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The dislocation resonance absorption of ultrasound in KBr crystals at low temperatures

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The frequency spectra of ultrasound dislocation losses in KBr single crystals with different dislocations density Λ have been researched at fixed temperatures in the T = 300–77 K interval. It is found that at any T = *const* within the mentioned range, the inversion effect is observed resulting from the sample deformation. The effect has been discussed in the framework of the dislocation interaction model. The viscosity coefficient B has been established to be independent of Λ within the whole temperature range. The experimental data on $B(\Lambda)$ have been found to agree with the conclusions from the Alshits-Indenbom theory of dynamic dislocation drag.

Исследованы частотные спектры дислокационных потерь ультразвука в монокристаллах KBr с разной плотностью дислокаций Λ при фиксированных температурах в интервале T = 300–77 K. Обнаружено, что при любой T = *const* указанного диапазона температур в частотном и амплитудном смещениях резонанса наблюдается эффект инверсии вследствие деформирования образца. Обсуждение указанного эффекта проведено в рамках модели дислокационного взаимодействия. Установлено, что коэффициент вязкости B не зависит от Λ во всем интервале температур. Отмечается, что полученные экспериментальные данные по $B(\Lambda)$ согласуются с выводами теории динамического торможения дислокаций Альшица-Инденбома.

Recently, considerable efforts were made to study the effect of loading pulses differing in shapes, duration, and amplitude [1], magnetic field [2–7], combined action of electric and magnetic fields [8], X-rays [9] and UV light [10] on the dislocation mobility as well as on dislocation inelasticity in pure and doped AHC. This work could be related to the above-mentione set, since it is aimed at the study of the dislocation dynamics features in ionic crystals under varying the dislocation structure state and the test temperature. In the actual operation conditions of AHC, the performance characteristics thereof may vary considerably due to dislocation deallocation from the pinning centers stimulated by the above external factors. Thus, the studies of this kind are no doubt of a practical interest.

To solve the problems connected with the study of mechanisms controlling the viscous dislocation drag in crystals, the pulse echo method in high frequency range [11] is widely used. According to the theory [12], the dislocation damping coefficient B is determined on the descending branch of dislocation resonance with its amplitude and frequency localization depending on the test temperature and the sample pre-strain. The influence of dislocation structure parameters changes due to the sample straining on the phonon dislocation retardation processes remained unknown for a long time, although some experiments in this field were conducted [13–15]. In [16, 17] it was established by systematic research on temperature shift of damped dislocation resonance in strained KBr crystals that the temperature lowering from 300 to 77 K, the resid-

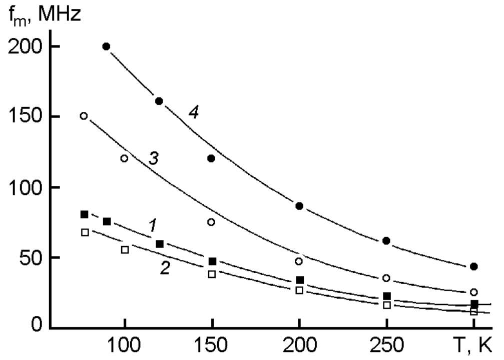

Fig. 1. Temperature variations of resonance frequency for KBr crystals with different dislocation density ($\Lambda \cdot 10^9$ m^{-2}): 2.2 (*1*); 4.5 (*2*); 9 (*3*); 13 (*4*).

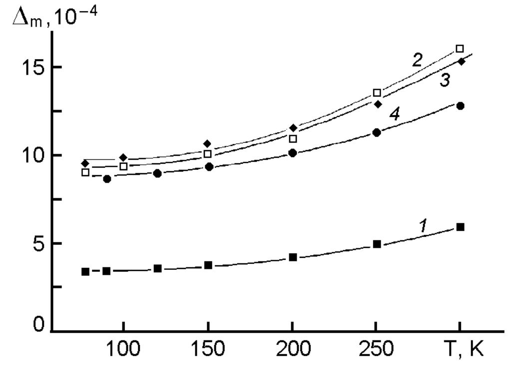

Fig. 2. Temperature dependences of resonance dislocation damping decrement for KBr crystals with different dislocation density ($\Lambda \cdot 10^9$ m^{-2}): 2.2 (*1*); 4.5 (*2*); 9 (*3*); 13 (*4*).

