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UNIVERSAL RELATION BETWEEN BAND RENORMALIZATION AND CARRIER DENSITY IN TWO-DIMENSIONAL ELECTRON-HOLE PLASMAS


4. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-7000 Stuttgart-80, F.R.G.

*Institut für Theoretische Physik, Universität Frankfurt, Robert-Mayer-Strasse 8, D-6000 Frankfurt-am-Main, F.R.G.

**Forschungsinstitut der Deutschen Bundespost, Am Kavalleriesand 3, D-6100 Darmstadt, F.R.G.

***Department of Elec. and Comp. Engineering, University of California, Santa Barbara, CA 93106, U.S.A.

Abstract:

We have investigated the band gap renormalization due to many-body effects in electron hole plasmas in quasi-two-dimensional multiple quantum well structures. A comparison of the data obtained in GaAs/GaAlAs-and GaSb/AlSb-structures show that the band gap shift - if scaled in effective Rydberg units - is independent of the material system. Theoretical calculations confirm this new universal relation governing the dependence of band renormalization on plasma density in two-dimensional systems.

Many-body effects in high density electron-hole plasmas (EHP) in semiconductors lead to a renormalization of the fundamental band gap [1]. In three-dimensional (3D) structures experiments [2] and many-body theories [3] give a universal law for the dependence of this renormalization on the plasma density independent of material parameters. The comparison of the band renormalization $\Delta E_g$ in two-dimensional (2D) structures with values from 3D EHP yielded in the case of the GaAs/GaAlAs-system a surprising difference: For constant interparticle distances the values of the 3D $\Delta E_g$ in meV are smaller by a factor of about 3 than the 2D values. In Rydberg units, however, the 3D band renormalization is stronger by about 1 Ry than the 2D renormalization [4]. Our theoretical considerations showed that this can be explained by the dimensionality dependence of screening effects.

To study the effects of material parameters on the band renormalization in 2D systems we performed systematic high excitation photoluminescence measurements at low temperatures. We used GaAs/GaAlAs-MQW-structures with well widths $L_z$ between 2.1 nm and 8.3 nm (Al-content: 43%) and GaSb/AlSb-MQW-samples with $L_z$ between 5.8 nm and 12.1 nm all grown by MBE. In all samples the barrier widths were large enough to avoid coupling between the wells. We excited the EHP using a pulsed dye laser (in the case of GaAs/GaAlAs; $\tau=10$ ns) or a frequency-doubled Nd:YAG-laser (in the case of GaSb/AlSb; $\tau=100$ ns) with excitation powers $P_{ex}$ between 100 $W/cm^2$ and 1MW/cm$^2$. The pulse widths were large enough to provide quasi-stationary conditions allowing a quasi-equilibrium description. Backscattering geometry was used to avoid the observation of stimulated emission.

(1)Now at CSIRO. Division of Radio Physics, Epping NSW 2121, Australia
In all systems we observe a strong broadening and red shift (up to 50 meV) of the plasma emission for increasing excitation intensities. The high energy edges of the spectra flatten as a consequence of the heating of the carrier system due to a nonresonant excitation of the samples and due to reduced carrier cooling rates in 2D structures [5]. Figure 1 depicts as a typical example the plasma spectra of a GaSb/AlSb-MQW-sample with $L_z = 7.8$ nm.

In order to obtain the plasma density, temperature and renormalized band gap we performed a line-shape analysis in a well-established 2D model [6]: Electrons and holes are distributed in parabolic subbands with a step-like 2D density of states. The subband energies are calculated for a rectangular potential well with finite barriers on the basis of aborption or excitation spectroscopy.

Comparison of experimental spectra with calculated lineshapes

We approximated the realistic nonparabolic valence band dispersion by using the bulk effective masses for the heavy and light holes. By comparison with calculated dispersion relations in the case of GaAs/GaAlAs we showed that these bulk values give a good approximation of the exact values if the well widths of the samples is close to the 2D limit. This is a consequence of the large band filling under high excitation conditions [7]. In the case of the highly stressed GaSb/AlSb layers (lattice mismatch 0.65%) we took into account the stress effects and calculated the in plane masses assuming the high stress limit [8].

