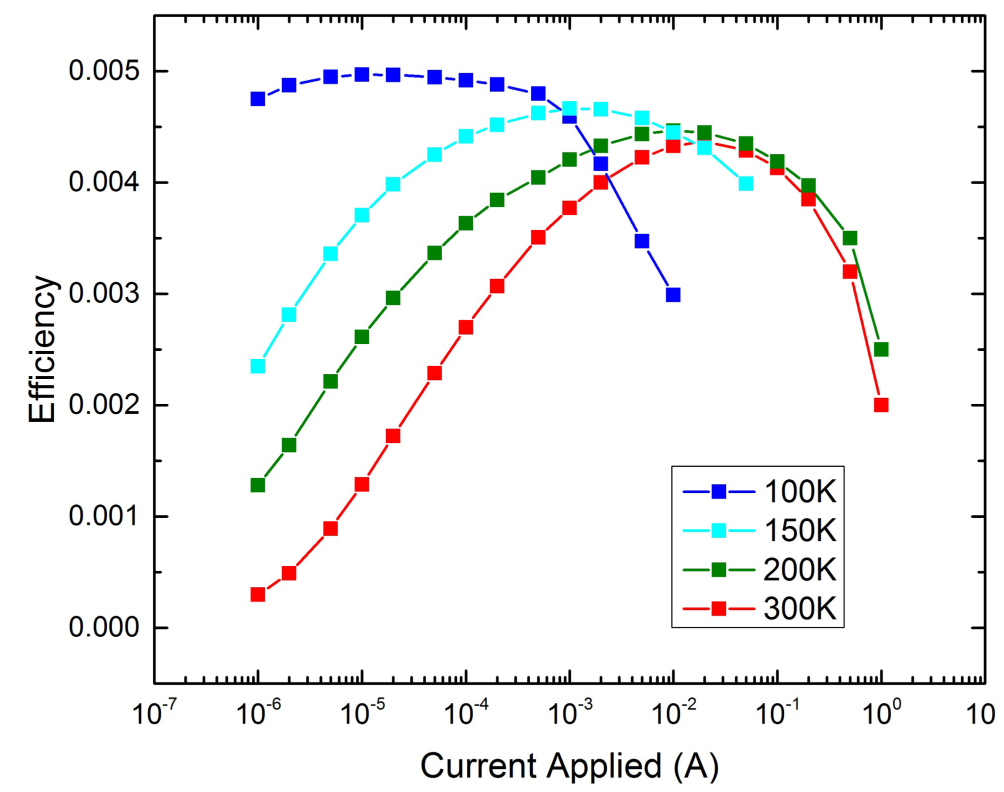
Imaging Laser-Excited Blue LEDs

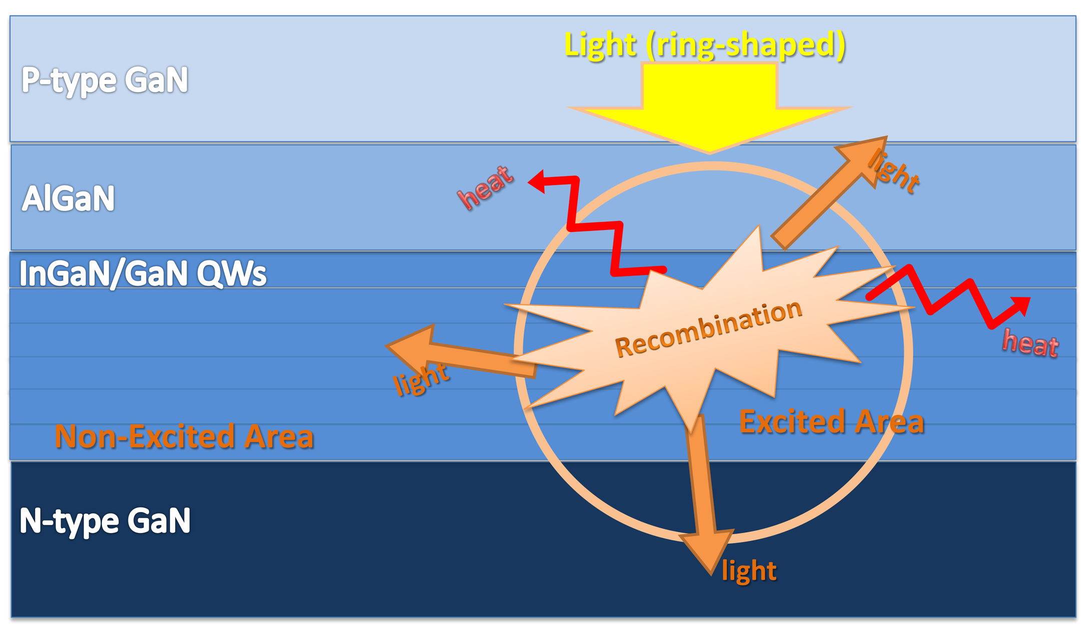
Ruiming Chen, Collin Epstein, and Tim Gfroerer *Davidson College, Davidson, NC*
Yong Zhang, *University of North Carolina at Charlotte, Charlotte, NC*
Zhiqiang Liu, *Institute of Semiconductors, Chinese Academy of Science, Beijing, CHINA*

