10-1-1994

Diamagnetic Shifts of Excitons Associated with Symmetrical and Antisymmetric Wave Functions in Coupled InxGa1-xAs-GaAs Quantum Wells

D. C. Reynolds

David C. Look
Wright State University - Main Campus, david.look@wright.edu

B. Jogai

C. E. Stutz

Repository Citation

Reynolds, D. C., Look, D. C., Jogai, B., & Stutz, C. E. (1994). Diamagnetic Shifts of Excitons Associated with Symmetrical and Antisymmetric Wave Functions in Coupled InxGa1-xAs-GaAs Quantum Wells. *Applied Physics Letters, 65* (18), 2293-2295.
https://corescholar.libraries.wright.edu/physics/49

Diamagnetic shifts of excitons associated with symmetric and antisymmetric wave functions in coupled $In_xGa_{1-x}As$-GaAs quantum wells

D. C. Reynolds, D. C. Look, and B. Jogai
University Research Center, Wright State University, Dayton, Ohio 45435

C. E. Stutz
Solid State Electronics Directorate, Wright Laboratory, WL/ELR, Wright–Patterson AFB, Ohio 45433

(Received 24 March 1994; accepted for publication 24 August 1994)

Magneto-optical data obtained from photoluminescence and photoluminescence excitation measurements performed in the presence of applied magnetic fields were used to determine the diamagnetic shifts of free excitons. The samples studied were coupled $In_xGa_{1-x}As$–GaAs quantum wells. In all cases the excitons associated with antisymmetric wave functions were found to have larger diamagnetic shifts than the excitons associated with symmetric wave functions. This suggests that the excitons associated with antisymmetric wave functions have a smaller binding energy than excitons associated with symmetric wave functions. These properties are consistent with the fact that excitons associated with antisymmetric wave functions are less confined than excitons associated with the symmetric wave functions. © *1994 American Institute of Physics.*

In symmetric coupled quantum wells (QWs) the electron and hole subband levels are split into levels associated with symmetric and antisymmetric combinations of isolated QW wave functions. Thus, the isolated QW heavy-hole subband is split into symmetric and antisymmetric heavy-hole levels associated, respectively, with symmetric and antisymmetric combinations of isolated well wave functions, while the light hole and electron subband levels are split similarly. The binding of a ‘‘symmetric electron’’ (e_s) and a ‘‘symmetric heavy hole’’ (hh_s) gives rise to a symmetric heavy-hole free-exciton (SHHFE). The symmetric light-hole free-exciton (SLHFE), the antisymmetric heavy-hole free-exciton AHHFE, and the antisymmetric light-hole free-exciton (ALHFE) are formed in an analogous manner.

Since the excitons associated with the antisymmetric wave functions are less confined than the excitons associated with the symmetric wave functions, it would be expected that they would have a smaller binding energy than the excitons associated with symmetric wave functions. It would also be expected that the excitons with the smaller binding energy will have a larger diamagnetic shift than the excitons with the larger binding energy. It is the purpose of this letter to show that the data from the magneto-optical experiments can be used to estimate the binding energies of excitons.

The coupled QW eigenstates were calculated from a four-band $\mathbf{K}\cdot\mathbf{P}$ model[1] that has proven to be accurate in predicting the subband transition energies in both strained and unstrained systems. This model uses the measured effective masses of the conduction, heavy-hole, light-hole, and split-off bands, as well as the measured energy gaps, to deduce the Luttinger parameters and Kane matrix elements for each host material. In this approach, boundary conditions between adjacent layers are rigorously implemented. The pseudomorphic system consisting of an $In_xGa_{1-x}As$ well and GaAs barriers is under biaxial in-plane compression with a resultant extension of the perpendicular lattice constant. The compressive strain both uniformly increases the $In_xGa_{1-x}As$ band gap and splits the heavy- and light-hole degeneracy at the Γ point. A valence band offset ratio of 0.4 was used since this value was previously found to provide a good fit to the difference in light and heavy-hole free exciton transition energies in pseudomorphic $In_xGa_{1-x}As$ quantum wells with similar In content.[2] The results of these calculations were used to identify light- and heavy-hole subbands associated with antisymmetric and symmetric wave functions.

