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Improved photoluminescence of 1.26 μm InGaAs/GaAs quantum wells assisted by Sb surfactant and indium-graded intermediate layers

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We have grown high-quality InGaAs/GaAs quantum wells (QWs) with emission wavelength range of 1.2–1.26 μm by metalorganic chemical vapor depositions. By incorporating Sb surfactant and the indium-graded intermediate layers into InGaAs/GaAs QWs, the photoluminescence (PL) intensity of the 1.26-μm $In_{0.45}Ga_{0.55}As$/GaAs QW is enhanced by a factor of 20 and the full width at half maximum value is reduced from 60.4 meV to 35.9 meV. The good crystalline quality is proved by temperature-dependent PL, which shows that the activation energies of $In_{0.45}Ga_{0.55}As$ and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ QWs are 20.87 meV and 27.09 meV. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2009048]

Semiconductor material with an emission wavelength range of 1.3–1.55 μm is required for potential applications in infrared lasers, integrated optoelectronic, and local-area-network systems. Several material systems, including In(Ga)As/GaAs quantum dots, GaAsSb/GaAs, and InGaAs(N)(Sb)/GaAs(N), have been demonstrated to construct the active region for the desired long-wavelength GaAs-based lasers.[1–6] Recently, many efforts have contributed to the incorporation of N into InGaAs quantum wells (QWs) due to the increased band offset, resulting in a more favorable characteristic temperature coefficient, and the large bowing in ternary GaAsN alloy to achieve 1.3–1.55 μm emission.[7,8] However, the incorporation of N beyond about 1% into InGaAs QWs has also been found to cause vast quenching of the luminescence and broaden the luminescence. While, postgrowth rapid-thermal annealing can enhance the PL intensity by a factor of 10–100, and a blueshift of the PL peak is found simultaneously.[9,10] InGaAs/GaAs QW structures have received much attraction to be the potential candidate due to their relatively uncomplicated and mature techniques. Unfortunately, the large lattice mismatch between InAs and GaAs alloys restricts the ternary InGaAs QW, grown on GaAs template, to possess crystalline quality of better photoluminescence (PL) characteristics with an emission wavelength toward 1.3 μm. Up until now, the progress of the simple InGaAs/GaAs QW structure has made possible an emission wavelength toward 1.24 μm.[11–13] However, the higher In content InGaAs QW, leading to the loath degradation of crystal quality, has been found to obtain better optical characteristics. Quite recently, Sung *et al.*[14] has demonstrated a 1.24 μm $In_{0.38}Ga_{0.62}As$/GaAs QW laser with a critical thickness of 8.8 nm by low-temperature-growth method using gas-source molecular-beam epitaxy. By optimizing the molecular-beam epitaxy growth conditions, an emission wavelength of 1.25 μm at room temperature (RT) with a narrow full width at half maximum (FWHM) of 30 meV is obtained as well.[15]

Previously, the Sb surfactant-mediated growth had been investigated in group-IV Si/SiC superlattices, and to a continuing employment for group III-V heterostructure materials. This, technology had been utilized in InGaP band-gap controlling, and during the lateral epitaxial overgrowth of GaN to alter the predominant facet formation.[16–18] More recently, the presence of Sb is shown to be an efficient surfactant, serving as an isoelectronic impurity, to provide the delay of lateral relaxation of the highly strained InGaAs QW. The Sb-assisted InGaAs has demonstrated a spectral FWHM of 30 meV with PL emission at 1.19 μm.[19] A PL emission of 1.27 μm is also achieved by a 9 nm thick $In_{0.41}Ga_{0.59}As_{0.992}Sb_{0.008}$ QW.[20] In a prior work, we demonstrated a highly strained 1.27 μm $In_{0.41}Ga_{0.59}As$:GaAs–$GaAs_{0.85}P_{0.15}$ vertical cavity surface-emitting laser and a PL emission of 1.214 μm is achieved.[21] However, the PL characteristics of the InGaAs:Sb QW structure with emission wavelength above 1.25 μm still need to be improved. In this letter, we try to insert an indium-graded intermediate layer into both sides of the Sb-assisted InGaAs QW by the gradual change of In composition at the interface of QW and barrier. The indium-graded intermediate layer can further provide the delay of the highly strain relaxation in a QW and to extend the emission wavelength with better PL characteristics as a result of the trapezoid potential.

