Stacked layers of InAs/GaAs sub-monolayer quantum dots: quantum dots or quantum wells?

M. Hayne*[1], S. Harrison[1], M. Young[1], P.D. Hodgson[1], R.J. Young[1], A. Strittmatter[2], A. Lenz[2], U.W. Pohl[2] and D. Bimberg[2]

[1] *Department of Physics, Lancaster University* [2] *Institut für Festkörperphysik, TU Berlin* *Email: m.hayne@lancaster.ac.uk

i) Introduction

The cycled deposition of less-than-one-monolayer (ML) of InAs and a few MLs of GaAs on a GaAs substrate creates novel nanostructures known as sub-monolayer quantum dots (SML QDs), which are presently being studied as an alternative to conventional Stranski-Krastanow QDs.

The absence of a wetting layer and high lateral density of dots means these samples are of particular interest in high-speed optoelectronic devices. Indeed, vertical-cavity surface-emitting lasers (VCSELs) utilising SML QDs have been shown to operate at up to 30 Gb/s [1].

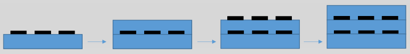

Fig 1. Nominal growth process for SML QDs, resulting in approximately 1 ML-high InAs QDs in a GaAs matrix.

iii)

Three samples were studied, each with ten-fold 0.5 ML InAs depositions capped with GaAs spacer layers of thicknesses of 1.5, 2 and 2.5 MLs each.

ii) Structural properties

Cross-sectional scanning tunnelling microscopy (X-STM), carried out at TU Berlin, shows that for small spacer layers (<4 ML) the growth process results in indium-rich QD-like agglomerations (outlined yellow in Fig. 2) with a large distribution of shapes and sizes, embedded in a lateral InGaAs quantum well (QW) [2].

This poses the question that ultimately motivates this work:

Are charge carriers confined in zero-dimensional QDs or in a two-dimensional QW?

Fig 2. Cross-sectional scanning tunnelling microscopy images of an SML QD sample with GaAs spacer layers of 2.8 ML. The lighter areas indicate a presence of indium and the yellow outlines indium-rich agglomerations.

iv) Magneto-photoluminescence (PL)

Magneto-PL is a powerful tool that enables one to probe the extent of exciton wavefunctions within the samples by confining it in the two dimensions perpendicular to the applied field.

The PL emission energy E dependence on the applied magnetic field B can be fitted using the so-called *excitonic model*, as is Fig. 3. It defines a parabolic low-field and a linear high-field regime, in doing so enabling one to obtain values for the exciton Bohr radius a_B (i.e. the extent of the exciton wavefunction), effective mass μ and diamagnetic shift coefficient β in the plane of the field.

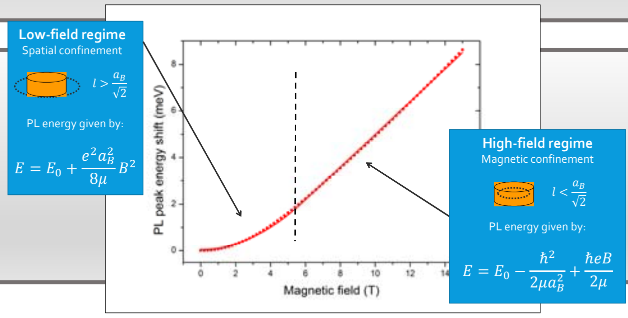

Fig 3. Magneto-PL curve for sample with 2 ML spacer-layer thickness at 2 K. Here, E_0 is the zero-field PL emission energy, and $l = \sqrt{\hbar/eB}$ is the magnetic length. The orange cylinder represents the Bohr radius and the dotted line surrounding or within it the magnetic length.

v) Evidence for a two-dimensional system

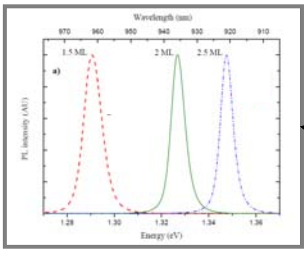

Fig 4. PL spectra of all three samples at zero-field and 2 K.

PL spectra are much more intense and with a smaller linewidth than one would expect from QDs in the sample. Fig 2. clearly shows a large distribution of QD sizes, which should result in broad PL spectra.

Lenz *et al.* [2] compared a PL spectrum from a SML QD sample very similar to ours against that from an InGaAs QW with the same indium content, finding a similar linewidth.

