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THE ELECTRON–HOLE LIQUID IN A POLAR SEMICONDUCTOR: CUBIC SiC

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The binding energy $E_B = (17 \pm 3)$ meV and density $n = (9.2 \pm 1.7) \times 10^{18}$ cm^{-3} of the EHL in cubic SiC are determined from excitation-dependent spectra. Comparing these values with ground state properties calculated with and without electron–phonon-interaction using newly determined valence band parameters evidence for the importance of e.p.i. in SiC is found.

In this paper a study of the excitation dependence of the electron–hole-liquid (EHL) [1] in the polar semiconductor cubic (β) SiC is presented. The TA_X phonon replica of the EHL is resolved at low temperatures leading to an accurate determination of the EHL binding energy. Similar results were found for 15R- and 4H-SiC [2]. The ground state properties of the EHL in this notably polar material ($\alpha = 0.31$ for electrons) in β-SiC are estimated with and without electron–phonon interaction (e.p.i.) using newly derived valence band parameters.

The experiments were carried out as reported in ref. [1]. High excitation, 1.8 K, luminescence spectra for three different excitation intensities I_0, $2.5I_0$ and $25I_0$ ($I_0 \approx 4$ MW/cm^2) are superimposed in fig. 1. By studying the time evolution of the main band [1] (for $25I_0$ it peaks at 5475 Å), which remained unshifted on its lower energy side for times up to 200 ns, it was concluded [1] that a condensed EHL had been formed. The density n of an EHL and thus its reduced gap E_g' remain constant during decay as opposed to an EH plasma. Unfortunately on the high energy side of the main band bound exciton features became more prominent [1], with increasing time thus preventing the observation of a time-independent chemical potential μ. These characteristic EHL properties should also be exhibited as a function of excitation intensity, as was

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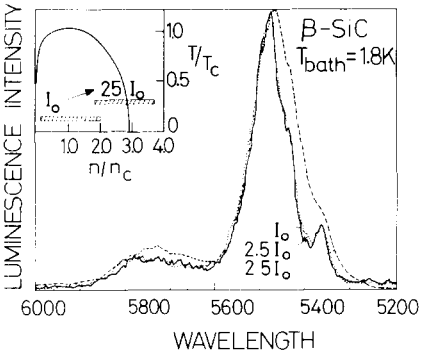

Fig. 1. High excitation intensity 1.8 K luminescence spectra for β-SiC. The insert shows a schematic phase diagram illustrating the probable EH densities for $I_{exc} = I_0$ and $25I_0$.

indeed found here. Over a range of excitation intensities $\frac{1}{4}I_0 < I_{exc} < 6I_0$ the lineshape did not change as shown for example by comparison of the spectra I_0 and $2.5I_0$ in fig. 1. By increasing I_{exc} the high energy side of the one and two phonon bands suddenly broadens for $I_{exc} > 10I_0$ and the phonon induced structure smears out, whereas the low energy side remains constant. This broadening is attributed to the occurrence of luminescence from a high density compressed phase. The process by which this arises on increasing I_{exc} from I_0 to $25I_0$ is shown in the schematic phase diagram in the insert to fig. 1. The individual excitation conditions are indicated by barred regions since the laser light from the N_2-laser employed is markedly spatially inhomogeneous. Thus the excited carrier density varies with position across the ≈ 1 mm focussed laser spot. As $I_{exc} = 25I_0$ is approached, the phase boundary on the right of the EHL region is crossed and a high density compressed phase is formed at the centre of the laser spot. Away from the centre the density is less and one remains within the boundary of the phase separation line. Even though this compressed phase has a higher density than the EHL, its binding energy will be somewhat smaller (see fig. 3). Thus its luminescence is expected on the high energy side of the EHL band.

From the I_0 and $2.5I_0$ spectra, structure arising from the presence of TA, LA, TO, LO momentum conserving (MC) phonon replicas of the EHL recombination is identified (fig. 2). The clearly resolved EHL–TA replica is used to derive a more precise EHL binding energy, to be compared with the results of the ground state calculations presented now. This calculation was carried out with and without the effects of e.p.i. The total energy of the EHL is given by $E_{TOT} = E^e_{kin} + E^h_{kin} + E_{exch} + E_{corr}$. The e.p.i. was incorporated in a twofold way: 1) The exchange energy term was calculated as proposed by Keldysh + Silin [3]. 2) The kinetic energy was calculated from polaron mass parameters [4]. A detailed account of the calculations and a discussion of the approximations employed are given elsewhere [5]. Electron (polaron) masses $m_\uparrow^* = 0.24m_0$, $m_\downarrow^* = 0.647m_0$ [6] and (hole polaron) valence band parameters (v.b.p.) $\gamma_\uparrow^* = 3.17$, $\gamma_\downarrow^* = 0.876$ and

