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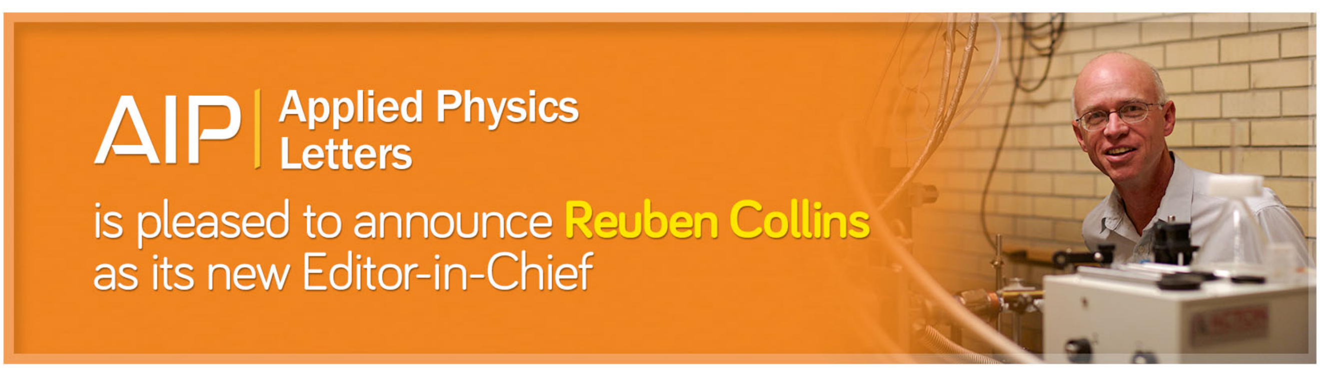

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HTML ABSTRACT + LINKS

APPLIED PHYSICS LETTERS **86**, 192105 (2005)

Room temperature near-ultraviolet emission from In-rich InGaN/GaN multiple quantum wells

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We grew In-rich InGaN/GaN multiple quantum wells (MQWs) using growth interruption (GI) by metalorganic chemical vapor deposition. The quality of overgrown InGaN/GaN QW layers in MQWs was largely affected by the crystalline quality and interfacial abruptness of the underlying QW layer. Introduction of 10 s GI was very effective in improving the crystalline quality and interfacial abruptness of InGaN QW layers, and we grew a ten periods of 1-nm-thick In-rich InGaN/GaN MQW with 10 s GI and obtained a strong near-ultraviolet (UV) emission (~390 nm) at room temperature. We believe that use of less than 1-nm-thick In-rich InGaN MQW can be a candidate for near-UV source, which might replace the conventional low-indium content (<10%), thicker InGaN QW layer. © *2005 American Institute of Physics.*
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Despite its practical importance,[1–5] InN still remains the least studied material among group-III nitride semiconductors. Several fundamental difficulties hinder the progress of the epitaxial growth technology of InN. These are the thermal instability of InN and the lack of suitable substrate materials matched to InN lattice constant, as well as thermal expansion coefficient.[1–5] However, the use of InN or In-rich InGaN may make it possible to develop optoelectronic and electronic devices, and the growth of two-dimensional InN or In-rich InGaN quantum structures on GaN substrate is inevitable.[6] In this case, the interfacial quality of heterostructures and well width fluctuations in quantum well (QW) layers are crucial for device performance.

