Towards the Efficiency Limit of Visible Light-Emitting Diodes

by

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Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

In this thesis, a thermophotonic method based on the heat-pump mechanism is proposed to potentially enhance the efficiency of visible light-emitting diodes (LEDs) for high-power operation. By leveraging this special mode of solid-state lighting by incoherent electroluminescent radiation and with the focus on gallium-nitride (GaN) technologies, we experimentally demonstrate a thermally enhanced blue LED operating in the low bias regime, and theoretically investigate the characteristics and criteria for efficiency visible lighting based on a thermodynamic study.

Thesis Supervisor: Rajeev Ram
Title: Professor of Electrical Engineering
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Chapter 1

Background

In the US, a large fraction of electricity (18%) is consumed in lighting [17]. But thanks to the mass production and deployment of visible light emitting diodes (LEDs) in recent years, this burden is being reduced as their maximum achievable power conversion efficiency has surpassed all other forms of lighting after decades of research and development. While playing a primary role in high-tech displays and starting to penetrate into other market segments such as automotive lighting, bio-medical applications, residential lighting and outdoor illumination, etc., different types of visible LEDs are still under active development and their efficiencies are expected to improve further as the lifetime cost of energy consumption far exceeds the manufacturing cost of the devices [18]. For instance, intensive research into efficient white LEDs has recently produced a device with luminous efficacy of 249 lm/W [19], which is approaching the conventional limit imposed by the spectral requirements of general-purpose lighting and the electrical-to-optical power conversion efficiency limit of 100%. However, this conventional power conversion limit fails to consider the thermodynamic content associated with the photon emission [20]. The presence of entropy in the incoherent electromagnetic radiation of LEDs opens a possibility of providing ambient heat as an additional input to the device, which clearly implies an electrical-to-optical power conversion efficiency limit above unity [21].

As the central element of violet, blue, green and white light emitters, high-quality gallium nitride (GaN) based LEDs now have peak electrical-to-optical power con-
version efficiency in the 70% range at medium current densities. At higher current
densities (for higher output power), the efficiency diminishes due to several droop
phenomena [3], which will be discussed in detail later. As a balance among eco-
nomics, application needs and thermal management, these LEDs typically operate
at 50-60% efficiency instead. Apart from the inefficient consumption of electricity,
the additional thermal degradation problem associated with these high-power LEDs
also necessitates the use of costly and physically bulky heat sinks, which significantly
limited the flexibility and further deployment of these solid-state emitters.

With the focus on GaN technologies, in this thesis we aim to improve the electrical-
to-optical power conversion efficiency of visible LEDs for high-power operation, and
also would like to acquire a good understanding of their efficiency limit based on a
thermodynamic analysis. In §1.1, we briefly review some important physics of basic
LED operation, which is closely related to this work. In §1.2, LED quantum efficiency,
power conversion efficiency, their origins, connections and implications are introduced
in details. In §1.3, we first review some major work discussing the current state-of-the-
art technologies for efficient visible lighting based on the GaN material system, and
also important theoretical studies investigating the efficiency limit of these devices.
Then we state the goals and objectives being achieved by this thesis, as well as their
significance. At last, a short thesis outline is provided as a whole in §1.4.

1.1 Important LED Physics

An LED is a type of optoelectronic device whose key component - the LED die is
essentially a p-n junction diode with photon emission capability under forward-biased
operation. A schematic plot of electronic energy band structure for today’s typical
GaN based blue LED die is shown in Figure 1-1. According to the figure, this LED
die consists of two metal contacts and four layers of different semiconductor alloys
between them: p-type GaN, p-type aluminum gallium nitride (AlGaN), undoped
indium gallium nitride (InGaN) and n-doped GaN, respectively. Among them, the
InGaN material has a lower energy bandgap compared to that of GaN due to the
incorporation of indium and thus forms a quantum well (QW) structure to confine injected carriers, while the AlGaN electron blocking layer (EBL) to the left side of it has a higher bandgap to further improve the effectiveness of electronic confinement.

Under an external forward bias voltage $V$, charged carriers, including free electrons in the conduction band and free holes in the valence band, are electrically pumped into higher energy states and being injected into the InGaN QW primarily due to diffusion mechanism, where they undergo recombination and photon emission afterwards. This external bias also splits the initially aligned Fermi energy level $E_F$ across different layers into $E_{FP}$ in the p-type side and $E_{FN}$ in the n-type side, which implies an input of electrical excitation energy in the amount of $E_{FN} - E_{FP} = qV$ for each carrier. In contrast, electrons confined in the QW stay approximately at the energy level of conduction band edge $E_C$ and corresponding holes at the energy level of valence band edge $E_V$, resulting in a photon emission of energy around $E_C - E_V$. From the illustration in Figure 1-1, we can see the photon energy is higher than the electrical excitation energy. This is due to the absorption of lattice heat by carriers during
the injection process, which will be discussed in details later. In the low-injection (non-degenerate) case, the electron density $n$ and hole density $p$ in the active region can be expressed as:

$$n = N_C \exp\left(-\frac{E_c - E_{FN}}{k_B T}\right) \quad p = N_V \exp\left(-\frac{E_{FP} - E_V}{k_B T}\right) \quad (1.1)$$

where $N_C$ is the effective density of states at conduction band edge, $N_V$ is the effective density of states at valence band edge, $k_B$ is Boltzmann constant and $T$ is junction temperature. The Shockley equation (or diode equation) expressing the injection current density $J$ in terms of bias voltage $V$ can be further derived as,

$$J = q \left( \sqrt{\frac{D_p}{\tau_p} \frac{n_i^2}{N_D}} + \sqrt{\frac{D_n}{\tau_n} \frac{n_i^2}{N_A}} \right) \exp\left(\frac{qV}{n_{\text{ideal}} k_B T}\right) - 1 \quad (1.2)$$

where $q$ is electron charge, and $n_i$ is the intrinsic carrier density. $D_p$ and $D_n$ are the hole and electron diffusion constants, respectively. $\tau_p$ and $\tau_n$ are the hole and electron minority carrier lifetime, respectively. $N_A$ and $N_D$ are the acceptor concentration in p-side and donor concentration in n-side, respectively. $n_{\text{ideal}}$ is the ideality factor of the diode.

GaN and other nitride based III-V semiconductor alloys inherently have strong polarity. For those commercial heterostructure GaN LEDs grown on c-plane sapphire substrates, the conventional [0001] growth direction is right along the polarization direction and hence can result in a large discontinuity of polarization density at GaN/InGaN/GaN layer interfaces in the QW active region due to a mismatch of spontaneous polarization between these different alloys (relatively small) and strain induced piezoelectric polarization (relatively large). The polarization discontinuity then induces an internal electrical field $\varepsilon_{pz}$ across the QW region directing from p-side to n-side, since the p-side wall of QW has stationary net positive charge accumulated and n-side wall has the negative (direction mainly determined by the large piezoelectric polarization of InGaN QW layer), as shown in Figure 1-1. $\varepsilon_{pz}$ is anti-parallel but much larger than the built-in field $\varepsilon_{bi}$ of an LED junction. This strong net field causes
the band structure to tilt in the QW region, displaces the electron and hole wavefunctions to opposite sides of the well, and leads to a significant reduction of wavefunction overlap $|\langle F_c | F_v \rangle|^2$, where $F_c$ and $F_v$ are the envelope of the electron and hole wavefunctions, respectively. This exact magnitude of wavefunction overlap is dependent on the crystal orientation of LED growth. A few typical growth directions/planes are shown in Figure 1-2 (a), and the corresponding polarization discontinuity (assuming a coherently strained In$_{0.20}$Ga$_{0.80}$N layer on GaN) is shown in Figure 1-2 (b).