ual deformation value being fixed, it always shifts it towards higher frequencies. The increase of sample pre-strain [18] at the fixed temperature (T = 300 K) results in a non-monotonous change of resonance parameters (decrement Δ_m and f_m frequency at maximum), following a curve showing a maximum. As the strain starts, the dislocation resonance rises in amplitude and shifts towards lower frequencies. Further, as the strain grows, the mentioned processes of resonance shift are retarded and, after stopping, reverse the motion direction. Basing on the observed inversion effect of resonance curves caused by the increasing straining of KBr samples, it has been established [18] that the damping coefficient B at room temperature is independent of dislocation density and of dislocation segment length L, the latter being changed considerably in the mentioned test conditions. Results [18] about the independence B of Λ confirmed convincingly similar data [19] got earlier for NaCl single crystals.

It is of interest to trace whether the type of functional relationship $B(\Lambda)$ and the inversion effect itself in the frequency curves $\Delta_d(f)$ at lower temperatures in the 77–300 K range will be conserved at noticeable decreasing phonon gas density and changing dislocation structure crystal state.

In this work, studied are the peculiarities of the dislocation resonance shift under varying strain at fixed temperatures lower than the room one. The necessity in such information is quite obvious. On the one hand, the data on the ultrasound resonance absorption in crystals containing the "fresh" dislocations are very important in clearing up the nature of phonon mechanisms controlling the mobility thereof under changing external effects (temperature and sample strain). On the other hand, the information on the influence of external factors on the dislocation structure change evolution (that is accompanied by high ultrasound energy losses in the sample) can be used in practical purposes, in particular, while developing the preparation technology of functional crystals intended to use in various acousto-optic devices.

Using the results from [16, 17] and some data not reported in those publications, obtained using the samples with different dislocation density in the temperature range 77–300 K, we have defined temperature dependences of damped dislocation resonance parameters $f_m(T)$ and $\Delta_m(T)$ shown in Figs. 1 and 2. It is seen from the figures that the lowering of test temperature for the investigated KBr samples always causes a monotonous increase of resonance maximum frequency f_m (Fig. 1) and smooth reduction of its amplitude value Δ_m (Fig. 2). Besides, the inversion effect connected with the increasing dislocation density Λ in crystals is seen clearly. As the sample strain increases, the curves $f_m(T)$ are shifted at first towards low frequencies (Fig. 1, curves *1* and *2*), then the shifting is stopped and it starts go on in the opposite direction (Fig. 1, curves *3* and *4*). The temperature shifting of resonance frequency maximum f_m is accompanied, as is seen in Fig. 2, by a synchronic but opposite in sign shifting of temperature dependences $\Delta_m(T)$. Here, the resonance losses of ultrasound in crystals, as the straining starts, are noticeably grown at first (curves *1*, *2*) and then, at large strain degrees, begin to decrease (curves *3* and *4*).

