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Well-width dependence of the quantum efficiencies of GaN/$Al_xGa_{1-x}N$ multiple quantum wells

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A set of GaN/$Al_xGa_{1-x}N$($x \approx 0.2$) multiple quantum wells (MQWs) with well widths, L_w, varying from 6 to 48 Å has been grown by metalorganic chemical vapor deposition under the optimal GaN-like growth conditions. Picosecond time-resolved photoluminescence spectroscopy has been employed to probe the well-width dependence of the quantum efficiencies (QE) of these MQWs. Our results have shown that these GaN/AlGaN MQW structures exhibit negligibly small piezoelectric effects and hence enhanced QE. Furthermore, GaN/$Al_xGa_{1-x}N$ MQWs with L_w between 12 and 42 Å were observed to provide the highest QE, which can be attributed to the reduced nonradiative recombination rate as well as the improved quantum-well quality. The decreased QE in GaN/$Al_xGa_{1-x}N$ MQWs with $L_w < 12$ Å is due to the enhanced carrier leakage to the underlying GaN epilayers, while the decreased QE in MQWs with $L_w > 42$ Å is associated with an increased nonradiative recombination rate as L_w approaching the critical thickness of MQWs. The implications of our results on device applications are also discussed. © *2000 American Institute of Physics.* [S0003-6951(00)04921-4]

The group III-nitride wide band gap semiconductors are recognized as very promising materials for many optoelectronic device applications such as blue-green and UV light emitting diodes (LEDs), laser diodes (LDs), UV solar blind detectors, and high-temperature/power electronic devices.[1] As demonstrated by LDs, LEDs, and electronic devices, many III-nitride based devices must take advantage of multiple quantum well (MQW) structures such as GaN/AlGaN and InGaN/GaN MQWs for optimized device performance. Recently, many efforts have been devoted toward the understanding, design, and fabrication of GaN/AlGaN MQWs for UV light emitter applications.[2–9] For the design and fabrication of these MQW structures, one important issue is to maximize the quantum efficiencies (QE), i.e., to maximize the optical emission from the confined states in the well regions and to minimize the optical losses outside the well regions.[8] It was shown recently that the QE of the GaN/AlGaN MQWs depends strongly on the growth conditions. For the growth of GaN/$Al_xGa_{1-x}N$ MQWs, one can choose the growth conditions to be the optimal growth conditions of either GaN epilayers (GaN-like) or $Al_xGa_{1-x}N$ epilayers ($Al_xGa_{1-x}N$-like). It was demonstrated recently that the optimal growth conditions for GaN/AlGaN MQWs by metalorganic chemical vapor deposition (MOCVD) are GaN-like.[9] It is also well known that the structural parameters, including both barrier and well widths of the MQWs, have strong effects on the QE. Previous studies have shown that GaN/AlGaN MQWs with high optical qualities could be achieved when the well width, L_w, is between 25 and 40 Å.[3,10,11] However, the mechanisms of well-width dependence of the QE of GaN/AlGaN MQWs have not yet been investigated so far. Thus, a systematic study on GaN/AlGaN MQWs to probe the underlying mechanisms related to the effects of well width on the QE is needed.

In this study, a set of GaN/$Al_xGa_{1-x}N$ MQWs with L_w varying from 6 to 48 Å and a fixed barrier width of 50 Å has been grown by MOCVD. Picosecond time resolved photoluminescence (PL) spectroscopy has been employed to probe the well-width dependence of the QE. Our results have shown that the highest QE can be achieved in MQWs with L_w between 12 and 42 Å, which can be attributed to the reduced piezoelectric effect and nonradiative recombination rate as well as the improved quantum well quality. The decreased QE in GaN/$Al_xGa_{1-x}N$ MQWs with $L_w < 12$ Å is due to the enhanced carrier leakage to the underlying GaN epilayers, while that in MQWs with $L_w > 42$ Å is related with an increased nonradiative recombination rate as L_w approaching the critical thickness of MQWs.

The GaN/$Al_xGa_{1-x}N$($x \approx 0.2$) MQW samples were grown on 0001-oriented sapphire substrate under the optimal GaN-like growth conditions by MOCVD.[9] The growth temperature and pressure were 1050 °C and 300 Torr, respectively. For each of the eight samples, prior to the growth of the MQWs, a 250 Å GaN buffer layer and a 1.3 μm undoped GaN epilayer were grown on the sapphire substrate. It was then followed by the growth of the MQW structure with thirty periods of GaN well and $Al_xGa_{1-x}N$ barrier. The well widths of these eight samples (with a fixed barrier width of 50 Å) were 6, 12, 18, 24, 30, 36, 42, and 48 Å. The well and barrier widths were determined by the growth rate of the GaN and $Al_xGa_{1-x}N$ epilayers under the optimal GaN-like growth conditions. Picosecond time-resolved photoluminescence (PL) spectroscopy[12] was employed to study the optical properties of these MQWs. The excitation wavelength and pumping power were 290 nm and 20 mW, respectively.

