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Current crowding and optical saturation effects in GaInN/GaN light-emitting diodes grown on insulating substrates

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Current crowding in mesa-structure GaInN/GaN light emitting diodes (LEDs) grown on insulating substrates is analyzed. A model developed reveals an exponential decrease of the current density with distance from the mesa edge. Devices with stripe-shaped mesa geometry display current crowding and a saturation of the optical output power at high injection currents. It is shown that the optical power saturation depends on the device geometry. It is also shown that saturation is less pronounced in LEDs employing a ring-shaped mesa geometry, which reduces current crowding, as compared to the conventional square-shaped mesa geometry. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1372359]

GaInN light emitting diodes (LEDs) emitting the blue, green, and yellow spectral range have been grown on insulating sapphire substrates[1] as well as on conductive SiC substrates.[2,3] SiC substrates have the advantages of smaller die size, high conductivity, and a better lattice match to GaN than sapphire. However, they are more expensive and more absorptive than sapphire. Therefore, most GaN based materials are currently grown on insulating sapphire substrates.[4] For such LEDs, mesa structures are employed so that the anode and cathode contacts are in a side-by-side configuration. Due to the lateral current transport in mesa-structure GaInN LEDs, the current crowds near the edge of the mesa.[5]

In this letter, the current crowding effect is analyzed in terms of a quantitative model. It is shown that the current density decreases exponentially with distance from the mesa edge.[6] In addition, experimental results are presented on the saturation of the emission power at high current density. The dependence of the saturation on the mesa geometry is investigated by comparing a square-shaped and a ring-shaped mesa.

A schematic structure of a *p*-side-up mesa LED grown on an insulating substrate is shown in Fig. 1(a). It is intuitively clear that the current across the *p*–*n* junction *crowds* near the edge of the *p*-type mesa as indicated in the figure. An equivalent circuit model of the LED is shown in Fig. 1(b). The model includes the *p*-type contact resistance and the resistances of the *n*-type and *p*-type cladding layers. The *p*–*n* junction region is approximated by an ideal diode.

Thompson[7] calculated the current spreading length in a *p*–*n* junction diode with *vertical* current transport grown on a highly conductive *n*-type substrate so that the resistivity of the *n*-type lower cladding layer and substrate can be neglected. In this case, the current spreads in the top *p*-type cladding layer. However, in GaInN/GaN LEDs with *lateral* current transport, neither the *p*-type nor the *n*-type layer resistance can be neglected. As will be shown in the following calculation, both types of material resistances play a peculiar role in the current crowding problem.

Assuming that the *p*-type metal contact has the same electrostatic potential at every point, application of Kirchoff's current law to two adjacent nodes together with the ideal diode equation yields

$$\frac{d^2V}{dx^2}=\frac{\rho_n}{t_n}J_0\left[\exp\left(\frac{eV_j}{kT}\right)-1\right]. \tag{1}$$

where J_0 is the reverse saturation current density, and ρ_n is the resistivity of the *n*-type cladding layer. The meaning of other symbols can be inferred from Fig. 1(b). Taking into account the resistance of the *p*-type cladding layer and the *p*-type ohmic contact, the voltage drop across the pn junction and the *p*-type resistors is given by

$$V=R_v I_0 \exp(eV_j/kT)+V_j, \tag{2}$$

where R_v (vertical resistance) is the sum of the *p*-type layer resistance and *p*-type contact resistance of the area element $w\,dx$, that is

$$R_v=\rho_p\frac{t_p}{w\,dx}+\rho_c\frac{1}{w\,dx}, \tag{3}$$

and ρ_p is the resistivity of the *p*-type layer and ρ_c is the *p*-type specific contact resistance. Calculating the second derivative of V with respect to x in Eq. (2) and inserting the result into Eq. (1) yields the differential equation

$$\frac{e}{kT}(\rho_c+\rho_p t_p)J_0\exp\left(\frac{eV_j}{kT}\right)\left[\frac{d^2V_j}{dx^2}+\frac{e}{kT}\left(\frac{dV_j}{dx}\right)^2\right]+\frac{d^2V_j}{dx^2}$$
$$=\frac{\rho_n}{(\rho_c+\rho_p t_p)t_n}\frac{kT}{e}\left[\exp\left(\frac{eV_j}{kT}\right)-1\right]. \tag{4}$$