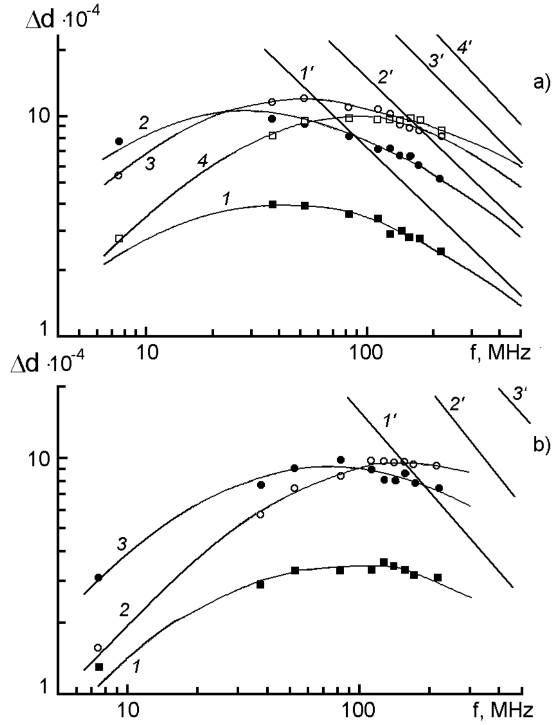

Fig. 3. (a) Frequency dependences of dislocation decrement at 200 K for KBr samples with different residual strain values (ε, %): 0.23 (*1*, 1′); 0.5 (*2*, 2′); 0.75 (*3*, 3′); 1 (*4*, 4′). No interrupted lines *1*, *2*, *3*, *4* are theoretical curves [20]; 1′, 2′, 3′, 4′, the high-frequency asymptotes thereof. (b) Frequency dependences of dislocation decrement at 77 K for KBr samples with different residual strain values (ε, %): 0.23 (*1*, 1′); 0.5 (*2*, 2′); 0.75 (*3*, 3′). The solid lines *1*, *2*, *3* are theoretical curves [20]; 1′, 2′, 3′, the high-frequency asymptotes thereof.

The inversion of resonance maximum caused by the samples straining at fixed temperatures 200 and 77 K is demonstrated more clearly in Figs. 3a and 3b. It is seen that at those temperatures, similar to the experiments [18] carried out at T = 300 K, the shift of resonance curves $\Delta_d(f)$ shows an inversion. The only difference is that the sets of resonance curves $\Delta_d(f)$ corresponding to 300 K [18], 200 and 77 K, have different frequency and amplitude localization. It is to note that the arrangement of resonance curves $\Delta_d(f)$ for other temperatures within the 77–300 K is qualitatively similar.

As it is seen from Fig. 3, the measured dislocation losses of ultrasound are of the resonance character. The experimental points are described well by the theoretical frequency profile found in [20] for the exponential distribution of dislocation loop lengths.

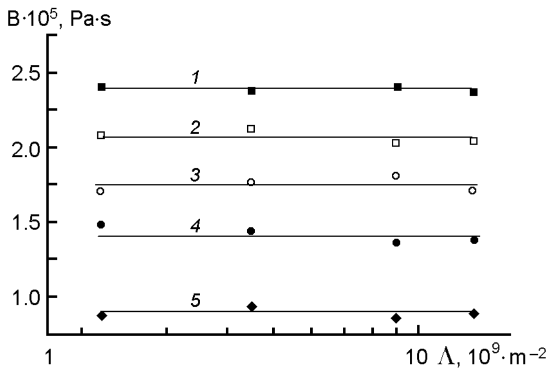

Fig. 4. Dependences of damping constant B on dislocation density Λ for KBr crystals at temperatures (T, K): 300 [18] (*1*); 250 (*2*); 200 (*3*); 150 (*4*); 77 (*5*).

According to [12], the relation describing the descending branch of frequency decrement dependence has the following form:

$$\Delta_\infty = 4\Omega G b^2 \Lambda / \pi^2 B f, \qquad (1)$$

where Δ_∞ is the dislocation decrement value for the frequencies $f > f_m$; f_m, the resonance maximum frequency; b, Burgers vector; Ω, the orientation factor; G, the shear modulus of the acting slip system; Λ, the dislocation density; B, the damping constant. From Eq.(1), it is easy to calculate the value, having determined previously Δ_∞ from the high frequency asymptote and Λ, using the etching pits.

Taking from [16, 17] the values of characteristics Ω, G, b^2 and Λ included in (1), we built the set of curves $B(\Lambda)$ for different temperatures of 77–300 K range, that is shown on Fig. 4. The damping coefficients of B are seen to be independent of dislocation density Λ caused by the sample plastic straining.

According to [11], the experimental confirmation of B independence of Λ show that B is a fundamental constant of damped dislocation but not a certain phenomenological parameter that varies depending on the experimental conditions and the sample prehistory. Such experiments make it possible to find absolute values of viscosity coefficient B in conditions excluding the influences of errors that are assumed when the dislocations density is determined using etching pits.

