Influence of point defects on formation and motion of kinks in dislocations in silicon

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The results of an experimental study of the mobility of individual dislocations in silicon single crystals under conditions of periodic pulsed loading are presented. The dependences of the average glide distance of individual dislocations in silicon single crystals on the load pulse widths and the intervals between load pulses with different shear-stress levels were investigated using the method of intermittent two-level loading. The experimental data are analyzed on the basis of a kinetic model which takes into account the fluctuation formation and expansion of kink pairs in the stress field as well as their relaxation when the load on the crystal is removed. Significant disagreements between the computational results and the experimental data have been found. The possibility of describing the observed facts by taking into account the changes of the dislocation and kink energies as a result of interaction with point defects, giving rise to specific regimes of one-dimensional motion of a kink in the field of a random source or in a random potential, is analyzed.

INTRODUCTION

More than 50 years ago, when the dislocation hypothesis of the plasticity of crystals was formulated, it was already acknowledged that in a crystal lattice exhibiting translational symmetry the energy of a dislocation and hence the resistance to the motion of a dislocation are periodic functions of the position of the dislocation in the glide plane (Peierls barriers) $W_p(y)$ (Fig. 1a). For stresses less than the Peierls stress $\tau_w = (1/b)[\partial W_p/\partial y]_{\max}$, where b is the magnitude of the Burgers vector, such barriers are overcome by creating nonlinear soliton-type excitations on the dislocation which subsequently evolve, resulting in formation of kink pairs. Kink pairs, growing via a series of fluctuations up to a configuration that is stable against collapse, expand by drifting until they annihilate with antikinks from adjacent pairs in the dislocation line.[1-3]

The average velocity of the stationary motion of a dislocation in the Peierls relief is determined by the probability of pair formation and the kink velocity along the dislocation line. These elementary acts occur in two neighboring valleys of the potential relief, which are separated by the interatomic separation distance. They have not yet been directly studied experimentally by the methods of high-resolution electron microscopy.

A method based on the analysis of the laws of motion of dislocations under conditions of periodic pulsed loading and making it possible to obtain specific information about the characteristics of elementary acts of dislocation glide, has been proposed only recently in Refs. 4 and 5. A comparison[5,6] of the experimental data, obtained by this method for silicon single crystals, with estimates made in the approximation of the theory of motion of dislocations in a uniform Peierls relief[1] revealed a number of serious contradictions.

The most significant contradiction is that the dislocations stop completely as the width of the load pulses decreases or as the duration of the pauses between the pulses increases. Repeated application of load pulses should give rise to drift of thermodynamically equilibrium kinks along the dislocation line; under the conditions of the experiment the contribution of such kinks to the motion of the dislocation is equal to at least 60% of its stationary velocity.[6]

It is natural to conjecture that the observed discrepancies are determined by the influence of point defects, which are always present in a crystal. Being distributed nonuniformly along a dislocation, point defects can, in particular, determine the specific nature of the one-dimensional motion of a kink along a dislocation line. The possibility of attaching a point defect to the dislocation core or detaching a point defect from the dislocation as the kink passes causes the energy of a kink pair to depend discontinuously on its size (Fig. 1c, curve *3*). There arises a unique "memory" effect, governed by the superposition of the contributions of several point defects to the interaction with dislocations. This results in the formation of a specific potential relief for kink motion. Petukhov[7-10] and Vinokur[11,12] investigated kink migration in such a relief theoretically; this migration is called "motion in the field of a random force."

The distinguishing feature of such motion is the existence of a critical stress

$$\tau_0=(c_1+c_2)u^2/(2kTab), \tag{1}$$

which separates two regimes of kink migration. Here a is the distance between the valleys of the potential relief, c_1 and c_2 are the concentrations of point defects in adjacent valleys of the potential relief, u is the energy of short-range interaction of a dislocation with a point defect, k is Boltzmann's constant, and T is the temperature. For high shear stresses $\tau > \tau_0$, kink motion can be described in terms of the standard drift, when the displacement depends linearly on the time, as in the case of a random potential generated by individual point defects or clusters of point defects.[13-15] For stresses $\tau < \tau_0$, however, the collective contribution of the point defects becomes significant and the kink motion can no longer be described in terms of the standard diffusion and drift. In particular, in the case of drift the kink path length is a sublinear function of the time:[12]

