

Energy-gap narrowing in a current injected InGaN/AlGaN surface light emitting diode

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The emission spectrum of a current injected InGaN/AlGaN surface emitting diode has been investigated. A clear redshift of the low energy edge with increasing injected current has been observed, and is attributed to the many body effects. The carrier density and band gap narrowing are obtained by fitting the line shape of the emission spectrum, using Landsberg model which includes many body effects. A redshift of around 92 meV of the low energy edge is obtained as injected current increases from 400 to 4000 mA. The band gap change can be described well in proportion to the 1/3 power of the carrier density, which is just suggested by the exchange energy of electron–electron, and hole–hole interactions. © 1997 American Institute of Physics.

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Recently, group III nitride semiconductors have attracted much attention as a material for fabricating blue and ultra-violet light-emitting diodes and lasers. Light-emitting diodes based on InGaN/AlGaN heterostructures have achieved a practical level.¹ More recently, successful fabrication of electrically pumped III-V nitride lasers have been reported.² But such material and related optoelectrical devices are still in the preliminary stage, and many physical mechanisms affecting their active medium behavior are not understood in detail.

Many body effects in highly excited semiconductors have been studied intensively both experimentally and theoretically for many years,^{3–6} and it is well known that many body Coulomb interactions between the carriers will lead to energy band renormalization or narrowing. Due to the large exciton binding energy, effective electron mass, and wide band gap of group-III nitride compounds, the effect of many body Coulomb interactions are expected to be more important.⁷ A redshift of the peak of stimulated emission spectra for optically pumped GaN-based materials has been observed by different authors.^{8–11} This redshift may be interpreted as strong many body effects overcoming a relatively small band filling effect. The investigations of many body effects are generally carried out using the optical pump method and are concentrated mainly on GaAs-based materials, with few studies on GaN-based materials.^{12–14} In this letter the band gap narrowing arising from many body interactions in the electron-hole plasma of current injected InGaN/AlGaN surface light-emitting diode (SLED) is investigated. The dependence of electroluminescence on the injected current density has also been investigated. A luminescence line shape analysis has been used to extract the

essential parameters such as carrier density and the renormalized gap of the current pulse injected InGaN/AlGaN SLED.

The SLEDs, comprised of In_{0.06}Ga_{0.94}N/AlGaN double heterostructures with a Zn- and Si-doped *n*-type active layer, are prepared by metalorganic chemical vapor deposition (MOCVD) on a sapphire (0001) substrate. The dark spot density in the samples were about $3 \times 10^7 \text{ cm}^{-2}$. The details of the device fabrication conditions, structure, and characteristics were described in previously reported results,¹⁵ but our samples had no optical feedback.

The SLEDs were mounted on a copper heat sink, and operated in pulsed mode with pulse width of 100 ns at a frequency of 1 kHz. Figure 1 shows the surface emitting spectra measured at various injected currents. (Similar emitting spectra were obtained in other samples also; the best

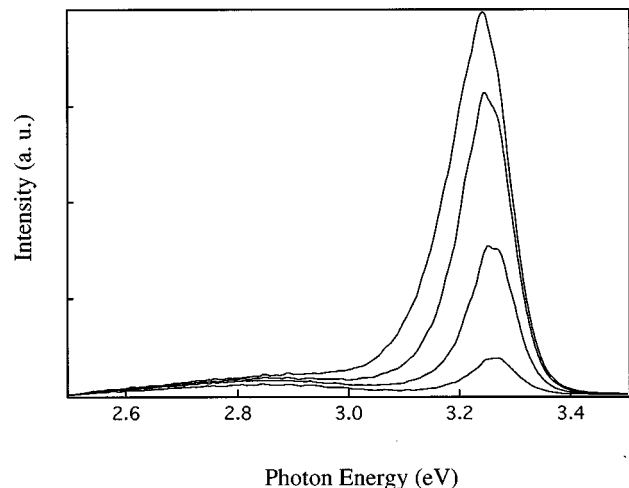


FIG. 1. The experimental emission spectra as function of photon energy at different injected currents of (from bottom to top) 0.4 A, 1 A, 2 A, and 3 A.

