CAPTURE OF HOLES BY NEUTRAL BORON ATOMS IN SILICON

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Usually the B and Si atoms can capture holes only if they are in the negatively charged state, B^-, and therefore the hole lifetimes τ, in monopole excitation, are determined by the concentration N_B^- and do not depend on the concentration N_B^0 of the neutral boron atoms. However, our investigation has shown that at sufficiently low temperatures the value of N_B^0 may turn out to exert a strong influence on τ.

The hole lifetimes τ were determined from the stationary hole concentration p_0 under conditions of optical generation, in the same manner as in [1]. The measurements were performed in the temperature interval 4.2 - 18°K.

Under our conditions $p_0 << N_D$, and therefore $N_B^- \sim N_D$, and $N_B^0(N_B - N_D) \sim N_B$, since $N_B >> N_D$ (N_B and N_D are the concentrations of the boron and of the compensating donors, respectively). With increasing N_B in samples with close values of N_D, the hole lifetime τ decreases significantly and its temperature dependence becomes stronger.

In samples with maximum ratio N_B^0/N_B^-, i.e., N_B/N_D, we observed a sharp drop of τ with decreasing temperature below a certain value T_0 (Fig. 1). When the electric field intensity is increased, the decrease of τ begins at higher temperatures. For example, in a sample with $N_B \sim 4.2 \times 10^{15}$ cm^{-3} and $N_D \sim 1.1 \times 10^{13}$ cm^{-3} we have $T_0 \sim 5.5$°K at E = 0.8 V/cm and $T_0 \sim 7$°K at E = 40 V/cm. The value of T_0 increased also with increasing illumination intensity I. The illumination intensity greatly influenced the value of τ at $T < T_0$.

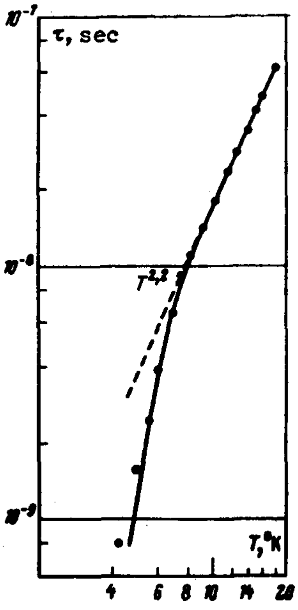

Fig. 1

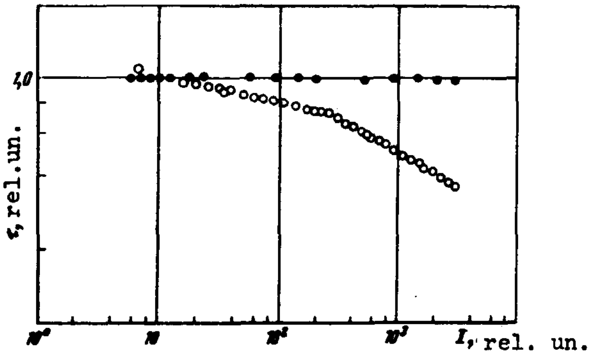

Fig. 2

Fig. 1. Temperature dependence of the hole lifetime τ in a sample with $N_B \simeq 5 \times 10^{15}$ cm^{-3} and $N_D \simeq 5.6 \times 10^{12}$ cm^{-3}.

Fig. 2. Dependence of the hole lifetime τ on the illumination intensity I: ● - $N_B \simeq 4.0 \times 10^{15}$ cm^{-3}, $N_D \simeq 5.7 \times 10^{13}$ cm^{-3}; o - $N_B \simeq 5.7 \times 10^{15}$ cm^{-3}, $N_D \simeq 1.5 \times 10^{13}$ cm^{-3}.

To investigate τ as a function of I, we used a CO_2 laser (wavelength 10.6 μ) with output power ∿10 W. In a sample with $N_B \sim 6 \times 10^{15}$ cm^{-3} and $N_D \sim 1.5 \times 10^{13}$ cm^{-3}, in which $T \sim 6°K$, τ decreased with increasing I at 4.2°K by almost a factor of 3 (Fig. 2). For comparison, the same figure shows the results for a sample with a smaller ratio N_B/N_D, in which no enhancement of the temperature dependence of τ was observed down to 4.2°K.

To explain the results, we assume that B can capture holes in the neutral state. The possibility of hole capture by neutral acceptors and electron capture by neutral donors with formation of A^+ and D^- centers was already pointed out in [2, 3]. Recent reports confirm the existence of A^+ and D^- centers in Si and Ge [4].

