Solid State Communications, Vol.27, pp. 949-953,
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0038-1098/78/0908-0949 $02.00/0

CAMEL'S BACK INDUCED STABILIZATION OF ELECTRON-HOLE LIQUIDS : GaP

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(received 16 August by E.F. Bertaut)

A camel's back-like nonparabolicity of the longitudinal electron mass enhances the density of states and strongly stabilizes an electron-hole-liquid. In GaP therefore the EHL density is doubled to 8.6 x $18^{18}cm^{-3}$ and the Fermi energy ratio E_F^h/E_F^e changes from 1.9 to 4.9. The theoretical binding energy agrees with the experimental E_B=17.5±3meV interpreting the luminescence at 2.30 eV as a superposition of liquid and plasma recombination radiation.

In the indirect gap III-V-compound semiconductors GaP, AlP, AlSb, AlAs, the lowest conduction band has a camel's back shape[1]. The camel's back (cab) is induced in these materials by the splitting of the lowest conduction band at the X-point into X_1- and X_3-bands when the inversion symmetry of the crystals is lifted by going from e.g. Si to GaP. The phonon replica of bound excitons[2], the excited states of donors[3,4], and the excitonic absorption[5] are strongly influenced by this band structure anomaly and give firm evidence for its existence in GaP.

In this letter it is demonstrated for the first time that the presence of a camel's back enhances the ground state energy, the density and therefore the critical temperature of an electron-hole liquid (EHL) and drastically changes the ratio of electron to hole Fermi energies. This is caused by the enhanced density of states at the bottom of the band, an effect which has not been previously appreciated. Results for the EHL[6-8] in GaP are presented and it is shown that the influence of the camel's back on the ground state properties is larger than that of the electron-phonon interaction[9]. The theoretically determined large binding energy is found to be in excellent agreement with experiment. Excitation dependent and time-resolved experiments give evidence that the luminescence band at 2.3 eV is composed of the momentum conserving phonon replicas of EHL and electron-hole plasma recombination.

The energy dispersion of the GaP conduction band in the longitudinal direction with cab is given in a first approximation[1] by

$$E(k) = Ak^2 - [(\frac{\Delta}{2})^2 + \Delta_o Ak^2]^{1/2} \qquad (1)$$

where Δ = 355 meV is the X_1- X_3 band splitting at the X-point[10], Δ_o is the energy difference between the conduction band minimum and the X_3-band and $A = \hbar^2/2\, m_{out}$, where m_{out} is the longitudinal mass at energies distant from the minimum. The properties of the ground state of an EHL depend weakly on the actual depth ΔE and the location in k-space of the cab[11]. For the calculation of the EHL properties we shall use the value of ΔE = 3 meV derived[11] from a scaling of the depths of the cabs of the two exciton bands determined by Humphreys et al.[5] using the theory of Altarelli et al[12]. This value for ΔE is in agreement with results of IR-absorption experiments[4]. An average longitudinal mass of m_{in} = 7.25 m_o close to the minimum of the camel's back was recently determined by Carter et al[3]. The free parameters Δ_o = 426 meV and m_{out} = 2.2 m_o of Eq.(1) are determined from ΔE and m_{in} using the first and second derivatives of Eq.(1).

Fig.1a shows the energy dispersion of the conduction band of GaP close to the X-point calculated with these values from Eq.(1) and for comparison a parabolic dispersion $E(k) = \hbar^2k^2/2m_{out}$. Fig. 1b contrasts the two d.o.s. curves calculated for the two dispersion curves of Fig.1a. The d.o.s. with cab at low energies is much larger than the d.o.s. without cab. Consequently it is possible to have a larger density of electrons with a relatively small mean kinetic energy with cab as compared to the case without. A strong reduction of the electron Fermi energy in the EHL (given in Fig.1b by the vertical lines) is therefore possible.

