Efficiency droop in AlGaInP and GaInN light-emitting diodes

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At room temperature, AlGaInP pn-junction light-emitting diodes (LEDs) emitting at 630 nm do not exhibit an efficiency droop. However, upon cooling the AlGaInP LEDs to cryogenic temperatures, they show a pronounced efficiency droop. We attribute the efficiency droop in AlGaInP LEDs to electron-drift-induced reduction in injection efficiency (i.e., carrier leakage out of the active region) mediated by the asymmetry of the pn junction, specifically the disparity between electron and hole concentrations and mobilities, with the concentration disparity exacerbated at low temperatures. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694044]

The decrease in efficiency with increasing forward current is a well-known effect for light-emitting diodes (LEDs) of the GaInN material system.[1] The efficiency droop in the III-V nitrides has been attributed to the saturation of the radiative recombination rate,[2] carrier leakage mediated by the asymmetry of the pn junction,[3,4] poor hole injection,[5] carrier leakage mediated by polarization effects,[6,7] carrier delocalization effects and enhanced non-radiative recombination at dislocations,[8,9] and Auger recombination.[10,11] To the present time, the efficiency droop has not been sufficiently studied in LEDs made from compound semiconductors other than III-V nitrides. Here we report the observation of efficiency droop in AlGaInP LEDs at cryogenic temperatures. We use these results to calculate the current density at which the onset of the droop is expected to occur in pn junction diodes like a GaInN LED, as well as the temperature dependence of the onset, to gain a better understanding of the droop in AlGaInP and GaInN LEDs.

The following characteristics of the AlGaInP material system are noteworthy: *First*, AlGaInP/AlInP heterostructure LEDs homo-epitaxially grown on GaAs substrates are lattice matched and thus have a negligibly small threading dislocation density. *Second*, AlGaInP quantum wells (QWs) used in the active region of the AlGaInP LEDs investigated here are numerous, and the individual QWs are thicker when compared to typical GaInN QWs. *Third*, AlGaInP/AlInP/GaAs heterostructures are not subject to spontaneous and piezoelectric polarization electric fields. These three characteristics are in marked contrast to the GaInN/GaN material system.[12]

The AlGaInP LEDs used in this study have a multiple quantum well active region consisting of 38 AlGaInP QWs and 39 AlGaInP quantum barriers, and a chip size of $350 \times 350\,\mu m^2$. The QWs have a thickness of roughly 4 nm. The emission wavelength of the LED is about 630 nm at room temperature. Although the measurements are done in continuous wave mode, self-heating effect can be neglected because droop is not found at all even at room temperature. Figure 1 shows the external quantum efficiency (EQE) of the red AlGaInP LED as a function of current at different temperatures with (a) linear and (b) logarithmic abscissa. Using the method developed by Shim *et al.*,[2] the peak internal quantum efficiency at 50 K is calculated to be more than 90%. From Fig. 1(a), we can observe a few recognizable trends: First, as the temperature increases, the magnitude of the peak efficiency decreases, due to increased Shockley-Read-Hall (SRH) non-radiative recombination. Second, because SRH recombination increases with temperature, the peak efficiency point shifts to higher currents at high temperature. Third, the magnitude of the efficiency droop increases with decreasing temperature and is largest at 50 K. As the temperature increases to 100 K, the efficiency droop is reduced, but still significantly larger than at room temperature. A similar droop behavior with respect to temperature has been reported for the GaInN/GaN material system.[13,14] Given the similarity of the measured EQE vs. current curves for AlGaInP and GaInN LEDs, it is likely that the droop has the same physical origin. One similarity of both material systems is the asymmetry of electron and hole concentration and mobility. As the temperature decreases in the AlGaInP LED, acceptor ionization, which is very high at room temperature, begins to decline.

Figure 2 shows a transmission electron micrograph (TEM) of the active region of the AlGaInP LED. The left image shows an overview of the entire LED layer sequence, showing all 38 AlGaInP QWs. The right image displays the active region at a higher magnification, with 3 QWs clearly visible. These QWs emit light with peak emission energy of roughly 1.97 eV. The high quality of the AlGaInP can be

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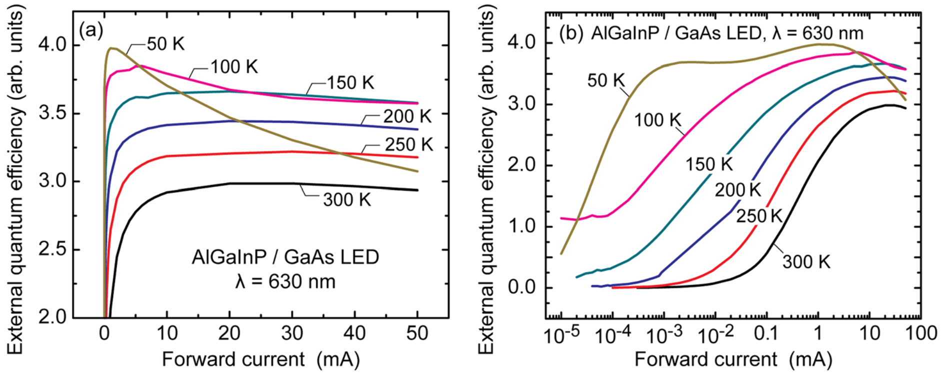

