Enhancement of optical quality in metamorphic quantum wells using dilute nitride buffers

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Strong enhancement of optical quality in quantum wells by incorporating nitrogen in metamorphic InGaAs buffers grown on GaAs substrates is demonstrated. This has resulted in 3.7 or 5.4 times enhancement of photoluminescence intensity from the metamorphic quantum wells when using dilute nitride superlattice alone or adding nitrogen in a strain compensated $GaAs/In_{0.3}Al_{0.7}As$ superlattice, respectively. This study shows great potentials by incorporating N in metamorphic buffers to further improve the quality of metamorphic optoelectronic devices. © *2010 American Institute of Physics*. [doi:10.1063/1.3483839]

Lattice mismatch has always been a problem limiting the designs of semiconductor heterostructures. Restricted by the availability of large and high-quality commercial substrates, only a small range of materials with a lattice constant close to that of certain substrates, such as GaAs and InP, could be chosen. Metamorphic growth is one of the solutions by which a virtual substrate with a desired lattice constant can be obtained after growing a mismatched but nearly relaxed buffer layer on a conventional substrate. The main challenges of this method are the rough interface and a high density of threading dislocations (TDs) in the active region of the devices.[1] The TD problem is more severe for optoelectronic devices, such as lasers, which have large areas, and therefore can easily contain TDs in the active region. Several different procedures have been implemented to reduce the TD density when growing a metamorphic buffer layer, e.g., use of a thick uniform buffer layer,[2,3] a step-graded buffer layer,[4,5] and a continuously graded buffer layer.[6–8] Some other structures like strained superlattice (SL) (Ref. 9) and quantum dots[10] are also employed to block TDs. Although there have been notable progresses for metamorphic optoelectronic devices based on these methods,[3,7,11,12] further reduction in the TD density and correspondingly the enhancement in optical quality is still required to improve the device performance and make them competitive with existing products. Recently, incorporation of nitrogen into tensile-strained GaAsP has shown its effect on strain relaxation, dislocation formation, and motion,[13] which could be helpful for the TD reduction in metamorphic structures. Dilute nitrides are well known to reduce the band gap of host materials and have been used to fabricate high performance 1.3 μm telecom lasers on GaAs.[14,15] In this letter, we demonstrated strong improvements of optical quality in metamorphic quantum wells (QWs) by incorporation of dilute nitrides in compressively strained InGaAs grown on GaAs substrates.

All the samples were grown by a Veeco EPI930 molecular beam epitaxy system. Figure 1 shows the schematic structure of the samples. First, a 100 nm thick GaAs buffer layer was grown at 580 °C measured by a pyrometer. A 200 nm uniform $In_{0.15}Ga_{0.85}As$ buffer layer is then directly grown on top of the GaAs buffer and relaxed with a high density of misfit dislocations (MDs). On top of that, a 200 nm thick "TD blocking region" is grown with different schemes described in Table I. An identical QW structure (blue shaded area) is grown in all the samples for comparison of optical quality. The 3 nm thick AlAs layer acts as a barrier to stop the diffusion of exited carriers between the QW region and the rest part of the sample, while the thin GaAs layers are used to smoothen the growth front and protect surface. It should be noticed that the In composition in the barrier is 10% which is 5% less than that in the buffer. This is due to the so-called "setback" problem,[16] as the 200 nm thick

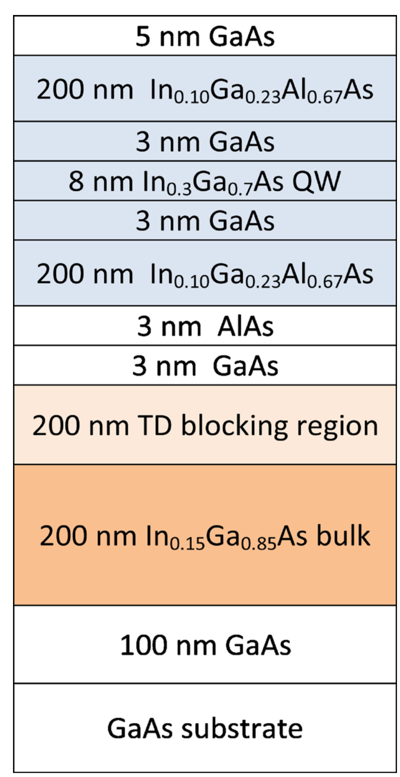

FIG. 1. (Color online) Schematic structure of the samples.

