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Light emission from InGaAs:Bi/GaAs quantum wells at 1.3 μm

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Highly strained InGaAs:Bi quantum wells (QWs) were grown on (001)-oriented GaAs substrates by molecular beam epitaxy (MBE). Photoluminescence (PL) reveals strong improvements in the optical properties evidenced by 10 times enhancement in PL intensity and extended emission wavelength up to 1.29 μm when Bi is introduced to InGaAs/GaAs QWs. The improved optical quality results from the Bi surfactant effect as well as the Bi incorporation. Post growth thermal annealing shows that Bi atoms in InGaAs/GaAs QWs do not show good thermal stability at 650 °C and tend to diffuse out of the QWs resulting in large wavelength blue-shifts. [http://dx.doi.org/10.1063/1.4769102]

Commercial telecom (1.3 and 1.55 μm) lasers made of InGaAsP/InP exhibit a low characteristic temperature due to insufficient carrier confinements,[1] thus requiring extra coolers to stabilize the lasing wavelength and leading to high energy consumption.[2] To improve energy efficiency of fiber communication and realize green information and communication technology, uncooled telecom lasers have attracted great attention recently. Such lasers are often fabricated on GaAs substrates using novel gain mediums such as dilute nitrides and InAs quantum dots, since the conventional InGaAs/GaAs quantum wells (QWs), limited by the critical thickness, can only reach light emission at 1.24 μm at room temperature.[3] Dilute nitrides make use of the large difference in electronegativity between N and As atoms resulting in a strong energy band bowing effect and deep conduction band offset to efficiently confine electrons. An opposite example of adding isoelectronic impurities is to incorporate Bi into GaAs. Both molecular beam epitaxy (MBE)[4] and metal organic chemical vapor deposition (MOCVD)[5] have been reported to successfully fabricate GaAsBi alloys. It has a similar band gap bowing effect like dilute nitrides with a value of 88 meV/%Bi on the valence band. Photoreflectance spectra demonstrate a temperature-insensitive band gap of GaAsBi compared with that of GaAs.[6] Incorporation of Bi can be achieved at temperatures below 450 °C for GaAsBi and increases with decreasing growth temperature. The unincorporated Bi atoms will float on the growth surface and act as surfactant. The surfactant effect in the growth of strained-layer has been demonstrated in many material systems, such as Ge/Si,[7] InGaAs, GaN,[8] and GaNAs[9] by both MBE and MOCVD. It enables the two-dimensional layer-by-layer growth beyond the critical thickness, reduces interface roughness and significantly improves the optical quality.

In this paper, we investigate Bi incorporation in highly strained InGaAs/GaAs QWs with emission wavelength close to 1.2 μm. The combined surfactant effect and the Bi incorporation in the QWs effectively delay the strain relaxation and extend emission wavelength up to 1.29 μm from InGaAs:Bi/GaAs QWs. Since Bi atoms have a larger atomic size and weaker bonding with Ga and In atoms compared with As atoms, it is expected that dilute bismides may be thermally

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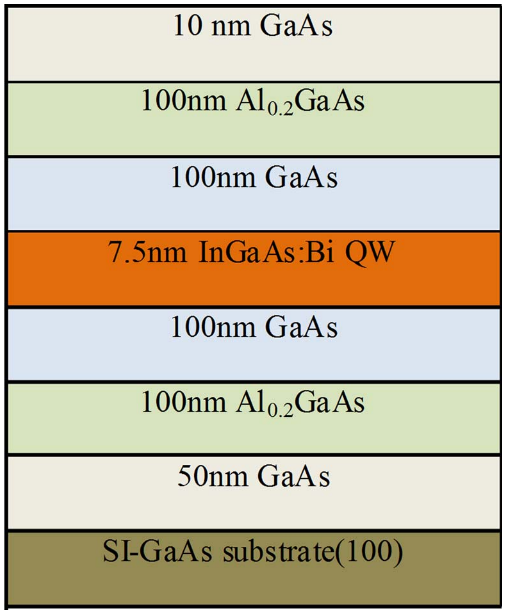

FIG. 1. Schematic structure of an InGaAs:Bi/GaAs QW structure.

unstable. We investigate this issue by employing post-growth rapid thermal annealing. Indeed, the thermal stability of InGaAsBi is found to be much less than that of GaAsBi. This finding is very important for any practical optoelectronic device applications using InGaAsBi as an active medium.