1.2 LED Efficiency

1.2.1 Carrier Recombination Schemes

Once free electrons and holes are injected into the LED active region, intensive recombination processes occur, which includes radiative recombination and non-radiative recombination, as depicted in Figure 1-1. Clearly, the normal functioning of LEDs relies on the former type of recombination scheme as it results in photon emission (i.e., producing light), while the latter type only release its energy as phonons to the crystal lattice (i.e., producing heat). There are several possible physical mechanisms of non-radiative recombination. As a major one of them, the Shockley-Read-Hall (SRH) recombination is a trap-assisted two-step process, in which a free electron from the conduction band falls into a trap site first, and then being recombined by a hole from the valence band (or vice versa), as shown in Figure 1-4 (a). The trap sites are usually introduced by crystal defects or dopant atoms, and have energy levels distributed deep in the bandgap. This mechanism can also be envisioned as an annihilation process completed by an electron-hole pair but only one carrier is involved at a time. The other major type of non-radiative recombination scheme is the Auger recombination. It is also a band-to-band transition process, but instead of releasing photons, the Auger recombination gives off its energy to another electron or hole and kicks it to a higher energy state. Thus it requires three carriers, as shown in Figure 1-4 (b).
Figure 1-2: Different growth direction and resultant polarization discontinuity: (a) illustration of typical orientations of GaN, including the conventional polar (c-plane) in blue, semipolar (2021) in purple, semipolar (2021) in green, and nonpolar (1010) m-plane in red; (b) total polarization discontinuity in the growth direction for a coherently strained In$_{0.20}$Ga$_{0.80}$N layer on GaN versus inclination angle from c-plane [1].
Figure 1-3: (a) Radiative recombination event of a free electron-hole pair results in photon emission. (b) Non-radiative recombination event results in phonon emission, and the energy transferred to crystal lattice [2].

Figure 1-4: (a) Shockley-Read-Hall recombination via deep trap states. (b) Three-particle Auger recombination. (c) Radiative recombination [2].
Light emission intensity from an LED is a result of competition among different recombination rates for a given injection current. Recombination rates of different types are then directly related to the carrier concentration in the LED active region, which can be described by a simple but widely used model (commonly known as "ABC" model). According to this model, if assuming both the electron and hole concentration in the active region are \( n \), then SRH recombination rate is \( An \), radiative recombination rate is \( Bn^2 \) and Auger recombination rate is \( Cn^3 \) as they are essentially one-, two- and three-carrier recombination processes, respectively, where \( A \) is SRH recombination coefficient, \( B \) is radiative recombination coefficient and \( C \) is Auger recombination coefficient. Since other non-radiative recombination mechanisms such as surface recombination are minimized, and leakage current escaping from the quantum well region is negligible for well-designed LED structures, the LED injection current density \( J \) can be expressed as:

\[
J = qt(An + Bn^2 + Cn^3)
\]  

(1.3)

where \( t \) is the thickness of LED active region. According to Equation 1.3, we also have,

\[
n^2 = N_e N_V \exp(-\frac{E_g}{k_BT}) \exp(\frac{qV}{k_BT}) = n^2_i \exp(\frac{qV}{k_BT})
\]  

(1.4)

Therefore, derived by the ABC model, an alternative relation between the injection current density \( J \) and LED bias voltage \( V \) is constructed as following,

\[
\frac{J}{qt} = An_i \exp(\frac{1}{2} \times \frac{qV}{k_BT}) + Bn^2_i \exp(1 \times \frac{qV}{k_BT}) + Cn^3_i \exp(\frac{3}{2} \times \frac{qV}{k_BT})
\]  

(1.5)

Each term on the right hand side has a different contribution to the LED current density arising from distinctive recombination mechanisms. Equation 1.5 also provides a method to obtain the experimental values of recombination coefficient \( A \), \( B \) and \( C \) only by measuring and fitting the \( J-V \) characteristics of the device. In the literature, these coefficients for GaN/InGaN layer in quasi-bulk or QW forms could be experimentally determined by different methods such as luminescent decay and re-
Table 1.1: Experimental values of the parameters in the ABC model

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<th>Authors</th>
<th>Substrate</th>
<th>(\lambda (nm))</th>
<th>(A (s^{-1}))</th>
<th>(B (cm^3s^{-1}))</th>
<th>(C (cm^6s^{-1}))</th>
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<td>Shen et al.</td>
<td>GaN</td>
<td>440</td>
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<td>(2.0 \times 10^{-30})</td>
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<td>Zhang et al.</td>
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<td>450</td>
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<td>Laubsch et al.</td>
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<td>(0.12 \times 10^{-11})</td>
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</table>

Combination lifetime analysis [22,23], device quantum efficiency vs. current injection measurement and ABC model direct fitting [24], large signal modulation measurements of turn-on delay by photo-excitation [25], or optical power and impedance measurement on packaged device [26]. All these methods have assumed the rate equation in the form of 1.3 and neglected the leakage current. Some of the experimental values of these parameters measured on devices grown on different substrates are listed in the Table 1.1.

From the coefficient values listed above, we can see that except those from Laubsch et al., all the others are in the same order of magnitude though the testing devices and testing methods are both different. The lower values of all recombination coefficients by Laubsch et al. is likely to be arise from the higher indium composition of QW layer, thus higher polarization discontinuity across the active region (due to c-plane growth), steeper band tilting and lower wavefunction overlap, which infers that the LED growth on non-polar or semi-polar directions may reduce the dependence of these recombination coefficients on the emission wavelength [12, 27]. As will be elaborated in the next section, the Auger recombination mechanism takes an important role in achieving high-efficient high-power LED operation. Therefore the variance of coefficient \(C\) (from \(\sim 10^{-31}\) to \(\sim 10^{-29}\)) from different GaN based LED structures was specifically studied and correlated to the quantum well properties such as electron-hole ratio, electric field, and hot carrier escape, etc [28].

### 1.2.2 External Quantum Efficiency and Wall-Plug Efficiency

The external quantum efficiency (EQE) is a key measure of an LED’s performance, which is defined as a ratio between emitted number of photons and total injected
number of carriers. In order to better understand the origin of EQE for LEDs (denoted as \( \eta_{EQ} \)), we break it down as following:

\[
\eta_{EQ} = \eta_{IQ} \times \eta_{ex} \times \eta_{inj}
\]

where \( \eta_{IQ} \) is the Internal Quantum Efficiency (IQE) of the LED, which specifically characterizes the probability of internal radiative recombination event. IQE can be simply expressed by the carrier concentration in LED active region through the ABC model introduced above:

\[
\eta_{IQ} = \frac{\text{# of carriers recombined radiatively}}{\text{total # of injected carriers}} = \frac{Bn^2}{An + Bn^2 + Cn^3}
\]

Therefore, we can see IQE is largely dependent on the actual design of LED structure and the material growth quality, which practically can vary from nearly zero to 90+\% \[15\]. \( \eta_{ex} \) is the light extraction efficiency, which is the ratio of photons finally escaping the LED to all photons radiated from the active region. For high-quality commercial GaN emitters it is typically near 80\%, while in laboratory condition the state-of-the-art extraction efficiency can be as high as 90\% \[29\]. The last term in Equation 1.6, \( \eta_{inj} \), is the electrical injection efficiency mainly counting the leakage current tunelling through the LED active region without undergoing recombination, which is usually taken as small and thus omitted from the EQE expression. As for the ohmic loss at metal contacts and the LED driver loss, they do not present in the expression of EQE.