The growth of InGaAs/GaAs QWs was prepared on a *n*-type GaAs(100) substrate by 50 Torr metalorganic chemical vapor deposition (MOCVD), in which the group-V precursors were the hydride sources of AsH_3 and PH_3. Trimethyl (TM-) sources of aluminum (Al), gallium (Ga), and indium (In) were used for group-III precursors. Trimethylantiminy (TMSb) was used for the appearance of Sb. Serial samples were grown, with or without the Sb surfactant and the indium-graded intermediate layer. For the simple InGaAs/GaAs samples which were grown with conventionally square-potential structure, the well and barrier thickness were 7 nm and 10 nm. The In composition was varied in the range of 0.4–0.45 with the aim of extending the emission wavelength. The Sb-assisted InGaAs/GaAs samples, which were grown with trapezoid-potential structure by inserting a 2.5 nm thick indium-graded intermediate layer into both sides of the QW, were schematically plotted in Fig. 1. For all Sb-assisted indium-graded InGaAs QWs, the full layer thickness was 10 nm. The Sb was only supplied during the growth of an indium-graded InGaAs QW, and stopped when growing GaAs barriers. All of these samples investigated here

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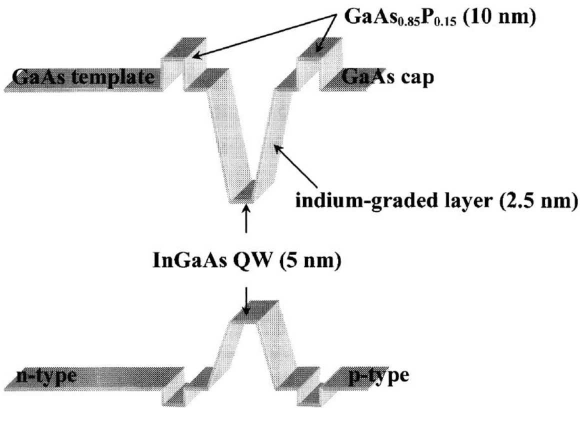

FIG. 1. A schematic plot of a Sb-assisted InGaAs/GaAs single-QW structure with indium-graded intermediate layer. The indium-graded intermediate layer is formed by the gradual change of In composition at the interface of QW and barrier.

were grown as single-QW structures, embedded into 10 nm thick $GaAs_{0.85}P_{0.15}$ layers, and capped by a 30 nm thick GaAs layer. The growth rate was about 0.5 nm/s and the growth temperature, which depends on the In composition, is varied from 500 to 530 °C. Other growth conditions were similar to our prior work.[21] After the epitaxial growth of the serial single-QW structures, PL measurement by a 514.5 nm Ar-ion laser was performed to investigate the optical quality of epitaxial films in a the temperature range of 17–300 K.

Figure 2 summarizes the RT PL intensity and the spectral FWHM of the simple and Sb-assisted indium-graded InGaAs/GaAs single-QW structures as a function of the PL emission wavelength. Each symbol corresponds to one individual single QW grown without (squares) and with a Sb-assisted indium-graded (circles) intermediate layer. Solid and open symbols represent the FWHM and the PL peak intensity, respectively. For the simple InGaAs/GaAs QWs, it is noteworthy that adding more In into InGaAs QWs leads to a loath degradation of PL characteristics, while the PL intensity decreases drastically with the broadened FWHM observed when the PL emission wavelength is extended beyond 1.22 μm. The vast disintegration of PL characteristics has been realized due to the nonradiative recombination process. Nevertheless, among these InGaAs/GaAs samples, the emission wavelength can be extended to 1.257 μm, and the spectral FWHM is broadened to a value of 60.4 meV.