All the InGaAs:Bi/GaAs QW samples were grown on semi-insulating (SI) (001)-oriented GaAs substrates using a Riber Compact21 MBE. Elements of In, Ga and Bi were supplied from dual filament effusion cells, and As in the form of As_2 was provided from a valved cracker. A schematic structure of InGaAs:Bi/GaAs QWs is shown in Fig. 1. A 50 nm thick GaAs buffer layer was first grown at 580 °C after deoxidation on the SI-GaAs substrate. The active layer consists of 7.5 nm thick InGaAs:Bi layer sandwiched between 100 nm thick GaAs barrier layers. The cladding layers were 100 nm thick $Al_{0.2}Ga_{0.8}As$ layers. All the layers were capped by a 10 nm GaAs layer on the top. The growth temperature of the InGaAs:Bi/GaAs QWs was in the range of 370 °C to 440 °C (measured by a thermocouple) and linearly increased up to 580 °C (measured by a pyrometer) afterwards. The As/III beam equivalent pressure (BEP) ratio is set to be 5.5, while the BEP of Bi is $1.6 \cdot 10^{-7}$ - $2.0 \cdot 10^{-7}$ Torr. The In composition is measured to be 0.43 from XRD measurements while the Bi content is estimated to be around 1% from the wavelength shift in photoluminescence (PL).

To investigate the thermal stability, post-growth rapid thermal annealing experiments were executed at 650 °C, 700°C and 750 °C for 2 min each using JIPELEC Jet First 100 Rapid Thermal Processor (RTP). The reference series of InGaAs/GaAs QWs without Bi have been grown for comparison. Photoluminescence was performed at room temperature using an Ar-ion laser as the excitation source. The emissions were dispersed by a Spex 1404 0.85 m double grating monochromator and detected by a liquid nitrogen-cooled North-Coast Ge detector. A standard lock-in amplifier was used to detect the signal. X-ray diffraction (XRD) measurements were implemented in the mode of rocking curve using a Philips X'Pert Materials Research Diffractometer.

Figure 2(a) displays PL spectra of two identical QWs with the same structure and the growth conditions (growth temperature of 440 °C) except for one being exposed to Bi. The sample with Bi shows 15 nm longer wavelength and more than 10 times stronger in intensity as compared with that of the reference sample. We believe that both the Bi surfactant effect and the Bi incorporation are responsible for the improvement. The former suppresses the strain relaxation via inhibiting the formation of 3D islands, thus improving surface smoothness[10] and resulting in more than 10 times

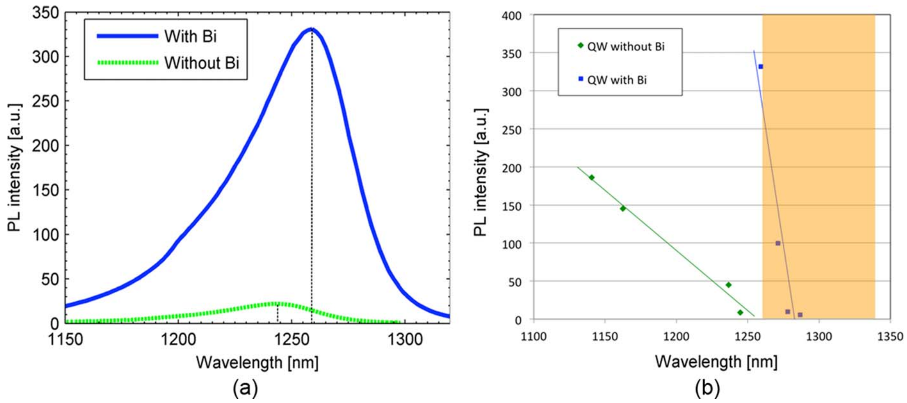

FIG. 2. (a) PL spectra of the two identical InGaAs QWs with and without Bi; (b) Summary of the PL intensity as a function of the PL wavelength. The lines are linear fit for the data points.

increase of PL intensity compared with the reference InGaAs QW. The 15 nm red shift of wavelength observed from the InGaAs:Bi/GaAs QW sample can be contributed to both the extended critical thickness as a result of the Bi surfactant effect and the large energy bowing effect due to the Bi incorporation.

More samples were grown to confirm the significance of the Bi effects. Figure 2(b) shows the summary of PL intensity as a function of emission wavelength for both sets of InGaAs:Bi and InGaAs QW samples. The wavelength extension can be achieved by steadily increasing the In source temperature (In flux and thus composition) under Bi exposure, while the growth time and the Ga source temperature are kept as constants. This leads to long PL wavelengths reaching a maximum of 1.29 μm at room temperature. The emitted wavelengths of most InGaAs:Bi/GaAs QWs have already fallen into the telecom wavelength region of 1.26 - 1.34 μm marked by the orange belt, indicating that InGaAs:Bi/GaAs QWs have a strong potential to prolong InGaAs QW lasers wavelength to the important telecom range of 1.3 μm. However, the PL intensity decreases at the same time.