In summary, with all factors properly optimized, EQE above 80\% has been achieved for a GaN based LED under certain operating condition and is expected to improve further \[15\].

On the other hand, the electrical-to-optical power conversion efficiency is an even more commonly seen and intuitive metric for the performance of all commercial lamps. For optoelectronic devices such as LEDs and lasers, it is also technically termed as wall-plug efficiency (WPE). If we look into each successfully emitted photon with
energy $\hbar\omega$, it actually comes from a pair of carriers excited by the external electrical work only in the amount of $qV$ before the radiative recombination event. Thus the energy conversion efficiency for such a single event is $\frac{\hbar\omega}{qV}$. Then the ensemble WPE, denoted as $\eta_{wp}$, for an LED (as a whole) includes the additional factor $\eta_{EQ}$ describing the photon emission probability.

$$\eta_{wp} = \eta_{EQ} \times \frac{\hbar\omega}{qV} \quad (1.8)$$

The above equation directly connects EQE and WPE for an LED at a given condition. Since the mean photon energy emitted from a specific device is almost constant, the WPE should be primarily determined by the bias voltage and the corresponding EQE in that condition.

For most visible lighting applications including residential lighting and flat-panel displays, high WPE is only meaningful at a designated brightness level. For LEDs it is typically high-power operation driven by a current density in the range of $5 \sim 35 A/cm^2$. In general, high output power for InGaN heterostructure LEDs just requires high current injection, i.e., high forward bias $qV \geq \hbar\omega$. However, the WPE of these devices usually has the maximum at a relatively low or medium current density (i.e., low bias), and decreases gradually for higher injections (i.e., higher bias). This is partially because of the reduction of energy conversion efficiency for single radiative recombination events, according to the second term in Equation 1.8, but the apparent drop of $\eta_{EQ}$ (to be more accurate, it should be $\eta_{IQ}$) has the major responsibility. This phenomenon, which is commonly referred to as efficiency droop at high current density (or current droop) [3], as shown in Figure 1-5, severely limits the further improvement of efficient lighting at high output power. In recent years, although this phenomenon is widely recognized and studied, its dominant mechanism, possibly due to or including Auger recombination, electron leakage, density activated defect recombination, etc., remains highly controversial [3,11,13,30,33].

In addition, like most semiconductor electronics, GaN based LEDs suffer from thermal degradation, i.e., the IQE of the device reduces at elevated temperatures.
This is also known as thermal droop \[4,34,36\], as illustrated in Figure 1-6, which is primarily due to reduced SRH lifetime at higher temperature, as it is approximately inversely proportional to the minority carrier thermal velocity \[2,37\]. Now assuming the following case: the inefficient high-power operation of GaN based LEDs (arising from the current droop problem) inevitably produces excessive heat to the device junction, leading to temperature rise. The over-heating of LED further reduces its IQE and thus output power by the thermal droop. In order to maintain the output power of LED, driving current density has to be increased and hence the IQE would drop further. This vicious cycle in high-power high-efficient visible lighting necessitates the use of physically bulky heat sinks for today’s commercial products, which severely hampered the further deployment of III-nitride high power LEDs and could impose additional manufacturing cost. The cost breakdown for a typically packaged high-power white LED without any thermal management is shown in Figure 1-7 (a) \[5\]. This data is for year 2015 and has assumed a device in mass production constituting of a 1mm\(^2\) die on a 100mm diameter sapphire substrate and being
packaged in ceramic with phosphors to produce warm white light. A different cost breakdown chart for similar LED packages but including external mechanical and thermal components (e.g., the heat sink) is shown in Figure 1-7 (b) [5]. This chart also indicates the difference for different intended high-power applications. We can see that in all high-power applications, a significant cost to prevent/mitigate the thermal droop effect of high-power visible LEDs is inevitable. For the case of outdoor lamps and residential down-lights, the heat sink even costs more than the LED die itself.

1.2.3 LED as Heat Pump

Since GaN based LEDs usually have low turn-on voltages compared to their wide bandgaps [2], photon energy $\hbar \omega$ greater than electrical input energy per electron $qV$ is commonly observed. Actually, this phenomenon is first reported in a SiC emitter [38], and readily accessible in all kinds of LEDs [39, 40]. In such an operating
(a) Cost breakdown for a typically packaged high-power white LED without heat sink.

(b) Cost breakdown for a typically packaged high-power white LED with heat sink.

Figure 1-7: Cost breakdown of a packaged white LED in mass productions

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regime \( qV < h\omega \), thermal excitation due to Peltier effect becomes necessary for a considerable amount of carrier injection. In other words, the LED works in a mode similar to a thermodynamic heat engine operating with charged carriers pumped into the active region by a combination of electrical work and Peltier heat (phonons) drawn from the lattice [41], as depicted in Figure 1-8. The absorption of Peltier heat near the junction can be better understood from the perspective of statistical mechanics: only carriers at the high energy tail of the Boltzmann distribution can be thermionically emitted against the diodes built-in potential barrier into the active region, with the remaining carriers absorbing heat from lattice (i.e. electron-phonon scattering) to restore the quasi-equilibrium distribution. In this manner, the thermo-electric pumping mechanism introduces an additional pathway of input energy other than the electrical work, thus improves the WPE of LEDs at the low bias regime. Also note that, if lattice temperature increases, carrier temperature also increases and thus the corresponding distribution profile moves towards higher energy. In this case the thermionic emission can happen more easily and the Peltier effect is more conspicuous.

In the low-bias heat-pumping regime as described above, it is not surprising to find out that the WPE of an LED can be actually greater than 100% if the device EQE is high enough, according to Equation 1.8. In this case, net heat is drawn from the LED lattice for electron thermal excitation, and then released to the ambient after being efficiently converted to photons, which produces a net cooling effect on the solid at the same time. This phenomenon, commonly known as electroluminescent cooling (ELC) by LEDs, has been studied since 1957, when a body of literature starts to theoretically establish the thermodynamic consistency of ELC and exploring its limits [16,21,42–57].

Despite the early recognition of the possibility of ELC in the neighbouring field of laser cooling of solids and its remarkable experimental progress [58–61], it is only recently that ELC by LEDs begins to gain wider visibility. Researchers had not reported a measurement of ELC from LEDs until 2012 when Santhanam et al. demonstrated a heated infrared GaInAsSb/GaSb LED with WPE over 200% at 135°C, using lock-in
Figure 1-8: (a) A thermophotonic LED converts both electricity ($W$) and heat ($Q_C$) to light ($L$). (b) A block diagram showing the heat pump model for such an LED. $T_{\text{cold}}$ and $T_{\text{hot}}$ represents the temperature for the cold and hot reservoir, respectively, and $Q_H = L$. (c) An illustration of energy band diagram for the heat-pumping operation of such an LED. In this figure, lattice phonons are shown in small wavy arrows, and emitted photons are shown in large wavy arrows. Applied external bias $V$ is smaller than the bandgap energy of active region in the condition drawn [6].
measurement tools \[62\]. Afterwards, a further demonstration at room temperature by another mid-infrared LED was reported in 2013 \[63\]. These ultra-efficient LEDs were all driven by extremely low bias \(V < k_B T/q\), and the output power densities were on the order of 100 \(nW/cm^2\). Although the net cooling power and light output power are still low at the bias level demonstrated due to low device IQE, ELC has been finally proved possible for LEDs based on the heat pump mechanism.