$$x \sim t^{\delta}, \tag{2}$$

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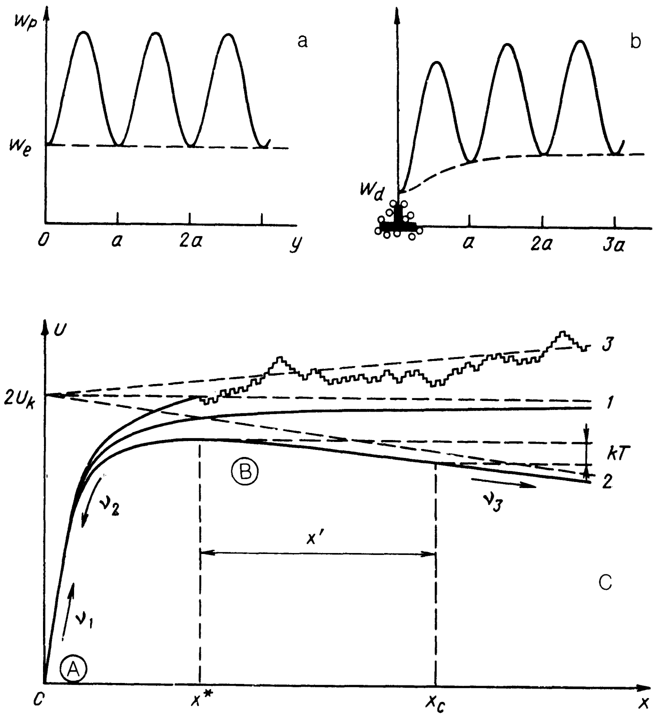

FIG. 1. a) The dependence of the energy of a dislocation on its position in the glide plane in an ideal crystal and b) in a crystal distorted by the interaction of the dislocation with a cloud of impurities. c) The free energy of a kink pair as a function of the pair size in an ideal Peierls relief in the absence of stress (*1*), with application of a load ($\tau > 0$) (*2*), and taking into account the interaction of the dislocation with point defects[9,16] with $\tau < \tau_{st}$ (*3*). The circled letters show the states of the dislocation which are studied in the system of equations (7). The rest of the notation is explained in the text.

where

$$\delta = 2kT\tau ab/[(c_1+c_2)u^2] = \tau/\tau_0 < 1. \tag{3}$$

Another possibility is associated with the change brought about in the energy of a dislocation as a whole by the action of a cloud of point defects. As the point defects redistribute themselves around a dislocation they decrease further the minimum of the potential relief at the location of the dislocation (Fig. 1b). Now the transfer of a dislocation into a neighboring valley of the potential relief under shear stresses less than some critical value, called the starting stress[16,9]

$$\tau_{st} = (c_1 - c_2)u/(ab) \tag{4}$$

is no longer energetically favorable. It should be noted that the quantities τ_{st} and τ_0 are not constants, but rather depend on the state of the impurity cloud, which in turn is determined by the speed of the dislocation.[9] The indicated decrease in the energy of the dislocation determines the additional force that stimulates relaxation of kink pairs and gives rise to the collapse of kink pairs.

In this connection it is of interest to investigate theoretically kink dynamics under conditions when the mechanisms predicted by the theory of motion in the field of a random force are realized. Such conditions can be achieved, in particular, when internal stresses stimulating the contraction of kink pairs are partially compensated by the application of an external stress or when the applied stress has the same sign as the internal stress and determines the process of relaxation of kink pairs.

In the present paper a method making it possible to realize such experimental conditions is developed. The results of an investigation of the effect of weak external forces on the dynamics of kinks in dislocations in silicon, performed by a modified method of periodic pulsed loading, are presented; the method makes it possible to investigate the transition from motion in the field of a random force to motion in a random potential.

EXPERIMENTAL PROCEDURE

In order to solve the problem posed above, we modified the method of intermittent pulsed loading, previously proposed in Ref. 4. In Refs. 4–6 the mechanisms of motion of individual dislocations under the action of a succession of load pulses τ_i, separated by pauses during which no load was applied to the sample, were investigated in Refs. 4–6. The width of a single pulse was comparable to the average time $t_a = a/V_s$ for transfer of a dislocation over a distance equal to the lattice spacing under conditions of stationary motion, where V_s is the average velocity of the dislocation under static loading.

It was found that by varying the width t_i of the pulses and the duration t_p between pulses and by measuring the characteristics of the distribution of dislocations over the glide distances it is possible to obtain information about the characteristic formation time of a stable kink pair in a dislocation line—diffusive growth of a pair from the critical size x^* up to $x_c = x^* + x'$ (Fig. 1c)—as well as about the characteristics of kink motion as the pair expands and contracts. This made it possible to estimate, on the basis of very general assumptions about kink formation and kink motion, the characteristics of these processes. Here x^* is the distance at which the mutual attraction of the kinks is balanced by external forces:[1]

$$x^* = (\alpha/\tau_i ab)^{1/2}, \tag{5}$$

x' is the diffusion length,

$$x' = kT/(\tau_i ab), \tag{6}$$

τ_i is the shear stress in the load pulse, and the constant α determines the elastic interaction energy of the kinks.

Periodic pulsed loading was achieved by four-point bending of the sample by means of a series of trapezoidal pulses, applied from a generator of pulses of a special form through an electromagnetic force transducer.[6] In this work, in order to accelerate or decelerate collapse of kink pairs during the "pauses" (the intervals between the load pulses) a definite stress τ_p was created by applying a constant load with the required sign. Two-level sign-alternating loading was achieved with a six-point scheme, similar to that employed in Ref. 17. The two-level loading with stresses of the same sign was achieved using the standard four-point scheme. A special setup was used to produce constant additional loading. It includes removable beams with supports that transmit the load to the sample; the beams are connected to the table for the weights, placed in the cold zone of the setup, by means of a hinge mechanism. This modification of the method makes it much more useful for investigating different regimes of kink motion.

