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Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp526-527

Droplet epitaxial growth of 1.55-μm wavelength InAs quantum dots on metamorphic InAlAs / GaAs(111)A

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Abstract

We demonstrated the droplet epitaxial growth of InAs quantum dots (QDs) emitting at telecommunication wavelengths on metamorphic InAlAs formed on GaAs (111)A substrates. We found that high quality metamorphic InAlAs can be formed on GaAs (111)A by inserting a thin InAs layer. On the InAlAs, InAs QDs were formed via droplet epitaxy. Most of the QDs exhibited a symmetrical shape due to C_{3v} symmetry of the surfaces. Photoluminescence (PL) from the capped QDs shows broad-band spectra which cover both at 1.3 and 1.55 μm. The strong PL signal was maintained up to room temperature.

1. Introduction

Self-assembled InAs quantum dots (QDs) have been intensively investigated by many groups for the application to the optical-fiber telecommunication (telecom) devices. For the InAs QD emission at a wavelength of around 1.3 μm, GaAs-based system has been usually used.[1] To achieve 1.55-μm wavelength emission, in contrast, InP-based system has been often used since large lattice mismatch between InAs and GaAs results in the significant blueshift of the QD emission.[2] However, the use of GaAs-based system is still highly desired for the emission at 1.55 μm when we consider the cost, thermal conductivity, and formation of high quality distributed Bragg reflectors (DBRs).[3]

Very recently, we have reported the formation of highly symmetrical InAs QDs on InAlAs/InP (111)A substrates by droplet epitaxy (DE), and demonstrated QD emissions at a wavelength of 1.5 μm toward the application to the on-demand entangled photon emitters.[4] In this paper, we report the combination of the DE technique with the formation of a high quality metamorphic InAlAs buffer layer on GaAs (111)A, which is also a newly developed technique. As a result, we create symmetric 1.55 μm QDs directly on GaAs substrates.

2. Experimental

The samples were grown on GaAs (111)A by solid source molecular beam epitaxy. After the growth of a 50-nm GaAs buffer layer at 500 °C, we grew 3 monolayers (ML) of InAs at 470°C. Then, 100-nm thick $In_{0.52}Al_{0.48}As$ was grown at the same temperature. For the formation of InAs QDs on $In_{0.52}Al_{0.48}As$, firstly, 0.4 ML (0.2 ML/s) of indium was supplied at 320°C without an As_4 flux. Next we supplied an As_4 flux of 3.0×10^{-5} Torr at 270°C for crystallization of indium droplets into InAs QDs. After annealing at 370°C for 5 min under an As_4 flux, InAs QDs were capped by a 75-nm $In_{0.52}Al_{0.48}As$ at 370°C. Finally, the samples were annealed at 470°C for 5 min to improve crystal quality.

Atomic force microscopy (AFM) and X-ray diffraction (XRD) have been used to characterize the surface morphologies and crystal structures. For the study of optical properties, we measured photoluminescence (PL) spectra using an InGaAs diode array detector at 9 K and room temperature.

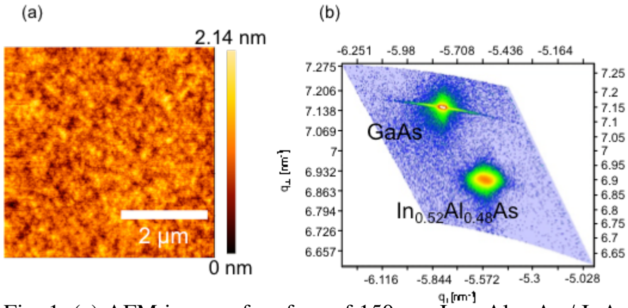

Fig. 1. (a) AFM image of surface of 150-nm $In_{0.52}Al_{0.48}As$ / InAs / GaAs(111)A, and (b) two dimensional reciprocal space map for 115 reflections GaAs and $In_{0.52}Al_{0.48}As$. $q_{\perp}$ and $q_{//}$ are the inverse lattice spacing along [111] and [-1-12] directions, respectively.

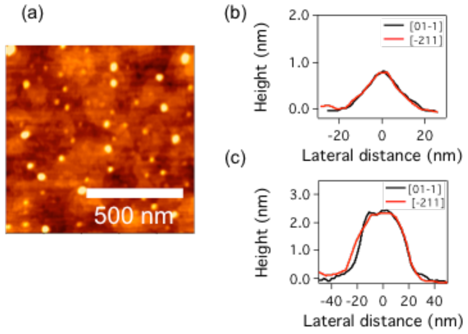

Fig. 2. (a) AFM image of uncapped InAs QDs on $In_{0.52}Al_{0.48}As$ / InAs / GaAs (111)A, and cross-sectional profile of (b) small QDs and (c) large QDs.