Improvement of interfacial abruptness and reduction of well thickness in In-rich InGaN/GaN heterostructures by growth interruption (GI) were reported in an earlier study,[7] where a high quality In-rich InGaN/GaN single quantum well (SQW) structure using GI resulted in a sharp photoluminescence (PL) peak at the near-ultraviolet (UV) region. By introducing GI immediately after the QW growth, the atomically flat InGaN/GaN interfaces were clearly observed and the InGaN QW layer thickness was reduced from 2.5 to 1 nm, resulting in a greatly improved quality of In-rich InGaN/GaN SQWs. We found that the decomposition and mass transport processes during GI in InGaN QW layer are responsible for this phenomenon.[8]

During the growth of In-rich InGaN QW layer, only TMIn and ammonia were supplied, however, to relieve the large lattice mismatch between InN and GaN (~11%), strain relaxation and solid-state intermixing occurred, and a defective In-rich InGaN QW layer with thickness fluctuation was formed instead of an InN QW layer. Medium energy ion scattering measurement showed that the actual indium composition in InGaN QW layer is 60%–70% and the intermixed regions are present at both the top and bottom interfaces.[9] Based on the measured indium compositional profile in the InGaN QW layer, we calculated energy levels in the SQW by the Fourier series method[10] and we could explain near-UV emission from In-rich InGaN/GaN SQW with compositional grading.[9]

In this letter, we report successful growth of ten periods of In-rich InGaN/GaN multiple quantum well (MQW) using 10 s GI that emits strong near-UV emission (~390 nm) at room temperature (RT). To find out the influence of interfacial roughness on optical and structural properties of In-rich InGaN/GaN MQWs, we varied the stacking sequence of InGaN/GaN QW layers. It was found that the quality of overgrown InGaN/GaN QW layers was largely affected by the crystalline quality and interfacial abruptness of the underlying QW layer. It was also found that the introduction of a 10 s GI time was very effective in improving the crystalline quality and interfacial abruptness of InGaN/GaN QW layers.

In-rich InGaN/GaN MQW structures were grown by metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia were used as Ga, In, and N sources, respectively. The In-rich InGaN/GaN MQWs were grown on 2-μm-thick GaN/sapphire templates [growth temperature (1080 °C)] and the growth of InGaN/GaN MQWs was performed at 730 °C. During the growth of In-rich InGaN QW layer, only TMIn and ammonia were supplied as precursors and N_2 carrier gas was used.[7] Immediately after the QW growth, TMIn was shut off and only ammonia was introduced during the GI. The growth time of all In-rich InGaN QW layers was 90 s. After various GI times, the GaN barrier layer was grown at the same temperature with the QW. The growth pressure was maintained at 300 Torr throughout the whole

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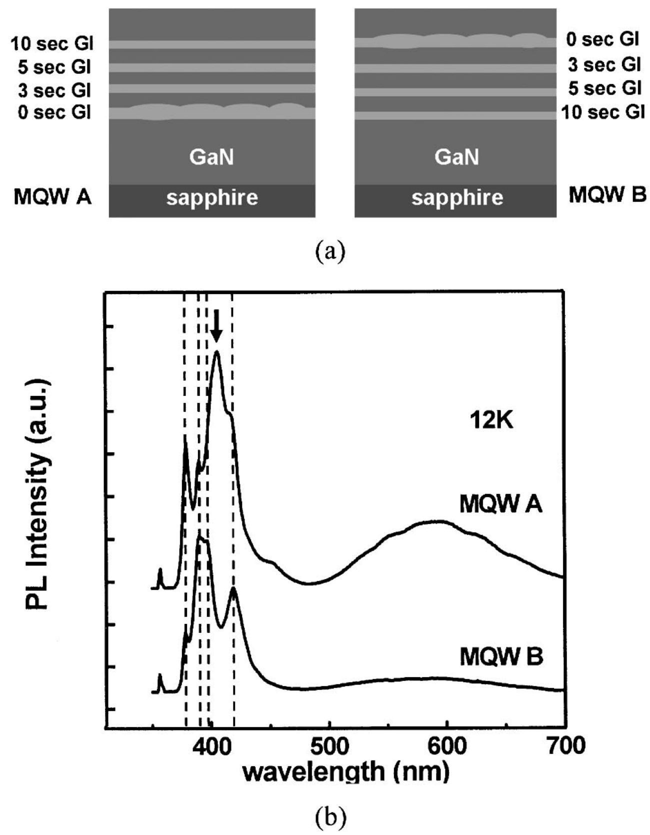

