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# CONCERNING THE NEW MECHANISM OF CARRIER RECOMBINATION IN SEMICONDUCTORS

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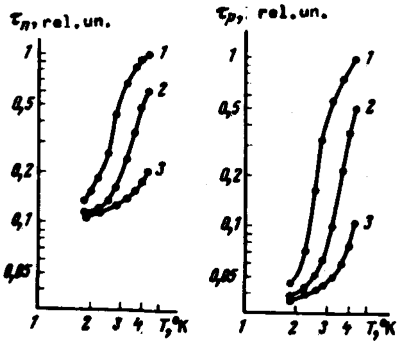
It is customarily assumed that at low temperatures and under interband photoexcitation of the carriers, the acceptors and donors that produce shallow levels become neutralized and do not take a significant part in the recombination [1, 2]. It is shown in the present paper that this point of view should 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 $\tau_n$ and $\tau_p$ [5].

It was observed that in Si samples with $N_D + N_A \lesssim 10^{13}$ cm$^{-3}$, the values of $\tau_n$ and $\tau_p$ 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 $\tau_n$ and $\tau_p$, 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 obtained dependences of the lifetime on the temperature and on the photoexcitation level, at the used impurity concentrations are not connected with inter-impurity recombination [6] and are not determined by the capture of electrons by the neutral boron [2]. The low concentration of the free carriers ($\lesssim 10^9$ cm$^{-3}$) excludes interband radiative, exciton, and Auger recombination. The experimental data point to the presence of a shallow recombination level due to boron, and are explained by the proposed mechanism of recombination via $A^+$ centers (see Fig. 2). At high temperatures, when the concentration of the $A^+$ centers is small because of the intense reemission of the captured holes, the recombination procedes via deep centers [7]. With decreasing temperature and increasing photoexcitation level, the concentration of the $A^+$ centers increases and the boron begins to exert a noticeable influence on the recombination process. A calculation carried out on the basis of the proposed model gives for $\tau_n$ and $\tau_p$ dependences on the temperature and on the illumination level that are close to the experimental ones, if the coefficient of capture of the hole by the neutral acceptor is set equal to $\alpha_p^0 = 10^{-7}$ cm$^3$sec$^{-1}$, the coefficient of capture of an electron by an $A^+$ center is $\alpha_n^+ = 5 \times 10^{-6}$ cm$^3$sec$^{-1}$, and the binding energy of the hole with the neutral boron is $\varepsilon_i = 5$ meV.

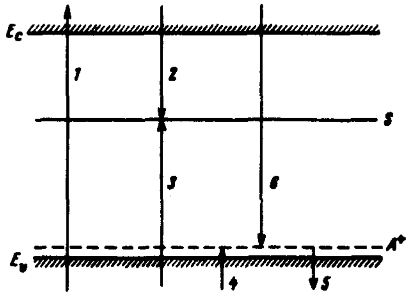


Fig. 2. S - deep level, $A^+$ - level of $A^+$ center, 1 - interband excitation of carriers, 2, 3 - capture of electrons and holes by deep centers, 4, 5 - capture of holes by neutral boron and their re-emission, 6 - capture of electrons by $A^+$ centers.

Analogous experiments were performed by us on n-Ge, p-Ge, and n-Si. The influence of the considered recombination mechanism in these materials comes into play at lower temperatures than in Si:B. This agrees with the fact that these substances are characterized by lower values of $\varepsilon_i$, as measured by us directly in [8].

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## OBTAINING THE "SINGLE-Q" STATE OF CHROMIUM BY ACTION OF LOW TEMPERATURES IN THE PRESENCE OF A MAGNETIC FIELD

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As is well known [1, 2], the "single-Q" state of chromium, characterized