In order to solve the differential equation, we restrict ourselves to the forward-bias operation of the diode and assume that the voltage drop across the *p*-type series resistance (R_v) is much larger than kT/e.[6] This condition applies to typical GaInN/GaN LEDs, so that Eq. (4) can be simplified to

$$\frac{d^2V_j}{dx^2}+\frac{e}{kT}\left(\frac{dV_j}{dx}\right)^2=\frac{\rho_n}{(\rho_c+\rho_p t_p)t_n}\frac{kT}{e}. \tag{5}$$

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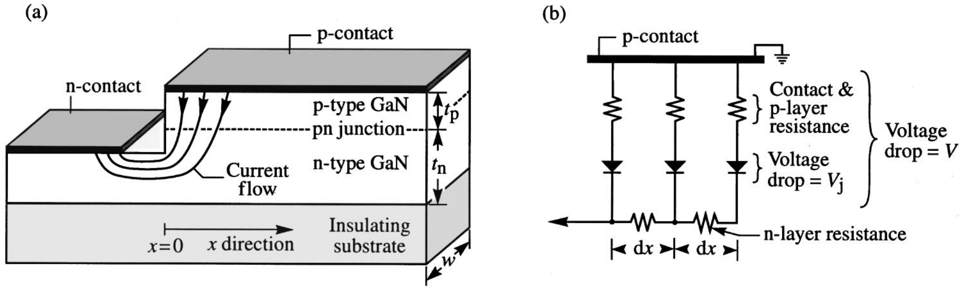


FIG. 1. (a) Illustration of current spreading in a mesa-structure GaN-based LED grown on an insulating or semi-insulating substrate. (b) Equivalent circuit consisting of *n*-type and *p*-type layer resistances, *p*-type contact resistance, and diodes representing the *p–n* junction.

Solving Eq. (5) for V_j and inserting V_j into the diode equation $J=J_0\exp(eV_j/kT)$ yields the current distribution as

$$J(x)=J(0)\exp(-x/L_s), \tag{6}$$

where $J(0)$ is the current density at the *p*-type mesa edge and L_s is denoted as the *current spreading length*, that is, the length over which the current density drops to the $1/e$ value of the current density at the edge, so that $J(L_s)/J(0)=1/e$. The current spreading length is given by

$$L_s=\sqrt{(\rho_c+\rho_p t_p)t_n/\rho_n}. \tag{7}$$

The equation shows that the current distribution depends on the epitaxial layer thicknesses and materials resistivities. Equation (7) provides a guide for the design of LEDs, including the resistivity and thickness of the cladding layers. A thick low-resistivity *n*-type buffer layer is needed to insure that current crowding is minimized.

The epitaxial layers of the LED wafer used in the experiments were grown by organometallic vapor phase epitaxy on a 17-ml-thick sapphire substrate. The epitaxial layers consist of a 2-μm-thick *n*-type cladding layer, a GaInN/GaN multiquantum well active region with ten GaInN wells and GaN barriers, and a 0.3-μm-thick *p*-type GaN upper cladding layer. Stripe-shaped, ring-shaped, and square-shaped mesas were formed by inductively coupled plasma etching. Titanium metallization (500 Å), annealed at 800 °C for 30 s in a N_2 ambient was used as *n*-type contacts. Ni metallization (500 Å), annealed at 400 °C for 300 s in a N_2 ambient was used as *p*-type contacts.

At injection current of 10 mA, the emission spectrum peaks at 464 nm corresponding to a peak energy of 2.67 eV. The full width at half maximum of the emission spectrum is 30 nm corresponding to 170 meV. At 10 mA injection current, the optical power measured with a single backside detector is 0.4 mW.

