Combined electron resonance in a one-dimensional dislocation band

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The intensity and width of the combined electron resonance line for dislocations in silicon are investigated as functions of temperature, microwave electric field, and illumination. The resonance intensity grows as $T^{-2.4}$ with decreasing temperature; this indicates that the electron mobility increases, and hence that band conduction rather than hopping along dislocations is the primary conduction mechanism. The energy of the dislocation band is found, and the saturation and width of the line are discussed.

INTRODUCTION

When crystals are deformed plastically, one-dimensional defects in the crystal structure (dislocations) are generated which have many interesting physical properties. The electron properties of the dislocations introduced in silicon by plastic deformation at $T<700$ °C are determined principally by finite groups (chains) of broken bonds whose electrical activity is very high.[1–3] When the specimens are annealed at $T>700$ °C, the broken bonds in the cores of the dislocations disappear, probably due to reconstruction.[4,5] The electrical activity of the dislocations is determined by the defects in their cores and by the curvature of the valence and conduction bands produced by the elastic strain fields around the dislocations. In addition, the regular regions of the cores in certain types of reconstructed dislocations could in principle play a role in the formation of deep one-dimensional energy bands.[3,4,6]

Although silicon has a cubic symmetry, the local structure of the dislocation cores is much less symmetric and lacks an inversion center. In systems without an inversion center, the spin-orbit interaction gives rise to terms in the Hamiltonian of the form $\alpha \mathbf{p}\times\mathbf{S}$, where $\mathbf{p}$ and $\mathbf{S}$ are the electron momentum and spin.[7,8] Under these conditions, the dielectric constant of the specimen should have a sharp peak (called a combined resonance peak in Refs. 7 and 8) at the frequency of the transition between the electron Zeeman sublevels.

In Refs. 9, 10 the dielectric constant in plastically deformed silicon was found to have a resonance peak, which we called the *Ch*-line. Analysis of the experimental results showed that this line was due to combined resonance of electrons trapped at a dislocation. This was strongly suggested, among other things, by the highly anisotropic dependence

$$A_{Ch}\sim[\mathbf{H}_0\times(\vec{\mathscr{E}}\times\mathbf{l}(\mathbf{E}_\omega\cdot\mathbf{l}))]^2 \qquad (1)$$

of the experimentally observed intensity of the *Ch*-line. Here $\mathbf{H}_0$ is the external magnetic field, $\mathbf{E}_\omega$ is the microwave electric field of frequency ω, at which the dielectric $\varepsilon_\mu=\varepsilon'_\mu+i\varepsilon''_\mu$ is measured, and the vectors $\mathbf{l}$ and $\vec{\mathscr{E}}$ lie along the dislocation line and along the crystal field perpendicular to it.

The relation (1) has a simple physical interpretation. Indeed, in the presence of a spin-orbit interaction (no inversion center), the spin of an electron moving along a dislocation with velocity $\mathbf{v}$ is subject to an effective magnetic field $\mathbf{h}\propto\mathbf{v}\times\vec{\mathscr{E}}/c$. If the specimen is placed in an external electric field $\mathbf{E}_\omega$, the velocity of the electron will contain a frequency-dependent component: $v_\omega\sim\mu\mathbf{l}(\mathbf{l}\cdot\mathbf{E}_\omega)$, which at resonance will cause transitions among the electron Zeeman sublevels with a probability proportional to

$$(\mathbf{H}_0\times\mathbf{h})^2\propto[\mathbf{H}_0\times(\vec{\mathscr{E}}\times\mathbf{v}_\omega)]^2.$$

The factor $\mathbf{l}(\mathbf{E}_\omega\cdot\mathbf{l})$ in the formula for $\mathbf{v}_\omega$ indicates that the electron motion is one-dimensional. The *Ch*-line thus corresponds to combined resonance in a one-dimensional system. According to Ref. 10, $\mathbf{l}$ and $\vec{\mathscr{E}}$ lie along the $[1\bar{1}0]$ and [001] directions, respectively, when silicon is plastically deformed along either the [110] or the [123] axes; that is, only dislocations parallel to $[1\bar{1}0]$ contribute to the *Ch*-line.

