RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 36, NUMBER 12 15 OCTOBER 1987-II

General relation between band-gap renormalization and carrier density in two-dimensional electron-hole plasmas

G. Tränkle, E. Lach, A. Forchel, and F. Scholz
4. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-7000 Stuttgart 80, Federal Republic of Germany

C. Ell and H. Haug
Institut für Theoretische Physik, Johann-Wolfgang-Goethe-Universität Frankfurt, Robert-Mayer-Strasse 8, D-6000 Frankfurt am Main 11, Federal Republic of Germany

G. Weimann
Forschungsinstitut der Deutschen Bundespost, Am Kavalleriesand 3, D-6100 Darmstadt, Federal Republic of Germany

G. Griffiths,* H. Kroemer, and S. Subbanna
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106
(Received 9 July 1987)

We have analyzed the dependence of the band-gap renormalization due to many-body effects on the carrier density in electron-hole plasmas in quasi-two-dimensional systems. A comparison of the data obtained at low lattice temperatures in various GaAs/$Ga_{1-x}Al_xAs$, GaSb/AlSb, and $In_xGa_{1-x}As$/InP multiple-quantum-well structures shows that the band-gap shift, if scaled in effective excitonic units, is independent of the material properties. This new general relation governing the dependence of the band-gap renormalization on the plasma density in two-dimensional systems is confirmed by theoretical considerations.

As a result of many-body effects in high-density electron-hole plasmas (EHP's) a renormalization of the fundamental band gap of semiconductors is observed.[1] Experiments[2] as well as many-body theories[3] give for three-dimensional (3D) structures a universal law for the dependence of this renormalization on the plasma density, which is independent of the material parameters. On the other hand, by comparing the band renormalization ΔE_g in two-dimensional structures with results from 3D EHP's, a surprising difference is found in the case of the GaAs/$Ga_{1-x}Al_xAs$ system: The values of the 2D ΔE_g in meV are larger by a factor of about 3 than the 3D values for the same interparticle distances. In effective Rydberg units, however, the 2D band renormalization is weaker by about 1 Ry than the 3D renormalization.[4] Our theoretical considerations showed that this can be explained by dimensionality dependence of screening effects.

In this paper we present systematic high-excitation photoluminescence measurements performed at low lattice temperatures to study the effects of material parameters on the band renormalization in 2D systems. We investigated GaAs/$Ga_{1-x}Al_xAs$ multiple-quantum-well (MQW) structures grown by molecular-beam epitaxy (MBE) with well widths L_z between 2.1 and 8.3 nm (Al content 43%), GaSb/AlSb MQW samples also grown by MBE with L_z between 5.8, and 12.1 nm and lattice-matched $In_xGa_{1-x}As$/InP MQW samples grown by metal-organic vapor-phase epitaxy (MOVPE) (using adducts as metal precursors) with L_z between 3.0 and 9.5 nm. The barrier widths were large enough in all samples to avoid coupling between the wells. We excited the EHP using a frequency-doubled Nd:YAG laser (where YAG is the yttrium aluminum garnet) (in the case of GaSb/AlSb and $In_xGa_{1-x}As$/InP, τ_{laser}=100 ns) or a pulsed dye laser (in the case of GaAs/$Ga_{1-x}Al_xAs$, τ_{laser}=10 ns) with excitation powers P_{ex} between 100 W/cm^2 and 1 MW/cm^2. The pulse widths were large enough to provide quasistationary conditions in the EHP's and to allow a quasiequilibrium description. Backscattering geometry was used to avoid the observation of stimulated emission. The samples have been characterized in the "zero-density" limit by absorption and excitation spectroscopy, respectively.

In the high-excitation measurements we observe a strong broadening and a pronounced red shift (up to 50 meV) of the low-energy edges of the plasma emissions with increasing excitation intensities. The high-energy edges of the spectra flatten as a consequence of the heating of the carrier system, which is a consequence of the nonresonant excitation of the samples and of the reduced carrier cooling in 2D structures.[5] In Fig. 1 we show as a typical example the plasma spectra of an $In_xGa_{1-x}As$/InP MQW sample with L_z=5.8 nm.