To clear out the reasons causing the inversion in frequency curves $\Delta_d(f)$ (Fig. 3), we have calculated the average effective length of the dislocation segment L using the formula [12]

$$L = \sqrt{\frac{0.084Gb^2}{Bf_m(1-\nu)}}, \qquad (2)$$

where ν is the Poisson ratio. In those calculations, we used the B and f_m values shown in Figs. 1 and 4, and the G and b^2 values taken from [16, 17] and ν ones calculated using the relation $\nu = C_{12}/(C_{11} + C_{12})$ [21], where the elastic constants C_{11} and C_{12} were taken from [16].

Using the calculation results, the dependences $L(\Lambda)$ for different fixed temperatures were plotted which are presented in Fig. 5. It is seen that as Λ rises due to the increasing crystal straining, the value L increases at first and then, having reached its maximum value, starts to decrease. The $L(\Lambda)$ dependence character remains unchanged when the test temperature drops to 77 K. The maxima in the $L(\Lambda)$ curves are seen at any temperature in the 77–300 K range at the dislocation densities $\Lambda \sim 4 \cdot 10^9$ m^{-2} corresponding to the strain $\varepsilon \sim 0.75$ %. The difference in the localization of $L(\Lambda)$ curve ascending branches is more pronounced in the field of rather low strains till ~0.5 % and becomes barely noticeable starting from $\varepsilon \geq 1$ %. The behavior of L with the growing Λ at a fixed temperature can probably be explained proceeding from the known dislocation interaction model [12].

As the crystal straining starts, the depinning of "growth" dislocations occurs and the new sources appear generating long dislocation loops. Perhaps the increasing number of such dislocations is the main cause of increasing Δ_m value and lowering f_m with the strain (because $\Delta_m = 2.2\Omega\Delta_0\Lambda L^2$, where $\Delta_0 = 8Gb^2/\pi^3C$, C being the dislocation linear tension and $f_m = (0.084 \cdot \pi \cdot C)/(2 \cdot L^2 \cdot B)$ [12]), that is seen in Figs. 1 and 2. But when the strains exceed ~0.75 %, the dislocations of primary glide planes begin to cross with "forest" dislocations. As a result of the dislocation interaction, the value L diminishes, that causes a lowering of Δ_m and the increase of the resonance frequency f_m. It is obviously that the theoretical model [12] allows to explain quite reasonably not only the $L(\Lambda)$ curves behavior, but the inversion effect of frequency spectra $\Delta_d(f)$, that is confirmed by the experimental data shown on Fig. 3 and 5. As to the descending of L value in crystals with small and large Λ at lowering temperature (Fig. 5), it is connected with the manifestation of the dislocation pinning by weak and strong pinning points [16].

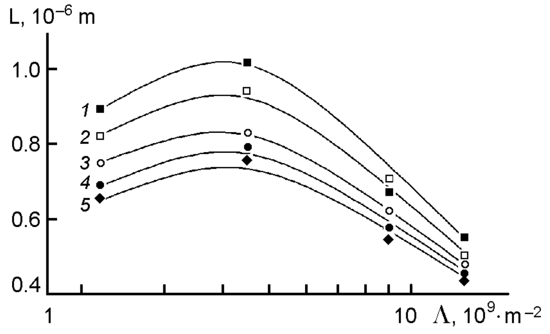

Fig. 5. Dependences of average effective length of dislocation segment L on dislocation density Λ for KBr crystals at temperatures (T, K): 300 [18] (*1*); 250 (*2*); 200 (*3*); 150 (*4*); 77 (*5*).

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Дислокаційне резонансне поглинання ультразвуку у кристалах KBr при низьких температурах

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Досліджено частотні спектри дислокаційних втрат ультразвуку у монокристалах KBr з різною густиною дислокацій Λ при фіксованих температурах в інтервалі T = 300–77 K. Виявлено, що при будь-якій $T = const$ у вказаному діапазоні температур у частотному та амплітудному зміщеннях резонансу спостерігається ефект інверсії внаслідок деформування зразка. Обговорення вказаного ефекту виконано у рамках моделі дислокаційної взаємодії. Встановлено, що коефіцієнт в'язкості B не залежить від Λ у всьому інтервалі температур. Зазначено, що одержані експериментальні дані з $B(\Lambda)$ узгоджуються з висновками теорії динамічного гальмування дислокацій Альшиця-Інденбома.