Improved Optical Quality and 1.26 µm Light Emission from (411) GaAsBi /GaAs MQWs Grown by MBE

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Abstract

We have grown GaAsBi/GaAs MQWs on GaAs (411)A and (411)B substrates by MBE and investigated arsenic pressure dependence of the Bi concentration of GaAsBi layers and optical characteristics of MQWs. The highest bismuth composition (x = 0.03) was obtained for GaAsBi layers grown under a arsenic pressure of 1.0x10^{-5} mbar for both (411)A and (411)B MQWs. The MQWs grown on both substrates at the optimized arsenic pressure show a PL peak at 1.26 µm. The MQWs on (411)A and (411)B substrate showed 3 times and 2 times stronger integrated RT PL intensity, respectively, than simultaneously grown (100) MQWs.

INTRODUCTION

The III-V semiconductors gain media in the 1.3–1.5µm wavelength range are currently under intense investigation because of the important role of lasers in optical fiber communications. Samples grown with Bi have numerous benefits, such as surface smoothing owing to its surfactant effect, large band gap reduction and temperature insensitive band gap. Such characteristics are favorable for developing long wavelength optoelectronic devices [1-4]. GaAsBi/GaAs MQWs are of interest for fabrication of laser diodes [5]. However, incorporation of Bi into MQWs is more complicated than into bulk alloys than that of conventional III–V alloys, e.g., In or Al atoms into InGaAs or AlGaAs [6]. The growth of GaAsBi has proven complicated, requiring very low growth temperatures (<400 °C) to incorporate significant fractions of Bi [7, 8]. The quality of GaAsBi is highly dependent on the Bi composition and the growth temperature. Improvement of optical quality and longer wavelength light emission is still the main issue of the GaAsBi related materials for optical device application. MBE growth of GaAsBi on high index substrates instead of (100) substrates is expected to change the growth mode drastically, enhance incorporation of Bi atoms and reduce the introduction of nonradiative centers. Especially (411)A and (411)B oriented substrates are good candidates to accomplish them [9, 10]. Up to now, literature on GaAsBi has mainly reported on thick layers [11], and only a few papers on the growth of MQWs structures have been published [12]. In this work, we have investigated growth of GaAsBi/GaAs MQWs on (411)A and (411)B face, and demonstrated much improved optical quality and longer wavelength emission.

EXPERIMENTAL

Samples consisting of eleven pairs of 9 nm thick GaAsBi and 14 nm GaAs were grown on (411)A, (411)B, and (100) GaAs substrates by MBE. Beam equivalent pressures (BEPs) of Ga and Bi were adjusted with an ion gauge to be 8.5x10^{-7} mbar and 5.4x10^{-7} mbar, respectively. The Ga BEP fixes the growth rate of the samples at 1.2 ML/s. The GaAsBi layers were grown at $T_{\mathrm{GaAsBi}} = 350$°C. During the growth of GaAsBi layers, some of bismuth atoms are incorporated and others are accumulated on the surface. After the growth of each GaAsBi layer, growth was interrupted. The substrate temperature was increased and kept at 550°C, and bismuth atoms on the surface were desorbed [13]. GaAs layers were grown at $T_{\mathrm{GaAs}} = 550$°C. We then prepared samples grown at different arsenic BEP between 3.5 x 10^{-6} and 2.0x10^{-5} mbar. The growth was interrupted for 2 min at every interface exchanging from GaAs to GaAsBi. A schematic illustration of the samples structure is shown in the fig. 1.

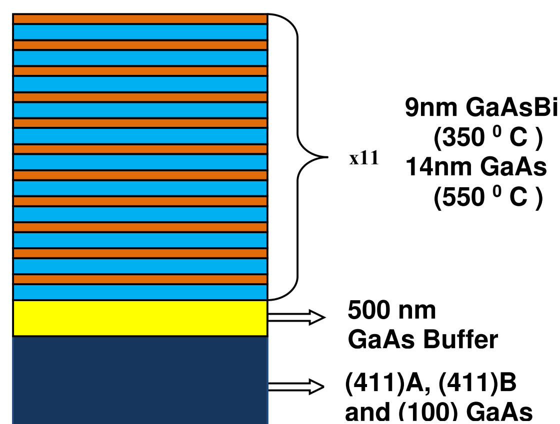

Fig 1. Schematic structure of 11 pairs of GaAsBi/GaAs multi quantum wells (MQWs) sample.

