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# TEM Analysis of InGaAs/GaAs Quantum Well-Quantum Dot Structures for Optoelectronics Applications

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Semiconductor heterostructures with quantum-size objects are widely used for optoelectronic devices such as laser diodes, light-emitting diodes (LEDs) and photoelectric (PV) convertors [1-3]. Both quantum wells and quantum dots are of high interest because they expand the spectral range in these devices. The hybrid quantum wells - quantum dots (QWD) may be of special interest for PV applications [4,5]. The structure-properties relationship is known to play an important role in optimization of the growth of the device structures to achieve the defect-free structures with the best optical properties. Therefore, we studied the structural transformation of $In_{0.4}Ga_{0.6}As$ thin layers deposited using MOCVD in 3D growth mode on vicinal GaAs substrates and their effect on the optical properties.

The structures studied were grown in a low pressure MOCVD reactor using hydrogen as carrier gas in the temperature range of 500-700$^{o}$C. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl) and diethylzinc (DEZn) were used as metal atom precursors. Arsine ($AsH_3$) and silane ($SiH_4$) were used as As and Si atom precursors, respectively. Growth was carried out on vicinal (100) GaAs substrates. Hybrid QWD structures were formed by depositing $In_{0.4}Ga_{0.6}As$ in the kinetically limited 3D growth mode and then capped with 40-nm-thick GaAs spacers grown in the 2D growth mode. Both photoluminescence (PL) and transmission electron microscopy (TEM) were employed to analyze the InGaAs QWD layers in a GaAs matrix surrounded with $Al_{0.3}Ga_{0.7}As$ barrier layers. PL spectra were recorded with 532-nm YAG:Nd laser and cooled Ge photodiode using the conventional lock-in technique. FEI Titan 80-300 electron microscope was employed to characterize cross-sectional samples.

Figure 1 shows cross-section TEM images of selected fragments of the structure containing 15 QWD layers formed by deposition of $In_{0.4}Ga_{0.6}As$ with nominal thickness of 8.1 ML. Each $In_{0.4}Ga_{0.6}As$ layer represents a two-dimensional quantum well with thickness and composition modulation (Fig. 1). This can be viewed as two-dimensional quantum well with surface corrugation that forms In-rich islands with high base-to-height aspect ratio of 4-7 and high surface density of about 3-5 x $10^{11}$ $cm^{-2}$ per layer. Such corrugation is caused by 3D growth of top InGaAs layer, whereas the bottom GaAs-to-InGaAs interface remains smooth owing to 2D growth of GaAs spacers. The composition modulation within the InGaAs layer has been confirmed by both EDS spectroscopy (not shown) and HAADF STEM imaging of the cross-sectional samples (see for example Fig. 1c).

Such In-rich islands are responsible for emission/absorption peak around 1.05 um in PL spectra (Fig. 2) taken at room temperature (RT) and 100K. Figure 2 shows the PL data from structure with one QWD layer formed by deposition of 8.1 ML of $In_{0.4}Ga_{0.6}As$ for different excitation powers. The RT spectrum recorded at low excitation density demonstrates a dominant peak at 1050 nm and a longer-wave shoulder at 1120 nm. The spectral position of the peak around 1.05 um can be controlled by the effective thickness of InGaAs deposited. Also, a two-dimensional quantum well, which can be treated as a thick wetting layer, is formed giving rise to spectral features at ~0.95 um. In addition, InGaAs islands with low surface density were revealed in TEM images. The structures have been shown to be promising for PV applications [6].

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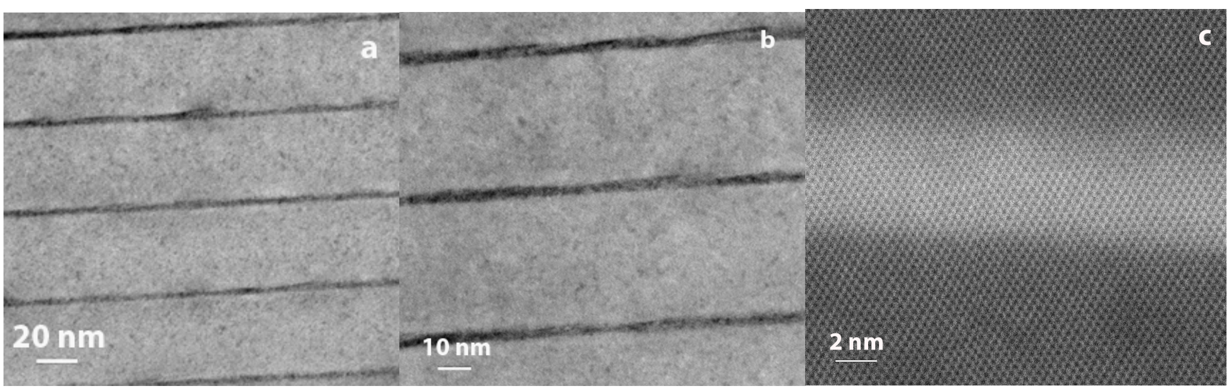


**Figure 1.** Typical bright field TEM (a,b) and HAADF STEM (c) images of $In_{0.4}Ga_{0.6}As$ QWD layers.

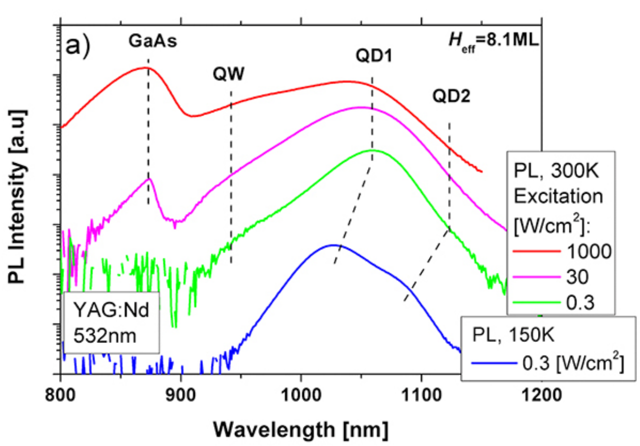


**Figure 2**. Room temperature and 150K (shifted for better clarity) PL spectra recorded at different excitation for one QWD layer based on $In_{0.4}Ga_{0.6}As$ with effective thickness of 8.1 ML.