The mechanism of the photoplastic effect

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A mechanism is proposed for the photoplastic effect associated with the recombination of photoexcited electron-hole pairs in deep centers, which are simultaneously dislocation pinning centers.

The photoplastic effect (PPE), which involves a substantial change in the deforming stress due to illumination of samples, was discovered in 1968 in CdS crystals deformed at a constant rate in the region of plastic flow.[1] This effect was later observed in many semiconductors and dielectrics,[2,3] in particular, in all A^2B^6 crystals. Subsequent experiments on different crystals revealed the basic characteristics of the PPE. 1) The peak in the PPE corresponds to the intrinsic absorption edge, i.e., the generation of electron-hole pairs is the starting perturbation of the electronic system. As the light intensity is increased, the PPE at first intensifies and then saturation sets in. 2) Both a positive (hardening) photoplastic effect PPPE[1] and a negative (softening) photoplastic effect NPPE can occur. The NPPE is observed in the case of plastic deformation due to the motion of dislocations in prismatic planes.[4] 3) The PPE decreases with increasing temperature. The dislocations in prismatic planes in this case may reveal the following peculiarity of the effect: As the temperature is increased, the NPPE becomes the PPPE,[5] i.e., softening is replaced by hardening. Only the PPE occurs in a system of basal dislocations; only temperature-induced extinction of the effect is observed here.

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In this letter we examine the mechanism of the PPE associated with the recombination of photoexcited excess electron-hole pairs at centers that are simultaneously dislocation pinning centers. The defective sites, which are local obstacles to the motion of dislocations, are rigidly coupled to the crystalline matrix, so that it is natural to expect that some of these stoppers can generate deep electronic states in the forbidden band of the semiconductor and can serve as recombination centers. Nonradiative transitions are accompanied by multiple generation of phonons at these centers. As a result of the local heating, which is determined by the electronic-vibrational spectrum of the center and which is manifested as Stokes losses Δ, the stopper is entrained into time-varying motion, which can be represented as a superposition of all possible phonon modes with a starting distribution of amplitudes and a total energy of Δ. The temporal development of such a lattice excitation, which is initially concentrated at the recombination center (or in its immediate vicinity), is described by the spreading of the wave packet and is characterized by the autocorrelation function of the defective site $\rho(t) = \langle u(t)u(0)\rangle$. The decay of ρ with time indicates that the center releases the excess energy. We will assume below that a defect-induced local phonon mode can occur. We will also assume that this mode is created by a mass defect with $Q = M/m \gg 1$ (M and m are the masses of the stopper and of an atom in the matrix), i.e., it falls into the continuous spectrum of crystalline phonons (quasilocal mode) and has the frequency[6,7]

$$\omega_k = \frac{\omega_D}{\sqrt{3(Q-1)}} \ll \omega_D \tag{1}$$

(ω_D is the Debye frequency) and that the autocorrelation function satisfies the condition

$$\rho_k(t) = \langle u_k(t)u_k(0)\rangle \propto (\omega_k t)\exp(-\gamma t), \tag{2}$$

where $\gamma^{-1} \sim \omega_D/\omega_k^2$ is the lifetime of the quasilocal mode. As shown in Ref. 7, a significant part of the Stokes losses goes into excitation of local modes (up to one-half of the losses in the case of the mass defect and the entire amount in the case of a defect of the force constants). The quasilocal oscillation has a very long lifetime ($\gamma \ll \omega_D$), so that for a long period of time the stopper oscillates at a comparatively low frequency ω_k and large amplitude $u_k(0) \sim (\Delta/M\omega_k^2)^{1/2} \sim (3\Delta/m\omega_D^2)^{1/2}$ (part of the liberated heat associated with the crystalline modes escapes into the volume over a time of $\sim \omega_D^{-1}$). The harmonic motion of the pinning center can substantially change the probability of fluctuation-induced surmounting of the local barrier by the dislocation. This question is investigated in Ref. 8 for a dislocation–stopper interaction potential of the form