The layers were characterized by high resolution x-ray diffraction (HRXRD) by Phillips X'Pert Pro Materials Research Diffractometer with an incident x-ray beam wavelength of CuKα, (λ = 0.15406 nm). The HRXRD scans were then fitted using “Epitaxy” software to determine Bi composition and epilayer thicknesses

assuming a GaBi lattice constant of 6.324 Å as zinc blende structure [14]. The PL measurements were conducted on this structure using 638 nm line of InGaP semiconductor laser as an excitation source. The laser excitation with power of 3.8 mW was focused onto the sample surface with its spot diameter of 200 µm.

RESULTS AND DISCUSSION

We focus on the effect of the As_4 BEP during the growth, and its impact on Bi incorporation and optical characteristics are investigated. The averaged Bi concentrations of GaAsBi layers within the GaAsBi MQWs grown on (411)A, (411)B, and (100) GaAs substrate obtained from line shape fitting using simulations of x-ray diffraction curves are summarized in fig. 2. The Bi concentration increased with increasing As_4 BEP for all series of samples. With the increase of As_4 BEP, we observe the distinctive increase of Bi concentration at As_4 BEP between $6.0\text{x}10^{-6}$ and $1.0\text{x}10^{-5}$ mbar, and then it seemed to be saturated at higher BEPs. The Bi compositions were nearly the same for samples grown at As_4 BEP between 1.0 $\text{x}10^{-5}$ and $2.0\text{x}10^{-5}$ mbar, suggesting transfer of growth mode at smaller or larger regime of 1.0 $\text{x}10^{-5}$ mbar As_4 BEP [15]. The largest Bi concentration of GaAsBi in MQWs is 3.8 % for (100), and 3 % for both (411)A and (411)B in the GaAsBi layer, even though all samples grown simultaneously. It indicates that the crystal quality and amount of Bi incorporation is not only sensitive to the As_4 BEP but also to substrate orientation.

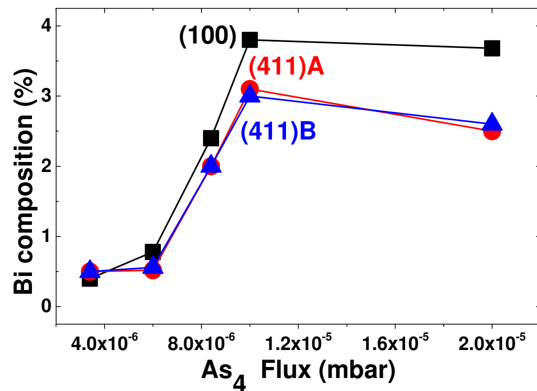

Fig 2. Bi concentration as a function of As_4 BEP for GaAsBi/GaAs MQWs grown on (411)A, (411)B and (100) substrate.

Figure 3 shows experimental and simulated HRXRD curves for GaAsBi MQWs on both (411)A and (411)B sample grown at a As_4 BEP $1.0\text{x}10^{-5}$ mbar. As seen in the HRXRD diffraction patterns of MQWs grown at As_4 BEP 1.0 $\text{x}10^{-5}$ mbar spectrum showed well defined clear satellite peaks, suggesting smooth interfaces grown under coherent growth conditions and uniform incorporation of Bi [14]. We assume that Bi atoms are evaporated with increasing substrate temperature prior to the growth of GaAs layer and uniformly distributed in GaAsBi layers and it also having a steep composition profile in simulation [13, 16], then obtained a good agreement between the experimental and simulated HRXRD curves [1]. The observed peaks in figure can be distinguished between -3rd and +1st order satellites adjacent to dominant main peak. The sharp and largest peaks located near 0th order satellite correspond to diffraction from GaAs buffer layer and substrate. The fit returns the width of MQWs having of 9 nm GaAsBi and 14 nm GaAs. Those samples contain 3.0 % Bi in GaAsBi layers. The difference observed in between full width at half maximum (FWHM) of (411)A and (411)B HRXRD spectrum due to lateral strain of GaAsBi layers average Bi composition fluctuation. However, the mismatch between GaAs and GaBi is very large, approximately 12%. Therefore, strain energy in GaAsBi epilayers with large Bi concentration also contributes to the deterioration of crystalline quality of samples. We observed the less Bi incorporation at low arsenic supply, revealed with poor HRXRD satellite peak spectrum, indicating Bi was not incorporated into the grown layers [14].

