Anisotropic excitation spectra of GaAs/AlGaAs quantum wells grown on vicinal plane substrates

D. J. Wentink

Department of Applied Physics, University of Twente, P. O. Box 217, 7500 AE Enschede, The Netherlands

P. Dawson

Department of Pure and Applied Physics, UMIST, P. O. Box 88, Manchester M60 1QD, United Kingdom

C. T. Foxon

Physics Department, Nottingham University, University Park, Nottingham NG7 2RD, United Kingdom

(Received 29 January 1993; accepted for publication 15 June 1993)

We report measurements of the photoluminescence excitation spectra of a series of GaAs/AlGaAs quantum well samples grown on vicinal plane substrates with differing off-cut angles. When the plane of polarization of the exciting light is changed we have observed a clear variation in the ratio of the strength of the $n=1$ light and heavy hole exciton transitions in samples grown on vicinal plane substrates. This behavior is attributed to anisotropic scattering at steps in the heterointerface.

With the increased understanding of the details of the molecular beam epitaxy (MBE) growth process it is hoped to fabricate low-dimensional structures of increased complexity. In particular it has been shown^{1,2} that it is possible to grow so-called grid inserted quantum wells and quantum wire arrays. In these structures use is made of the particular property of MBE, under certain growth conditions,³ whereby the growth is essentially two dimensional and proceeds from step edges on the epitaxial grown material. A necessary condition for the production of these structures is that the initial growth must occur on a vicinal plane substrate to ensure that step flow growth dominates over random growth at two-dimensional islands. The successful growth of the grid-inserted quantum wells and quantum wire arrays was characterized^{1,2} by measurements of the photoluminescence excitation spectra as a function of the plane of polarization of the exciting radiation (optical polarization excitation spectra) where a clear oscillation in the ratio of the strengths of the $n=1$ heavy and light hole exciton transitions was observed. In this work^{1,2} the observed anisotropy was assigned to variation of the in-plane component of the electron wave vector. However, recent theoretical work^{4,5} has shown that such anisotropy could be caused by a number of effects. In particular Bauer and Sakaki discussed the effects on the optical polarization spectra of a random strongly anisotropic island structure and showed that it is possible to obtain small in-plane optical anisotropy without any quantum wire or superlattice formation at all. Indeed anisotropic optical polarization excitation spectra would result from any intrinsic or extrinsic perturbation that breaks the four-fold symmetry.

As already mentioned, the production of grid inserted quantum wells and quantum wire arrays involves MBE growth in the step flow mode from step edges on vicinal plane substrates. Thus inevitably there might be an intrinsic anisotropy in the plane of such a quantum well struc-

ture due to the intrinsic step edges. Furthermore, there is clear evidence^{6,7} from scanning tunneling microscopy studies that under As-rich conditions [i.e., with a (2×4) reconstruction present during growth] that the growth proceeds more rapidly in the $[-110]$ direction which will lead to anisotropic islands in the growth plane. In this letter we report optical polarization excitation spectra from a series of GaAs/AlGaAs multiple quantum well structures grown on vicinal plane structures with varying nominal off-cut angles (0° – 6°) from the (001) direction allowing us to investigate the influence of step edges in detail.

The measurements were performed on GaAs/Al_{0.33}Ga_{0.67}As multiple quantum well structures grown on GaAs SI substrates with varying degrees of off-cut, the different samples were grown simultaneously. The off-cut angles were measured by x-ray diffraction with a precision of $\pm 0.1^\circ$, however the off-cut direction was not established. The samples were grown in a Varian Gen II MBE machine under As-rich conditions. The growth sequence was as follows: (i) a GaAs buffer layer with an initial growth temperature of 580°C , during the growth of the buffer layer the growth temperature was gradually ramped up to 630°C (at this temperature the growth should proceed in the step flow mode),³ and maintained at this temperature for the subsequent growth, (ii) $1400\text{ \AA}$ of Al_{0.33}Ga_{0.67}As, (iii) 60 periods of $25\text{ \AA}$ GaAs and $145\text{ \AA}$ Al_{0.35}Ga_{0.65}As, and (iv) $1400\text{ \AA}$ Al_{0.35}Ga_{0.65}As capping layer.

