AUGER RECOMBINATION IN THE ELECTRON-HOLE DROPS IN Si AND Ge

Klaus Betzler

Universität Osnabrück,
FB 4, 45 Osnabrück,
Postfach 4469, Fed. Rep.
Germany

ABSTRACT

Luminescence measurements on Si and Ge at temperatures of about 1.5 K are presented, which indicate that Auger recombination is the main recombination process inside the electron-hole drops (EHD) in both materials.   In silicon a broad spectrum near 2 Eg due to Auger-excited hot electrons could be detected.   From its intensity, an Auger lifetime can be derived which corresponds to the total EHD lifetime. In germanium, the evaluation of magnetooscillation in the luminescence intensity yields a quantum efficiency of only 25% and leads to the conclusion that 75% of the carriers inside the EHD recombine in Auger processes.

Recently, Auger recombination (AR) in the EHD was taken into consideration as important nonradiative process by several authors.[1-3] While in germanium AR was only thought as important for the generation of free electrons and holes from the EHD,[1] in Si and Si-Ge alloys AR was considered as possibly EHD-lifetime-determining.[2,3] In the present paper luminescence measurements on Si and Ge are presented which can only be explained by the assumption that AR is the most important recombination process in the EHD in both materials.

For the case of silicon, the experiments were performed on highly pure samples cooled to about 2 K and excited by a pulsed GaAs laser (peak power 5 W, pulse length 1 μsec, duty factor 1%).   Signal detection after a 0.75 m grating monochromator was carried out using an S 11 photomultiplier tube and special digital Boxcar technique.[4]

The near-2-Eg spectrum of silicon measured under these conditions is shown in Fig. 1.   Besides the relatively intense two-electron transitions line at 2.27 eV,[5,6] a weak, slightly structured spectrum
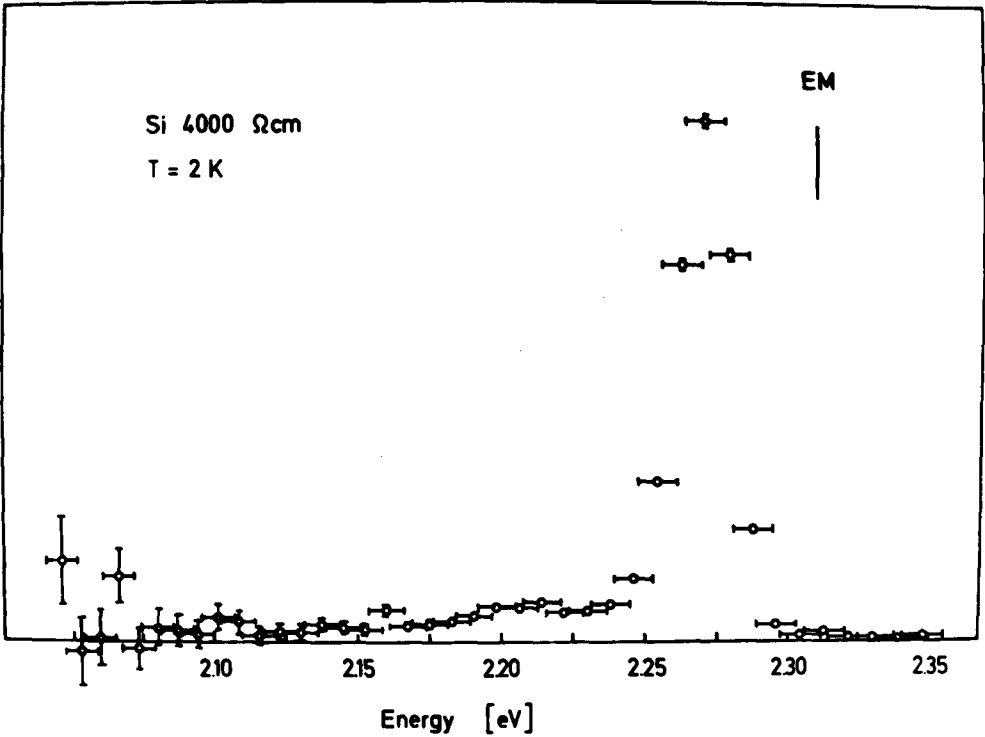
Fig.1. The near-2-Eg luminescence spectrum of silicon. The relatively intense
line at 2.27 eV is caused by two-electron band-to-band transitions.

at energies lower than 2 Eg arises. A better measurement of this

region is shown in Fig. 2, the experimental points are indicated with

their error bars. The process responsible for this spectrum is the

following:[7] An electron is excited to a higher conduction band state

by means of a phonon-assisted Auger-process in the EHD. During the

relaxation from this state, there is the possibility for the electron

to recombine radiatively with a condensed hole. This recombination

causes the measured spectrum.