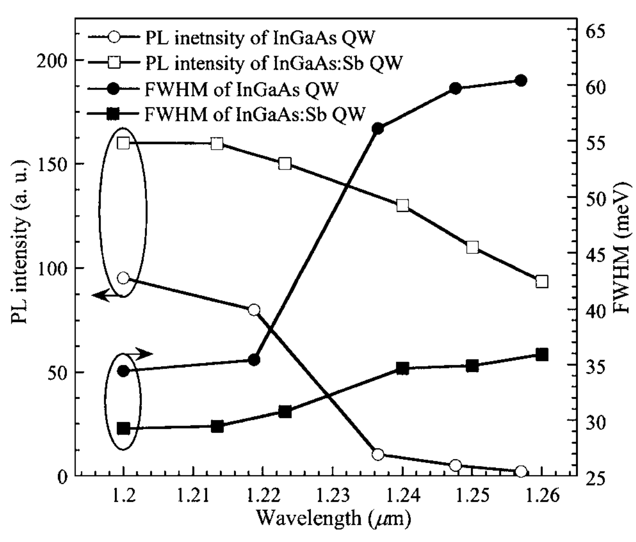

FIG. 2. RT PL intensity and the spectral FWHM of the simple and Sb-assisted indium-graded InGaAs/GaAs single-QW structures as a function of the PL emission wavelength. Solid and open symbols represent the FWHM and the PL peak intensity, respectively. Squares and circles represent the single QWs grown without and with Sb-assisted indium-graded intermediate layer, respectively.

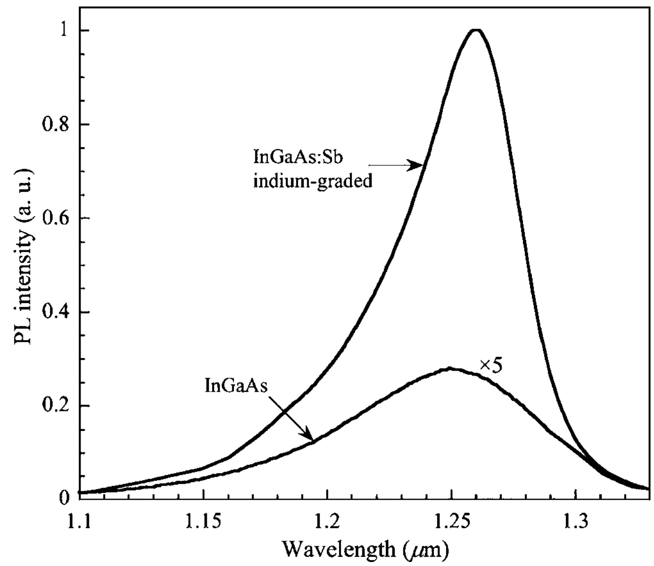

FIG. 3. A comparison of the RT PL spectra for the simple and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single QWs.

The PL characteristics of the InGaAs/GaAs single-QWs are beneficially improved with the assistance of Sb and the use of an indium-graded layer. For these Sb-assisted indium-graded InGaAs QWs, the Sb flux is fixed to a value of 0.5% in the InGaAs QWs. Leisure decrease of the PL intensity is found and the FWHM only increases from 29.3 meV to 35.9 meV when the In composition in the InGaAs QW is increased from 0.4 to 0.45. The emission wavelength of the Sb-assisted indium-graded InGaAs QW can be extended to 1.26 μm with a narrow FWHM value of 35.9 meV. A comparison of the RT PL spectra for the simple and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single QWs is obtained as indicated in Fig. 3. The peak intensity of the QW emission is increased by a factor of 20 and shows a reduction of the FWHM from 60.4 meV to 35.9 meV. Noteworthily, a slight PL redshift (8 meV) is found with the assistance of Sb and indium-graded intermediate layer, which results in a decreased energy height of quantized level.

Variable temperature spectra for the simple and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single-QW structures are shown in Fig. 4, respectively. Smooth Gaussian peaks with strong luminescence are observed for both structures and the peaks are dominated by the near-band-edge emission. When the temperature of the simple $In_{0.45}Ga_{0.55}As$ single-QW structure is increased from 17 to 300 K, the peak emission wavelength shifts from 1.04 to 0.993 eV, and the corresponding FWHM value varies from 32.8 to 60.4 meV. For Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single-QW structure, the peaks are sharper, while the peak emission wavelength and the corresponding FWHM value change from 1.055 to 0.984 eV and 23.9 to 35.9 meV when the temperature is increased from 17 to 300 K. Thus, the quality of the Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single QW is considered to be excellent. After fitting the experimental data to the Varshni semiempirical relationship, the band-gap en-

