EXCITON LOCALIZATION IN InGaN/GaN QUANTUM WELLS

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Time-resolved cathodoluminescence (CL) techniques have been employed to examine the optical properties and kinetics of carrier relaxation in a InGaN/GaN single quantum well (QW) sample. CL images of the QW sample revealed a spotty cellular pattern indicative of local In compositional variations, which induce local potential fluctuations and result in a strong lateral excitonic localization at InN-rich regions in the InGaN QW layer.

1 Introduction

The study of InGaN/GaN heterostructures and quantum wells (QWs) has received a great deal of interest recently because of rapid progress and realization of high quality blue and green InGaN single QW light emitting diodes and lasers.[1] Time-resolved photoluminescence has been used to study the radiative recombination in InGaN QW structures.[2,3] Several authors observed that the emission results mainly from recombination of excitons localized at certain potential minima originating from large $In_xGa_{1-x}N$ compositional fluctuations.[4,5]

In this study, we have employed spatially, spectrally, and temporally resolved cathodoluminescence (CL) to investigate the carrier relaxation and recombination in InGaN/GaN heterostructues and single QW samples. The impact of large $In_xGa_{1-x}N$ compositional fluctuations on the spatial variation in the luminescence intensity and lifetime is explored. Quantitative lifetime information is obtained in connection with these spatial variations.

2 Results and Discussion

A 4-nm-thick InGaN single QW sample was studied here. The sample was grown by atmospheric pressure metalorganic chemical vapor deposition (MOCVD) using a closed space showerhead reactor via a multi-step growth approach[6] on a sapphire (0001) substrate, followed by a 70-nm-thick GaN capping layer. The InGaN/GaN heterostructure was grown under conditions similar to the QW, but without a GaN cap layer. All samples were undoped and have a 16% average In composition. The time-resolved CL and CL imaging experiments were performed with a modified JEOL-840A scanning electron microscope (SEM) using a 15 keV electron beam with various probe currents.[7] The temperature of the sample was maintained at ~87 K.

Spatially averaged CL spectra of the QW sample, acquired under various excitation currents (I_b), are shown in Fig. 1. The beam currents vary from 0.2 to 15 nA and the beam was raster scanned over an area of 25.6 X 18.8 μm^2. All spectra are normalized to have the same intensity; the scaling factors are indicated to the right of each spectrum. The peak position of the QW emission shifts toward shorter wavelengths as the beam current increases, resulting in a ~36 meV blue-shift as the beam current is increased from 0.2 to 15 nA. This effect can be attributed to the rapid band filling of localized $In_xGa_{1-x}N$ radiative centers composed of large In concentrations. The full widths at half-maximum (FWHM) of these spectra also increase from 76.6 to 87.5 meV in the 0.2 to 15 nA range.

A scanning monochromatic CL image of the QW peak wavelength (λ = 412 nm) over the area of 25.6 × 18.8 μm^2 is shown in Fig. 2(a). The spotty nature of the CL image, showing distinct bright and dark emission regions, is consistent with a strong localization of excitons prior to radiative recombination.[5] The minimum lateral size of these islands is estimated at ~0.1 µm. The actual size of the In-rich regions cannot be determined from the present data, owing to the 50-100 nm carrier diffusion length which limits the spatial resolution in CL imaging.[4,5] Figure 2(b) is a CL wavelength image (CLWI) of the same region to assess the spatial variations in the QW band gap induced by the compositional fluctuations of InGaN. The mapping of the wavelength of peak CL intensity, $\lambda_{m,}$ into a color-scale representation is shown by the color bar indicating the wavelength scale. A good spatial correlation between the bright regions of Fig. 2(a) and longer wavelength regions of Fig. 2(b) clearly shows that carrier localization in the InGaN QW is attributed to the spatial variation of the InGaN composition in the QW region. Figure 2(b) also shows that most parts of the QW have larger band gap energies (GaN-rich) which is consistent with the large Stokes-like shift observed by Chichibu *et al*.[5] The CL intensity of the 412-nm emission at different positions along an arbitrary line in Fig. 2(a) and corresponding peak wavelengths in Fig. 2(b) are plotted in Fig. 2(c), which clearly shows the good correlation between the carrier localization and InGaN composition undulation.

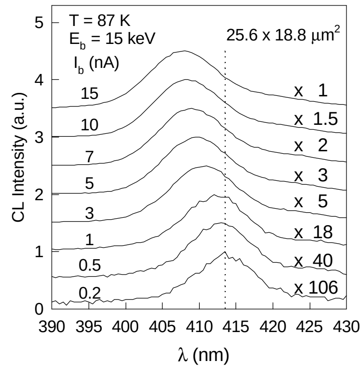

Figure 1. Stack plots of normalized CL spectra for the InGaN/GaN QW sample using various probe currents.

In order to further understand the spatial variation in the carrier relaxation and recombination, time-resolved CL was performed by positioning the e-beam in varying proximity to bright and dark regions. Transients of the CL intensity decay versus time were acquired at various positions relative to exciton localization centers. Figure 3 shows typical transients, denoted as P1 and P2, corresponding to the e-beam positioned to a bright center and dark boundary region, respectively. The CL decay lifetimes are obtained by fitting the initial decay with a constant lifetime, as shown in the semi-logarithmic plots of Fig. 3. The fits indicate that the region corresponding to P1 exhibits a longer lifetime (2.3 ns) than the region corresponding to P2 (1.4 ns). Further, a strong correlation was observed between the CL intensity and carrier lifetime for e-beam positioning at other dark and bright regions. The carrier lifetimes are generally longer and shorter for higher and lower CL intensities, respectively, along the line scan. The reduced lifetime in the darker boundary regions can be attributed to defects or impurities acting as nonradiative centers which reduce the total lifetime of excess carriers.

