9-3 RADIATIVE TWO-ELECTRON TRANSITIONS IN THE ELECTRON-HOLE PLASMA IN SILICON AT 2 K +

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The observation of zero-phonon two-electron radiative transitions within the electron-hole condensate in highly excited Si at He-temperature is reported. The lineshape of this green luminescence agrees well with that calculated from the model of Pokrovsky et al. A value for the transition coefficient is obtained.

1. INTRODUCTION

At low temperature and high excitation levels there appear new emission lines in Si [1] and Ge [2]. These lines have been attributed either to the formation of excitonic molecules [1] or to the formation of an electron-hole condensate [2], [3], which was proposed by Keldysh [4]. To distinguish between these models, radiative two-electron transitions are useful, because different photon energies for these transitions are expected for both models. Such transitions were established in former papers [5], and first results led to the conclusion that the condensate model is correct [6]. In this paper we will give further and more accurate results and a theoretical discussion of the lineshape.

2. EXPERIMENT

The experiment was the same as described previously [6]: A slice of pure Si (p-type, 4000 Ωcm at room temperature) was immersed in liquid He, which was pumped below the λ-point. The sample was excited by a GaAs diode laser with a duty cycle of about one percent. The luminescence was resolved by a 0.75 m Spex grating monochromator. For detection of the luminescence near E_g, a slice of InP was used as a filter to cut off the excitation light. For detection of the high energy luminescence due to two-electron transitions near 2 E_g a Schott BG 18 filter was used for suppressing the excitation light. The luminescence near E_g was detected by an EMI 9684 B photomultiplier with S 1 response and that near 2 E_g was detected by an EMI 6256 A photomultiplier with S 11 response. The registration was carried out in an automatic cycle using the "digital boxcar integration" method described in our previous work [5]. Every filling of the He-dewar lasted 24 hours, and in this time we have registrated the whole spectrum. Because of the low signal to noise ratio of the 2 E_g luminescence we averaged the results of several runs (we now got a better ratio than reported previously [6]). All spectra are corrected for the spectral response of the system, for reabsorption in the sample and for the transfer from the wavelength scale to the energy scale.

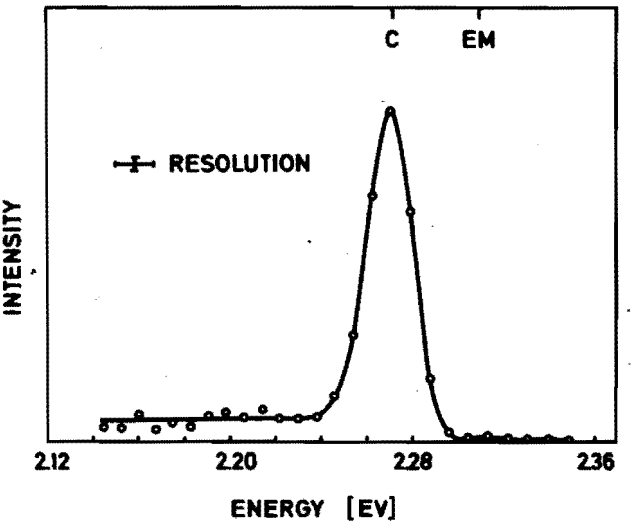

Fig.1: High-energy luminescence from Si. The energetic position of two-electron transitions to be expected from the condensate model and the excitonic molecule model are indicated by C and EM respectively.

3. RESULTS AND DISCUSSION

Fig.1 shows the spectrum near 2 E_g. A broad line appears at the energy to be expected from the model of Pokrovsky et al. [3] for a zero-phonon two-electron transition (in the figure indicated by C). No emission appears at the energy which is expected from the excitonic molecule model (in the figure indicated by EM). The linewidth also agrees with the condensate model. Towards lower energies there appears a tail. Because of the broad structure we do not attribute this tail to phonon replicas in disagreement with our former conclusion from data at higher temperature, where we had indications for phonon assisted two-electron transitions [5].