Motivation: LED Droop



The efficiency of blue LEDs decreases with current after reaching a maximum value, a phenomenon commonly known as droop. At lower temperatures, the peak efficiency has higher values, and occurs at lower currents.

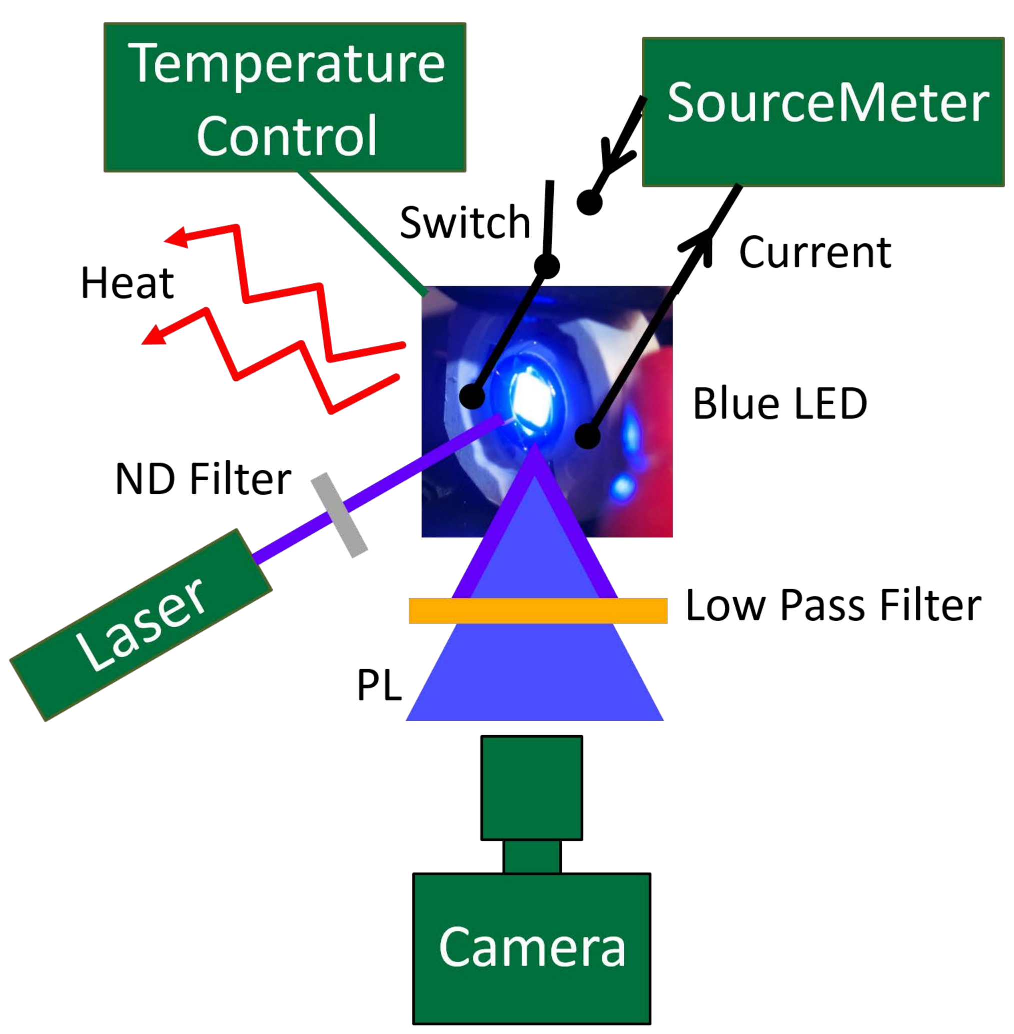
Efficiency



When the device is excited by light or electricity, An electron (negative charge) combines with a hole (positive charge) to produce either a photon (photoluminescence or electroluminescence) or heat. The radiative efficiency is the ratio of the light produced and the optical or electrical energy input.

