Heterodimensional Charge-Carrier Confinement in Sub-Monolayer InAs in GaAs

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Abstract

Low-dimensional semiconductor nanostructures, in which charge carriers are confined in a number of spatial dimensions, are the focus of much solid-state physics research, offering superior optical and electronic properties over their bulk counterparts. Both two-dimensional (2D) and zero-dimensional (0D) structures have seen wide-ranging applications in laser diodes, solar cells and LEDs to name but a few. Here we present the concept of heterodimensionality: the ability of a structure to confine electrons and their positive counterparts, holes, in different dimensionalities. Our heterodimensional samples contain stacked layers of sub-monolayer (SML) indium arsenide (InAs) depositions in gallium arsenide (GaAs), i.e. incomplete single atomic layers of InAs in a GaAs matrix. The <1 monolayer cycled deposition of InAs in GaAs results in the formation of In-rich InGaAs agglomerations within a 2D InGaAs "quantum well" (QW) of lower In concentration [1]. We have seen experimentally that holes are confined within these In-rich regions - our quantum dots (QDs) - whilst electrons see only the QW.

These results are backed up by a COMSOL Multiphysics® model of the energy levels within our structure. The Conical Quantum Dot model was used as a base for modelling the system as a 5-nm-wide spherical QD with high In concentration within an infinitely-wide 13-nm-high QW with lower In concentration (Fig. 1). The geometric dimensions were picked because of their similarity to a typical SML stack.

Electron and hole energy levels were calculated and the values compared to the conduction and valence band edge energies (EC and EV, respectively, in Fig. 1). In agreement with experimental results, holes are confined within the QD whilst electrons are in the QW (Fig. 1).

To give further weight to this argument, the calculation was repeated iteratively over all possible In concentrations, enabling us to draw a "phase diagram" for electron and hole confinement within the system (Fig. 2) The heterodimensional phase occupies the largest and most probable region on the diagram.

High-speed lasers using SML systems have already been fabricated using this system, demonstrating speeds up to 30 Gbits/s [2]. Such speed may be a direct consequence of this

heterodimensionality, which offers both the advantages of a 2D system, such as efficient carrier injection, and a 0D system, such as quantized energy states. We also expect our research to provide an insight into other technologically important devices where composition-driven carrier localization is important.

Reference

1. A. Lenz et al., Applied Physics Express 3, 105602 (2010); A. Lenz et al., J. Vac. Sci. Technol. B 29, 04D104 (2011).

2. N. N. Ledentsov et al., Nanoscale Res. Lett. 2, 417 (2007).

Figures used in the abstract

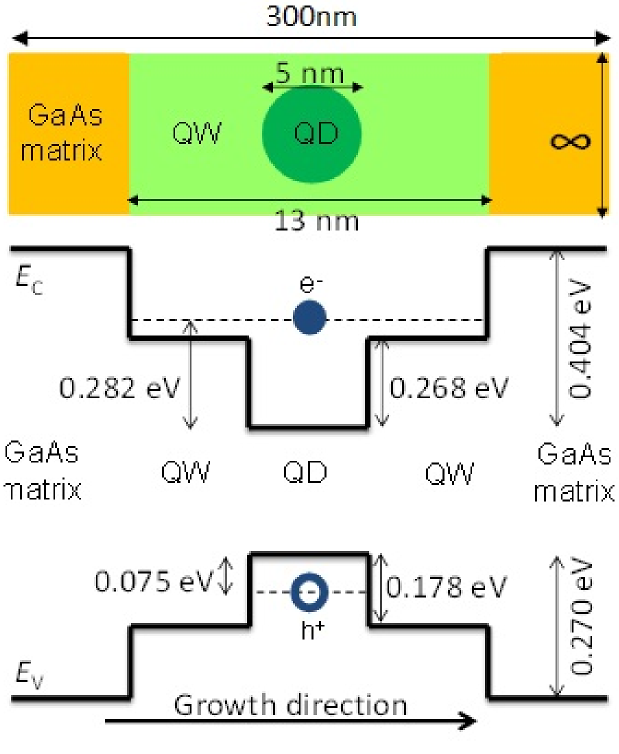

Figure 1: The upper part shows the geometry of the model and the lower part shows the calculated energy levels for a QD with In content x = 0.5 and a QW with In content y = 0.15. Holes are confined to the QD, whilst electrons are in the QW.

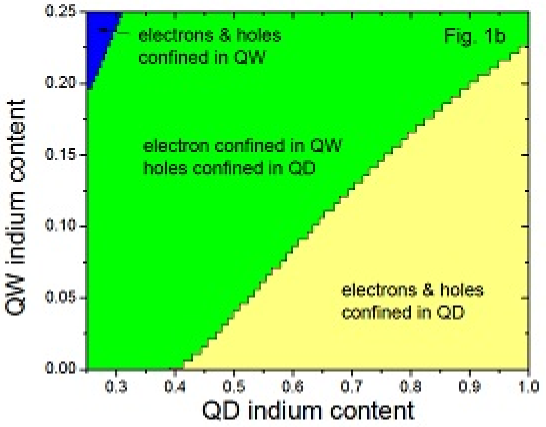

Figure 2: Phase diagram of electron and hole confinement for a 5-nm, spherical In(x)Ga(1-x)As QDs in a 13-nm In(y)Ga(1-y)As QW. The heterodimensional phase (2D electrons and 0D holes) occupies the most likely regions of the parameter space.