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Self-Assembled Quantum Dots: Engineered Gain Medium

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1. Introduction

Self-assembled quantum dots (QDs) exhibit three-dimensional quantum confinement and give rise to fundamentally different electronic properties that make them desirable for many applications. For example, it was predicted that laser diodes with QD gain medium would have superior thermal, modulation characteristics and reliability as compared to the conventional quantum well (QW) lasers [1, 2]. However, these exciting benefits have not evolved into devices so far due to inhomogeneous broadening of the QD electronic spectrum resulting from the size dispersion of QDs, relatively slow relaxation of carriers to the ground level in the QDs, relatively low gain of the QD medium, existence of excited states in the dots and evaporation of carriers from the dots to the wetting layer and barrier. The indicated problems can potentially be solved using various nano-engineering approaches. The focus of the paper is on the management of QD properties through design and molecular beam epitaxial growth and modification of QD heterostructures.

2. Experimental

All the studied self-assembled QD heterostructures were grown on n-GaAs(001) substrates using an EPI Mod Gen II MBE system. Typical QD growth conditions are a follows: growth temperature 470 ^{0}C, InAs growth rate of 0.05 ML/s (ML stands for monolayer), flux ratio As_2/In = 10, and total thickness of InAs coverage of 2.4 ML. In-situ RHEED and Auger spectroscopy were used to study formation, evolution and decay of QDs on the surface as well as overgrowth dynamics. AFM and TEM imaging were employed for structural studies, and photoluminescence spectroscopy for optical characterization.

3. Results and Discussion

Development of a QD ensemble for laser gain medium is usually a set of trade-offs within a quite narrow window of parameters limited by kineics and thermodynamics of self-assembly. In fact, usually the improvement of one particular parameter (e.g. narrowing size distribution) results in degradation of other properties (e.g. emission efficiency). Therefore, development of the methods to control optical properties of QD medium is essential for progress in applications.

The benefits of QDs are mainly related to strong localization of carriers. In order to increase the bandgap of the barrier for QDs, we have employed an AlAs/GaAs short period superlattice (SPSL) which can be grown at low temperature (< 500 ^{0}C). In addition, SPSL provides another variable to control QD growth on either GaAs or AlAs surfaces. Manipulation of underlayer chemistry was used for fine tuning of the QD sizes and density. Intermediate properties were obtained for QDs grown on 1 ML of GaAs on SPSL terminated by AlAs. These QDs with AlAs capping exhibit reduced volume with E_{gr} = 1.11eV, narrow size distribution (FWHM = 34 meV), large ground-to-excited state separation energy Δ_{exc} = 87meV, and acceptable PL intensity. This QD ensemble might be considered as a first pass optimized design of a laser medium.

The analysis of QD capping results reveals two processes on the surface. The first one is an evolution of QDs towards larger sizes and lower densities with time. The second effect is the surface redistribution of In out of the QDs on top of the growing capping layer. The effectiveness of AlAs as compared with GaAs as a capping layer for QDs is attributed to “freezing” of the growth surface during capping, and prevention of QD evolution on the surface

We also employed shape-engineering process which resulted from In-redistribution from partially overgrown dots [3]. These QDs with a shape of truncated pyramids with flat tops entirely covered by the AlAs layer, have demonstrated better volume uniformity with the PL FWHM of 29 meV The beneficial (more symmetrical) shape of the QDs was shown to increase the electron-hole coupling and ground-to-excited state separation energy up to 90-100 meV.

Thermal escape of carriers from the QDs reduces gain and modulation performance of the laser medium. Strong localization requires a large barrier to escaping of the carriers, large ground-to-excited state separation energy, and lack of any intermediate levels with high density of states such as those in a wetting layer. In general, this set of requirements is good enough to ensure localization as long as the relaxation process of carriers to the QD ground state is fast enough [4]. It should be emphasized that the wide bandgap barrier by itself is not enough to guarantee strong localization in the dots. We engineered the QD heterostructures to enhance the carrier localization by placing the dots into narrow wells, and destroying the influence of the wetting by a 2ML AlAs coverage. These steps resulted in large observed barrier for escape from QDs (450 meV) Because of strong localization at high temperatures, these QDs exhibited unsurpassed, over two orders of magnitude higher defect tolerance than QWs at room temperature against defects introduced by ion implantation (Fig. 1) [4]. This QDs ensemble has been used in edge-emitting laser diodes that demonstrated unsurpassed thermal stability with a maximum lasing temperature of 219^{o}C and an extremely high characteristic temperature of 380 K at room-temperature operation [5].