The present paper is concerned with a detailed investigation of combined resonance at dislocations in silicon.

TEMPERATURE DEPENDENCE

We studied silicon specimens which were doped with phosphorous to $2\cdot10^{14}$ at./cm^3 and deformed plastically by compression by 1.5–2% along the [110] direction at 700 °C, resulting in an induced dislocation density $N_D=(1-2)\cdot10^9$ cm^{-2}. The specimens were then annealed for 30 min at 800 °C to eliminate the broken bonds in the dislocation cores. We used a superheterodyne EPR spectrometer capable of microwave measurements at powers down to $\sim10^{-10}$ W and frequencies $\omega/2\pi\approx9300$ MHz. The specimen was positioned at a maximum of the electric field inside a rectangular resonant cavity; the specimen and cavity were at the same temperature, and the specimen was carefully shielded from light, including infrared radiation from the warmer regions of the cryostat and from the microwave components. The magnetic field was modulated at 80 Hz with an amplitude of 0.1 Oe; this enabled us to record the frequency dependence of $\partial\varepsilon'_\mu/\partial H_0$ and $\partial\varepsilon''_\mu/\partial H_0$. The specimen was aligned so as to maximize the magnitude of the *Ch*-line, i.e., $\mathbf{E}_\omega\|\mathbf{l}$ and $\mathbf{H}_0\|\mathbf{E}_\omega$.

When the specimen was not externally illuminated, the *Ch*-line was observed only in specimens which had been doped with shallow donors. The activation energy for the specific resistance of the specimens analyzed was ~0.3 eV, which indicates that at low temperatures all the electrons from the shallow donors were trapped by deep dislocation levels. The *Ch*-line was thus due to electrons from shallow

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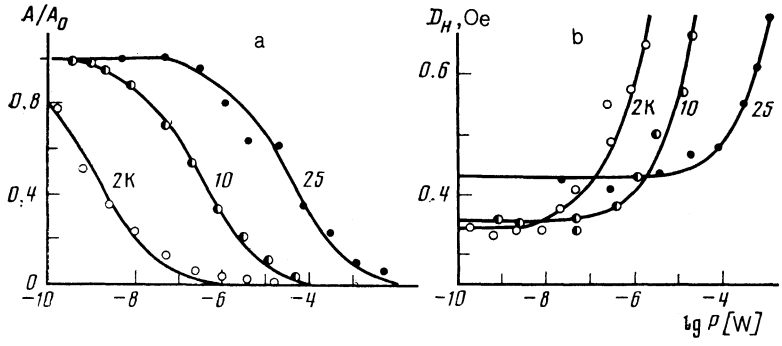

FIG. 1. Saturation curves for the *Ch*-line: a) line amplitude $\partial\varepsilon_\mu''/\partial H_0$, normalized by the calculated value $\partial\varepsilon_\mu''/\partial H_0$ in the absence of saturation; b) calculated halfwidth versus microwave power P.

donors which were trapped by deep dislocation states, which we will denote by E_{Ch}.

Figure 1a, b shows how the amplitude and halfwidth D_H of the *Ch*-line depend on the microwave power P fed to the cavity ($P \propto E_\omega^2$). At $T = 25$ K, the *Ch*-line is seen to saturate at 10^{-5} W, while for $T < 4$ K it is partially saturated even for P down to 10^{-10} W.

Figure 2 shows the temperature dependence of the intensity A of the *Ch* line; A is equal to the amplitude of the signal $\partial\varepsilon_\mu''/\partial H_0$ multiplied by the square of the line halfwidth. The intensity A has been normalized relative to the EPR signal intensity from a paramagnetic reference material, which was positioned at a maximum of the magnetic field in the resonant cavity. The microwave power was low enough to exclude saturation. Figure 3 shows the temperature dependence of the halfwidth D_H of the *Ch*-line measured at a microwave power corresponding to the flat portion of the curves in Fig. 1b.

