High field magnetoluminescence spectroscopy of self-assembled (InGa)As quantum dots on high index planes


a Institute for Solid State Physics, University of Tokyo, Roppongi, Minato-ku, Tokyo 106, Japan
b Department of Physics, University of Nottingham, Nottingham NG7 2RD, UK

Abstract

Structures are investigated with InAs and (InGa)As self-organised quantum dots embedded in GaAs matrices grown on (1 0 0) and (3 1 1)A substrates. The photoluminescence line widths for quantum dots on the high index planes are significantly narrower than have previously been reported. From the diamagnetic shift of the photoluminescence in magnetic fields up to 42 T, the spatial extent of the carrier wave function is estimated and compared with the geometrical size of the dots. This comparison allows a qualitative explanation of the narrow photoluminescence of the quantum dots grown on (3 1 1) planes.

Keywords: Self-assembled quantum dots; High-index substrate planes; (InGa)As–GaAs

There has recently been great interest in the properties of quantum dot (QD) semiconductor heterostructures. Such structures have been grown by a variety of techniques, including self-assembled growth on lattice-mismatched substrates by the Stranski-Krastanow method [1], and by selective etching and regrowth [2]. Self-assembled InAs QDs grown by the former method on GaAs substrates are the subject of intense interest because of possible applications in electro-optical devices. Although the photoluminescence (PL) spectrum from an individual QD is a discrete sharp line [1,3], the PL of an array of InAs QDs takes the form of a rather broad band in the energy range 1.1 eV–1.3 eV, with a line width (full-width at half-maximum) Δ typically around 50 meV due to the distribution of dot sizes.

This paper reports a high magnetic field study of the PL spectra of self-assembled InAs and In0.5Ga0.5As QDs on GaAs substrates with (1 0 0) and (3 1 1)A crystal orientations, respectively. A 0.68 nm In0.5Ga0.5As wetting layer (WL) on a (3 1 1)A substrate was also measured to compare with the QD structures. The structures were grown by molecular beam epitaxy. During growth of the strained layer, if QDs were required deposition was stopped as soon as the RHEED pattern showed a transition from 2D to 3D growth (1.13 nm for...
Fig. 1. PL spectra of (a) the (1 0 0) quantum dot (QD) and (b) the (3 1 1)A QD and wetting layer (WL) samples, at approximately equal intervals of magnetic field applied parallel to the growth axis. The values of the line width $D$ are for $B = 0$. The spectrum at $B = 0$ is at the bottom in each set of spectra. Spectra are offset vertically for clarity.

Fig. 2. Shift in energy $\Delta E$ of the PL line with magnetic field $B$ applied both parallel and perpendicular to the growth axis. The shifts of the PL lines ($\Delta E$) are shown in Fig. 2. The peak positions were obtained from Gaussian fits to the PL spectra.
The application of a weak magnetic field perturbs the electron and hole wave functions in the QD, affecting their spatial extent. In the limit of a weak magnetic field $B$ applied along the growth axis $z$, a diamagnetic shift of the PL energy is expected, proportional to $B^2$. The magnitude of the shift is dependent on the reduced effective mass of the electron and hole, $\mu$, and on the mean square spatial extent of the carrier (or exciton) wave function perpendicular to the applied magnetic field $\langle x^2 \rangle = \langle y^2 \rangle$ [7,8]. At very high magnetic fields, confining potentials become less important and Landau levels are formed, $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.

The diamagnetic shift for the (1 0 0) InAs QDs is very similar to that found in lower fields [8], but there is a deviation from quadratic behaviour at the higher very similar to that found in lower fields [8], but there as solid lines in Fig. 2. Landau levels are formed, conning potentials become less important and $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.

The diamagnetic shift for the (1 0 0) InAs QDs is very similar to that found in lower fields [8], but there is a deviation from quadratic behaviour at the higher very similar to that found in lower fields [8], but there as solid lines in Fig. 2. Landau levels are formed, conning potentials become less important and $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.

The application of a weak magnetic field perturbs the electron and hole wave functions in the QD, affecting their spatial extent. In the limit of a weak magnetic field $B$ applied along the growth axis $z$, a diamagnetic shift of the PL energy is expected, proportional to $B^2$. The magnitude of the shift is dependent on the reduced effective mass of the electron and hole, $\mu$, and on the mean square spatial extent of the carrier (or exciton) wave function perpendicular to the applied magnetic field $\langle x^2 \rangle = \langle y^2 \rangle$ [7,8]. At very high magnetic fields, confining potentials become less important and Landau levels are formed, $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.

The diamagnetic shift for the (1 0 0) InAs QDs is very similar to that found in lower fields [8], but there is a deviation from quadratic behaviour at the higher very similar to that found in lower fields [8], but there as solid lines in Fig. 2. Landau levels are formed, conning potentials become less important and $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.

The diamagnetic shift for the (1 0 0) InAs QDs is very similar to that found in lower fields [8], but there is a deviation from quadratic behaviour at the higher very similar to that found in lower fields [8], but there as solid lines in Fig. 2. Landau levels are formed, conning potentials become less important and $\Delta E$ increases more linearly with $B$, and is dependent on $\mu$ but not on $\langle x^2 \rangle$. Note that the value of $\mu$ may be different in the two limits for an inhomogeneous medium such as a QD. At intermediate fields, the magnetic field dependence is more complicated but can be fitted following the method of MacDonald and Ritchie for 2D hydrogenic systems [9], with only one fitting parameter, $\mu$. These fits to the data are shown as solid lines in Fig. 2.
extent of the carrier wave functions in the different samples has been compared with the geometrical dot size. A qualitative model has been proposed to explain the narrow PL of the quantum dots grown on the (3 1 1)A plane.

R.K.H. and L.E. are grateful for fellowships from JSPS and EPSRC, respectively. M.H. acknowledges financial support from the British Council. This work is supported by Monbusho and EPSRC.

References