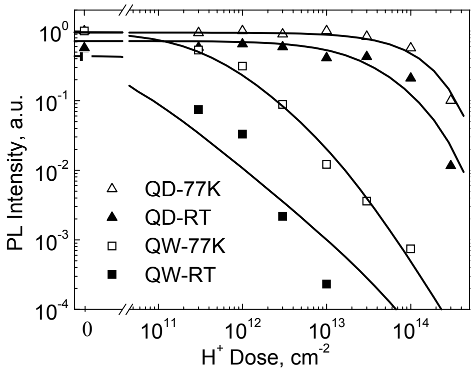

Fig. 1 Quenching of the integrated PL intensity vs. irradiation proton dose of nano-engineered QD and QW structures at 77 and 300 K. Solid lines correspond to dynamic model [4].

The maximum (saturation) gain of a QD medium (Table 1) is significantly less than that of quantum wells (QWs). This value can be increased by engineering approaches described above: reduction of inhomogeneous broadening, enhancement of overlap between electrons and holes, and reduction of carriers escape. Another effective way to improve the gain is to increase capture to the lasing level using tunnel injection of carriers into QDs from a QW.[6] The QW is working as a reservoir for electrons and holes with high density of states and, therefore, with large capture cross-section.

Table I. Comparison of engineered multiple-layer QD gain medium without and with tunnel injection in edge-emitting lasers. J_{th} is a laser threshold current and L_{min} is a minimum cavity length for lasing in a waveguide with cleaved mirrors

MQD laser medium	3xQD	7xQD	4x(QDs on QW)	3x(QW on QDs)
Lasing wavelength, μm	1.22	1.12	1.16	1.13-1.11
Minimum J_{th}, A/cm^2	56	155	95	255
L_{min}, mm	0.87	0.41	0.49	0.13
Max. modal gain (per layer), cm^{-1}	16 (5.3)	31 (4.4)	26 (6.6)	~90 (30)

We have developed tunnel QD-on-QW and QW-on-QDs structures with a QD ground state transition which is red-shifted ~35 meV relative to QW ground state [7]. This transition with narrow linewidth, 21.6 meV at T=77K, indicates an efficient LO-phonon assisted tunneling of carriers from QW into QD states. Optimized triple-pair tunnel QW-on-QDs laser diodes (Fig.2) emitting at 1145 nm exhibited a saturated modal gain exceeding 90 cm^{-1} with minimum cavity length of 0.13 mm (Table I). Small signal modulation characteristics of these lasers were measured. From the damping factor and resonance frequency dependence on driving current, the damping-limited cut-off frequency for this QW-on-QDs medium can be estimated as exceeding 30 GHz. All-epitaxial vertical cavity surface emitting lasers with triple-pair tunnel QW-on-QDs as active medium demonstrated continuous wave mode lasing at 1130 nm, with 1.8 mA minimum threshold current, 0.7 mW optical power, and 12 % slope efficiency.

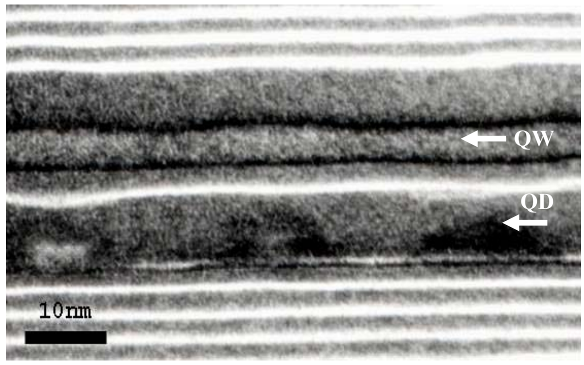

Fig. 2 TEM (200) dark-field micrographs of tunnel QW-on-QDs structure: 3 nm-thick $In_{0.33}Ga_{0.67}As$ QW separated from the top of InAs QDs by a 4.5 nm-thick GaAs and AlAs (2ML) barrier.

3. Conclusions

We studied formation and properties of InAs QDs self-assembled on surfaces of different compositions, QD capping and shape-engineering within the molecular beam epitaxy reactor. These approaches were employed to control size, density, shape, and ultimately both homogeneous and inhomogeneous electronic spectrum of QDs. Band engineering of QD to enhance carrier localization, as well as tunnel injection from quantum wells to accelerate carrier transfer to the lasing state, were used to improve optical gain and efficiency of the QD medium. Beneficial properties of the developed QD media were demonstrated at room temperature in thermally stabile laser diodes, lasers with high waveguide modal gain, and in all-epitaxial VCSELs.

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