The valence band parameters used for the ground state calculation of the EHL are γ_1 = 4.05, γ_2 = 0.489 and γ_3 = 1.247[13]. The kinetic energy of the holes was calculated, employing as density of states mass the theoretical cyclotron resonance mass for $H \| <110>$[14].

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(++) supported by the National Science Foundation

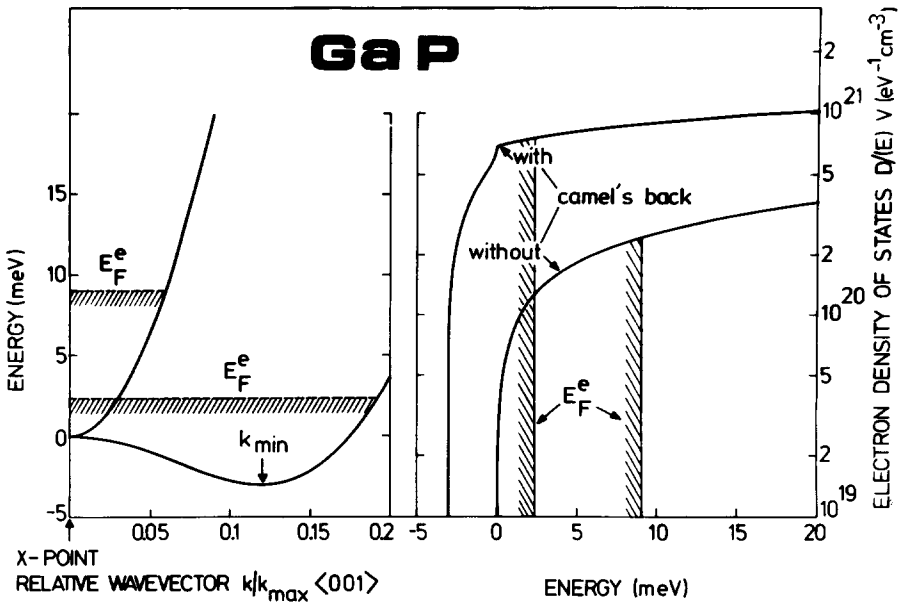

Figure 1

a: Energy dispersion of the conduction band of GaP with and without a camel's back of 3 meV.
b: Density of states of the conduction band of GaP with and without a camel's back of 3 meV.

The total energy of the EHL as a function of the density was evaluated from $E_{tot} = E^e_{kin} + E^h_{kin} + E_{exch} + E_{cor}$. A calculation of the exchange and correlation energy in GaP is difficult because of the complicated band structure. However, we can approximate $E_{exch}+E_{cor}$ by a scaling argument[11] since the sum of these two quantities is very often nearly independent of band structure when expressed (as a function of r_s) in units of exciton Rydbergs. An argument of this type enabled Störmer et al[15] to explain the density and binding energy of the EHL in Ge in large magnetic fields. We use here $E_{exch}+E_{cor}$ from the work of Vashishta et al[16] appropriately scaled.

Keldysh and Silin (KS) and Beni and Rice[17] have pointed out that the electron-phonon interaction will also enhance the binding of an EHL. We corrected the exchange interaction in the way proposed by KS[17]. In the table some of the results of our calculations are given. A comparison of lines 2 and 3 shows that the influence of the electron-phonon interaction on the EHL properties is rather small - using the low frequency dielectric constant in both calculations - in contrast to cubic SiC where a strong influence is found[11].

On the other hand, the influence of the camel's back (lines 1 and 2) is very important. The density is doubled and the ratio of the Fermi energies E_F^h/E_F^e changes from 1.9 to 4.9. This strong difference of the Fermi energies should give rise to a pronounced negative charge of the drop[18].

