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TWO-ELECTRON TRANSITIONS IN GERMANIUM*

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Measurements of two-electron transitions in the EHD in Ge at 2 K are presented. A comparison with Si and measurements in Ge at 100 K leads to the conclusion that these transitions are forbidden and enhanced by electron–hole correlation.

IN PREVIOUS papers[1,2] we have reported about zero-phonon radiative two-electron transitions in the electron–hole droplets (EHD) in Si, which gave the first experimental evidence of the Pokrovsky model[3] in Si. In this paper we report about zero-phonon radiative two-electron transitions in the EHD in Ge. In contrast to Si, these transitions should be forbidden in Ge because of the parity selection rule. The conduction band electrons in Si have no defined parity at the Δ-point, whereas in Ge they have a defined parity at the L-point of the Brillouin zone. Therefore in Ge the two-electron initial state as well as the two-electron final state has positive parity and a dipole-transition should be forbidden. Only electrons outside the exact minimum may contribute to the radiative two-electron transitions. At liquid nitrogen temperature these transitions are indeed very weak.[4] In the EHD we find them to be stronger, which we attribute to enhancement by electron–hole correlation.[5,6]

A slice of Ge, 30 Ωcm, 0.5 mm thick, was immersed in liquid He, which was pumped below the λ-point. The sample was excited by a Q-switched Nd–YAG laser from the back side, peak power was 1 kW, pulse duration 0.5 μsec, and repetition rate 1 kHz. From the front side the radiation was focused to a 0.75 m SPEX double-monochromator and detected by a RCA photomultiplier C31034B which has a rapid drop of the quantum efficiency between $2E_g$ of Ge and the excitation energy. In this arrangement the Ge slice itself served as a filter for the excitation light. Signal registration was carried out in digital boxcar integration method, which is described elsewhere.[4] Every day the spectrum was registrated automatically and the results of several days were added to obtain a reasonable signal to noise ratio.

Figure 1 shows the results. The experimental points indicate comparably strong zero-phonon two-electron band to band transitions in the EHD's. Two theoretically possible lineshapes were calculated by phase space integration. The dashed line represents the shape for first order forbidden transitions, the full line for allowed transitions, considering symmetry braking. The lineshapes are given by

$$I(E)\mathrm{d}E \propto \mathrm{d}E \int \frac{2\pi}{\hbar} \cdot M^2 \cdot g(E_1, E_2, E_3, E_4) \times \delta(E - E_1 - E_2 - E_3 - E_4) \cdot \delta(\Sigma k_i) \cdot d^{12}k,$$

where g is the combined density for the four recombining particles, and M is the transition matrix element. For the allowed transitions, M is assumed to be constant, for the first order forbidden transitions M is chosen to be proportional to the sum of the absolute momenta of the particles, measured with respect to the band extrema. Within experimental error we cannot distinguish, whether the parity selection rule is fulfilled or not.

A quantitative determination is complicated because of the question, whether the EHD's reach to

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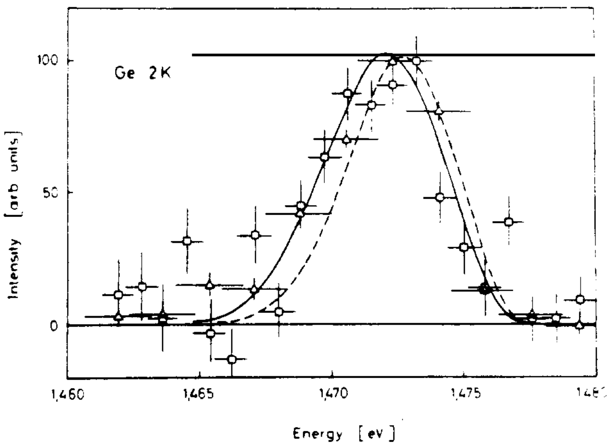

FIG. 1. Radiative two-electron transitions in the EHD's in Ge at 2 K.

the surface of the sample within the small reabsorption length of the $2E_g$-luminescence. To avoid this problem, we have compared the $2E_g$-luminescence with the low energy background radiation, which is caused by the radiative recombination of non-equilibrium Auger-particles. This background radiation has the same density dependence, i.e. n^2p^2, and nearly the same reabsorption. In this way we can compare the transition probability at different temperature, as the coefficients of the phonon assisted Auger-recombination depend weakly on temperature. The high-temperature values of the bipolar Auger-coefficient are about $C = 2 \cdot 10^{-31}$ $cm^6\,sec^{-1}$ in the case of Ge[7] and $C = 3 \ldots 5 \cdot 10^{-31}$ $cm^6\,sec^{-1}$ for Si.[8,9] The corresponding values in the EHD's can be calculated from lifetime measurements to be $C = 2 \cdot 10^{-31}$ $cm^6\,sec^{-1}$ for Ge,[10,11] and $C = 1.4 \cdot 10^{-30}$ $cm^6\,sec^{-1}$ for Si.[12] Assuming a relaxation velocity of the Auger-particles of $v = 3 \cdot 10^{11}$ $eV sec^{-1}$ and a radiative one-electron transition probability of $B = 10^{-15}$ $cm^3\,sec^{-1}$ for indirect transitions,[13] we get the results of Table 1 for the fourth order recombination coefficient of the two-electron transitions

$$D = I_2 \cdot B \cdot C \cdot (I_a \cdot v)^{-1}$$

where I_2 is the luminescence intensity of the two-electron transitions and I_a is the luminescence intensity per eV of the Auger-tail. The comparison of the transition coefficients indicates that the two-electron transitions in Ge are forbidden in first order.

From the comparison of the coefficients at different temperature, we get an enhancement for the low temperature transition-probability of 4 in the case of Si and > 1 in the case of Ge.

Table 1. Intensity ratios and two-electron transition coefficients

	Ge		Si	
	100 K	2 K	100 K	2 K
I_2/I_a [eV]	< 0.05[4]	0.05	0.3[14]	0.4[2]
D [$cm^9\,sec^{-1}$]	$< 3 \cdot 10^{-59}$	$3 \cdot 10^{-59}$	$5 \cdot 10^{-58}$	$2 \cdot 10^{-57}$

This enhancement indicates that electron–hole correlation is indeed important for radiative transitions in the EHD's as reported for the one-electron transitions by Benoit a la Guillaume *et al.*[5] and Brinkman and Rice.[6]

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Über strahlende Zwei-Elektronen Übergänge im Elekron–Loch Kondensat im Germanium bei 2 K wird berichtet. Aus Vergleichen mit Si und Ge-Messungen bei 100 K ergibt sich, daß der Übergang verboten ist, aber durch Elektron–Loch Korrelation verstärkt wird.