Inhomogeneous electroluminescence for characterizing lateral transport in semiconductor devices

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Abstract — In multilayer semiconductor devices, carrier transport perpendicular to the growth axis is important for generating uniform current density and minimizing local heating. However, lateral transport within individual layers of the structure can be hindered by fluctuations in layer thickness, alloy composition, and other defects. Impediments to lateral transport can be analyzed by imaging electroluminescence as a function of temperature and injection density. Inhomogeneity in the emission pattern distinguishes preferred current channels from less favorable pathways through the device. The temperature dependence of the nonuniformity can be used to gauge the localization energy and the dependence on injection current can be used to estimate the density of laterally localized states. In this report, we use an InGaN/GaN diode to demonstrate this characterization technique. We find that lateral transport in this device is thermally activated with an activation energy of 37 meV. Our analysis also shows that the density of localized states in the lower energy regions is relatively small, saturating at a current density of approximately 0.5 mA/cm².

Index Terms — III-V semiconductor materials, quantum well devices, electroluminescence, optical imaging.

I. INTRODUCTION

Semiconductor devices are generally multi-layered structures that are grown along a specific axis of a crystalline substrate. Device operation relies on the motion of charge carriers perpendicular to these layers and parallel to the growth axis. For example, photovoltaic cells and light-emitting diodes incorporate a built-in electric field along the growth axis that drives the vertical motion of charge carriers through the device. Photocurrent generation and optical emission depend primarily on the vertical drift of charge carriers between the p- and n-type regions of the structure. Nevertheless, lateral motion perpendicular to the growth axis is also important for device performance. Diffusive spreading of charge carriers within individual layers facilitates a uniform flux through the active region, mitigating current crowding problems that arise when carriers follow preferred channels through the junction. [1]–[3]

Inhomogeneity in the flow of carriers implies variation in charge carrier density across the active region, which affects the local rates of nonradiative and radiative recombination. When the injected electron and hole densities are nearly equal \( n = p \), the rate of defect-related Shockley-Reed-Hall (SRH) recombination varies approximately linearly with \( n \) or \( p \). [4] Meanwhile, the rate of bimolecular radiative recombination is proportional to the product of electron and hole densities \( n \times p \).

Hence, radiative rates are usually higher in higher density regions. However, the Auger recombination rate is proportional to the cube of the carrier density, so Auger recombination can dominate where the density is highest. Since SRH and Auger recombination are nonradiative mechanisms that generate heat, they cause inefficiency and local heating, degrading device performance. Alternatively, we note that localization of charge flow can also improve performance by restricting access to detrimental extended defects. [5]

In this report, we use electroluminescence (EL) imaging to assess lateral transport in a blue LED. The EL appears sparkly at low temperature under low injection conditions, but becomes more uniform with increasing temperature and/or current density. The sparkling LED emission pattern indicates that isolated current channels are favored and lateral transport is inhibited when the thermal energy is not sufficient to overcome
energetic barriers and the carrier density is smaller than the density of laterally localized states. Higher temperatures and/or currents alleviate these restrictions.

II. EXPERIMENT

Our test device for demonstrating this characterization technique is a high-brightness blue LED. The structure consists of p-GaN, several InGaN/GaN quantum wells (QWs), and n-GaN grown on a sapphire substrate. Details are comparable to those of Device B described in Reference [5]. The 1 mm² device is mounted in an Oxford Instruments Optistat DN cryostat and connected to a Keithley 2400 SourceMeter configured to source current. Images of the emission pattern are acquired with a cooled QImaging Monochrome Rolera XR CCD camera equipped with an Edmund Scientific VZM 300 imaging lens at 3X magnification, yielding a spatial resolution of ~ 4 μm. Representative snapshots of the EL pattern at current density $J$ and temperature $T$ are shown in Fig. 1.