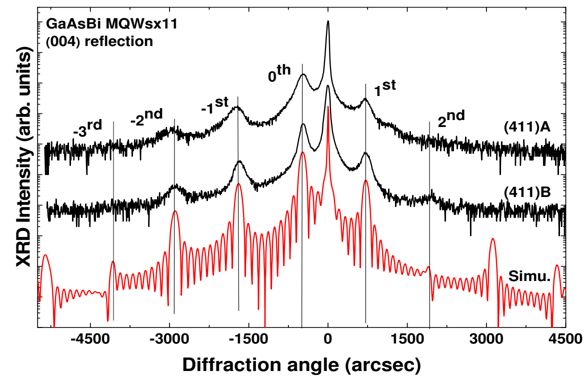

Fig 3. HRXRD spectra experimental (black) and simulation (red) for GaAsBi MQWs (411)B sample grown at $1.0\text{x}10^{-5}$ mbar As_4 BEP with x=0.03.

Figure 4 shows the results of PL measurements for the series of GaAsBi MQWs on (100), (411)A and (411)B at 10 K with respect to substrate orientation dependence for various As_4 BEP. Overall, we observe clear redshift of the spectral wavelength with increase of As_4 BEP, probably induced by introduction of larger amounts of Bi as suggested by Fig. 2 [17]. Therefore, the PL wavelength can be precisely controlled by regulating the As_4 BEP. This controllability of emission wavelength is the great advantage for device application. To understand optical properties and transition mechanism keenly the MQWs on (411)A and (411)B substrates needed to be investigated more critically.

The sharp and single luminescence peak obtained from MQWs grown at $1.0\text{x}10^{-5}$ mbar As_4 BEP on (100), (411)A and (411)B as shown in fig. 5(a). Samples grown at the same As_4 BEP showed relatively preferable spectral features having their peaks at 1102 nm and 1145 nm with their FWHM of 130 nm and 152 nm for MQWs grown on (411)A and (411)B substrate respectively. For (411)B sample longest wavelength achieved due to

GaAsBi layers lateral strain and broadening of PL FWHM as compared to (411)A and (100). At this condition, the MQWs grown on (100) substrate showed its peak position at 1110 nm with width of 80 nm, similar to the values of previous reports [14, 18]. This agrees with fact that Ga rich (411)A and As rich (411)B side carriers are confined in the Bi rich region, ascribed to enhanced quantum confinement. This observation suggested that optical properties and amount of Bi incorporation is sensitive to the As_4 BEP for MBE growth.

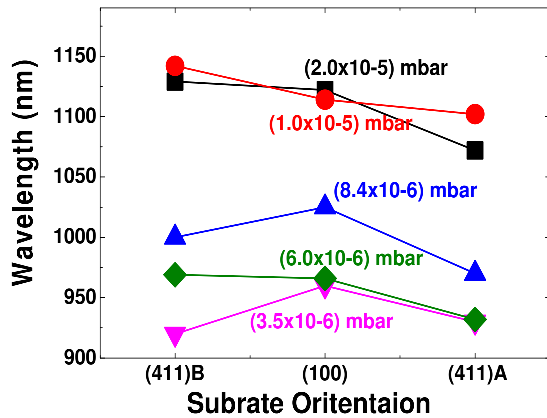

Fig 4. PL peak wavelength for (411)A, (411)B, and (100) GaAsBi MQWs grown at different As_4 BEP

We observe a broad luminescence peak having its full width at half maximum (FWHM) larger than 80 nm for GaAsBi MQWs grown over wide range of As_4 BEP. In addition, we recognize multiple peaks for spectra obtained from samples grown at As_4 BEP of 3.5×10^{-6} mbar on (411)A and (411)B substrates [19]. Most significantly, the structural disorder can induce localized accumulations or depletions of carrier within MQWs. This localized electronic states act as a trapping centers for electrons and holes, which reduce introduction to nonradiative centers. That can greatly modify optical transition energies, for example by optically active deep level formations, such phenomena have been reported up to now [20,21]. The features of broad peaks for all samples as well as appearance of additional peaks could be explained by this carrier localization [19].

The further investigation carried out at room temperature PL (RT PL) of samples. Figure 5(b) shows, the RT PL spectra from (411)A and (411)B GaAsBi/GaAs MQWs showed 1.26 µm wavelength emission which is almost the same as RT PL emission wavelength for a single 8.5 nm thick GaAsBi layer with a Bi composition of 0.06 [19], indicating that GaAsBi/GaAs MQWs with effectively narrow energy gap material is grown using GaAsBi layers with much less Bi composition. At high temperature, majority of carriers are delocalized and the subsequent FWHM increase is due to increased thermal distribution.