$$radiative\ efficiency = \frac{light\ out}{excitation} = \frac{light\ out}{light\ out + heat}$$

Experiment

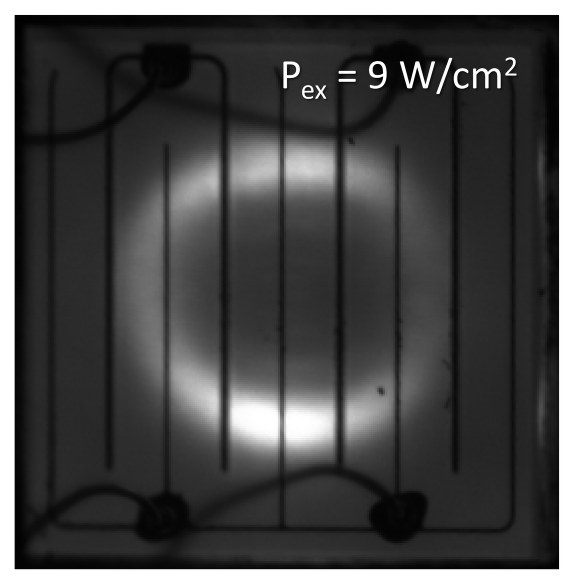


For photoluminescence measurements, the current switch is opened. For electroluminescence measurements, the switch is closed and the SourceMeter is used to simulate the photoluminescence experiment.

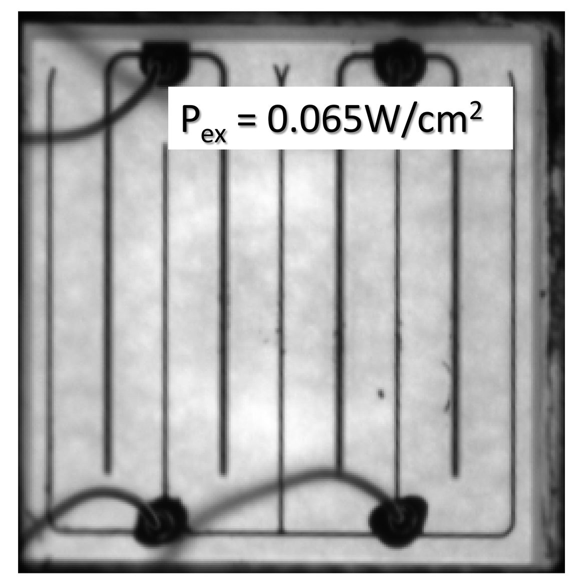
Abstract

Blue LEDs are known for their critical role in producing white light, since high-energy blue light is required to generate a spectrum of lower-energy light. In this experiment, we capture and analyze images of the optical emission from a blue LED under different temperatures and excitation conditions. Under non-uniform laser excitation, previous research has shown that light is emitted from areas without direct excitation (ELPE: Electro-Luminescence due to Photo-Excitation). Through further investigation, we discover that LED droop (reduced device efficiency at high excitation) is only present in the ELPE from the non-excited area. At lower excitation levels, our theoretical model shows that heat loss is faster and more detrimental in the laser-excited region. These results provide important clues to the internal mechanisms that impede the performance of blue LEDs.

