-frequency waves, which promote the appearance of a nondecaying current. A model is proposed according to which properties of dislocations are determined by regularities in interactions of atoms that keep moving at an arbitrarily low temperature.

Investigation [1-3]of the effect of nets of basis dislocations on microcontact spectra (MCS) of zinc single crystals, which can be recorded at 1.5 K, have shown that anomalies emerging at energy $E > kT$ are inherent in these spectra. Athermal anomalies result from the probable emission capabilities of dislocations that are microwave sources and to a high degree depend on the distance between them in the vicinity of the point contact. The discovery of athermal dislocational anomalies in MCS of zinc single crystals [1-3] made it possible to obtain new data on the state of extended defects in the microwave region. However, the causes of microwaves in the area of the dislocation core are still unclear.

The objective of the present work was to establish the regularities of variations in initial MCS regions in zinc single crystals [0001] (0001) and the conditions of emergence of microwave oscillations due to nets of basis dislocations.

As earlier [1-3], the contact axis coincided with the [0001] crystallographic direction. Examples of the MCS behavior in the athermal region are illustrated by Fig. 1, which presents characteristic curves of the second derivative of the volt-ampere characteristic V_2 as a function of the energy (E) supplied to the contact. We denote the extremal V_2 value as V_2^0 and the corresponding E value as E_0.

The main dependences of the observed anomalies of the MCS are $V_2^0(E_0)$ (Fig. 2) and $E_0(R_c)$ (Fig. 3), where R_c is the resistance of the point contact. Experimental dependences $V_2(E_0)$ and $E_0(R_c)$ show that zero MCS anomalies can be divided into two groups. Features of the first group include independence of the position of the quantity $E_0 = h\nu_0$ at $\nu_0 = 0.36$ THz on the resistance of the contact (Fig. 3a) and realizability of the relation

$$E_0 = -q_0 V_2^0, \tag{1}$$

where q_0 is the charge, which varies with the parameter V_2^0 within the limits of $1-8\cdot10^{-14}$ C. Expression (1) corresponds to the condition of monochromatic emission of charge-density microwaves. The sign of the effect is determined by the direction of motion of the charge with respect to the microwave source.

The following properties are inherent in the second group of anomalies: an increase in the parameter E_0 by 1 meV with a decrease in the point-contact resistance (Fig. 3b) of from 2 Ω (E_0 = 1.5 meV) to 1 Ω (E_0 = 2.5 meV) and a nonmonotonic form of the $V_2^0(E_0)$ dependence (Fig. 2b). It should be noted that discontinuities (Fig. 1b) and, with an increase in the energy of the contact bias, jumps in the second derivative of the volt-ampere characteristic [2] are inherent in this group of initial MCS regions, which are associated with probable instability

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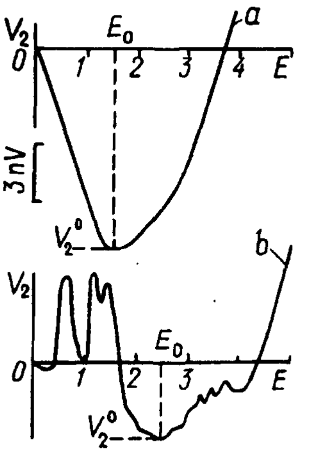

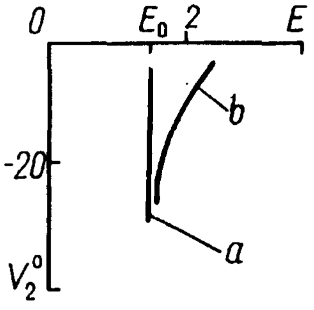

Fig. 1. Characteristic types of initial MCS regions at energies $E > kT$ (group a is characterized by a fixed value of E_0, group b is characterized by nonmonotonic E_0 values) as functions of the parameter V_2^0. E, meV, V_2, nV.

Fig. 2. Relationship between the positions of E_0 and V_2^0 for type a and type b anomalies. V_2^0, nV.

of dislocation motion in the microcontact field. Inasmuch as anomalies in the initial MCS regions are due to a net of basis dislocations [2], the properties of the dislocation ensemble are likely to manifest themselves in the measured $V_2^0(E_0)$ and $E_0(R_c)$ dependences. Thus, if the net of basis dislocations is unstable with respect to an external action and its segments participate in vibrational motion, the energy of such a defect system will be somewhat greater than the eigenenergy of basis dislocation hexagons in the ground state. This circumstance can affect the monochromaticity of microwaves emitted by dislocations (Fig. 2b) and variation of the potential V_2^0, which completely depends on the presence of dislocations, and, therefore, we shall call it dislocational. It is to a high degree determined by the interaction of atoms within the dislocation core. Regularities established in the present work make it possible to consider in more detail the properties of dislocations and determine the possible causes of microwave emission. If the properties of dislocations are mainly governed by their cores, the cause of high-frequency oscillations should be sought first of all in the interaction of atoms of the dislocation core. This question remains almost uninvestigated so far. Assumptions made in [4] according to which the dependence of the energy in the dislocation core has the form

$$E_d = Gb^2 \alpha d / 4\pi d_0 , \tag{2}$$

where α is a coefficient, d is the region of the tension field of the dislocation, d_0 is the mean size of the dislocation core require experimental substantiation. According to the hypothesis [5], the dislocation core behaves like a fluid. Therefore, the energy density in the dislocation core cannot exceed the specific latent melting heat. However, experiments contradict the assumptions.