Due to the quasi-equilibrium conditions we assumed common quasi-chemical potentials for the subbands of the electrons and holes, respectively, and a common temperature for all carriers. Furthermore the model included momentum conservation, constant matrix elements for the transitions between different subbands and a collision broadening in the form suggested by Landsberg [9]. This energy broadening has a maximum at the band edge and vanishes at the chemical potential. It does not affect the line widths of the spectra which are a measure of the plasma densities.

The experimental data and the fitted curves agree in all systems very reasonable [4]. The solid lines of figure 1 are typical results of our lineshape analysis in the GaSb/AlSb samples. From the line-shape fits we obtained the plasma density and the renormalized band edges in the high-density plasma. The band gaps for very low densities can be measured in absorption or excitation spectroscopy taking into account the appropriate exciton binding energies. In the case of the of the GaAs/GaAlAs-samples we took binding energies obtained in magneto-optical measurements [10]. In the case of the GaSb/AlSb-system where the exciton binding energies are already expected to be small they were taken to be negligible because the electron-hole interaction is largely screened even at low excitation intensities by a relatively high background carrier concentration (about $10^{10}$ cm$^{-2}$) [11].
In figure 2 we show the dependence of the band renomalization on the carrier density for well widths smaller than 12 nm in the two material systems. In both systems the relation between the plasma density and the band renormalization is close to $\Delta E_g \propto n^{1.6}$. This agrees with theoretical expectations [12]. The renormalization reaches values between 25 meV and 50 meV for densities between $4 \times 10^{11}$ cm$^{-2}$ and $2 \times 10^{12}$ cm$^{-2}$. In any system we observed no systematic dependence of the band renormalization on the well width. This is a clear evidence that the 2D limit is reached in our samples. The absolute values of the band renormalization in the 2D systems are much larger than those obtained in 3D structures of comparable materials (Figure 2 contains for example the values obtained in 3D GaAs/GaAlAs-mesa structures [2] and in GaSb-bulk samples [13] at comparable densities).

![Graph showing band gap renormalization](image)

The appropriately scaled experimental results for the 2D systems are shown in figure 3. Consistent with the parabolic approximation of the hole subbands used in the line shape analysis, we calculated the Rydberg energies and the effective Bohr radii using the heavy hole masses of the bulk (high stress limit in the case of GaSb/AlSb). These masses represent the complicated valence-band structure best for the investigated well widths and densities [7]. The experimental results are compared with numerical calculations of the band gap shrinkage $\Delta E_g$ in 2D systems and experimental [2] as well as theoretical [3] results which are well established for 3D systems.

![Graph showing band-gap shift scaled by the dimensionless interparticle distance](image)

Fig. 3 Band-gap shift $\Delta E_g$ scaled by the 2D and 3D Rydberg energies vs the dimensionless interparticle distance $r_a$ for different 2D and 3D structures (Si(4,1) denotes Si under high uniaxial stress parallel to the [110] axis [14]). The numerical results for a 2D plasma are calculated in a dynamical RPA with a single plasmon pole approximation. The universal 3D law is taken from Ref. 3.
The 2D self-energies have been calculated in the dynamical random-phase approximation (RPA) with a single-plasmon pole approximation [12]. We have shown previously that the results are very similar to those obtained from a Hubbard modified dynamical RPA which takes into account the influence of short-range correlations [4].

Figure 3 clearly shows that in the universal units Rydberg energy and Bohr radius in both 2D systems investigated yield a comparable band gap shrinkage close to the theoretical result. Like in 3D systems band gap renormalization in 2D structures is independent of material properties. There is a universal law governing the dependence of the band gap shrinkage on plasma density. Compared to 3D systems the band renormalization is considerably smaller for the same interparticle distances which can be traced to a reduced efficiency of screening in 2D structures [4].

In summary, we have presented measurements and calculations for the density dependence of the band-gap renormalization in 2D EHP in different material systems. In appropriate Rydberg units there is a universal relation governing this dependence independent of material properties. Scaled in the natural units the band gap shift in the 2D EHP is considerably weaker than in the 3D case, as a result of the reduced efficiency of screening in two dimensions. However, the absolute values of the band-gap shifts in 2D are found to be much larger than the corresponding 3D ones. This is due to the increase of the Rydberg energy by a factor of about four going from 3D to 2D.

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