DISLOCATION MOBILITY IN ALKALI HALIDE CRYSTALS AT LOW TEMPERATURES

E. Gutmanas

► To cite this version:

E. Gutmanas. DISLOCATION MOBILITY IN ALKALI HALIDE CRYSTALS AT LOW TEMPERATURES. Journal de Physique Colloques, 1976, 37 (C7), pp.C7-595-C7-600. 10.1051/jphyscol:19767139 . jpa-00216863

HAL Id: jpa-00216863

<https://hal.science/jpa-00216863>

Submitted on 1 Jan 1976

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

DISLOCATION MOBILITY IN ALKALI HALIDE CRYSTALS AT LOW TEMPERATURES

E. Y. GUTMANAS

Department of Materials Engineering, Technion-Israel
Institute of Technology, Haifa, Israel

Résumé. — La variation de la vitesse des dislocations avec la contrainte de scission appliquée a été mesurée à basse température dans des cristaux purs de NaCl, LiF et KI. La dépendance en température de la contrainte de scission résolue a été étudiée jusqu'à 4,2 K avec les mêmes cristaux et également avec des cristaux purs de KCl, KBr et RbI. Les résultats obtenus sont discutés brièvement.

Abstract. — Dislocation velocity dependences on applied shear stress were measured in pure NaCl, LiF and KI crystals at low temperatures. Temperature dependences of the critical resolved shear stress (down to 4.2 K) of the same crystals and also of pure KCl, KBr and RbI were studied. The results obtained are briefly discussed.

1. **Introduction.** — The plastic strain rate $\dot{\epsilon}_p$ may be expressed as

$$\dot{\epsilon}_p = \rho b v, \quad (1)$$

where ρ is the density of mobile dislocations, b is the Burgers vector and v is the average dislocation velocity. ρ and v should depend on interaction of moving dislocations with phonon and electron subsystems and with various types of barriers, connected both with the periodical structure of crystals (Peierls barrier) and with lattice defects (impurities, other dislocations, etc.). Examination of v and ρ dependences on various parameters can make it possible to reveal the mechanisms of motion, drag and multiplication of dislocations. When these mechanisms are known, the plastic behavior of crystals (for $\dot{\epsilon}_p > 0$) can be predicted and probably changed in a controlled way.

Studies of dislocation velocity v dependence on applied shear stress τ in a wide range of v in alkali halide crystals have shown [1-4] that in these crystals v is very sensitive to τ in the low-velocity region ($v < 10^2$ cm/s) increasing by many orders of magnitude, following a relatively small increase of the stress. In the high velocity region ($v > 10^{-2} v_s$, where v_s is the sound velocity) a linear dependence of v on τ has been observed. It has also been shown that in the low-velocity region v is very sensitive to divalent cation impurities concentration c_i . Small additions of such impurities ($10 \div 100$ ppm) decrease v by many orders of magnitude. In the high-velocity region v is insensitive to c_i .

The data for the v dependence on τ in alkali halides were obtained mainly in the room temperature region. There are experimental results of the v on T dependence for the low-velocity region in NaCl of high

purity ($c_i < 10$ ppm) [5] and in pure NaCl ($c_i \approx 10$ ppm) [6] down to 77 K and for the high-velocity region in heavily γ -irradiated (10^8 rad) NaCl [7].

An investigation of the mobile dislocation density ρ dependence on τ , T and c_i is rather complicated because of difficulties to separate between the mobile and immobile dislocations in the slip bands already at the beginning of plastic deformation. Usually the density of all dislocations in slip bands is measured. That is why v is the main characteristic used to describe the plastic behavior of crystals. It is also a fact that at room temperature at a stress τ equal to the critical resolved shear stress τ_s , v is relatively low ($10^{-5} \div 10^{-3}$ cm/s) [1-4]. It means that stresses corresponding to a low v produce enough mobile dislocations to get $\dot{\epsilon}_p > 0$ (i. e. a slope change of the stress-strain curve). In [5] and [6] it has been observed that at low temperatures τ_s corresponds to higher v .

In the present work $v(T)$ dependences in wide range of v (and τ) in pure NaCl, LiF and KI were studied at low temperatures (down to 4.2 K in NaCl and down to 77 K in LiF and KI). Temperature dependences of the critical resolved shear stress (down to 4.2 K) of the same crystals and also of pure KCl, KBr and RbI were measured.