FIG. 1. (Color online) External quantum efficiency vs. current of an AlGaInP LED for different temperatures using (a) linear and (b) logarithmic abscissa.

observed in both magnifications of the TEM, with no dislocations visible. Because the AlGaInP material system is so mature, the distribution of constituent atoms is highly uniform; this should result in a uniform carrier distribution across the QWs, at least at 300 K.

Next, we analyze the efficiency droop in the framework of carrier leakage driven by the asymmetry in carrier transport characteristics. We consider the case when there is a significant disparity between electron and hole concentrations as well as mobilities such that $n \gg p$ and $\mu_n \gg \mu_p$. These two conditions are indeed fulfilled in the AlGaInP and the AlGaInN material system.[12]

Based on Shockley's pn junction theory, it is known that the carrier concentration injected into the neutral regions increases with applied forward voltage. Under low-level injection conditions, the current has an exponential relationship with applied bias. The low-level injection condition can be expressed by the following inequality $\Delta n_p(0) \ll p_{p0}$, where $\Delta n_p(0)$ is the injected electron concentration at the edge of the p-type neutral region of a pn homojunction. When this condition is not fulfilled, high-level injection occurs, and both drift and diffusion currents must be considered.[15] An important consideration, however, is the conductivity in each region of the device. When the conductivity of the depletion region becomes comparable to that of the p-side, the series resistance of the p-type neutral region begins to play a role. We therefore generalize the low-level condition to include the effect of carrier mobility

$$\mu_n \Delta n_p \ll \mu_p p_{p0}. \tag{1}$$

When this generalized condition is not fulfilled, the depletion region is flooded with electrons and its resistivity becomes smaller than that of the p-type region. As a result, an electric field will develop in the p-type neutral region. In contrast, the field in the n-type neutral region is smaller by a factor of $(p\mu_p)/(n\mu_n)$ and thus negligible. Furthermore, in the case of high injection, i.e., when, for example, $\Delta n_p(0) = p_{p0}$, the electron-drift current at the edge of the p-type neutral region (where $n = p$) is higher by a factor of μ_n/μ_p than the hole drift current. The mobility ratio can exceed a factor of 10 for AlGaInP and GaInN semiconductors. Therefore, material systems with an asymmetric mobility ($\mu_n \gg \mu_p$) have a unique property that makes them more prone to enter into the high-level injection regime.

Next, we derive a quantitative condition for the onset of electron drift in the p-type neutral region of III-V semiconductor LEDs. We use GaInN/GaN as an exemplary material system, which is presently of great interest. In pn *homojunctions*, the electron concentration injected into the p-type neutral region is given by $\Delta n_p(0)$. In pn *heterojunctions*, the electron concentration injected into the p-type neutral region is, due to a heterojunction barrier, considerably smaller. In pn heterojunctions, we will denote the electron concentration injected into the p-type neutral region by the same symbol, $\Delta n_p(0)$. Given that the p-type GaN cladding layer is shorter than the electron diffusion length, we write the electron diffusion current leaking out of the active region of a GaInN/AlGaN/GaN heterojunction LED as[12]

$$J_{\text{Diffusion}} = \frac{eD_n \Delta n_p(0)}{L_{\text{p-GaN}}}, \tag{2}$$

where $L_{\text{p-GaN}}$ is the thickness of the p-type GaN region and the other symbols have their usual meaning. The drift current of electrons injected into the p-type neutral region, at the edge of the neutral region, is given by

$$J_{\text{Drift}} = e\mu_n \Delta n_p(0) E = eD_n \frac{e}{kT} \Delta n_p(0) \frac{J_{\text{Total}}}{\sigma_p}, \tag{3}$$

where we employed the Einstein relation, and E, J_{Total}, and σ_p, is the electric field in the p-type GaN, the total current density in the p-type GaN, and the p-type GaN conductivity ($\sigma_p = ep_{p0}\mu_p$), respectively. Significant droop occurs when

