Lifetime and mobility of electrons in the silicon D^- band

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(Submitted 10 July 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 4, 170–172 (25 August 1987)

A photoconductivity involving the D^- band has been observed for the first time. The lifetime and mobility of the electrons in the D^- band in doped silicon have been determined.

It was shown in Ref. 1 that the lifetimes of photoexcited electrons in doped Si are determined by indirect recombination involving the capture of electrons by neutral impurity centers, followed by either (a) a hopping of these electrons along impurity centers or (b) a drift of the electrons through the D^- band to attraction centers, and then a recombination. The model presupposes that the captured carriers spend a fairly long time in the D^- band and can contribute to a photoconductivity.

We have observed a photoconductivity involving the D^- band (σ_g) for the first time. We have determined the most important quantitative characteristics: the lifetime τ_g and the mobility μ_g of the electrons of the D^- band. The results were found for doped Si ($N > 3\times 10^{16}$ cm^{-3}) with a very slight compensation ($K < 10^{-4}$) through measurements of the photoconductivity σ, the Hall constant R_H, and the photoconductivity relaxation time $\tau_{\rm rel}$ (Ref. 2). The experiments were carried out at a low intensity of the impurity excitation, $W_{\rm ph}N$ ($W_{\rm ph} \cong 4$ s^{-1}). The results are illustrated here by the results for two Si:B samples which have identical concentrations of the main impurity ($N \cong 5.9\times 10^{16}$ cm^{-3}) but different compensating concentrations N_k: 1) 3.5×10^{13} cm^{-3}; 2) 2×10^{12} cm^{-3}. We will discuss n-type materials here.

Figure 1 is a simplified diagram of the electronic transitions involved in the indirect capture. Electrons photoexcited from impurity centers (transition 1, probability

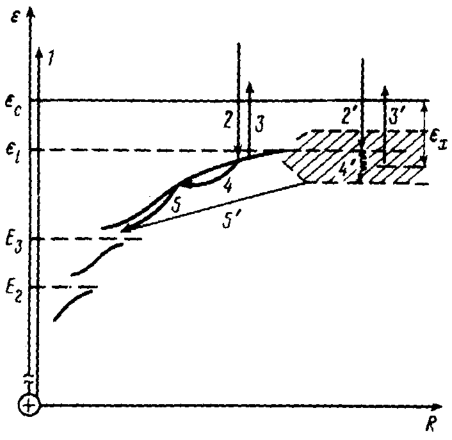

FIG. 1. Diagram of electronic transitions during indirect capture.

$W_{\rm ph}$) are captured by attractive centers (a) near the attractive centers into states with an energy $\epsilon = \epsilon(R_{\rm eff})$ (transition 2, $\alpha_{\rm eff} N_k$; Ref. 1) and (b) far from the attractive centers, into a band of delocalized D^- states (transition $2', \alpha^0 N$). For the captured electrons there are the following possibilities: (A) a thermal scattering into a free band (transitions 3,3': $W_t = \alpha^0 N_c \exp(-\epsilon/kT)$, where (a) either $\epsilon \approxeq \epsilon(R_{\rm eff})$ or (b) $\epsilon \approxeq \epsilon_x, \epsilon_x$ is the energy position of the maximum of the electron distribution in the D^- band; (B) a descent along the energy scale in the band of D^- states (transitions 4,4'; W_d), terminating in a capture by attractive centers (transitions 5,5'). The lifetime in the free band is generally described by

$$\tau_c^{-1} = \alpha^0 N \frac{W_d}{W_t + W_d} + \alpha_{\rm eff} N_k, \qquad (1)$$

where W_d is the reciprocal of the time required for a descent of a distance $\approxeq kT$ along the energy scale, and $\alpha_{\rm eff}$ is the indirect capture coefficient, which is determined by the radius ($R_{\rm eff}$) of that sphere for which we have[1] $W_t(R_{\rm eff}) \approxeq W_d(R_{\rm eff})$. In the selected samples with N close to the threshold for the delocalization of D^- states, an increase in N_k by a factor $\approxeq 20$ significantly reduces the volume of the region spanned by delocalization[3] and thus the relative importance of the terms in (1). At "large" values of N_k we have $\tau_c = 1/\alpha_{\rm eff} N_k$ (Ref. 1) and $\sigma_c \gg \sigma_g \approx 0$; at "small" values of N_k, and with an extended D^- band, we have

$$\tau_c \approxeq (W_d + W_t)/\alpha^0 N W_d \qquad (2)$$

and, presumably, $\sigma_c \approxeq \sigma_g \neq 0$.