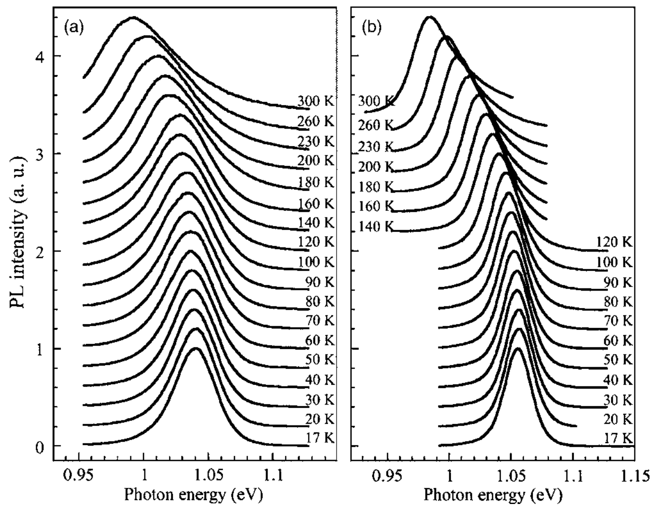

FIG. 4. Variable temperature spectra for (a) the simple $In_{0.45}Ga_{0.55}As$ and (b) the Sb-assisted indium-graded single-QW structures.

ergy at 0 K, α and β coefficients are 1.039 eV, $4.4\pm0.7 \times 10^{-4}$ eV K^{-1}, and 547 ± 121 K for the simple $In_{0.45}Ga_{0.55}As$, and 1.054 eV, $6.3\pm1.1\times10^{-4}$ eV K^{-1}, and 485 ± 124 K for the Sb-assisted indium-graded single-QW structure, respectively. Figure 5 shows the log of the integrated PL intensity plotted as a function of reciprocal temperature for the simple and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single QW structures. It is worth mentioning that the integrated PL intensity of the Sb-assisted indium-graded is larger than that of the simple $In_{0.45}Ga_{0.55}As$ single-QW structure for all temperature ranges. Fitting our data to the classical Arrhenius law $I=I_0/\{1+c\exp(-E_a/KT)\}$, according to the thermal carrier transfer mechanism, the activation energies (E_a) of our simpler and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single-QW structures are 20.87 meV and 27.09 meV, respectively. The result suggests that the quality of our single-QW structures with the

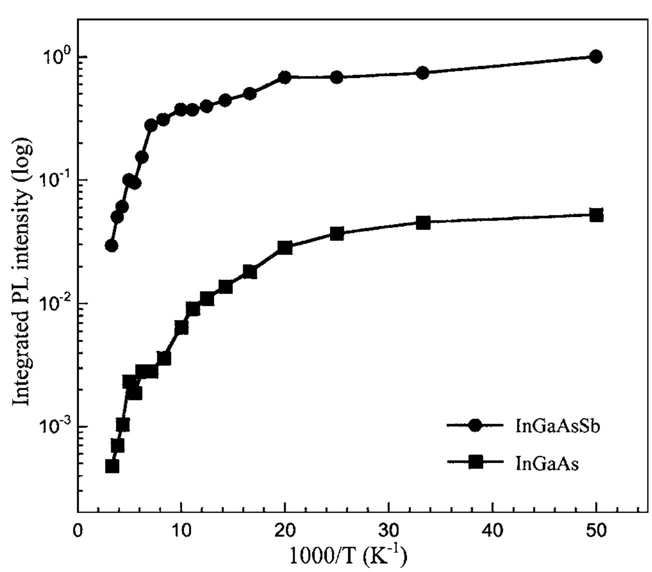

FIG. 5. The log of the integrated PL intensity plotted as a function of reciprocal temperature for the simple and Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$ single QW structures.

emission wavelength around 1.26 μm is heading the list of successful candidates, and the concentration of nonradiative recombination centers is rarely small.

In conclusion, the high In-content InGaAs/GaAs single-QWs are grown by low-pressure MOCVD. It is noteworthy that the Sb surfactant and the indium-graded intermediate layers improve the PL characteristics. An emission wavelength of 1.26 μm is achieved of the Sb-assisted indium-graded $In_{0.45}Ga_{0.55}As$/GaAs single-QW, and the PL intensity is enhanced by a factor of 20 with a FWHM value of 35.9 meV. The results of temperature-dependent PL also show that the quality of our simple and Sb-assisted indium-graded InGaAs/GaAs single-QWs is excellent. The methods are very significant for improving crystal and optical qualities of long-wavelength InGaAs/GaAs QWs and further fabricating laser devices.

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