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luminescence efficiency has investigated here.) A broad emission band at around 2.8 eV, which may be due to the free to bound acceptor or donor-acceptor pair recombination,¹⁶ tends to saturate as the injected current increases and the band edge recombination emission at around 3.26 eV becomes more and more intense. The saturation of the broad emission at around 2.8 eV may be due to the limited impurity concentration. With an increase in the injected current, a clear redshift of the low energy edge, along with a broadening and a shift in peak energies of the emission spectra, is observed. These phenomena can be caused by heating effect or many body effects. By fitting to the high energy tail of the measured spectra, with the Boltzmann factor $\exp[-(h\nu - E_g)/kT]$, the carrier temperature T can be obtained; here $h\nu$ is photon energy, E_g is the band gap energy, and k is the Boltzmann factor.¹⁷ Although not shown here, when the high energy tail of the spectra was plotted as a function of photon energy on a logarithmic scale, it gave a constant temperature for all the injected current levels, which was close to bath temperature. Moreover, no shift in the peak energy of the spectra is observed with increasing current pulse frequency. Therefore, the redshift of the low energy edge and broadening of the emission spectra can be attributed to the many body effects, and is not due to the heating effect.

As no evidence of stimulated emission has been seen in measured emission spectra, we tacitly assume that stimulated emission was negligible in our experiment. Similar to photoluminescence (PL) spectra the luminescence is described by the following intensity relation:¹⁸

$$I(h\nu) \propto \int \int D_e(E_e) D_h(E_h) \delta(E_e - E_h - h\nu) dE_e dE_h, \quad (1)$$

where $D_{e,h}(E)$ are the number of electrons (holes) per unit energy range and unit volume (density of states times Fermi distribution function), which assumes that the redshift of the low energy edge is due to collision broadening of the electron and hole states, and is given by:¹⁹⁻²²

$$D_e(E) \propto \frac{1}{2\pi} \int_0^\infty \frac{\Gamma(E_1)}{(E - E_1)^2 + [\Gamma(E_1)/2]^2} \times \frac{(E_1)^{1/2}}{1 + \exp[(E_1 - E_F^e)/kT]} dE_1. \quad (2)$$

For the parameter Γ of the Lorentzian function, we take Landsberg's expression.²⁰ The fit parameters are the quasi-Fermi energies $E_F^{e,h}$ of electrons and holes, broadening parameter Γ_0 which is included in Γ , and the renormalized gap E'_g . The carrier density is obtained from the relation:

$$n = \int_{-\infty}^{+\infty} D_e(E) dE. \quad (3)$$

In our calculation, reabsorption effects are not considered for the following reasons. First, in surface light-emitting diodes, the reabsorption is very small and the spectra will resemble that of PL. Second, the absorption coefficient corresponding to photons of lower energies is smaller than that corresponding to higher energies. Third, because lower energy states of

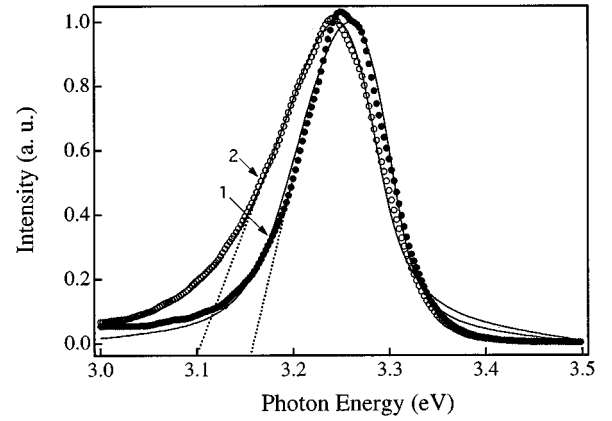


FIG. 2. Normalized emission spectra of InGaN/AlGaIn diode with two different injected current, (1) 1 A; (2) 3 A; the symbols are experimental data, and the solid curves represent theoretical results. The broken line in lower energy side is used to obtain E'_g according to Tarucha's method.

the conduction and valence bands are almost occupied under strong excitation, reabsorption mainly takes place on the higher energy side of photon energy and has little effect on the low energy edge. Since the renormalized band gap is determined by lower energy side of the spectra, reabsorption will have little effect on the calculated results of band gap narrowing.

