 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp489-490

Controlled Growth and Properties of InAs Nanostructures

Itaru Kamiya, Ronel Christian Roca

Quantum Interface Laboratory
Toyota Technological Institute
2-12-1 Hisakata, Tempaku, Nagoya 468-8511, Japan
E-mail: kamiya@toyota-ti.ac.jp

Abstract

Growth control on InAs-based nanostructures by molecular beam epitaxy (MBE) is discussed. While InAs quantum dots (QDs) have been extensively investigated, precise control of its morphology, determining the electronic properties, remains to be a challenge. Here, we report the recent developments on the growth of InAs nanostructures and their physical properties.

1. Introduction

InAs quantum structures have attracted attention for their unique optoelectronic properties that are particularly suited for near infrared (IR) devices. Prior to the invention and development of epitaxial growth, InAs was used as one of the few materials that intrinsically exhibit two-dimensional electron gas (2DEG) properties [1].

Techniques such as molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD) were established for the growth of ultrathin films of materials such as AlGaAs with monomolecular layer resolution in the 1980s. This lead those working in on IR related materials to grow similar structures of InAs-based materials. However, while various heterostructures could be grown relatively easily with AlGaAs system, InAs suffered a ca. 7% lattice mismatch that inhibited planar epitaxial growth. People observed roughening of surface as one proceed deposition of InAs on the commonly used GaAs(001) substrate either by MBE or MOCVD.

However, through careful studies on the morphology of these “rough surfaces” by techniques such as scanning probe microscopies (SPMs), the society started to recognize that the rough InAs structures formed on the surface beyond a critical thickness, following Stranski-Krastanov (SK) mode, were either conical or pyramidal on the order of about 5 nm in height and few tens of nm laterally [2]. The structure met the criteria of the quantum dot (QD), in which carriers can be confined three dimensionally, that had been proposed [3] by yet to be realized for practical use. This structure is now widely known as the self-assembled (SA) or SK QDs [4].

The growth and optoelectronic properties of SK QDs have been extensively investigated, and today IR devices such as photodetectors or photoemitters are realized. However, it was a mystery why the wavelength of the detectors or emitters remained ca. 1.3 μm or shorter despite the fact that the bandgap of InAs is ca. 0.35 eV. It was suggested that strain due to the lattice mismatch was responsible for the blue shift of the quantized energy through observation using modified cap (barrier layer on top) or without cap [5].

We had extended this effort, and by a combination of buried “seed” QD layer and modified cap layer, reduced the strain, and demonstrated that photoluminescence (PL) from SK InAs QDs can be longer than 1.6 μm at low temperature (4K) and also over 1.7 μm at room temperature, exceeding the communication wavelength of 1.55 μm [6].

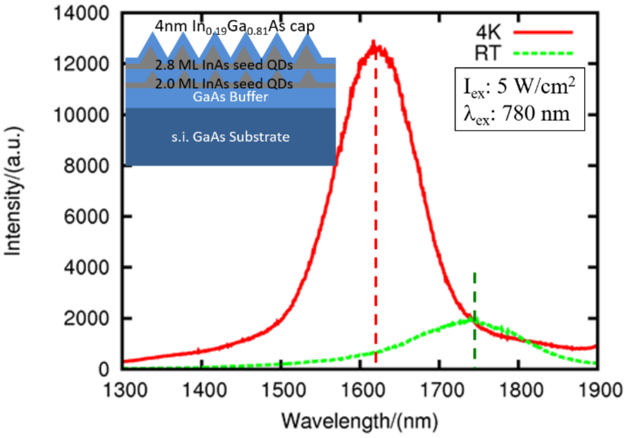

Fig.1 SK QD with a seed layer realizing PL peak tuned to be over 1.6 μm at 4K and over 1.7 μm at RT [6].

Besides, we have been preparing and studying the optoelectronic properties of two-dimensional island structure, which we call quantum well island (QWI) [7]. QWIs can be prepared by SK growth of InAs on GaAs(001) as well, only by limiting the deposition of InAs to less than the critical thickness of 1.7 monolayers (MLs). The structure, ideally a disc-like shape, is 2 or 3 ML in height with lateral extension of a few tens to a few hundreds of nm thereby quantum confining the carriers in the vertical (growth) direction and weakly confining them laterally. We have shown that photon upconversion can occur, most likely by biexciton Auger interaction, possibly at efficiency higher than that of QDs. More importantly, it was shown that near IR (NIR) photons can be upconverted to the visible. This opens novel possibilities for applications such as intermediate band solar cells (IBSCs) [8] or IR detectors.

However, for either QD or QWI, the SA process limited the controllability of their morphology. The QDs were pyramidal (conical) with a wetting layer (WL), and the QWIs can only be 2 or 3 MLs in height. To overcome such difficulties, we have adopted the so-called submonolayer (SML) growth [9], in which SML InAs and a few MLs of GaAs are deposited alternately. With these mode, both QDs and QWIs are grown with better shape control free of WL. We show the potential of SML growth.

2. Experimental

QDs and QWIs were prepared by alternately depositing 0.4-0.8 ML InAs and 1.5-2.0 GaAs by MBE on semi-insulating GaAs(001) substrates. After oxide desorption at 600°C, 100-nm GaAs buffer was grown at 590°C, thereafter, the temperature was lowered to 500°C. The reproducibility of the temperature adjustment was confirmed by the transition of the reflection high-energy electron diffraction (RHEED) pattern from 2×4 to c(4×4) at a fixed As4 flux of 7×10^{-4} Pa. Following growth of a 30-nm GaAs spacer layer, the InAs/GaAs SML structures were grown.

