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SPECTRUM OF THE ELECTRON-PHONON INTERACTIONS OF ZINC SINGLE CRYSTALS INDUCED BY A BASAL-DISLOCATION NETWORK

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A dislocation spectrum of the electron-phonon interactions (EPI) of zinc single crystals is obtained for the first time. It is shown that dislocations are a source of hypersonic waves. Possible mechanisms of energy dissipation in vibrations of the network of basal dislocations in the point-contact zone are considered. It is noted that a change in the effective transport function of EPI results from the inertial properties of dislocations.

Different mechanisms of the interaction of movable dislocations with electrons and phonons, which, in combination, could lead to unified notion of the dislocation spectrum of EPI, are investigated in [1, 2]. To settle this problem, it is necessary to have experimental results associated with a definite structural state. In considering the data on dynamic retardation of dislocations, ultrasound damping, and high-speed deformation, attention is drawn to the fact that the values of the viscous retardation coefficient obtained in different investigations for the same material are inconsistent [3–6]. The reason for this should be sought, first of all, in the specific features of the defect structure of the investigated crystals.

Recent experimental data [7, 8] show how substantially modified the microcontact spectra (MCS) of zinc single crystals are upon introducing metastable structures such as basal dislocation networks into the point-contact zone.

The purpose of the present work is to find and study specific features of the dislocation spectrum of EPI of zinc single crystals.

For this, we used the MCS method for single-crystal electrodes whose axis was strictly parallel to the direction [0001] in order to avoid slipping, at the moment of contact, of the light-basal system. The crystallographic basal plane (0001) served as a base for forming point contacts in the low-temperature region.

To obtain the dislocation spectrum proper from the MCS (Fig. 1, curve 1) recorded at 1.5 K on single crystals containing the basal-dislocation networks (see Fig. 2), the reference spectrum (Fig. 1, curve 2) typical for single crystals with the minimum density of basal $N_b = 10^8$ m^{-2} and pyramidal $N_p = 3 \cdot 10^6$ m^{-2} dislocations was substracted. For the difference curve not to undergo radical changes, it was necessary to measure the MCS $V_2(E)$ at the same voltage level for the first harmonic of the modulating signal V_1 and contact diameter d_c. Therefore, the spectra were grouped with respect to such data as V_1, d_c, and N_b ($N_b >> N_p$) before and after an increase in the dislocation density. In our experiments the resolving power of the MCS method, determined by the thermal smearing of the Fermi step and the modulation broadening of the spectral bands, was 0.7–0.8 meV.

The procedure for constructing the hexagonal networks of basal dislocations and obtaining $V_2(R)$ is described in [9, 10]. Dislocation spectra were obtained on the basis of more than 20 reproducible initial MCS and the spectra induced by dislocation networks.

A typical spectrum of electron-phonon interaction of a nerwork of basal dislocations is shown in Fig. 1, curve 3. Introducing dislocation networks into the point contact zone is accompanied by the appearance, first of all, of anomalies occurring at the energies $E > kT$. Athermanous anomalies of the second derivatives of the current-voltage characteristics – $V_2(E)$ of point contacts – may be detected only in the case where the distance between the dislocations d_r differs severalfold from the contact diameter $d_c = 10–50$ nm. In the case, when d_r is 100 μm,

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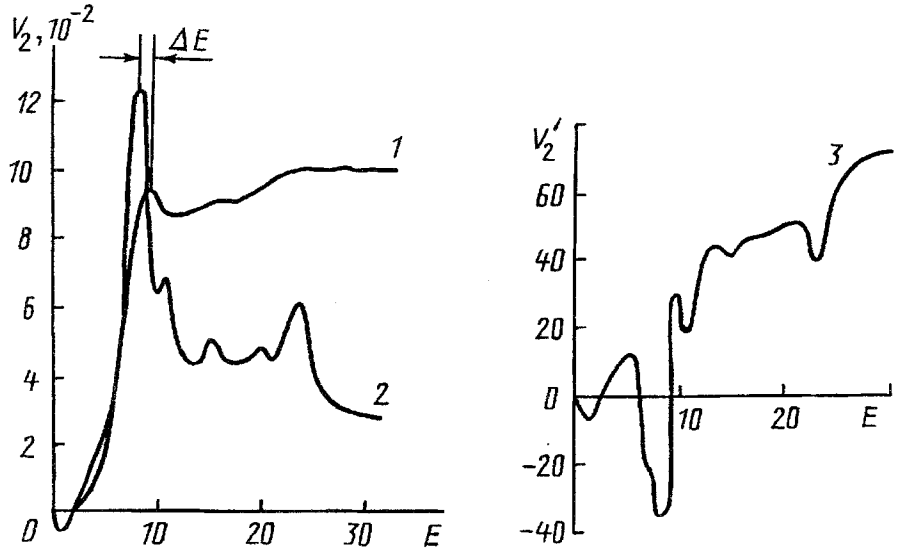