An experimental result on the current crowding effect in a GaInN/GaN LED grown on a sapphire substrate is shown in Fig. 2. A micrograph of the optical emission from the LED is shown in Fig. 2(a). The picture was taken from the sapphire substrate side of the LED and shows the blue light emission. The micrograph clearly reveals that the emission intensity decreases with increasing distance from the mesa edge. Figure 2(b) shows the experimental intensity as a function of the distance from the mesa edge and a theoretical fit (dashed line) to the experimental data using the exponential decrease in current density derived earlier. The experimental and the theoretical data exhibit very good agreement for a current spreading length of 550 μm.

As a result of current crowding, high current densities occur near the mesa edge. The light output power of the LED versus current is shown in Fig. 3 for different duty cycles. Several physical mechanisms can cause the saturation, in-

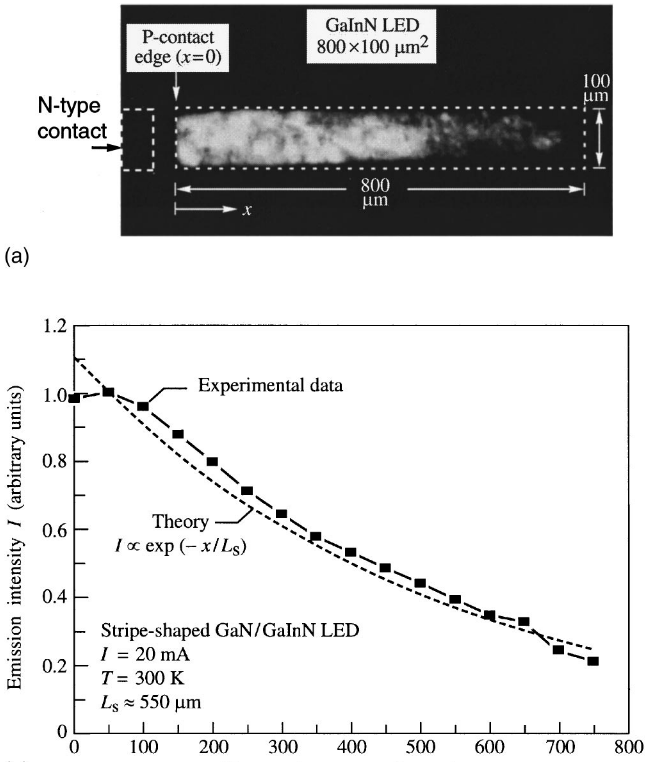


FIG. 2. (a) Micrograph of optical emission from mesa-structure GaInN/GaN LED grown on an insulating sapphire substrate. The LED has a stripe-shaped 800 μm×100 μm *p*-type contact. (b) Theoretical and experimental emission intensity vs distance from the contact edge of the LED.

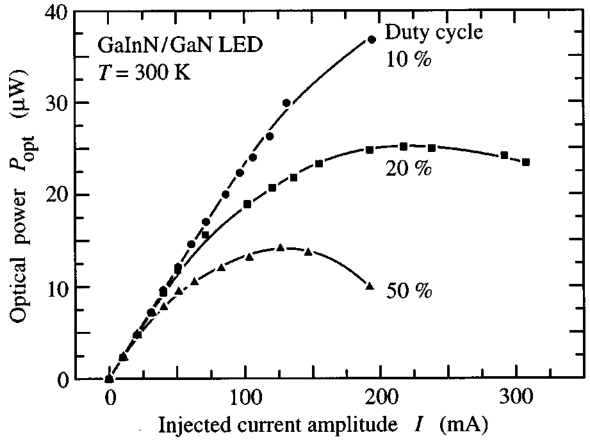
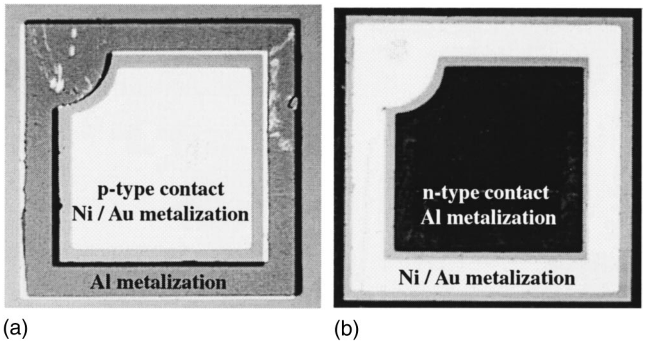


FIG. 3. Optical emission power vs injected current for pulsed mode operation of a GaInN/GaN LED.