Table 1. Diamagnetic shift β in the vertical growth direction and exciton Bohr radius a_B in the lateral direction for the three samples, at 2 K.

Spacer-layer thickness (ML)	Stack height (nm)	Vertical diamagnetic shift, β (eV T^{-2})	Lateral Bohr radius a_B (nm)
2.5	15.5	1.07×10^{-5}	16.1
2.0	13.0	9.44×10^{-6}	15.6
1.5	10.5	7.40×10^{-6}	15.0

Laterally (along SMLs)
Values for the Bohr radius of between 15-16 nm at 2 K were found. This is considerably larger than the roughly-5 nm-large indium-rich agglomerations, implying charge carriers are not confined within them.

Vertically (growth direction)
As spacer-layer thickness decreases, we see a decrease in the diamagnetic shift β (the amount by which the magnetic field perturbs energy levels). As $\beta \propto a_B^2$, this hints at a smaller extent of the exciton and that this extent is governed by the stack height, not by SMLs.

vi) Evidence for a zero-dimensional system

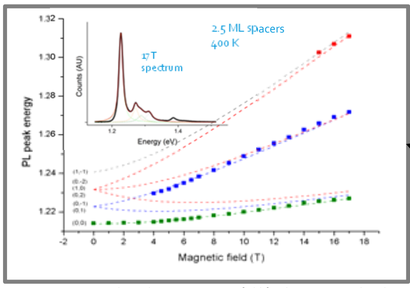

Fig 5. PL emission energy dependence on magnetic field for the main PL peak and excited states, at 400 K for the sample with 2.5 ML spacer-layer thickness, fitted by a Fock-Darwin spectrum. The inset shows the spectrum at 17 T.

At high temperatures, excited state PL peaks become resolved and display a field dependence that can be described by a Fock-Darwin spectrum. This indicates that dot-like states are present.

vii) An explanation

To explain these paradoxes, we postulate different dimensionalities of confinement for electrons and holes.

Indium-rich agglomerations are too small to confine the light electrons, and so they see an InGaAs QW. Heavier holes however are confined within the dot-like indium-rich regions.

viii) Modelling the system

To prove this explanation, a simple 2D mathematical model is used, in which a circular 5 nm-wide InGaAs QD with high indium concentration ($In_{0.5}Ga_{0.5}As$) is placed within a 13 nm-high InGaAs QW with a low indium concentration ($In_{0.15}Ga_{0.85}As$), both surrounded by a GaAs matrix. The model solves the 1-band Schrödinger equation in the effective mass approximation for this system, in doing so giving energy eigenvalues for both electron and hole states.

The results show that, indeed, electrons are confined within the QW, whilst holes are confined within the QD, as in Fig 6.

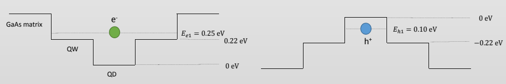

Fig 6. Calculated first electron and hole energy levels, E_{e1} and E_{h1} respectively, within a simple SML QD system. Not to scale.

In addition, these results hold even when indium concentrations are altered drastically, suggesting that this system of different dimensionalities is common for all InAs/GaAs SML QDs with spacer-layer thickness in the order of a few MLs.

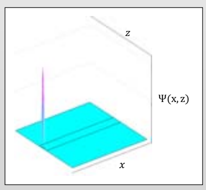

Fig 7. Representation of the hole's wavefunction produced by the model, showing a sharp peak indicating heavy confinement.

ix) Conclusion

Three SML QD samples with different GaAs spacer-layer thicknesses have been studied in an attempt to determine the nature of confinement. Intense and narrow PL, along with large lateral Bohr radii and vertical Bohr radii governed by the stack height, imply a two-dimensional system. The presence of Fock-Darwin states at high temperatures suggest a zero-dimensional system. These paradoxes are explained by postulating that the relatively light electrons see a QW whilst the heavier holes are confined within indium-rich dot-like regions. Solving the 1-band Schrödinger equation for this system gives weight to this argument.

This work was supported by the Engineering and Physical Sciences Research Council, the Royal Society and SFB of DFG. Many thanks to A. Lenz, H. Eisele and M. Dähne for the X-STM images.

[1] N. N. Ledentsov *et al.*, Nanoscale Res. Lett. **2** 417 (2007)
[2] A. Lenz *et al.*, Appl. Phys. Express **3** 105602 (2010)

EPSRC Pioneering research and skills