We performed a line-shape analysis in a well-established model for the combination of carriers in a 2D EHP's[4,6] to obtain the plasma density, the carrier temperature, and the renormalized band gap. In this model electrons and holes are distributed in parabolic subbands with a steplike 2D density of states. The energies of the subband edges are calculated for a rectangular potential well with finite barriers on the basis of the results of the absorption or the excitation spectroscopy.

In the case of the GaAs/$Ga_{1-x}Al_xAs$ and $In_xGa_{1-x}As$/InP samples we approximated the realistic nonparabolic valence-band dispersion[7] by using the bulk effective masses for the heavy and light holes. In the case of GaAs/$Ga_{1-x}Al_xAs$ we showed by comparison with cal-

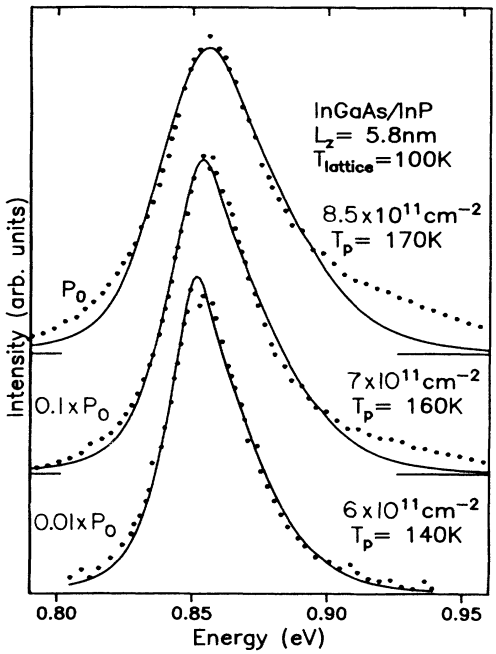

FIG. 1. Luminescence spectra and line-shape fits (solid lines) for an $In_xGa_{1-x}As/InP$ sample of $L_z = 5.8$ nm as a function of the excitation intensity ($P_0 \simeq 500$ kW/cm^2).

culated dispersion relations that these bulk values give a good approximation of the effective values if the well widths of the samples are close to the 2D limit.[8] This is a consequence of the large band filling under the high-excitation conditions. 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.[9]

We assumed common quasichemical potentials for the subbands of the electrons and holes, respectively, and a common temperature for all carriers, which is justified by the quasiequilibrium conditions. Additionally the model included momentum conservation, constant matrix elements for the transitions between the different subbands, and a collision broadening in the form suggested by Landsberg[10] to account for the low-energy edge of the plasma spectra. This energy broadening has a maximum at the band edge and vanishes at the chemical potential of the EHP's. It does not affect the linewidths of the spectra which are the measure of the plasma densities.

The solid lines of Fig. 1 are the results of our line-shape analysis for the $In_xGa_{1-x}As/InP$ sample with $L_z = 5.8$ nm. The experimental data and the calculated line shapes agree very well as in all other systems.[6] From the line-shape fits we obtained the plasma densities and the renormalized band edges in the high-density plasmas. Taking into account the appropriate exciton binding energies the band gaps for very low densities can be measured in absorption or excitation spectroscopy. In the case of the $GaAs/Ga_{1-x}Al_xAs$ samples we took binding energies obtained in magnetooptical measurements.[11] In the other materials where the exciton binding energies are already expected to be small they were taken to be negligible in our samples. The samples showed a relatively high background carrier concentration (about 10^{10} cm^{-2}) which reduces the exciton binding energies markedly.[12]