A theoretical EHL binding energy of 14.0 meV is derived, a value larger than calculated hitherto[8,9] (0-10 meV) using an exciton binding energy of E_X=19.3 meV[19]. The remaining difference of 3.5 meV to the experimental value find its explanation in the steep E_{TOT} (r_s)-dependence.[20]

remark	E_G meV	n $10^{18}cm^{-3}$	E_F^e	E_F^h meV	ΣE_F
no cab, no e.p.i.	26.3	4.4	9.0	17.0	26.0
cab, no e.p.i.	30.9	8.2	5.2	25.8	31.0
cab, e.p.i.	33.3	8.6	5.4	26.7	32.1

Table - Ground state energy E_G, density n, and electron and hole Fermi energies E_F^e, E_F^h of an EHL in GaP, with and without camel's back (cab), and electron-phonon-interaction (e.p.i.).

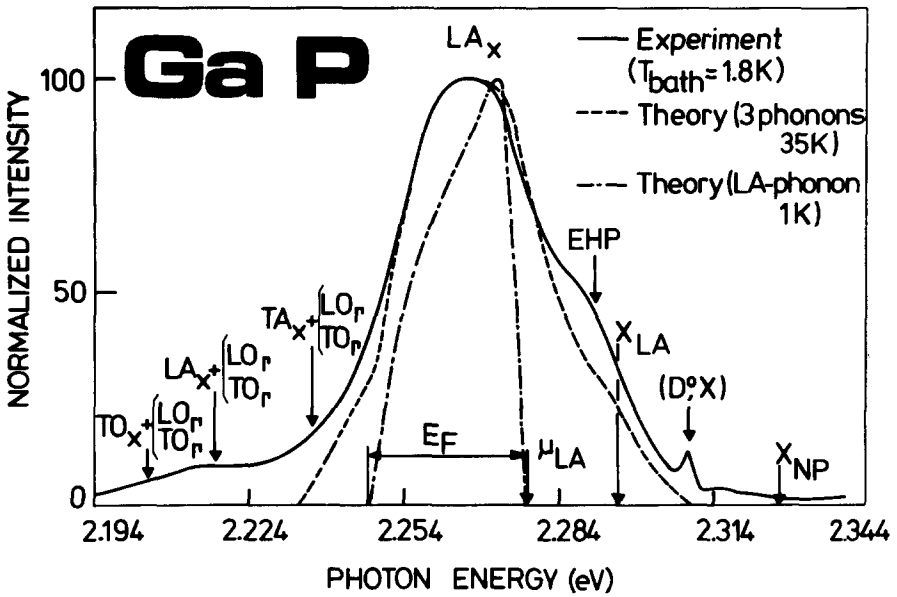

Figure 2

Comparison of experimental and theoretical lineshapes of the EHL. The full line is an experimental curve for T_{bath} = 1.8 K at high excitation intensity ∿ 5 MW/cm^2. (D°,X) is the zero phonon line of an exciton bound to a neutral S (or Te) donor. The dashed line is a fit with a T = 35 K theoretical lineshape (3 phonons) and the dashed-dotted line is the corresponding T = 1 K LA-phonon component of this line. μ is the chemical potential, X the low energy edge of the free exciton (according to Ref. 20), E_F is the Fermi energy and TA, LA, TO designate the different phonon replica.

Theoretical spectra were calculated as a sum of the three phonon replicas $\hbar\omega(TA_X)$=13.1 meV, $\hbar\omega(LA_X)$=31.5 meV and $\hbar\omega(TO_X)$=45.4 meV with the intensity ratio I(TA):I(LA):I(TO)=0.34:1:0.4 derived from free exciton luminescence spectra[21]. The lineshape of each one phonon band was calculated as a convolution integral of the correct electron and hole densities of states for the theoretically derived density.

The dashed line in Fig.2 shows a theoretical spectrum for T=35K and the dashed-dotted line shows the corresponding LA-phonon line for T=1K. An experimental spectrum taken at 1.8K with an excitation intensity of ~5MW/cm^2 on high purity epitaxial crystals (N_D-N_A~10^{15}cm^{-3}) is superimposed to give a best fit at the peak and the low energy side.

The time gate of the boxcar detection system was positioned at the maximum of the EHL luminescence; at this time the contribution of the impurity lines was negligible and so corrections could be avoided.