Although the Kramers-Kronig formula relating $\varepsilon_\mu'(H_0)$ and $\varepsilon_\mu''(H_0)$ holds quite accurately for low microwave powers, the shape of the curves $\varepsilon_\mu'(H_0)$ and $\varepsilon_\mu''(H_0)$ is peculiar and suggests a mixture of the resonance curves for dispersion and absorption.

Figure 2 shows that the intensity of the *Ch*-line, normalized relative to the signal intensity from the EPR reference, decreases as T increases. This finding is of particular interest, since A is expected to be proportional to the number of electrons trapped in the state E_{Ch}, to the field $\vec{\mathscr{E}}$, and to a numerical factor which depends on μ and relates the velocity v_ω to the electric field E_ω. Since the temperature dependence of the electron concentrations in the specimens indicates that the states in E_{Ch} lie at a depth of at least 0.2–0.3 eV, the number of electrons N_{Ch} trapped in E_{Ch} should not depend on temperature in the range $T < 40$ K of interest. For the same reason, $\mathscr{E}$ should also be independent of T. The observed dependence $A(T)$ can thus be explained only by postulating a temperature dependence $\mu(T)$. If the length L of the conducting regions of the dislocations is very large, then since $h_\omega = (\mu\mathscr{E}/c)E_\omega$, the intensity of the *Ch*-line should, by analogy with ordinary EPR, be proportional to $N_{Ch}(g\mu_B H_0/2kT)(\mu\mathscr{E}/c)^2$. Recalling that A is normalized by the signal intensity from the paramagnetic EPR reference, we have

$$A \propto N_{Ch}(\mu\mathscr{E}/c)^2.$$

The interpretation of the factor $(\mu\mathscr{E}/c)^2$ is evident; it characterizes the degree of coupling between the spin system and the microwave electric field. In general, μ is complex-valued. If the time τ_i required for the system to relax after a field pulse is very long, we have

$$m^*\dot{v} = eE_0 \exp(i\omega t),$$

which gives $\mu_\infty = e/i\omega m^*$. However, the T-dependence of μ immediately implies $|\mu| \ll |\mu_\infty|$. In this case, μ is real and can be interpreted as the local conductivity of an electron within conducting regions of finite extent in the dislocations.

The situation is more complicated if the length L of the conducting regions of the dislocations is not large. In this case, the specimen can be modeled as a matrix with dielectric constant ε_B, within which conducting dislocation segments are distributed. The quantity ε_B is real, because silicon crystals doped to $2 \cdot 10^{14}$ cm^{-3} have negligible conductivity for

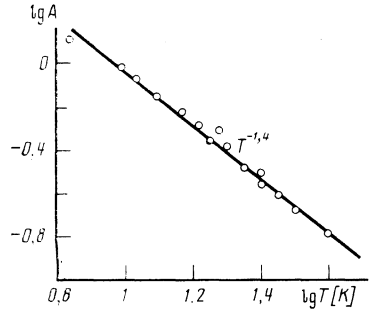

FIG. 2. Temperature dependence of the intensity of the *Ch*-line, normalized by the amplitude of the EPR signal from a paramagnetic reference ($CuSO_4 \cdot 5H_2O$).

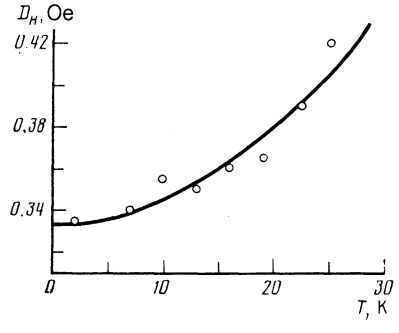

FIG. 3. Halfwidth of the *Ch*-line as a function of temperature.

