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Tunability of InGaN/GaN quantum well light emitting diodes through current

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In the recent years, InGaN/GaN quantum well (QW) light emitting diodes (LEDs) have gathered much importance through the introduction of white LEDs and dual wavelength LEDs. However, the continuous tunability of InGaN/GaN QW LEDs has not been well addressed or discussed. In this paper, we introduce the tunability of an InGaN/GaN QW LED having a well width of 4 nm and In mole fraction of 0.3. The results, obtained from self-consistent solutions of the Schrödinger and Poisson equations, show that the transition energy of the LED may be continuously tuned by the device current. A prominent nonlinearity of the transition energy with the device current is generated, which should be of interest to the research workers in the field of optoelectronics. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4813225]

I. INTRODUCTION

With major advances in material growth and device fabrication technology in the recent years, light emitting diodes (LEDs) and their applications are undergoing revolutionary changes. Very important light emitting active layers are the InGaN/GaN single or multiple quantum wells (QWs). They draw special attention because of their unique material characteristics and device performance.

Despite the large density of defects that exists in the InGaN material,[1,2] it has a direct band gap from 3.4 to 0.7 eV (Refs. 3 and 4); and in the InGaN/GaN QWs, the radiative recombination efficiency is surprisingly high, LEDs can achieve an external efficiency as high as 20%.

Recently, white LEDs and dual wavelength LEDs have been proposed and reported.[5–7] These types of LEDs consist of a stack of InGaN/GaN QWs with designated emission wavelengths in different colour regions. The QWs with different emitting colours are grown sequentially where the different emission colours come from the InGaN/GaN QWs with different well and barrier widths and different In compositions.

A number of research works have been carried out to improve the performance of the LED analyzing the carrier transport mechanism in detail,[8–14] but the tunability of the emission wavelength has not been well-addressed in literature. In this paper, we propose a continuously tunable LED. We have analyzed in detail InGaN/GaN QW LEDs using the Schrödinger and Poisson equations. From the result, it is seen that the transition energy in certain QW LEDs has a strong dependence on the bias current.

II. THEORETICAL DETAILS

For simulations, we consider a simple GaN pn junction diode structure consisting of an InGaN single QW at the junction. The mole fraction of In and the width of the well are considered to be 0.3 and 4 nm, respectively, which are commonly used values for In rich QW devices. The n-type and p-type doping concentrations in the GaN barriers are kept as $5 \times 10^{18}\,\mathrm{cm}^{-3}$. The electron and hole concentrations in the QW layer for a forward bias and the corresponding interband transition energies are computed by solving the Schrödinger and Poisson equations self-consistently using finite difference method.[15] To calculate the carrier density, the partial ionization of the impurities is taken into account. The ionization energy of donor and acceptors is considered to be 30 meV and 200 meV, respectively.[16] For any external bias, the energy of the hole quasi-Fermi level is considered as the reference level with zero value.

The polarization in GaN and $\mathrm{In_xGa_{1-x}N}$ is calculated from the empirical relations, developed by Fiorentini *et al.*[17] It is found that the change of polarization across the $\mathrm{GaN/In_{0.3}Ga_{0.7}N}$ interface is $0.0534\,\mathrm{C/m^2}$, which corresponds to an electrostatic field of 5.21 MV/cm.

The current density through the structure is obtained from the relation[18,19]

$$J = qd(U_{SHR} + U_{b-b} + U_A), \tag{1}$$

where U_{SHR} is the Shockley-Hall-Read (SHR) recombination rate, $U_{b\text{-}b}$ is the band to band or radiative recombination rate, U_A is the Auger recombination rate, d is the width of the QW, and q is the electronic charge. Using the detailed calculation in Ref. 18, $U_{b\text{-}b}$ and U_A are approximated for high level injection as

$$U_{b-b} = R_{sp} np \tag{2}$$

and

$$U_A = \frac{1}{2} C_a np(n+p), \tag{3}$$

where R_{sp} is the radiative recombination coefficient, C_a is the Auger recombination coefficient, n is the electron concentration in the conduction band edge, and p is the hole concentration in the valance band edge. It is observed that even in high level injection the difference between n and p is not negligible so we use both the terms instead of the more simple relation

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TABLE I. Parameters used in the simulation. P^{pz}, P^{sp}, and b are the piezoelectric polarization, spontaneous polarization, and band gap bowing parameter, respectively. V. law stands for Vegard's law.

Parameter	GaN	InN	$In_{0.3}Ga_{0.7}N$
T (K)		300	
P^{pz} (C/m^2)[a]			0.0479
P^{sp} (C/m^2)[a]	−0.034		−0.0284
b[b]			1.4
E_g (eV)	3.43[c]	0.7[d]	2.317
ε (ε_0)[b]	10.28	14.61	V. law
M^*_e (m_0)[b]	0.2	0.07	V. law
m^*_{hh} (m_0)[b]	1.02	1.25	V. law
ΔE_c: ΔE_v[e]			68:32
R_{sp} ($cm^3\ s^{-1}$)[f]			2×10^{-11}
C_a ($cm^6\ s^{-1}$)[f]			1.5×10^{-30}
A_{nr} (s^{-1})[f]			10^7

[a]Reference 17.
[b]Reference 20.
[c]Reference 3.
[d]Reference 4.
[e]Reference 21.
[f]References 19 and 22.

as used in Ref. 19. In our calculations, U_{SHR} is simply approximated as

$$U_{SHR} = A_{nr} n, \tag{4}$$

where A_{nr} is the SHR coefficient. The parameters, used in the calculations, are given in Table I.

