# Letters to the Editor

## *CROSS SECTIONS OF POSSIBLE NONRADIATIVE RECOMBINATION IN SEMICONDUCTORS*

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ONE process that can occur in a semiconductor is nonradiative recombination, the inverse of the ionization of trap electrons by conduction electrons (or holes). Using the wave functions and ideas proposed by Bess[1] for the character of this interaction, we performed the calculations (in a manner somewhat different than in reference 1) for the collision between a thermal hole and a slow conduction electron near a filled trap with subsequent recombination of the trap electron with a hole (the trap electron is considered as a free level for the hole) and transfer of the liberated energy to the conduction electron. We used the following wave functions,

$$u_{\mathrm{I}}(r_1r_2) = u_n(r_1)\,u_h(r_2) \quad \text{(initial state)},$$

$$u_{\mathrm{II}}(r_1r_2) = u_f(r_1)\,u_{bh}(r_2) \quad \text{(final state)}.$$

Here $u_{bh}(r_2)$ is the wave function of the hole localized on the impurity, and the remaining symbols are those used in reference 1. In this case the electron and the hole are different particles and the wave functions need not be symmetric.

Considering that $p \gg p_0$, we obtain:

$$\sigma_{2e}(p_0) = 4\pi^2\left(\frac{16\hbar^2c^2m^*}{p^2a_Hm\varepsilon_0}\right)^2\left(\frac{p}{p_0}\right)(a_t^3N_e)\,F^4\left(\frac{pa_t}{\hbar c}\right),$$

$$\sigma_{2h}(p_0) = \sigma_{1e}(p_0) = \sigma_{2e}(p_0)\,N_h/N_e, \quad \sigma_{1h}(p_0) = \sigma_{2e}(p_0),$$

where

$$a_t = \sqrt{\frac{\mathscr{E}_r}{\Delta}}\,a_H, \quad F(x) = \frac{1}{1+x^2}.$$

$\mathscr{E}_r$ is the Rydberg energy, $\Delta$ the depth of the level from the bottom of the conduction band (for holes — the height from the valence band); $m$ and $m^*$ are the ordinary and effective masses of the electrons (or holes), $a_H$ the radius of the Bohr orbit, $\epsilon_0$ the dielectric constant, $N_e$ and $N_h$ the concentrations of the conduction electrons and holes in the valence band respectively, $\sigma_{2e}$ the cross section for the collision of two conduction electrons with subsequent transition of one electron to the free impurity level, $\sigma_{2h}$ the cross section for the collision of two holes with transition of one hole to the impurity level occupied by the electrons, $\sigma_{1e}$ the cross section for the collision between a conduction electron and a hole with transition of the electron to the free impurity level, and $\sigma_{1h}$ the cross section for the collision between a hole and a conduction electron with transition of the hole to impurity level occupied by the electron.

If the carrier concentration $N_e$ or $N_h$ is $\sim 3 \times 10^{13}\ \mathrm{cm}^{-3}$, then $\sigma_{1e}$ and $\sigma_{2e}$ are of the same order ($3 \times 10^{-21}\ \mathrm{cm}^2$), and are even one order of magnitude less than the cross sections obtained by Bess for radiative recombination ($\sigma_{re}$ and $\sigma_{rh}$). The above mechanism of nonradiative recombination cannot therefore explain the experimentally-observed short lifetime of the carriers in germanium (at a carrier concentration $\sim 3 \times 10^{13}\ \mathrm{cm}^{-3}$), and will come into play only when this concentration is substantially increased.

It must be said that Bess' cross sections $\sigma_{1h}$ and $\sigma_{1e}$ include recombinations between a conduction electron and a thermal hole, which is considered a free level for the electron. But in this case he merely assumed, for the electron in the valence band, the wave function of the free hole without the Bloch factor. Since the wave functions $u_n(r_1)$ and $u_h(r_1)$, taken for this case in reference 1, describe an electron with the same momentum $p_0$ in the conduction and the valence bands respectively, they should be orthogonal to each other, a fact not taken into account by Bess. It is therefore natural that in this very case the matrix element (3) of reference 1 (and consequently the cross sections $\sigma_{1h}$ and $\sigma_{1e}$), calculated without orthogonal functions, is many orders of magnitude greater than that calculated by us.

[1] L. Bess, Phys. Rev. **105**, 1469 (1957).

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