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TABLE I. Detail structures of the “TD blocking region” consisting of a SL except for the reference sample.

Label	Structure of the “TD blocking region”
Reference	200 nm bulk $In_{0.15}Ga_{0.85}As$
N1	(5 nm $In_{0.15}Ga_{0.85}As$+5 nm $In_{0.15}Ga_{0.85}N_{0.012}As$) ×20 periods
S1	(5 nm GaAs+5 nm $In_{0.3}Al_{0.7}As$)×20 periods
S2	(5 nm $GaN_{0.012}As_{0.988}$+5 nm $In_{0.3}Al_{0.7}As$)×20 periods
S3	(5 nm GaAs+5 nm $In_{0.3}Al_{0.7}N_{0.012}As_{0.988}$)×20 periods
S4	(5 nm $GaN_{0.012}As_{0.988}$+5 nm $In_{0.3}Al_{0.7}N_{0.012}As_{0.988}$) ×20 periods
S5	(5 nm GaAs+5 nm $In_{0.336}Al_{0.664}N_{0.012}As_{0.988}$) ×20 periods

$In_{0.15}Ga_{0.85}As$ buffer grown on GaAs is not fully relaxed. Therefore, a reduced In composition in the following structure is required to match the lateral lattice constant and avoid formation of new MDs above the TD blocking region. The validity of the chosen value is confirmed by the (115) and $(11\bar{5})$ rocking curves of x-ray diffraction (XRD). The measured relaxation rate is 95% and 100% for the $In_{0.15}Ga_{0.85}As$ buffer and the $In_{0.1}Ga_{0.23}Al_{0.67}As$ layer in the reference sample, respectively. The whole structure except the first GaAs buffer layer was grown at 500 °C. Samples were characterized by atomic force microscopy (AFM), transmission electron microscopy (TEM), photoluminescence (PL) and XRD. The AFM measurements were performed using a Veeco Dimension 3000 SPM with a height resolution of 0.1 nm. For the PL measurements, an argon-ion laser (514.5 nm line) was used as the excitation source. The emissions were dispersed by a Spex 1404 0.85 m double grating monochromator and detected with a liquid nitrogen-cooled North-Coast Ge detector. A standard lock-in amplifier was used to detect the signal. All the PL measurements were performed at room temperature.

For sample N1, the nitrogen source was turned on and off after each 5 nm growth of $In_{0.15}Ga_{0.85}As$ resulting in an $In_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}N_{0.012}As_{0.988}$ SL. By comparing the blue and green-dashed curves in Fig. 2 we find that incorporation of N dramatically improves the optical quality which indicates a strong TD blocking effect from the nitrogen.

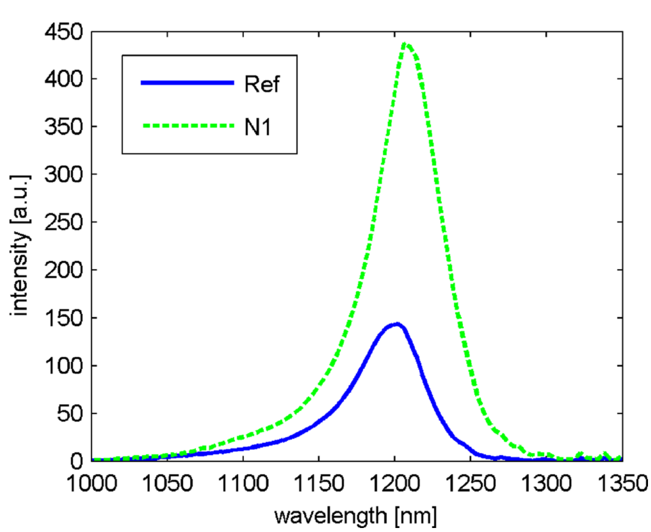

FIG. 2. (Color online) PL spectra of the sample Ref and N1.

