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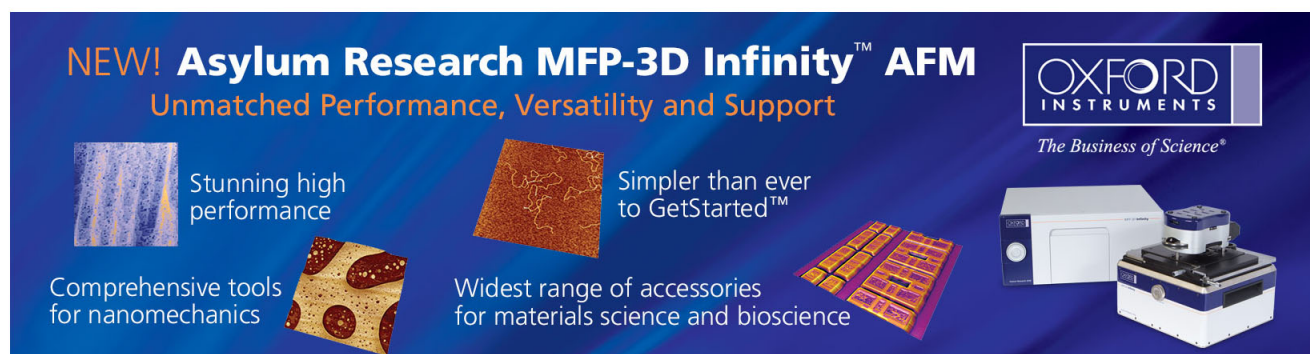
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Enhancing luminescence efficiency of InAs quantum dots at 1.5 μm using a carrier blocking layer

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The authors report an effective way to enhance the optical efficiency of InAs quantum dots (QDs) on GaAs emitting at the wavelength of 1.5 μm . It is found that the loss of holes from QDs to their proximity via the high indium composition InGaAs overgrown layer, which is necessary for achieving long wavelength emission, is the origin of photoluminescence intensity degradation at high temperature. Inserting a 4 nm thick $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ layer, acting as a carrier blocking layer, into the GaAs capping matrix can improve the room temperature photoluminescence peak intensity by five and two times for the ground and first excited states, respectively. © 2006 American Institute of Physics. [DOI: 10.1063/1.2245374]

With the advantages of mature material technology over InP and low dimensional quantum effect, InAs quantum dot (QD) lasers on GaAs substrate emitting at 1.3 or 1.55 μm have been actively pursued for lightwave communications. In the past few years, much progress has been made on 1.3 μm QD lasers based on self-assembled InAs/GaAs QDs grown by molecular beam epitaxy, in terms of threshold current,¹ modulation speed,^{2,3} linewidth enhancement factor,^{3,4} characteristic temperature,^{3,5} and differential quantum efficiency.⁶ However, the work on 1.5 μm range QD lasers has not been so successful due to the rapid deterioration in structural and optical properties of the high indium containing heterostructure unless a metamorphic buffer layer is used.⁷ There are also several groups trying to achieve the same target using metal-organic chemical vapor deposition (MOCVD), which is considered a better technique for mass production. So far, there are only two groups that have been able to extend the emission wavelength of InAs QDs on GaAs to 1.5 μm regime using MOCVD.^{8,9} However, the luminescence efficiency of the QDs still decreases significantly as the emission wavelength is extended to 1.5 μm by capping the QDs with a high indium composition InGaAs layer. It hampers the realization of 1.55 μm QD lasers on GaAs.

Previously, we have demonstrated that the luminescence efficiency of long wavelength InAs QDs can be improved by using triethylgallium precursor for the growth of the GaAs cap layer.⁹ In the present study, we find an effective way to further improve the luminescence efficiency of InAs QDs. A wide band gap material, which acts as a carrier blocking layer (CBL), is inserted into the GaAs matrix to effectively alleviate photoluminescence (PL) quenching of InAs QDs.

The samples were grown by low-pressure MOCVD in a vertical reactor. The precursors are trimethylindium (TMI), trimethylgallium (TMG), triethylgallium (TEGa), trimethylaluminum (TMAI), and arsine (AsH_3). We prepared two types (types I and II) of samples in this study. The schematic drawings of type-I and type-II samples are shown in Figs. 1(a) and 1(b), respectively. Type-I samples are designed to

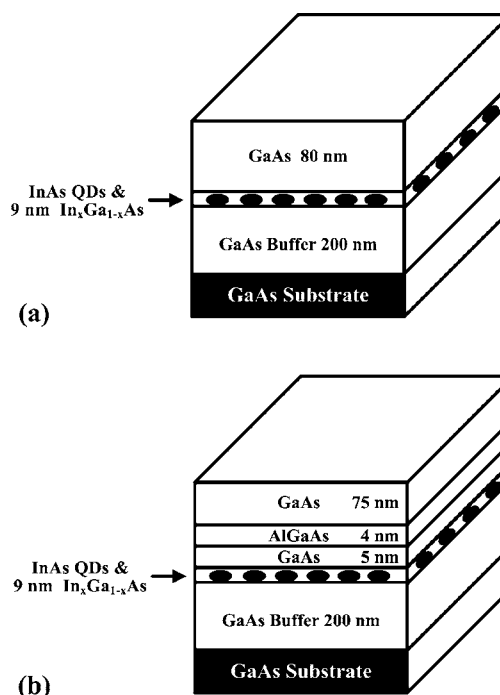


FIG. 1. Schematic of InAs QDs embedded in GaAs matrix (a) without and (b) with carrier blocking layer.

