Room-temperature continuous-wave operation of GaInNAs/GaAs quantum dot laser with GaAsN barrier grown by solid source molecular beam epitaxy

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Abstract

We present the results of GaInNAs/GaAs quantum dot structures with GaAsN barrier layers grown by solid source molecular beam epitaxy. Extension of the emission wavelength of GaInNAs quantum dots by ~170nm was observed in samples with GaAsN barriers in place of GaAs. However, optimization of the GaAsN barrier layer thickness is necessary to avoid degradation in luminescence intensity and structural property of the GaInNAs dots. Lasers with GaInNAs quantum dots as active layer were fabricated and room-temperature continuous-wave lasing was observed for the first time. Lasing occurs *via* the ground state at ~1.2µm, with threshold current density of 2.1kA/cm^2 and maximum output power of 16mW. These results are significantly better than previously reported values for this quantum-dot system.

I. Introduction

GaInNAs material is promising for application in 1.3-1.55µm laser diodes on GaAs substrate,[1,2,3,4] since introducing of N into GaInAs effectively reduces the energy bandgap due to the large bowing coefficient between GaN and GaAs. Moreover, the addition of N to GaInAs predominantly affects the conduction band states leading to large conduction band offset. This is of great advantage to laser diodes, which are required to operate at high temperature. GaInNAs/GaAs quantum well (QW) lasers emitting at 1.3µm[2,3] and 1.52µm have been reported.

Following the development of GaInNAs QWs, studies on self-assembled GaInNAs quantum dots (QDs) have attracted much interest. Theoretically, QDs can potentially improve laser performance due to its unique state density function, which increases the optical gain and limits the thermally-induced carrier distribution.[5,6] Furthermore, it is expected that the effect of N incorporation on bandgap reduction in GaInNAs QDs will enable extension of emission wavelength to longer values compared to the GaInAs QD system. In recent years, GaInNAs QDs have been successfully grown by molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy.[7,8,9] Sopanen *et al.* reported the growth of GaInNAs QDs by gas-source MBE and demonstrated wavelength extension by tuning the photoluminescence (PL) emission from 1.04µm to 1.52µm. This was achieved by increasing the N composition in the $Ga_{0.3}In_{0.7}NAs$ QDs from 0 to 4%. However, increase in N content causes quality degradation of the dilute nitride material[10], and this affects the optical quality of the GaInNAs QDs. The PL intensity of the GaInNAs QDs degrades by 2-3 orders of magnitude following increase in N from 0 to 4%. Furthermore, strong local strain around the N atoms may cause compositional undulation in the GaInNAs layer.[11] As a result, GaInNAs dots were found to exhibit greater size nonuniformity’ and broader PL spectra following increase in N composition. Hence, this suggests the N composition in GaInNAs QDs should be as low as possible. Using relatively low nitrogen composition (1%), Makino *et al.* reported lasing from $Ga_{0.5}In_{0.5}N_{0.01}As_{0.99}$ QDs at 77K under pulsed current injection on materials grown by chemical beam epitaxy. However, due to the low N composition, the lasing wavelength is around ~1.0μm. Hence, it is obvious that the key challenge for realizing a GaInNAs QD laser is through growth optimization for obtaining high-quality GaInNAs QDs. The integral issue is how to extend the wavelength of GaInNAs QDs without deteriorating its optical quality.

This paper reports the growth of GaInNAs QDs using solid-source MBE, and the demonstration of room temperature CW lasing from such QD structures for the first time. A relatively low N composition of ~1% was chosen to avoid degradation in material quality caused by high N content. The use of GaAsN as barriers (instead of GaAs) for the GaInNAs QD layer helps to extend the emission wavelength of the GaInNAs QDs without serious degradation to the optical quality. The fabricated laser demonstrates significantly better performance compared to previously reported data for such a quantum-dot system.