Figure 2 shows results on the behavior $\sigma R_H(T) = \mu^*$ for sample No. 1 (curve 1) and sample No. 2 (curve 2). We see that for sample No. 1 we have $\mu^* = \text{const} = \mu_c$ (μ_c is the mobility corresponding to scattering by impurity centers), so that we have[1] $\sigma = \sigma_c \sim 1/\alpha_{\rm eff} N_k \sim T^{2.3}$ (curve 1'). For sample No. 2, μ^* varies with T, implying that there are two conduction mechanisms, with different mobilities and different T depen-

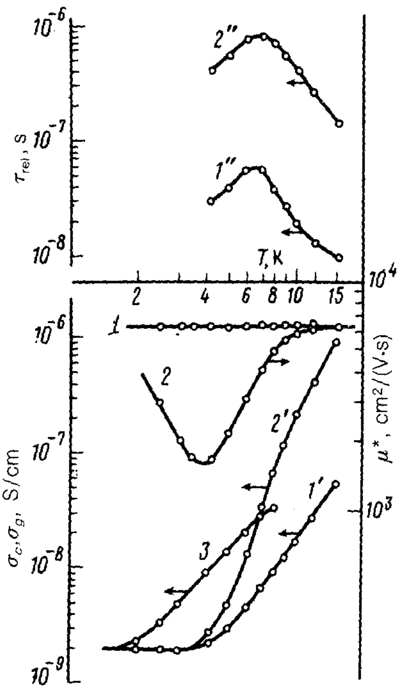

FIG. 2. Temperature dependence of μ^*, σ_c, and τ_{rel} for sample No. 1 (1,1′,1″, respectively) and for sample No. 2 (2,2′,2″): $\sigma_g(T)$ for sample No. 2 (curve 3).

dences. Under the assumption $\mu_g/\mu_c \ll 1$, and in weak magnetic fields H $[(\mu_g H/c)^2 \ll 1]$, we can ignore the contribution of the D^- carriers to the Hall field. According to the two-band conductivity model, we would then have

$$R_H = \frac{\sigma_c \mu_c}{(\sigma_c + \sigma_g)^2 + \sigma_g^2 \mu_c^2 H^2/c^2} \; ; \qquad \sigma = \sigma_c + \sigma_g . \tag{3}$$

Analyzing the data with the help of (3), we find the values of σ_c (curve 2′) and σ_g (curve 3). We have $\sigma_g \sim T^2$, and the dependence $\sigma_c(T)$ at 5 K $< T <$ 10 K is approximately exponential, $\sigma_c \sim \tau_c \sim N_c \exp(-\epsilon_x/kT)$ (curve 2 in Fig. 3), where $\epsilon_x \cong 36$ K; i.e., τ_c corresponds to expression (2) at $W_t \gg W_d$ ($W_d = W_t$ at $T = T_k \cong 5$ K). The behavior of the ratio σ_g/σ_c as a function of T is shown by the dashed line in Fig. 3. At $T = 4.2$ K we have $\sigma_g/\sigma_c \cong 3$. For sample No. 2 at $T = 4.2$ K, the photoconductivity is provided primarily by the D^- band, and the relaxation of the transient photoconductivity should correspond to the relaxation of σ_g.

Let us examine the processes responsible for the relaxation of the photoconductivity in these samples. For the relaxation time of σ_c we find the following approximate results[2)] from the kinetic equations:

$$\tau_{rel}(\sigma_c) \cong \tau_c \left(1 + \frac{\alpha^0 N}{W_t + W_d}\right). \tag{4}$$