More recently, evidence of thermophotonic operation have been observed for visible LEDs at useful output powers \[64\], including the case in Ref \[15\] even when the LED operates at over 100 \(W/cm^2\). However, to realize true ELC in the regime of \(k_B T \ll qV < \bar{h}\omega\) for GaN based visible LEDs, the realization of a higher device EQE (close to unity) is a necessary condition. As for practically useful high-power ELC, other properties such as low thermal droop as well as low current droop are further required.

1.3 Previous Work and Thesis Objectives

1.3.1 LED Characterization

Standard & Non-standard Method

Using an integrating sphere as an experimental platform for LED characterization has been considered as the most convenient and accurate method to determine various optical properties of the specimens, particularly for the radiant power (or luminous flux) measurement. As shown in Figure 1-9, a typical commercial integrating sphere has a hollow spherical cavity with its inner surface coated with white diffuse reflecting material (e.g., barium sulfate \(\text{BaSO}_4\)). The test light source is either fixed at the sample holder on the central stage of the sphere for room temperature measurements, or on a side port of the inner wall, where a heater is installed to control the operating temperature of the specimen thus enables high temperature measurements. There are also small openings on the sphere wall for the entrance and exits of light beams if necessary. During the measurement, all radiations emitted by the specimen will be
trapped inside the sphere and undergoes Lambertian reflection on the inner surface, so that the interior light intensity is uniformly distributed after multiple reflecting events. In this manner, a complete mixing of the radiation could be achieved (theoretically) independent of the radiation pattern of the light source. To conduct optical measurements, a detector is mounted to the inner sphere wall, and the collected optical power $P_{\text{ind}}$ (also called induced irradiance) has a relation with the total radiation power of the specimen $P_{\text{LED}}$, as shown below,

$$P_{\text{ind}} = \frac{P_{\text{LED}}}{4\pi R^2} \cdot \frac{\rho}{1 - \rho} = \frac{P_{\text{LED}}}{4\pi R^2} M(\rho)$$  \hspace{1cm} (1.9)

where $R$ is the inner radius of the integrating sphere, $\rho$ is the inner surface reflectance and $M(\rho)$ is the sphere factor which specifies how much the throughput of the integrating sphere varies as a function of the coating reflectance. Equation 1.9 clearly indicates that the measured radiation power $P_{\text{ind}}$ is independent on the position of the detector, but only on the size of the sphere and the coating properties. With this equation, $P_{\text{LED}}$ can be determined by $P_{\text{ind}}$ with an integrating sphere of known parameters. Note that the reflectance $\rho$ not only has a conspicuous influence on the measurement throughput of an integrating sphere, but is also a key factor determining its measurement accuracy. High reflectance is usually helpful to achieve optimal mixing of the light, thus increases the accuracy. But it also can be sensitive to coating aging or dirt induced non-uniformity at the same time.

Knowing the working mechanisms and measurement principles (e.g., multiple Lambertian reflections) of the integrating sphere, it is comprehensible that the detector mounted on the inner wall must be protected against any direct irradiation of the test sample, typically by a baffle, for a better measurement accuracy, as shown in Figure 1-10. In addition, the test sample itself may contribute to the light absorption in the integrating sphere, thus cause an attenuation to the measurement result dependent on its own physical properties such as size and color. A correction can therefore be made with the assistance of an auxiliary light source, which is also protected by a baffle to avoid direct illumination to the sample/detector (also shown in the figure).
A halogen lamp of wide spectral range is typically used for this purpose. During measurements, the spectral absorption of the test sample is always determined first by the auxiliary light source, and then offsets with the detector reading to obtain actual measurement results. Furthermore, the measurement quality can also be affected by the relative size of the integrating sphere and the test sample. In order to keep the interference of the specimen itself as low as possible, a large sphere (compared to the sample size) is desirable. However, the measurement throughput and sensitivity reduce at the same time. As a guideline, the total surface of the test sample should be smaller than 2% of the surface of the sphere [7].

As introduced above, the integrating sphere is a standard and mature instrument for LED characterization. Nevertheless, its application is limited in some special cases. For instance, unconventional test samples may not be compatibly mounted on the standard sample holder of a commercial integrating sphere, or the test temperature is beyond its capability of measurement (for commercial products, the service temperature is typically below 150°C). In this case, the direct employment of such a
standard instrument is no longer feasible, and an experimental platform specifically tailored for the non-standard specimens and also meeting the requirements of study objectives need to be carefully designed and constructed by our own. For an example, following we briefly introduce a high temperature LED characterization platform built by Santhanam for his study of the heat-pump phenomenon on an infra-red LED sample [8].

A schematic plot of the experimental setup illustrating its basic structure is shown in Figure [1-11] (a). An actual setup image is shown in Figure [1-11] (b). The infra-red LED sample under test is shown in the inset. From the figure, we can see that the LED specimen is inserted in a hollow copper rod and face to a light collection system comprising a lens and a photodetector. The copper rod also serves as a temperature control unit by which the specimen can be heated with a resistive heater and the temperature can be monitored by a thermocouple or thermister. The basic function of this LED characterization setup is similar to a commercial integrating sphere, but it is clear that the latter is not directly applicable here as the specimen (commer-
Figure 1-11: (a) Schematic plot of the high temperature LED characterization platform; (b) An actual setup image with all key components labeled. Inset in its bottom right corner shows the packaged test device [8].
cially available, not fabricated by the author) is neither un-packaged nor comes with a compatible adapter to the sample holder of an integrating sphere. Instead, the LED die has a metal package and two wire connected terminals. It is possible to modify it for integrating sphere measurement, but with the risk of being damaged. In addition to the advantage in sample adaptation, compare with the employment of integrating sphere, such an LED characterization platform can be more flexible in temperature control. Although the service temperature of this specific setup is also within to 150°C which is mainly due to the limitation of its mechanical support, this can be solved by replacing a few components (greater detailed will be explored in Chapter 2). However, with this setup, the light collection efficiency and the measurement accuracy might deteriorate, since not all light radiated by the specimen can be captured by the focusing lens and collimated to the photodetector. Even if the design of the light collection system is optimized (i.e., efficiency close to 100%) considering the radiation pattern of the specimen, other measurement errors, such as the light reflection and absorption by the lens, or interfering ambient light can still be inevitably introduced, which may cause significant deviations to the test results, particularly in low light conditions. Therefore, a calibration of the light collection efficiency is typically necessary for a self-built experimental setups to achieve a greater measurement accuracy. Again, an integrating sphere could serve this purpose, which will be discussed further in the subsequent chapter.

Thesis Objectives on LED Characterization

In the present thesis work, experimental investigations pertinent to high temperature LED characterization will be conducted. However, the standard method with the employment of commercial integrating spheres is not feasible in our case due to the limitation of their maximum service temperature and the difficulty in sample probing, which are basic requirements of our study and will be elaborated in the later part of the thesis. Therefore, in order to facilitate the implementation of our experimental studies and ensure the measurement accuracy, we constructed and calibrated our own setup for our unique samples. With continuous optimization in the design and two-
generation developments from the initial setup, the final upgraded version of our high temperature LED characterization platform meets all the requirements of the study objectives, and has proven to be efficient and robust in the subsequent tests.