III. RESULTS

The images in Fig. 1 show clear trends of increasing EL uniformity with increasing current density and temperature. At low density and temperature, numerous sharp points shine brightly over a dimmer background emission. But at higher current density or temperature, the background gains strength relative to the inhomogeneous glitter. In order to quantify the observed changes in inhomogeneity, we focus our analysis on the bright spot circled in red in Fig. 1. We seek to compare the EL signal at the location of the spot with the average EL signal in the surrounding region. Hence, we define the EL contrast $C$ as follows:

$$C = \frac{E_{L_{local}} - E_{L_{avg}}}{E_{L_{avg}}}$$

where $E_{L_{local}}$ is the local spot signal and $E_{L_{avg}}$ is the average signal in the adjacent region. We use the radial profile plugin for ImageJ to obtain an average measure of the EL signal as a function of radial distance from the location of the spot. The analysis region is limited by nearby electrodes, but large enough to give a good measure of the average signal in the vicinity of the analysis site. The EL contrast is plotted against current density in Fig. 2.

At 100K, the contrast decreases steadily with increasing current density. The linear fit in Fig. 2 represents the relation $C \propto e^{-0.53 \log J}$, meaning that the contrast decreases at a relative rate of 0.6 per decade. In absolute terms, the contrast falls to 1/e when $J = 0.5 \text{ mA/cm}^2$. With an active device thickness $d = 6 \text{ QWs} \times 3 \text{ nm/QW} = 18 \text{ nm}$, this current density corresponds to a carrier injection rate of $1.7 \times 10^{21} \text{ cm}^{-3}\text{s}^{-1}$. Meanwhile, in steady-state, the generation rate equals the recombination rate $B \times n^2$ to estimate the average carrier density under these conditions. Estimating $B \approx 2 \times 10^{-10} \text{ cm}^{-3}\text{s}^{-1}$ at 100K [8] yields $n \approx 3 \times 10^{15} \text{ cm}^{-3}$. Since this is the average density in the QWs, the local density in the active current channels would presumably be considerably larger.

IV. ANALYSIS

Fig. 2 also shows that EL contrast decreases with increasing temperature in the low-injection regime. We attribute this behavior to thermal activation out of laterally localized states. As more thermal energy becomes available, more carriers have enough energy to overcome the barriers to lateral motion that restrict current flow along isolated channels. If we consider a specific temperature above 100K, we see that the EL contrast does not change appreciably with increasing current density until we reach a common threshold where state saturation ensues. Assuming that the carriers obey Boltzmann statistics, each temperature will dictate a specific fraction of carriers with energies exceeding the barrier height. Therefore, thermal activation depletes a fixed fraction of localized carriers, independent of the injection rate. However, when all of the
remaining laterally-localized states are filled, the carriers begin to spill over the barriers and the EL becomes more uniform. The threshold for this phenomenon, characterized by the solid blue line in Fig. 2, should be roughly independent of temperature. The experimental results are indeed consistent with this picture.

An Arrhenius plot of the EL contrast when $J = 10^{-5}$ A/cm$^2$ is shown in Fig. 3, where the associated thermal activation energy is 37 meV. Other bright spots in the image that were tested by the same procedure produced similar results. This energy is less than half of the LO phonon energy (87 meV) deduced from phonon replicas in the emission spectrum, but comparable to the activation energy for diffusive (i.e. non-drift related) non-radiative recombination that we obtained in a prior study (44 meV). [6] In that investigation, open- and short-circuit photoluminescence and photocurrent measurements were used to characterize photovoltaic and photoluminescence efficiencies. The open-circuit model required the aforementioned 44 meV thermally activated SRH mechanism, while modeling of the short-circuit response produced lower error when this recombination mechanism was omitted. This result implied that the non-radiative process did not play a significant role when the carriers drift vertically. It was suggested that motion along the direction of the internal field could preclude capture at the diffusion-related recombination centers that dominate in the open-circuit configuration.

With the present inhomogeneous EL analysis, we verify that lateral motion is indeed constrained in these devices. Diffusive in-plane motion, which spreads the carriers uniformly across the device, requires thermal activation over energetic barriers within the constituent layers. Therefore, we postulate that the thermal activation of SRH recombination reported in Ref. 6 and the thermal activation of EL homogeneity reported here have the same underlying basis, namely, the onset of lateral transport. This interpretation is qualitatively consistent with the conclusions drawn by numerous prior investigations, which assert that carrier delocalization plays an important role in the operation of InGaN-based quantum well devices. [5, 9]

REFERENCES


Fig. 3. Arrhenius plot of the temperature-dependent electroluminescence contrast at an injection current of 0.01 mA/cm$^2$. The slope yields a thermal activation energy of approximately 37 meV.