$T < 30$ K. The conducting regions of the dislocations can be approximated as highly elongated ellipsoids of length L, whose radius r_0 is comparable to the transverse radius of the wave function of the trapped electrons ($L \gg r_0$). After some straightforward algebra, the expressions

$$\varepsilon_\mu' = \varepsilon_B\left[1 + N\pi r_0^2 L \frac{\mathscr{D}y^2 + x + \mathscr{D}x^2}{\varkappa}\right]$$
$$\varepsilon_\mu'' = N\pi r_0^2 L \varepsilon_B y/\varkappa, \qquad (2)$$

for the dielectric constant for such a inhomogeneous specimen can be derived from an expression given in Ref. 11; here $y = \varepsilon''/\varepsilon_B$, $x = \varepsilon'/\varepsilon_B - 1$, and $\varkappa = 1 + 2\mathscr{D}x + \mathscr{D}^2x^2 + \mathscr{D}^2y^2$; N is the number of conducting dislocation segments, whose dielectric constant is $\varepsilon = \varepsilon' + i\varepsilon''$, and

$$\mathscr{D} = \frac{4r_0^2}{L^2}\left[\ln\left(\frac{L}{r_0}\right) - 1\right]$$

is the depolarization factor. For $\omega\tau_i \ll 1$, i.e., $|\mu| \ll |\mu_\infty|$, we have to first order

$$\varepsilon = \varepsilon' + i\varepsilon'' = \varepsilon_B - \frac{N_{Ch}}{N\pi r_0^2 L}\left(Z\chi - i\frac{4\pi e\mu}{\omega}\right), \qquad (3)$$

where $Z = (\mu\mathscr{E}/c)^2$, N_{Ch} is the number of electrons trapped by the N conducting segments, and μ is their mobility far from resonance. For the susceptibility $\chi = \xi' + i\chi''$ we have in the Bloch approximation

$$\chi'' = \frac{g^2\mu_B^2 H_0}{2kT}\frac{\gamma\tau_2}{1 + 4\pi^2\tau_2^2\gamma^2(H_0 - H_r)^2 + S},$$
$$\chi' = \frac{g^2\mu_B^2 H_0}{2kT}\frac{\gamma^2\tau_2^2(H_0 - H_r)}{1 + 4\pi^2\tau_2^2\gamma^2(H_0 - H_r)^2 + S} \qquad (4)$$

where H_r is the resonance field, $(\gamma\tau_2)^{-1}$ is the natural linewidth, and

$$S = {}^1/_4\gamma^2\tau_1\tau_2 Z E_\omega^2 \qquad (5)$$

is the saturation factor (τ_1 is the spin-lattice relaxation time). These formulas are clearly valid only for a weak spin-orbit interaction, as is the case for silicon, and we will use them only for qualitative estimates.

According to (2), unless L is very large both ε' and ε'' contributed to ε_μ' and ε_μ'', as was found experimentally. Comparing the amplitudes of the *Ch*-lines for a specimen located at a maximum of the microwave electric field E_ω and at a maximum of the microwave magnetic field (at which $E_\omega \approx 0$), we find that

$$\left(\frac{\partial\varepsilon_\mu''}{\partial H_0}\right)\Big/\left(\frac{\partial\chi''}{\partial H_0}\right) \approx \left(\frac{\mu\mathscr{E}}{c}\right)^2 > 2000,$$

i.e., $\mu\mathscr{E} \geqslant 10^{12}$ cm/s. Since the mobility satisfies $\mu \ll |\mu_\infty|$, taking $\mu < (10^3$–$10^4)$ cm$^2\cdot$V$^{-1}\cdot$s^{-1} we have $\mathscr{E} \geqslant 10^9$ V/cm. Such large values $\mathscr{E}$ indicate that the electron wave function is tightly localized near the core of the dislocation, i.e., in the plane perpendicular to I; this is consistent with the substantial depth of the state E_{Ch}. If we take $r_0 = 3$ Å, $N_{Ch} = 2\cdot10^{14}$ cm^{-3}, and $N_{Ch}/N = \text{int}(N_{Ch}/N_\perp)$, with $N_\perp L = N_D$, where the dislocation density is given by $N_D \approx 10^9$ cm^{-2}, then only the parameters μ, $\mathscr{E}$, and L remain undetermined. Figure 4 plots the amplitude $\partial\varepsilon_\mu''/\partial H_0$ of the *Ch*-line as a function of μ.

