The influence of the *p-n* junction induced electric field on the optical properties of InGaN/GaN/AlGaN light emitting diode

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The temperature dependence of photoluminescence measurement was performed on an undoped $In_{0.126}Ga_{0.874}N$/GaN multiple quantum well (MQW) structure and a light emitting diode (LED) structure using this MQW as an active region. The emission energy of the LED structure showed a red shift of about 230 meV at room temperature compared with the undoped $In_{0.126}Ga_{0.874}N$/GaN MQW. This behavior of the LED structure is attributed to the quantum-confined Stark effect due to its *p-n* junction induced electric field. This conclusion was confirmed by a calculation and a detailed discussion based on the theory of the quantum-confined Stark effect. © *1999 American Institute of Physics.* [S0003-6951(99)05110-4]

Although much progress has been made in developing blue light emitting diodes (LED) and laser emission diodes using InGaN/GaN multiple quantum wells (MQW) as the active region,[1] their optical properties are still not fully understood. In this respect, it is interesting to make comparison with GaAs-based III–V semiconductor system. As we know, GaN band gap is approximately 2.4 times larger and the carrier effective masses are almost three times larger, which results in very much larger exciton binding energy −28 meV compared with about 5 meV. This means that excitons are much more stable at room temperature, implying, in turn, that the quantum confined Stark effect (QCSE) is likely to be of greater importance in GaN-based electronic devices.[2,3] We can anticipate two manifestations of this effect. The first one results from the strain-induced piezoelectric field due to lattice mismatch between GaN barriers and InGaN wells. Our recent letter[4] has reported that there indeed exists piezoelectric field induced QCSE in InGaN/GaN single quantum well structure, but there is no piezoelectric field in 10 periods MQW with same well thickness and indium composition. The second one occurs in the *p-i-n* junction structures used in blue light emitters where the built-in junction field is operative. If we consider a built-in potential corresponding to the GaN band gap (3.4 eV) applied across an active MQW system with 100 nm thickness, we arrive at an electric field of 3.4×10^7 V/m.

The majority of letters published to-date[5–7] have been concerned with strain-induced QCSE, rather than with junction-induced QCSE, but it is necessary to understand the latter effect in view of their relevance to practical devices. The purpose of the present letter is to explore the optical properties of a GaN-based MQW in a real device structure: We first report a large red shift of the emission energy from an InGaN/GaN/AlGaN LED as a function of temperature, together with a strong reduction of emission intensity, compared with the same active region when not in a LED. We suggest an explanation based on the QCSE due to the built-in junction field.

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The samples were grown on (0001) sapphire substrates by horizontal atmospheric metal organic chemical vapor deposition (MOCVD) system.[8] The LED structure consists of 25 nm low-temperature buffer layer, 3 μm of *n*-doped GaN, 0.5 μm of *n*-doped $Al_{0.15}Ga_{0.85}N$, 0.15 μm of *n*-doped GaN, a MQW region, consisting of ten periods undoped (2.5 nm/7.5 nm) $In_{0.126}Ga_{0.874}N$/GaN multiple-quantum wells, followed by 0.15 μm *p*-doped GaN, 0.5 μm *p*-$Al_{0.15}Ga_{0.85}N$ and 0.25 μm *p*-doped GaN. The *n*- and *p*-doping levels are of order 10^{18} and $10^{17}\,cm^{-2}$, respectively, as determined by Hall measurement. Our LED structure exhibited a high-brightness blue light emission, which has been reported.[9] For comparison, we also grew an undoped ten periods $In_{0.126}Ga_{0.874}N$/GaN MQW structure, which is the same as above structure but without the *p-n* junction. We shall refer to this simply by ''MQW structure.''

For photoluminescence (PL) measurement, the sample was mounted on the cold finger of a helium closed-circuit refrigerator which allowed a temperature range from 20 K to room temperature. The luminescence was dispersed by a 0.85 m monochromator and detected by a water-cooled GaAs photon-multiplier interfaced with lock-in amplifier. For PL excitation, a continuous wave (cw) He–Cd laser was used.

Figure 1 shows the temperature dependence PL spectra of the LED structure from 20 K to room temperature. At 20 K, the spectrum is dominated by a single, sharp emission at a photon energy of 3.08 eV, though there also appear to be several other weak peaks. This very strong emission is attributed to the localized exciton transition from $In_xGa_{1-x}N$ well region, as reported in earlier letters.[10–22] Its full-width at a half-maximum is about 47 meV, indicating a high quality of our sample. In this letter, we would like to concentrate on the study of this main peak since it is generally accepted that this peak is responsible for laser action.[11–13]

Figure 2 shows the temperature dependence PL of the MQW structure. At low temperatures, the emission is closely similar to the localized exciton from the LED structure, being at the same photon energy (within about 20 meV) and having almost the same line width of about 47 meV. However, at higher temperatures (above about 120 K), there is a marked discrepancy between the two samples, i.e., the emis-