FIG. 1. (a) Schematic diagram of MQW A and B and (b) 12 K PL spectra of MQW A and B. The dotted lines indicate the PL peak positions from In-rich InGaN/GaN SQWs with 10, 5, 3, and 0 s GI from left to right, respectively.

process. Optical properties of In-rich InGaN/GaN MQWs were characterized by PL using a He-Cd (325 nm) laser as a pumping source. Structural properties of MQWs were examined by transmission electron microscopy (TEM). The prepared TEM specimen was examined by a JEOL-JEM 3000F microscope operating at 300 kV with a point-to-point resolution of 0.17 nm.

To clearly understand the influence of GI and interfacial roughness on optical and structural properties in In-rich InGaN/GaN heterostructures, four layers of SQW were intentionally grown with different GI times. The thickness of the GaN barrier layer was kept constant at 5 nm and that of the final GaN capping layer was 20 nm. In MQW A, a In-rich InGaN QW layer without GI was grown first and the subsequent QW layers with increased GI times were grown. On the other hand, in MQW B, the growth sequence was

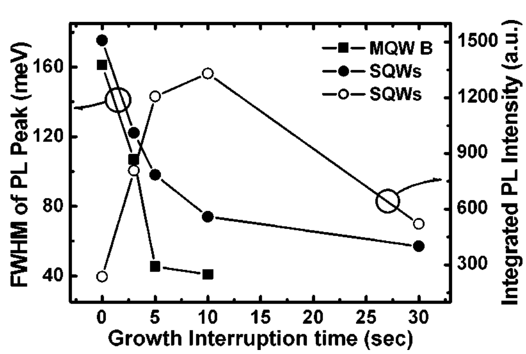

FIG. 2. Changes in integrated PL intensity and FWHM of In-rich InGaN/GaN SQWs and MQW B at various growth interruption times.