We see that the intensity of the *Ch*-line always increases with μ; this is important, since it implies that the experimental dependence $A(T)$ corresponds to a drop in μ as T increases, and in fact we have $\mu \propto T^{-(0.6-1)}$ in the interval 10–40 K. We recall that μ is the local mobility over a finite segment of dislocation bounded by defects whose potential barriers are high enough to confine the electrons at low temperatures. The increase in μ with cooling indicates strongly that band conduction rather than hopping along dislocations is the dominant conduction mechanism. This is the first direct evidence that the regular regions of dislocations can give rise to a one-dimensional band.

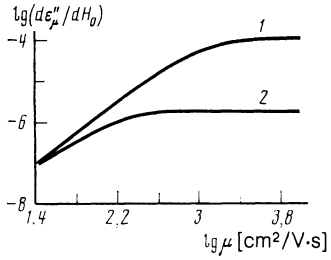

FIG. 4. Calculated *Ch*-line intensity $\partial\varepsilon_\mu''/\partial H_0$ as a function of μ for $L = 1000$ Å (1) and 500 Å (2).

Turning now to an analysis of the saturation of the *Ch*-line (Fig. 1a, b), we observe that the experimental curves are adequately approximated by

$$A(P) \approx A_0(1+S)^\beta,$$
$$D_H(P) \approx \Delta H_H + \Delta H_0(1+S)^{1/2}, \qquad (6)$$

where $-\beta = 0.3$–0.5 and $\Delta H_H/\Delta H_0 = 5$–$15$. Equations (4) and (5) imply that for an ordinary Lorentzian line, we have $D_H(P) = \Delta H_0(1+S)^{1/2}$ and $-\beta = 1$–1.5. It follows that the *Ch*-line is nonuniformly broadened, the inhomogeneous width ΔH_H being $\sim$5–15 times greater than the homogeneous width ΔH_0. We are unable to derive an analytic expression for $A(P)$ for $\Delta H_H/\Delta H_0$ in this range. Nevertheless, the temperature dependence $(\mu\mathscr{E}/c)^2\tau_1\tau_2(T)$ can be estimated roughly; the results imply that $(\mu\mathscr{E}/c)^2\tau_1\tau_2$ is proportional to $T^{-(6-4)}$. Taking into account the dependence $\mu(T)$, we get $\tau_1\tau_2 \propto T^{-(3-4.5)}$ for 7 K $< T <$ 35 K. The experimental results for $D_H(T)$ in Fig. 3 are closely approximated by $D_H(\text{Oe}) = 0.33 + 1.2\cdot10^{-4}T^2$ (solid curve in Fig. 3). Assuming ΔH_H independent of T and recalling the considerable error in measuring $D_H(T)$, we have $\tau_2 \propto T^{-(1-2)}$, whence $\tau_1 \propto T^{-(1.5-3.5)}$. Unfortunately, this result for τ_1(T) is too crude to permit a detailed analysis. However, the experimental dependence $\tau_1(T)$ is much weaker than might be predicted for conventional two-phonon relaxation processes involving ordinary three-dimensional phonons, and the relaxation process is thus not completely trivial. We can think of two possible reasons for this. First, quasilocal dislocation oscillation modes might contribute substantially; second, spin-lattice relaxation may proceed by an exotic mechanism made possible by strong coupling between the electron spin and kinetic degrees of freedom.

To account for the exceptionally small homogeneous width of the *Ch*-line, we note that in addition to the familiar sources of broadening (dipole-dipole and hyperfine interactions), the thermal motion of the electrons can also cause broadening in our system. Owing to the spin-orbit interaction, the average thermal velocity $v_T = (kT/m^*)^{1/2} \approx 4\cdot10^5 T^{1/2}$ cm/s should give rise to a field