Figure 3(a) and 3(b) summarizes the normalized PL intensity and the wavelength blue shift as a function of the annealing temperature, respectively. The temperature of 580 °C is referred as the reference since it was used during the growth of the upper AlGaAs barrier and the GaAs cap layer. We also fabricated two more samples, 200 nm thick GaAsBi bulk and 7.5 nm thick InGaAs:Bi QWs with 50 nm GaAsBi barriers, for comparison. The Bi alloy in all of the four samples was grown at 370 °C. For the InGaAs QW, the intensity decreases dramatically after being annealed at 650 °C. For the InGaAs:Bi QW sample, the PL intensity is enhanced by 3 times after being annealed at 700 °C due to the improved crystal quality, and then decreases at higher temperatures. All the samples except GaAsBi show wavelength blue shift after annealing. The InGaAs:Bi QW has a strong blue-shift of ∼66 nm at 650 °C as compared with ∼12 nm from the InGaAs QW. The wavelength blue shift fluctuates between 40-66 nm for annealing at higher temperatures. The reason is unclear and could be related to the non-uniform in-plane distribution of Bi atoms. We believed that the 66 nm blue shift is due to the Bi out diffusion from the InGaAs:Bi QW, which is supported by further experimental analysis below. The GaAsBi bulk sample reveals a negligible wavelength blue shift at the annealing temperature of 650 °C. At higher annealing temperatures, the GaAsBi surface damage is too high to generate any PL signal. The InGaAs:Bi QW inserted in the GaAsBi barrier shows a combined result of the GaAsBi bulk and the InGaAs:Bi QWs, resulting in a ∼8 nm blue shift at 650 °C. This confirms that the Bi out diffusion from the InGaAs:Bi QW can be effectively suppressed by using GaAsBi barriers. At annealing temperatures of 700 °C and 750 °C, we did not detect any PL signals of the InGaAs QW, GaAsBi bulk and GaAsBi/InGaAsBi QW. Therefore, PL intensity was defined as zero while the wavelength was undefined.

For further analysis, XRD measurements were performed for the same sample before and after annealing, as shown in Fig. 4(a) and 4(b) for the InGaAs and the InGaAs:Bi QW samples,