We have calculated a model in which light-generated holes from neutral atoms B^0 can be captured both by the B^- centers and by B^0. In accordance with [2], we have assumed that the ionization energy ε_1 of the B^+ centers is much lower than the ionization ε_0 of the neutral B^0 atoms, so that thermal emission of holes from the B^+ centers predominates in the investigated temperature interval. In such a model, at $T < T_0$, where

$$T_0 \sim \frac{\epsilon_1}{k \ln\left[\frac{\alpha_p N_v}{4\sigma_{ph} I}\left(\frac{N_D}{N_B}\right)^2\right]},$$

$$\tau \approx \frac{1}{N_B^0}\left[\frac{N_v \exp(-\epsilon_1/kT)}{\sigma_{ph} I \alpha_p^-}\right]^{1/2},$$

N_v is the effective density of states in the valence band, σ_{ph} is the photoionization cross section of the B^0 centers, and α_p^- is the coefficient for the capture of hole by a B^- center.

The expressions obtained for τ and T_0 make it possible to explain satisfactorily all the experimental results described above. By varying ε_1, we have drawn a theoretical curve through the experimental points for the sample shown in Fig. 1. It turned out that $\varepsilon_1 \sim 0.0047$ eV, in satisfactory agreement with [2, 4].

In an electric field E we have

$$T_0 \sim \frac{\epsilon_1}{k \ln\left[\frac{\alpha_p^0(kT) N_v}{4\sigma_{ph} I} \frac{\alpha_p^-(E)}{\alpha_p^0(E)} \left(\frac{N_D}{N_B}\right)^2\right]},$$

where $\alpha_p^0(E)$ and $\alpha_p^0(kT)$ are the coefficients for the capture of holes by B^0 centers in a field E and under equilibrium conditions. It is seen that T_0 should increase in an electric field, if one makes a natural assumption that $\alpha_p^-(E)/\alpha_p^0(E)$ decreases with increasing E.

It must be emphasized that when $T > T_0$ calculation yields for τ the usual expression $\tau \sim (\alpha_p^- N_B^-)^{-1}$, i.e., τ should not depend on N_B^0. In our experiments, however, τ decreased noticeably with increasing N_B^0 also if $T > T_0$. This correlates with the decrease of the probability of photothermal ionization in samples having close compositions under the same conditions [5], and apparently evidences an increase of the coefficients for the trapping of holes by excited states of B with increasing N_B^0. The physical mechanism of this phenomenon is still unclear.

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[3] R.A. Broan and M.L. Burns, Phys. Lett. 32A, 513 (1970).
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[5] This reference is missing from the Russian original.

CONCERNING THE NEW MECHANISM OF CARRIER RECOMBINATION IN SEMICONDUCTORS

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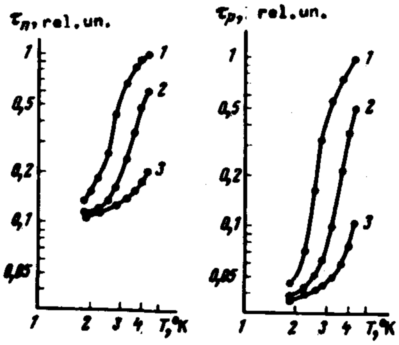
It is customarily assumed that at low temperatures and under interband photoexcitation of the carriers, the acceptors and donors that produce shallow levels become neutralized and do not take a significant part in the recombination [1, 2]. It is shown in the present paper that this point of view should be revised: neutral shallow impurities can, under certain conditions, determine completely the lifetime of the free carriers. In this case the recombination is due to the capture of either an electron by a neutral donor (formation of D^- center) with subsequent capture of a hole by an attracting center, or of a hole by a neutral acceptor (A^+ center) with the subsequent capture of an electron. Although the idea of the formation of D^- (A^+) centers was advanced earlier [3], possible recombination via these centers was rejected without justification [4].

We have investigated the recombination processes using silicon doped with boron with $N_B = 10^{14} - 5 \times 10^{14}$ cm^{-3}, and with compensation $\lesssim 10\%$, under interband photoexcitation of the carriers in the temperature interval T = 1.7 - 4.2°K and under cyclotron-resonance conditions, making it possible to investigate separately the electron and hole lifetimes τ_n and τ_p [5].

It was observed that in Si samples with $N_D + N_A \lesssim 10^{13}$ cm^{-3}, the values of τ_n and τ_p vary little with the temperature ($\tau \sim T$ to $T^{3/2}$) and are practically independent of the photoexcitation intensity. In samples doped with boron, with $N_B \gtrsim 10^{14}$ cm^{-3}, a strong temperature dependence occurs for both τ_n and τ_p, namely, for electrons it can be $\tau_n \sim T^4$ to T^5, and for $\tau_p \sim T^6$ to T^7. Figures 1a and 1b show plots of $\tau_n(T)$ and $\tau_p(T)$ for a Si:B sample with $N_B = 1.5 \times 10^{14}$ cm^{-3}. $N_D = 1.2 \times 10^{13}$ cm^{-3} under different illumination levels (the photoexcitation level increases from 1 to 3). Such plots are typical of doped samples. This reveals clearly the influence of the photoexcitation level on the carrier lifetime.



a b

Fig. 1

The foregoing data cannot be explained within the framework of the known recombination mechanisms. Estimates show that the