Laser Excitation Images



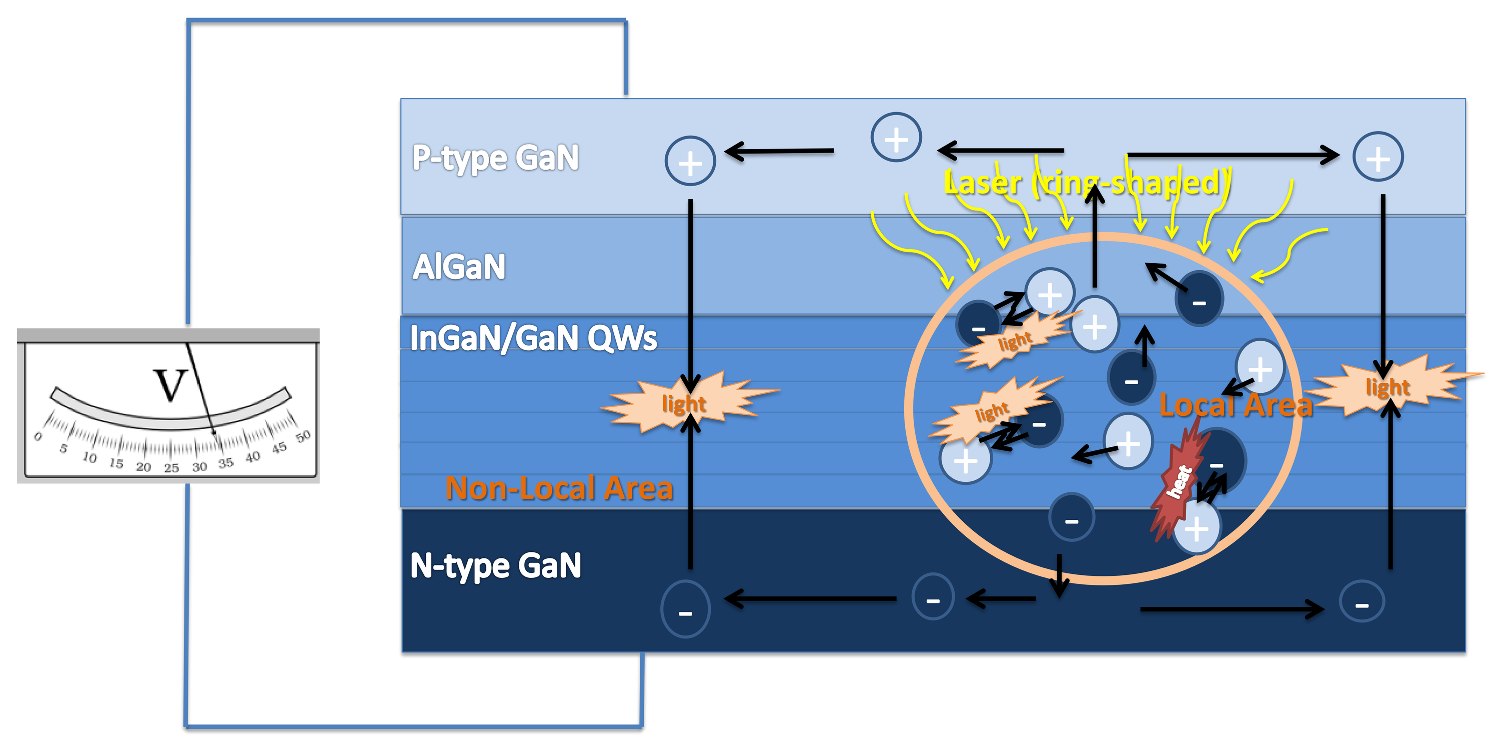
High Power, 100K



Low Power, 300K

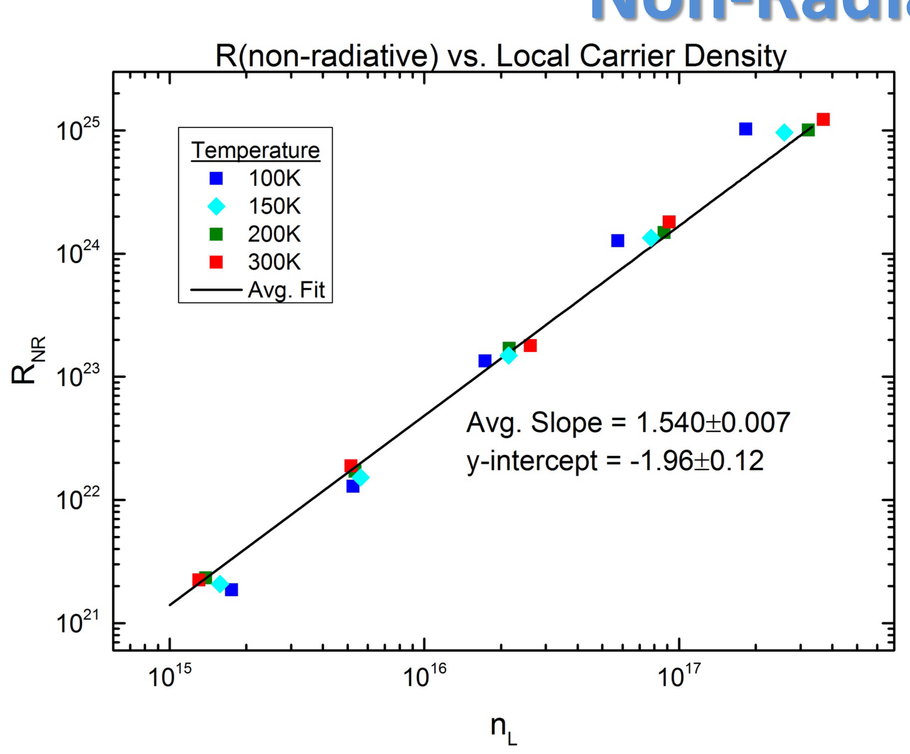
The ring-shaped region shows the laser excitation area of our 1 mm^2 device. Previous experiments have shown that a significant amount of light is emitted from outside of the excited area at higher temperatures and lower powers. We seek to explain and quantify this phenomenon.

