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Carrier leakage in InGaN quantum well light-emitting diodes emitting at 480 nm

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Pulsed light–current characteristics of InGaN/GaN quantum well light-emitting diodes have been measured as a function of temperature, with sublinear behavior observed over the whole temperature range, 130–330 K. A distinctive temperature dependence is also noted where the light output, at a fixed current, initially increases with temperature, before reaching a maximum at 250 K and then decreases with subsequent increases in temperature. On the basis of a drift diffusion model, we can explain the sublinear light–current characteristics and the temperature dependence by the influence of the large acceptor ionization energy in Mg-doped GaN together with a triangular density of states function characteristic of localized states. Without the incorporation of localization effects, we are unable to reproduce the temperature dependence whilst maintaining emission at the observed wavelength. This highlights the importance of localization effects on device performance. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1570515]

There is currently strong interest in GaN based light emitting diodes (LEDs) since they are able to produce light over a broad spectral range from red/infrared to ultraviolet, with applications ranging from printing, and information storage to white-light sources. Despite the presence of high concentrations of defects caused by the large mismatch of lattice and thermal expansion coefficients between the GaN and the sapphire substrate, devices are being manufactured with acceptable power output. It has been suggested that nonradiative recombination at these defects is inhibited because carriers are localized away from the defects by band bending at the defects, band gap narrowing due to In inhomogeneities in the InGaN quantum well (QW), or by thickness variations in the wells, thereby reducing the deleterious impact of defects on the internal radiative efficiency. If carrier loss occurs only by nonradiative recombination within the QW we would expect the light–current ($L-I$) curves to be superlinear[1] but this is not observed universally. In many cases, as in this work, the $L-I$ curves are sublinear so carrier loss must also occur by other processes. To obtain greater insight into these processes we have made a detailed analysis of the temperature dependence of $L-I$ characteristics together with measurements of emission and absorption spectra from the active region. We find that carrier leakage by drift and diffusion is important in these devices, but that it is only possible to achieve a consistent description of both the $L-I$ characteristics and the spectra by regarding the emission to originate from states in a tail on the density of states function. This work gives insight into the role of these tail states in determining the form of the $L-I$ characteristics.

The LEDs investigated were grown by low-pressure metalorganic vapor phase epitaxy on (0001) orientated sapphire and consist of 0.9 μm undoped GaN and 1.35 μm Si-doped n-GaN with an active region of five 2.6 nm $In_{0.16}Ga_{0.84}N$ QWs embedded between 18 nm undoped GaN barriers and with a top cap of 0.2 μm of Mg doped p-GaN. X-ray diffraction was used to determine the In percentage. The LEDs had an area of 5.49×10^{-8} m^2 and the $L-I$ characteristics were measured pulsed with a low duty cycle (0.1%, pulse width 1 μs) to avoid self-heating. The devices emitted at about 480 nm.

Results in Fig. 1 show that the $L-I$ curves are sublinear over the temperature range investigated, from 130 to 330 K. Since radiative recombination increases approximately as the square of the number of electrons there must be a nonradia-

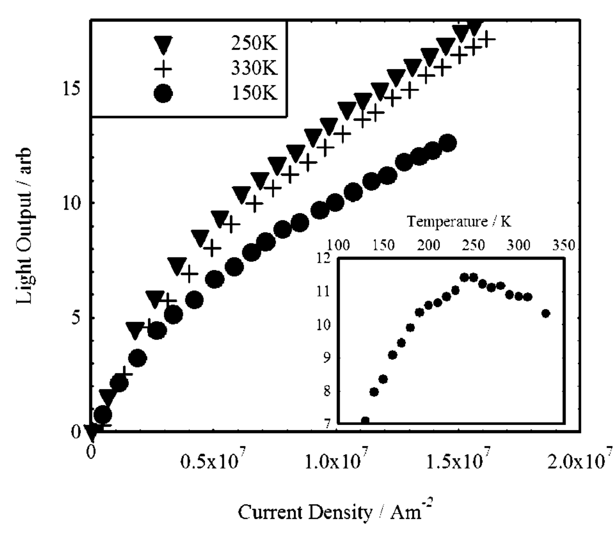

FIG. 1. Experimental $L-I$ characteristics over the temperature range 150–330 K. The inset shows the light output at a fixed current density of 10^7 A m^{-2} as a function of temperature.

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TABLE I. Parameters used in simulation.