II. Experimental Details

The samples were grown on GaAs (100) by MBE with radio frequency (RF) plasma assisted N source. GaInNAs dot layer was deposited after the GaAs buffer and a several-nm GaAsN layer, and then covered by another GaAsN layer and a GaAs cap layer. The N composition in the GaInNAs QDs and GaAsN barriers was kept at 1% by controlling the flow rate of high-purity nitrogen and RF power, while the In composition was varied from 30% to 100% for different samples. The GaInNAs QD layers were grown at 480 to 500°C and under As_4/Ga beam equivalent pressure ratio of 18. During GaInNAs deposition, reflection high-energy electron diffraction (RHEED) pattern transforms from streaky to spotty characteristic, indicating initiation of the self-organized islanding process of 2D-3D transition. Atomic force microscopy (AFM) measurements were performed in uncapped GaInNAs QD samples grown under identical conditions. PL measurements were performed in a closed-cycle He cryostat. The PL spectrum was excited by Ar^+ 514.5nm laser and detected by a cooled Ge detector.

III. Results and Discussion

Fig.1 compares the low-temperature (5K) PL spectra from 5ML-thick $Ga_{0.5}In_{0.5}N_{0.01}As_{0.99}$ QD samples with GaAs barrier, 5nm-thick $GaAs_{0.99}N_{0.01}$ barrier, and 10nm-thick $GaAs_{0.99}N_{0.01}$ barrier. For the GaInNAs QD sample with GaAs barrier, the emission wavelength is 1030nm with full-width at half maximum

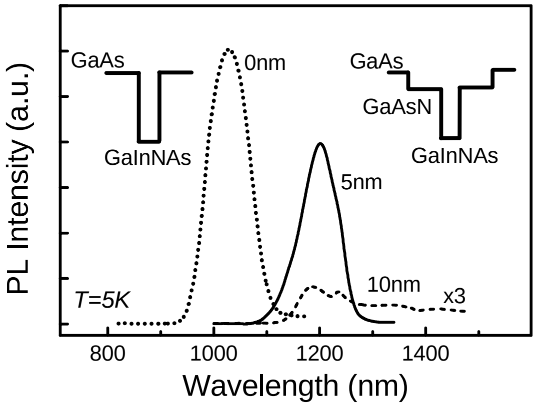

Figure 1 Comparison of low-temperature (5K) PL spectra from 5ML-thick $Ga_{0.5}In_{0.5}N_{0.01}As_{0.99}$ QD samples with GaAs barriers, 5nm-thick $GaAs_{0.99}N_{0.01}$ barriers, and 10nm-thick $GaAs_{0.99}N_{0.01}$ barriers.

(FWHM) of 92nm. For the GaInNAs QD sample with 5nm-thick GaAsN barrier, the PL peak wavelength redshifts to 1200nm with narrower FWHM of 81nm. This comparison indicates that using GaAsN as barrier layer is an effective method to extend the emission wavelength. The PL redshift is potentially related to lower GaAsN energy barrier and changes in QD size or internal strain. Amongst these, lower GaAsN barrier should be the dominant factor. This is because adding 1% N into GaAs barrier greatly lowers the barrier bandgap by ~200meV,[12] while the corresponding strain change in the dots is not more than ~3x10^{-3}, and QD size on GaAs or 5nm-thick $GaAsN_{0.01}$ has no big difference as measured by AFM.

Fig.1 also shows that the integral intensity of the PL spectrum of GaInNAs QDs with 5nm-thick GaAsN barrier is approximately 30% lower compared to that of GaInNAs QDs with GaAs barrier. However, increasing GaAsN barrier thickness to 10nm did not result in further redshift of the PL peak wavelength, but caused much weaker PL intensity and broader spectrum. These results suggest the GaAsN barrier should be kept reasonably thin to avoid degradation in optical quality. To understand the effect of GaAsN barrier on PL intensity of GaInNAs QDs, several aspects should be considered. It was reported that using tensile-strained GaAsP barrier for GaInNAs quantum wells resulted in improved optical luminescence due to partial strain compensation.[13] Therefore, similar benefit may also occur for GaInNAs QDs sandwiched between tensile-strained GaAsN barriers. However, the use of GaAsN barriers could potentially introduce some problems. Firstly, compared to GaAs, GaAsN barriers could introduce N-induced defects, such as Ga vacancies, nitrogen interstitials, and As_{Ga}-antisites,[14,15,16] which behave as nonradiative recombination centers. This can potentially degrade the optical quality. Secondly, the GaInNAs/GaAsN interface has larger strain compared to the GaInNAs/GaAs interface. Hence, depending on the GaAsN thickness, this may induce surface roughness and dislocation formation, which will degrade the structural and optical quality of the GaInNAs QDs. As evidenced from our PL results, weakening of the PL intensity observed in the sample with 10nm-thick GaAsN barrier could possibly be the result of a combination of the above processes.