The cw PL spectra of these eight samples measured at 10 K are shown in Fig. 1. The main emission peaks (varying

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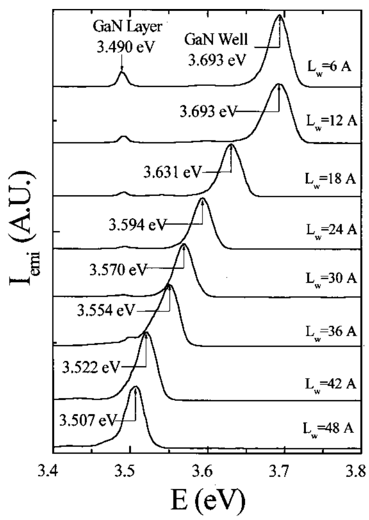

FIG. 1. PL spectra of GaN/$Al_xGa_{1-x}N$ MQW samples with well width varying from 6 to 48 Å and a fixed barrier width of 50 Å measured at 10 K.

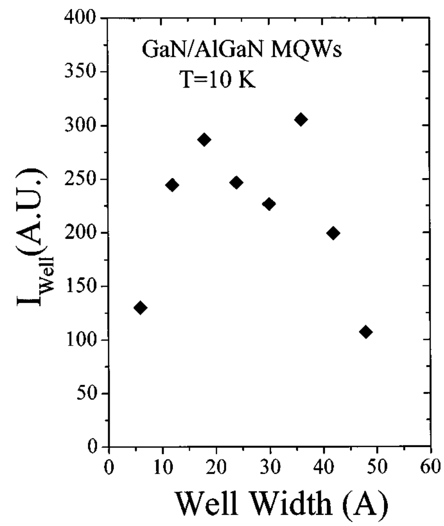

FIG. 2. The integrated well emission intensity vs well width for the GaN/$Al_xGa_{1-x}N$ MQWs measured at 10 K.

from 3.507 to 3.693 eV) in these spectra are due to the excitonic recombinations in the GaN-well regions. The low energy emission peaks around 3.490 eV are from the underlying undoped GaN epilayers. No transition peaks from the $Al_xGa_{1-x}N$-barrier regions are observed, indicating that the PL emission and carrier confinement in the well regions are highly efficient, which is consistent with our previous result that barrier transition is absent in GaN/$Al_xGa_{1-x}N$ MQWs grown under the optimal GaN-like growth conditions.[9] Compared with the emission peaks from the underlying GaN layers around 3.490 eV, the main emission peaks from the quantum wells are all blue shifted, which results from both the quantum confinement and the biaxial compressive strain in the well regions.[3,7,11]

From Fig. 1, the linewidths of the well emission peaks of these MQWs are between 25 and 35 meV, which are among the narrowest values reported for the GaN/$Al_xGa_{1-x}N$ MQW system. This indicates that the interface quality of these MOCVD grown MQWs is reasonably high, which should result in more efficient carrier confinement in these MQWs. An increased interface quality can also lead to a decreased nonradiative recombination rate at the interface and thus an enhanced radiative recombination rate or higher QE in the quantum wells.

The integrated well emission intensity versus L_w measured at 10 K for these GaN/$Al_xGa_{1-x}N$ MQWs is plotted in Fig. 2, which shows that the highest QE are achieved when L_w is between 12 and 42 Å. The uncertainty in the integrated emission intensity is mainly due to the slight variations in crystal growth between different runs. However, the general trend shown in Fig. 2 is still quite clear despite the experimental uncertainties. The high QE resulted from an improved quantum well quality, a reduced nonradiative recombination rate, and a decreased piezoelectric effect in these MQWs.

The time-resolved spectra of the 48 Å GaN/$Al_xGa_{1-x}N$ MQWs are presented in Fig. 3, where the well emission peak position demonstrates a total red shift with delay time of only about 5 meV. Similar behavior has been observed for all GaN/$Al_xGa_{1-x}N$ MQW samples studied here, implying the contribution from the piezoelectric field is negligibly small in GaN/$Al_xGa_{1-x}N$ MQWs studied here. Previous studies have shown the time-resolved spectra of the well emission of GaN/$Al_xGa_{1-x}N$ MQW samples ($L_w \geqslant 40$ Å) grown under different conditions to exhibit a large redshift (~60 meV) with delay time due to the presence of a strong piezoelectric effect together with the photoexcited carrier screening.[7] It is well known that the piezoelectric field will cause a spatial separation of the electron and hole wave functions and hence a large redshift of the well emission peak with respect to the GaN epilayers as well as a reduction of the radiative recombination rate (or QE).[13–16] It seems that the piezoelectric field is greatly reduced and the QE thus enhanced in these GaN/$Al_xGa_{1-x}N$ MQWs grown under the optimal GaN-like growth conditions by MOCVD.[9]

In addition to the reduced piezoelectric effect, the high QE achieved in the GaN/$Al_xGa_{1-x}N$ MQWs with L_w between 12 and 42 Å can be attributed to the reduced nonradiative recombination rate as well as the improved quantum well interface quality. The decreased QE seen in GaN/$Al_xGa_{1-x}N$ MQWs with larger L_w(>42 Å) suggests that the nonradiative recombination channels start to play an