$\mathbf{h}_T = \mathbf{v}_T \times \vec{\mathscr{E}}/c$ acting on the spins. For $(\mathscr{E}/c)^2 = 2\cdot 10^{-3}$ $v^2\cdot s^2\cdot cm^{-4}$ and $T = 10$ K, we have $h_T \approx 150$ Oe. This random field should broaden the line by an amount $\Delta H_0 \approx h_T(\cos\eta + h_T/H_0) = h_{\text{eff}}$, where η is the angle between H_0 and h_T. Even if $\eta = \pi/2$ (as in our case), $\Delta H_0 \approx 7.5$ Oe greatly exceeds the experimental width. The narrowness of the line is evidently due to the smallness of the pulse autocorrelation time $\tau_i = m^*\mu/e$. In a coordinate system rotating at the resonance frequency, transverse relaxation is essentially a diffusion process in which the spin direction diffuses with a characteristic scale much less than 1. During a time t, the direction of the spin vector diffuses by an angle $\sim \gamma h_{\text{eff}} \tau_i (t/\tau_i)^{1/2}$. The thermal motion thus gives a broadening of order

$$\Delta H_0 \approx (\gamma Z k T/e\mu)\,[\cos\eta + (kTZ)^{1/2}/H_0\mu m^{*1/2}]^2.$$

For $T = 10$ K and $\mu = 1000$ $cm^2\cdot V^{-1}\cdot s^{-1}$, we obtain $\Delta H_0 \approx 7\cdot 10^{-4}$ Oe if $\eta = \pi/2$.

Because of the large length L of the conducting dislocation segments, the thermal motion of the electrons effectively smooths out the dipole-dipole and hyperfine interactions, and this is responsible for the narrowness of the *Ch*-line.

EFFECT OF ILLUMINATION ON THE PARAMETERS OF THE *Ch*-LINE

We determined the energy position of the E_{Ch} band by analyzing how illumination at optical wavelengths affected the intensity of the *Ch*-line. The resonator cavity was equipped with an optical window, through which the specimen was irradiated by light from a halogen lamp passing through an SPM monochromator. We studied both *P*-type and *n*-type silicon crystals doped with boron and phosphorous to 10^{13} at./cm^3 and $2\cdot 10^{14}$ at./cm^3, respectively. The specimens were prepared as described above. Figure 5 shows the spectral dependence of the amplitude $\partial\varepsilon''_\mu/\partial H_0$ of the *Ch*-line for an annealed *p*-type specimen. Curves 2 and 1 were recorded with and without illumination by low-intensity white light. Figure 6 shows the results of similar measurements for an annealed *n*-type specimen. All the spectra were recorded at 10 K.

Two difficulties in interpreting the spectra may be noted. First, the steady-state response is highly nonlinear and saturates with increasing light intensity. Second, in addition to admitting light from the monochromator onto the specimen, the window in the resonator wall also transmits infrared radiation which induces additional optical transitions. Thus even if the monochromator slit is kept closed, the *Ch*-line in *n*-type specimens is broadened by 50% and the amplitude A drops when the resonator window is opened.

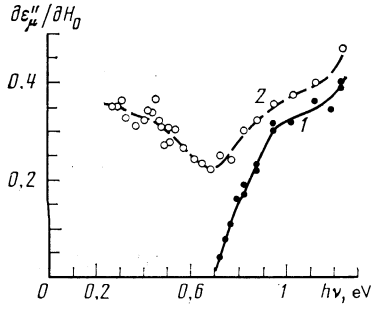

FIG. 5. Spectral dependence of the intensity of the *Ch*-line for a *p*-type specimen (1); curve 2 was recorded using additional illumination by white light.

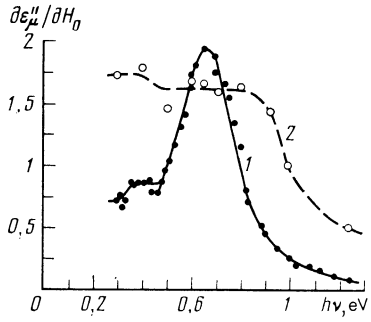

FIG. 6. Spectral dependence of the intensity of the *Ch*-line for an *n*-type specimen (a); curve 2 was obtained using additional illumination by white light.

We were able to get more accurate measurements for energies $h\nu > 0.9$ eV. Figure 7 shows the spectral dependence of dA/dt found by measuring the initial slope of the curves $A(t)$ when light of a given wavelength was first turned on. The curve, which has been normalized by the number of incident photons, characterizes the spectral dependence of the probability for the optical transitions responsible for attenuating the *Ch*-line in this energy interval.