We attribute the tail to the radiative recombination of non-equilibrium Auger-particles created in the condensate by Auger-recombination. From the ratio of the total two-electron transition intensity J_2 and the luminescence intensity per unit energy of the Auger-particles $J_a(E)$, one can calculate the transition coefficient D of the two-electron transitions from the relation

$$J_2/J_a(E) = D\hbar\omega(BC\tau)^{-1} \qquad (1)$$

where $B = 4\cdot10^{-15}cm^3sec^{-1}$ [7] is the transition coefficient for indirect radiative transitions, $C = 2\cdot10^{-31}cm^6s^{-1}$ [8] is the transition coefficient of the Auger-recombination (high-temperature value) and $\hbar\omega/\tau = 5\cdot10^{11}eVs^{-1}$ (mean phonon energy over the mean collision time) is the velocity of the energy relaxation of the Auger-particles. From the experimental value $J_2/J_a(E) = 0.4$ eV one obtains a value of about $D = 10^{-57}cm^9s^{-1}$ in agreement with our previous rough theoretical estimate for the direct process but in disagreement by four orders of magnitude with our previous experimental high-temperature value [5]. This discrepancy may be caused by a wrong density calculation near the surface in that paper. Because of the short reabsorption length of the light, the effect is very sensitive to the surface conditions. In the present experiment we had a positive long-time drift of the intensity, which we attribute to a change of surface parameters.

To get a more accurate comparison with the condensate model we measured the emission band with higher resolution. This is shown in Fig.2. From the condensate model we calculated theoretical lineshapes from a phase-space integration. We as-

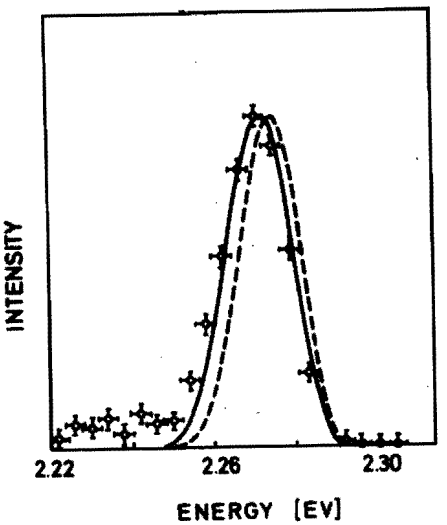

Fig.2: High-energy luminescence spectrum with higher resolution. The curves are theoretical calculations for the condensate model with (full line) and without (dashed line) momentum conservation.

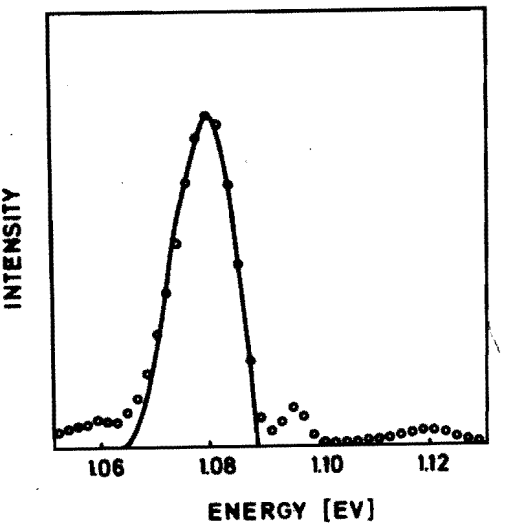

Fig.3: The spectrum near E_g. The full line indicates our fit with the condensation model.

sumed parabolic bands with a lowered bandgap and zero temperature. We fitted the parameters, i.e. the carrier density n and the reduced bandgap E_g' with a measurement of the condensation line near E_g'. The fit is shown in Fig.3. With $n = 3.0 \cdot 10^{18} cm^{-3}$ and $E_g' = 1.122$ eV we carried out the integration over 12 coordinates of the four particles

$$J_2(h\nu) = \int \ldots \int \delta(h\nu - E_g - \Sigma \hbar^2 k_i^2/2m_1)\, \delta(\Sigma k_i)\, dk_1 \ldots dk_{12} \qquad (2)$$

in the limits of the Fermi surface by means of a Monte Carlo computer calculation. The calculation was carried out with and without momentum conservation, i.e. with and without the momentum δ-function because of the following reason: In a zero phonon transition one would expect that momentum is con-

served. On the other hand, in a degenerated Fermi gas there is a short screening length so that momentum is uncertain. The experimental result agrees well with the theoretical curve calculated with momentum conservation.

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FOOTNOTES AND REFERENCES

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DISCUSSION AND COMMENTS

B.V. ZUBOV: What is the thickness of the samples in your experiment? Did you investigate influence of surface states on the experiment?

R. CONRADT: Thickness was about 1 mm. We did not investigate the influence of the surface, but we observed a long time efficiency change which we attribute to a change of surface parameters. The effect should be very sensitive to the surface parameters because of the low penetration depth of the $2E_g$ light.

Ya. POKROVSKY: What time does it take to obtain each experimental point?

R. CONRADT: About one day.