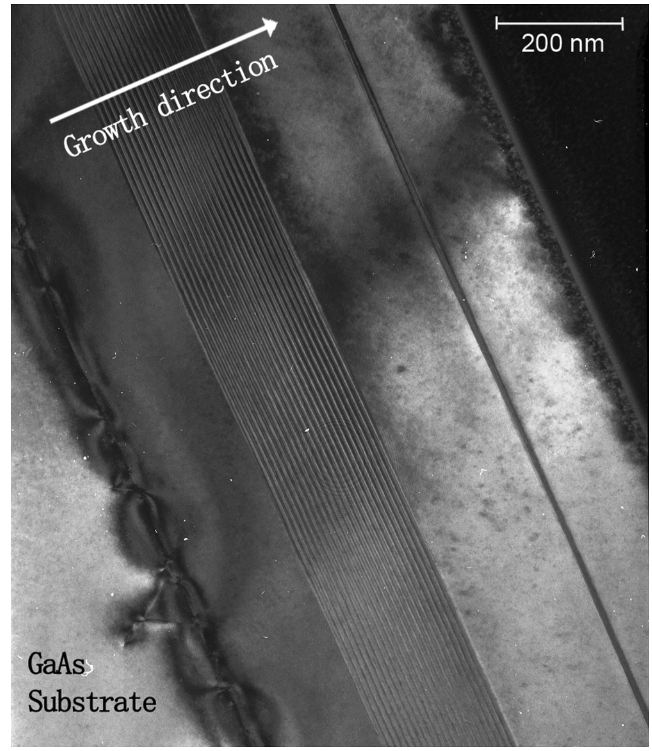

FIG. 3. A cross-section TEM image of the sample S1.

TEM has been performed in 100 nm thick species with a scan range of 10 μm. No obvious TDs are observed in the reference and other samples, indicating a low initial TD density in 10^7 cm^{-2} or lower. A typical TEM image is shown in Fig. 3. The QW and all other interfaces are very smooth confirming the two-dimensional growth nature. Heavy MDs are observed at $GaAs/In_{0.15}Ga_{0.85}As$ interface but few TDs are found in the image. Thus the strain relaxation is solely caused by formation of MDs rather than three-dimensional islands. For such a low TD density, TEM is not an ideal tool to compare the TD density. The AFM (not shown here) reveals a typical cross-hatch pattern for all the samples with a root-mean-square roughness value of 2 nm. The textured surface pattern prohibits using sensitive etching methods to count the etch pity density which directly links to the number of TDs. For these reasons, we will use PL as the main tool to assess material quality below. As photoexcited carriers can diffuse in QWs for a long distance in micrometers, they are very sensitive to the TDs. Therefore, PL offers a sensitive but indirect way to detecting the existence of TDs.

The origin of the N effect on dislocation dynamics may have two sources: the effect of minor tensile strain caused by the small covalent radius of N and the lattice hardening effect due to high bond strengths of N with group-III atoms.[17] The lattice hardening effect has also been observed in other materials, for example, when GaAs is highly doped by Si (Ref. 18) and the alloy of AlGaAs (Ref. 19) or InAlAs (Ref. 20) with high Al concentrations. This effect was evidenced by the increase in critical thickness by hindering the formation and motion of MDs as a result of the enhanced bonding strength.[17,18] The same impact could also make it difficult for the TDs to thread through the hard material and forces them to be bent.[19] In order to further investigate both effects, we incorporate N into different parts of a strain compensated $GaAs/In_{0.3}Al_{0.7}As$ SL (the S-series samples shown in Table