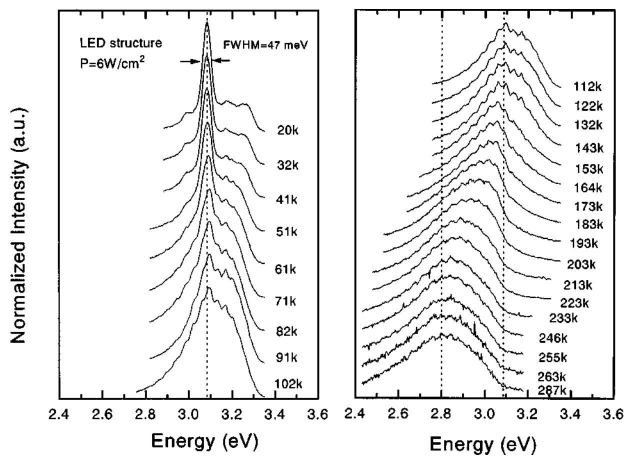

FIG. 1. The temperature dependence of PL spectra of the LED structure from 20 K to room temperature. A dash line is a guide to eye. The red shift of about 250–300 meV from 20 K to room temperature is observed.

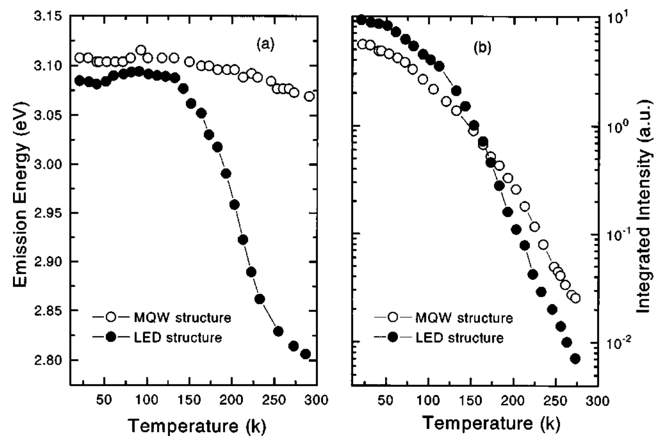

FIG. 3. (a) The temperature dependence of the emission energy, and (b) the temperature dependence of the integrated intensity, which are obtained from Figs. 1 and 2.

sion peak of the MQW structure shifts only slightly to lower energy (by roughly 50 meV at room temperature) and shows only a small increase in linewidth, whereas the emission peak of the LED structure shows a much larger red shift (about 280 meV at room temperature) and is considerably broadened.

Figures 3(a) and 3(b) describe the temperature dependence of the emission energy and the integrated intensities of these two samples, respectively. It appears that there is a slight increase in emission energy at low temperature for both samples which is consistent with an interpretation based on a band tail model (i.e., due to thermal excitation), but above about 120 K, the LED sample shows much greater red shift, reduction intensity and increase in linewidth, compared with the MQW sample. The shift of MQW structure corresponds approximately to temperature-induced change in band gap. Therefore, we are seeing a net shift of about 230 meV in the LED sample if the temperature effect is excluded. Clearly, the presence of the *p*- and *n*-doped layers in the LED sample has a strong influence on the PL properties, which suggests an interpretation in terms of the QCSE, as outlined in the introduction.

Figure 4 shows the excitation power dependence of PL spectra of LED structure at room temperature. The emission peak of LED structure shows a clear blue shift with increasing excitation power. The excitation power dependence PL measurement is a standard method to examine QCSE, which was often used in InGaN/GaN system.[5,7]

First, we would like to make an approximate estimation of the emission energy shift produced by an electric field of 3.4×10^7 V/m corresponding to a built-in potential of 3.4 V across the 100 nm active region. The potential ''tilt'' across each well is 85 mV and, if the confined states are then located in the tilted regions of the wells, we can estimate energy as, roughly, $h\nu=E_g(\mathrm{InGaN})-100\,\mathrm{meV}$. Comparing this with the zero-field case, with confinement energies $E_{\mathrm{CB}}=86\,\mathrm{meV}$ and $E_{\mathrm{VB}}=32\,\mathrm{meV}$, we find $h\nu=E_g(\mathrm{InGaN})+118\,\mathrm{meV}$, giving a net shift of about 220 meV between these two situations. This agrees with our measured red shift in the LED sample between about 120 K and room temperature. The implication of this is to suggest that the observed red shift is due to the QCSE, but this only raises the question of why there is no QCSE to be observed at low temperatures. There are two possible explanations: first, we note that, at low temperature, the doped contact regions in the LED sample are probably intrinsic as a result of carrier freeze-out, thus reducing the built-in field to negligible proportions. This will almost certainly be true for the *p* region due to the larger acceptor binding energy of the Mg