Fig. 1. Microcontact spectrum due to the basal dislocation network (1), EPI reference spectrum of zinc single crystals (2), EPI spectrum of the hexagonal network of basal dislocations (3). V_2, μV; E, meV; V_2', nV.

the anomalies are absent. It is typical for the dislocation spectrum in an athermanous region to have anomalies at the energy $E_0 = 1.5$ meV that are independent of the contact resistance R_c (Fig. 3). Consequently, $E_0 = h\nu_0$ ($\nu_0 =$ 0.36 THz) is one of the basic parameters of the hexagonal network of basal dislocations bordering the point contact. This is indicative of the fact that dislocations are a source of hypersonic waves and in conformity with the data of [11] phonons do not penetrate into the region of a dislocation core. When electrons and photons, emitted by a contact and interacting with segments of basal dislocations, come across a dislocation scattering source, they can probably exert an influence on the linear tension of the latter. In turn, the changed linear tension of the dislocations may affect the reflectivity of quasiparticles that return in the point-contact zone and change the dependence $V_2(E)$.

The expression for the linear tension as an energy per unit length of a dislocation has the form

$$\Phi = \alpha G b^2 . \tag{1}$$

The force required for bending the dislocation to the radius r_k is determined by the relation

$$F_c = \Phi / r_k . \tag{2}$$

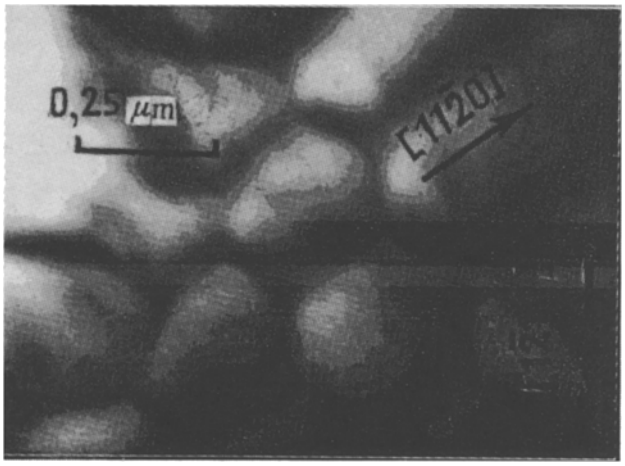
If we assume that F_c is proportional to the force of dynamical retardation, which depends on the velocity of vibrating dislocations V_d, then the measure of energy dissipation by this motion may be characterized by the effective viscosity as

$$B = \Phi / r_k V_d . \tag{3}$$

An increase in the energy applied to the contact will probably favor a change in both F_c and the effective velocity of oscillatory motion of the dislocation segments near the equilibrium position. The available experimental data allow one to consider possible reasons for energy dissipation in oscillatory motion of the network of basal dislocations in the field of an electrothermal source.

We now turn to the position of the extrema of the dislocation spectrum for which the following expression characterizing their position is valid in a first approximation:

$$V_2' = E^2 d_c d_r m / 16 b B \eta e n h C , \tag{4}$$



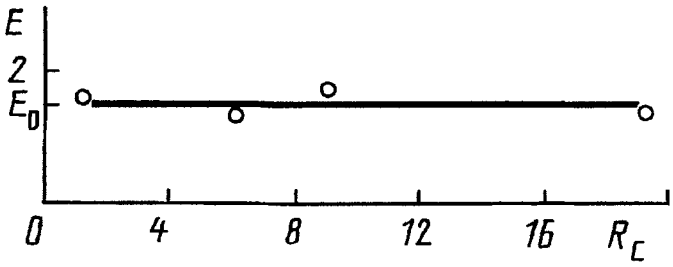


Fig. 2. Network of basal dislocations in the point-contact zone.

Fig. 3. Energy applied to the contact vs its resistance in the field of the extremum of zeroth anomalies. R_c, Ω.

where E is the energy applied to the contact; d_c is the contact diameter; h is the Planck constant; e is the electron charge; n is the electron density; C is a coefficient equal to unity for $E > kT$ and 1/3.62 for $E < kT$. Taking into account the experimental value $V_2 = 10$ nV for E_0, $d_c = 30$ nm, $\eta = 28$ Å [12], $d_r = 1.7d$ ($d = 250$ nm), we determine a damping coefficient $B = 0.3 \cdot 10^{-12}$ MPa·sec. According to the theory [2], in normal metals at low temperature the main mechanism responsible for dislocation retardation is the electron viscosity, which is independent of temperature. The coefficient of electron retardation is specified by the deformation potential λ, mass m, and wave vector k_F and has the following form:

$$B = 2\lambda^2 m^2 b^2 k_F/(2\pi\hbar)^3 . \tag{5}$$

In the calculations, the parameter B changes in the range 10^{-13}–10^{-11} MPa·sec as a function of λ. The observed satisfactory agreement between the experimental and theoretical estimates allows us to assume that the segments of basal dislocations in the athermanous region of the spectrum transfer energy to different excitation branches of a crystal lattice by the mechanism of electron retardation.

