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Mechanism of photoluminescence in $GaN/Al_{0.2}Ga_{0.8}N$ superlattices

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We present photoluminescence (PL) and time-resolved photoluminescence measurements in $GaN/Al_{0.2}Ga_{0.8}N$ superlattices grown by metalorganic chemical vapor deposition under the optimal GaN-like growth conditions. We found that the carrier confinement of our samples is better than most of the previous reports. The dependence of the PL emission energy and intensity on temperature, in the low temperature regime, is consistent with recombination mechanisms involving localized states attributed to a small degree of interface fluctuations. Picosecond time-resolved photoluminescence spectroscopy has been employed to probe the well-width dependence of the lifetime of these superlattices. We see that the recombination lifetime increases with the decrease of well width. This behavior can be interpreted by the fact that the effect of localization keeping carriers away from nonradiative pathways can be enhanced by a decrease in the well width. This explanation is consistent with the temperature-dependent PL data. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1420495]

The group III-nitride wide-band-gap semiconductors have been recognized as very important materials for many optoelectronic devices, such as blue ultraviolet (UV) light emitting diodes (LEDs), laser diodes (LDs), and high-temperature/high-power electronic devices.[1–3] As demonstrated by LDs, LEDs, and electronic devices, many III-nitride based devices must take advantage of multiple quantum well (MQW) structure.[4–6] Therefore, many different optical techniques have been applied to the study of $GaN/Al_xGa_{1-x}N$ MQWs.[6–8] In addition to the potential applications, these QWs are of particular interest for basic investigations, because there the QW consists of binary material and thus no alloy-broadening effects arising from the QW material have to be taken into account. In this letter, we present photoluminescence (PL), time-resolved photoluminescence (TRPL) measurements in $GaN/Al_{0.2}Ga_{0.8}N$ superlattices with different well widths. The anomalous behavior of luminescence spectra as a function of temperature and the lifetime of excitons are measured. Based on the idea of carrier localization by interface roughness, all the measurements can be clearly understood. Our results thus firmly establish that the underlying mechanism of the luminescence in $GaN/Al_{0.2}Ga_{0.8}N$ superlattices arises from the radiative recombination by interface fluctuations. A detailed description of sample preparation and measurement techniques has been given elsewhere.[8,9]

The cw PL spectra of these three samples measured at 15 K are shown in Fig. 1. The main emission peaks in these spectra are due to the excitonic recombination in GaN-well regions. The inset to Fig. 1 shows the intensity of luminescence as a function of excitation intensity at 15 K. A linear relation was obtained for all the three samples, which indicates that the PL emission of the superlattices at 15 K is due to excitonic recombination.[10] No transition peaks from the $Al_{0.2}Ga_{0.8}N$ barrier regions are observed, indicating that our $GaN/Al_{0.2}Ga_{0.8}N$ MQWs grown under the optimal GaN-like growth conditions has an excellent carrier confinement. It is better than most of the previous reports with the same Al concentration, in which the emission of the barrier layers can be easily observed.[9] Compared with the emission peaks from the underlying GaN layers around 3.488 eV, the main emission peaks from the quantum wells are all blueshifted, which results from both the quantum confinement and the biaxial compressive strain in the well regions.[11,12]

In Fig. 1, the linewidth of the well emission peaks of these superlattice are between 25 and 35 meV, which is 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 superlattices is reasonably high, which should result in more efficient carrier confinement in these MQWs.

Figure 2(a) shows the luminescence peak position as a function of the temperature of W12 sample. The spectrum exhibits an anomalous behavior, in which the peak energy decreases, then increases with increasing temperature in the range of 45–85 K and finally decreases with temperature rapidly. Similar behavior has also been found in the other samples (W24 and W36). This so-called inverted S shape[13] has previously been observed in the quantum well structures.[14–16] This anomalous emission characteristic has been attributed to the presence of localized states, which is due to a certain degree of disorder occurring mainly at interfaces.

A model has been recently proposed to explain the blue temperature-induced shift in InGaN-based quantum well luminescence. The model is based on band-tail filling of a Gaussian density of states (DOS) with a parameter σ which describes the dispersion of the DOS (i.e., its width). The model calculation is given by[14,17,18]