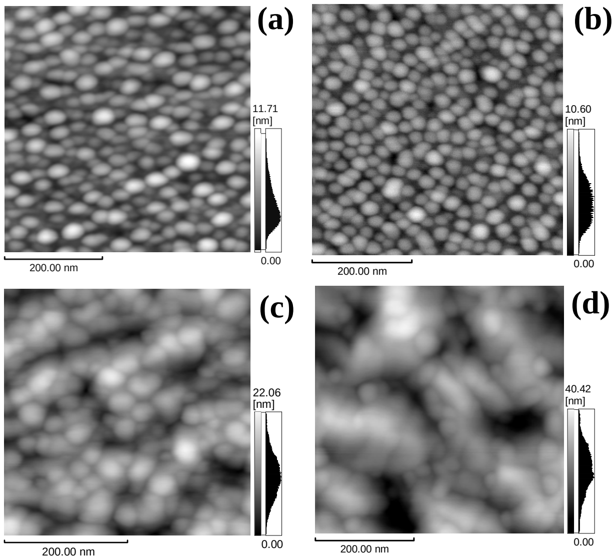

Figure 2 Comparison of AFM images of uncapped $Ga_{0.5}In_{0.5}N_{0.01}As_{0.99}$ QD samples with different GaAsN barrier thickness of (a) 0nm, (b) 5nm, (c) 10nm, and (d) 20nm. The scanned area is 0.5μm×0.5μm.

Fig.2 shows the AFM images taken on uncapped 5ML-thick $Ga_{0.5}In_{0.5}N_{0.01}As_{0.99}$ QD samples with different GaAsN barrier thickness (0, 5, 10, and 20nm). Fig. 2(a) shows that GaInNAs dots grown on GaAs layer have average diameter d ~ 33nm, height h ~ 5nm, and surface density ρ ~ 8.6×10^{10}/cm^{2}. As seen in Fig. 2(b), GaInNAs dots grown on 5nm-thick GaAsN layer have similar dot sizes and density (d ~ 30nm, h ~ 4.8nm, ρ ~ 1.1×10^{11}/cm^{2}) and appeared to have better uniformity. The size similarity of dots on GaAs or 5nm-thick $GaAsN_{0.01}$ suggests that the strain condition for

Table I. Summary of RT pulsed and CW threshold current density, and lasing wavelength for lasers with different GaInNAs active layer structure.

Device	Structure of active layer	Pulsed *J_{th} (A/cm^2)	CW J_{th} (A/cm^2)	Lasing λ (μm)
A	GaIn$_{0.2}$NAs QW (6nm) + GaAsN (5nm)	1000	1400	1.08
B	GaIn$_{0.3}$NAs QDs (28ML) + GaAsN (5nm)	1200	2124	1.18
C	GaIn$_{0.5}$NAs QDs (5ML) + GaAsN (5nm)	6000	**	1.08

* Pulsed measurement condition for Device A: (1000Hz, 10μs); Device B: (1000Hz, 5μs); Device C: (500Hz, 2μs).
** Failed to lase.

GaInNAs growth is not significantly changed by the GaAsN$_{0.01}$ layer. This agrees with another experimental observation, which shows the critical thickness of Ga$_{0.5}$In$_{0.5}$N$_{0.01}$As$_{0.99}$ on GaAsN$_{0.01}$ or GaAs layer has no obvious difference (~3ML), estimated from RHEED observation. However, increasing the GaAsN thickness to 10nm or 20nm resulted in obvious increase in surface roughness, as shown in Figs. 2(c) and 2(d). The GaInNAs dots appeared rather irregular with poor uniformity. This could have contributed to possible structural degradation associated with the drop in PL intensity.

Based on the above results, laser structures with GaInNAs dots as active layer and with 5nm-thick GaAsN barriers were fabricated. Fig.3 shows a schematic diagram of the laser structure and a cross-sectional transmission electron microscopy (TEM) image of the 28ML-Ga$_{0.7}$In$_{0.3}$NAs QD active region. The growth temperature used for laser structures was 480°C for the N-containing layers, 690°C for the n-AlGaAs cladding layer, and 600°C for the rest layers. Oxide-stripe edge-emitting lasers with uncoated facets were fabricated using standard processes. The device characteristics were measured under both CW and pulsed conditions.