In this connection, it is necessary to consider a model that describes satisfactorily the experimental data. Let us assume that the dislocation core consists of a set of rotors, and that each of the rotors is a circling atom. The behavior of a set of rotors in the dislocation core is likely determined by the conditions of compression of core atoms by atoms of the crystalline lattice in the vicinity of the dislocation. The energy of a rotor depends on the operator of the squared moment of momentum, which takes only a series of discrete integer values $k = 0, 1, 2, \ldots$:

$$E_r = h^2 k (k + 1) / 8\pi^2 M_i , \tag{3}$$

where $M_i = mr^2$ is the moment of inertia. Then the minimum distance between energy levels of the rotors can be represented by the relationship

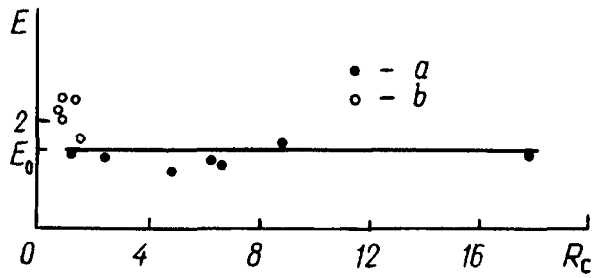

Fig. 3. Dependence of energy E_0 in initial MCS regions on the resistance of the contact R_c, Ω.

$$d_{r0} = h^2/4\pi^2 M_i , \tag{4}$$

and the oscillation frequency in a first approximation is as follows:

$$\nu_r = h^2/8\pi^4 M_i \tag{5}$$

and for zinc does not exceed 10^9 Hz. Therefore, individual elements of the dislocation series can function as sources of high-frequency waves that also do not decay at zero temperature. If one takes into account the dimensions of the basis dislocation hexagon $d_r = 250$ nm [2] surrounding the point contact, one can estimate, on the basis of dimensions of the zinc atom, 2.7 Å, the number of interacting rotors in the dislocation core as $\sim 10^4$. In this case, dislocations can be treated as hexagonal chains of interacting atoms. The superposition radiation of interacting rotors corresponds to an effective oscillation frequency in the terahertz region and to the experimentally estimated eigenfrequency of oscillations of the dislocation ensemble ν_0, which is also conserved when $T \to 0$.

Since a hexagon of basis dislocations is essentially a microwave circuit that surrounds the microcontact and generates nondecaying oscillations, then, given a charge q_0 localized in the vicinity of dislocations, a nondecaying current

$$i_d \sim - q_0 \nu_0 , \tag{6}$$

is possible, whose value is limited to 6 mA. Decay of the electric current at $\nu > \nu_0$ is due to the propagation conditions of microwaves emitted by dislocations and depends on the velocity of coherent phonons. When the bias voltage on the contact starts to grow, the electric field strength E_{st} increases from zero, and coherent photons propagate antiparallel to E_{st}, thus stimulating a drift current. Upon reaching the critical value of the field strength corresponding to the bias energy on the contact E_0, the drift current changes its direction and becomes antiparallel to the direction of the initial current. The change of the direction of the current, as has been noted, is reflected in the sign of the effect. In order to amplify microwaves, one should apply an electric field such that the electron velocity v_e exceeds the speed of a sound wave v_s. Inasmuch as the drift velocity of electrons in the vicinity of a dislocation ensemble can be determined as

$$v_e = j_d/ne , \tag{7}$$

where n is the electron concentration, e is the elementary charge, and j_d is the current density, which depends on the effective parameters of the dislocation circuit: the hexagon side $d_r = 250$ nm and the transport scattering cross-section of the basis dislocation in zinc $\eta = 28$ in [6] at

$$j_d = i_d/6d_0\eta , \quad j_d = 6 \cdot 10^9 \ \text{A/m}^2 , \tag{8}$$

the directed electron velocity v_{e0} related to the energy E_0 by the parameter v_s, and electron mass m_e and equal to

$$\nu_{e0} = E_0/\nu_s m_e, \quad \nu_{e0} \sim 10^6 \text{ m/sec}, \tag{9}$$

is the essentially the upper limit for the solid state, where ν_{e0} does not exceed 10^6 m/sec [7]. In this case, $\nu_{e0} > \nu_s$ and microwaves are amplified.

Summing up the above-presented considerations explaining the behavior of athermal dislocational anomalies of MCS, we should emphasize the fundamentally new features of dislocations found in the experimental investigation:

1. Dislocations fixed in the form of stable configurations emit monochromatic microwaves, which induce charge-density waves.

2. Dislocational configurations with a degree of freedom in the point-contact field emit nonmonochromatic waves in the terahertz frequency range.

3. The presence of microwave oscillations in the region of the dislocation core is an inherent property of dislocations.

4. According to the model proposed, the properties of dislocations are determined by regularities in atomic interactions in the dislocation core that prevent atoms from being in a state of rest at an arbitrarily low temperature.

Thus, judging from a combination of indicators, dislocations in a metallic crystal can be considered as sources of solitons, i.e., solitary waves. Soliton excitations have been studied most completely in a number of dislocation problems [8] and in a quasi-1D system with period doubling [9]. In this connection, we can hope that further investigations of dislocation spectra can lead to a more complete understanding of sources of solitary waves in the solid state.

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NOTATION

V_2, the second derivative of the volt-ampere characteristic; V_2^0, dislocation potential; E, energy supplied to the contact; E_0, extremal value of E; R_c, contact resistance; h, Planck's constant; ν_0, extremal oscillation frequency of basis-dislocation hexagon; q_0, charge localized on dislocations; G, shear modulus; b, Burgers vector; M_i, moment of inertia; m, atomic mass; r, atomic radius; i_d, dislocation current; ν_e, electron drift velocity; ν_s, sound-wave velocity; j_d, density of dislocation current; ν_{e0}, directed electron velocity.

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