The high energy onset μ_{LA} of the 1K LA-phonon line marks the position of the LA chemical potential of the EHL. The energy difference between μ_{LA} and X_{LA}, the low energy onset of the LA-phonon replica of the free exciton, gives an experimental binding energy E_B=17.5±3meV, in good agreement with the theoretical value. The relatively large error of ~3meV takes into account the uncertainty in the determination of the actual EHL temperature[11].

The peak at lower energy (~2.2 eV) in Fig.2 is due to combined zone center and momentum conserving phonon replicas as indicated. The high energy shoulder at 2.3 eV of the main line is not predicted by the lineshape fit. It cannot be due to the TA_X phonon replica of the EHL since the energy difference to the main peak is 6.4 meV larger than the known energy difference $\hbar\omega(LA_X)$-$\hbar\omega(TA_X)$. Wavelength dependent decay times were measured. The decay time at the position marked EHP is larger by ~25% than that found for the rest of the line(37± 2nsec) Also the high energy shoulder was found to become relatively weaker with increasing excitation intensity as shown in Fig.3. It is suggested that this shoulder is due to the recombination from a lower density electron-hole plasma which coexists with the EHL.

Finally the thermodynamical scaling constant $\beta=\sqrt{n_o}/T_c$ is found to be 6.5 x 10^7cm$^{-3/2}$ K^{-1} using the density n_o determined here and the critical temperature T_c=45K determined from the temperature dependence of time delayed spectra[11]. This value is in excellent agreement with

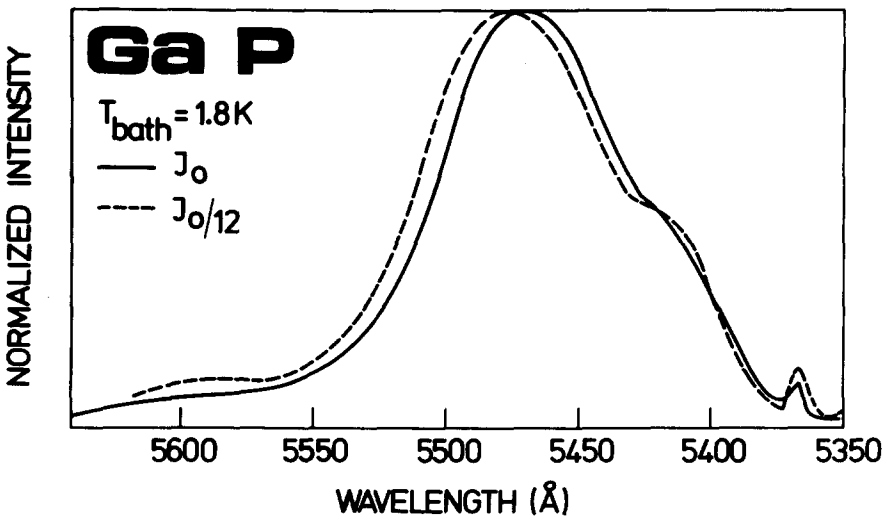

Figure 3

Intensity dependence of the EHL line at two different intensities I_o and $I_o/12$ at T_{bath} = 1.8 K. $I_o \sim 5$ MW/cm^2. The full line "I_o" is the same as the experimental curve in Fig. 2.

the corresponding values for Ge, Si and SiC. An important deviation from the values for these three materials would occur if the density were calculated without taking into account the cab.

In conclusion it has been shown that a camel's back band structure is a stabilizing factor for an EHL and has a strong effect on its ground state properties due to its large density of states. The calculated binding energy of 14 meV agrees well with that derived from a lineshape fit and is larger than assumed hitherto.

Acknowledgements - We are very indebted to P.J.Dean, R.H.Humphreys and U.Rössler for various helpful discussions and to K.Dransfeld, G.Landwehr and H.J.Queisser for their interest. Many thanks are due to C.Weyrich and D.R.Wight for the samples and to H.Krath for his experimental assistance.

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