To explain these results, we propose the energy diagram shown in Fig. 8. The hatched regions correspond to localized states, which do not contribute to ε_μ. The distortions of the conduction (E_c) and valence bands (E_v) shown in Fig. 8 represent the band bending caused by the elastic fields of the dislocations. Their existence is demonstrated by measurements of the optical absorption spectra,[12,13] as well as by measurements of the microwave conductivity in plastically deformed hydrogenated silicon crystals.[3] According to Ref. 3, $E_{De} = E_c - 0.086$ eV and $E_{Dh} = E_v + 0.07$ eV. States in the bands E_3, E_6, and E_5 have been observed in DLTS spectra for plastically deformed silicon specimens,[1] and the states E_6, E_3 are in all probability produced by dislocation defects (they are not numerous enough to be due to regular segments of dislocation cores). This can also be seen from the absence of an appreciable microwave conductivity for the annealed *p*-type specimens.[3] We note that for lightly doped specimens, Hall-effect measurements indicate that the Fermi level E_{FO} lies near $E_v + 0.3$ eV. This means that

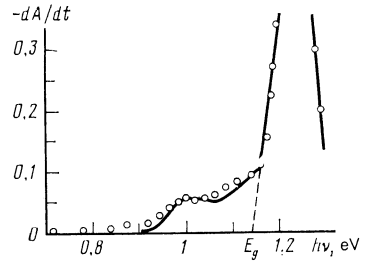

FIG. 7. Spectral dependence of the rate of change of the intensity of the *Ch*-line at the onset of illumination (*n*-type specimen).

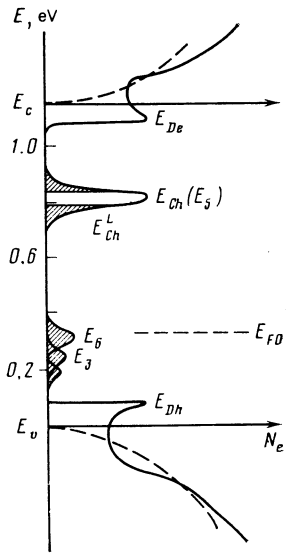

FIG. 8. Energy diagram (see text).

for electrically neutral dislocations, levels below this energy are completely filled while those above it are empty. In specimens annealed after plastic deformation, the DLTS data indicate that the only states capable of forming a dislocation band are of the type E_5. We will now demonstrate that the one-dimensional band responsible for combined resonance corresponds to the E_5 peak in the DLTS spectrum.

Indeed in p-type specimens the band $E_{Ch} \equiv E_5$ is empty and the dislocations are positively charged due to hole trapping in the states E_6, E_3. There is no *Ch*-line unless the system is illuminated; the line first appears at $h\nu \gtrsim 0.7$ eV with the onset of the transition $E_{Dh} \rightarrow E_{Ch}$ (Figs. 5, 8). Trapping of holes in the valence band by the localized states E_3 and E_6 is responsible for the persistence of the *Ch*-line after the light is discontinued. If a weak beam of white light is present (Fig. 5, curve 2), some electrons will already be present in the E_{Ch} band. The attenuation of the *Ch*-line for $0.35 < h\nu < 0.6$ eV is due in part to excitation of electrons from E_{Ch} to E_c, which makes recombination with holes trapped at E_3, E_6 more likely and in part to excitation of holes from E_3 and E_6 into E_v followed by recombination with electrons in E_{Ch}.