A further increase in the energy applied to the contact leads to an increase in the phonon concentration in the contact zone, which may give rise to an MCS maximum at $E = 5.5$ meV. The mean number of phonons for the elastic mode with frequency ν_F in thermal equilibrium is described by the Planck expression

$$n_F(\nu_F) = [\exp(h\nu_F/kT) - 1]^{-1} , \tag{6}$$

where $h\nu_F$ is the phonon energy. Assuming the number of modes in a unit interval to be proportional to ν_F^2, we obtain an energy distribution of phonons with the maximum frequency

$$\nu_m = 2.82\, kT/h . \tag{7}$$

Here it should be borne in mind that the heating-up temperature is related to the contact voltage U_c by the relation [13]

$$T = eU_c/3.62\, k . \tag{8}$$

In this case a maximum on the energy scale at $E = 5.5$ meV will be observed at $T = 17.6$ K, which corresponds to $\nu_m = 1$ THz. For $E < kT$ the shape of the dislocation spectrum will differ from $V_2(E)$ in the athermanous region due to a possible increase in the viscosity upon oscillatory motion of dislocations in the thermal field of an electrothermal source. Indeed, according to estimates by formula (4) at $C = 1/3.62$ stemming from the thermal

model [13], the viscosity increases by a factor of 11.7: $B = 3.5 \cdot 10^{-12}$ MPa· sec and satisfies data for Raman scattering by basal dislocations [14].

A subsequent increase in the energy applied to the contact entails the most pronounced change in the shape of the dislocation spectrum at $E = 9.5$ meV with the damping coefficient $4.2 \cdot 10^{-12}$ MPa·sec. Over this part of the spectrum the temperature in the contact zone is 30.5 K and corresponds to the temperature of manifestation of the flutter-effect in zinc $T_{fl} \lesssim 0.1 T_d$, for which $T_{fl} = 29.5$ K. As is mentioned in [15], the occurrence of the flutter-effect is associated with dislocation vibrations in the thermal field of the lattice and the accompanying emission of phonons. In this case, phonons may be scattered by local modes of dislocation vibrations [16, 17]. The damping coefficient induced by the flutter-effect does not exceed, according to the calculated results for zinc, $6.5 \cdot 10^{-12}$ MPa·sec [18]. Since at $E = 9.5$ meV the temperature in the contact zone is $T \sim T_{fl}$ and the retardation coefficient found experimentally is $B \sim B_{fl}$, we may assume that the changes in the dislocation spectrum in this energy range are caused by predominance of the flutter-effect over the other mechanism of energy dissipation. Then it is quite possible that the observed shift of the main MCS maximum by the value $\Delta E = 1.5$ meV (Fig. 1, curve 1) toward high energies after incorporation of the dislocation network into the contact zone is related to manifestation of this scattering mechanism.

With an increase in the contact temperature at $E > 10$ meV the additional energy dissipation by vibrating dislocations leads to a sharp increase in the spectral background and a further increase in $B > 7 \cdot 10^{-12}$ MPa·sec, which may be caused by the mechanism of thermoelastic dissipation.

In conclusion, basal dislocations, being a packet of high-frequency terahertz waves, are the main source of quasiparticle retardation. The spectral features of a network of basal dislocations depend on their inertial properties, which are related to the damping parameter.

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NOTATION

$V_2(E)$, microcontact spectrum, or second derivative of the current-voltage characteristic as the function of the energy applied to the contact, μV; N_b, density of basal dislocations, m^{-2}; N_p, density of pyromidal dislocations, m^{-2}; d_c, diameter of the point contact, nm; V_1, first harmonic of the modulating signal, mV; d_r, mean distance between the dislocations, μm; ν_0, eigenfrequency of the oscillations of dislocation segments, THz; α, coefficient of dislocation interaction; G, shear modulus, MPa; b, Burgers vector, Å; V_d, mean velocity of the oscillating dislocations, m/sec; B, damping coefficient, MPa·sec; η, effective transport cross section of scattering by a basal dislocation, Å; U_c, bias voltage at the contact, mV.

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