1.3.2 Towards Higher Efficiency

Literature Review: Increase $\eta_{IQ}$

Since high-brightness GaN based blue LEDs were commercialized in 1993 \cite{65}, their promising properties and wide applications have attracted considerable interest to continuously improve their efficiency as well as maximum output power for the past two decades \cite{66}. Being interpreted as the probability of internal radiative recombination, $\eta_{IQ}$ has always been the central parameter to manipulate in almost all studies attempting to improve LED efficiency. Among all the factors affecting $\eta_{IQ}$, reducing defect-activated SRH recombination rate, or namely, reducing coefficient $A$ in Equation 1.7, is considered as the most fundamental and straightforward way to improve LED efficiency in all conditions \cite{67}. Particularly, for GaN based LEDs, this can be achieved by adopting high-quality bulk GaN substrate for LED growth instead of the traditional sapphire or SiC substrate, since the bulk GaN substrate has fundamentally lower threading dislocation density (TDD, the main source of defect density, in the order of $10^{5} \text{cm}^2$ for the bulk GaN substrate) than that of sapphire or SiC substrate (in the order of $10^{8} \text{cm}^2$ for high-quality sapphire) \cite{9,67,70}. Detailed comparisons of physical properties for GaN LED growth on different substrates were substantially investigated, and a brief summary is provided in Figure 1-12 \cite{9}. Besides the dramatic change of TDD brought by different substrates, impurity incorporation during LED fabrication could also make a difference on the SRH recombination coefficient, thus affecting device IQE. In fact, though the level of impurity incorporation can be strongly dependent on the growth direction/methods for the case of using bulk GaN substrates, no evidence is found that it could be directly correlated to the type of substrates used (native or foreign) \cite{67,71,72}. In one case of study on power device fabrication, Hashimoto et. al showed that GaN epitaxial growth on low-TDD GaN
Figure 1-12: Comparison of substrate, epitaxy, and operational characteristics of LEDs based on foreign substrates and native bulk GaN substrate [9].

substrate actually introduced lower level of impurities compared to sapphire, as indicated in Figure 1-13 [10]. Leveraging on the advanced bulk GaN growth technology, Soraa has already commercialized their high-power high-efficiency blue and white emitters [73].

Another straightforward method to improve $\eta_{IQ}$ is to directly increase the radiative coefficient $B$ while keeping non-radiative coefficients $B$ and $C$ unchanged or increasing less, according to Equation 1.7. Since most of the conventional GaN based LEDs are grown along the polar $c$-plane (0001) with sapphire or SiC substrate, this can be achieved by engineering the strength of polarization field in the active region to increase the wavefunction overlap $|\langle F_c | F_v \rangle|^2$, thus make electrons and holes to recombine faster and more efficiently. For instance, growing LEDs in semi-polar direction [2021] can reduce $\varepsilon_{pz}$ and make it partially cancel with $\varepsilon_{bi}$. In this case, the wavefunction overlap is greatly enhanced in the flat QW region and hence the radiative recombination rate is high (large $B$ coefficient), so as $\eta_{IQ}$. Although coefficients
Figure 1-13: Depth profiles (by secondary ion mass spectrometry) in the layers of (a) on GaN substrate and (b) on sapphire substrate [10].

$A$ and $C$ are increased in this manner as well, IQE (or EQE) can still be improved remarkably when Auger recombination is not dominant ($A$ is considered small in the case due to the growth on low-defect-density bulk GaN substrate introduced above).

In Figure 1-14, EQE for the above two cases (polar and semi-polar) are simulated and compared in different injection conditions. In Figure 1-15, LED band structure in more growth directions are simulated and compared. In fact, reduced total polarization field in the LED active region not only increases the device IQE in an overall manner, but also helps mitigate the current droop effect at high injection, which can be observed in Figure 1-14 and will be elaborated later in the next section.

**Literature Review: Mitigate the Current Droop Effect**

Currently the biggest issue hindering the further progress of high-power high-efficient visible lighting is the high-current-density induced efficiency droop effect (current
Figure 1-14: Simulated EQE curves for a 3 nm single QW LED are shown for the case of [0001] growth direction (polar, blue) and [2021] growth direction (semi-polar, green). [1].

droop). Although the dominant mechanism of this current droop, possibly originated from Auger recombination or electron leakage, remains highly controversial in recent years, methods to mitigate the effect have been proposed.

Before remedies are introduced, let us first take a step further from Equation 1.7 by including other non-idealities to the expression of IQE for a better understanding of all the mechanisms leading to the current droop effect [11]:

$$\eta_{IQ} = \frac{Bn^2}{An + Bn^2 + Cn^3 + k(n - n_0)^m + \frac{I_{LK}}{qV_{QW}}}$$

(1.10)

where $I_{LK}$ represents the electron leakage current (through QW without recombination) and $V_{QW}$ indicates the actual volume of LED active region. Other than the SRH (term $An$) and Auger (term $Cn^3$) recombination, $k(n - n_0)^m$ accounts for another non-radiative loss mechanism associated with carrier delocalization, which is a density-activated defect recombination process (activated at high injection) [74, 76]. $n_0$ is the corresponding threshold of carrier density and $m$ is a fitting constant with
Figure 1-15: Simulated energy band diagrams of 3 nm single QW LED with GaN barriers at a current density of 100 A/cm² for (a) polar c-plane, (b) semipolar (20\text{21}) plane, (c) semipolar (20\text{21}), and (d) nonpolar (10\text{10}) plane are plotted, assume $N_D = 10^{18} \text{cm}^{-3}$ and $N_A = 10^{19} \text{cm}^{-3}$. The directions of the piezoelectric field and p-n junction built-in field, as well as the envelope of ground-state electron and hole wavefunction $F_c$ and $F_v$ are indicated [1].
Figure 1-16: Carrier recombination schemes revealing the mechanisms of current droop effect in a single-QW GaN based LED [11].

its value typically greater or equal to two. This expression is also illustrated in Figure 1-16.

Auger recombination is arguably the most dominant (also most intuitive) loss mechanism responsible for current droop [33], as it has the strongest dependence of carrier density in the active region, according to the $Cn^3$ term in Equation 1.10. Although the magnitude of coefficient $C$ (in the order of $10^{-30}$ or lower) is typically much smaller than those of $A$ (in the order of $10^7$) and $B$ (in the order of $10^{-11}$) [11], high local carrier density $n$ still makes Auger recombination the major contributor in strong droop effect. In most cases, high local carrier density is not simply a direct result from high current injection, but actually the consequence of non-uniform carrier distribution in LED active region, which can be caused by short QW width, improperly designed multiple-QW (MQW) structure (electrons and holes are stuck in different QWs) [77], strong polarization field induced wavefunction separation (so electrons and holes tend to accumulate at the two ends of the QW, as shown in Figure 1-17) [12, 27], or lateral current crowding [78]. Therefore, in these particular cases, the remedy of current droop is to reduce the local carrier density, i.e., increasing the QW length [79, 82], increasing the number of QWs [83], refining/optimizing the
Figure 1-17: Illustration of increased carrier density due to polarization field induced large wavefunction separation [12].

MQW structure [84, 85], utilizing non-polar or semi-polar planes for LED growth [1, 36, 70, 86], improving the lateral current uniformity [87], or directly up-sizing the lateral dimension of the chip [4]. Another newly developed approach is to grow nano-column structure in the non-polar direction for an increased active region volume at a given substrate area and an enhanced wavefunction overlap, thus to reduce local carrier density at high injection [88].