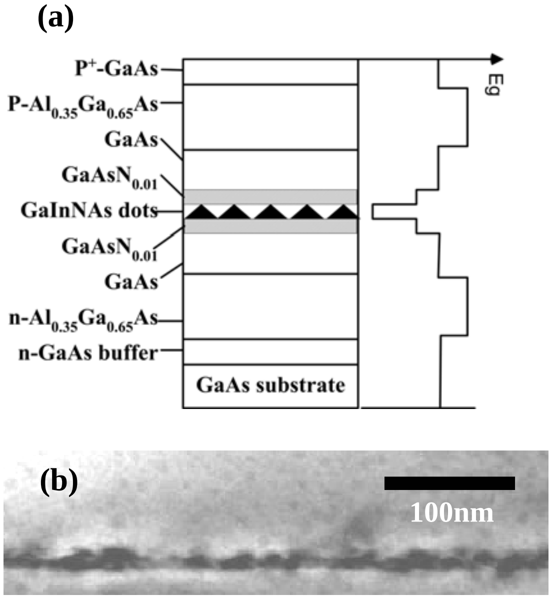

Figure 3 (a) Schematic diagram of QD laser structure, and (b) cross-sectional TEM image of the GaInNAs QD active region.

Table I summarizes the results from lasers with different GaInNAs QD active layers. All devices have GaAsN barrier layers. At room temperature, both QD lasers (Devices B and C) achieved lasing under pulsed condition. Device B, with Ga$_{0.7}$In$_{0.3}$NAs QDs, also achieved lasing under CW condition. In comparison to the reference device with Ga$_{0.8}$In$_{0.2}$NAs QW active layer (Device A), the threshold current density of the GaInNAs QD lasers is higher. This can be attributed to nonuniformity of the QD sizes. The maximum lasing wavelength of 1.18µm at room temperature CW operation was achieved from Device B. For Device C, the lasing wavelength is shorter (1.08µm), and the threshold current density much higher (6kA/cm^2). This could suggest that lasing in Device C occurred at higher excited states other than ground state. Figure 4 shows the room temperature CW voltage-current (V-I) and light output-current (L-I) characteristics of a $Ga_{0.7}In_{0.3}NAs$ QD laser (Device B) with cavity length of 2000µm and oxide stripe width of 50µm. Lasing started at threshold current of 2.1A and maximum light power of 16mW was achieved. The inset in Fig. 4 shows the lasing spectrum of Device B; the peak wavelength is located at 1176nm with spectral linewidth of 0.3nm.

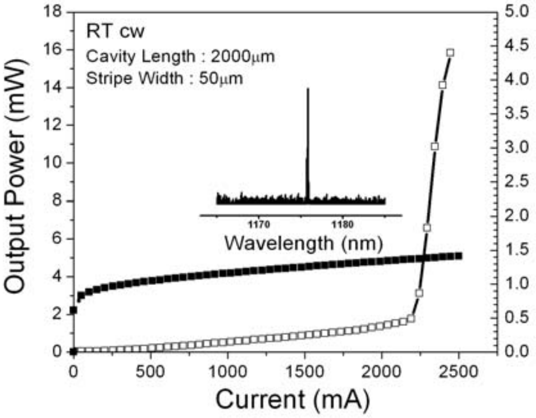

Figure 4 Room temperature CW I-V and L-I characteristics of $Ga_{0.7}In_{0.3}N_{0.01}As_{0.99}$ QD laser. The inset shows the room temperature electroluminescence lasing spectrum.

IV. Conclusion

In conclusion, this letter reports the growth of self-assembled GaInNAs QDs using solid source MBE, and extension of its emission wavelength using GaAsN barrier layers. Suitable thickness of GaAsN barrier layer is important to prevent degradation of structural and optical quality of the GaInNAs dots. Room temperature CW lasing at J_{th}=2.1kA/cm^2 and λ~1.2µm has been achieved in lasers with GaInNAs QDs as active layer and GaAsN as barriers. To the best of our knowledge, this is the first observation of room temperature CW lasing in GaInNAs QD devices grown using solid source MBE.

Acknowledgement

The authors would like to express their appreciation to Doan My The from the Institute of Microelectronics, Singapore for their technical support.

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