The main energy relaxation process for hot electrons in non-polar

semiconductors - such as Si and Ge - well above the band edge is

optical and acoustical deformation potential scattering.[8] For these

two processes the relaxation rates have been calculated by Conwell.[9]

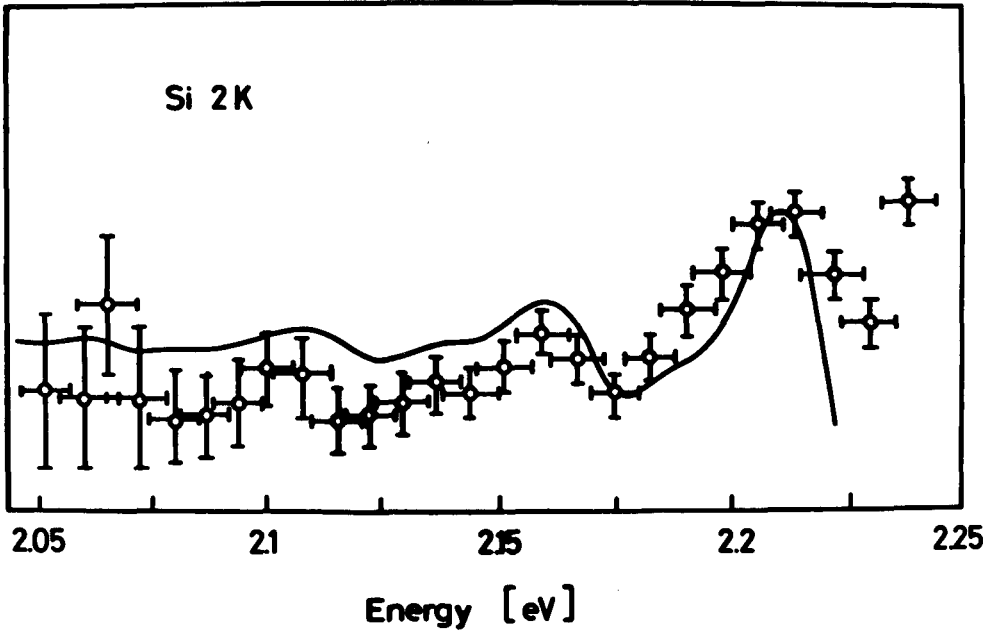Taking her formulas and the set of deformation potential constants from

Fig.2. Luminescence spectrum below 2 Eg with better resolution. The full line gives the theoretically expected shape.

Jørgensen *et al.* [10] we have calculated the theoretically expected shape of the near-2-Eg spectrum originating from the described process. This is given by the full line in Fig. 2.

There have been 2 parameters fitted: One is the ratio of optical to acoustical relaxation rates which for a good fit could be chosen only 20% from the calculated value (this may indicate the accuracy of the deformation potential calculation). The other is the absolute intensity of the spectrum, the fit of which, taking into account the radiative recombination coefficient [11] and the reabsorption, [12] yields the AR coefficient for the electron-electron-hole (eeh) process in the EHD in silicon. This value is found to be $C_e = 1.5 \times 10^{-31}$ cm^6 sec^{-1}, which is slightly enhanced compared to the high temperature value. [13] The enhancement will be even more if one takes into account that the AR coefficient should increase with the temperature because of the particip-ipation of an acoustical phonon.

The value of C_e results in an Auger lifetime for the eeh-process of $\tau_{eeh} \approx 500$ nsec; the ehh process should be a little bit stronger in Si,[13] so that the lifetime for both processes in AR is approximately 200 nsec. This is very close to the total lifetime of EHD in Si, which was found to be about 150 nsec.[14]

On germanium, measurements of the magnetooscillations in the luminescence intensity have been performed. To the highly pure samples, which again were excited by a GaAs laser, a magnetic field in (100) direction could be applied in Faraday configuration. For signal detection a Ge photodiode (risetime $\lesssim 1\,\mu$sec) and Boxcar technique was used.