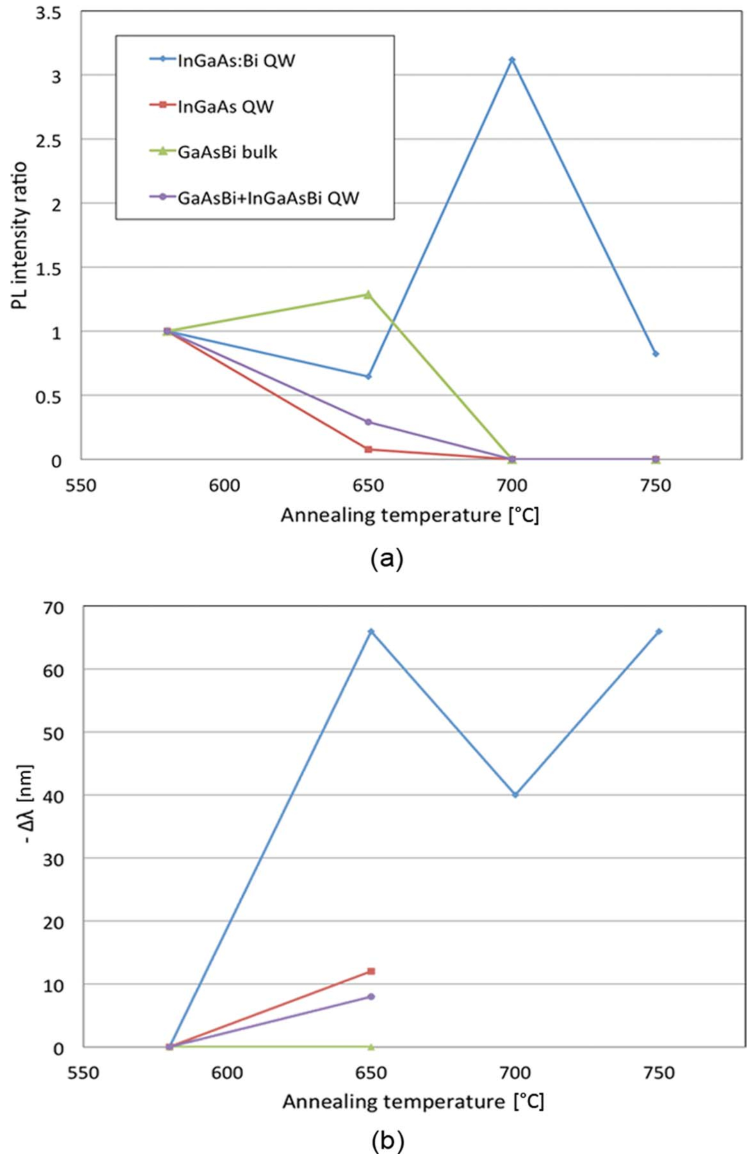

FIG. 3. (a) Normalized PL intensity after the annealing with respect to the initial sample and (b) wavelength blue shift as a function of annealing temperature. Four samples are marked in different colors.

respectively. In both cases, the QW peaks move to the right side with increasing the annealing temperature. For the InGaAs QW, it indicates strain relaxation that is supported by the decrease of the PL intensity. Simulation shows 7% strain relaxation in the $In_{0.43}Ga_{0.57}As$ QW, leading to ∼10 times decrease of the PL intensity. For the InGaAs:Bi QW sample, both strain relaxation and Bi out diffusion from the QW can cause the peak shift. However, the strong enhancement of the PL intensity excludes the possibility of strain relaxation. So we believe it is due the Bi out diffusion that lowers the overall strain in the QW. This is also corroborated by the large wavelength blue shift found in PL results. Further evidence is that the GaAsBi bulk with a high incorporated Bi content shows no wavelength shift and the GaAsBi/InGaAs:Bi QW exhibits a small wavelength shift since the out diffusion of Bi atoms from the InGaAs:Bi QW is suppressed due to the GaAsBi layers.

The present study shows that using Bi can significantly improves the quality of InGaAs QWs on GaAs substrate, resulting in a maximum wavelength of 1.29 um and more than 10 times enhancement

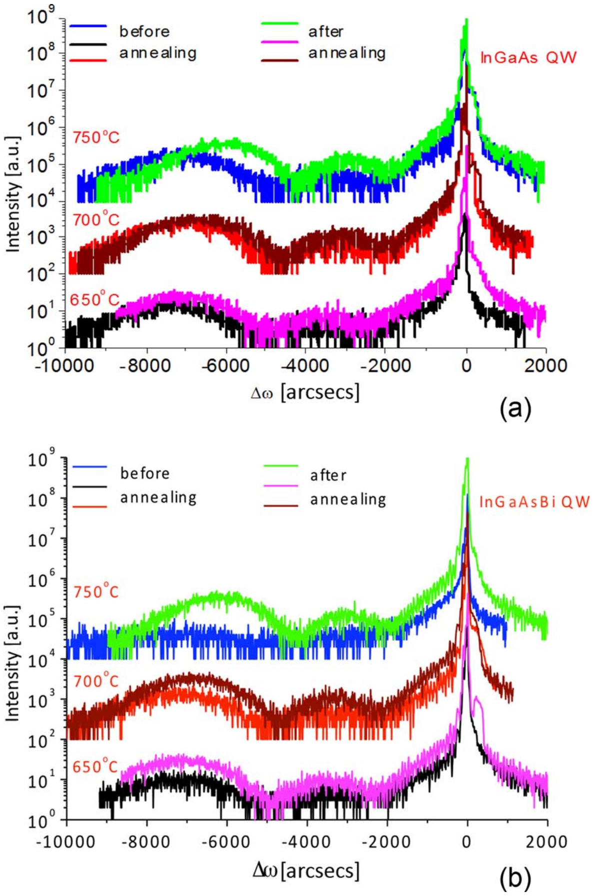

FIG. 4. XRD spectra of the two identical InGaAs QWs (a) with Bi; (b) without Bi under different annealing conditions.

of the PL intensity. These results signify that InGaAs:Bi QWs are promising novel gain materials to achieve 1.3 μm telecom lasers on GaAs. However, Bi atoms inside InGaAs/GaAs QW do not show good thermal stability and tend to diffuse out compared with those in GaAsBi after being annealed up to 650 °C, which poses a big technical challenge for making the 1.3 μm InGaAsBi lasers on GaAs.

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