The structures studied were nominally symmetric, coupled, $In_xGa_{1-x}As$-GaAs double QW structures grown by conventional solid source molecular beam epitaxy (MBE) on (001) GaAs substrates and consisted of wide (5000 Å) GaAs outer barriers surrounding two $In_xGa_{1-x}As$ QWs/10 monolayers (MLs) in width, separated by ‘‘coupling’’ barriers of widths 20, 30, or 120 Å. A total of three structures was studied. The nominal growth x value for each structure was 0.10, although the actual x values as determined by agreement between theory and experiment, varied from 0.08 to 0.095. The growth procedure used was nearly identical to that reported[3] for high quality, single $In_xGa_{1-x}As$-GaAs QW structures and is not repeated here. The growth conditions used were chosen to optimize heterointerface quality; however, these conditions result in reduced control over the exact indium mole fraction (x value) in the QWs. Although the nominal x value for each structure is 0.10, the actual x values are somewhat less than this value and varies from sample to sample due to small uncertainties in substrate growth temperatures.[3] Previous studies[2] of single $In_xGa_{1-x}As$-GaAs QW structures have shown that a comparison of transition energies, obtained via photoluminescence with theoretical calculations, using the x value as an adjustable parameter, results in excellent agreement with the actual x value determined by x-ray diffraction measurements. This approach is equally valid for coupled well structures and was used in the present study. The theory used to calculate the transition energies has been previously described in this letter.

The optical transitions were observed using photolumi-

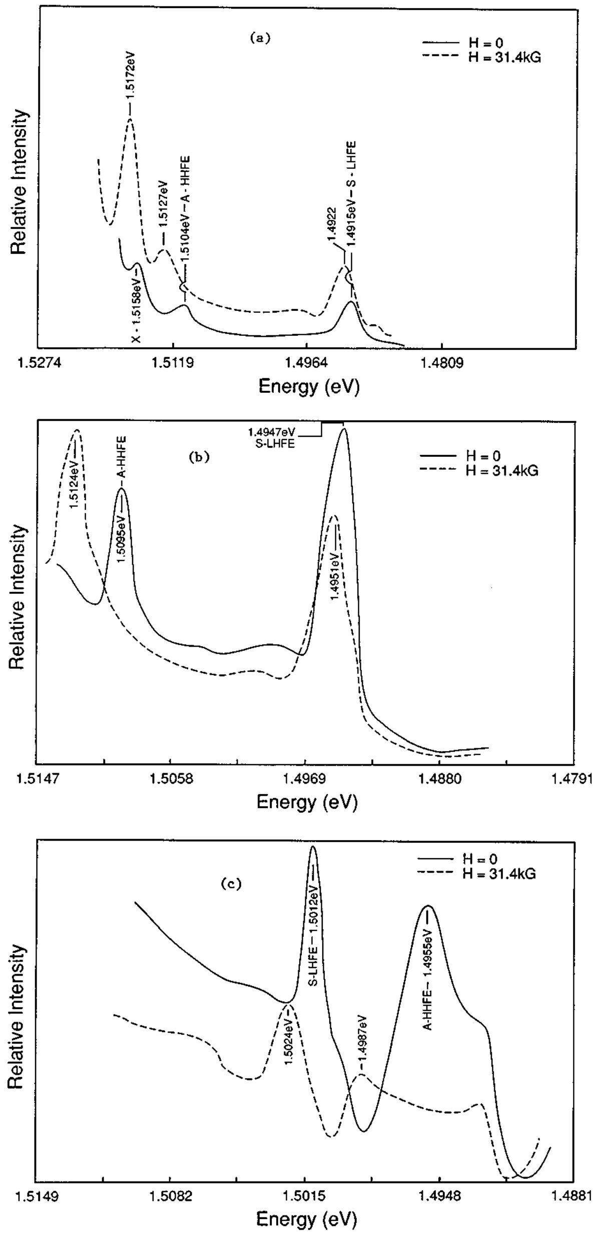

FIG. 1. The SLHFE and AHHFE transition energies in zero magnetic field (solid curves) and applied magnetic field of 31.4 kG (dashed curves). (a) 20 Å barrier, (b) 30 Å barrier, and (c) 120 Å barrier.

TABLE I. Experimental exciton energies and calculated subband energies for 10 ML QW structures with coupling barrier widths $L_B=120$, 30, and 20 Å. The best-fit x values are also given along with the exciton diamagnetic shifts determined from magneto-optical data.