We now consider the data in Fig. 6 obtained for n-type specimens. In this case, the dislocations are negatively charged and the E_{Ch} band is appreciably populated even when there is no illumination. The increase in the *Ch*-line amplitude in curve 1 for the interval $0.4 \text{ eV} < h\nu < 0.6$ eV may be explained by assuming that only some of the electrons in E_{Ch} contribute to the *Ch*-line, those trapped by sufficiently long defect-free segments. Some of the states in the E_{Ch} band are strongly localized by various defects present on the dislocations and do not contribute to combined resonance. As we noted above, extraneous illumination can either broaden or narrow the *Ch*-line. We attribute this to trapping of excess holes and electrons in states E_3, E_6, E_{De}, and E_{Dh}, so that intense nonuniform fields are generated at the dislocations. These fields cause substantial inhomogeneous broadening of the *Ch*-line, yet at the same time they also confine the electrons more closely to the E_{Ch} band, thereby tending to decrease the intensity of the *Ch*-line. In this case, activation of electrons from the lower localized states in E_c may cause these electrons to be trapped by portions of the dislocations whose defect concentration is lower; the result is an increase in the amplitude of the *Ch*-line. Although activation of holes from states in E_3, E_6 into the E_v band does reduce the number of electrons in E_{Ch}, the decrease may be more than offset by the looser confinement of the electrons remaining in the E_{Ch} band (the *Ch*-line amplitude also increases with decreasing localization).

The transitions that weaken the *Ch*-line in p-type specimens thus enhance it in n-type crystals. We note that the peak in curve 1 (Fig. 6) exhibits a perceptible narrowing, while the cavity quality $Q \propto (\varepsilon''_\mu)^{-1}$ drops for $h\nu > 0.4$ eV. This is consistent with the above discussion.

The attenuation of the *Ch*-line in Fig. 7 for $h\nu > 0.9$ eV in the n-type specimens may be ascribed to transitions $E_v \rightarrow E_c$ in the immediate vicinity of the dislocation cores, where elastic strain makes the forbidden gap narrower. The small peak near 1 eV may be attributed to quantum splitting of the states E_{De} and E_{Dh} from the continuous spectrum. The solid curve in Fig. 7 shows results found using the semiempirical formulas proposed in Refs. 12, 13 for calculating the light absorption coefficient due to interband transitions in elastic strain fields near dislocations. The *Ch*-line amplitude for n-type specimens drops because the freshly generated holes are trapped in the E_{Ch} band, whereas the electron capture probability for a negatively charged dislocation is much smaller. The reverse situation holds for p-type specimens, accounting for the observed enhancement of the *Ch*-line in this spectral range.

Figure 9 shows temperature curves for the intensity (a) and halfwidth (b) of the *Ch*-line before and after the specimen was briefly exposed to "white" light (the field maximum occurred at $\approx 1\ \mu$m, and the cavity was shielded from the light). The attenuation and broadening of the line after the illumination stopped are due to the formation of levels with excess populations. For $T < 10$ K, this excess persists in the dark for at least a few hours. Upon heating the system

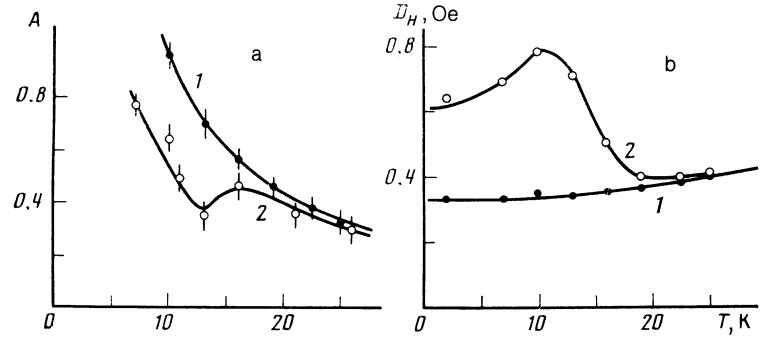

FIG. 9. Temperature curves for the *Ch*-line intensity, normalized by the signal amplitude from a paramagnetic reference (a), and halfwidth (b). Curve 1 was recorded without illumination, curve 2 after brief exposure to "white" light at 4.2 K.

relaxes to equilibrium, as may be seen from Fig. 9. The activation energies for the relaxation process range from 10 to 30 meV and are small compared to the depth of the localized states of interest. This implies that the states are localized at dislocations, i.e., within a radius of at most 10–30 Å from the dislocation lines, and activation into bands in the bulk of the semiconductor is not required for the carriers to become redistributed.

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