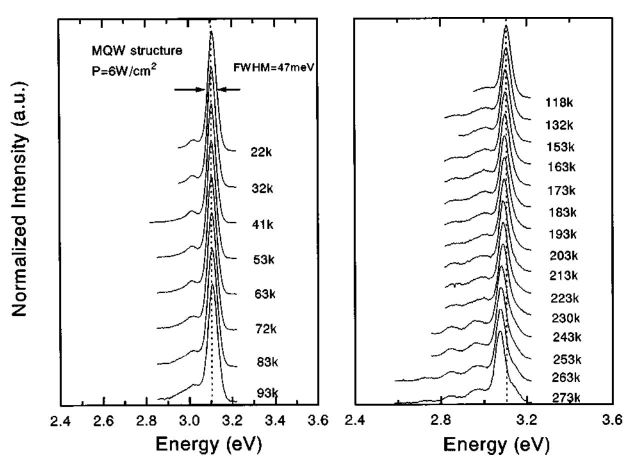

FIG. 2. The temperature dependence of PL spectra of the InGaN/GaN MQW. A dash line is a guide to the eye. The red shift of emission energy from 20 K to room temperature is about 50 meV.

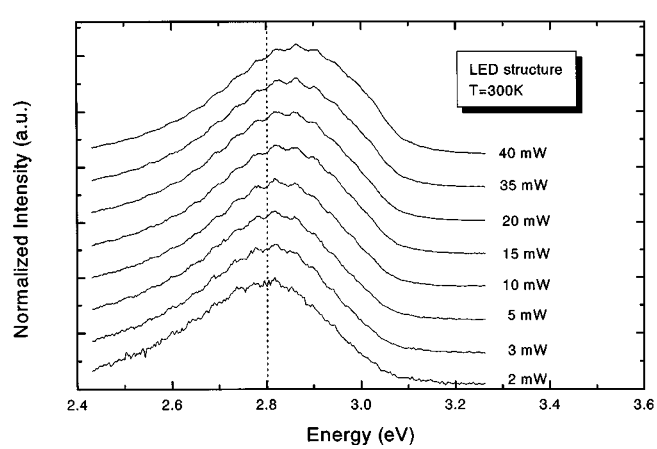

FIG. 4. The excitation power dependence of PL spectra of LED structure measured at room temperature. With increasing excitation power, the emission peak shows a clear blue shift.

acceptors employed and may well be true for the *n* region as well, though this case is less clear-out due to the reduction in donor activation energy with heavy doping. The second explanation lies with free carrier screening of the builtin field. If we follow Ridley[23] and choose a two dimensional screen length $\lambda = 2\epsilon kT/e^2 n$ (*n* is carrier density, ϵ is a static permittivity, other symbols have usual meaning), it follows that free carrier screening may be significant at low temperature ($\lambda < L_z$, quantum well thickness), but negligible at room temperature ($\lambda > L_z$). If we assume that screening is just significant at $T = 120$ K ($\lambda = L_z$), we estimate a value of $n = 7\times 10^{11}\,\mathrm{cm}^{-2}$ in the wells. Such a carrier density may appear unlikely at low temperature due to carrier freeze-out, but if we include the possibility of modulation doping of the wells by carriers generated in the GaN barriers (''undoped'' GaN is usually doped at about $n = 10^{17}\,\mathrm{cm}^{-3}$), it becomes entirely probable. In either event, we can argue for such an explanation, i.e., at high temperature, there exists a strong builtin field which results in a strong red shift, but it is of negligible significance at low temperatures. This explanation is consistent with our observation that the two samples show almost identical low temperature spectra. We also note that the strong reduction intensity of the LED sample as the temperature is raised towards room temperature is also consistent with the QCSE, because the spatial separation of the electrons and holes by the field reduces their wave-function overlap. The observed increase in linewidth is also consistent with earlier observation of line broadening by the QCSE in the GaAs system.[2,3]

The *p*-*n* junction induced electric field can be screened by photogenerated carriers. The increase of the excitation power weakens the QCSE and thus increases the transition energy, resulting in a blue shift, which is clearly shown in Fig. 4. This definitely proves our above discussion.

There thus appears to be a completely self-consistent explanation of all our experimental observation in terms of the QCSE due to the *p*-*n* junction built-in field. In conclusion, we first reported QCSE on luminescence properties of InGaN/GaN/AlGaN LED structure due to the *p*-*n* junction induced electric field by comparing the temperature dependence PL spectra of the LED structure and simple MQW structure without *p*-*n* junction. The red shift of about 230 meV in our LED structure is observed. Based on the detailed discussion, our conclusion can be confirmed. This effect should be highly emphasized in designing laser or other optical devices of GaN-based system.

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