2. **Experimental details.** — Investigations were made on pure annealed NaCl, LiF, KI, KCl, KBr and RbI single crystals. The total content of divalent impurities present did not exceed 30 ppm for RbI and 10 ppm for the other crystals. A pulse loading method and etch-pit technique were used to determine the velocities of individual dislocations v as a function of applied shear stress τ . The procedures for annealing,

introducing fresh dislocations and for pulse loading were in principle the same, as those previously described [2]. Etchants of 50 % formic acid and 50 % acetic acid for NaCl, water with FeCl_3 for LiF [1] and of hexyl alcohol saturated with CdI_2 [8] for KI were used in order to reveal dislocations. The density of grown-in dislocations was not higher than 10^4 cm^{-2} and the average size of subgrains where displacements of fresh dislocations were measured was $> 1 \text{ mm}^2$. The studies of the critical resolved shear stress τ_s were performed on an *Instron* testing machine at a strain rate

of about $2 \times 10^{-5} \text{ s}^{-1}$. The samples were tested in compression. τ_s was determined as the beginning of a slope change of the stress-strain curve.

3. Experimental results and discussion. — The results of dislocation velocity measurements both edge and screw dislocations at 4.2, 20, 77, 173 and 295 K in pure NaCl are presented in figures 1a and 1b (low-velocity range, $\log v - \log \tau$ scale) and in figures 2a and 2b (high velocity range, $v - \tau$ scale). The results of

FIG. 1. — Dependence of average velocity v of screw (a) and edge (b) dislocations on applied shear stress τ in NaCl (low-velocity range, $\lg v - \lg \tau$ scale) at various temperatures.

FIG. 2. — Dependence of average velocity v of screw (a) and edge (b) dislocations on applied shear stress τ in NaCl (high-velocity range) at various temperatures.

$v(\tau)$ measurements both edge and screw-dislocations at 77, 173 and 295 K in pure LiF and KI are presented in figures 3 and 4 correspondingly. Every point of $v(\tau)$ dependences corresponds to an average velocity of $50 \div 100$ freshly introduced dislocations, which during their motion do not encounter any subgrain boundaries or other regions with high dislocation density.

FIG. 3. — Dependence of average velocity v of edge (solid line) and screw (dashed line) dislocations on applied shear stress τ in LiF ($\lg v$ - $\lg \tau$ scale) at various temperatures.

FIG. 4. — Dependence of average velocity v of edge (solid line) and screw (dashed line) dislocations on applied shear stress τ in KI ($\lg v$ - $\lg T$ scale) at various temperatures.

The dislocation mobility in the low-velocity region where v in alkali halides is very sensitive to divalent impurities concentration c_i is usually described by the thermally activated process of overcoming impurity barriers by moving dislocation. The average velocity v in this case is given by

$$v = \frac{S}{L} v \exp \left[- \frac{\Delta H(\tau, c_i)}{kT} \right] \quad (2)$$

where S is the mean area swept out by dislocation after overcoming a barrier, $L/2$ is the mean distance between the barriers, v is the frequency factor and $H(\tau, c_i)$ is the enthalpy of activation. According to expression (2) the dislocation velocity dependences in the low-velocity region should give straight lines in a $\lg v - 1/T$ scale. But as it can be seen from figure 5 the experimental

FIG. 5. — Dependence of $\lg v$ (edge type) on $1/T$ for NaCl ($\tau = 150$ N/cm²), LiF ($\tau = 150$ N/cm²) and KI ($\tau = 150$ N/cm²).

curves for NaCl, LiF and KI are not straight lines on the scale mentioned. The experimental results obtained in [6] were in good agreement with the expression obtained for v using a statistical treatment to dislocation motion in crystal with impurity pinning centers [9]

$$v = v_0 \left\{ 1 + \frac{Ac_p[1 - (T/T_0)^{1/2}]}{\tau} \right\} \times \exp \left\{ - \frac{Ac_p[1 - (T/T_0)^{1/2}]}{\tau} \right\} \quad (3)$$

where v_0 is the dislocation velocity in a crystal without pinning centers, A is a constant of the order of G (shear modulus), c_p is the concentration of pinning centers ($c_p \sim c_i$) and T_0 is the temperature at which breakaway from pinning centers occurs because of thermal fluctuations (see [10]). According to expression (3) dislocation velocity dependences should give straight lines in a $\log \frac{v_0}{v} - T^{1/2}$ scale, where v_0 corresponds to an extrapolation of the high-velocity region of the $v(\tau)$ dependence to lower τ (to the experimental points in the low-velocity region). As can be seen from figure 6 experimental results for NaCl are in good agreement with (3) excluding 4.2 K.

In the high velocity region the dislocation mobility is usually described by viscous drag processes and the average velocity is given by

$$v = \frac{b}{B} \tau, \quad (4)$$

FIG. 6. — Dependence of $\lg v_0/v$ on $T^{1/2}$ (according to equation (3)) for NaCl ($\tau = 150 \text{ N/cm}^2$, v_0 corresponds to extrapolation of figure 2 data to lower τ).

where B is the viscous drag coefficient. As it can be seen from figures 2a and 2b experimental results obtained in NaCl for the high-velocity region are in good agreement with expression (4) for viscous dislocation motion. On figure 7 the dependence of viscous drag coefficient B , calculated from the linear portion of $v(\tau)$ curves, on temperature in NaCl is presented. It can be seen from figure 7 that B decreases when temperature decreases and that the decrease is more strongly pronounced when the temperature decreases from 77 down to 4.2 K. This result agrees with various theories predicting a decrease of phonon-dislocation interaction with a temperature decrease (see the recent review [11]).