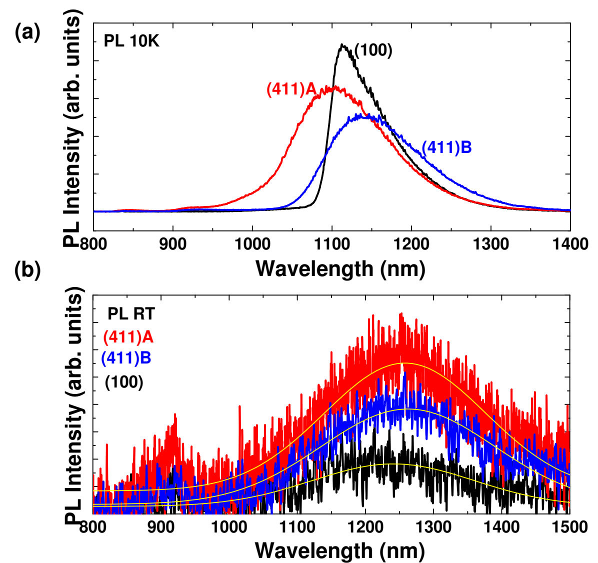

Fig 5. PL spectra at10K (a) and at RT (b) for GaAsBi MQWs grown on (411)A, (411)B and (100) substrate at 1.0×10^{-5} mbar As_4 BEP. Smooth lines are obtained by Gaussian curves fitting.

To clarify nonradiative recombination process of (411)A, (411)B and (100) samples grown at 1.0×10^{-5} mbar As_4 BEP, the temperature dependent integrated PL intensity (IPL) of the GaAsBi MQW peak is plotted in fig. 6 as a function of temperature reciprocal. At low temperature IPL intensity is approximately unchanged for all samples due to localization of excitons, their integrated intensity values are observed almost same. When temperature was changed from 100 K to RT, IPL intensity decreases exponentially by almost two orders of magnitude. Therefore, with increasing temperature, excitons are delocalized and can be captured by nonradiative centers, electron suffers lattice vibration and gains energy to overcome Coulomb force and would easily escape away from GaAsBi/GaAs interfaces. We observed distinct difference between (411) samples and (100) sample is their gradient of the slope, indicating that larger localization potential barriers [20, 21] or smaller density of nonradiative centers, which enhances effective localization potential barrier. The activation energy obtained from slopes are as 48 meV, 54 meV and 68 meV from (100), (411)A and (411)B, respectively. GaAsBi MQWs on (411)A and (411)B substrate have 3 and 2 times larger integral PL intensity compared to (100) MQWs at RT. Here, (411)A and (411)B samples have larger activation energy, indicating that this nonradiative recombination process is more difficult to happen, which makes the PL intensity drop slower as temperature rises than (100) sample. These activation energy values might be related to lateral confinement potential for electron and holes produced by Bi composition fluctuation. This implies that (411)A and (411)B MQWs have much better optical quality than (100) MQWs. The result obtained here should be useful for the room temperature operation of optoelectronic devices based on GaAsBi/GaAs quantum wells.

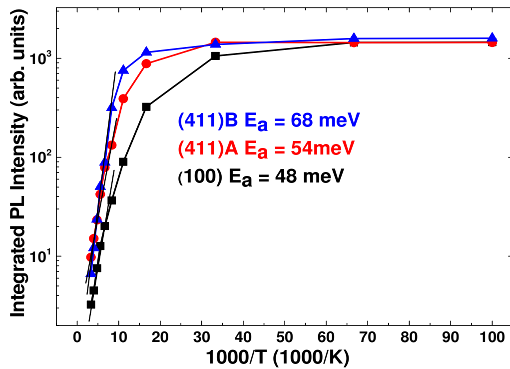

Fig 6. Temperature dependence of integrated PL intensity for GaAsBi /GaAs MQWs grown on (411)A, (411)B and (100) samples at $1.0x10^{-5}$ mbar As_4 BEP.

CONCLUSIONS

In summary, GaAsBi MQWs have been successfully grown by MBE on (411)A and (411)B GaAs substrates at optimal As_4 BEP and 1.26 µm wavelength PL emission from them were obtained at RT. High optical and structural quality has been demonstrated and confirmed by HRXRD and PL measurement. The (411)A sample and (411)B sample show 3 and 2 times higher integral PL intensity compared to that of the (100) GaAs sample simultaneously grown, respectively. The result indicates that GaAsBi MQWs grown on (411)A and (411)B GaAs substrates by MBE is expected to have better performance when they are applied to optical devices.

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ACRONYMS

MBE: Molecular Beam Epitaxy
MQWs: Multiple quantum wells
HRXRD: High Resolution X-Ray Diffraction
RT: Room temperature
PL: Photoluminescence
FWHM: Full width half maximum
BEP: Beam equivalent pressure