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# Effects of strain-control layers on piezoelectric field and indium incorporation in InGaN/GaN blue quantum wells

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We investigated the effects of a strain-control layer on piezoelectric fields and indium incorporation in blue-emitting InGaN/GaN quantum wells (QWs) using reverse-biased electroreflectance spectroscopy. With this technique, we could determine the change in both indium incorporation and the piezoelectric field by the inserted buffer layer. We compared two test samples, which have identical structures except for the insertion of an additional InGaN layer at the bottom of the blue-QW. The magnitude of the piezoelectric fields in the QWs with the added layer was significantly smaller even with a slightly higher indium composition. The result shows that the strain in the QW is partially released and can be controlled quantitatively by the strain-control layer underneath.

InGaN quantum well (QW) structures grown in a (0001) direction on GaN layers are highly compressive-strained, which results in huge (~1 MV/cm) piezoelectric fields in the QWs [1]. It is known that the existence of the field is one of the most crucial factors for determining the efficiencies of the device performance [2].

In some cases, people try to insert a strain-control layer right below the QW to control the piezoelectric fields [3]. However, the exact effect of that layer on the piezoelectric field and indium (In) incorporation for each sample is still vague. The piezoelectric field is influenced by the sample structure and growth conditions such as partial release of strain by inserting a buffer layer, the n-GaN growth conditions and the In mole fraction during the QW growth period. It is not enough to analyze the change of the peak position to determine the piezoelectric field in the QW, because the peak position can be affected by both the strain and the In composition change. To make things more complex, it has been reported that partial release of the strain can change the In incorporation even with the identical growth conditions of the QW [4]. Measuring the magnitude of the blue-shift as the injection current increases, which is sometimes used to determine the relative magnitude of the piezoelectric field [1], cannot be an accurate method either because the blue-shift can be induced not only by screening the field by injected carriers but also by a filling of the localized state generally created by the fluctuation of In composition in the QW [5]. Therefore, in order to fully utilize the strain-control layer for optimization, an accurate determination of In incorporation and the piezoelectric field at the same time with a given growth condition and device structure is important.

In this work, we experimentally determine the magnitude of the piezoelectric field and In content by using electroreflectance (ER) spectroscopy, which shows that the effects of the strain-control layer are significant on both the piezoelectric field and In composition even in commercial-grade blue-emitting InGaN/GaN QW structures. The ER spectroscopy, where the modulation in reflectance by a repetitive perturbation of the applied electric field is measured [6, 7], is proven to be a powerful technique for investigating the properties of InGaN/GaN QWs. The piezoelectric fields and the In composition are obtained by observing phase inversion in ER spectra as the applied electric field by the dc reverse bias cancels the in-well piezoelectric field.

The InGaN/GaN blue light emitting diodes (LEDs) in this work were grown on a *c*-plane sapphire substrate by a standard metal-organic chemical vapor deposition (MOCVD) system. A 5 μm thick Si doped n-GaN layer was deposited on a *c*-plane sapphire substrate. Two pairs of InGaN/GaN QWs and Mg doped p-GaN layers were deposited subsequently on top of the n-GaN. The QWs consisted of 3.2 nm thick InGaN wells and 10 nm thick GaN barriers. For comparison, another sample with an identical structure except for the insertion of a strain-control layer was also prepared. The 405 nm emitting InGaN layer was inserted between the n-GaN layer and the active QWs.

Figure 1(a) shows photoluminescence (PL) spectra of a typical LED when the applied biases are smaller than the turn-on voltage. The peak position of the PL is blue-shifted when the forward bias is decreased. Since the direction of the piezoelectric field is opposite to the direction of the built-in electric field formed by the p–n junction [1], the total electric field in the QW decreases as the reverse (forward) bias increases (decreases), resulting in a blue-shift by the quantum confined Stark effect. By measuring the complete compensation of the electric field in the QW by the external field, one can estimate the magnitude of the piezoelectric field [8]. The intensity of PL decreases rapidly as the forward bias decreases, which is due to a severe escape of carriers from the QW as the reverse (forward) bias increases (decreases) [9]. This severe carrier escape practically makes it impossible to use PL in most cases for the determination of the compensation voltage ($V_{\text{comp}}$).

