Carrier lifetime in doped semiconductors with a very slight compensation

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The carrier lifetime τ has been found to be anomalously short in doped silicon ($N^{1/3}a_0 > 4\times 10^{-2}$) with a compensation $K = 10^{-3}$–10^{-5} in the temperature range $T = 4.2$–20 K. The results are explained in terms of a capture of carriers by neutral centers, followed by a transition to an attractive center and recombination there.

The lifetime τ of electrons (or holes) excited from neutral centers is usually determined by a cascade capture by attractive centers[1]: $\tau = \tau^+ = (1/\alpha^+ N^+)$, where α^+ and N^+ are the capture coefficient and the concentration of attractive centers. Here α^+ and τ^+ are independent of the concentration of neutral centers (N).

Our measurements showed that τ is substantially shorter than τ^+ in doped silicon with a low value of K over a broad range of the temperature T (with $N^+ = KN$). The ratio τ^+/τ reaches 10^4. The results show that τ not only depends on N but may be determined entirely by it. This effect is evidence that a different recombination mechanism is playing a dominant role. We believe that this mechanism is captured by a neutral center followed by a transition of the carrier to an attractive center (indirect capture by an attractive center). This mechanism becomes the governing mechanism in materials with small values of K with a sufficient doping level, in which the overlap of D^- (A^+) states sets the stage for either a hopping among neutral centers[2] or a drift motion of the carriers to the attractive centers through the D^- band[3] (samples of the first and second groups, respectively). The experimental results which we are reporting here refer to Si:B ($N = 10^{13}$–10^{17} cm^{-3}); the results for Si:P and Si:Ga are similar. We are discussing n-type semiconductors here. The measurements are carried out over the temperature range $T = 4.2$–20 K at various carrier excitation intensities $W_{ph}N$ over the wavelength interval $\lambda = 8$–12 μm. The value of W_{ph} is varied over the range $\simeq 10^{-2}$–10^2 s^{-1}; the electron mobility and density (n) are determined from measurements of the photoinduced Hall effect; and τ is calculated as $n/(W_{ph}N)$.

Figure 1a shows the behavior $\tau(N)$ for $W_{ph} \simeq 0.25$ s^{-1} and $T = 10$ K for samples 1–16 (Table I). At $N < 2\times 10^{16}$ cm^{-3} and $K = 10^{-3}$–10^{-4} (samples of the first group) the points are scattered in a random manner: Samples with approximately equal values of N but different values of N^+ have completely different values of τ. It can be seen from Fig. 1b that the ratio τ/τ^+ is independent of N^+ and decreases monotonically with N. At $N < 5\times 10^{15}$ cm^{-3}, we see the usual cascade capture by attractive centers: $\tau/\tau^+ = 1$. At large values of N, τ becomes smaller than τ^+. An important point is that small values of τ/τ^+ cannot be attributed to an increase in N^+

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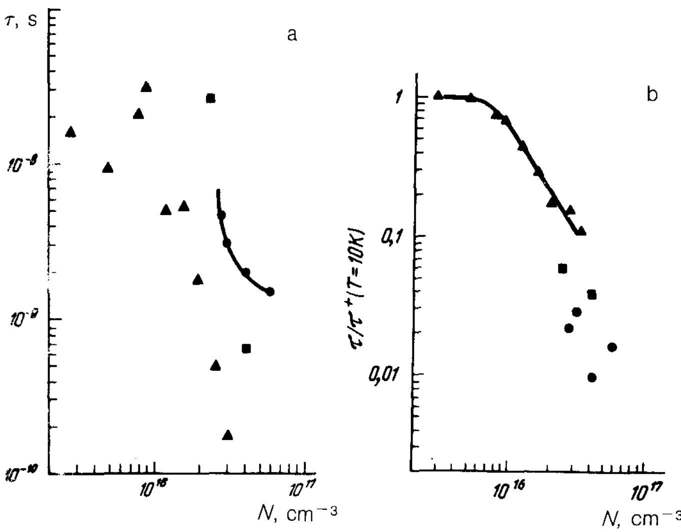

FIG. 1. a: τ as a function of N at $T=10$K and $W_{\mathrm{ph}} \simeq 0.25\ \mathrm{s}^{-1}$. b: τ/τ^{+} as a function of N. ▲—Samples of the first group; ■—intermediate samples; ●—samples of the second group.

in comparison with KN: According to the estimates of Ref. 2, at the value of W_{ph} used here the increase in N^{+} is substantial only at lower temperatures T (e.g., at $T<5.5$ K at $K<10^{-5}$). For the samples of the second group ($K \simeq 10^{-5}$), the values of τ/τ^{+} are even smaller. Here we find the opposite situation: a significant scatter of the points for τ/τ^{+} and a monotonic curve for $\tau(N)$ (Fig. 1a). These results are evidence that τ becomes independent of N^{+} in heavily doped samples and is determined by N alone. These are the samples for which the experiments reveal a conductivity through the D^{-} band.[3]

Figure 2 shows the temperature dependence of $\tau/\tau_{10}^{+} < \tau_{10}^{+}$ corresponds to $T=10$ K) for samples with various values of N. The T dependence strengthens with increasing N, from a power law $\tau \sim T^{-s}$ ($s=1.3$–1.5 at $N<5\times10^{15}\ \mathrm{cm}^{-3}$) to an exponential law $\tau \sim \exp(-\epsilon/kT$ ($\epsilon=2$ meV for sample #11). Let us discuss the experimental results.