The dependence of the band renormalization on the carrier density in the three material systems is depicted in Fig. 2 for samples with well widths smaller than 12 nm. The renormalization reaches values between 25 and 50 meV for densities between 4×10^{11} and 2×10^{12} cm^{-2}. We observed no systematic dependence of the band renormalization on the well width in any system. This is a clear evidence that the 2D limit is reached in our samples. In all samples the relation between the plasma density and the band renormalization is close to $\Delta E_g \propto n^{1/3}$. This agrees with theoretical expectations. The absolute values of the band renormalization in the 2D systems are much larger than those obtained in 3D structures of the same materials. (Figure 2 contains, for example, the values obtained in 3D $GaAs/Ga_{1-x}Al_xAs$ mesa structures[2] and in GaSb bulk samples[14] at comparable densities.)

The experimental results for the 2D systems have been scaled with the appropriate effective Rydberg energies and Bohr radii [i.e., $r_s = (\pi n a_0^2)^{-1/2}$]. Consistent with the

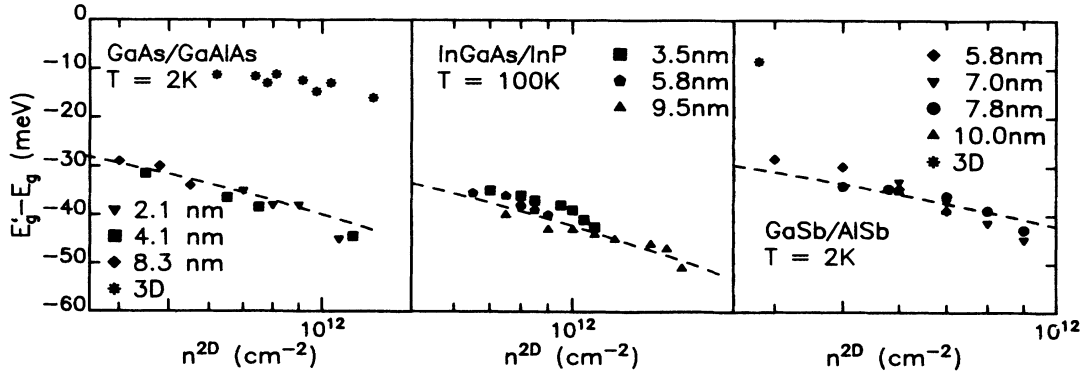

FIG. 2. Measured density dependence of the band renormalization for various MQW structures of the systems $GaAs/Ga_{1-x}Al_xAs$, $In_xGa_{1-x}As/InP$, and GaSb/AlSb as well as for bulk GaAs (Ref. 2) and bulk GaSb (Ref. 14). The density axes for the 2D and 3D cases are based on the interparticle distance. the 2D band renormalization depends in all systems on the density proportional to $n^{1/3}$ as expected theoretically (Ref. 13) (dashed lines).

TABLE I. Natural units used for the three systems studied.

System	Rydberg energy (meV)	Bohr radius (nm)
GaAs/GaAlAs	19.9	5.7
InGaAs/InP	13.3	8.7
GaSb/AlSb	12.2–14.5	9.7–8.1

parabolic approximation of the hole subbands used in the line-shape analysis, we calculated the Rydberg energies and Bohr radii using the heavy hole 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.[8,9] In Table I we summarize these natural units used for the three material systems. The experimental results are compared with numerical calculations of the band-gap shrinkage ΔE_g in 2D systems and experimental[2] as well as theoretical[3] results which are well established for 3D systems. The 2D self-energies have been calculated in the dynamical random-phase approximation (RPA) with a single-plasmon pole approximation.[13] 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 natural units of Rydberg energy and Bohr radius all 2D systems yield a comparable band-gap shrinkage which is close to the theoretical result. As in 3D systems band-gap renormalization in 2D structures is independent of the material properties. There is a new universal relation 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's in different systems. In effective Rydberg units there is a general relation governing this dependence independent of material properties. Scaled in the natural units the band-gap shift in the 2D EHP's 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.