The experiments were performed on samples of n-type silicon, cut from a dislocation-free ingot, grown by the method of crucibleless zone melting and doped, during growth, with phosphorus until a resistivity of 150 Ω/cm was reached. The samples had the form of rectangular prisms with edge orientations $[1\bar{1}0]$, $[11\bar{2}]$, and $[111]$ and dimensions of $35 \times 4 \times 1.5$ mm^3. In order to introduce individual dislocations in the (111) faces stress concentrators were created with the help of a small pyramidal diamond indentor. The dislocation half-loops which formed from them under subsequent loading were revealed by selective chemical etching using the method described in Ref. 18. The use of Sirtl's etchant made it possible to distinguish 60-degree and screw segments from the form of the etch pits.[19] The glide distances of only those dislocations that did not exhibit surface bending were considered in the measurements.[18] In this paper we present the results obtained for 60-degree segments of dislocation half-loops of the glide system $(1\bar{1}1)$ [011], which were introduced on the compression side of the sample.

In order to determine the temporal characteristics of kink formation and kink motion the dependence of the average glide distance $\bar{l}$ of dislocations on the pulsed-loading parameters was measured. Two types of experiments were performed: we measured the dependence $\bar{l}(t_i)$ with constant inverse-duty factor $Q = 2$ ($t_p = t_i$), where t_i and t_p are the widths of the load pulses and the durations of the "pauses" between them, respectively, as well as the dependences $\bar{l}(t_p)$ for fixed width of the load pulses (t_i = const). The total width of the load pulses Σt_i was chosen to be equal to the static loading time t_s within which the dislocations moved over distances of 20–30 μm, and remained unchanged in each series of experiments. The width of the leading edge of the load pulses was held constant ($t_f = 4$ ms). The loading was performed at a temperature of $T = 600$ °C. The temperature was measured with a thermocouple, placed adjacent to the sample, and was maintained constant to within an accuracy of 1 °C.

RESULTS AND DISCUSSION

Figure 2 shows the average glide distances of dislocations as a function of the width of the load pulses for the case $t_p = t_i$ with different shear stresses during the "pauses" between the pulses. One can see that even the application of a comparatively weak stress τ_p substantially changes the dependence $\bar{l}(t_i)$. If a weak additional load whose sign is opposite that of τ_i (curve *1*) is applied during the "pauses," the glide distances decrease to zero for pulse widths substantially larger than in the absence of the additional loading (curve *2*). Both curves have an s shape with a point of inflection. If, however, a small stress of the same sign as in the pulses is applied during the "pauses," the dependence $\bar{l}(t_i)$ becomes weaker and the dislocation glide distances do not drop to zero, even for the smallest values of t_i employed in the experiment (curve *3*).

Figure 3 shows curves of the average glide distances of the dislocations versus the duration of the pauses between the load pulses. The curves were obtained with fixed pulse widths. The curves *1–4* were obtained with different shear stresses during the pauses between the pulses. It is clear that in all cases as t_p increases the glide distances decrease. Application of a small positive stress τ_p during the "pauses" slows down the decrease of $\bar{l}$ as t_p increases. Application of a small stress with the opposite sign (with respect to τ_i), however, not only increases the rate of decrease of the glide distances as t_p increases, but even changes the form of the dependence. If in the absence of additional loading during the pauses between the pulses (curve *2*) and with additional loading $\tau_p = +1$ MPa (curve *3*) the curves are s-shaped and have a point of inflection, then in the case of loading with the opposite sign ($\tau_p = -1.1$ MPa) the glide distances decrease almost linearly (curve *1*).

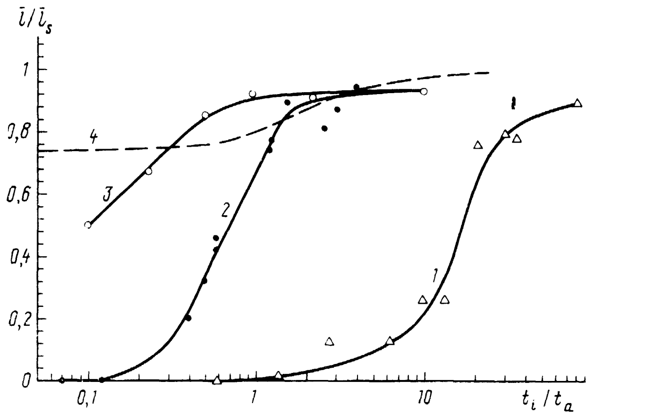

FIG. 2. The average glide distances of dislocations, normalized to the value for static loading, as a function of the relative load pulse widths ($t_p = t_i$) with different level of stresses applied during the pauses: $\tau_p = -1.1$ MPa (*1*), no additional loading ($\tau_p = 0$) (*2*), $\tau_p = +1$ MPa (*3*). $\tau_i = 7$ MPa, $\Sigma t_i = t_s = 3600$ s. Curve *4* is the computed dependence obtained from the relation (14) for $W_m = 1.6$ eV, $\tau_i = 7$ MPa, and $\tau_a = 76$ ms (*4*).

