Pergamon

0038-1101(95)00337-1

Solid-State Electronics Vol. 40, Nos 1–8, pp. 585–589, 1996

0038-1101/96 $15.00 + 0.00

MAGNETOOPTICAL INVESTIGATIONS OF SYMMETRICALLY STRAINED (GaIn)As/Ga(PAs) MULTIPLE QUANTUM WELL STRUCTURES

M. VOLK[1], S. LUTGEN†[1], T. MARSCHNER[1], W. STOLZ[1], E. O. GÖBEL‡[1], P. C. M. CHRISTIANEN[2] and J. C. MAAN[2]

[1]Materials Sciences Center and Department of Physics, Philipps-University, D-35032 Marburg, Germany
[2]High Field Magnet Laboratory and Research Institute for Materials, University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands

Abstract—Magnetooptical studies have been performed on symmetrically strained (GaIn)As/Ga(PAs) multiple quantum well heterostructures (MQWHs) of high crystalline perfection. In addition to the strong allowed optical transitions, also weaker quasi-forbidden transitions are observed in the experimental magneto-photoluminescence excitation spectroscopy (magneto-PLE) spectra, in particular at high magnetic fields. These forbidden transitions have been analyzed using the model of a two-dimensional exciton in a magnetic field. This leads to an independent determination of the electron and the heavy hole mass in the MQWHs. The accuracy of the method in determining the carrier effective masses is evaluated and discussed. A consistent description of the subband structure parameters (exciton binding energy, electron and heavy hole mass) as a function of incorporated strain is obtained.

1. INTRODUCTION

The study of the magnetooptical properties of semiconductor bulk layers, as well as quantum well heterostructures (QWHs) and superlattice (SL) structures, is a powerful tool to determine the respective bandstructure in these layers, e.g. Ref. [1]. In particular, QWHs in various material systems have been investigated in recent years using magneto-photoluminescence excitation spectroscopy (PLE)[2–5]. The observed optical transition energies as a function of the applied magnetic field perpendicular to the layer structures have been analyzed by using the model of a two-dimensional exciton in a magnetic field[2–6]. From this analysis of the allowed optical transitions as a function of the magnetic field the exciton binding energy, as well as the reduced effective mass, are obtained. Further assumptions on one of the constituent carrier masses are necessary to extract the other mass. As the reduced mass is dominated by the electron mass in the above mentioned structures, the hole mass can only be obtained with a large error bar from this analysis.

In the present communication, the quasi-forbidden optical transitions, which are observed experimentally with weaker transition strength as compared to the allowed optical transitions in the magneto-PLE spectra, are analyzed in addition. *This allows an independent determination of the electron and hole masses with higher accuracy than the standard evaluation procedure using the intrinsic optical transitions in an absorption experiment.* As a model system for this evaluation procedure, symmetrically strained (GaIn)As/Ga(PAs)-MQWHs have been studied for different values of compressive strain in the (GaIn)As quantum well layers. The analysis of the magneto-photoluminescence (magneto-PL) as applied to *n*-type modulation doped QWHs[7,8] is restricted to doped heterostructures. In addition, any kind of relaxation processes are neglected in the analysis of the magnetic field dependence of the recombination process.

The present communication is organized as follows. The experimental conditions for the epitaxial growth and the magneto-PLE studies are briefly summarized in Section 2. In Section 3, the polarization-dependent magneto-PLE investigations are detailed. The theoretical analysis using the model of the two-dimensional exciton in a magnetic field is described. The obtained values for the exciton binding energy, the electron and the hole mass as a function of strain are presented. The accuracy of the presented method, analysing the quasi-forbidden optical transitions in the magneto-PLE spectra, for the independent determination of the electron and hole mass is discussed. The obtained results are summarized in Section 4.

†Present address: Max-Born-Institut für Nichtlineare Optik and Kurzzeitspektroskopie, D-12489 Berlin, Germany.
‡Present address: Physikalisch-Technische Bundesanstalt (PTB), D-38116 Braunschweig, Germany.