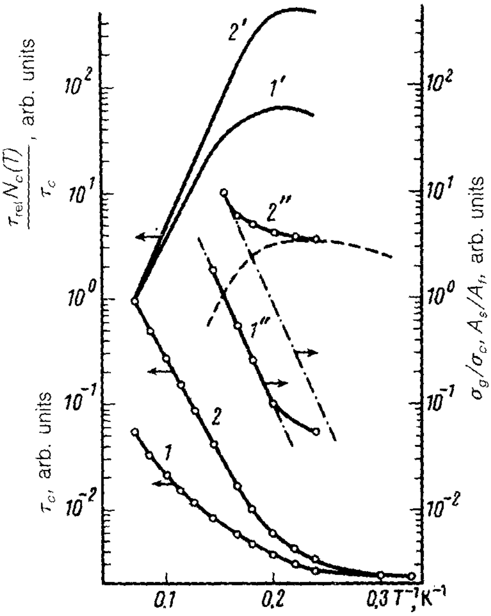

FIG. 3. Temperature dependence of τ_c, $(\tau_{\rm rel}N_e)/\tau_c$, and A_s/A_f for sample No. 1 (1,1′,1″, respectively), and for sample No. 2 (2,2′,2″, respectively). Dashed line—behavior of σ_g/σ_c; dot-dashed line—calculated behavior of $A_s/A_f = W_t/W_d$ for sample No. 2.

At $W_t \gg W_d$ the impurity centers serve as ordinary attachment levels,[4] and the decay of σ_c is described by a single time constant. Here the behavior of $\log(\tau_{\rm rel}N_c/\tau_c)$ as a function of $1/T$ is linear (curves 1′ and 2′ in Fig. 3). From the slope of curve 2′ we can find ϵ_x. The value that we find, $\epsilon_x \approxeq 38$ K, is close to the value for ϵ_x found from the curve of $\tau_c(T)$ for sample No. 2.

Under the condition $W_t < W_d$ we have, for indirect capture $\tau_c = 1/\alpha^0 N$ and $\tau_{\rm rel}(\sigma_c) = W_d^{-1}$; i.e., the relaxation time of σ_c is determined by the cooling time of the electrons in the band of D^- states. Furthermore, two characteristic regions should be observed on the curve of the decay of the photoconductivity pulse: a region with a fast decay (with an amplitude A_f and $\tau = \tau_c$) and a region with a slow decay (with an amplitude A_s and $\tau \approxeq W_d^{-1}$) of σ_c. The amplitude ratio A_s/A_f should fall off exponentially with decreasing T. The reason for this decrease is that the ratio of the rate of generation from D^- centers and the rate of generation from impurity centers decreases with decreasing T: At $W_t < W_d$ the number of carriers in D^- states (n_g) is determined by the value of W_d: $n_g = W_{\rm ph}N/W_d$, so that we have $A_s/A_f \approxeq n_g W_t/W_{\rm ph}N \approxeq W_t/W_d$. This dependence $A_s/A_f(T)$ is exhibited by sample No. 1 (curve 1″ in Fig. 3).

The relaxation of σ_g is determined by the time spent by electrons of the D^- band in a conducting state: τ_g. The times τ_g and W_d^{-1} are not identical, but they are similar in meaning and (apparently) in magnitude. Accordingly, again in sample No. 2, in the region in which σ_g is dominant, we should observe a photoconductivity with a decay constant close to W_d^{-1} (Fig. 2).

In summary, measurements of solely the decay constants of the photoconductivty are not capable of distinguishing σ_g from σ_c. The dependence $A_s/A_f(T)$ is imporant for identifying the photoconductivity mechanism. Figure 3 shows a calculated curve of A_s/A_f for sample No. 2 found by ignoring σ_g (the dot-dashed line). Also shown here are the experimental results on $A_s/A_f(T)$ (curve 2″). The experimental results are radically different from the theoretical predictions; the measured values of the ratios A_s/A_f and σ_g/σ_c are approximately the same at $T = 4.2$ K. We perceive this fact as independent confirmation that a D^--band photoconductivity is exhibited by sample No. 2 at $T < 5$ K. The value measured for $\tau_{\rm rel}$ in this case corresponds to τ_g ($\tau_g \cong 4\times 10^{-7}$ s). Hence, knowing σ_g and N_k and assuming $\tau_g = 1/\alpha_g N_k$, we find values for μ_g and α_g: $\mu_g \cong 1$ cm/(V·s) and $\alpha_g \cong 10^{-6}$ cm^3/s.

We wish to thank E. M. Gershenzon, Yu. A. Gurvich, and A. G. Zhdan for constant interest in this study.

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[2] This question will be examined in detail in a separate paper.

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Translated by Dave Parsons