The oscillations found in the luminescence intensity of the EHD-LA line of 709 meV are shown in Fig. 3. They change continuously in their amplitude with increasing delay time between excitation and signal detection, but the extrema positions remain fixed.

The oscillations are connected with oscillations of the carrier density inside the EHD[16] according to the following formula.[17]

$$\frac{\Delta i(H,t)}{i_o(t)} = \frac{\Delta n(H)}{n_o} \left(1 - t(B \cdot n_o - 2 \cdot C \cdot n_o^2)\right) \qquad (1)$$

where i_o, n_o are intensity and carrier density at zero field, Δi and Δn are the oscillatory parts, B and C are the recombination coefficients for radiative recombination (RR) and AR, respectively, and t is the time between excitation and signal detection. For the oscillations of the time integrated intensity $I(H) = I_o + \Delta I(H) = \int_o^\infty i(t)\, dt$ we can derive:[17]

$$\frac{\Delta I(H)}{I_o} = \frac{\Delta n(H)}{n_o} \cdot \frac{A - C \cdot n_o^2}{A + B \cdot n_o + C \cdot n_o^2} \qquad (2)$$

where A is the coefficient for impurity-induced nonradiative recombination.

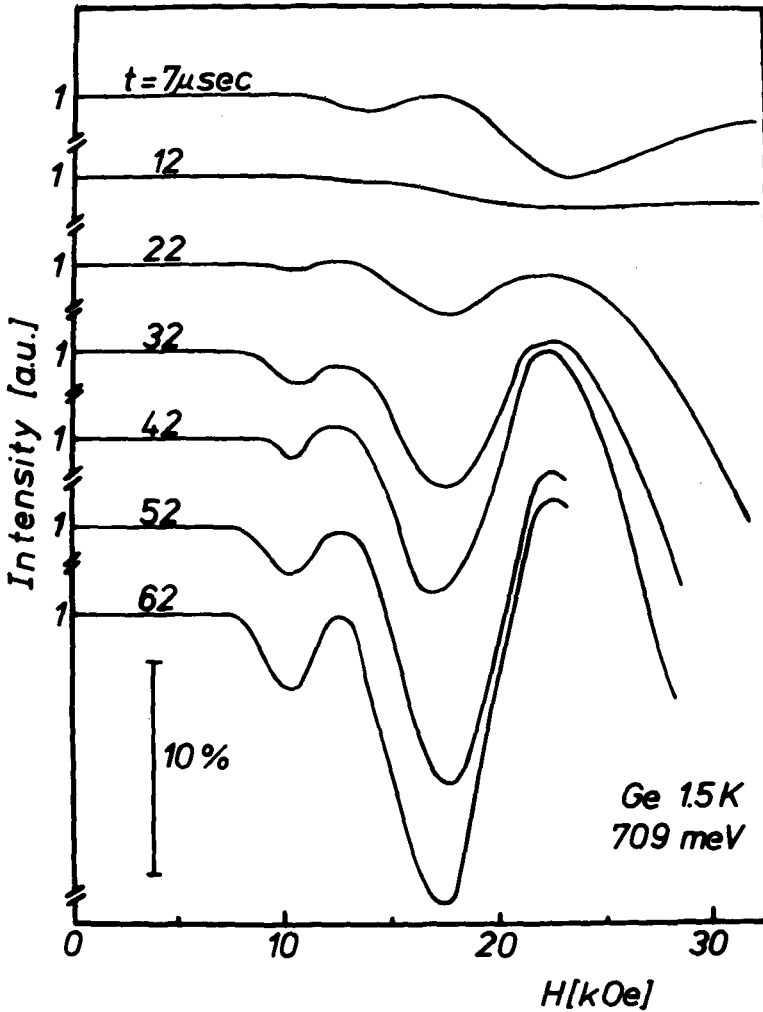From the curves in Fig. 3 those for t = 0 and for the integrated

Fig.3. Intensity oscillations of the LA–phonon assisted
EHD line in Ge for different times t between
excitation and detection. All curves are normal–
ized to their intensity at H = 0.

intensity have been derived (Fig. 4). The curve for i(H,0) directly

gives the variation of the equilibrium density inside the EHD as a

function of the magnetic field (see eq. (1)). A comparison of the

two curves gives the following condition for A and C: $A/C \cdot n_o^2 < 0.1$.