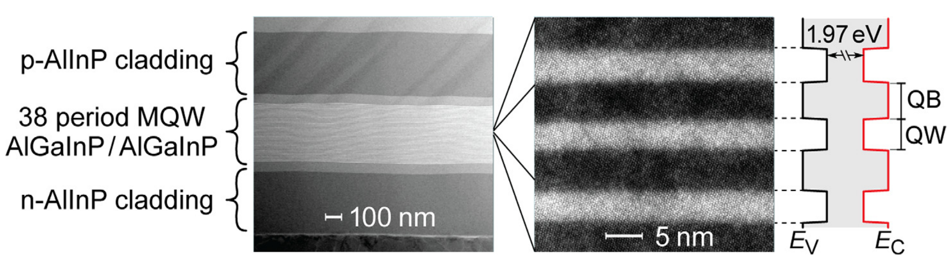

FIG. 2. (Color online) Transmission electron micrograph of the active region of the AlGaInP LED used in this study.

the drift current (Eq. (3)) is as large as the diffusion current (Eq. (2)); equating the two equations yields

$$J_{\text{Total}}|_{\text{Droop}} = \frac{\sigma_{\text{p}}}{L_{\text{p-GaN}}}\frac{kT}{e} = \frac{p_{\text{p0}}\mu_{\text{p}}}{L_{\text{p-GaN}}}kT. \quad (4)$$

The *onset* of the droop may occur at a current density much lower than the one calculated for significant droop (see Eq. (4)). Using a factor of 10 to identify the onset, we write

$$J_{\text{Onset-of-droop}} = 0.1 \times J_{\text{Total}}|_{\text{Droop}} = 0.1 \times \frac{p_{\text{p0}}\mu_{\text{p}}}{L_{\text{p-GaN}}}kT. \quad (5)$$

As a numerical example, we choose the following parameters for a GaInN LED: $p_{\text{p0}} = 2 \times 10^{17}\,\text{cm}^{-3}$, $\mu_{\text{p}} = 2.5\ \text{cm}^2/(\text{V s})$, and $L_{\text{p-GaN}} = 200\,\text{nm}$. Using these parameters, Eq. (5) yields an onset current-density of $J_{\text{Onset-of-droop}} = 10.4\,\text{A/cm}^2$. Furthermore, the temperature dependence of $J_{\text{Onset-of-droop}}$, i.e., a decreasing $J_{\text{Onset-of-droop}}$ with decreasing T, can be attributed to the explicit dependence on T, and also due to the implicit dependence of p_{p0} on T (see Eq. (5)). Both the onset of droop and its temperature dependence are in agreement with experiments on GaInN LEDs.[1–9] It may be noted that while the GaInN system has a low hole concentration and mobility, the AlGaInP system also has a low hole concentration and mobility (although not as problematic as GaInN). This similarity of the material properties can explain the occurrence of droop in these two material systems.

To realize how asymmetric carrier concentration influences the carrier distribution with increasing current, we simulate AlGaInP pn diodes with symmetric and asymmetric carrier concentrations by using the simulation software APSYS. The simulated structure is an $Al_{0.3}Ga_{0.2}In_{0.5}P$ pn diode with a 5 μm n-type region and a 5 μm p-type region. In the symmetric pn diode, the concentration of both electrons and holes is $4.5 \times 10^{17}\,\text{cm}^{-3}$. In the asymmetric pn diode, the hole concentration is changed to $1.0 \times 10^{17}\,\text{cm}^{-3}$, while the electron concentration remains unchanged. The electron mobility and hole mobility is 100 $\text{cm}^2/(\text{V s})$ and 7 $\text{cm}^2/(\text{V s})$, respectively. The material parameters utilized in this simulation are similar to previous reports.[16–18] Figures 3(a) and 3(b) show the carrier distribution in the symmetric and asymmetric pn diodes, respectively, for current densities ranging from 0.2 A/cm^2 to 40 A/cm^2. Using the electron distribution n, and hole distribution p, one can define the mean position of recombination $\bar{x}$ by the following formula:

$$\bar{x} = \int xnp\,\text{d}x \Big/ \int np\,\text{d}x. \quad (6)$$

Figures 3(c) and 3(d) show $\bar{x}$ versus current density in the symmetric and asymmetric AlGaInP pn junction, respectively. For current densities ranging from 0.2 A/cm^2 to 40 A/cm^2, $\Delta\bar{x}$ in the symmetric junction is 4.8 nm while in the asymmetric junction it is 20.5 nm. We attribute this large $\Delta\bar{x}$ to the leakage caused by the voltage drop in the lightly doped region.