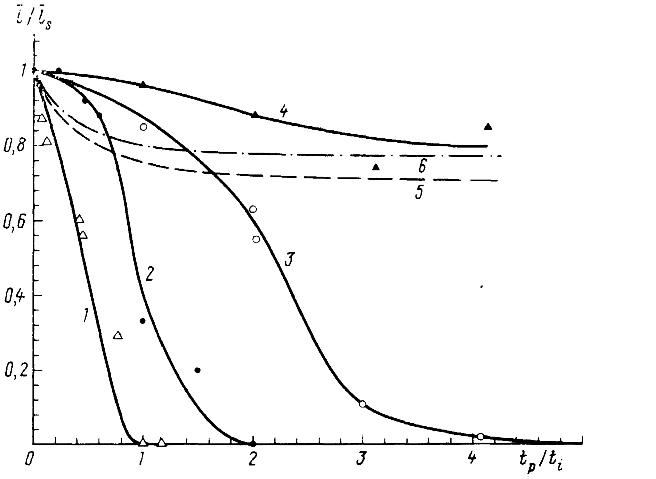

FIG. 3. Average glide distances, normalized to the value with static loading, as a function of the relative length of the pauses between the load pulses ($\tau_i = 34$ ms = const) for different level of stresses applied during the pauses ($\tau_i = 7$ MPa, $\Sigma t_i = t_s = 3600$ s): $\tau_p = -1.1$ MPa (*1*), no additional loading ($\tau_p = 0$) (*2*), $\tau_p = +1$ MPa (*3*), and $\tau_p = +1.5$ MPa (*4*). Curves *5* and *6* are the computed dependences obtained from the relation (15) ($t_a = 76$ ms): $W_m = 1.6$ eV, $\tau_i = 7$ MPa (*5*) and $W_m = 1.55$ eV, $\tau_i = \tau_{\rm eff} = 5.5$ MPa (*6*).

It is interesting to note that the glide distances are observed to decrease to zero even when a small constant additional load of the same sign as in the pulses (curve *3*) is applied during the intervals between the pulses. However when the stress during the pauses is increased up to + 1.5 MPa (curve *4*), the dependence $\bar{l}(t_p)$ becomes significantly weaker and the glide distances do not drop to zero right up to $t_p = 4t_i = 136$ ms.

We now compare the experimental data presented above with the theory of dislocations moving in a perfect crystal,[1,20-24] where kink motion is determined by the uniform Peierls relief of the second kind. At the present time the nonstationary motion of dislocations, which is realized under our experimental conditions, has still not been given a rigorous theoretical interpretation that takes into account the kinetics of kink nucleation and kink propagation. For this reason, for comparison, we shall employ a simple model (with some refinements) based on the scheme proposed in Refs. 25 and 26 for processing experimental data obtained with periodic pulsed loading and no additional loading during the pauses.

In this approach the probability of finding a dislocation in one of two states is studied: "no kinks" C_1 and "with a pair of kinks" C_2. These states are indicated by the circled letters *A* and *B* in Fig. 1c. The time dependence of C_1 and C_2 is described by the system of equations

$$dC_1/dt = -dC_2/dt = -\nu_1 C_1 + \nu_2 C_2 + 2v_k C_2^2, \tag{7}$$

where ν_1 is the rate of formation of kink pairs with critical size x^*, ν_2 is the rate of collapse of pairs, and $2v_k C_2 \equiv \nu_3$ is the rate of annihilation of kinks with antikinks from adjacent pairs on the dislocation line as the pairs undergo drift expansion. The arrows in Fig. 1c indicate the directions of these processes, v_k is the drift velocity of a kink

$$v_k = (D_k/kT)\tau_i ab, \tag{8}$$

D_k is the diffusion coefficient of a kink

$$D_k = \nu_D b^2 \exp(-W_m/kT), \tag{9}$$

ν_D is the Debye frequency, and W_m is the effective activation energy of kink motion.[1]

The dislocation velocity is determined by the transfer time of a dislocation into an adjacent valley of the potential relief $V = a/t \approx a\nu_3$. Then the stationary velocity can be written in the form

$$V_s = 2v_k a C_2^s, \tag{10}$$

while the average dislocation velocity during the load pulse is

$$V = \frac{a}{t_i}\int_0^{t_i} \nu_3(t)\,dt = \frac{2av_k}{t_i}\int_0^{t_i} C_2(t)\,dt. \tag{11}$$