$$V(x) = -V_0 + \zeta x^2; \qquad x = u - u_k(0)\cos(\omega_k t), \tag{3}$$

where u is the displacement of the end of the dislocation segment associated with the stopper, and $u_k(0)$ and ω_k are the amplitude and frequency of the oscillations of the stopper. Satisfaction of the condition $x \geqslant x_{cr} = (V_0/\zeta)^{1/2}$ is adopted as the criterion for detachment. We shall use the results in Ref. 8 for the case in which the following condition is satisfied:

$$p\frac{\omega_k}{\omega_D} \ll 1; \quad p \sim \frac{u_k(0)}{\sigma}, \qquad \sigma^2 \sim T/\zeta, \tag{4}$$

where σ is the variance of the stochastic dislocation displacements. In this case, the frequency of the fluctuation-induced detachment from the oscillating stopper is

$$\nu_{\omega_k} = \frac{\nu_0}{\pi} \int_0^{\pi} d\theta \exp\left(cp\cos\theta - \frac{p^2}{2}\cos^2\theta\right); \qquad c^2 \equiv \frac{V_0}{T}\left(1 - \frac{\tau}{\tau_c}\right)^2 . \tag{5}$$

The frequency of detachment from a stationary stopper is $\nu_0 \sim \omega_D \exp(-c^2/2)$, τ is the deforming stress, and $\tau_c = 2\zeta x_{cr}/al$ (a is the lattice constant, and l is the length of the segment). The ratio ν_{ω_k}/ν_0 is the qualitative characteristic of the PPE in the mechanism proposed by us. The magnitude of this ratio depends on the parameter c, which is determined by the characteristics of the stopper, the temperature, and the load, as well as on the value of p, which is proportional to the amplitude of oscillations of the stopper as a result of the stopper-induced recombination. For clarity, we present the limiting expression for ν_{ω_k}/ν_0, derived from (5) with $p \ll 1$,

$$\frac{\nu_{\omega_k}}{\nu_0} = 1 - \frac{p^2}{2}(1 - c^2) . \tag{6}$$

For $c < 1$ the oscillations of the stopper decrease the detachment frequency, i.e., there is a tendency for hardening to occur, while for $c > 1$ the detachment frequency increases and the NPPE can be realized. As p is increased, when the expansion (6) is no longer applicable, the ratio ν_{ω_k}/ν_0 can become much larger, depending on c, (see Ref. 8). This behavior of ν_{ω_k}/ν_0 makes it possible to qualitatively understand some features of the PPE. In particular, the interaction of basal and prismatic dislocations with stoppers can differ substantially. Thus, the yield stress with basal slipping τ_s^b is less than with prismatic slipping τ_s^p. The depths of the wells V_0 can also be different. If it is assumed that for prismatic dislocations the parameter $c = c^p > 1$ for a certain range of values of τ and T, then the NPPE is realized on them. An increase in temperature decreases the value of c^p and when values $c^p < 1$ are attained, the NPPE must be replaced by the PPPE, in agreement with the experimental observations.[5] If $c^b < 1$ in the same region of τ and T for basal dislocations, then the PPPE, which is realized in this case with increasing temperature because $p \sim T^{-1/2}$, will be quenched without changing sign.

Thus far we have been discussing the relationship between the type of PPE and the parameters that determine the dislocation flow. However, the model studied here can also be used to describe the correlation with the spectral properties of the recombination centers. We note, for example, that the magnitude of the PPE can be predicted from optical data on the Stokes losses. It follows from simple estimates that for high Stokes losses (~ 1 eV) that occur, for example, in A^2B^6 compounds, an appreciable ($\sim 100\%$) change in the flow stress of the crystal with PPE may be expected.

In conclusion, we note that local modes of another type, for example, modes stemming from a defect of the elastic constants, in principle play the same role as the modes examined above.

[1)]The nonlinear temperature dependence of the resistance was also pointed out in Refs. 3 and 4.

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