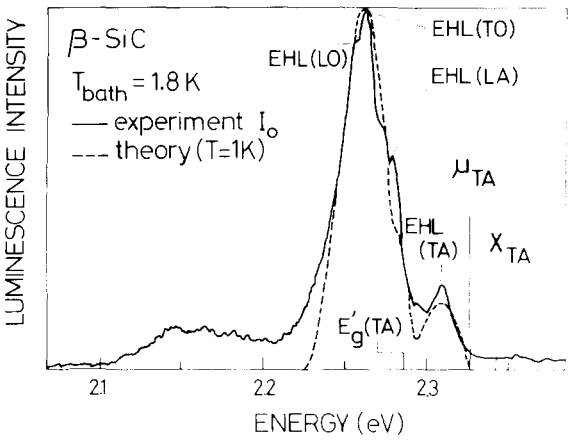

Fig. 2. Comparison of theoretical (T = 1 K) and experimental lineshapes. X_{TA} is the free exciton TA energy and μ_{TA} the EHL–TA chemical potential.

$\gamma_3^* = 1.07$ and dielectric constants $\epsilon_0 = 9.72$ and $\epsilon_\infty = 6.52$ were used. These v.b.p. are different from the parameters resulting from an interpolation between Si and C values reported earlier [1]. The new v.b.p. were calculated in a similar way to that employed by Lawaetz [7]. The basic parameters in the momentum matrix elements are obtained, however, not from Ge but from the experimental v.b.p. of Si ($\gamma_1 = 4.285$, $\gamma_2 = 0.339$, $\gamma_3 = 1.446$) [8]. The resulting bare mass parameters ($\gamma_1 = 3.44$, $\gamma_2 = 0.96$, $\gamma_3 = 1.17$) were corrected for the hole–phonon interaction [4]. With these parameters the exciton ground state energies are $E_{3/2} = 25.8$ meV and $E_{1/2} = 24.06$ meV [9]. The results of the EHL calculations are compared in the table with the experimental results. The influence of the e.p.i. in increasing the EHL binding from 9.8 meV to 16.7 meV is immediately clear. Notable also is the large increase in the Fermi energy from 35 meV to 50 meV. A theoretical lineshape (including e.p.i.) was generated as the sum of the four MC phonon replicas with the same phonon energies and intensities as given in ref. [1]. The lineshape of each one phonon band was calculated as the convolution integral over the joint electron and hole densities of states.

In fig. 2 the peak of the theoretical lines has been aligned (with no other adjustment) to agree in position and height with that of the experimental I_0 spectrum. The general agreement between the shapes of the two curves is good; a lineshape calculated without e.p.i. (not shown in fig. 2 for the sake of clarity), however, shows significant deviations from the experimental curve. In fig. 2 μ_{TA} indicates the chemical potential, which is the same for the theoretical and experimental curves. The EHL binding energy E_B is given by the difference between μ_{TA} and the free exciton TA-replica X_{TA}; it is (17 ± 3) meV in close agreement with the theoretical value (see table 1). In contrast the experimental values for E_F and n are only in moderate agreement with the theoretical ones.

This partial disagreement between theory and experiment can be plausibly explained if we consider the dependence of E_{TOT} on the density parameter

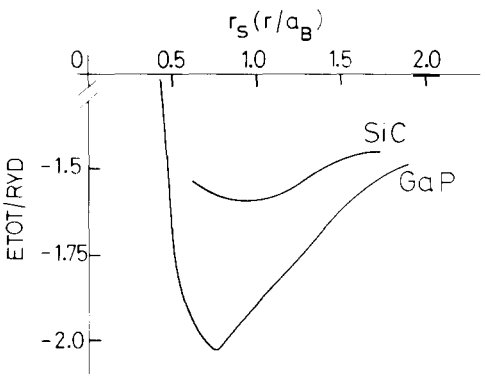

Fig. 3. Theoretical variation of the EHL ground state energy versus interparticle spacing r_s for SiC and GaP.

$r_s = 1/(\frac{4}{3}\pi n)^{1/3} a_{\text{Bohr}}$ (fig. 3). For SiC E_{TOT} close to its minimum varies only slightly with r_s. Thus the binding energy of the EHL is not very sensitive to changes in r_s. One might expect on the other hand that small variations of the input parameters or modifications of the calculation of E_{TOT} can yield quite different values for n, leaving E_B almost unchanged. This situation differs significantly from that found in GaP (fig. 3), where $E_{\text{TOT}}(r_s)$ forms a well-defined minimum and small changes of r_s can drastically alter E_{TOT}.

The shallow minimum of the $E_{\text{TOT}}(r_s)$-curve found in β-SiC should make this material a suitable testing ground for calculations of the correlation energy.

Table 1

	Ground state energy E_{TOT} (meV)	Binding energy E_B (meV)	Density n (cm^{-3})	Fermi energy E_F (meV)
theory without e.p.i.	35.6	9.8	7.4×10^{18}	34.8
theory with e.p.i.	42.5	16.7	12.8×10^{18}	50.2
experiment	42.8	17.0 ± 3	$(9.2 \pm 1.7) \times 10^{18}$	40 ± 5

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