Morphological observation was made on uncapped samples by atomic force microscopy (AFM), and the optical measurements were made by PL on capped samples using Ti-sapphire laser as the excitation light source ($\lambda_{ex} \approx 740$ nm: 1.68 eV) and InGaAs multichannel detector with a He cryostat.

3. Results and Discussion

The sample structure is schematically illustrated in Fig. 2(a), and the PL spectra are shown in Fig. 2(b). Sharp PL peaks with FWHM ca. 10 nm are observed for samples with 0.4 or 0.6ML InAs per cycle, whereas much broader peaks are observed when 0.8ML InAs was supplied per cycle [10].

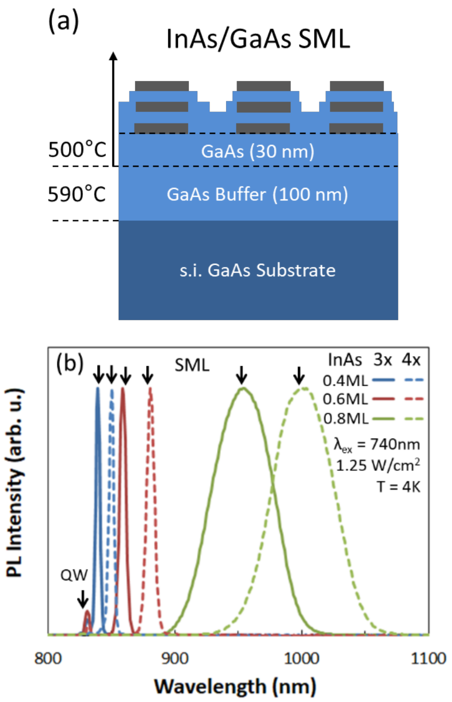

Fig. 2 (a) Structure of the SML structure grown. The figure illustrates the structure without cap layer for AFM, and the ones for PL studies were capped with GaAs. 0.4-0.8 ML of InAs was deposited followed by 1.5-2.0ML GaAs per cycle (stack), with 3 or 4 stacks. (b) The PL spectra obtained from these structures [10].

We attribute the change in the PL width and wavelength to the transition from QWI to QD-like structure by additional supply of InAs. With 0.8ML/cycle, the total amount of InAs deposited is either 2.4ML (3 stacks) or 3.2ML (4 stacks), far exceeding the critical thickness of 1.7ML for the SK growth. Even with 0.6ML/cycle, the total InAs is 1.8 or 2.4ML for 3 or 4 stacks, respectively, but still maintaining the 2D structure. The critical thickness is larger for the SML growth than SK, leaving us with higher freedom of fine tuning the morphology.

We also emphasize the high controllability of the PL wavelength of the QWI/QD structures. We performed growth with further variation in a) amount of InAs, b) amount of GaAs, and c) number of stacks (cycles). We find that the PL wavelength can be fine-tuned with high reproducibility, showing the potential of SML growth for application to IR devices. Results that show the controlled growth of these quantum structures will be presented.

4. Conclusions

We have been investigating controlled growth of InAs-based quantum structures on GaAs(001) and their optoelectronic properties. Submonolayer growth, in which submonolayer of InAs and a few monolayers of GaAs are alternately supplies, have seen to be a potentially powerful method, providing us with an opportunity to overcome the difficulties we have been facing with Stranski-Krastanov growth

Acknowledgements

The work was supported by the Iketani Science and Technology Foundation, and the Research Center for Smart Energies, TTI, supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

References

[1] S. Kawaji, S. Miki, & T. Kinoshita, J. Phys. Soc. Jpn. **39** (1975) 1631.
[2] T. R. Ramachandran, R. Heitz, P. Chen, & A. Madhukar, Appl. Phys. Lett. **70** (1997) 640.
[3] Y. Arakawa & H. Sakaki, Appl. Phys. Lett. **40** (1982) 939.
[4] D. Leonard, M. Krishnamurthy, C. M. Reaves, S. P. Denbaars, & P. M. Petroff, Appl. Phys. Lett. **63** (1993) 3203
[5] K. Nishi, H. Saito, S. Sugou, & J-S. Lee, Appl. Phys. Lett. **74** (1999) 1111; Z. Z. Sun, S. F. Yoon, W. K. Loke, & C. Y. Liu, Appl. Phys. Lett. **88** (2006) 203114.
[6] K. Shimomura & I. Kamiya, Appl. Phys. Lett. **106** (2015) 082103; K. Shimomura, *et al.*, J. Appl. Phys. **118** (2015) 185303.
[7] D. M. Tex, I. Kamiya, & Y. Kanemitsu, Phys. Rev. B **87** (2013) 245305; ibid, Sci. Rep. **4** (2014) 4125.
[8] A. Luque & A. Martí, Phys. Rev. Lett. **78** (1997) 5014.
[9] I. L. Krestinikov, N. N. Ledentsov, A. Hoffmann, and D. Bimberg, Phys. Stat. Sol. A **183** (2001) 207.
[10] R. Roca & I. Kamiya, Phys. Stat. Sol. B, submitted.
[11] R. Roca & I. Kamiya, to be submitted.