Scale time for interband Auger recombination involving a spin–orbit-split valence band in p-type GaSb crystals

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The efficiency of interband Auger recombination of electrons and holes involving a spin–orbit-split valence band has been determined for the first time in a direct-band, p-type semiconductor (for the particular case of GaSb crystals).

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In p-type semiconductor crystals in which the gap width E_g is approximately equal to the spin-orbit splitting Δ there may be an effective interband Auger recombination of an electron and a hole accompanied by the excitation of a second hole in a spin-orbit-split valence band (the CHSH process). Theory derived for this process[1–4] shows that it may be the mechanism primarily responsible for the lowering of the quantum luminescence yield and the decrease in the carrier lifetime which accompany the doping of many $A^{\rm III}B^{\rm V}$ compounds. A decrease in the luminescence intensity caused by the CHSH process has been observed in doped GaSb (Ref. 5) and InAs (Ref. 6) crystals. As yet, however, no reliable quantitative description has been found for this process; the theoretical papers which have been published are in serious disagreement, and the experimental information available is clearly inadequate.

For the GaSb crystals, for example, the theoretical predictions of the Auger coefficient C_p differ by four orders of magnitude, ranging from 10^{-28} (Ref. 1) to 10^{-24} cm^6/s (Ref. 3). The only experimental study of the efficiency of Auger recombination in GaSb has been an indirect study of the change in the integrated luminescence intensity upon doping.[5] At 77 K, these measurements yielded the estimate $C_p = 10^{-25}$ cm^6/s, but this value leads to times that are too short: 10^{-13} s at a hole density $p = 10^{19}$ cm^{-3}.

In this letter we are reporting the first direct study of the photoelectron lifetime in p-type GaSb crystals over the (Zn) doping range $5 \times 10^{17} \leqslant N_p \leqslant 5 \times 10^{19}$ cm^{-3} at $T = 77$ K. The lifetimes were determined by an optical orientation method which can reveal lifetimes as short as 10^{-11} s (Ref. 7). We simultaneously monitored the change in the integrated luminescence intensity with the doping.

Figure 1a shows the dependence of the photoelectron lifetime τ on the doping level. This dependence indicates that two recombination processes are operating in this doping interval. The first causes a rapid decrease in the lifetime in the low-density region and reaches saturation at $N_p \geqslant 2 \times 10^{18}$ cm^{-3}. With heavier doping, we observe a new decrease in the lifetime-evidence that a second process has come into play. The change in the integrated luminescence intensity accompanying the doping (Fig. 1b) demonstrates that these processes differ in nature: The intensification of

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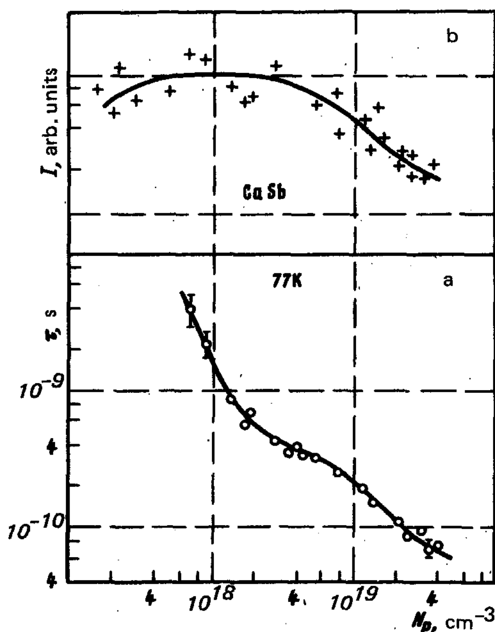

FIG. 1. a–Photoelectron lifetime; b–integrated luminescence intensity, both plotted as functions of the doping level of p-type GaSb crystals.

the first process with the doping does not change the luminescence intensity, whereas the onset of the second process leads to a rapid attenuation of the luminescence. Benz and Conradt[5] have shown that the second process results from interband Auger recombination and is a CHSH process.

