Change in recombination mechanism in narrow-gap semiconductors during uniaxial compression

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During uniaxial compression of a narrow-gap semiconductor, the rate of Auger recombination decreases, while the rate of radiative recombination increases, because of a restructuring of the band spectrum. It is thus possible to raise the limiting lifetime and also to identify the recombination mechanism.

The narrow band gap ε_g and the large ratio of the effective masses of the holes and electrons in narrow-gap semiconductors (InSb, $Cd_xHg_{1-x}Te$ at $x > 0.16$) cause a competition among several recombination mechanisms. The contribution of each of these mechanisms—radiative, interband impact (Auger recombination), and extrinsic (Shockley–Read recombination)—depends on the temperature T, the gap ε_g, and the

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concentration of recombination centers.[1,2] The intrinsic recombination mechanisms (radiative and Auger), which set a theoretical upper limit on the carrier lifetime, are of fundamental theoretical upper limit on the carrier lifetime, are of fundamental importance. However, the competition between these mechanisms in the low-temperature region ($T < 100$ K) remains an open question for narrow-gap semiconductors.[2] In the present letter we show that a transformation of the energy spectrum during uniaxial compression may cause a different recombination mechanism to become predominant, so that, from another standpoint, deformation may provide a method for identifying the recombination mechanism.

We wish to stress that substantial changes in the recombination rate occur even at a slight deformation (at which ε_g increases negligibly), since the splitting of the valence band, ε_0, become comparable to the average hole energy $3T/2$. During compression, the states of heavy and light holes mix[3] (in this case it is convenient to speak in terms of $V_{\pm}$ states), and their effective masses change significantly (Fig. 1), becoming $m/(\gamma_1 \pm 2\gamma)$ for the longitudinal direction and $m/(\gamma_1 \mp \gamma)$ for the transverse direction (m is the mass of a free electron, and γ_1, $\gamma \approx \gamma_{2,3}$ are the Luttinger parameters in the isotropic approximation). Since the effective masses of the V_+ band decrease significantly in comparison with the mass of the heavy holes of the undeformed material [which is $m/(\gamma_1 - 2\gamma)$], a large fraction of the holes undergoes localization in the region of small momenta with increasing ε_0, so that direct radiative transitions

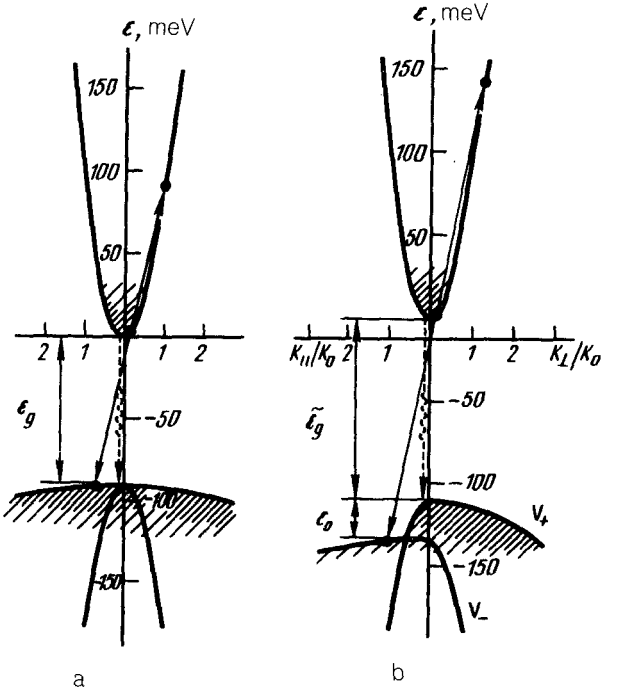

FIG. 1. Energy spectrum of $Cd_xHg_{1-x}Te$ ($x = 0.20$). a: $P = 0$. b: $P = 2$ kbar, $\mathbf{P} \| [001]$. The arrows show recombination transitions. Dashed lines—Radiative; solid lines—radiationless. The characteristic wave vector is $k_0 \approx 4 \times 10^6$ cm^{-1}.