$$E(T)=E(0)-\frac{2\alpha}{e^{\Theta/T}-1}-\frac{\sigma^2}{K_BT}, \quad (1)$$

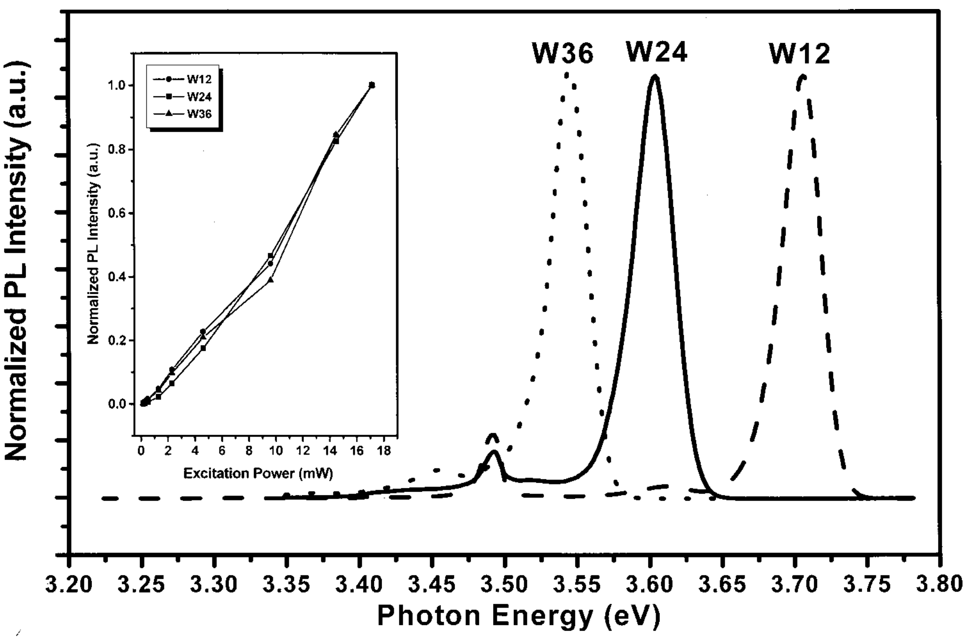

FIG. 1. Photoluminescence (PL) spectra of $GaN/Al_{0.2}Ga_{0.8}N$ superlattice samples with well width varying from 12 to 36 Å and a fixed barrier width of 50 Å measured at 15 K. The inset shows the PL intensity as a function of the laser excitation power.

where $E(0)$ is the transition energy at 0 K, α is the strength of the electron–phonon interaction, Θ is related to the average phonon energy, σ is the dispersion of the DOS (its width), and K_B is the Boltzmann constant. This model is valid in the temperature range where thermal equilibrium has been established. In our case, it is approximately around ~45 K and above. We use this model to analyze our data in order to estimate the extent of the DOS in the superlattice. The fitting is presented in Fig. 2(a). The fit resulted in the following values: $\alpha = 126$ meV, $\Theta = 523$ K, and $\sigma = 6.93$ meV. The value of σ is relatively small compared to the value of the superlattice emission (~3.8 eV) indicating the high quality of the superlattice interfaces.

The inset in Fig. 2(a) plots the PL linewidth of the superlattice sample with well width 12 Å. Similar to the peak position, the linewidth characteristic can also be separated into three different temperature regimes. In the first regime, the linewidth of PL emission increases slowly due to the exciton trapped into stronger localized states. Then, the linewidth of PL emission increases very fast in the second regime, because the excitons gain more thermal energy and are activated to higher energy states. Above the 85 K, the linewidth increase normally just due to the interaction of exciton with phonons. This behavior provides an additional evidence to support that the localized states are indeed responsible for the PL signal.

Figure 2(b) shows the luminescence intensity as a function of temperature. The PL intensity of the superlattice gradually decreases with increasing temperature. It appears that the data could be fitted well to the relationship used for amorphous semiconductors:[13]

$$I_{\mathrm{PL}} = \frac{I_0}{1 + A^* e^{T/T_0}}, \tag{2}$$

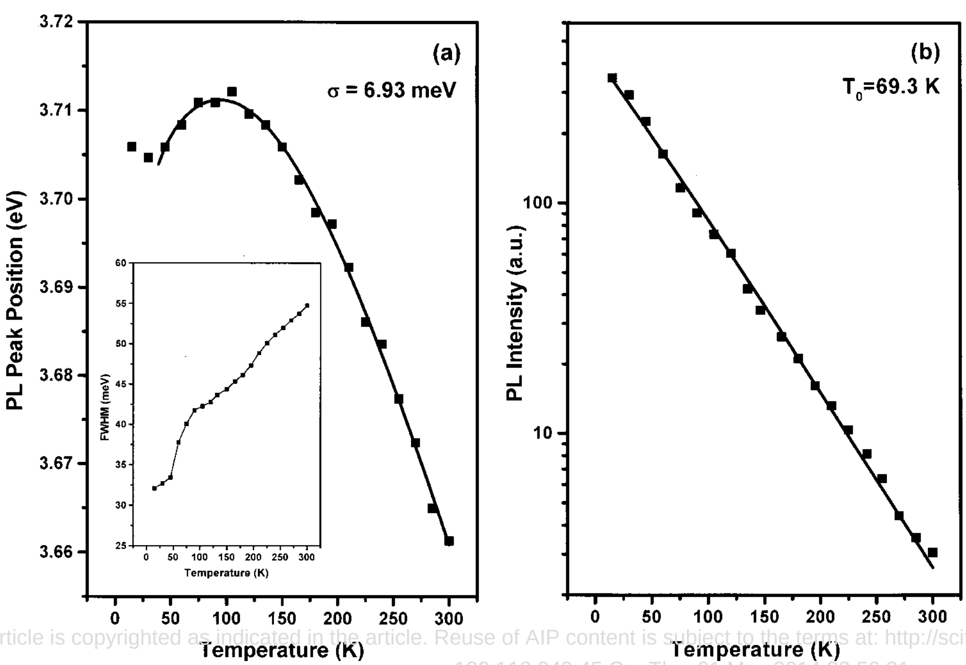

FIG. 2. (a) Temperature dependence of the photoluminescence (PL) peak position of the W12 sample. The line represents the result of Eq. (1). The inset depicts the PL linewidth as a function of temperature. (b) Integrated photoluminescence intensity as a function of temperature. The line is calculated fit following Eq. (2).