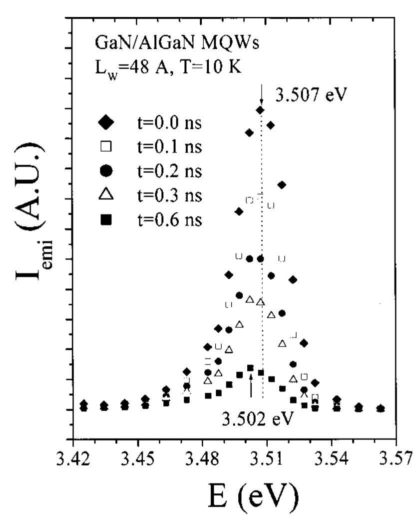

FIG. 3. Time-resolved PL spectra of the 48 Å well GaN/$Al_xGa_{1-x}N$ MQW sample, showing a total redshift with delay time of about 5 meV.

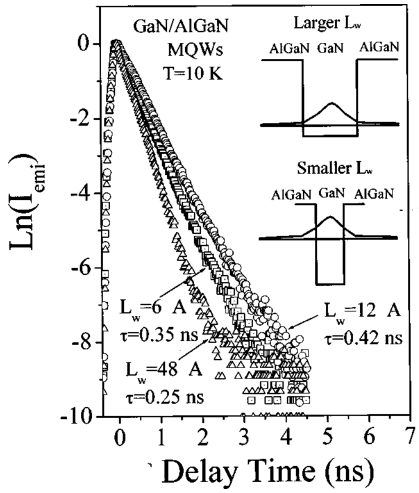

FIG. 4. PL temporal responses of the well transitions of three representative GaN/Al_xGa_{1-x}N MQWs with L_w=6, 12, and 48 Å measured at 10 K. The inset shows the electron wave function distribution in GaN/Al_xGa_{1-x}N MQWs with large and small well widths.

important role. This is consistent with the observation that the recombination lifetime of the well transition is shortest in the 48 Å GaN/Al_xGa_{1-x}N MQW sample. In Fig. 4, the PL temporal responses of the well transitions for three representative MQW samples are shown. We see that the recombination lifetime of the well transition in the 48 Å GaN/Al_xGa_{1-x}N MQWs is 0.25 ns, which is shorter than the value in the 6 Å (0.35 ns) or in the 12 Å (0.42 ns) GaN/Al_xGa_{1-x}N MQW sample. The low temperature lifetimes in all other GaN/Al_xGa_{1-x}N MQWs range between 0.30 and 0.40 ns (not shown). The reduced recombination lifetime in the 48 Å well width GaN/Al_xGa_{1-x}N MQW sample is due to an increased nonradiative recombination rate. It is expected that the misfit dislocation density in the GaN-well regions increases sharply as the well width approaches the critical thickness of MQWs, which results in an enhanced nonradiative interface recombination rate and thus lower QE.

On the other hand, the decreased QE in GaN/Al_xGa_{1-x}N MQWs with small L_w (less than 12 Å) is due to the enhanced carrier leakage to the underlying GaN epilayer. For MQWs with narrow L_w, the electron and hole wave functions will extend further into the barrier regions as illustrated schematically in the inset of Fig. 4, which leads to an increased (decreased) carrier recombination outside (inside) the well regions. As shown in Fig. 1, PL emission intensity at 3.490 eV from the underlying GaN epilayer is largest in the 6 Å well GaN/Al_xGa_{1-x}N MQW sample and decreases as L_w increases. This clearly indicates that the carrier leakage from the well regions to the underlying GaN epilayer increases with a decrease of L_w.

The temperature variations of the recombination lifetime and emission intensity have been measured for these MQW samples. For GaN/Al_xGa_{1-x}N MQW samples with L_w <48 Å, the lifetime increases linearly with temperature up to 80 K, which implies that the radiative exciton recombination dominates in these MQWs at low temperatures. For $L_w=48$ Å, the linear increase of lifetime with temperature is not observed due to an increased nonradiative recombination rate. The overall trend of the well-width dependence of the integrated emission intensity is similar to that shown in Fig. 2 for all temperatures.

In conclusion, a set of GaN/Al_xGa_{1-x}N MQWs with well width varying from 6 to 48 Å has been grown by MOCVD under the optimal GaN-like growth conditions. The quantum efficiencies of these MQW samples have been studied by picosecond time-resolved PL spectroscopy. It was found that the highest QE can be achieved in GaN/Al_xGa_{1-x}N MQWs with L_w between 12 and 42 Å, attributing to the reduced piezoelectric effect and nonradiative recombination rate as well as the improved quantum well quality. The decreased QE in GaN/Al_xGa_{1-x}N MQWs with $L_w<12$ Å is due to the enhanced carrier leakage to the underlying GaN epilayer, while in GaN/Al_xGa_{1-x}N MQWs with $L_w>42$ Å is attributed to the increased nonradiative recombination rate as L_w approaching the critical thickness of MQWs. Our results have shown that very high QE can be achieved in GaN/Al_xGa_{1-x}N MQWs grown under the optimal GaN-like growth conditions with well width between 12 and 42 Å, which is highly desirable for blue/UV light emitter device applications.

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