The system of equations (7) can be solved, if the contribution of terms that are quadratic in C_2 is neglected. In particular, during a load pulse

$$C_2(t) = C_2^s - [C_2^s - C_2(0)]\exp(-\nu t), \tag{12}$$

where $\nu = \nu_1 + \nu_2$ and C_2^s is the value of the probability C_2 under conditions of stationary motion of the dislocation. In determining $C_2(0)$ the fact that the solution of the system of

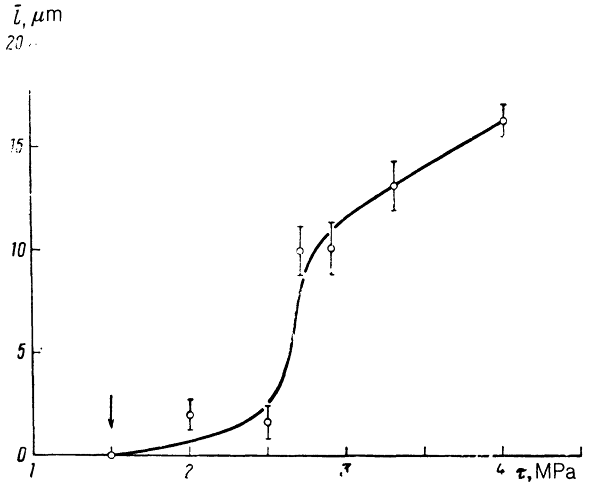

FIG. 4. The average glide distance of 60-degree dislocations in silicon under conditions of static loading as a function of the shear stress, $T = 600$ °C. The duration of the loading $t = 9000$ s.

equations (7) has a cyclical character $[C_2(t) = C_2(t + t_i + t_p)]$ must be taken into account. Since $\nu_1 \ll \nu_2$, we obtain the following expression for the dislocation velocity under the conditions of periodic pulsed loading:

$$\frac{V}{V_s} = 1 - \frac{\{1-\exp(-z)\}}{z}\left(\frac{2(C_2^s - C_2(0))}{C_2^s}\right) = 1 - \frac{(\gamma-1)\{1-\exp(-z)\}\{1-\exp(-y)\}}{\gamma z\{1-\exp[-(y+z)]\}}, \tag{13}$$

where ν_2' and ν_2'' are, respectively, the probabilities that a kink pair collapses during a pause and during a load pulse, $\gamma \equiv \nu_2'/\nu_2'' = \exp(x^*/x')$, $y \equiv \nu_2' t_p$, $z \equiv \nu_2'' t_i$.

The relation (13) makes it possible to calculate the dependences $\bar{l}(t_i)$ and $\bar{l}(t_p)$. In the case $t_p = t_i$ the equality $y = \gamma z$ is satisfied. This leads to the expression

$$\frac{\bar{l}(t_i)}{\bar{l}_s} = 1 - \frac{(\gamma-1)\{1-\exp(-z)\}\{1-\exp(-\gamma z)\}}{\gamma z[1-\exp\{-(1+\gamma)z\}]} = 1 - \frac{(\gamma-1)\{1-\exp(-\nu_2'' t_i)\}\{1-\exp(-\gamma\nu_2'' t_i)\}}{\gamma\nu_2'' t_i\{1-\exp[-(1+\gamma)\nu_2'' t_i]\}}. \tag{14}$$

In the case $t_i =$ const the expression (13) gives the following expression for the average dislocation glide distance:

$$\frac{\bar{l}(t_p)}{\bar{l}_s} = 1 - \frac{(1-\varkappa)(\gamma-1)\{1-\exp(-\nu_2' t_p)\}}{\gamma\nu_2'' t_i\{1-\varkappa\exp(-\nu_2' t_p)\}}, \tag{15}$$

where $\varkappa \equiv \exp(-z) = \exp(-\nu_2'' t_i) =$ const.

Calculations using Eqs. (14) and (15) were performed on the basis of the diffusion model, where the rate of collapse of kink pairs of size x^* is determined by the diffusion coefficient of the pair $\nu_2'' \approx 2D_k/(x^*)^2$. The coefficient D_k (and correspondingly W_m) can be estimated from the relation[6]

$$2D_k = (x')^2/(2t_i^*), \tag{16}$$

where x' is the diffusion growth length of a pair (6) from the critical size x^* (5) up to the stable configuration x_c (Fig. 1c), and t_i^* is the pulse width corresponding to the position of the point of inflection on curve *2* in Fig. 2—the characteristic formation time of a stable kink pair on the dislocation line. The estimates made according to Eqs. (16) and (9) give the value $W_m \approx 1.6$ eV. The dashed curves in Fig. 2 (curve *4*) and Fig. 3 (curve *5*) show the dependence calculated according to Eq. (14) and (15) for this value of W_m. Decreasing W_m results in a shift of the "step" at short times and a decrease of its "depth"; increasing W_m results in the opposite effect. However, even if W_m is set equal to the effective activation energy of the motion of the dislocation as a whole $U_{\text{eff}} \approx 2.13$ eV, the computed change in the glide distances does not exceed 40%.

