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InAs/In(Ga,Al)AsSb Quantum Dot Heterostructures for Photonic Devices

Jen-Inn Chyi[1,2,3], Pei-Chin Chiu[1], Meng-Jie Shiau[1], Tung-Po Hsieh[1], and Mao-Nan Chang[4]
[1]Department of Electrical Engineering, National Central University
300 Jhongda Road, Jhongli 32001, Taiwan, R.O.C.
Phone: +886-3-425-8241 E-mail: chyi@ee.ncu.edu.tw
[2]Department of Optics and Photonics, National Central University, Jhongli, Taiwan, R.O.C.
[3]Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan, R.O.C.
[4]National Nano Device Laboratories, Hsinchu, Taiwan, R.O.C.

1. Introduction

In the past ten years, rapid progress has been made on the development of InAs/GaAs quantum dot (QD) lasers, which have great potential for optical-fiber communications. To extend the emission wavelength of InAs/GaAs QDs to 1.3 μm and above, depositing an InGaAs overgrown layer, i.e. strain-reducing layer (SRL), on InAs QDs or embedding the QDs in an InGaAs well is often used. However, these approaches lead to a low barrier height, poor carrier confinement and a small state separation between the ground and first excited state of the QDs, which results in a low characteristic temperature when the QD lasers are operated above room temperature. In fact, lower than expected characteristic temperature of 1.3 μm InAs QD lasers has been a subject of intensive investigation lately as it is one of the most critical requirements for practical applications.

Recently, Sb-mediated growth of InAs QDs has received much attention as it is shown to be effective in improving the thermal stability and optical properties of InAs quantum dots. In this work, we investigate the effects of InGaAsSb overgrown layer on the structural and optical properties of InAs QDs and propose the mechanism the governs the behavior of these QDs. Wide bandgap InAlAs overgrown layer has also been proposed to replace InGaAs as it increases the confinement potential and at the same time reduces the compressive strain in InAs QDs for long wavelength emission. It is experimentally verified that the use of an InAlAs overgrown layer results in a ground to first excited state separation greater than 100 meV, which is a desirable characteristic for better device performance. However, even with these advantages, the InAs/InAlAs structure has not been able to replace its InAs/InGaAs counterpart because degraded luminescence efficiency and broadened spectral line-width are often observed when the high aluminum-containing layer becomes thicker. As the typical growth temperature for the aluminum-containing layer is much lower than the optimized one, material defects are believed to be the origin for the degraded optical properties. To cope with the issue mentioned above, we propose the use of InAlAsSb overgrown layer to replace InAlAs by taking advantage of Sb, which acts as a surfactant during the growth.

2. InGaAsSb overgrown layer

InAs quantum dots with an InGaAs and InGaAsSb overgrown layer, respectively, are grown by molecular beam epitaxy on GaAs. Figure 1 shows the photonluminescence (PL) spectra of these two samples. With the addition of Sb to the overgrown layer, the ground state emission of InAs quantum dots is redshifted from 1346 nm to 1390 nm. Note that the PL intensity of quantum dots does not degrade at all when using the InGaAsSb overgrown layer. Cross-section scanning transmission electron microscopy (STEM) study indicates that the redshift of emission wavelength could be attributed to the increase of dot size as shown in Figure 2a and 2b. From the TEM image, the average height of the InAs quantum dot with an InGaAsSb overgrown layer is greater (9.3 nm) as compared to the QDs with an InGaAs overgrown layer (8.5 nm). Besides, it is worth noting that InGaAsSb layer leads to a more conformal coverage on QDs than InGaAs as Sb is a surfactant for heteroepitaxy.

The robustness at high temperature for the InAs QDs with an InGaAsSb overgrown layer is also enhanced as evidenced by the rapid thermal annealing experiments in an N_2 ambient. Figure 3a and 3b show the PL spectra of QDs after thermal annealing at temperatures ranging from 650 to 850 ^{o}C for 20 seconds. The sample with an InGaAsSb overgrown layer survives the thermal treatment up to 750 ^{o}C. The mechanism of the suppression of In-Ga intermixing by this Sb-based material is not clear and under further investigation. In spite of this, the results of this study indicate that the Sb-based matrix is promising for long wavelength InAs quantum dot photonic devices.