TABLE I.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N_A, 10^{16} cm^{-3}	0.03	0.28	0.5	0.8	0.9	1.2	1.6	2	2.4	2.6	2.8	3	3.1	4	4.2	5.8
N_g, 10^{12} cm^{-3}	1.5	1	14	5	3.2	14	8.3	18	0.3	45	0.7	1.5	90	8.8	0.8	1.6
K, 10^{-5}	500	35	280	62	36	120	50	90	1.2	170	2.4	5	290	22	2.5	2.8
Notation	▲	▲	▲	▲	▲	▲	▲	▲	■	▲	●	●	▲	■	●	●

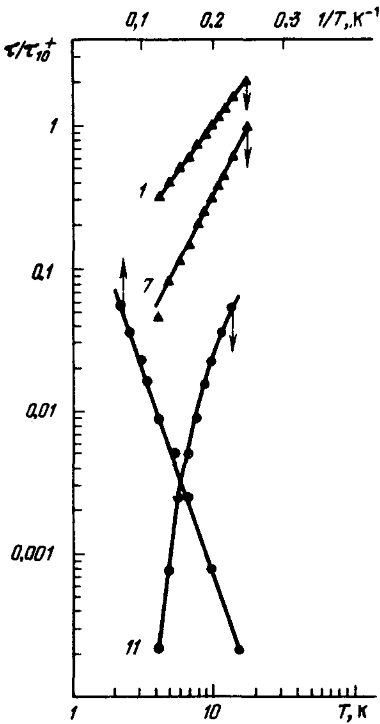

FIG. 2. τ/τ_{10}^+ as a function of T (τ_{10}^+ corresponds to $T = 10$ K) for samples 1, 7, and 11.

We first consider the samples of the first group. Since τ/τ^+ does not depend on N^+, we can write $(\tau^+)^{-1} = \alpha_{\text{eff}}(N)N^+$, where $\alpha_{\text{eff}}(N)$ is the effective coefficient for capture by attractive centers; this coefficient increases with N. The process by which the carriers are captured by the attractive centers, at a rate which depends on the number of neutral centers, can be described as follows: The electrons are initially captured by neutral centers at distances $R \gg R_c$ from the attractive centers, with a capture coefficient[4] $\alpha(R)$. They form D^- centers with a binding energy $\epsilon = \epsilon_j + (e^2/\kappa R)$, where ϵ_i is the binding energy of an isolated D^- center (~ 2 meV for Si:B) with a radius a_i; there $R_c = (3/4\,\pi N)^{1/3}$. If the electrons are not thermally excited into the band [with a probability $W_T = \alpha(R)N_c \exp(-\epsilon/kT)$], they then hop along neutral centers toward attractive centers, losing energy. The rate of this energy loss is $W_l \propto \exp(-R_c/a_i)$, which is equal to the reciprocal of the time over which the energy of an electron decreases by an amount on the order of[2] kT. The last step is a transition of the electron from the D^- center to the attractive center (the annihilation of a $D^- - D^+$ complex) with a probability W_a which depends on the distance between the D^- and D^+ centers.[2] The probability $W_T(R)$ increases with increasing R, while $W_l(R)$ dereases. The condition $W_T(R_{\text{eff}} = W_l(R_{\text{eff}})$ determines the effective capture radius R_{eff}, i.e., the radius of the sphere in which the neutral centers surrounding an attractive center serve as capture centers. The centers with $R > R_{\text{eff}}$ are attachment centers; the electrons at these centers are at equilibrium with the electrons of the

conduction band. For $\alpha_{\text{eff}}(N)$ we can write $\alpha_{\text{eff}}(N) \approx \alpha^+ + \alpha(R_{\text{eff}})(4\pi/3)R_{\text{eff}}^3 N$. Under the condition $\alpha^+ \ll \alpha(R_{\text{eff}}) \times (4\pi/3) R_{\text{eff}}^3 N$, indirect capture is predominant.

Using the experimental values[2] of W_l, and assuming that W_l, like the hopping probability, is proportional to the difference between the energies of the iniital and final states,[2] we can estimate R_{eff} and α_{eff}. The results found on the behavior of α_{eff} as a function of T and N and the values of l are close to the experimental results in order of magnitude.

We turn now to the samples of the second group. The D^- states are basically delocalized. An electron captured by a neutral center far from an attractive center now moves substantially more rapidly toward the attractive center—through the D^- band. The remote neutral centers (most of the centers!) are thereby converted from attachment centers into capture centers, and they begin to determine τ. As a result, τ/τ^+ decreases sharply.

To pursue the discussion, we assume that the D^- band has developed well: Its width far from the attractive center is at least several times kT. Electrons that reach the D^- band cool off, are randomized near the bottom of the band, and then diffuse toward the attractive centers. The distribution function of the cooling electrons does not depend on the concentration N^+; it is determined exclusively by the rate of energy diffusion. If this cooling occurs sufficiently slowly, an equilibrium is established between the electrons of the conduction band and the cooling electrons of the D^- band. In this case, N and therefore τ should be independent of N^+ and should be exponential functions of T. Furthermore, τ should decrease with increasing N because of an increase in the number of states in the D^- band.

Lying between the samples of the first and second groups there are of course samples which represent intermediate cases, in which either the first or second transport mechanism may be governing, depending on the external conditions: T, W_{ph}, and the electric field E.

In summary, we believe that all these experimental results can be explained in a natural way in terms of indirect capture. Indirect capture significantly reduces the photosensitivity of doped materials.

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