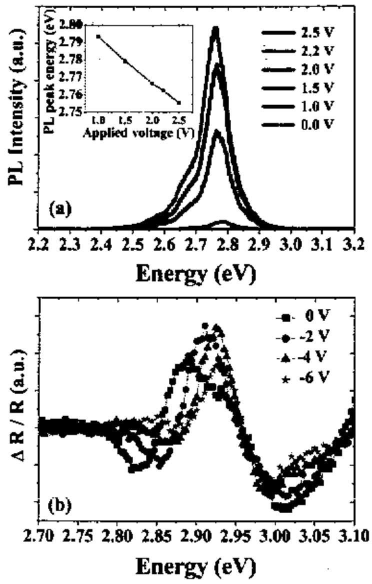

**Figure 1** (online colour at: www.pss-rapid.com) (a) PL spectra of a typical InGaN/GaN blue LED when the applied biases are smaller than the turn-on voltage. The inset shows the peak position of PL. (b) ER spectra of the same sample that show a continuous blue-shift as the reverse bias increases. All the measurements were done at room temperature.

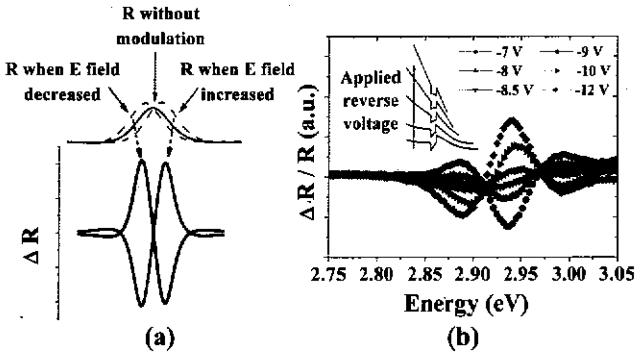

**Figure 2** (online colour at: www.pss-rapid.com) (a) Phase inversion of the ER peak signal. (b) Typical ER spectra with different DC reverse biases from a InGaN blue-QW. The inset schematically shows the conduction band diagrams with applied reverse voltages.

On the other hand, the ER spectra (Fig. 1(b)), which represent the absorption nature, show a continuous blue shift of the QW transition as the reverse bias increases. At 0 V, where a strong electric field still exists in the QW, the ER spectrum cannot be fitted with a single transition, but shows an additional forbidden transition at ~2.95 eV, which is induced by a strong electric field breaking the symmetry of the electron and hole wavefunction [10]. As the reverse bias increases, this forbidden transition disappears and the spectra become a single allowed transition.

When the reverse bias further increases and becomes larger than $V_{\text{comp}}$, a phase inversion of the ER peak signal is expected, which is due to the fact that the modulation bias increases (decreases) the electric field in the QW when the reverse bias is larger (smaller) than $V_{\text{comp}}$ (Fig. 2(a)). Figure 2(b) shows typical ER spectra with different reverse voltages. As shown in Fig. 2(b), the phase inversion of the QW peak is clearly observed at around −8 V. Indium composition can also be determined by the peak position in ER near $V = V_{\text{comp}}$. This is advantageous since the peak position is free from ambiguity induced by the quantum confined Stark effect.

In order to investigate the effect of a strain-control layer on the piezoelectric field and In incorporation, sample A (without buffer layer) and B (with buffer layer) were prepared under identical growth conditions. A 180° phase change occurs in both samples as shown in Fig. 3.

