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InAs Self-Assembled Quantum Dots Coupled with GaSb Monolayer Quantum Well

Masaomi Yamaguchi[1], Yoshihiro Sugiyama[1], Yoshiaki Nakata[1], Toshio Ohshima[2], Hirotaka Sasakura[3], Shunichi Muto[3], Yuji Awano[1], and Naoki Yokoyama[1]

[1]Fujitsu Limited, [2]Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan
Tel: +81-46-250-8247, Fax: +81-46-250-8844, Email: masaomi@qed.flab.fujitsu.co.jp
[3]Department of Applied Physics, Faculty of Engineering
Hokkaido University, N-13, W-8, Kita, Sapporo, Hokkaido 060-8628, Japan

1. Introduction

Because of the zero-dimensionality of density of states in quantum dot (QD), QD has great potential in both optical and electron devices in terms of high performance and new concept device[1,2]. So far, we have shown a possibility of wavelength multiplexing optical memory (holeburning memory) using InAs self-assembled quantum dots (SAQDs) buried in GaAs pin diode[3]. Since InAs/GaAs QD is type I heterostructure, external bias is necessary to separate electron from hole in InAs/GaAs QD. However, part of the residual hole also tunnels from the QD, which decreases the retention time. Therefore, QD coupled with type II heterostructure of which either type of carrier can tunnel from QD to quantum well (QW) (or QD) without applying external bias is appropriate to improve the retention time of the residual carrier. In addition, energy or spin relaxation between 0D and 2D (0D) in such a coupled heterostructure also attract much interest not only for physics but also for novel devices in quantum computing[4].

In this paper, we report the first proposal of QD coupled QW structure using InAs SAQD and GaSb monolayer (ML) QW, and corresponding results on AFM and TEM observations. We also report a tunneling barrier thickness dependence of photoluminescence (PL) spectrum to investigate the hole tunneling from QD to QW varying the barrier thickness from 43 ML to 9 ML.

2. Proposal of InAs SAQDs Coupled with GaSb monolayer Quantum Well

We propose a coupled quantum structure consisting of InAs SAQDs as an optical absorption layer and GaSb ML QW as a hole trapping layer combined with GaAs tunneling barrier layer as shown in Fig. 1(b). A biased type I QD is also shown for comparison. This structure of (b) allows hole at the ground state of SAQD to tunnel without external bias through the potential barrier to the QW more easily than to QD because of the band continuum of 2D above the ground state in GaSb ML QW.

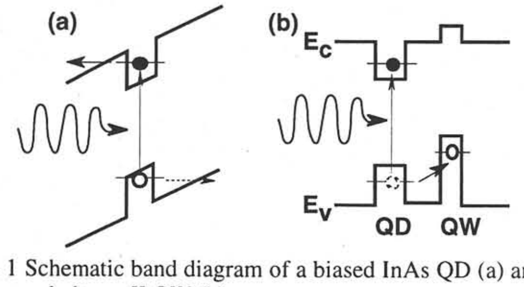

Fig. 1 Schematic band diagram of a biased InAs QD (a) and a QD coupled type II QW (b).

3. MBE growth

Samples used in this experiment were grown by conventional molecular beam epitaxy. A 100-nm-GaAs buffer layer was grown on (001) semi-insulating GaAs substrate at 600°C, followed by 100-nm-$Al_xGa_{1-x}As$ (x=0.2) buffer layer, and 100-nm-GaAs buffer layer. The growth temperature (T_g) of the second GaAs buffer layer was controlled from 600°C to 510°C at the top surface. Subsequently, Sb_4 beam was supplied to the GaAs buffer layer for 5 seconds[5], followed by monolayer GaSb growth, Sb_4 beam supply for 140 seconds[5], GaAs barrier layer (thickness, L_B), 2 ML InAs, 100-nm-GaAs overgrowth layer increasing T_g from 510°C to 600°C, 50-nm-$Al_xGa_{1-x}As$ (x=0.2) layer, and 30-nm-GaAs cap layer. AFM and cross-sectional TEM (XTEM) were used to estimate the structure of the SAQDs. AFM was measured in the atmosphere.

Fig. 2 shows AFM image of InAs islands grown on GaAs. Typical island density was 4.3×10^{10} cm^{-2} and average lateral size was 27 nm. Similar result was obtained with the coupled structure with GaAs barrier thickness of 43 ML, excepted a slightly different dot density.

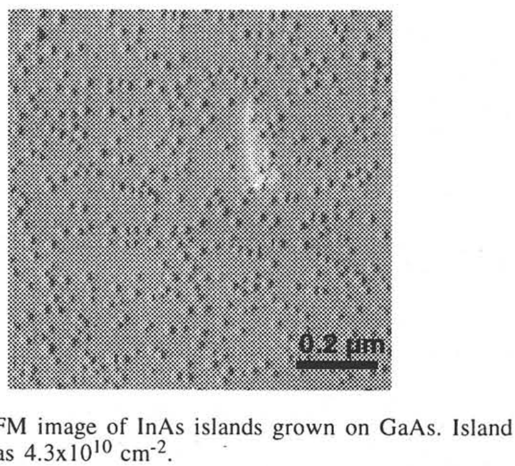

Fig. 2 AFM image of InAs islands grown on GaAs. Island density was 4.3×10^{10} cm^{-2}.

Fig. 3 shows the XTEM image of the coupled structure with L_B=43 ML. Schematic sample structure is also shown. We can see that the wetting layer of GaSb was clearly observed under the GaAs barrier layer, and InAs SAQDs were successfully grown on the GaAs barrier layer. The same result was obtained even with L_B=13 ML. Accounting for the supply rate of Ga and Sb_4 beams, the GaSb wetting layer is considered to be a monolayer structure. The dot density estimated by XTEM was almost the same as that of AFM.