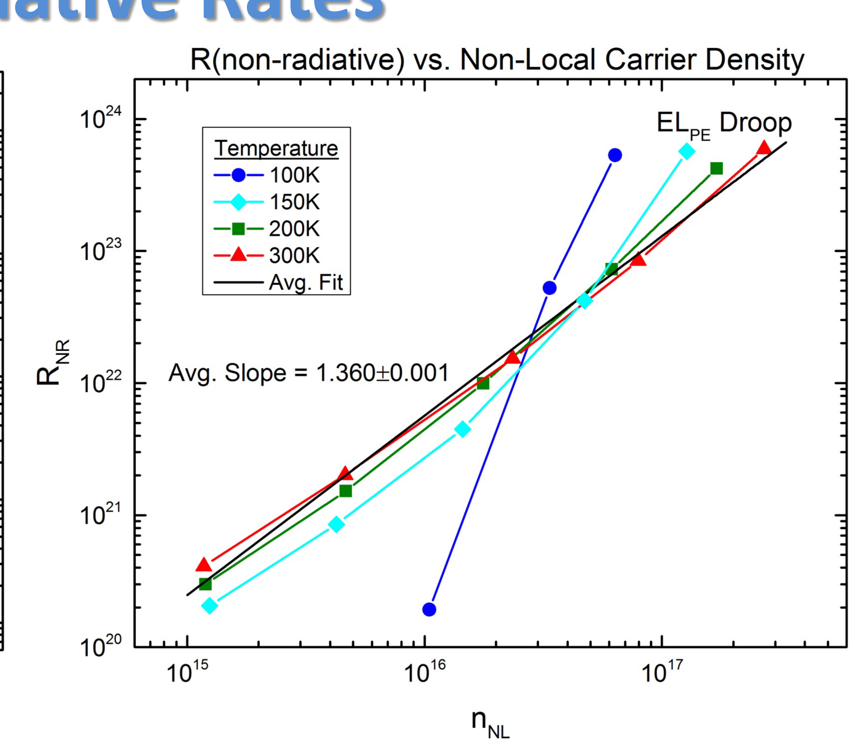
Device Model



This diagram shows the side view of our LED device. Light is produced through both photoluminescence (PL in the local area) and electroluminescence (EL_{PE} in the non-local area). The EL_{PE} results from electrons and holes that leave the excited region, diffuse within the N- and P-type GaN layers, and recombine in the nonlocal area.