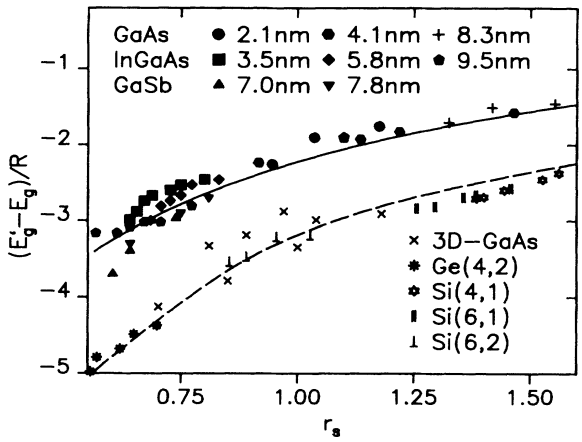

FIG. 3. Band-gap shift ΔE_g scaled by the 2D and 3D Rydberg energies (R) vs the dimensionless interparticle distance r_s for 2D and 3D structures. Si(4,1) denotes Si under high uniaxial stress parallel to the [110] (Ref. 15). The numerical result for a 2D plasma is calculated in a dynamical RPA with a single-plasmon pole approximation (full line). The universal 3D law (Ref. 3) is given by the dashed line.

We thank M. Pilkuhn for stimulating discussions. The work has been supported by the Deutsche Forschungsgemeinschaft, partly under Contract No. Pi-71/20 and partly through the Sonderforschungsbereich Frankfurt-Darmstadt. Part of this work was carried out in the framework of the European Joint Optical Bistability program, supported by the Commission of the European Communities.

*Present address: Commonwealth Scientific and Industrial Research Organization, Division of Radio Physics, Epping NSW 2121, Australia.

[1] *Proceedings of the Third Trieste International Centre for Theoretical Physics IUPAP Semiconductor Symposium, Trieste, 1984,* edited by M. H. Pilkuhn [J. Lumin. **30**, (1985)].

[2] M. Cappizzi, S. Modesti, A. Frova, J. L. Staehli, M. Guzzi, and R. A. Logan, Phys. Rev. B **29**, 2028 (1984).

[3] P. Vashistha and R. K. Kalia, Phys. Rev. B **25**, 6492 (1982).

[4] G. Tränkle, H. Leier, A. Forchel, H. Haug, C. Ell, and G. Weimann, Phys. Rev. Lett. **58**, 419 (1987).

[5] J. Shah, A. Pinczuk, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **54**, 2045 (1985).

[6] G. Tränkle, A. Forchel, E. Lach, F. Scholz, M. H. Pilkuhn, G. Weimann, H. Kroemer, S. Subbanna, G. Griffiths, and M. Razeghi, in *Proceedings of the 13th International Symposium of GaAs and Related Compounds, Las Vegas, Nevada—1986,* Institute of Physics Conference Series No. 83 (The Institute of Physics, Bristol, 1987), p. 221.

[7] M. Altarelli, J. Lumin. **30**, 472 (1985).

[8] G. Tränkle, E. Lach, A. Forchel, D. A. Broido, T. L. Reinecke, and G. Weimann (unpublished).

[9] E. Lach, G. Tränkle, A. Forchel, H. Kroemer, and S. Subbanna (unpublished).

[10] P. T. Landsberg, Phys. Status Solidi **15**, 623 (1966).

[11] J. C. Maan, G. Belle, A. Fasolino, M. Altarelli, and K. Ploog, Phys. Rev. B **30**, 2253 (1984).

[12] D. A. Kleinman, Phys. Rev. B **32**, 3766 (1985).

[13] S. Schmitt-Rink, C. Ell, H. E. Schmidt, and H. Haug, Solid State Commun. **52**, 123 (1984).

[14] O. Hildebrand, E. O. Göbel, K. M. Romanek, H. Weber, and G. Mahler, Phys. Rev. B **17**, 4475 (1978).

[15] A. Forchel, Ph.D. thesis, Universität Stuttgart, 1982 (unpublished).