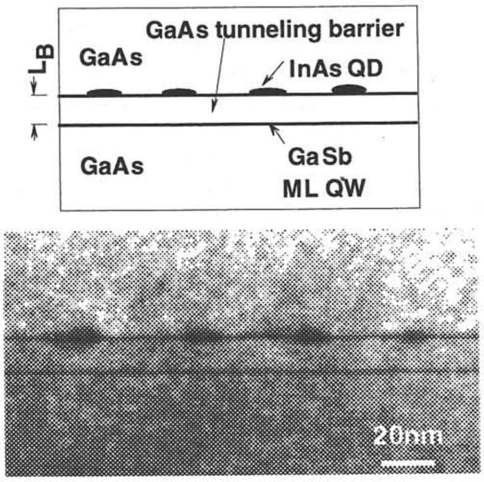

Fig. 3 Cross-sectional TEM image of InAs SAQDs coupled with GaSb ML QW. GaAs barrier thickness of L_B was 43 ML. Schematic sample structure is also shown.

4. Photoluminescence properties

Fig. 4 shows PL spectra of InAs SAQDs (a) and GaSb ML QW (b), at 77K respectively. Each sample was made for reference, independently. Ar ion laser and a cooled Ge pin diode were used. Typical excitation power was 10 mW. The peak energies from (a), (b) were 1.22 eV and 1.26 eV, respectively. PL of GaSb ML QW shows slight blue shift for excitation intensity, which seems to be type II heterostructure[5].

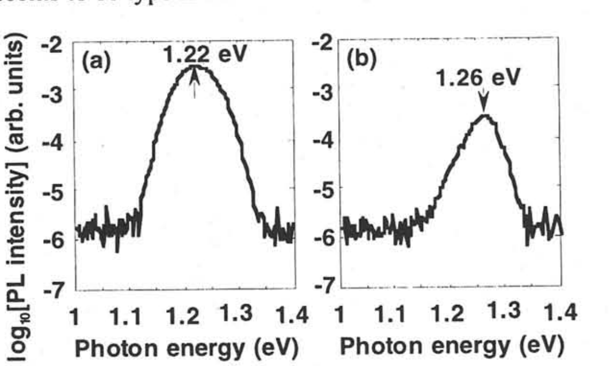

Fig. 4 PL from InAs SAQDs (a) and GaSb ML QW (b). Spectra of (a), and (b) were obtained from independent samples.

Fig. 5 shows the PL spectra of InAs SAQDs coupled with GaSb ML QW with L_B=43 ML and 9 ML. PL peak energy decreased as L_B decreased. PL peak energy of L_B=9 ML is around 1.1 eV that corresponds to the separation energy between the electron ground state of InAs SAQDs (1e(QD)) and the hole ground state of GaSb ML QW (1h(QW)). The coupled heterostructure enhances the tunneling rate of hole at the ground state (1h(QD)) due to the decrease of tunneling barrier thickness and the radiative recombination rate between 1e(QD) and 1h(QW). Therefore, PL of InAs QD decreases and PL of 1e(QD)-1h(QW) transition increases. These relationship on the band diagram was shown in Fig. 6. The result of Fig. 4 was also included. The appearance of PL around 1.1 eV shows the hole tunneling between 1h(QD) and 1h(QW) because the separation energy between the

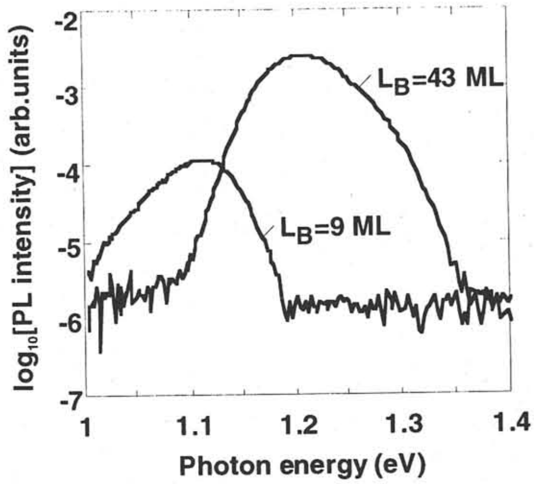

Fig. 5 PL spectra of InAs SAQDs coupled with GaSb ML QW having GaAs barrier thickness of 43 ML and 9 ML, respectively, at 77K.

1h(QW) and 1h(QD) is estimated to be 0.11 eV taking 1e(QD) to be -0.15 eV from the conduction band edge of GaAs[6]. TDPL is needed to discuss this phenomenon, and will be presented at the conference.

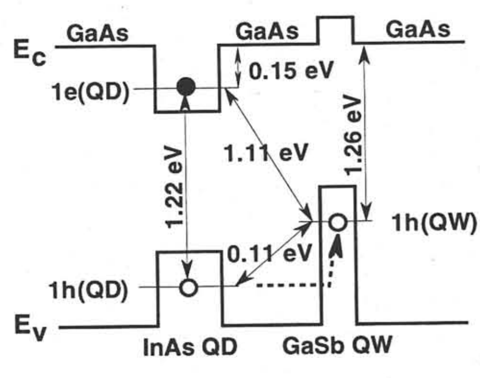

Fig. 6 The obtained schematic band diagram of InAs SAQDs coupled with GaSb ML QW.

5. Conclusion

In summary, we have proposed the InAs self-assembled quantum dots coupled with GaSb monolayer quantum well for the application of optical memory and novel device for quantum computing. We successfully obtained the coupled structure by MBE. PL peak energy decreased as the GaAs barrier thickness decreased. The lower energy peak is considered to be the transition between 1e(QD) and 1h(QW). This shows the hole tunneling between QD and QW.

Acknowledgments

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