III. RESULTS AND DISCUSSION

Fig. 1 shows the variation of the lowest interband transition energy with the change in the current density as obtained from the self-consistent calculations. It is seen that the transition energy increases monotonically with the current density. The change in the transition energy is nearly 9.8% in the range from 10 A/cm^2 to 1000 A/cm^2. If current pulses are used, the current density can be further increased and the LED may be tuned to much higher energy.

The field distribution in the structure for three different current densities is shown in Fig. 2. The electric field consists of three components, the pn junction field (F_{pn}), the field due to excess carriers (F_{ex}), and the polarization field (F_p). F_{pn} arises from the space charges in the depletion region and F_{ex} is the contribution of the injected carriers in the QW. Both F_{pn} and F_{ex} have direction opposite to F_p. Initially without any external bias F_{ex} is zero and F_p is screened by F_{pn}. With increase of the forward current on application of a forward bias, the magnitude of F_{pn} reduces due to the narrowing of the depletion region, whereas the magnitude of F_{ex} is enhanced because of the increment in the injection of carriers into the QW. In the present case, the change of F_{ex} is greater than the change of F_{pn}. This results in a monotonic screening of F_p with the operating current. Hence the quantum confined Stark effect (QCSE) reduces gradually and the transition energy increases monotonically.

The band profile in the InGaN/GaN QW in the LED is shown in Fig. 3. The typical bending due to the built in polarization field is depicted. With increase in the operating current, the bending decreases resulting in a monotonic and

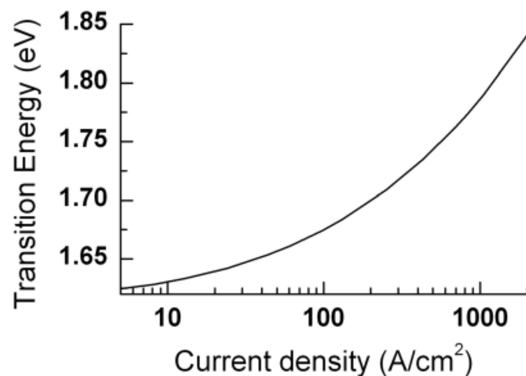

FIG. 1. Transition energy as a function of current density.

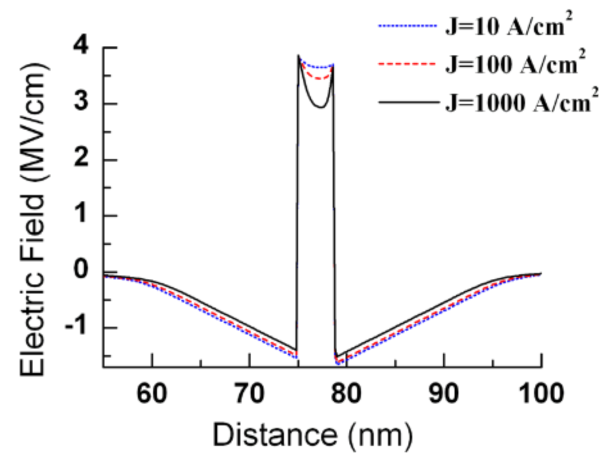

FIG. 2. Field distribution in and around the QW for different current densities.

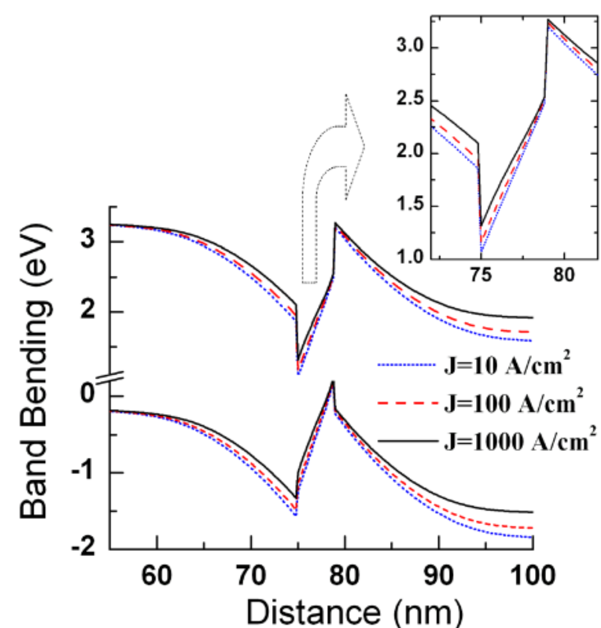

FIG. 3. Conduction and valance band for different current densities. Inset shows different bending of the conduction band QW.

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continuous shift of the transition energy. It should be noted that the lowest interband transition energy at any current is much smaller than the band gap energy in the QW due to the QCSE.

IV. CONCLUSIONS

In this paper, we have presented a monotonic nonlinearity of the transition energy with current of an InGaN/GaN based LED. This should make fine tuning of the emission energy of such LEDs possible. Although multiple wavelength LEDs and white LEDs with QWs working in a tandem have been well discussed in literature, the fine tunability of InGaN/GaN LEDs has not been addressed. This should be of much interest to the research workers in the field of optoelectronic devices.

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