Table 1. Structural parameters of the symmetrically strained (GaIn)As/Ga(PAs) MQWHs as determined by X-ray diffraction analysis. The individual layer thicknesses are determined within an error bar of 0.5 nm, the individual compositions within a relative error of about 5%[10]

Number	x_{In}	$d_{(GaIn)As}$ (nm)	d_{GaAs1} (nm)	y_P	$d_{Ga(PAs)}$ (nm)	d_{GaAs2} (nm)
1	0.052	9.2	1.7	0.100	8.8	1.8
2	0.079	9.1	1.2	0.206	8.6	1.5
3	0.124	8.5	1.2	0.272	8.2	1.6
4	0.156	7.8	1.3	0.334	7.6	1.4

2. EXPERIMENTAL

The epitaxial growth of the symmetrically strained (GaIn)As/Ga(PAs) MQWHs has been performed by metalorganic vapour phase epitaxy (MOVPE) in a commercial equipment (Aix 200, Aixtron Corp.) at a reactor pressure of 100 mbar and a substrate temperature of 650°C. The MQWH layer sequence consists of 50 periods of a (Ga In)As/GaAs/Ga(PAs)/GaAs building block. The thin GaAs intermediate layers in between the ternary (GaIn)As and Ga(PAs) layers have been deposited to avoid the possible formation of strained quaternary (GaIn)(PAs) interface layers. The total strained layer sequence has been grown on a buffer layer consisting of an (AlGa)As layer and an (AlGa)As/GaAs short-period superlattice to improve the growth surface morphology on semiinsulating (100) GaAs substrates (exact orientation within $\pm 0.25°$). Details of the optimization as well as the precise evaluation of the real incorporated strain profile in the symmetrically strained MQWHs have been published elsewhere[9,10]. The structural parameters of the samples, selected here for magneto-PLE investigations are summarized in Table 1.

The magneto-PLE studies have been performed in a Bitter magnet system for magnetic fields up to 20 T. The sample was mounted in a liquid He bath cryostate inside the bore of the magnet system excited using an Ar-ion pumped Ti:sapphire laser system. The excitation light was circular polarized by using an achromatic quarter-wavelength retarder plate. The luminescence light was dispersed by a 0.64 m single pass grating monochromator and detected by a liquid nitrogen cooled Ge-detector using lock-in technique.

3. RESULTS AND DISCUSSIONS

The high-crystalline perfection of the symmetrically strained (GaIn)As/Ga(PAs) MQWHs under investigation here has been established by high-resolution X-ray diffraction[10] as well as PL and PLE spectroscopy[11]. Typical PLE linewidths of the lowest exciton resonance are in the range of 4–5 meV (FWHM). The PL lines with a typical linewidth around 3 meV (FWHM) are "Stokes"-shifted by about 2 meV with respect to the exciton resonance in the PLE spectrum.

The experimentally obtained PLE spectra for one symmetrically strained (GaIn)As/Ga(PAs) MQWH sample for different applied magnetic field strengths are summarized in Fig. 1. The full and dashed lines represent the data obtained from left and right circular polarized light excitation. The individual spectra have been shifted on the intensity scale for clarity. The evolution of the Landau level fan structure is clearly detected for all samples under investigation here at low magnetic field strengths in the range of 1–2 T, pointing again to the high crystalline perfection of these samples. In addition to the strong peak structures, caused by allowed optical transitions, weaker peak structures, as indicated by arrows in Fig. 1, are detected in particular for high magnetic fields.

The characteristic Landau level transitions are analyzed by solving Schrödinger's equation for a two-dimensional exciton in a magnetic field[1]

$$[-\partial^2/\partial\rho^2 - 1/\rho\,\partial/\partial\rho + m^2/\rho^2 - 2/\rho + (\gamma\rho)^2/4]R_{n,m}(\rho) = E_{n,m}R_{n,m}(\rho) \quad (1)$$