In order to precisely determine the lifetimes τ_{nR} corresponding to the CHSH process, it is necessary to determine the nature of the recombination at a lower doping level. Benz and Conradt[5] found an internal quantum yield $\eta \approx 10^{-3}$ for crystals doped at a level $N_p \approx 10^{18}$ cm^{-3} and concluded on this basis that the recombination was also radiationless in this doping interval. This conclusion, however, is at odds with certain other data and with the results of our own experiments. Crystals of GaSb doped at a level $N_p \approx (2\text{-}3) \times 10^{17}$ cm^{-3} have internal quantum yields in the range[8] $\eta = 0.5\text{-}0.8$. It can be seen in Fig. 1b, on the other hand, that an increase in N_p from 2×10^{17} to 6×10^{17} cm^{-3} intensifies the luminescence by a factor of about 1.5-2. This result suggests that the quantum yield on the plateau in Fig. 1b actually is approximately unity and that the recombination here should be of a radiative nature. This conclusion is also supported by a comparison of the values found for the lifetime τ with the theoretical predictions of the efficiency of radiative recombination in GaSb ($\tau_R = 1.3 \times 10^{-9}$ s at $N_p = 1 \times 10^{18}$ cm^{-3} and $T = 77$ K; Ref. 9).

Where there is a competition between radiative and radiationless recombination processes the change in the integrated luminescence intensity as a function of the doping is described by the simple expression $I = A\eta$. Here the constant A is determined by the excitation level and by the parameters of the experimental apparatus; we would have $A = I$ in the case $\eta = 1$. The internal quantum yield is given by $\eta = \tau_{nR}/(\tau_{nR} + \tau_R)$. The measured photoelectron lifetimes are $\tau = \tau_{nR}\tau_R/(\tau_{nR} + \tau_R)$. It can

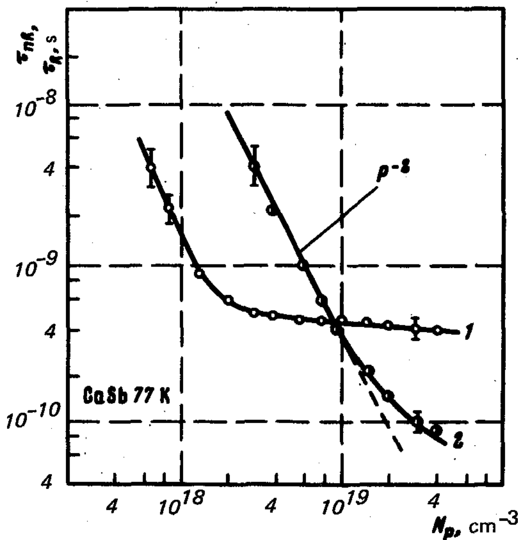

FIG. 2. 1–Radiative lifetime; 2–radiationless lifetime, both plotted as functions of the doping level.

be seen that simultaneous measurements of τ and I can furnish independent values for the scale times for radiative and radiationless recombination.

Curves 1 and 2 in Fig. 2 show the results found for the dependence of the times τ_R and τ_{nR}, respectively, on the doping level. At a level $N_p \geqslant 2 \times 10^{18}$ cm^{-3} the decay of the radiative lifetimes becomes markedly slower; at this doping level a "metallization" of acceptors causes the holes to become free and degenerate at 77 K (Ref. 10). Dumke[11] has predicted minimum values τ_{R0} for the radiative lifetimes in degenerate crystals. The observed times are approximately equal to that expected for GaSb: $\tau_{R0} = 5.5 \times 10^{-10}$ s.

The radiationless lifetimes τ_{nR} corresponding to the CHSH process were determined in the hole-degeneracy region (curve 2 in Fig. 2). Initially, these times fall off in inverse proportion to the square of the hole density, $\sim p^{-2}$ (in degenerate crystals, $p = N_p$), and then they decrease slightly more slowly at $p > 10^{19}$ cm^{-3}. In the region with $\tau_{nR} \sim p^{-2}$ the Auger coefficient is found to be $C_p = 2.5 \times 10^{-29}$ cm^6/s.

This value is much lower than all theoretical predictions of C_p for GaSb crystals. The shortest radiationless lifetime which has been achieved is $\tau_{nR} = 0.8 \times 10^{-10}$ s at $p = 4 \times 10^{19}$ cm^{-3}. The reason for the discrepancy should evidently be sought, as Gel'mont[12] has pointed out, in the incorrect approach which has been taken to evaluate the overlap integrals of the electron and hole wave functions at the values of the carrier wave vectors which represent the threshold for the CHSH process. According to Gel'mont,[12] this approach should indeed lead to theoretical values that are too high.

The slowing of the decay of the times τ_{nR} at $p > 10^{19}$ cm^{-3} is an effect expected for the CHSH process–a consequence of an intensification of the screening of the electron–hole interaction as the hole concentration increases.

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