Transition	Exciton energy expt. (eV)	Subband energy calc. (eV)	Diamagnetic shift (meV) (31.4 kG)	L_B (Å)	x value
SHHFE	1.4874	1.4918	0.61	120	0.08
AHHFE	1.4955	1.5014	3.2	120	0.08
SLHFE	1.5012	1.5072	1.0	120	0.08
SHHFE	1.4733	1.4813	0.89	30	0.085
SLHFE	1.4947	1.5005	0.4	30	0.085
AHHFE	1.5095	1.5201	2.9	30	0.085
SHHFE	1.4646	1.4735	1.0	20	0.095
SLHFE	1.4915	1.4967	0.7	20	0.095
AHHFE	1.5104	1.5245	2.3	20	0.095

nescence (PL) and photoluminescence excitation (PLE) spectra which were excited with an Ar^+ laser pumped tunable dye laser using Styryl 9 dye. The sample excitation power density was approximately 1.25 W cm^{-2}. The measurements were made at 2 K with the sample immersed in liquid He. The spectra were analyzed with a high resolution 4-m spectrometer equipped with an RCAC31034A photomultiplier tube for detection. Magneto-optical measurements were made with a conventional iron core magnet with the field oriented approximately parallel to the layers.

The SHHFE transition energy was observed by PL, while the SLHFE energy and the AHHFE energy were observed by PLE. The ALHFE transition energy was not observed as it is not confined in these structures. The PLE spectra for all three structures are shown in Fig. 1, where in each case, the detector hold position is the SHHFE. The SLHFE and AHHFE transition energies are shown in Fig. 1(a) for the 20 Å barrier, in Fig. 1(b) for the 30 Å barrier, and in Fig. 1(c) for the 120 Å barrier. The solid curves represent transitions in zero magnetic field, and the dashed curves in an applied field of 31.4 kG. The increased diamagnetic shift of the transition associated with the antisymmetric wave function is quite obvious.

In coupled quantum wells excitons associated with antisymmetric wave functions are less confined than excitons associated with symmetric wave functions. The greater confinement reduces the extent of the wave function resulting in enhancement of the Coulomb interaction. The exciton binding energy increases with the enhanced Coulomb interaction leading to a reduction in the diamagnetic shift. When a magnetic field is applied parallel to the layer, as in the present work, the carrier motion is normal to the layers. In this orientation the longitudinal carrier mass becomes important. The longitudinal mass increases with confinement and will impact the diamagnetic shift in the same way as the enhanced Coulomb interaction. This result is qualitatively clear from the fact that a strong localization of the carriers along the growth axis renders them less mobile in that direction. This qualitative description is supported quantitatively by eight-band $\mathbf{K}\cdot\mathbf{P}$ calculations by one of the authors[4] and by published reports.[5,6] These two effects will lead to reduce diamagnetic shifts as the confinement increases. Measurements of the diamagnetic shifts of excitons associated with symmetric and antisymmetric wave functions allow a qualitative determination of which has the greater binding energy. Excitons associated with antisymmetric wave functions have the least confined states and in all cases have greater diamagnetic shifts than excitons associated with symmetric wave functions. This agrees with the assumption that excitons associated with the least-confined states will have the smallest binding energies.

A list of the observed excitonic and calculated subband transition energies along with the exciton diamagnetic shifts are given in Table I. It is noted in all cases that the exciton associated with the antisymmetric wave function has the largest diamagnetic shift. The agreement between the observed exciton transition energies and the calculated subband energies is quite reasonable considering that the exact x values are not known, and fluctuations in well size and barrier width were not considered.

In conclusion, it is clear that magneto-optical measurements are a convenient way of obtaining estimates of the relative binding energies of different excitonic transitions in a given QW structure.

The authors would like to thank J. E. Ehret and E. N. Taylor for crystal growth support and G. L. McCoy and C. W. Litton for technical support. This work was partially supported by AFOSR. The work of D.C.R., D.C.L., and B.J. was performed at Wright Laboratory, Solid State Electronics Directorate (WL/EL), Wright–Patterson Air Force Base under United States Air Force Contract No. F33615-91-C-1765.

[1] B. Jogai and P. W. Yu, Phys. Rev. B **41**, 12650 (1990).

[2] D. C. Reynolds, K. R. Evans, C. E. Stutz, B. Jogai, C. R. Wie, and P. W. Yu, Phys. Rev. B **45**, 11156 (1992).

[3] K. R. Evans, C. E. Stutz, and J. E. Ehret, J. Vac. Sci. Technol. B **9**, 2427 (1991).

[4] B. Jogai (unpublished).

[5] T. Ando, J. Phys. Soc. Jpn. **50**, 2978 (1981).

[6] G. Bastard and J. A. Brum, IEEE J. Quantum Electron. **QE-22**, 1625 (1986).