FIG. 7. — Dependence of viscous drag coefficient B on temperature in NaCl for edge and screw dislocations.

The data for the $v(\tau)$ dependence in NaCl at 4.2 K (low-velocity region) are in disagreement not only with expressions (2) and (3) (see Fig. 5 and 6), but with all expressions obtained from various theories for dislocation motion. As it can be seen from figures 1a and 1b in the whole range of velocities the measured v at 4.2 K are higher than those at 20 K and there is a wide range of velocities where v at 4.2 K is even higher than at 77 K. For a wide range of τ , the velocities of dislocations at 4.2 K are by two orders of magnitude (and more) higher than at the same stress level at 20 K. Even if we take into account that in (2) $v \sim 1/B$ [12, 13] and in (3) $v_0 \sim 1/B$ this will give us only a ~ 1.5 times increase in the pre-exponential when passing from 20 down to 4.2 K.

Granato [14] considered inertial effects (connected with an electron viscous drag coefficient B_e change during a superconducting transition) on overcoming of pinning centers by moving dislocation in a model of a viscous vibration of a loaded dislocation string. It is difficult to use the results obtained in [14] to analyze the present results. In [15] a rougher, but at the same time, more simple model is considered: the kinetic energy of a dislocation segment, directly interacting with the pinning center is taken into consideration. The kinetic energy of such a segment can be expressed as

$$E_K = \frac{mv_0^2}{2} = \frac{\pi r^2 \cdot l \cdot d \cdot v_0^2}{2}, \quad (5)$$

where m is the mass of the segment, d is the radius of the dislocation core, l is the length of the segment, d is the density of the crystal and v_0 is the velocity of viscous dislocation motion between pinning centers. Then using the experimental data obtained (Fig. 1 and 7), taking $r = 2b$ and $l/2 = 3b$ at $\tau = 240 \text{ N/cm}^2$ we will obtain for kinetic energy of screw dislocations

$$E_K^s = 3.3 \times 10^{-3} \text{ eV (at 295 K)}$$

and

$$E_K^s = 0.22 \text{ eV (at 4.2 K)}$$

and for kinetic energy of edge dislocations $E_K^e = 4.5 \times 10^{-3} \text{ eV (at 295 K)}$ and $E_K^e = 0.2 \text{ eV (at 4.2 K)}$. The estimated values of E_K for 4.2 K are of the same order of magnitude as the binding energy between dislocations and pinning centers produced by divalent impurities in alkali halides (see measurements in room temperature region in LiF [1] and in KBr [16] and calculations made recently in [17]). It can be concluded that the kinetic energy of viscous motion of dislocation segments can be of great importance in overcoming pinning centers at low temperatures. Measurements of the $v(\tau)$ dependences at helium temperatures in various crystals both in the low and high-velocity regions are of great interest.

Data on the temperature dependences of the critical resolved shear stresses τ_s for the same pure NaCl, LiF and KI are presented in figure 8. The temperature

FIG. 8. — Dependence of critical resolved shear stress τ_s on temperature in NaCl, LiF and KI.

FIG. 9. — Dependence of critical resolved shear stress τ_s on temperature in KCl, KBr and RbI.

dependences of τ_s for pure KCl, KBr and RbI are presented in figure 9. It can be seen from these curves that for all crystals investigated there are two regions of temperature: from room temperature down to ~ 100 K and at very low temperatures, where τ_s is insensitive to temperature. In table I data for dislocation velocities $v(\tau_s)$, corresponding to the critical resolved shear stress τ_s at various temperatures for NaCl, LiF and KI investigated are listed. It can be seen from the table that $v(\tau_s)$ increases when the temperature decreases. For NaCl at 4.2 K the value $v(\tau_s)$ is very high. Making an estimate of ρ , using equation (1) and taking $\dot{\epsilon}_p \approx 2 \times 10^{-5} \text{ s}^{-1}$, $b \approx 4 \times 10^{-8} \text{ cm}$ and $v(\tau_s) \approx 3 \times 10^4 \text{ cm/s}$ we obtain $\rho \ll 1$ at τ_s in NaCl at 4.2 K. This means that the density of mobile dislocations during plastic deformation of NaCl at 4.2 K is very low (since $\dot{\epsilon}_p > 0$ only when $\tau \geq \tau_s$); it also means that the plastic deformation is controlled (and the τ_s on temperature dependence is determined) at low

temperatures not by the dislocation motion process but by processes and mechanisms of dislocation multiplication. In such a case an investigation of the $\tau_s(T)$ dependences at various strain rates makes it possible to determine the parameters of dislocation multiplication mechanisms.

