Possibility of experimentally studying the formation kinetics and mobility of kinks on a dislocation line

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Evidence has been found for a radical change in the distribution of dislocations in path length upon a change in the length and duty factor of a periodic pulsed loading. These observations can be used to learn about the formation and evolution of the nonlinear excitations which limit the mobility of dislocations in the Peierls relief.

The translational symmetry of a crystal necessarily determines the degeneracy of its ground state and the periodic dependence of the energy of a dislocation on its position in the glide plane, i.e., the presence of Peierls potential barriers, which a dislocation must overcome as it glides through the crystal. The time required for the transition of a dislocation to the neighboring valley of the potential relief, τ_t, consists of the time (τ_f) required for the formation of a double kink of critical size λ_c and the time (τ_m) over which it expands before it annihilates with antikinks moving in the opposite direction, over a distance $\mathscr{L}_k$ (Fig. 1). The value of λ_c is determined by equating the force of the mutual attraction of the kinks forming a pair (the force that stimulates its collapse) to the external force that tends to repel the kinks.

For dislocations of sufficient length ($\mathscr{L} > \mathscr{L}_k = \sqrt{2v_k/J}$), the velocity of their steady-state motion in the potential relief is $v = a/\tau_t = a\sqrt{2Jv_k}$, where a is the lattice constant along the dislocation glide direction, J is the probability for the formation of

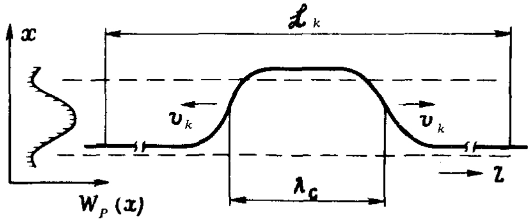

FIG. 1. The surmounting of a Peierls barrier by a dislocation at stresses below the Peierls stress, $\tau_P = |dW_P(x)/dx|_{\max}$.

double kinks per unit length of the dislocation line per unit time, and v_k is the velocity of the lateral movement of a kink. A detailed and sophisticated theory has been worked out for the motion of dislocations in a Peierls relief.[1-3] However, a comparison of the theoretical predictions with experimental data on the mobility of individual dislocations in semiconductor single crystals has revealed several paradoxical contradictions.[4-6] A resolution of these contradictions requires separate study of the characteristics of the processes which limit formation and mobility of solitons on a dislocation line. In the present letter we report an experimental study of the dynamics of individual dislocations in silicon single crystals subjected to pulsed periodic stresses, with the length of a single pulse comparable to the time τ_t. These results seem to point to the solution of this problem.

The dislocation velocities were measured in tetrahedral-prism samples with edge lengths $1.5\times4\times35$ mm along the $[1\bar{1}1]$, $[\bar{1}12]$, and [110] directions. The samples were cut from dislocation-free silicon bars grown by crucible-free zone melting. Dislocation half-loops of semihexagonal shape, 800–1000 μm in diameter, were first produced in the sample by four-fulcrum bending around the $[\bar{1}12]$ axis at $T = 600$ °C. The point at which 60° and screw segments of the half-loops emerged at the $\{111\}$ surface were

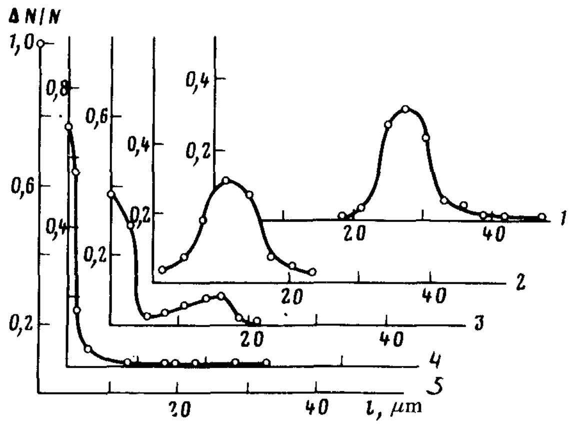

FIG. 2. Distribution of 60° dislocations in the path length in n-type Si grown by crucible-free zone melting, with a resistivity of 150 $\Omega\cdot$cm. 1—Static loading, $T = 600$ °C, $\sigma = 0.7$ kg/mm^2, $t_c = 7200$ s; 2–5—pulsed loading with $t_s = 94$ ms, $\Sigma t_s = t_c$; 2—$t_p/t_s = 1.8$; 3—2; 4—3; 5—5.

visualized by selective chemical etching by the procedure of Ref. 7.