Thus, in the above model of the motion of a dislocation in a uniform potential relief the glide distances of dislocations do not decrease to zero, as they do in Ref. 6. The mechanism, incorporated in the model, of kink-pair relaxation by means of diffusion probably does not allow for the pairs to return efficiently to the centers of nucleation; this is the reason for the significant disagreement between the computed and experimental dependence for short pulse widths (Fig. 2, curve *2*) and quite prolonged pauses (Fig. 3, curve *2*).

We now examine the possibility of describing the results presented in Figs. 2 and 3 on the basis of the theory in which the effect of point defects on kink-pair formation and kink-pair motion is taken into account. As we have already mentioned, the result of the interaction of a moving dislocation with point defects is to redistribute the defects which, accumulate in the stress field and in the dislocation core. This, in particular, gives rise to the starting stresses for dislocation motion.[27–29] In order to reveal them, in this work we investigated the average glide distance of individual dislocations as a function of the shear stress. Figure 4 shows this dependence. One can see that as the stress decreases the nearly linear dependence is replaced at $\tau < 3$ MPa by a sharp drop of the dislocation glide distances and at $\tau = 1.5$ MPa (marked by the arrow) dislocation motion cannot be observed within the time of the experiment. This quantity was taken as the starting stress τ_{st}.

The interaction of a dislocation with point defects determines whether or not formation of kink pairs for $\tau < \tau_{\text{st}}$ is energetically favorable, since, to a first approximation, a constant effective stress, equal in magnitude to $(-\tau_{\text{st}}) = -(1/b)[\partial W_d/\partial y]_{\max}$ and returning them to the nucleation center (Figs. 1b and c), acts on them. In this case the kink pairs formed on the dislocation line during the load pulse will relax during the pauses under the action of the internal stress $(-\tau_{\text{st}})$ by drifting and not diffusion, as assumed in the preceding work[4–6] and the first part of the discussion. The reason, studied here, for the relaxation of kink pairs may permit explaining qualitatively the significant change, observed in our experiments, of the dislocation glide distances as a function of the load pulse width and the duration of the pauses.

If, now, the action of the internal forces is balanced during a load pulse by application of an external stress during the pauses between the load pulses, the relaxation of kink pairs should be determined by random walk of the kinks. In order to check this assumption we performed experiments with periodic pulsed loading of the samples, when a stress $\tau_p \approx \tau_{\text{st}}$, balancing the action of the internal stresses, was applied during the pauses. Curve *4* in Fig. 3 shows the dependence, obtained under these conditions, of the normalized average glide distance of dislocations on the duration of the pauses between the load pulses. The dot-dashed curve (curve *6*) in Fig. 3 shows the dependence calculated from Eq. (15); the amplitude of the pulsed stress was taken to be $\tau_{\text{eff}} = \tau_i - \tau_{\text{st}} = 5.5$ MPa. In these calculations W_m was used as an adjustable parameter. One can see that for $W_m = 1.55$ eV the computed change in dislocation glide distances for large values of t_p agrees qualitatively with the change determined in the experiment. But the rate of change of the dependence, i.e., the kink relaxation kinetics during the pauses, cannot be satisfactorily explained on the basis of the usual model of kink diffusion.

This discrepancy could be due to the characteristics of the one-dimensional motion of kinks in the specific potential relief formed by the superposition of the contributions of many point defects to the energy of a kink pair. Under these conditions, kink motion cannot be described in terms of the standard diffusion and drift and must be analyzed on the basis of the theory of motion in the field of a random force.[7–12] Diffusion in the field of a random force must be slower than in a random potential, according to the law $x \sim \ln^2 t$.[12] This can determine, in principle, the discrepancy between the curves *4* and *6* in Fig. 3.

In order to answer this question we measured the characteristic relaxation times τ_p^* of kink pairs of different sizes, the starting size of a pair being determined by the load pulse width t_i. Curve *1* in Fig. 5 shows the dependence of the critical duration of the pauses t_p^* on the pulse width t_i in the absence of additional loading during the pauses. In order to construct this dependence in the experiments we constructed the curves $\bar{l}(t_p)$ ($\tau_i = \text{const}$) for different values of t_i and determined the position of the points of inflection t_p^* on curves similar to the curve *2* in Fig. 3.