This indicates that in the EHD impurity induced nonradiative processes

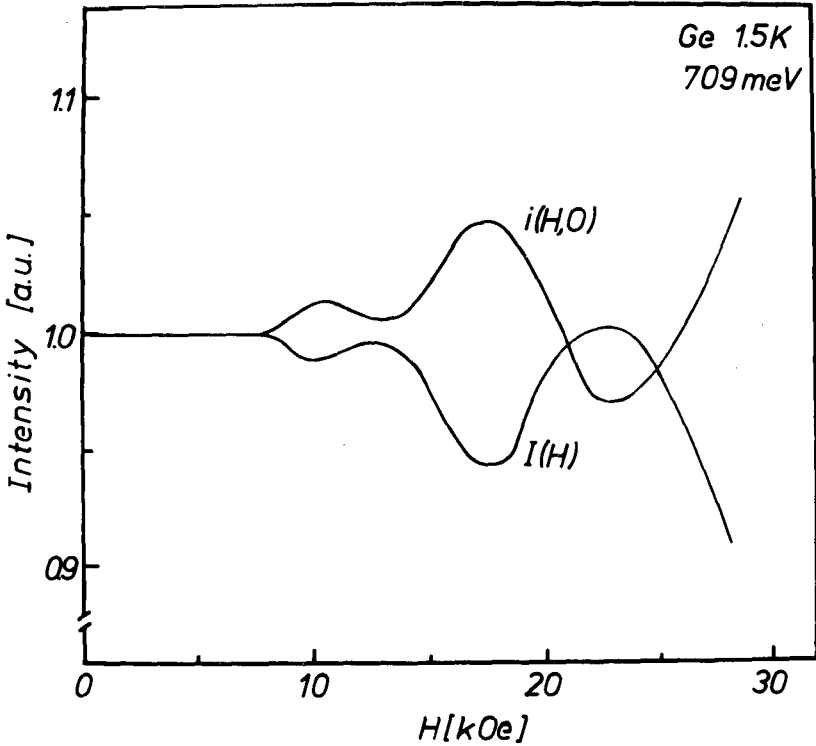can be neglected compared to AR. Assuming $A \approx 0$, the quantum efficiency

Fig.4. Oscillations of the luminescence intensity
at t = 0 and of the time integrated
luminescence intensity (calculated from
the measurements in Fig. 3).

from the EHD can be derived to be $Q \approx 25\%$.   This value is less by a

factor of 2 and 3, respectively, than former estimations.[18,19]

   With a total lifetime of $\tau = 36$ μsec,[20] the transition coeffcients

for RR and AR in the EHD can be calculated to be $B = 3 \times 10^{-14}$ cm^3 sec^{-1}

and $C = 4 \times 10^{-31}$ cm^6 sec^{-1}.   The corresponding high temperature values

are[21,11] 1.1×10^{-14} cm^3 sec^{-1} and[22] 2×10^{-31} cm^6 sec^{-1}.   From a com-

parison we can derive enhancement factors due to electron-hole correla-

tion in the case of RR and to combined electron-electron or hole-hole

and electron-hole correlation in the case of AR of $\rho_B = 3$ and $\rho_c \gtrsim 2$.

These values are very close to the theoretical ones which may be derived

from the values calculated by Vashishta *et al.*[23]

In Table 1 the results concerning the lifetime for RR and AR in the EHD are listed. For comparison also the lifetimes for two-

Table 1: Lifetimes for different recombination processes in the EHD in Si and Ge

	τ_{tot}	τ_{rad}	τ_{Auger}	τ_{2-2}
Si	150 nsec [a]	30 μsec [b]	500 nsec (eeh only)	10 sec [c]
Ge	36 μsec [d,e]	150 μsec	50 μsec	3×10^6 sec [c]

a See ref. 14, b high temperature value from ref. 11
c ref. 15, d ref. 20, e ref. 17

electron band-to-band transitions have been added, a fourth order process, which also has been found in both materials[6,15] but does not play an important role for the total lifetime. A comparison of the times shows the importance of Auger recombination in the EHD in both materials. Only in Ge radiative recombination may be nearly as strong as AR.

ACKNOWLEDGEMENTS

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