A weak temperature dependence of τ_s in the region of room temperature is usually observed for pure alkali halides and other pure crystals. Temperature independent regions of τ_s at very low temperatures have been also observed in pure W [18]. In alkali halides this τ_s independency on T is probably connected with a change of dislocation multiplication mechanism in these crystals at low temperature, for instance, from multiple cross-slip to multiplication of dislocations on stress concentrators. A decrease of the viscous drag coefficient B at low temperatures can also give a growth in the number of dislocation loops of critical size from thermal or stress fluctuations.

TABLE I

Dislocation velocities $v(\tau_s)$, corresponding to the critical resolved shear stress, τ_s , at various temperatures in NaCl, LiF and KI crystals

		$T \text{ K}$				
crystal		295	173	77	20	4.2
$\sim v(\tau_s)$	NaCl edge	10^{-5}	10^{-4}	3×10^{-2}	2×10^4	3.1×10^4
	NaCl screw	2×10^{-6}	5×10^{-5}	7×10^{-3}	1.8×10^4	3.3×10^4
	LiF	10^{-5}	10^{-4}	10^{-1}		
	KI	10^{-6}	10^{-5}	10^{-3}		

References

- [1] JOHNSTON, W. G. and GILMAN, J. J., *J. Appl. Phys.* **30** (1959) 129.
- [2] GUTMANAS, E. Y., NADGORNYI, E. M. and STEPANOV, A. V., *Sov. Phys.-Solid State* **5** (1963) 743 ;
GUTMANAS, E. Y. and NADGORNYI, E. M., *Sov. Phys.-Solid State* **10** (1969) 1799 ;
GUTMANAS, E. Y., ph. d. Thesis, Moscow (1970).
- [3] PARIISKII, V. B., LUBENETS, V. S. and STARTSEV, V. I., *Sov. Phys.-Solid State* **8** (1966) 976.
- [4] LUBENETS, S. V. and STARTSEV, V. I., *Sov. Phys.-Solid State* **10** (1968) 15.
- [5] ARGON, A. S. and PADAWER, G. E., *Phil. Mag.* **25** (1972) 1073.
- [6] BOBROV, V. S., GUTMANAS, E. Y. and KISEL, V. P., Physical Processes of Plastic Deformation at Low Temperatures, Conf. Abstracts, Kharkov (1971), p. 32.
- [7] ERMAKOV, G. A. and NADGORNYI, E. M., *Sov. Phys.-Solid State* **13** (1971) 513.
- [8] GUTMANAS, E. Y. and NADGORNYI, E. M., *Sov. Phys. Crystallogr.* **13** (1968) 85.
- [9] GUTMANAS, E. Y. and NADGORNYI, E. M., *Sov. Phys.-Solid State* **10** (1969) 1805.
- [10] FOREMAN, A. J. E. and MAKIN, M. J., *Phil. Mag.* **14** (1966) 911.
- [11] AL'SHITS, V. I. and INDENBOM, V. L., *Sov. Phys.-Uspekhi* **18** (1975) 1.
- [12] INDENBOM, V. L. and ESTRIN, Yu. Z., *Phys. Status Solidi* (a) **4** (1971) K 37.
- [13] NATSIK, V. S., *Sov. Phys.-JETP* **34** (1972) 1359.
- [14] GRANATO, A. V., *Phys. Rev. B* **4** (1971) 2196.
- [15] GUTMANAS, E. Y., *Phil. Mag.* to be published.
- [16] PARIISKII, V. B. and TRET'YAK, A. I., *Sov. Phys.-Solid State* **9** (1968) 1933.
- [17] ISHII, K., *Phil. Mag.* **33** (1976) 909.
- [18] OKU, T. and GALLIGAN, J. M., *Phys. Rev. Lett.* **22** (1969) 596.

DISCUSSION

R. W. WHITWORTH. — The anomalous behaviour of the dislocation velocity in NaCl below 20 K is very interesting because anomalies have also been observed in the charge carried by dislocations in this temperature range (STUART, R. A. and WHITWORTH, R. W., *Phil. Mag.* **15** (1967) 1057 and FRÖHLICH, F. and SEIFERT, P., *Phys. Stat. Sol.* **25** (1968) 303). These effects may be related to impurities, particularly anions.

Could you comment on the purity of your specimens ?

E. Y. GUTMANAS. — The total content of divalent impurities present including anions O_2 and S_2 did not exceed 10 ppm for NaCl crystals. There is not enough reason to relate the anomalous behavior of the dislocation velocity in NaCl below 20 K with the charge carried by dislocations.