We now examine the possibility of describing the dependence $t_p^*(t_i)$ for kink motion in the a random force field and in a random potential. During a load pulse with $\tau_i > \tau_0$ (1) kink pairs expand by the standard diffusion and drift processes. Assuming (as in Refs. 4 and 6) that during a load pulse a kink pair grows to a stable configuration by diffusion over the time t_i^* and then expands by drift, while during a pause the pair contracts under the action of a force equal to $(-\tau_{\text{st}}ab)$, likewise in the regime of linear drift (motion in a random potential), we obtain, equating the path lengths of the kinks during pair expansion and relaxation during a pause t_p^*, the following equation describing the dependence $t_p^*(t_i)$:

$$kT/[(\tau_i-\tau_{st})ab]+2(D_k/kT)[(\tau_i-\tau_{st})ab](t_i-t_i^*)$$
$$=2(D_k/kT)(\tau_{st}ab)t_p^*. \qquad (17)$$

The first term on the left side of Eq. (17) is the diffusion length (6), modified by replacing τ_i by $\tau_i - \tau_{\text{st}}$. The second term is the drift distance of a kink pair during the load pulse minus t_i^*—the formation time of a stable pair. The right-hand side of the equation is the path length of kinks in the case of drift-induced pair contraction under the action of the internal stress $-\tau_{st}$, i.e., $x(t_p) = 2v_k' t_p$, where $v_k' = (D_k/kT)\tau_{st}ab$.

In the case of motion in the field of a random force the path length of the kinks in the case of drift-induced pair contraction under the action of the internal stress $\tau = -\tau_{st}$ is described by the expression (2). In this case the dependence $t_p^*(t_i)$ is described by the equation

$$kT/(\tau_i-\tau_{st})ab+2(D_k/kT)[(\tau_i-\tau_{st})ab](t_i-t_i^*)=x_0(t_p^*/t_0)^\delta, \quad (18)$$

where $x_0 = kT/(\tau_{st}ab)$ and $t_0 = (x_0)^2/(2D_k)$.

The dashed lines in Fig. 5 show the behavior calculated using Eqs. (17) and (18). One can see by studying kink motion in the random potential (17) that the experimental data disagree even qualitatively with the computed dependence (curve *5*). However, in the case of motion in the field of a random force the computed dependence can be matched with the experimental data for short pulse widths ($t_i < 110$ ms) with $\delta = 0.4$ (curve *3*).

The disagreement between the computed and experimental curves in Fig. 5 for large pulse widths could be caused, in principle, by two factors. The first possibility is associated with the fact that for relatively large t_i kink pairs reach sizes when annihilation of kinks from neighboring pairs on the dislocation line may be more probable than return of the kinks to the centers of nucleation.[6] However, the experiments performed when the two-level loading alternates in sign (Fig. 3, curve *1*) show that a significant number of kinks can return to the nucleation centers even after the dislocation moves over several valleys of the potential relief.

Indeed, if all kinks from adjacent pairs were annihilated within times $t_i \approx 2t_a$ corresponding to regions of rapid growth of t_p^* (Fig. 5), dislocation glide could not be reversible under sign-alternating loading with pulses of width greater than $2t_a$ (τ_p is too small to stimulate nucleation of pairs of kinks of opposite sign during the pauses). It is evident from curve *1* in Fig. 3, however, that under the conditions of reversible loading with load pulse widths $t_i \leqslant 10t_a$ the dislocation glide distances are short. The dislocation glide distances start to increase only when the pulse widths are sufficiently long: $t_i > 10t_a \approx 700$ ms. This type of motion of dislocations is possible when the dislocations contain widely separated barriers which prevent annihilation of some kinks from adjacent pairs. The increase in the dislocation glide distances for $t_i > 10t_a$ can be interpreted in this case as overcoming of barriers by the superkinks formed or the onset of motion of defects, forming the obstacles, under the action of linear tension forces of the bowed dislocation.

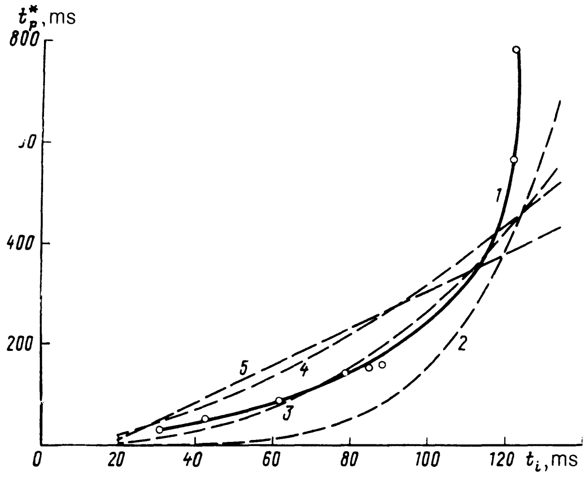

FIG. 5. The critical length of a pause as a function of the load pulse width: experimental data ($\tau_i = 7$ MPa, $\tau_p = 0$, $\Sigma t_i = 7200$ s) (*1*), results of calculations of the nonlinear-drift-relaxation times for a kink pair during a pause under the action of stress $\tau_{st} = 1.5$ MPa [using the formula (18)] with $\delta = 0.2$ (*2*), 0.4 (*3*), and 0.6 (*4*), as well as the linear-drift-relaxation times [computed using the formula (17)] (*5*).