The optical experiments were performed with the samples mounted in a continuous flow cryostat at 9 K . The optical polarization excitation spectra were performed by exciting the front face of the samples with a pyridine dye laser and recording the photoluminescence intensity of the low energy tail of the $n=1$ heavy hole exciton transition while the dye laser was scanned over the energy range encompassing the $n=1$ light hole and $n=1$ heavy hole exciton transitions. These spectra were recorded with the plane of polarization of the exciting radiation at varying

FIG. 1. (a) Low temperature (9 K) photoluminescence spectrum of the sample for the nominally 6° orientated substrate excited with light of photon energy 1.789 eV and an incident power density ~ 10 W/cm². (b) Low temperature (9 K) photoluminescence excitation spectrum of the same sample with a detection energy of 1.711 eV.

angles in the plane of the quantum well structure. This was accomplished by passing the laser beam through a Fresnel rhomb system which was the last optical element in the system before the cryostat. The photoluminescence intensity was found to be linear with excitation power when exciting with a fixed excitation energy close to the exciton transitions and the measured spectra were corrected for the change in the output power of the dye laser. Typical photoluminescence and excitation spectra from the sample with the 6° misorientated substrate are shown in Figs. 1(a) and 1(b), respectively. The transitions at 1.735 and 1.773 eV in the excitation spectra are identified as the $n=1$ heavy hole and $n=1$ light hole exciton transitions, respectively. Also indicated in Fig. 1 are the peak height intensities (hh, lh) used to measure the ratio of the heavy and light hole transition strengths.

Applying⁸⁻¹¹ Fermi's Golden Rule and using Kane's $\mathbf{k} \cdot \mathbf{p}$ theory it is possible to derive the probabilities α_{lh} and α_{hh} for the $n=1$ light hole and $n=1$ heavy hole transitions, respectively. Thus it can be shown that

$$\frac{\alpha_{lh}}{\alpha_{hh}} = \frac{1}{3} \frac{\tan^2 \Phi + 4 \sin^2 \xi + \cos^2 \xi}{\tan^2 \Phi + \cos^2 \xi}.$$

The important terms in the above expression are first $\tan \xi$ where

$$\tan \xi = \frac{|\mathbf{k}_{well}|}{k_z},$$

where $|\mathbf{k}_{well}|$ and k_z are the electron wave vectors in the plane of, and perpendicular to the quantum well, respectively, and second, Φ which is the angle of the plane of polarization of the exciting radiation (in our case this angle is measured with respect to an arbitrary direction Φ_0 in the different samples). If $|\mathbf{k}_{well}| = 0$ then α_{lh}/α_{hh} would always be equal to 1/3 irrespective of the direction of the plane of polarization of the exciting radiation but if $|\mathbf{k}_{well}| \neq 0$ (caused by quantum confinement in the quantum well plane or by anisotropic scattering) then α_{lh}/α_{hh} varies as a function of Φ with a period of 180° and an amplitude governed by $\tan \xi$.

TABLE I. Modulation depth Δ and the nominal and real off-cut angles as measured by x-ray diffraction of the samples studied.

Sample	Nominal off-cut angle	Measured off-cut angle	Δ
A	0°	0.0°	0.00
B	2°	6.0°	0.04
C	4°	4.5°	0.03
D	6°	5.7°	0.05

Although the nominal off-cut angles for our substrates were 0°, 2°, 4°, and 6°, experimentally the off-cut angles were found to be 0°, 6.0°, 4.5°, and 5.7°, these values are tabulated in Table I where we refer to the samples as A, B, C, and D, respectively. In Fig. 2 we show the variation of ratio of $n=1$ light hole to $n=1$ heavy hole exciton peak heights (i.e., α_{lh}/α_{hh}) as a function of the angle of the plane of polarization of the exciting light for the different samples. In Table I we show the depth of modulation Δ of optical polarization excitation spectra for the different samples where Δ is defined as

$$\Delta = \left(\frac{\alpha_{lh}}{\alpha_{hh}} \right)_{\max} - \left(\frac{\alpha_{lh}}{\alpha_{hh}} \right)_{\min}.$$