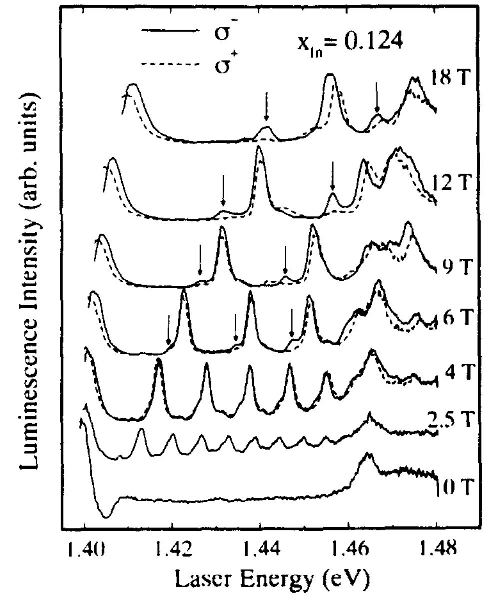

Fig. 1. Photoluminescence excitation spectra of a symmetrically strained (GaIn)As/Ga(PAs)-MQWH as a function of the applied magnetic field perpendicular to the MQWH for an In-concentration in the compressive strained (GaIn)As quantum well of $x_{In} = 0.124$. The full (dashed) line represent PLE spectra recorded using left (right) circular polarized light excitation.

$$E_{101,n,m} = E_{n,m} - (m_e - m_h)/(m_e + m_h)^* \gamma m. \quad (2)$$

In these equations energies are expressed in units of the Rydberg $R_y = \mu e^4/2(4\pi\epsilon h^2)^2$, lengths in units of Bohr radius $a_B = 4\pi\epsilon h^2/\mu e^2$ and γ is given by the ratio of $\gamma = h\omega_c/2R_y$. *The ground state and excited electron states are labeled by* n *similar to the hydrogen model, while* m *represents the exciton angular momentum quantum number*[1].

Two approaches have been applied to solve eqns (1) and (2). The first one is the direct numerical solution of Schrödinger's equation. As the exciton is not strictly two-dimensional in the present MQWHs, the exciton binding energy is taken as a parameter in this evaluation as in the literature for similar magnetooptical experiments[3,5,6]. This scaling of the exciton binding energy is similar to the introduction of a scaling factor for the exciton dimensionality[12]. The second approach is an extension of the analytic two-point Padé approximation of the hydrogenic energy levels in two dimensions at arbitrary magnetic fields, as introduced by MacDonald and Ritchie[13]. This analytic solution has been extended by taking the finite hole mass of the exciton explicitly into account. Both methods yield the same result, however, the use of the analytic approximation leads to a drastic reduction in computation time.

The value of m = 0 *corresponds to* s*-type solutions in terms of the exciton model and to* ΔN = 0 *in terms of the Landau-level transitions. The selection rule* ΔN = 0 *with applied magnetic field relates to* Δk = 0 *without applied field.* Thus, k-conservation implies that only $m = 0$ transitions are allowed, therefore, only eqn (1) has to be considered, which only depends on the binding energy and the reduced effective mass of the exciton. This analysis is the standard procedure for obtaining these two quantities from the experimental data, as has been performed for various material systems in the literature[2–6]. This method, however, does not directly lead to the electron and hole effective mass. Further assumptions, or the knowledge of one of the two quantities in general, are necessary in order to determine the other.

The forbidden transitions with $m = \pm 1$, $m = \pm 2$ correspond to p- and d-type solutions in the exciton picture, or to transitions between the electron and hole Landau levels of different Landau quantum numbers N[1]. As possible mechanisms for the observation of these transitions, scattering mechanisms (impurities[7], interface roughness or alloy disorder), as well as the presence of electric fields[14], are discussed. The additional analysis of the quasi-forbidden transitions leads to an independent determination of the electron and hole mass in these structures. As the application of an electric field in the range below 5 kV cm^{-1} perpendicular to the MQWH layers leads only to minor changes in the energetic positions of the subband levels, this method seems to be generally applicable to any kind of MQWH in a Schottky- or p-i-n-type layer structure. In the present case the surface charge depletion field† is assumed to cause the experimental observation of the quasi-forbidden optical transitions.