The discrepancy between the computed and experimental curves in Fig. 5 could also be caused by the specific nature of the one-dimensional motion of a kink in a time-dependent random force field. In the theory of motion in a random force field[7-12] point defects are assumed to be stationary. This is valid only for times shorter than the relaxation time of a cloud of point defects after a dislocation has moved into the next valley of the potential relief. The quantity τ_{st} (4) should decrease with time because the point defects are redistributed to the new position of the dislocation. If, however, the force moving the kinks is weak, the theory[9] predicts that for sufficiently long kink paths a kink can "stick" to a large fluctuation of the random force field generated by point defects, i.e., so-called quasilocalization can occur. Under these conditions the average kink velocity becomes equal to zero, and the dislocation segment that has crossed into the next valley of the potential relief during a load pulse does not return into the initial valley for any length of the pause.

Kink quasilocalization should in principle also be observed in the process of drift expansion of a pair using low-amplitude load pulses. This should result in qualitative changes in the mechanism of dislocation motion. In particular, "sticking" of kink pairs as they expand makes it possible for gliding to extend to the successive valleys of the potential relief. This should cause superkinks to form. The superkinks formed as a result of forces generated by linear stretching of a dislocation stimulate escape of kinks from traps in the random force field. For even weaker stresses, when superkink formation becomes energetically unfavorable, dislocations once again approach the rectilinear form. In this case, however, the dislocation velocity should decrease sharply, since under these conditions kinks can escape from traps only by thermal activation.

In order to determine the possibility of observing this phenomenon we performed experiments with periodic pulsed loading with small-amplitude pulses, when quasilocalization of kinks should occur. Figure 6 shows the results of our investigations of the dependence $\bar{l}(t_i)$ for $t_p = t_i$. These results were obtained without additional loading during the pauses and with different stresses during the load pulses. One can see that for the highest stress $\tau_i = 7$ MPa (curve *1*) the dependence of the average glide distance of dislocations on the load pulse widths attains the value of the average glide distance in the case of static loading under the same conditions with relatively short pulse widths $t_i \sim t_a$, which corresponds to displacement of a dislocation over a distance on the order of one lattice spacing.

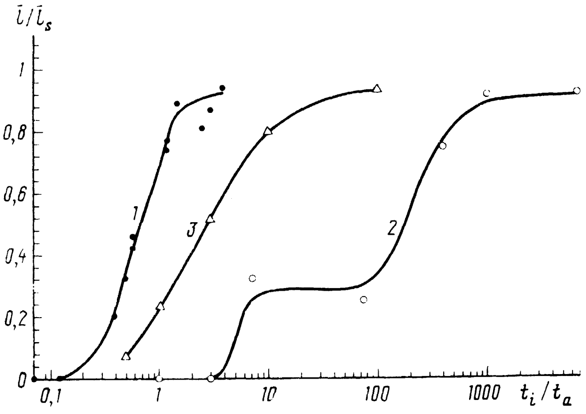

FIG. 6. Average glide distances of dislocations, normalized to the static values, as a function of the relative pulse width ($t_p = t_i$) for different shear stresses ($\tau_p = 0$):$\tau_i = 7$ MPa ($t_a = 76$ ms) (*1*), 4 MPa ($t_a = 129$ ms) (*2*), and 3 MPa ($t_a = 228$ ms) (*3*).

When the stress in the pulses is reduced to 4 MPa (curve *2*) the dependence of the average glide distance on the relative pulse width changes substantially. In particular, the average glide distances reach the values obtained with stationary motion under the same conditions with significantly larger relative pulse widths $t_i \approx 10^3 t_a$, i.e., under these conditions, as the dislocation enters the regime of stationary motion, separate sections of a dislocation glide over distances $\sim 10^3 a$. Formation of superkinks on the dislocation line then becomes unavoidable. As τ_i is further decreased to 3 MPa (curve *3*) the stationary glide distances are reached for much lower relative pulse widths than for $\tau_i = 4$ MPa. As one can see from Fig. 4, however, in this stress range the dislocation velocity starts to depend sharply on the stress.

It should be noted that the distortion of the form of the dislocation line in the region of weak applied stresses was observed previously in Refs. 18 and 28 with the help of x-ray tomography and was interpreted as resulting from the action of strong stoppers on the kink motion. The experiments performed show that fluctuations of the random force field can act as stoppers.

Thus the modified method of periodic two-level loading makes it possible to achieve, by varying τ_i and τ_p, different regimes of kink motion along a dislocation line and to obtain information about the accumulation of point defects from the volume of the crystal by the dislocation. When these experimental data are compared with the theory it is necessary to take into account the fact that the interaction of a dislocation with a cloud of point defects, which gives rise to the starting stress, is of a dynamic nature and depends on the preceding history of the crystal. In addition, it should be noted that the mechanism, studied in this work, of kink stopping in the relief created by the random force field is only one of the possible mechanisms. Potential barriers, associated with the dependence of the kink energy on the position of the kink relative to the point defect, are also obstacles to kink motion.[13,14] In a real crystal both possibilities are evidently realized and the random barrier and the random force field are superposed. Unfortunately, a strict theory of kink motion in which all indicated possibilities are taken into account has still not been developed.

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