3. InAlAsSb overgrown layer

The room temperature PL spectra of InAs/GaAs, InAs/InAlAs and InAs/InAlAsSb QDs samples are shown in Fig. 4a. Both the ground- and first excited-state transitions of the QDs are observed. For InAs/GaAs QDs, the ground-state transition is located at 1245 nm with a full width at half maximum (FWHM) of 45 meV. For the QDs with an InAlAs layer, the ground-state transition is red-shifted to 1301 nm and the FWHM is reduced to 24 meV, indicating good size uniformity of the quantum dot ensemble. The energy separation between the ground- and first excited-state transitions increases significantly from 72 meV for the InAs/GaAs sample to 104 meV for the InAs/InAlAs sample due to a larger barrier potential offered by InAlAs than GaAs. Replacing the InAlAs overgrown layer by InAlAsSb allows the ground-state emission to red-shift to 1313 nm with an FWHM of 26 meV. Besides, the sample also has a large state separation of 103 meV comparable to that of the InAs/InAlAs sample. This is not surprising because the Sb content in the InAlAsSb overgrown layer is too low to make any significant change in the barrier potentials. Although the spectral line-shape, FWHM and state separation of InAs/InAlAs and InAs/InAlAsSb QDs are alike, a markedly enhanced ground-state luminescence efficiency of the latter is observed. Its room temperature PL intensity is higher than that of the InAs/InAlAs QDs by a factor of 4.5. The increase in the PL intensity of QDs involving Sb has been reported previously and is attributed to the decease of coalescence of neighboring dots and increase of QD density. In those studies, Sb is introduced before the growth of InAs QDs. Consequently, QD density is increased because Sb is said to suppress the migration of Indium adatoms. However, in this study, Sb is introduced during the deposition of InAlAsSb overgrown layer, i.e., after the growth of InAs QDs. There is no obvious change in quantum dot density observed on our samples, so this reason can be ruled out. Since the Sb content in the overgrown layer is so small, the change in quantum confinement is not large enough to cause such a significant change in luminescence efficiency either. It is therefore very likely to be the improved material quality of the InAs/InAlAsSb heterostructure that gives rise to such a marked increase in luminescence efficiency. This is confirmed by the PL spectra of the InAlAs and InAlAsSb overgrown layers that shown in the inset of Figure 4a, which indicates that InAlAsSb overgrown layer indeed has higher luminescence efficiency than that of InAlAs. The improved crystal quality might be attributed to Sb, which acts as a surfactant in highly strained hetroepitaxy and prevents the formation of 3-dimensional islands as well as nonradiative recombination centers.

The temperature-dependent PL spectra further manifest the usefulness of the InAlAsSb overgrown layer. Figure 4b shows the temperature-dependence of the integrated PL intensity over the temperature range from 15 to 450 K. The thermal activation energy of the InAs/GaAs sample is determined to be 406 meV while that of InAs/InAlAs and InAs/InAlAsSb is 537 and 530 meV, respectively. It is worth noting that the PL measurements have to be done at temperatures as high as 450 K so as to faithfully determine the activation energies of the InAs/InAlAs and InAs/InAlAsSb samples because their PL intensity quenching is not obvious at 300 K. This confirms the fact that adding Sb to InAlAs overgrown layer does not affect much the band structure and thermal characteristics of the present heterostructure.

4. Conclusion

Both InGaAsSb and InAlAsSb overgrown layer have been shown very effective in improving the optical properties of InAs QDs with emission wavelengths at 1.3 μm and above. It is attributed to the surfactant nature of Sb, which lowers the interface energy of QD and its matrix and leads to overall improved material quality.

Acknowledgement

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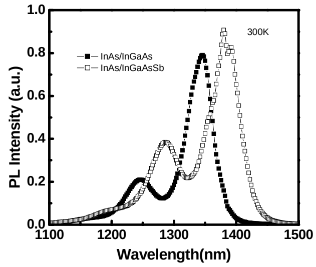

Fig. 1. Room temperature PL spectra of InAs QDs capped by InGaAs and InGaAsSb overgrown layers.

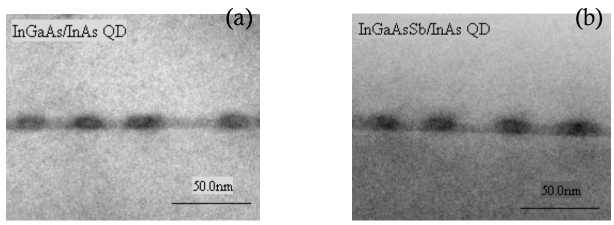

Fig. 2. Cross-sectional STEM images of InAs QDs capped by an (a) InGaAs (b) InGaAsSb overgrown layer.

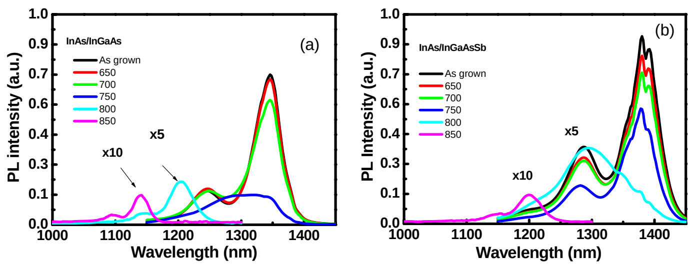

Fig. 3. PL spectra of InAs QDs capped by an (a) InGaAs and (b) InGaAsSb overgrown layer subject to thermal annealing at various temperatures for 20 seconds in nitrogen ambient.

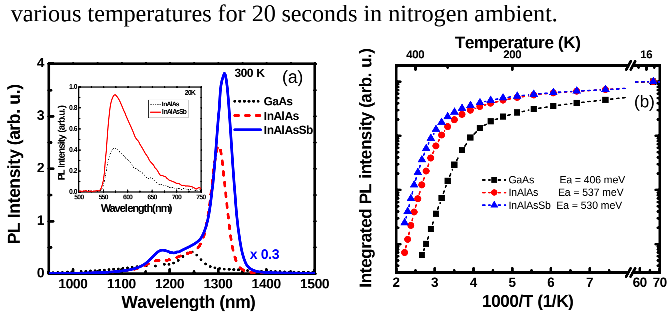

Fig. 4. (a) Room temperature PL spectra of InAs QDs with a GaAs, InAlAs, and InAlAsSb overgrown layer. The Inset shows low temperature photoluminescence spectra of the InAlAs and InAlAsSb overgrown layers; (b) Temperature dependence of the integrated PL intensity of QDs with a GaAs, InAlAs, and InAlAsSb overgrown layer.