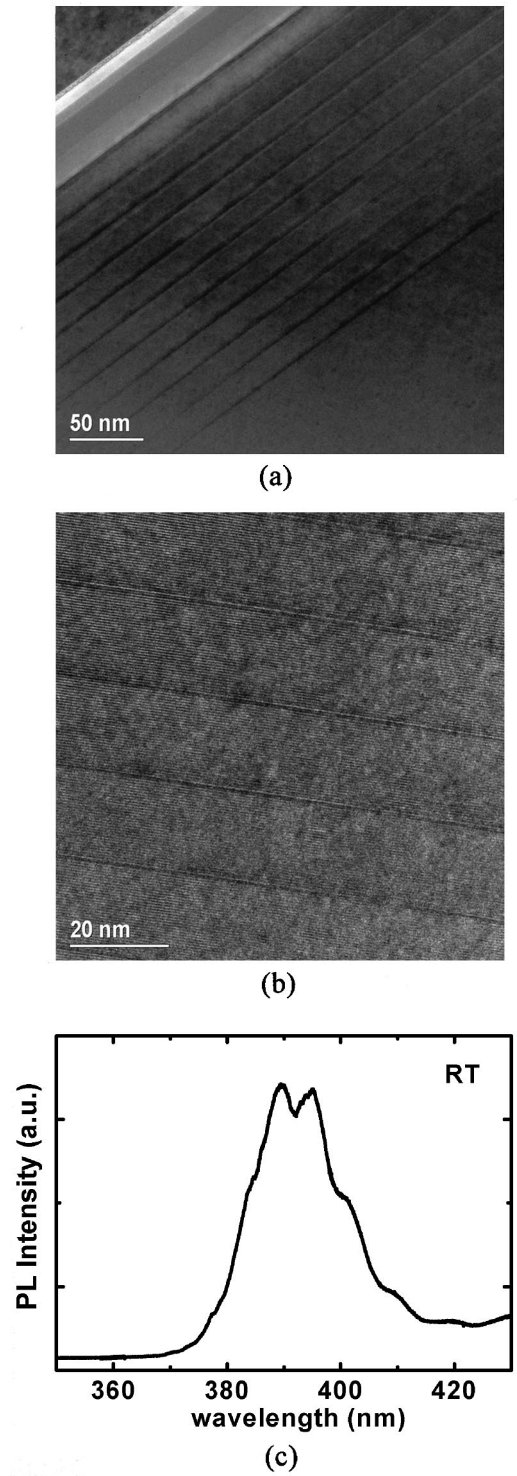

FIG. 3. (a) Cross-sectional TEM image of ten periods of In-rich InGaN/GaN MQW with 10 s GI, (b) high-resolution image of (a), and (c) its room temperature PL spectrum.

reversed. Schematic drawing of the two MQWs can be seen at Fig. 1(a). From the high resolution TEM images, we could confirm that MQW A was successfully grown and InGaN QW layers became flatter and thinner with GI times.[8]

From 12 K PL measurements, we observed four strong PL peaks corresponding to four InGaN QW layers with different GI times, as shown in Fig. 1(b). The dotted lines from left to right in Fig. 1(b) indicate the PL peak positions obtained from In-rich InGaN/GaN SQWs grown separately with 10, 5, 3, and 0 s GI, respectively,[7] for comparison pur-

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poses. In MQW B, the emission wavelengths of the PL peak originated from four individual InGaN QW layers were well-matched with the dotted lines. However, in MQW A, the emission wavelength of the InGaN QW layer with a 3 s GI (marked by an arrow) is quite different from that of SQW. From our earlier results,[7,8] there exist thickness fluctuations and many structural defects in the InGaN QW layer without GI as well as in the subsequent GaN capping layer. Therefore, the emission wavelength of the InGaN QW layer with a 3 s GI was shifted from that of SQW with a 3 s GI and the quality of overgrown InGaN/GaN QW layers was degraded, resulting in prominent yellow luminescence intensity in MQW A.[11] On the other hand, in MQW B, since the first InGaN/GaN QW layer was smooth and less defective, overgrown three QW layers could maintain the identical PL peak position. It was found that the quality of overgrown InGaN/GaN QW layer was very sensitive to the crystalline quality and interfacial abruptness of the underlying QW layer.

Figure 2 shows the changes in integrated PL intensity and the full-width at half-maximum (FWHM) of SQWs with GI time. Results from MQW B were also included for comparison. It clearly shows that the introduction of a 10 s GI time in MQW B as well as SQWs was very effective in improving the crystalline quality and interfacial abruptness of the InGaN/GaN QW layer. Based on these results, we finally grew ten periods of In-rich InGaN/GaN MQW with a 10 s GI time. 20-nm-thick GaN barrier layers were chosen for this structure.

From the cross-section high-resolution TEM images, as shown in Figs. 3(a) and 3(b), we found that the In-rich InGaN/GaN MQW was successfully grown and it was of high quality. We also observed a very strong near-UV emission at RT, as shown in Fig. 3(c). The FWHM of this PL peak is about 8.0 kT at RT, which is similar with those of typical blue (8.2 kT at 465 nm) and green (7.0 kT at 515 nm) sources made of InGaN QW layers.[12] The origin of multiple peaks near 390 nm is not clear at this moment and further study is currently under way. The use of less than 1-nm-thick In-rich InGaN QW layer as an active layer can be a candidate for near-UV source, which might replace the conventional low-indium content ($<10\%$), thicker InGaN QW layer.[13–15]

In conclusion, In-rich InGaN/GaN MQWs were grown by MOCVD. It was found that the control of interfacial quality by means of GI is a very important factor in improving structural properties of MQWs. A strong near-UV emission was observed from the ten periods of In-rich InGaN/GaN MQW at room temperature. In-rich InGaN MQWs can be a candidate for near-UV source, which might replace the conventional low-indium content ($<10\%$), thicker InGaN QW layer.

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