Electron current leakage is also argued and supported by a lot of experimental evidence as one of the origins of current droop effect [3, 11]. Similar to the cause of intensive Auger recombination, this leakage can be also enabled by the polarization fields in MQW and EBL regions [13], the asymmetry in carrier concentration and mobility [31], and the current crowding [87]. Other possibility such as defect related tunneling mechanism is also considered [89]. As believed to be the primary contributor of electron leakage, a comparison of the droop effect with or without polarization matching structure is shown in Figure 1-18. Solutions to mitigate the leakage has been focused on the improvement of electron confinement, including the adoption of non-polar/semi-polar plane for LED growth [36, 70, 86, 90], engineering the quantum barrier for polarization matching [91, 97], optimizing the alloy composition of EBL...
structure [98][100], improving the design of active region by adding additional layers [14][101][102], enhancing lateral current spreading [87], exploring N-polar growth [103], etc. To achieve improved electron confinement by adding additional layers in the active region, for example, a staircase structure can be used, as shown in Figure 1-19.

From the previous studies and debates mentioned above, we found that the growth direction of LED dies always makes a difference and basically affects the maximum achievable efficiency and efficiency droop in all means. In a summary, the conventional c-plane devices suffer from a shrinkage of effective active region volume over which carriers are actually distributed (such as the low potential corner of InGaN QWs) due to large polarization related electric fields, nonuniform carrier injection, and potential fluctuations, etc., thus high carrier density are presented non-uniformly in the active region and maintained during high-power operation. It exacerbates the effects of Auger recombination and carrier overflow leakage, leading to a more serious droop effect. For semi-polar LEDs, polarization-related electric fields are significantly reduced, thus a single thick QW can be adopted without the problem of effective active region shrinkage, resulting in an increased wavefunction overlap, reduced potential fluctuations and lowered carrier density. It reduces the effects of Auger recombination and carrier overflow leakage. Efficiency droop could still present but is much reduced. Note that the non-polar m-plane growth could have also been used for a similar purpose, but problems were found associated to the indium incorporation of QW, which could dramatically reduce the device efficiency when the emission wavelength is longer than 400nm [9][104].

**Thesis Objectives on Improving LED Efficiency**

Researchers have been actively investigating the origins and remedies for the current droop problem of GaN based high-power LEDs for years. However, other than the passive cooling, a specific solution to the temperature induced efficiency droop (thermal droop) was not reported. In the present thesis, we investigate the possibility of thermoelectric pumping in wide-bandgap GaN based LEDs to take advantage of high junction temperature rather than avoiding the problem of thermal droop through
(a) Energy band diagram of a reference GaInN/GaN LED (polar) as well as GaInN/AlGaN LED with polarization-matched MQW structure under a forward bias condition.

(b) IQE and leakage current ratio of GaInN/GaN and GaInN/AlGaN LEDs with and without polarization effect in the MQW and/or the EBL.

Figure 1-18: Comparison of the droop effect due to electron leakage with/without polarization matching structure [13].
Figure 1-19: Calculated overflow electron current/total electron current as a function of applied forward voltage across a 6 nm thick In_{0.20}Ga_{0.80}N active region for the LED without a staircase structure, and the other LED with a one-layer In_{0.10}Ga_{0.90}N staircase structure. EBL is not included in both cases. The inset shows the band diagrams for the LEDs with and without the staircase structure [14].

external cooling. We experimentally demonstrate a thermally enhanced 450 nm high power GaN emitter, in which a nearly fourfold enhancement in light output power is achieved at 615 K (compared to 295 K room temperature operation), with virtually no reduction in the wall-plug efficiency. In this optimal operating regime at 615 K, the LED injection current (3.26 A/cm²) is of similar magnitude to the operating point of common high power GaN based LEDs (5 ∼ 35 A/cm²) [64]. This result suggests the possibility of removing the bulky heat sinks in current commercial high power LED products, thus realizing significant cost reduction and improved design flexibility. In addition, this demonstration also indicates that in order for an blue emitter to realize an effective thermal enhancement of the performance at the proposed operating regime, the maintenance of a relatively high device IQE is a necessary condition, which in turn requires it to have the properties of low thermal-induced droop as well as low current-induced droop.
1.3.3 Theoretical Study on the Efficiency Limit

Literature Review

The efficiency of today’s visible LEDs is approaching the conventional limit of unity, which inevitably opens the question about its potential of further enhancement. This is however addressed by a heat-pump argument of LEDs, which shows room left for WPE improvement.

The ELC phenomenon of LED resulted from the heat-pump mechanism has been investigated for over 50 years. In 1957, Tauc pointed out that radiation process in p-n junctions could take thermal energy from the surroundings [42]. After Tauc’s work, a series of papers theoretically investigated ELC associated with LEDs and put thermodynamic limitations on the conversion efficiency from heat into light [16, 21, 43, 46, 52]. Similar to the etendue conservation of optical systems and Shockley-Queisser limit of photovoltaic cells [105, 106], these theoretical studies mainly focused on thermodynamic and statistical analysis.

Planck first calculated the entropy content of an ideal Bose gas (e.g., photon field) in thermal equilibrium, and introduced the temperature definition of quantum resonators occupied by bosons at more than a century ago [20]. Later Rosen developed an expression for the entropy flux of radiation in all polarizations in 1954 [107], and Landsberg extended the application of entropy calculation of a Bose gas to the non-equilibrium case [108]. Meanwhile in 1946, Landau studied the limitations of photoluminescence imposed by thermodynamics, and found that the luminescent output power may exceed the photo-excitation input [109]. A similar investigation for the case of electroluminescence was reported by Weinstein in 1960 [21], and the accompanying cooling effect by Dousmanis et al. in 1964 [43]. Then in 1968, an extended discussion was finally brought up by Landsberg et al. to address the efficiency limit specifically for LEDs [44], followed by a more complete review for optoelectronic devices in general in 1980 [46].

In what follows, a brief thermodynamic interpretation for the LED efficiency limit is given first, and then a short analytical derivation is provided.
Essentially, the WPE of LEDs can be greater than unity since the output of incoherent electroluminescence contains finite entropy, while the input electrical work does not. According to the Second Law of Thermodynamics, the LED electronic system is then allowed to absorb some heat from the lattice as an extra energy input and convert this heat into optical energy as long as the total entropy in the system does not decrease during steady-state operation. Once the total optical output surpasses the electrical part of the input, the WPE exceeds unity together with an ELC effect, where an upper bound exists and shall be reached when the entropy influx carried by the net heat absorbed exactly balances the quota imposed by that of the output electroluminescence.

A quantitative analysis to reveal the thermodynamic upper limit of LED efficiency can start from the entropy content of ideal incoherent electroluminescence. For the Lambertian radiation field produced by an LED, suppose a net energy flux density $I_r$ is measured together with its spectral profile at a position close to the LED emitting surface covering a $2\pi$ solid angle. If $f(\nu)$ represents the mean photon occupancy per mode at frequency $\nu$, the distribution of $f$ over the frequency range of interest can be obtained by,

$$I_r = \frac{c}{4} \int h\nu f(\nu)g(\nu) \, d\nu$$

where $c$ is vacuum light speed, $h$ is Planks constant, and $g(\nu)$ is the density of optical modes per unit volume. The coefficient $1/4$ is introduced from the integration of $2\pi$ solid angle, similar to the case of poking a hole on the cavity of an ideal radiator [110]. Here vacuum is also assumed, so refractive index of the medium is omitted.