We point out that the asymmetry of a pn junction made of III-V semiconductors can be exacerbated at low temperatures: acceptor ionization energies are generally higher than donor ionization energies. As a result, the freeze-out of holes is more severe than the freeze-out of electrons. Thus, the asymmetry, and thus the efficiency droop, is expected to increase at low temperatures. This expectation is consistent with the finding that the efficiency droop in AlGaInP is greater at cryogenic temperatures than at room temperature. In addition, we note that AlGaInP is not known to have strong composition fluctuations. This lack of strong compositional fluctuations is supported by the narrow emission lines that are found for this material system. Furthermore, AlGaInP LEDs are homo-epitaxially grown on GaAs substrates so that the dislocation density is negligibly small. Therefore, it is doubtful that the efficiency droop in AlGaInP

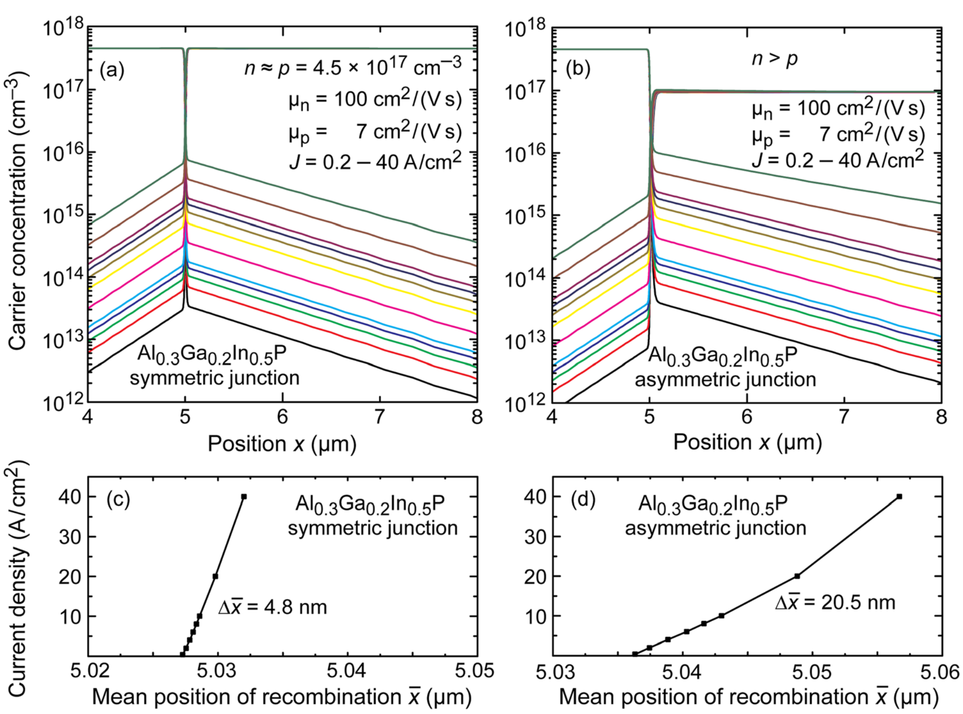

FIG. 3. (Color online) The carrier distribution in (a) the symmetric pn-junction diode and (b) the asymmetric pn-junction diode and the corresponding mean position of recombination for current densities ranging from 0.2 A/cm^2 to 40 A/cm^2 in (c) the symmetric pn-junction diode and (d) the asymmetric pn-junction diode.

LEDs could be attributed to a carrier-delocalization effect and enhanced recombination at dislocations, which was proposed for the GaInN materials system. In addition, spontaneous and piezo-electric polarization-field effects are along the growth direction absent in the AlGaInP/AlInP/GaAs material system. For this reason, polarization effects cannot be the primary cause of the efficiency droop in AlGaInP LEDs.

Furthermore, since the QWs in the AlGaInP LEDs are relatively thick, and the number of QWs is large, the carrier concentrations in the active region are relatively small and Auger recombination is not expected to be a major effect in AlGaInP LEDs. The absence of droop at room temperature and the presence of the droop at cryogenic temperatures suggest that the droop-causing mechanism becomes stronger at low temperatures. This temperature dependence is contrary to what is expected from Auger recombination. For these reasons, we rule out Auger recombination as a major factor in causing the efficiency droop in AlGaInP LEDs.

In conclusion, we report on the occurrence of the efficiency droop in LEDs of the AlGaInP/AlInP/GaAs material system. The LEDs emit at 630 nm and exhibit a strong efficiency droop at cryogenic temperatures. We attribute the efficiency droop to electron-drift-induced reduction in injection efficiency (i.e., electron leakage out of the active region) mediated by the asymmetry in carrier-transport properties of the pn junction. The asymmetry is exacerbated at low temperatures due to the stronger freeze-out of holes compared with electrons. We calculate the current-density onset of the efficiency droop and obtain agreement with the room-temperature onset in GaInN LEDs as well as the temperature dependence of the onset. We rule out material-composition fluctuations, defect-related mechanisms, as well as Auger recombination as the primary cause of the efficiency droop in AlGaInP LEDs.

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