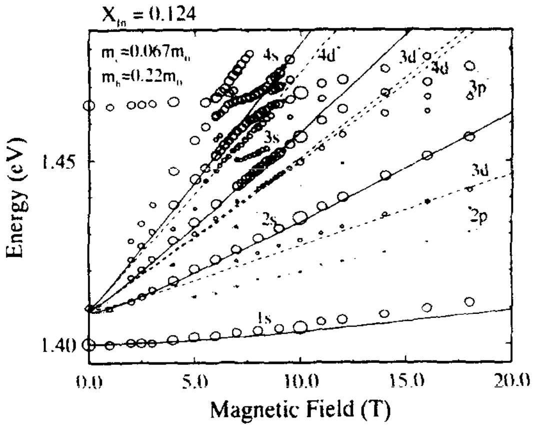

Fig. 2. Laundau level fan chart of a symmetrically strained (GaIn)As/Ga(PAs)-MQWH for an In-concentration in the compressive strained (GaIn)As quantum well of $x_{In} = 0.124$. Experimentally observed optical transitions are plotted as circles. The respective transition strength is indicated by the symbol size for the various optical transitions. The lines result from the theoretical description using the two-dimensional exciton in a magnetic field model as detailed in the text. The full lines represent allowed s-type exciton transitions, while p-type and d-type exciton transitions are shown by dotted and dashed lines, respectively.

The Landau level fan chart, resulting from the magneto-PLE spectra in Fig. 1 for left circular light polarization is summarized in Fig. 2. The symbol size represents the strength of the experimental detected optical transitions. The lines describe the theoretical dependence based on the above described model of the two-dimensional exciton in a magnetic field. Full lines represent allowed s-type excitonic transitions, while p- and d-type transitions are shown as dotted and dashed lines, respectively. An almost perfect *agreement* between experimental transition energies and the theoretical data is obtained.

It is important to note that the $3d^-$ *transition in the symmetrically strained (GaIn)As/Ga/(PAs) MQWHs is only detected under* σ^- *excitation in agreement with theory*[15]. However, the $2p^-$ transition is weakly observed experimentally for both polarizations in contrast to the theoretical description, *where this transitions should be detected only for* σ^+ *excitation*[15]. Also in the case of unstrained QWHs the $2p^-$ as well as the $2p^+$ transitions are detected experimentally for both polarizations[14]. This behaviour needs to be clarified by additional investigations.

In the following, we will concentrate on the achievable accuracy in particular for the determination of the hole mass using this novel evaluation procedure. Therefore, detailed model calculations have been performed for all samples under investigation here.

†For a residual doping level of below 1^*10^{15} cm^{-3}, the surface charge depletion layer is estimated to be in excess of the 1 lm thickness of the MQWH layer structure.