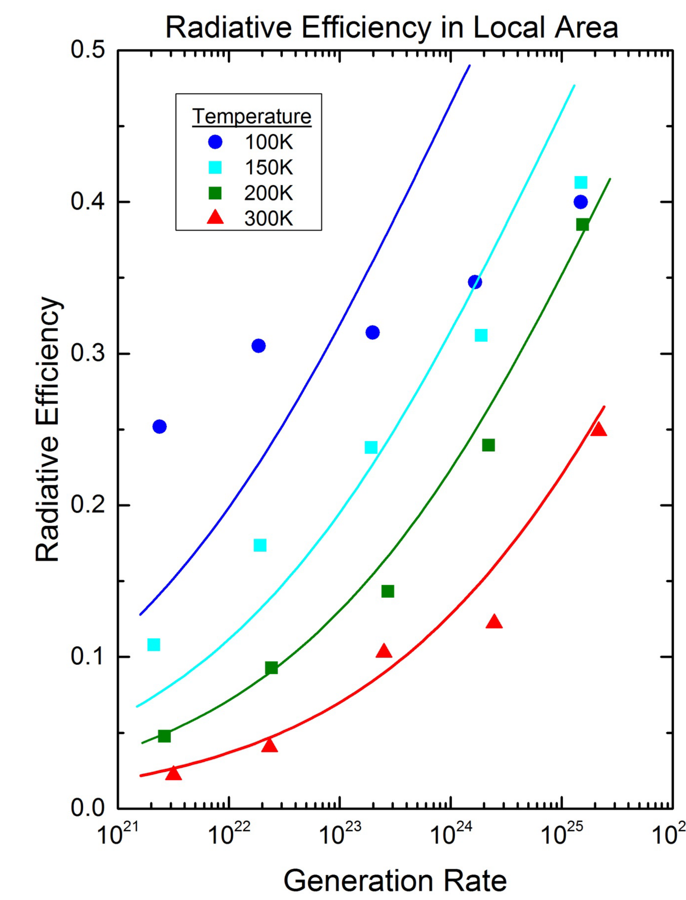
Non-Radiative Rates

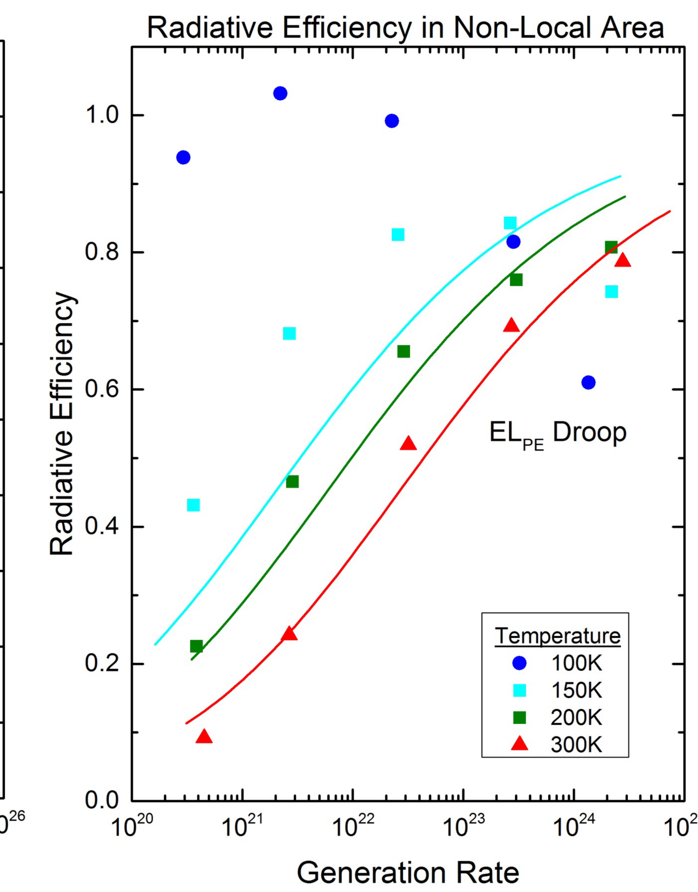




The linearity of the log-log plots shows the exponential relationship between non-radiative rates and charge densities. What's more, the non-local plot shows an increase of R_{NR} at higher densities, indicating that droop occurs in non-local area of photoluminescence. This loss increases with decreasing temperature.

Radiative Efficiency





Using the experimentally obtained non-radiative rates, we can calculate the radiative efficiency vs. generation rate. Above 200K, measured local and non-local efficiencies agree with this theoretical model. Under comparable conditions, the efficiency in excited area is much lower than the efficiency in the non-excited area. The efficiency in non-excited area experiences droop at higher generation rates, particularly at low temperature.