Parameter	Value
Electron mass	0.2 m_0
Heavy hole mass	1.6 m_0
Light hole mass	1.6 m_0
Spin orbit	0.17 m_0
Electron lifetime	
in QW	30 ns
in barrier	0.5 ns
in p-GaN	0.5 ns
GaN band gap	3.42 eV
Valence band offset	0.67
Minority electron Mobility	900 $cm^2/V\,s$
Number of donors in p-GaN	3×10^{19} cm^{-3}
Number of acceptors in p-GaN	6×10^{19} cm^{-3}

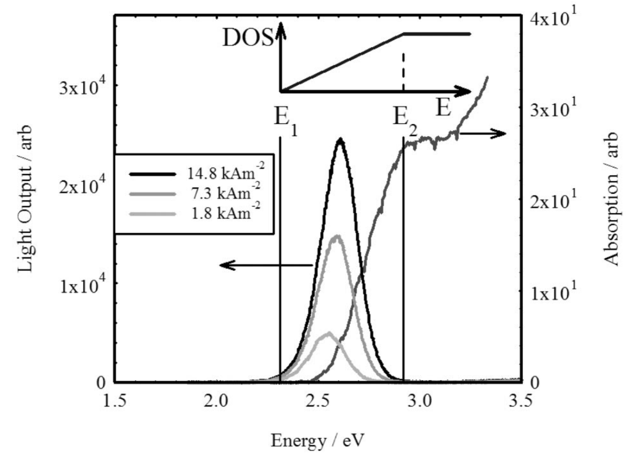

FIG. 2. Top emission spectra at 1.8, 7.3, and 14.8 kA m^{-2} (left axis) and edge absorption spectrum (right axis), both at room temperature. Inset shows a schematic diagram of the triangular density of states used in the simulation.

tive process increasing at greater rate to produce the sublinear behavior. Auger recombination is unlikely to be significant in wide gap materials since the Auger coefficient has been estimated to be as low as $C=10^{-34}$ $cm^6\,s^{-1}$.[2] Furthermore, Auger recombination cannot easily explain the initial increase in light with temperature at fixed current, with the output going through a maximum at 250 K as shown in the inset in Fig. 1. Similar temperature behavior has been observed by others.[3]

A more plausible explanation which readily explains both the sublinear $L-I$ curves and the distinctive temperature dependence of the light output is the thermally activated leakage of electrons through the p-type GaN cap layer by drift and diffusion. The drift rate is controlled by the field across the p-type capping layer, which is given by

$$E=\frac{(J_{\mathrm{Rad}}+J_{\mathrm{nr}})}{\sigma_p(T)}, \tag{1}$$

where $J_{\mathrm{Rad}}+J_{\mathrm{nr}}$ is the sum of the total radiative and nonradiative current densities through the cap layer to the active region. The temperature dependent conductivity of the p-type capping layer is given by

$$\sigma_p(T)=ep(T)\mu_p(T), \tag{2}$$

where $p(T)$ is the hole concentration and $\mu_p(T)$ is the mobility. The temperature dependence of the mobility was taken from experimental results[4] with the room temperature value equal to 6.1 $cm^2/V\,s$. The ionization energy of Mg acceptors in GaN is large, reportedly 170 meV,[5] consequently the hole concentration increases rapidly with temperature, causing an increase in conductivity and a decrease in the field. This leads to a decrease in the drift leakage current and an increase in the light output at fixed current. At sufficiently high temperature the rate of increase in the number of electrons excited from the well outweighs the decrease in field and the leakage due to both drift and diffusion increases with temperature and the radiative output decreases.

To test this explanation quantitatively and in detail we have simulated the $L-I$ characteristics using a drift-diffusion model based on work done on AlGaInP lasers.[6–8] The model incorporates the temperature dependence of the recombination and leakage processes. Table I lists the values of the parameters used. The calculation included radiative[9] and nonradiative[7] recombination in the barriers and assumed the electrons and holes to be individually in quasiequilibrium and specified by quasi-Fermi levels. Initially the well depth was chosen to give emission at the wavelength of the measured emission spectra shown in Fig. 2. While the calculated leakage current showed the anticipated decrease with increasing temperature, we found that the magnitude of the leakage current was too small to produce the observed behavior of the light output at fixed current shown in Fig. 1. Furthermore, the predicted ratio of light emission from the well and the GaN cap layer is a factor 10^6 smaller than we observe. Fundamentally these effects occur because the electron quasi-Fermi level is too far below the conduction band of the GaN cap layer. Artificially increasing Fermi energy within the model increases the leakage current but the emission spectrum becomes much broader than we observe. Increasing the quasi-Fermi energy by increasing the subband separation produces emission at too high photon energy. From this work we concluded that, using reasonable values for parameters, we could not reproduce the behavior of the $L-I$ curves and the emission spectra using a step density of states function characteristic of a simple quantum well.