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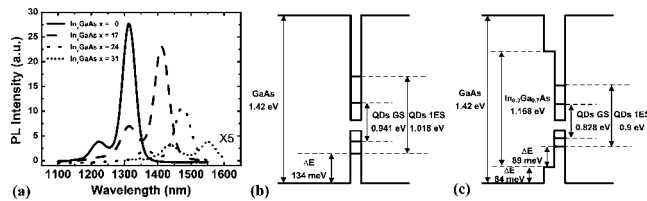


FIG. 2. (a) PL spectra of QDs with an InGaAs overgrown layer of various indium compositions and the band diagram for the InAs QDs (b) without and (c) with an InGaAs overgrown layer.

extend the emission wavelength of InAs QDs by a single overgrown layer while the second set of samples (type II) contains an additional CBL in the GaAs cap matrix for the enhancement of luminescence efficiency of QDs. Before the growth of the InAs QDs, a 0.2 μm thick GaAs buffer layer was grown on (100) 2° off towards (111)A Si-doped n +GaAs substrate at 650 $^\circ\text{C}$ using TMGa and AsH₃ as the source materials. The substrate temperature was then lowered to 500 $^\circ\text{C}$ for the growth of QDs and all the layers above the dots. Self-assembled InAs QDs were grown by depositing 2.7 ML of InAs with a deposition rate of 0.1 ML/s. From atomic force microscopy measurements on separate samples, these growth parameters led to QDs of about 20 nm in diameter, 6 nm in height, and a typical dot density of about $2 \times 10^{10} \text{ cm}^{-2}$. The InAs QDs were then embedded in a 9 nm thick InGaAs overgrown layer using TMGa, TMI, and AsH₃ as the source materials. For tuning the emission wavelength of QDs, indium composition of the InGaAs overgrown layer was varied from 0% to 31%. Samples were finally capped with an 80 nm thick GaAs grown using TEGa and AsH₃. For the type-II samples, a 4 nm thick Al_{0.45}Ga_{0.55}As layer, grown by TMAI, TMGa, and AsH₃, was inserted into the GaAs cap matrix, as shown in Fig. 1(b). The PL measurements were carried out between 10 and 300 K using the 514.5 nm line of an Ar ion laser as the excitation source.

Figure 2(a) shows the room temperature PL spectra of type-I samples. Here, the overgrown layer is In_xGa_{1-x}As with indium composition $x=0, 0.17, 0.23,$ and $0.31,$ respectively. The QDs with a pure GaAs overgrown layer [solid line in Fig. 2(a)] exhibited two PL peaks at 1.31 and 1.22 μm , which correspond to the ground state and the first excited state transitions, respectively. For the QDs with an InGaAs overgrown layer, the PL wavelength shifts to longer wavelength with increasing indium composition of the InGaAs overgrown layer. Emission wavelength for the ground state transition as long as 1.55 μm is obtained for the QDs with an In_{0.31}Ga_{0.69}As overgrown layer. There are two mechanisms proposed to account for the redshift of the QD emission by an overgrown layer. One is the relaxation of compressive hydrostatic strain in QDs (Refs. 10 and 11) and the other is the increased volume of QDs caused by phase separation of the InGaAs overgrown layer.¹²⁻¹⁴ Concurrently, the PL intensity of QDs decreases seriously as the indium composition of the overgrown layer is increased. According to previous works,^{8,9} the degradation of PL intensity of QDs with high indium composition InGaAs overgrown layer is attributed to two defect-related reasons. One is the increased nonradiative recombination centers within the high indium composition InGaAs layer.⁸ The other is proposed by the authors that nonradiative recombination centers in the GaAs cap layer also play a role in PL quenching because the resultant large

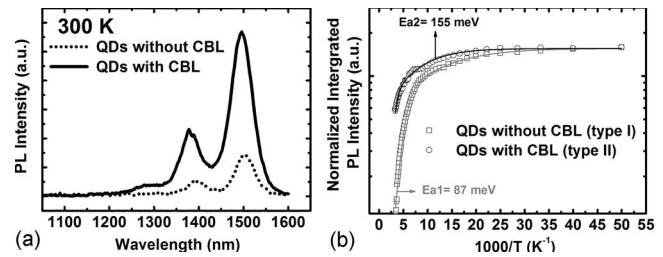


FIG. 3. (a) PL spectra of QDs embedded in GaAs matrix with and without CBL at 300 K, and (b) temperature dependence of the integrated PL intensity of QDs embedded in GaAs matrix with and without a carrier blocking layer.