will occur more rapidly out of the conduction band. In other words, the radiative-recombination time decreases with increasing compression. In the absence of deformation, the Auger process involving a transition of an electron to a heavy-hole state is essentially unaffected by a threshold.[4] During compression, the Coulomb matrix element makes a finite contribution, but the thresholds for Auger processes increase rapidly for all mechanisms because of the decrease in effective mass, except in the case of the transition of an electron to a state of the V_- band, with a momentum parallel to the deformation direction (as before, this branch of the energy spectrum is characterized by the mass of a heavy hole). Since the density of V_- holes decreases with increasing compression, the frequency of the dominant Auger process will decrease (in contrast with the behavior of the radiative recombination).

These changes in the recombination processes are found in calculations of the rates of radiative recombination ($1/\tau_R$) and of Auger recombination ($1/\tau_A$) on the basis of the Kane model, with allowance for uniaxial deformation along the [001] axis. The dispersion relations and the wave functions are written on the basis of Ref. 3, and the overlap integrals and optical matrix elements are written as in Refs. 4 and 5. Because of the anisotropy of these quantities, the integrals which result simplify only near the thresholds for these processes, at which we find simple estimates of the deformation dependence at small and large values of ε_0/T. For the time scale of the radiative recombination in an n-type material we have

$$\frac{1}{\tau_R} = \frac{e^2}{\hbar c}\sqrt{\kappa}\left(\frac{\mathcal{P}}{c}\right)^2 \frac{\tilde{\varepsilon}_g}{\hbar} \frac{n}{N(\epsilon_0/T)}, \tag{1}$$

where κ is the dielectric constant, $\mathcal{P}$ is the Kane interband matrix element, n is the electron density, $\tilde{\varepsilon}_g$ is the width of the band gap during the deformation, and the characteristic density $N(\varepsilon_0/T)$ describes the increase in the number of holes in the V_+ band. The function $N(\varepsilon_0/T)$ (and thus τ_R) varies monotonically with the deformation; the ratio $N(0)/N(\infty)$ is approximately 2. The time scale of Auger recombination is

$$\frac{1}{\tau_A} = \frac{R}{\hbar}\left[\frac{n^2}{M_+(\epsilon_0/T)}\exp(-E_t^{(+)}/T) + \frac{n^2}{M_-(\epsilon_0/T)}\exp(-E_t^{(-)}/T)\right], \tag{2}$$

$$E_t^{(+)} = \left(\frac{\gamma_1}{2\gamma} - \frac{1}{2}\right)\tilde{\varepsilon}_g, \qquad E_t^{(-)} = \left(\frac{\gamma_1}{2\gamma} - 1\right)(\tilde{\varepsilon}_g + \epsilon_0),$$

where R is the effective rydberg, $M_\pm(\varepsilon_0/T)$ are factors with the dimensionality of a square density [which are proportional to $(\varepsilon_g m/\gamma\hbar^2)^3$ and which depend only weakly on the other parameters], and $E_t^{(\pm)}$ specify the thresholds (i.e., the minimum values of the sum of the kinetic energies of the electrons and hole involved in the process) as functions of the width of the band gap, $\tilde{\varepsilon}_g$, which is increasing as a result of the hydrostatic component of the deformation [Fig. 1(b)]. Since we have $(\gamma_1/2\gamma - 1) \ll 1$, the process involving an Auger transition of an electron into the V_+ band is suppressed by the high threshold, while the process involving a transition to the V_- band has a low threshold, as in the undeformed material. The basic deformation de-