TABLE I. The computer-calculated parameters in $GaN/Al_{0.2}Ga_{0.8}N$ superlattices. The second column is the dispersion of the density of states (DOS); the third column is the characteristic temperature corresponding to the energy depth of localized states; and the fourth column is the temperature of the turning point.

Well width (Å)	σ meV	T_0 K	The temperature of turning point (K)
12	6.93	69.3	85
24	4.21	66	79
36	2.96	60.3	68

where I_{PL} is the PL intensity, T is the measured temperature, T_0 is the characteristic temperature corresponding to the energy depth of localized states, A is the tunneling factor, and I_0 is the PL intensity at the low-temperature limit. The underlying mechanism of Eq. (2) is due to the existence of localized tail states. Therefore, Eq. (2) can be used to fit our measurement, rather than a typical Arrhenius-type relationship, indicating the origin responsible for the PL signal comes from localized states. The other samples of W24 and W36 show a similar trend and have similar theoretical fits. The corresponding fitting parameters of the samples with different well width are listed in Table I. All the fitting parameters decrease with increasing well width. This implies that as the well width increases, the depth of localized states from interface roughness decreases. This result is also consistent with the prediction of interface roughness.

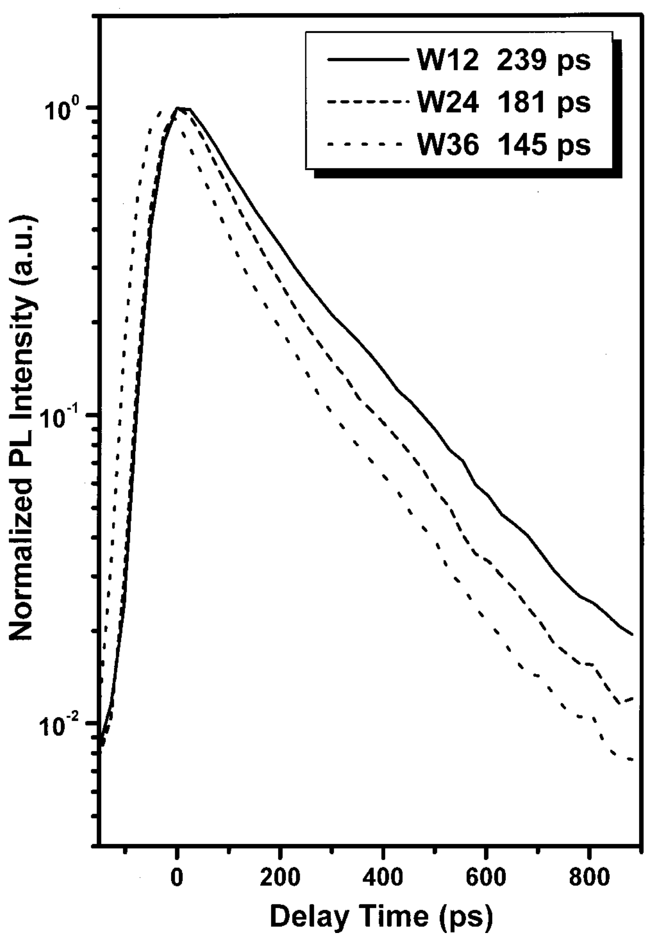

FIG. 3. Temporal responses of the transitions of three representative $GaN/Al_{0.2}Ga_{0.8}N$ superlattices with well width 12, 24, and 36 Å measured at room temperature.

To further investigate the recombination dynamics, the time-resolved decay of the three representative superlattice samples are shown in Fig. 3. We see that the recombination lifetimes of the well transition are 239, 181, and 145 ps for the samples with well width 12, 24, and 36 Å, respectively. According to the influence of interface roughness, this behavior can be easily understood because the localization depth increases with decreasing well width. The photoexcited electrons and holes are very easily trapped in the local potential minima. Due to the stronger localized effect with decreasing well width, the trapped electron-hole pair forming the exciton has more probabilities to be confined and recombine in the localized states. Therefore, the effect of localization keeping carriers away from nonradiative pathways enhances with the decrease of well width, and hence the lifetime increases.

In conclusion, a set of $GaN/Al_{0.2}Ga_{0.8}N$ MQWs with well width varying from 12 to 36 Å has been grown by MOCVD under the optimal GaN-like growth conditions. We have found that the carrier confinement of our studied sample is better than most of the previous reports. Through a detailed study of the dependencies of PL spectra on temperature, pumping power, well width of superlattices, and time-resolved PL, we show that the origin responsible for the PL transition is the interface roughness of $GaN/Al_{0.2}Ga_{0.8}N$ superlattices.

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