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Surface-Related Reduction of Photoluminescence in GaAs Quantum Wires and Its Recovery by New Passivation

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Abstract

Etched GaAs quantum wires (QWRs) and selectively grown (SG) QWRs were fabricated, and dependence of their photoluminescence (PL) properties on QWR width, W , and QWR distance to surface, d , were investigated. PL intensity greatly reduced with reduction of W and d , due to non-radiative recombination through surface states. Surface passivation by growing a Si interface control layer (Si-ICL) on group III-terminated surfaces greatly improved PL properties.

Keywords: GaAs, AlGaAs, quantum wire, surface passivation, surface states, photoluminescence

1. Introduction

Low-dimensional III-V nanostructures such as quantum wires (QWRs) and quantum dots (QDs) are promising candidates of basic building blocks for next generation electronics and photonics. However, III-V materials possess high-density surface states, and their effects increase in nanostructures due to increased surface-to-volume ratio. In fact, the photoluminescence (PL) intensity of GaAs quantum wells (QWs)[1, 2] and etched QWRs [3] was reported to reduce drastically with reduction of feature sizes. However, its mechanism as well as a method to avoid it has not been established so far.

In this paper, effects of the surface related key structural parameters on the PL properties were investigated for two typical GaAs QWR structures, i.e., the etched QWR and the selectively grown (SG) QWR. Then, attempts were made to recover PL intensity by a new surface passivation process of growing a Si interface control layer (Si-ICL) on group III-terminated surfaces which was recently found to be very effective [4, 5].

2. Structure and fabrication of QWR samples

The structure of the etched QWR is shown in **Fig. 1(a)**. QWR arrays running along $\langle -110 \rangle$ direction were fabricated by EB lithography and wet chemical etching on an MBE grown (001) wafer having $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}/\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$ (buffer) layers. For this QWR having air-exposed side edges, the geometrical wire width, W , was taken to be the key structural parameter. QWR arrays, having different values of

W, and the same nominal total area for PL emission, were formed on a same chip in order to avoid chip-to-chip variations of optical set-up for PL measurements.

The selectively grown (SG) QWR sample is shown in **Fig. 1(b)**. It was formed by using our selective MBE growth process [6]. Namely, an array of mesa stripes running along <-110> direction was formed on (001) GaAs substrate by EB lithography and wet chemical etching. Then, GaAs buffer ridge structures were grown by MBE. Subsequently, by growing Al_{0.3}Ga_{0.7}As/GaAs/ Al_{0.3}Ga_{0.7}As structure on ridges by MBE, completely embedded QWRs were formed due to selective growth. For this QWR, the distance, d, between surface and QWR i.e., the thickness of the Al_{0.3}Ga_{0.7}As top barrier layer, was taken to be the key structural parameter. The value of d was systematically reduced by changing the growth thickness of the top AlGaAs layer.

3. Effects of Key Structural Parameters on PL Properties

Both types of QWR structures exhibited clear PL peaks originating from QWRs. Examples of PL spectra obtained at 25K from an etched QWR with W = 1600nm and a SG QWR with d=300nm are shown in **Figs. 2(a)** and **(b)**, respectively. The observed values of energy positions of both types of QWRs were in agreement with the calculated values where the blue shifts came mainly from vertical confinements. In the case of the SG QWRs, additional PL peaks coming from bottom and side quantum wells (QWs) were also observable in agreement with our previous study [6], and a Gaussian deconvolution of peaks were made in order to determine the height of the main QWR peak.

Figures 3(a) and **3(b)** summarize the observed dependences of the QWR PL peak intensity at 25K on the key structural parameters, W and d, for both types of QWR samples. Both of the structural parameters, W and d, exhibited strong influences on the PL intensity. Namely, PL intensity started to drop very rapidly when the value of W or d is reduced below a certain critical value of W = 800 nm or d = 100 nm.

This remarkable size effect of PL intensity can be explained in terms of surface recombination through surface states at QWR edge or at QWR surface via tunneling. To show this, the present etched QWR structure and the SG QWR structure are replaced by simple models shown in **Figs. 4 (a)** and **(b)**, respectively. Here, each QWR is represented by a rectangular stripe with a width, W, and a thickness, t. W_o is the width of the depletion layer due to Fermi level pinning at air exposed edge, or the so-called “dead” layer, which is present at both edges of the etched QWR. To proceed further, we assumed that rates of the radiative recombination and non-radiative surface recombination processes are both limited by supply of minority carriers (holes) under weak excitation, and that the QWR width, W, is smaller than the diffusion length of minority carries in the QWR. Then, the PL intensity, I_{PL}, from the etched QWR and from the SG QWR is given by the following simple equation (1a) and (1b), respectively.

$$I_{PL} = A_1 \frac{1}{1 + \frac{2\tau_{RAD}S}{W - 2W_0}} \phi \quad (1a)$$

$$I_{PL} = A_2 \frac{1}{1 + \frac{\tau_{RAD}S}{t} \exp(-\alpha d)} \phi \quad (1b)$$

where S is the surface recombination velocity measured directly on the QWR surface when it is exposed to air, τ_{RAD} is the radiative lifetime of minority carriers in QW, α is the tunneling decay rate of the minority carrier wave function within the barrier layer, φ is the incident photon excitation flux intensity, and A₁ and A₂ are constants related to minority carrier supply from barrier region and photon collection efficiency for both QWR structures. Both of the above equations give constant PL intensities at large values of W and d, and rapid

reduction of PL intensities takes place when W and d are reduced, being in good agreement with experiments in spite of simplifications of QWR structures and of various assumptions. The gradual change of PL intensity above the exponentially decaying region seen in **Fig. 3(b)** is due to change of carrier supply from barrier layers as discussed previously for InP-based QWRs [7].