The phase change occurs at a significantly lower reverse voltage in sample B. We obtained $V_{\text{comp}}$ of −9.6 V and −7.7 V in samples A and B, respectively, by tracking the high energy maximum minus low energy maximum (H−L) of the respective ER spectrum. $V_{\text{comp}}$ values are obtained when the sign of H−L is reversed, as shown in the insets in Fig. 3. The electric fields in the QWs were then calculated by the equation in Ref. [11]. The obtained elec-

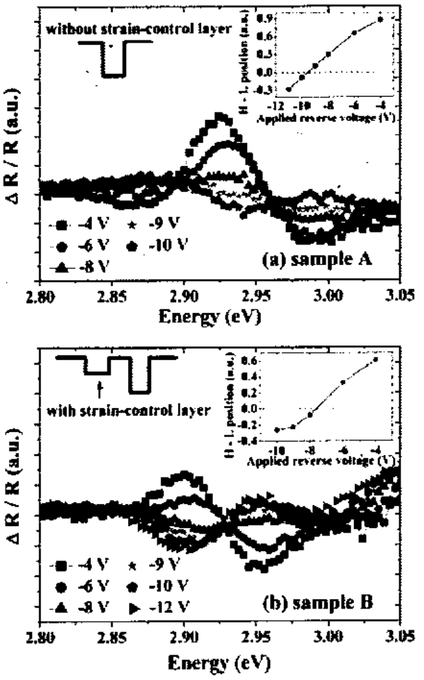

**Figure 3** (online colour at: www.pss-rapid.com) (a) Measured ER as a function of applied reverse voltage in sample A (without a strain-control layer). (b) ER spectra in sample B (with a strain-control layer). Insets show the high energy maximum minus the low energy maximum (H–L) of the respective ER.

tric field is 1.3 MV/cm in sample A and 1.1 MV/cm in sample B. The In composition is also determined by the peak position near $V = V_{\mathrm{comp}}$, which is the largest value of the QW transition energy. The transition energies are obtained by the least-square fitting procedure with the first derivative of a Lorentzian functional form given by [6]

$$\Delta R/R = \mathrm{Re}\,[A\,\mathrm{e}^{i\theta}(E - E_0 + i\Gamma)^{-2}]\,, \qquad (1)$$

where $A$, $\theta$, $E_0$, and $\Gamma$ are the amplitude, phase, transition energy, and broadening parameter, respectively.

The difference in transition energy between samples A and B in Fig. 3 is indeed not very large, which is understandable because they were grown under identical conditions. However, it is discernable that the transition energy in sample A is higher than that in sample B. The transition energy in the flat band condition is fitted to 2.98 eV in sample A and 2.96 eV in sample B, respectively. To calculate the In composition, we used the proportion of conduction to valence band offset as 7 to 3 and used the same parameters as in Ref. [12]. The In compositions in sample A and B were 16.7% and 17.3%, respectively. The obtained total electric field in the QWs is the summation of the fields induced by spontaneous and piezoelectric polarization. However, it is expected that the measured difference in the electric field is mostly due to the change in the piezoelectric field, because the In composition is measured to be only changed by less than 1%. This result shows that the QWs with the strain-control layer underneath have larger In content, but smaller piezoelectric field, which implies that the strain in the QWs is partially released by the insertion of the buffer layer. The increase of In composition in sample B can be interpreted based on the so called In-pulling-effect, which means the smaller strain enhances the incorporation of In atoms in the InGaN lattice [4].

We measured electroluminescence spectra at 20 mA, and the spectrum has the peak at 2.744 eV and 2.720 eV from sample A and B, respectively. The optical power from sample A and B was measured to be 8.15 mW and 13.3 mW, respectively. This shows that the strain-released QWs give enhanced efficiency.

In conclusion, we experimentally determined the change in both indium incorporation and piezoelectric field in InGaN/GaN blue QWs by an inserted buffer layer underneath. The indium composition of QWs with the additional layer is larger, while the piezoelectric field is smaller even with higher In composition. The results suggest that strain-control layers can in fact control the piezoelectric field and In incorporation in InGaN QWs, and can be optimized with precision through this method.

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