QDs make smooth coverage of QDs by the GaAs cap layer difficult.⁹ Although we have used triethylgallium precursor for the growth of the GaAs cap layer to improve their optical property in 1.55 μm range, the PL intensity of the QDs decreases still to about one-thirtieth as the indium composition of the overgrown layer is increased from 0% to 31% and their activation energy deduced from the temperature-dependent integrated PL intensity decreases from 133 to 87 meV as well. These values are comparable to the energy difference between the hole first excited states in QD and the valence bands of GaAs (~ 134 meV) and InGaAs (~ 89 meV) as illustrated in Figs. 2(b) and 2(c), respectively. This is in good agreement with our previous studies on carrier escape mechanisms using PL and photocurrent techniques.^{15,16} It is therefore speculated that the high indium-content InGaAs overgrown layer, which is used to extend the emission wavelength of QDs, provides an easy path for holes to thermally escape from QDs.

To clarify this point, type-II samples were prepared, containing a 4 nm thick Al_{0.45}Ga_{0.55}As layer named as CBL as will be explained later. Figure 3(a) shows the PL spectra of two samples emitting at 1.5 μm with (type II) and without (type I) CBL at room temperature. In both samples, the indium composition of the InGaAs overgrown layer was 30%. By introducing the CBL, the PL intensity increased about five times for the ground state peak and two times for the first excited state peak. A possible reason for this is that carriers could be confined in the QD structure due to the CBL as indicated by the blueshift (~ 6 meV) in emission wavelength. However, the improved quantum confinement along cannot account for such a significant enhancement in luminescence efficiency, especially when the CBL is not directly in contact with QDs.¹⁷ It is illustrative to compare the present case with the reported ones, which employ wide band gap overgrown layers, such as Al(Ga)As (Ref. 18) and InAlAs.¹⁹⁻²¹ In those cases, the energy difference between the ground state and the excited state emission is increased by about 10–40 meV as compared to the case where an InGaAs cap layer is deposited, like in our type-I sample. However, our type-II sample shows an increase of only 6 meV, indicating that the AlGaAs CBL does not increase quantum confinement as much as wide band gap overgrown layers do.

For more insight into the PL improvement mechanism of InAs QDs with an AlGaAs CBL, the temperature dependence of the integrated intensity of both types of QD samples (types I and II) was examined. Figure 3(b) shows the Arrhenius plot of integrated PL intensity of type-I and type-II samples between 20 and 300 K. The type-I sample shows a typical behavior of thermally activated nonradiative recom-

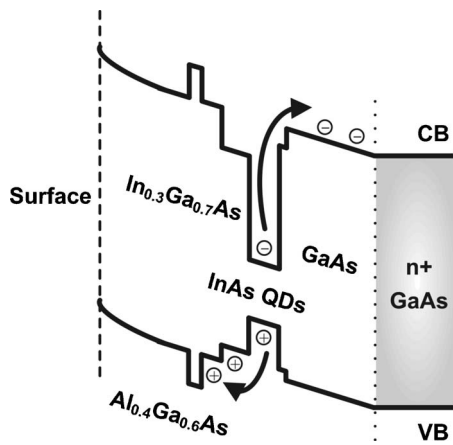


FIG. 4. Carrier escape processes of InAs QDs embedded in GaAs matrix with a carrier blocking layer.

bination of QDs. Its integrated PL intensity quenches slowly as the temperature increases from 20 to 130 K and then rapidly from 130 to 300 K. This behavior is usually attributed to thermally enhanced carrier recombination in nonradiative centers located at the vicinity of the QDs,²² or carrier escape and then recombination in the wetting layer and/or GaAs matrix.¹⁵ The type-II sample, on the other hand, shows a more extended high intensity range. Its activation energy is estimated to be 155 meV as compared to 87 meV for the type-I sample. Though the increase of activation energy is not as high as the energy barriers introduced by the AlGaAs CBL for holes, this value is still higher than the case with only a GaAs overgrown layer. The lower than expected activation energy might be attributed to hole tunneling that enhanced by the built-in field due to surface band bending. This process can be depicted by Fig. 4, which is the schematic band diagram of the type-II sample. The holes that blocked by this barrier may create a retarded field to prevent further escape of holes from the QDs or even enhance the retrapping process,²³ as implied by the slight increase in PL intensity when the temperature increases from 130 to 140 K. Although this carrier blocking and retrapping effect becomes less pronounced above 140 K due to the increased thermal energy of holes, the overall PL intensity of the type-II sample is still much higher than that of its type-I counterpart.

In summary, we have shown that the optical efficiency of InAs QDs emitting at 1.5 μm grown on GaAs can be improved with the presence of a high band gap material acting as a carrier blocking layer. Our results indicate that the loss of holes via high indium composition InGaAs overgrown layer is responsible for the PL degradation of InAs QDs emitting at 1.5 μm range. By inserting an AlGaAs layer in the GaAs matrix, the PL intensity is effectively enhanced as a result of holes blocking and retrapping process. High luminescence efficiency InAs QDs on GaAs emitting at 1.5 μm

can thus be prepared without complicated metamorphic buffer growth.

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