After obtaining $f(\nu)$, an entropy formula for ideal Bose gas in a small frequency interval $\nu$ can be developed to calculate the total entropy flux contained in the LED radiation $I_r$. In a simplified case under thermal equilibrium condition, consider a system enclosing a fixed number $P$ of indistinguishable photons of frequency $\nu$, and these photons are to be distributed into $N$ distinctive modes in every possible manner. Transforming this model into a simple permutation problem, the total number of
microstates $\Omega$ of the system can be written as,

$$
\Omega = \frac{(P + N - 1)!}{(N - 1)!P!}
$$

(1.12)

Since thermal equilibrium has been assumed, all microstates are equally likely to happen. Applying the well-known entropy formula and using Sterling’s approximation to eliminate the factorial, total entropy $S_{sys}$ of the system at this small frequency interval is derived as [20],

$$
S_{sys} = k_B \log \Omega = k_B[(N + P) \log(N + P) - N \log N - P \log P]
$$

(1.13)

The equivalent entropy per mode $S_{mode}$ can be simply expressed as,

$$
S_{mode} = S_{sys}/N = k_B[(1 + f(\nu)) \log(1 + f(\nu)) - f(\nu) \log f(\nu)]
$$

(1.14)

Now, utilizing Equation 1.14, the net rate of entropy leaving the LED carried by $I_r$ can be calculated as,

$$
\Phi_r = \frac{c}{4} \int k_B[(f(\nu) + 1) \ln (f(\nu) + 1) - f(\nu) \ln (f(\nu))]g(\nu) \, d\nu
$$

(1.15)

Combining Equation 1.11 and 1.15 $\Phi_r$ can be obtained for any measured $I_r$ and its spectral information. Note that, thermal radiation is not considered as part of the LED optical output here since it is negligible due to detailed balance with the ambient [21].

The next step is to investigate the energy and entropy flow in the LED electronic system. Consider an LED in forward-biased steady-state operation. Charged carriers are electrically pumped by entropy-free input work with current density $J$ and bias voltage $V$. Along with the process of minority carrier injection, the electronic system also absorbs net heat from the lattice at the rate $Q$ per unit area due to Peltier effect near the diode junction. This heat transfer process is related to the restoration of the carrier distribution, and is assumed to take place close enough to the quasi-neutral
regions of the LED such that the carrier temperature can be considered the same as that of the lattice due to fast electron-phonon scattering processes. Suppose the lattice temperature is $T_l$, then the net entropy transfer rate into the electronic system carried by $Q$ is approximately $Q/T_l$. Thus in steady state, two rate equations can be written,

$$\frac{1}{A} \frac{dE}{dt} = JV + Q - I_r = 0 \quad (1.16)$$

$$\frac{1}{A} \frac{dS}{dt} = \frac{Q}{T_l} + \Delta \Phi - \Phi_r = 0 \quad (1.17)$$

where $A$ is the area of LED emitting surface, $E$ and $S$ are the total internal energy and entropy of the system, respectively. $\Delta \Phi$ is the internal entropy generation rate (per unit area) of the system, which is non-negative due to any irreversible processes associated with non-ideal LED operations. Combining Equations $1.16$ and $1.17$ leads to a key inequality,

$$\Delta \Phi = \Phi_r - \frac{I_r - JV}{T_l} \geq 0 \quad (1.18)$$

Through simple transformations, an upper bound of the WPE (denoted by $\eta_{wp}$) is found as,

$$\eta_{wp} = \frac{I_r}{JV} \leq \frac{I_r}{I_r - T_l \Phi_r} \quad (1.19)$$

which is consistent with literature $[21,44]$ and always greater than unity as expected. In this manner, the thermodynamically imposed efficiency limit can be calculated for any LED operating at any brightness as long as the emission spectrum and working temperature are known.

**Thesis Objectives on the Theoretical Study of LED Efficiency**

Other researchers have studied the thermodynamic efficiency limit of LEDs mainly focusing on the methodology (model construction and detailed derivation procedures, etc.) and is general for incoherent electroluminescence of all wavelengths. To better understand the potential of visible LEDs for further efficiency improvement at useful light intensities, in this thesis we present a comprehensive thermodynamic analysis
investigating the characteristics and criteria for efficient visible lighting and cooling.

Previous work investigating the thermodynamic bound of energy conversion efficiency for photoluminescence and electroluminescence are all in the case of reversible limit. Here, we also propose a tighter bound of the efficiency for a further step by considering a thermodynamic irreversibility associated with the mechanism of passive optical extraction. In the present thesis, an irreversible thermodynamic model for energy conversion in an LED will be developed by considering and comparing the temperatures of the internal and far-field radiation fields. A new efficiency limit will then be derived, and shown to be tighter and more realistic than the reversible case.

1.4 Thesis Outline

In this thesis, a thermophotonic method based on the heat-pump mechanism is proposed to potentially enhance the WPE of visible LEDs for high-power operation. In Chapter 2, experimental approaches for a demonstration with GaN based blue emitters are given as an example. The chapter first describes the motivations and objectives of this investigation, and then focuses on the requirements, design and development of the necessary experimental platform, as well as its calibration. In Chapter 3, test results are analyzed and discussed to elaborate how an LED operates by feeding on waste heat. In Chapter 4, a comprehensive thermodynamic analysis is presented to investigate the characteristics and criteria for efficient visible lighting, as well as to explore the necessary conditions for LED electroluminescent cooling. In addition, by combining the idea of passive optical extraction, a new upper bound of LED efficiency is further derived in Chapter 4 based on the Second Law of Thermodynamics, which turns out to be tighter and more realistic than that in the literature \cite{21}. In Chapter 5, some relevant future work is further discussed.
Chapter 2

Thermally Enhanced Blue LEDs -
Experimental Design and Setup

2.1 Motivation and Objective

As we have introduced in Chapter 1, thermal excitation of injected carriers is responsible for photon emission of LEDs under low electrical bias $V < \hbar \omega / q$. Moreover, the heat-pump mechanism is also essential for LEDs to realize the long-anticipated electroluminescent cooling phenomenon which was first speculated half a century ago [42]. Only recently, the ELC effect was experimentally observed in an infrared LED based on InGaAsSb material system operating at extremely low bias ($V < kT / q$) and elevated temperature [62]. In this experiment, although the net cooling power and light output power are still low at the bias level demonstrated due to the low internal quantum efficiency, the idea of thermally assisted electrical pumping (i.e., thermoelectric pumping) could be practically useful for improving the WPE of LEDs (not necessarily over unity) at useful output power levels. Therefore, as the next step of this study, our motivation is to further exploit the heat-pump mechanism, and investigate how it is able to affect or improve the WPE of some widely used visible LEDs, for example, the GaN based blue or violet LEDs in different operating conditions.

As a commonly known fact, GaN based LEDs usually have the over-heating issue — waste heat produced due to inefficient LED operation would raise the junction tem-
perature and thus degrade the wall-plug efficiency mainly through exacerbated SRH non-radiative recombination, i.e., the thermal droop problem introduced in Chapter 1. As a result, integrating external heat sinks to LEDs for effective passive cooling becomes a typical solution for commercial products to avoid any serious efficiency reduction, particularly in the field of high-power applications. However, such a common practice is contradictory to our idea of utilizing heat, either self-produced or externally supplied, as an additional useful energy input to enhance the device WPE. Therefore, our objective here is to eliminate the necessity of using bulky and costly heat sinks on these high-power LEDs while keeping or achieving a non-trivial WPE enhancement at useful output powers. It would require appropriate experimental study to investigate how significant the effect of thermoelectric pumping could take place in wide-bandgap GaN based LEDs and thus make use of the high junction temperature to overcome (or overwhelm) the thermal degradation of its own. A set of experiments need to be designed and conducted for this study.