3. Results and discussion

Quality of metamorphic InAlAs

Figure 1(a) shows an AFM image of a surface of 150-nm $In_{0.52}Al_{0.48}As$ / 3-ML InAs / GaAs(111)A. A flat and smooth surface is clearly visible. The root-mean-square roughness is only 0.37 nm. Figure 1(b) shows the two dimensional reciprocal space map for the XRD 115 reflections of GaAs and $In_{0.52}Al_{0.48}As$. The 115 peak of $In_{0.52}Al_{0.48}As$ is located close to the position of unstrained one and the formation of strained $In_{0.52}Al_{0.48}As$ is not visible. It has been reported that drastic strain relaxation occurs by introducing dislocation at the interface during the growth of 1.5~5 ML InAs on GaAs(111)A.[5] In the case of 3 ML InAs growth, therefore, partially relaxed InAs are formed. We suggest that this InAs layer relieves the lattice-mismatch between the InAlAs and GaAs, resulting in the formation of high quality InAlAs. We also observed strong PL emission in 3-nm $In_{0.53}Ga_{0.47}As$ multiple quantum wells (MQWs) formed on this $In_{0.52}Al_{0.48}As$ / InAs / GaAs(111)A. In contrast, on the $In_{0.52}Al_{0.48}As$ directly grown on GaAs(111)A without 3 ML-InAs, the MQWs emission is weaker. Therefore, high quality metamorphic $In_{0.52}Al_{0.48}As$ can be formed on GaAs (111)A by inserting a thin InAs layer.

Formation of InAs QDs on InAlAs

Figure 2 (a) shows an AFM image of uncapped InAs QDs on $In_{0.52}Al_{0.48}As$ / InAs / GaAs(111)A. Well-defined InAs QDs were formed. The density of QDs is 5×10^9 /cm^2, and average lateral size and height are 41 and 1.6 nm, respectively. The distribution of the lateral size and height is ±23% and ±28%, respectively. The QDs exhibit highly symmetrical shape, as shown in the cross-sectional profiles of the QDs (Fig. 2 (b) and (c)). The symmetrical shape is owing to the three-fold rotational symmetry of the (111) growth plane.[6]

Figure 3(a) shows the PL spectrum of capped InAs QDs measured at 9 K. Broad PL spectrum (λ = 900 nm ~ 1.6 μm) centered at around 1.5 μm is observed. Note that abrupt quench in the PL intensity at $\lambda > 1.6$ μm reflects the

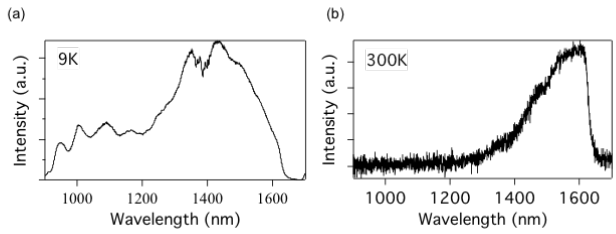

Fig. 3. PL spectra of capped InAs QDs measured at (a) 9 K and (b) 300 K.

detection sensitivity. The broad emission is consistent with the large size distribution of QDs. The PL spectrum consists of multiple emission peaks. We attribute them to different groups of QDs whose heights vary by a ML step. The PL emission from the QDs can be clearly visible up to room temperature, shown in Fig. 3(b). The observed intense room temperature PL emission strongly suggests that the crystal quality of the InAs QD is not significantly degraded by using the metamorphic InAlAs buffers that were formed by the specific method with 3ML-InAs insertion.

3. Conclusions

We demonstrated the formation of 1.55-μm wavelength InAs QDs on metamorphic InAlAs / InAs / GaAs(111)A. By using thin InAs layer, high quality metamorphic InAlAs was grown on GaAs (111)A. Using the metamorphic InAlAs, symmetrical InAs QDs were formed by DE. The InAs QDs showed efficient PL emission at a wavelength of 1.55 μm up to room temperature. We believe that this system is promising to realize GaAs based InAs QDs emitting at telecommunication wavelengths.

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