Figure 2 also shows a photovoltage absorption spectrum of the LED active region. This has no well-defined absorption edge and comparison with the emission spectra shows that at all currents the LED emission occurs at the low energy edge in the absorption tail. Taken together, the emission and absorption spectra suggest that the quantum wells are inhomogeneous, due for example to composition fluctuations, or well width nonuniformity[10] and that the emission occurs from localized regions where the subband separation is smallest.[11,12] We have therefore modeled the joint density of states by a triangular function as shown in Fig. 2, which extends from the lowest photon emission energy and which becomes constant at the value for a single subband where the absorption spectrum flattens out. Because the density of states at the band edge is reduced compared with a uniform well the quasi-Fermi energy for a given light output is increased. We note that the density of states function of a uniform well subject to a piezoelectric field is also a step func-

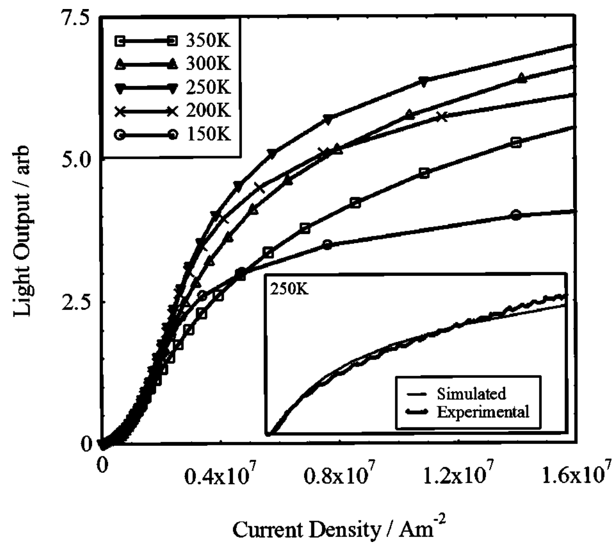

FIG. 3. Calculated $L-I$ characteristics at various temperatures. The inset is a comparison with experimental results at 250 K, both curves were normalized at a current density of 10^7 A m^{-2}, with light output plotted on the y axis and current density on the x axis. The x-axis scale ranges from 0 to 2×10^7 A m^{-2}.

tion, and while the field does shift the transition energy and the Fermi level it does not reduce the density of states at the band edge. The graded density of states function is caused by lateral inhomogeneity in the subband energies which could be due to a combination of the piezoelectric field and well width inhomogeneity, but not the field alone. By using the experimental spectra to define the density of states function we automatically take account of the influence of piezoelectric effects on the transition energy and avoid the need to assume a particular mechanism for the localization which leads to the tail states.

Figure 3 shows $L-I$ curves calculated using this triangular joint density of states function. The radiative recombination coefficient (B) for carriers in the tail states was defined in terms of the total carrier population in the well by reference to the observed ratio of emission from the wells and the cap layer, based on a value of 5×10^{-11} cm^3 s^{-1} for the GaN cap. The value obtained of $B=3\times10^{-8}$ cm^2 s^{-1} is smaller than we would expect for an InGaN well and in the context of the model proposed here we suppose this is because the whole electron population is unable to recombine with the whole hole population due to localization. The value of B may also be reduced by the piezoelectric effect. Figure 3 shows that this model reproduces the sublinear $L-I$ curves and produces a maximum in light output at 250 K as observed in our experiments. This calculation is also consistent with the emission and absorption spectra. The inset to Fig. 3 shows a comparison between experimental and simulated results at 250 K, where both curves were normalized at a current density equal to 10^7 A m^{-2}.

We conclude that the sublinear $L-I$ characteristics and the temperature dependence of the light output at fixed current can be explained by the influence of the large acceptor ionization energy on electron leakage by drift through the p-GaN cap layer. However, it is only possible to achieve detailed agreement with experimental $L-I$ data and emission spectra by using a nonsquare density of states function, characteristic of an inhomogeneous quantum well. This has the effect of giving emission at the observed wavelength while placing the quasi-Fermi energy sufficiently close to the conduction band of the GaN for the leakage current to make a significant contribution to the total current. Carrier leakage would be insignificant in this structure for uniform wells emitting at the observed photon energy, and this work highlights the profound effect of localization on the behavior of the $L-I$ characteristics.

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