Clearly from the results shown in Fig. 2 we do not observe any anisotropy for the 0° sample (within the experimental error) but for the other three samples there is a distinct anisotropy. It should be noted that the oscillations observed for the different samples are out of phase because no particular effort was made to orientate the different samples with respect to the plane of polarization of the exciting radiation, i.e., Φ_0 is arbitrary and different for the different samples. As discussed below we believe the optical anisotropy to be caused by the step edges, thus the random orientation of the samples with respect to the plane of polarization would explain the variable phase factor.

As we discussed previously there are two possible sources of anisotropic scattering in quantum well structures grown on vicinal plane substrates, i.e., the step edges and the anisotropic islands intrinsic to the growth process. The absence of anisotropy in the optical polarization excitation spectra for the 0° orientated sample allows us to dismiss the anisotropic islands as a cause of the anisotropy in the optical polarization spectra of the samples grown on the vicinal plane substrates. Thus we conclude that the step

FIG. 2. Variation of the ratio α_{lh}/α_{hh} as a function of the angle $\Phi - \Phi_0$ of the plane of polarization of the exciting radiation for (a) samples B and C and (b) samples A and D.

edges caused by the growth on vicinal plane substrates can lead to measurable anisotropy in optical polarization spectra. We note that the depth of modulation in the α_{lh}/α_{hh} ratio that we have measured is much less than in the experiments on quantum wires and grid inserted quantum wells. This is, of course, a consequence of the much smaller amount of anisotropic scattering at the step edges in comparison with the scattering caused by an inserted grid.^{1,2}

In conclusion, we report optical polarization spectra on a series of quantum well structures that have been grown on 0° orientated and vicinal plane (001) substrates. We have observed anisotropy ($\Delta \sim 0.04$) in spectra of the samples grown on the vicinal plane substrates which we attribute to scattering at the step edges of the quantum well interfaces. Anisotropy in optical polarization spectra can be used as evidence for the successful growth of quantum wire structures, we would like to make it clear that it is not the purpose of this report to cast doubt on any previously reported data^{1,2} but to point out that anisotropic polarization spectra can be caused by other effects. Indeed in the previous work^{1,2} the reported anisotropy ($\Delta \sim 1.5$ and 0.3, respectively) was much greater than that reported here.

Nevertheless we feel that great care must be taken in the interpretation of anisotropy in optical polarization spectra as being unequivocal evidence for the successful fabrication of quantum wire structures.

The experimental part of this work was carried out at Philips Research Laboratories, Redhill, England. We would like to thank Professor B. A. Joyce of Imperial College, England for useful discussions.

¹ M. Tsuchiya, J. M. Gaines, R. H. Yan, R. J. Simes, P. O. Holtz, L. A. Coldren, and P. M. Petroff, *Phys. Rev. Lett.* **62**, 466 (1989).

² M. Tanaka and H. Sakaki, *Appl. Phys. Lett.* **54**, 1326 (1989).

³ J. H. Neave, P. J. Dobson, B. A. Joyce, and J. Zhang, *Appl. Phys. Lett.* **47**, 100 (1985).

⁴ G. E. W. Bauer and H. Sakaki, *Phys. Rev. B* **44**, 5562 (1991).

⁵ G. E. W. Bauer and H. Sakaki, *Surf. Sci.* **267**, 442 (1992).

⁶ M. D. Pashley, K. W. Haberen, W. Friday, J. M. Woodall, and P. D. Kirchner, *Phys. Rev. Lett.* **60**, 2176 (1988).

⁷ E. J. Heller and M. G. Lagally, *Appl. Phys. Lett.* **60**, 2675 (1992).

⁸ A. Messiah, *Quantum Mechanics* (North-Holland, Amsterdam, 1961).

⁹ R. Loudon, *The Quantum Theory of Light* (Clarendon, Oxford, 1983).

¹⁰ E. O. Kane, *J. Phys. Chem. Solids* **1**, 249 (1957).

¹¹ G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Les Éditions de Physique, Paris, 1988).