(a) (b)

FIG. 4. Micrograph of a GaInN LED with (a) square-shaped *p*-type contact inside of ring-shaped *n*-type contact and (b) ring-shaped *p*-type contact outside of a square-shaped *n*-type contact.

cluding carrier overflow and local heating of the device. The fact that the power saturation is less pronounced for pulsed injection currents with a small duty cycle, indicates that thermal effects cause the saturation.

We believe that the saturation is related to the *p*–*n*-junction current density. It is desirable that the current flow is uniform across the mesa and does not crowd near the mesa edge. Therefore, mesa and contact geometries exhibiting less crowding should be employed.[8] We have investigated two different mesa geometries, namely a square-shaped mesa, as shown in Fig. 4(a) and a ring-shaped mesa, as shown in Fig. 4(b). The two device structures have the same *p*-type contact and *n*-type contact areas.

The optical power versus injected current of the two types of LEDs is shown in Fig. 5. Inspection of the figure reveals that both mesa geometries result in a saturation of the optical power. However, the LED with ring-shaped *p*-type mesa saturates at a higher injection current as compared to the LED with square-shaped mesa, indicating that the saturation behavior of the LED with the conventional contact geometry is more pronounced. The length of the current flow in the *n*-type layer under the ring-shaped mesa is *shorter* as compared to the square-shaped mesa. That is, the lateral current transport length in the *n*-layer is shorter than the current spreading length thus resulting in less current crowding. Furthermore, due to the ring-shaped mesa geometry, the mesa wall surface is more than doubled, resulting in improved light extraction efficiency towards lateral directions. Thus, the improvement in optical emission intensity displayed in Fig. 5 can be attributed to both, reduced current crowding and higher light extraction efficiency.

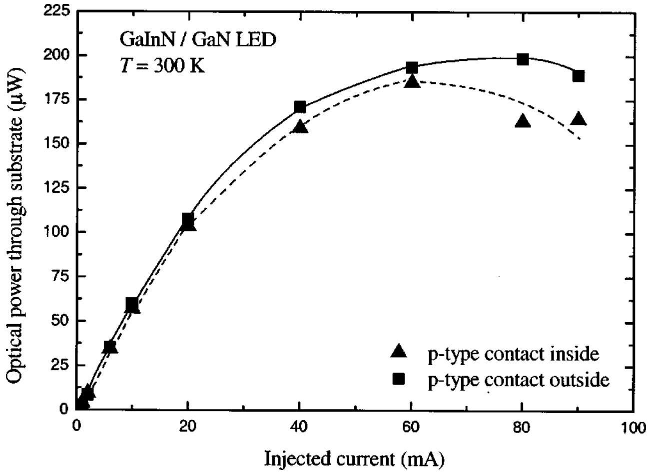


FIG. 5. Comparison of optical power emitted through sapphire substrate of a GaInN/GaN LED with square-shaped and ring-shaped *p*-type mesa structure.

In conclusion, the current crowding effect in mesa-structure GaInN/GaN LEDs grown on insulating substrates is analyzed. A model is developed that reveals an exponential decrease of the current density with distance from the mesa edge. The model serves as a guide for the design of LEDs, including the resistivity and thickness of the cladding layers. Devices with square-shaped mesa geometry display current crowding and a saturation of the optical output power at high injection currents. It is shown that the optical power saturation depends on the device geometry and that the saturation is less pronounced in LEDs employing a ring-shaped mesa geometry designed to reduce current crowding.

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