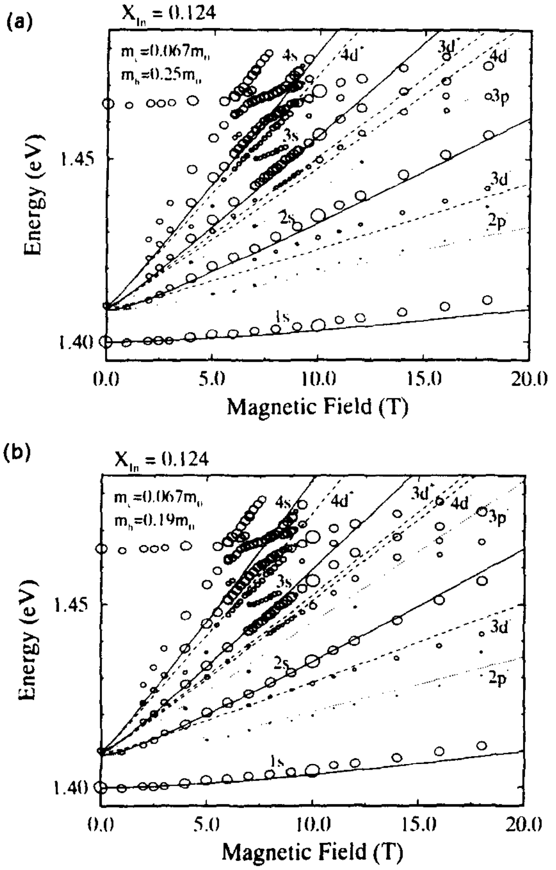

Fig. 3. Landau level fan chart of symmetrically strained (GaIn)As/Ga(PAs)-MQWH for an In-concentration in the compressive strained (GaIn)As quantum well of $x_{In} = 0.124$. Experimentally observed optical transitions are plotted as circles. The respective transition strength is indicated by the symbol size for the various optical transitions. The lines result from the theoretical description using the two-dimensional exciton in a magnetic field model using an in-plane electron mass of $m_e^* = 0.067$ and an in-plane heavy hole mass of (a) $m_{hh}^* = 0.25$ and (b) $m_{hh}^* = 0.19$.

For the symmetrically strained (GaIn)As/Ga(PAs) MQWH with an In-concentration of 0.124, the best description of the experimentally detected transitions is obtained for an exciton binding energy of 10 meV, an electron mass of $m_e^* = 0.067$ and a heavy hole mass of $m_{hh}^* = 0.22$. By variation of these parameters in the model calculation the error bars are established. The comparison of the model calculations with the experimental data by deliberately increasing (decreasing) the heavy hole mass to a value of 0.25 (0.19) is shown in Fig. 3(a) and (b), respectively. While only minor changes in the theoretical energy positions for the allowed optical transitions occur, significant deviations are observed for the forbidden transitions. This is most apparent for the *2p*- and *3d*- transitions. For an increase in the heavy hole mass the theoretical transitions lie below the experimental observed transitions for all magnetic field strengths, while the opposite holds true for a decrease in heavy hole mass. Thus an accuracy of the determined hole mass of below 0.03 results from these studies, which is a clear improvement as compared to the standard evaluation procedure. *The obtained values for the exciton binding energies, the electron and the hole masses of the samples investigated in this work are summarized in Table 2.*

Based on these findings a consistent description of the subband structure as a function of strain is obtained. In particular, the significant decrease of the in-plane hole mass with increasing strain is established quantitatively. *This reduction of the in-plane heavy hole mass results from the reduced intervalence subband mixing due to the increased energetic splitting of heavy and light hole subband levels caused by the incorporated strain.* This is discussed also in more detail in conjunction with the results reported elsewhere in the literature in the strained material system[16].

4. SUMMARY

In conclusion, magnetooptical studies have been performed on symmetrically strained (GaIn)As/Ga(PAs) MQWHs of high crystalline perfection. In addition to the strong allowed optical transitions, also weaker quasi-forbidden transitions are observed in the experimental magneto-PLE spectra, in particular at high magnetic fields. These forbidden transitions have been analyzed using the model of a two-dimensional exciton in a magnetic field, leading to an independent determination of the electron and the heavy hole mass with a significant improved accuracy as compared to the standard procedure. *As the quasi-forbidden transitions are easily observable by applying a weak electric field in the $kV\,cm^{-1}$-range perpendicular to the MQWH layers, this evaluation procedure seems to be a versatile and generally applicable method.* The accuracy of the method in determining the carrier effective masses has been evaluated and discussed.

Table 2. Strain $\epsilon_{(GaIn)As}$, exciton binding energies E_x and carrier effective masses in units of the free electron mass m_0 of the symmetrically strained (GaIn)As/Ga(PAs) MQWHs. The error bars of the different quantities as determined from the theoretical analysis are indicated

Num^b	x_{In}	$\epsilon_{(GaIn)As}$	E_x[meV] ± 1.5	$m_e[m_0]$ ± 0.001	$m_{hh}[m_0]$ ± 0.03	$\mu[m_0]$ ± 0.002
1	0.052	0.37%	9.0	0.0674	0.30	0.056
2	0.079	0.58%	10.0	0.0672	0.25	0.054
3	0.124	0.90%	10.0	0.0670	0.22	0.053
4	0.156	1.12%	10.0	0.0667	0.19	0.052

Acknowledgements—Expert technical support by T. Ochs during MOVPE growth is gratefully acknowledged. This work has been supported by the Deutsche Forschungsgemeinschaft (DFG, Bonn) and by the Commission of the European Community in the "Large Installations Plan".

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