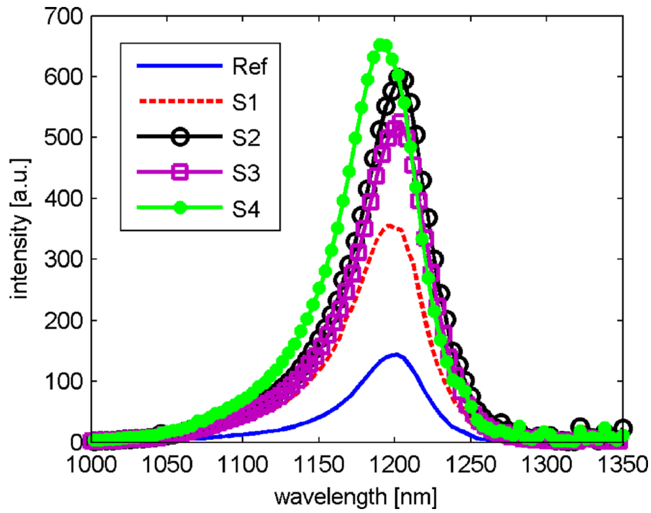

FIG. 4. (Color online) PL spectra of the Ref and the S-series samples with a strain compensated SL.

I). The GaAs layers in the SL are tensile-strained while the $In_{0.3}Al_{0.7}As$ layers are compressively-strained when grown on an $In_{0.15}Ga_{0.85}As$ buffer. The average strain of the SL is matched to the $In_{0.15}Ga_{0.85}As$ buffer. PL results of these samples are shown in Fig. 4. The strain compensated SL alone without N (S1) increases the PL intensity by about 2.5 times as compared with the reference. This is due to the fact that both the tensile GaAs and the compressive $In_{0.3}Ga_{0.7}As$ are able to bend TDs forming MDs and thus blocking TDs.[9] When N is incorporated into the SL, further improvement can be obtained as shown from samples S2–S4. A difference can be observed when the N is in the GaAs or in the $In_{0.3}Al_{0.7}As$ layers of the SL. This could be explained by the additional tensile strain brought by N. If N is incorporated into the GaAs layers, it adds tensile strain as well as the strain difference between the two parts of the SL. However, if it is in the $In_{0.3}Al_{0.7}As$ layers, the compressive strain is partly compensated and the strain difference becomes smaller. The larger strain difference leads to a more effective blocking of TDs and consequently a higher PL intensity of sample S2 than S3. This effect shows that strain counts for at least part of the reasons of the dislocation blocking effect when adding N. Although the strain is partly compensated in S3, an almost 50% increase in PL intensity can still be obtained compared with the S1 with a $GaAs/In_{0.3}Al_{0.7}As$ SL. Even more, sample S4, which has N in both the GaAs and the $In_{0.3}Al_{0.7}As$ layers, shows the highest PL intensity. To explicitly confirm the N hardening effect on blocking of TDs, we design sample S5 with the same strain as that of sample S3 by suing a slightly higher In of 33.6% to compensate the tensile strain of 1.2% N. The PL intensity is further improved by 20% as compared to S3. This improvement together with the enhancement of the PL intensity of sample N1 with respective to the reference sample where the strain effect is minor show unambiguous evidences of the lattice hardening effect. This effect is independent of and stronger than the strain effect.

In conclusion, we have demonstrated strong enhancement of optical quality in QWs by incorporating N in metamorphic InGaAs buffers grown on GaAs substrate. A 3.7 or 5.4 times improvement of PL intensity from the QW can be obtained when using a dilute N SL alone or combining dilute N with a strain compensated $GaAs/In_{0.3}Al_{0.7}As$ SL, respectively. This study shows great potentials by incorporating N in already optimized metamorphic structures to further improve the quality to meet demanding requirements necessary for metamorphic optoelectronic devices.

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