4. Effects of Si-ICL-based Passivation

To attempt to remove observed surface state effects, our Si-ICL based surface passivation process described in Refs. [4,5] was applied to two QWR structures. Namely, after irradiating Ga flux on the QWR surface to change the surface from the As-rich one to the group III-rich one, a 1nm-thick Si layer was grown on the QWR surface at a substrate temperature of 300 °C from a Si K-cell held at 1,215 °C. Then, the Si-ICL was subjected to direct partial nitridation at room temperature, using a nitrogen radical beam.

MIS C-V curves taken on a planar GaAs MIS test structure having a Si-ICL gave larger capacitance variations up to high frequencies with smaller frequency dispersion than those of the sample without Si-ICL. A minimum interface state density in the $10^{10}\text{cm}^{-2}\text{eV}^{-1}$ range was achieved. The results of passivation of two types of QWRs are shown in **Figs. 5(a)** and **(b)** with reference to the cases without Si-ICL. Remarkable increase of PL intensity is evident in both cases. The improvement is also plotted in **Figs. 3(a)** and **(b)**. The result gives a great promise for future.

5. Conclusion

In two typical GaAs QWR structures, i.e., the etched GaAs QWR and the selectively grown (SG) QWR, the PL intensity reduced drastically with reduction of their surface related geometrical sizes due to non-radiative recombination through surface states. Surface passivation by our new Si-ICL process greatly recovered PL intensities.

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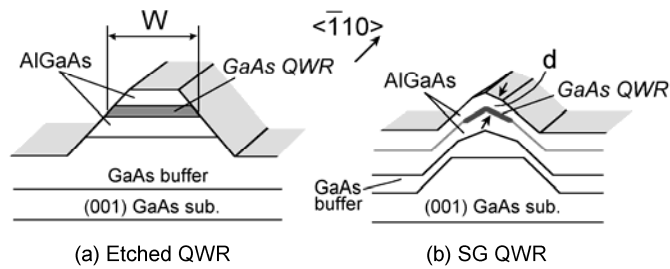


Fig.1. Structures of QWR samples: (a) Etched QWR and (b) Selectively-Grown QWR.

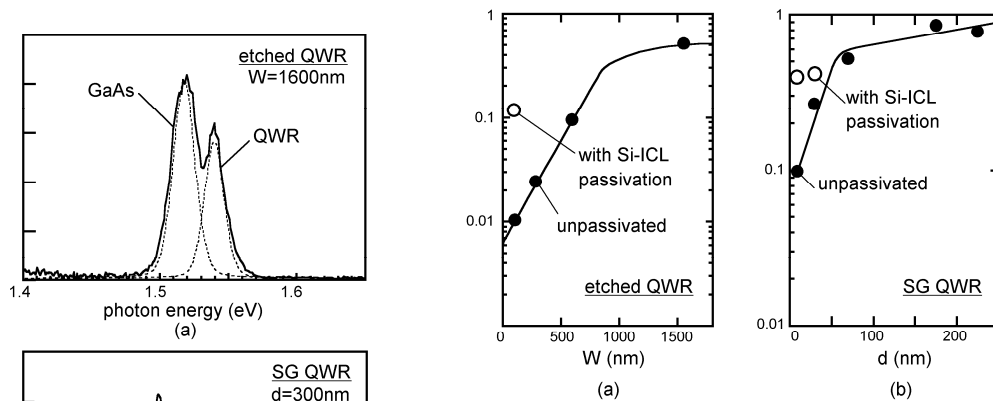


Fig.3. Effect of variation of structural parameters (W and d) on PL intensities for: (a) etched QWR and (b) selectively grown QWR.

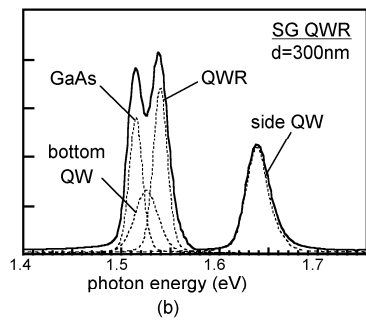


Fig.2. Examples of measured PL spectra obtained from: (a) etched QWR and (b) selectively grown QWR.

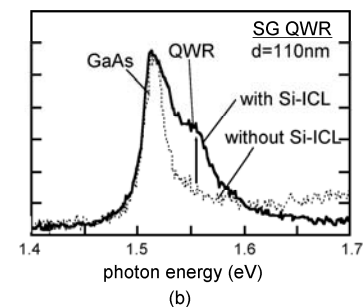
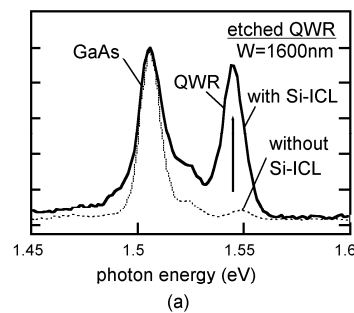


Fig.5. Effect of Si-ICL passivation on two QWR samples: (a) etched QWR and (b) selectively grown QWR.

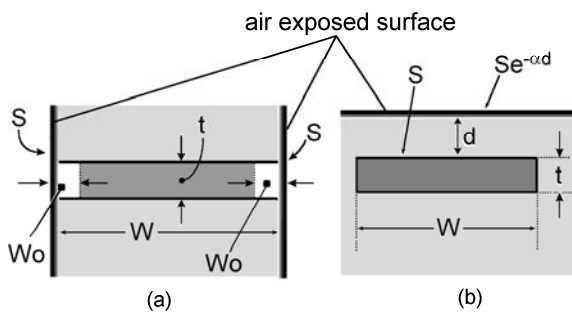


Fig.4. Simplified models for: (a) etched QWR and (b) selectively grown QWR.