Results of the line shape fitting are shown in Fig. 2. Theoretical fits are in very good agreement with the measurements. A decrease in the renormalized band gap E'_g with increasing injected current is clearly observed. According to Tarucha *et al.*²³ the renormalized band gap can also be determined by the lower energy side of the spectra, and the redshift of the band gap can be directly approximated by an intercept of the tangent at half the peak intensity of the lower energy side. However this method gives only relative redshift of the band gap, not the exact renormalized band gap. The results obtained by the two methods are shown in Fig. 3, which indicates similar injected current dependence of renormalized band gap E'_g . A redshift of around 92 meV of the

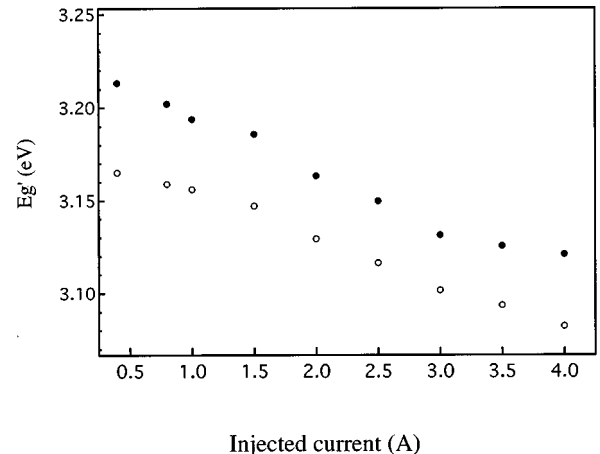


FIG. 3. Injected current pulsed dependence of the renormalized E'_g . The dots are exacted from spectra line shape fitting, and circles are obtained by Tarucha's method.

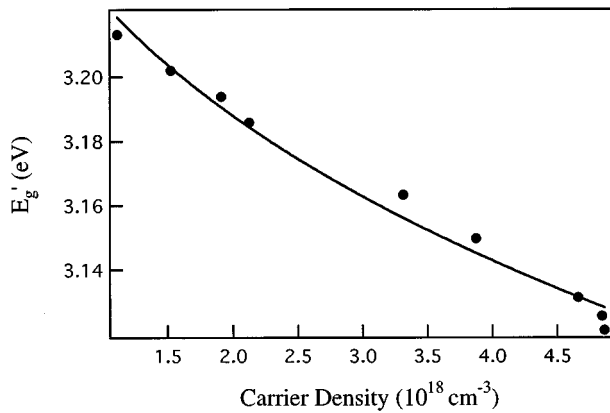


FIG. 4. Renormalized E'_g as a function of carrier density. The dots represent spectra shape line fit results, and the solid curve is for that calculated ones using $E'_g = E_g - 5.8 \times 10^{-8}(n^{1/3} + p^{1/3})$ (eV) with $E_g = 3.324$ eV.

low energy edge has been found as the pulsed injected current increased from 400 to 4000 mA.

The band gap narrowing due to many body interactions can be calculated theoretically considering the exchange energy of the electron–electron and hole–hole interactions. Stern²⁴ showed simple relation between the band gap narrowing and the carrier density:

$$E'_g = E_g + A(n^{1/3} + p^{1/3}), \quad (4)$$

where n and p are electron and hole concentration, respectively, and A is a constant.

The above equation is valid only if the ratio of intercarrier spacing to the electron Bohr radius in the crystal is less than unity, and the carrier–impurity interaction and carrier–carrier Coulomb interactions are not considered. Our experimental results are in good agreement with the above relation, with $A = -5.8 \times 10^{-8}$ eV/cm, and $E_g = 3.324$ eV (the band gap energy of $\text{In}_{0.06}\text{Ga}_{0.94}\text{N}$ at room temperature), which is shown in Fig. 4. Experimental observations of band gap narrowing for GaAs (Ref. 25) and InP (Ref. 26) can also be described by the above relation, with a relatively smaller value of A , -2.15×10^{-8} and -2.25×10^{-8} eV/cm, respectively. The large value of A for InGaN may indicate stronger many body effects than that for GaAs and InP. Zhang *et al.*¹⁴ have also a reported similar relation of band gap with carrier concentration for optical pump on GaN, however, with a much smaller value (-1.1×10^{-8} eV/cm) of the constant term A . In our opinion, they may have overestimated the value of carrier concentration by taking a small value for A because they did not consider the carrier density pinning effect which occurs in the strong stimulated emission case.

In summary, we have measured and analyzed emission spectra of a current injection InGaN/AlGaN surface emitting diode. A clear redshift of the low energy edge with increasing injected current has been observed, and is attributed to

many body effects. The carrier density and band gap narrowing are extracted by emission spectra line shape fit using the Landsberg model which includes many body effects causing collision broadening of the electron and hole states. The band gap change can be described well in proportion to the $1/3$ power of the carrier density, and further supports our supposition that band gap narrowing is caused by many body effects which is a more effective phenomenon for group III nitrides.

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