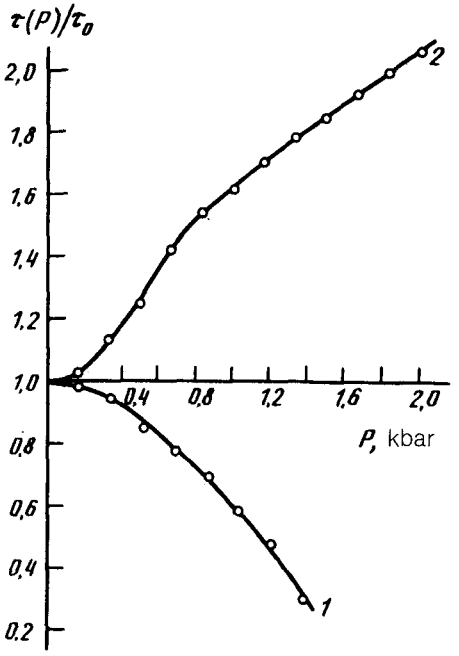

FIG. 2. Deformation dependence of the lifetime of the current carriers in $Cd_xHg_{1-x}Te$, $\mathbf{P}\|[001]$, $\tau_0 = \tau(0)$. 1—$x = 0.29$, $T = 170$ K; 2—$x = 0.20$, $T = 120$ K. The parameter values of the samples at 77 K were as follows: 1—$n = 1.5\times10^{14}$ cm^{-3}, $\mu_n = 2.9\times10^4$ cm^2/(V·s); 2—$n = 5.1\times10^{14}$ cm^{-3}, $\mu_n = 1.6\times10^5$ cm^2/(V·s).

pendence in (2), $M_-(\varepsilon_0/T) \sim \exp(\varepsilon_0/T)$, arises because of the decrease in the hole density in the V_- band, so the time scale of the Auger recombination increases significantly at $\tilde{\varepsilon} \sim T$.

The deformation dependence of the lifetime, $\tau(P)$, was found experimentally from measurements of the steady-state photoconductivity over the temperature range $T = 77$–250 K and over the deformation range $P = 0$–2.0 kbar for n-type $Cd_xHg_{1-x}Te$ samples with compositions $x \sim 0.30$ ($\varepsilon_g \sim 0.25$ eV) and $x \leqslant 0.20$ ($\varepsilon_g \leqslant 0.10$ eV). The particular composition was dictated by the circumstance that the lifetime of the current carriers for the composition $x \sim 0.30$ in the temperature region of intrinsic conductivity is determined by radiative recombination, while at $x \lesssim 0.20$ it is determined by Auger recombination.[2] This conclusion is supported by the corresponding exponential dependence $\tau(T)$ and by a comparison of the theoretical and experimental values of τ. Consequently, at temperatures $T > 160$ K for $x \lesssim 0.30$ and $T > 110$ K for $x \lesssim 0.20$ it is possible to essentially eliminate extrinsic recombination from consideration. The experimental procedure is described in Ref. 6.

In the temperature range 160–250 K, we see a decay of τ with increasing deformation for samples with $x \approx 0.27$–0.30, while for $x \leqslant 0.20$ we see a clearly defined increase in τ (Fig. 2).[1)] The observed $\tau(P)$ dependence shown by experimental curves 1 and 2 agrees (within 30–50%) with expressions (1) and (2), respectively; for the maximum value of the ratio ε_0/T realized experimentally, ~ 2.5, the time τ changes by a factor of 2–2.5. An important point is that the very nature of the change in τ with the deformation (an increase or decrease) unambiguously determines the intrinsic recom-

bination mechanism. Expressions (1) and (2) can also be used to estimate the limiting lifetime, $1/\tau = 1/\tau_R + 1/\tau_A$, which can be substantially longer than τ in the undeformed crystal if P and T are chosen correctly.

[1)]For the purest $Cd_xHg_{1-x}Te$ samples ($x \leqslant 0.20$), Auger recombination is also predominant in the region of extrinsic conductivity ($T \sim 70$–80 K). In this case again there is an increase in $\tau(P)$.

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