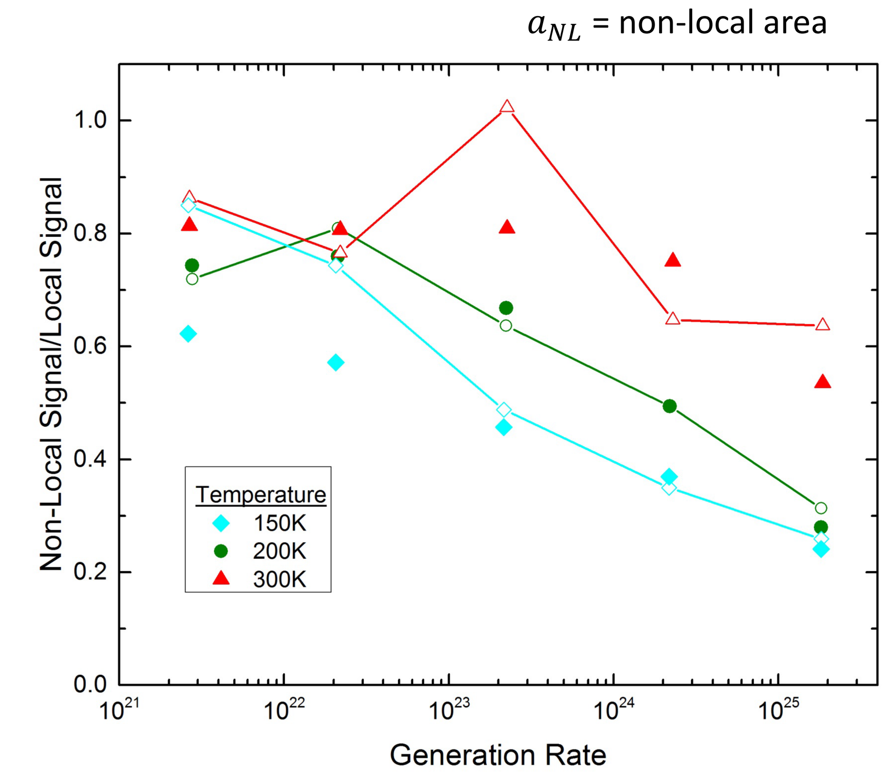
Model

The ratio of the optical emission from the local and nonlocal regions equals the ratio of the local and nonlocal radiative rates, which is proportional to the carrier density squared:

$$\eta = \frac{B{n_{NL}}^2}{G_{NL}} \rightarrow B(T){n_{NL}}^2 = \eta(\frac{I}{qV}) \qquad \text{Local Signal}$$

$$G_L = B(T){n_L}^2 + 10^{-1.96}{n_L}^{1.54} + \frac{I}{qV}(\frac{a_{NL}}{a_L + a_{NL}}) \qquad \text{Nonlocal Signal}$$

$B(T)$ = radiative recombination coefficient
n_{NL}= carrier density in non-local area
n_L= carrier density in local area
I/qV = current/(charge x Volume)
η = electroluminescence radiative efficiency
G_L= generation rate in local area
G_{NL}= generation rate in nonlocal area
a_L= local area
a_{NL} = non-local area



This graph shows both experimental and theoretical results for the ratio between non-local ($B{n_{NL}}^2$) and local ($B{n_L}^2$) signals. The model generally fits well, except at low temperature and high generation rate (EL_{PE} droop). The theoretical scatter is due to extreme sensitivity in current measurements.

Conclusions

1. Defect-related non-radiative recombination is often assumed to be linear with carrier density. We find non-radiative rates that increase super-linearly with density due to the nature of the defects.
2. Radiative efficiencies in the local area are lower than those in the non-local area, suggesting that there is greater heat loss in the local area, perhaps due to the directionality of charge motion.
3. Droop occurs in the non-excited regions, where EL_{PE} (Electroluminescence due to Photo-Excitation) happens. EL_{PE} droop has the same temperature dependence as EL caused by an electric current, indicating that the droop mechanism occurs within or between the P- and N-type layers of the device.

Acknowledgement

We would like to thank the Faculty Study and Research Committee and the Davidson College Department of Physics for support of our research. We acknowledge preliminary work by Ben Stroup '16 and Grace Watt '15.