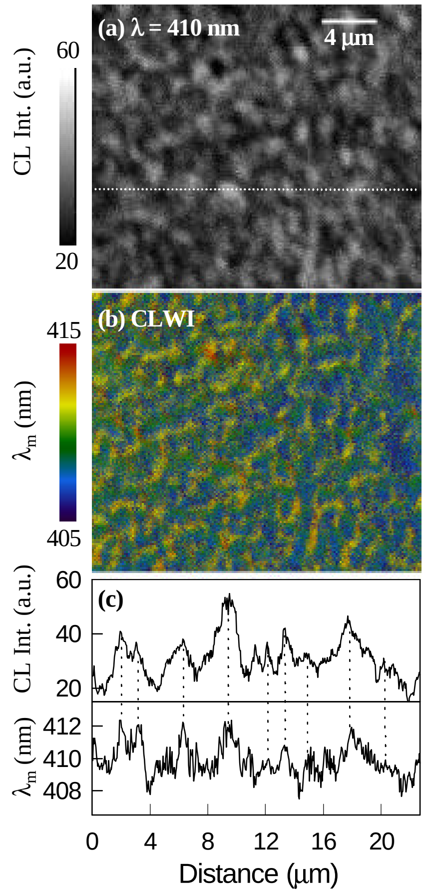

Figure 2. Monochromatic CL image (a), CLWI image (b), and line scan analysis (c) for an e-beam current of 1 nA.

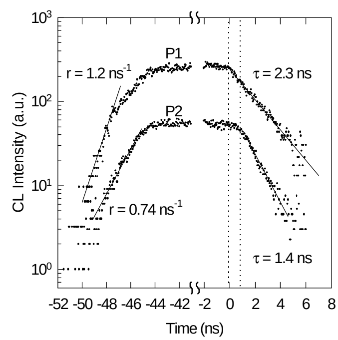

Figure 3. CL transients including the onset and decay near P1 and P2 regions.

A closer examination of the CL transients, P1 (bright region) and P2 (dark region) in Fig. 3, shows marked differences during the onset and the initial stages of the intensity decay. The P1 region exhibits a faster onset rate, *r*, and its decay follows an exponential behavior beginning with the trailing edge of the e-beam pulse (time≈0). The P2 region, conversely, exhibits a slow onset and its CL intensity decays very slowly during the first ~1 ns after the trailing edge of the e-beam pulse and then proceeds to decay exponentially. This unusual delayed decay behavior was observed consistently for other dark valley regions which were found in close proximity of sharp peaks. The delayed time ranged from 0.2-1.0 ns.

The different onset rates of P1 and P2 as well as the delay for P2 can be explained by considering a simple model that involves carrier generation in dark boundary regions and transport to the lower bandgap InN-rich centers. At the trailing edge of the e-beam excitation, excess carriers can diffuse and drift from the higher to lower bandgap regions. Thus, we expect the field-induced drift of carriers to play an important role in funneling and collection of carriers at the InN-rich centers. At the trailing edge of the e-beam pulse, generated carriers in the higher band gap dark regions (P2) must traverse the ~0.1 to 1.0 μm distance prior to collection and recombination in the InN-rich centers. This process gives rise to the apparent 0.2-1.0 ns delay in the CL transient as carriers are continuously fed to the luminescence centers. This process likewise explains the slower onset rate of P2, as the onset is delayed by the initial carrier transport to the InN-rich centers.

In summary, CLWI reveals a spatial variation in the near-bandgap energy resulting from the In composition undulation throughout the InGaN film. The lifetime of carriers excited in dark regions located between the InN-rich centers is reduced and a 0.2-1.0 ns delay in the transient decay signal is observed, owing to diffusion and drift of carriers. The lateral bandgap variation throughout the QW may lead to interesting reduced-dimensionality effects, which could influence InGaN-based lasers.

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3 References

1. S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, Appl. Phys. Lett. **68**, 3269 (1996).
2. C.-K. Sun, S. Keller, G. Wang, M. S. Minsky, J. E. Bowers, and S. P. DenBarrs, Appl. Phys. Lett. **69**, 1936 (1996).
3. E. S. Jeon, V. Kozalov, Y.-K. Song, A. Vertikov, M. Kuball, A. V. Nurmikko, H. Liu, C. Chen, R. S. Kern, C. P. Kuo, and M. G. Craford, Appl. Phys. Lett. **69**, 4194 (1996).
4. Y. Narukawa, Y. kawakami, M. Funato, and S. Fujita, Appl. Phys. Lett. **70**, 981 (1997).
5. S. Chichibu, K. Wada, and S. Nakamura, Appl. Phys. Lett. **71**, 2346 (1997).
6. J. T. Kobayashi, N. P. Kobaysahi, P. D. Dapkus, X. Zhang, and D. H. Rich, Mater. Res. Soc. Symp. Proc. Vol. **468**, 187 (1997).
7. H. T. Lin, D. H. Rich, A. Konkar, P. Chen, and A. Madhukar, J. Appl. Phys. **81**, 3186 (1997).