A distinctive feature of the present experiments was that we supplemented the conventional static loading[7] with a pulsed loading under the same experimental conditions, with stress pulses of a length t_s comparable to the time (τ_t) required for the transition of a dislocation to a neighboring valley of the potential relief. The purpose was to find the characteristics of the kink mobility and of the formation of nonlinear excitations on the dislocation line. The sample was deformed by a train of square pulses applied with a given duty factor (i.e., the stress pulses were separated by corresponding pulses of length t_p, during which the applied stress was $\sigma = 0$) from a square pulse generator through an electromagnetic force transducer. The active-loading time, i.e., the sum of the lengths of the stress pulses, was equal to the static-loading time over which the dislocations moved a distance $l \approx 30$ μm.

Curve 1 in Fig. 2 shows the distribution of 60° dislocations in the path length under a static stress $\sigma = 0.7$ kg/mm^2 at $T = 600$ °C over a loading time $t_c = 7200$ s. Curves 2–5 correspond to pulsed loading with constant values of both the duration of a single pulse ($t_s = 94$ ms) and the total stress time, $\Sigma t_s = t_c$. These curves differ in the lengths of the pauses between the stress pulses. We see that as the time (t_p) over which the crystal is left in an unstressed state is increased, there is not only a decrease in the mean free path of the dislocations but also a qualitative change in the shape of the histogram (undisplaced dislocations appear), and at $t_p/t_s = 5$ the motion of the dislocations is completely halted (curve 5).

Analysis of the histograms yields curve 1 in Fig. 3, which shows that this dislocation mean free path $\bar{l}$ decreases with increasing length of the pauses, from the value measured in the static experiment, $\bar{l}_{st}$, to 0. On curve 1 there is an inflection point at $t_p/t_s \approx 2$.

In a study of the dislocation mean free path as a function of the pulse length at $t_p = t_s$ and with $\Sigma t_s = t_c$ (curve 2 in Fig. 3), we found that the dislocation mean free path increases with increasing t_s from 0 to values comparable to l_{st} (at $t_s > 100$ ms).

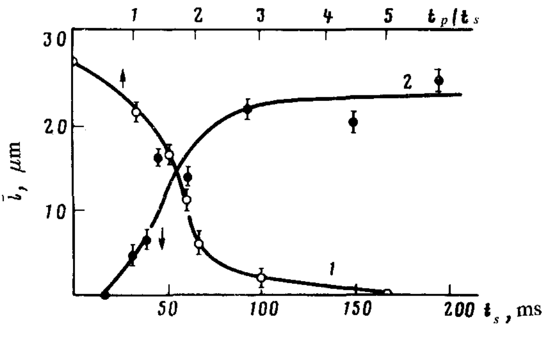

FIG. 3. 1—The dislocation mean free path $\bar{l}$ versus t_p/t_s at $T = 600$ °C, with $\sigma = 0.7$ kg/mm^2, $t_c = 7200$ s, $t_s = 94$ ms, and $\Sigma t_s = t_c$; 2—dislocation mean free path versus the pulse length with $t_p = t_s$ under the same experimental conditions.

These effects can be explained in terms of the processes that occur as a dislocation overcomes a Peierls barrier. If the length of the stress pulse is shorter than the time required for the formation of a double kink of critical size ($t_s < \tau_f$), double kinks with $\lambda \geqslant \lambda_c$ do not form at any time during the loading, and we find $l = 0$ (the initial part of curve 2 in Fig. 3). If $\tau_f < t_s < \tau_t = \tau_f + \tau_m$, then a dislocation does not have time during the pulse to completely reach the neighboring valley of the potential relief, and double kinks remain there. These double kinks contract during the pause under the influence of the attractive forces of the kinks that form the pair. If the length of the pause is longer than the scale time for the backward motion of a kink, then the kinks forming a pair will annihilate before the beginning of the next stress pulse, and the dislocation mean free path over the time t_c will also be 0 (the last part of curve 1 in Fig. 3). Since these processes are of a statistical nature, the critical value of t_p or t_s will correspond not to an abrupt transition from (or to) $\bar{l} = 0$ but to the inflection points on the curves in Fig. 3. From these points we can independently determine the kink formation time and motion time.

The present experiments show that the motion of kinks along a dislocation line is thermally activated. Analysis of the results on the basis of the model of Ref. 1 yields an activation energy ~ 1.5 eV for the motion of a kink. This activation energy was found to depend on the impurity state of the crystal, showing that the existing theory needs to be refined to take into account the particular features of the one-dimensional motion of a kink in the field of random forces.

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