Since the wavelengths of GaN based LEDs are much shorter than the previously demonstrated infra-red case (thus the photon emission is of higher-energy), a stronger thermal excitation is expected to be necessary for a conspicuous heat pump phenomenon. Therefore, the experiments would require a high-temperature compatible optical characterization system with a wide and precise temperature control function. In order to facilitate the delivery of a designated temperature to the sample, all contacts between the heater, test LED and other optical components involved must be highly thermally conductive while not affecting the light collection. Thus it imposes stringent requirements on the design of the optical heating stage to balance the light collection efficiency and thermal conduction efficacy. In addition, typical LED packaging materials such as silicone or epoxy could not withstand the high temperature we are aiming to test at (above 300°C), which restricts the testing vehicle to be an un-packaged bare die. In this case, a suitable probing system and a microscope are also necessary.
2.2 Construction of Experimental Setup

An experimental setup that generally fits the above requirements were built in the beginning and used for some preliminary measurements in the early stage of the study. The setup basically worked as expected, but a few problems and difficulties were also encountered meanwhile, which primarily focus on the following three categories, (1) low light collection efficiency as well as poor thermal conduction to the sample; (2) substandard maximum achievable temperature and potentially inaccurate temperature monitoring; (3) unstable probe landing due to thermal expansion, thus resulting in inconsistent contact resistance. Apparently, a well-designed and robust experimental setup is essential for the study of any device physics. Given the existing problems stated above which could seriously hamper our subsequent experiments, the construction of a new generation setup with all issues fixed is the first step to go. By considering and balancing all the necessary improvements required for the three core sub-systems involved, namely, (a) light collection, (b) heating & temperature monitoring, and (c) probing & sourcing, a new design of the high-temperature LED characterization system was developed, and the setup was then constructed, which had proven to be much more reliable in the subsequent tests. As a comparison of the design, the schematic drawing of the initial and the improved experimental setups are plotted in Figure 2-1 and Figure 2-2, respectively. Details of the improvements made are discussed in the following for each of the sub-systems.

2.2.1 (a) Light Collection

In the initial experimental setup, the optical stage for LED die characterization is basically built on a horizontally held copper arm, as depicted in Figure 2-1. A bare LED die under test (approximately 5 mm by 5 mm in size) is placed on a thin glass cover slip (a typical image can be found in Figure 2-3 (a)) sitting on the flattened top surface of the copper arm at its front end. A small opening is drilled vertically through the copper arm underneath where the sample is located, so part of the light emitted by the LED during testing could transmit through the bottom cover slip
Figure 2-1: Schematic drawing of the initial setup for high temperature LED characterization.
Figure 2-2: Schematic drawing of the improved setup for high temperature LED characterization.
and reach a silicon photodetector (10 mm by 10 mm in size) about 10 cm away below the optical stage. This space is necessary as the photodetector must remain cool at room temperature to have an accurate reading of the light collected, while the copper arm above also serves as a heating stage, which will be elaborated in the next subsection. As this space is large compared to the size of the photodetector and there is no collimation optics built in-between, the light collection efficiency ($\eta_{c,v1}$) turns out to be very low, which can be estimated by,

$$\eta_{c,v1} = \frac{\text{Area of the Photodetector}}{(4\pi \cdot \text{Distance from LED to the Photodetector}^2)} = \frac{(1 \text{ cm})^2}{4\pi \times (10 \text{ cm})^2} = 0.08\%$$

Such a low $\eta_c$ made the experimental setup very insensitive to low light conditions, particularly for measurements near the LED turn-on voltage. Therefore, the second generation setup was made with an emphasis on maximizing the light collection efficiency and the design was tailored for the specifications of the un-packaged LED test sample. First of all, instead of using the glass slip in the initial setup, the LED die is now placed on the top plane surface of a hemispherical sapphire solid-immersion lens with a diameter of 10 mm (in order to fit this sapphire dome, the original copper arm is also modified accordingly, as depicted in Figure 2-2). This sapphire dome is supplied by Swiss Jewel Company as a customized product. A close image of it can be found in Figure 2-3 (b). At 450 nm (the central emission wavelength of the test sample), as sapphire ($i.e.$, Al$_2$O$_3$) has a refractive index $n_{\text{Sapphire}} = 1.78$ closer to that of GaN $n_{\text{GaN}} = 2.49$ compared to the glass $n_{\text{Glass}} = 1.53$, the light escape cone at the bottom of the LED substrate increases from 1.32 to 1.89 (in solid angle, converted from their corresponding critical angles of total internal reflection). In addition, all light beams leaving the hemispherical lens now have a normal incident angle on the inner concave interface, since the LED active region can be considered as a point light source located at its center, which results in less internal reflection (total inter-
nal reflection is avoided in this manner). The sapphire lens also has a visible-window broad-band anti-reflection coating applied on its concave surface to further reduce the Fresnel reflection (provided by VisiMax Technologies Inc.), which results in a transmission above 99.8% at 450 nm according to the data sheet provided.

Figure 2-3: (a) Thin glass cover slips used in the initial setup; (b) sapphire hemispherical lens used in the second generation setup.

The employment of the sapphire hemispherical lens has increased the light extraction from the LED die, but a collimation is yet to perform for the ease of light collection. As the LED structures grown on the transparent GaN substrate are basically $4\pi$ emitting and the top-emitting half is not easily collectable in our case due to the position of probes and the microscope above, we must collect the remaining $2\pi$ of bottom-emitting light as much as possible. To focus the light emerging from a dome lens (roughly with a spherical radiation pattern), a compound parabolic concentrator (CPC) typically used in flash lights for light collimation and beam shaping can be a perfect match here. The structure of this device as well as a simple illustration of the function is shown in Figure 2-4 below. The specific CPC employed in our setup is made of polycarbonate, with bowl diameter of 3 cm and height 2 cm. It also has a dome-shaped rear opening of diameter 1 cm so that the sapphire lens can be inserted into it for a maximum light coupling. Once the light is collimated and leaving the CPC, they are all collected by a photodetector closely attached to the bottom of the CPC, as depicted in Figure 2-2. This photodetector employed, as shown in Figure 2-5, is of model #.53-374 from Edmund Optics. It is a normal response silicon photodetector with a large active area of 613 $mm^2$, and the responsivity at 450 nm is
0.13 $A/W$ according to the data sheet provided (calibration is not specifically mentioned by the manufacturer). As the detector is of circular shape with a diameter of 14 $mm$ that is larger than the CPC’s outer diameter, no other focusing optics is further required between them.

![Figure 2-4: Structure and function of a typical compound parabolic concentrator.](image)

Figure 2-4: Structure and function of a typical compound parabolic concentrator.

![Figure 2-5: The 613 $mm^2$ large-area silicon photodetector employed in the second generation setup.](image)

Figure 2-5: The 613 $mm^2$ large-area silicon photodetector employed in the second generation setup.

A sapphire hemispherical lens, a compound parabolic concentrator and a large-area photodetector together form a complete and optimized light collection system for the particular sample LED die we have. For this improved new generation of setup, the light collection efficiency ($\eta_{c,v2}$) can be roughly estimated by calculating
the product of transmission at all interfaces along the pathway of the light:

\[
\eta_{c,v2} = 0.5 \cdot (\text{GaN/sapphire}) \cdot (\text{sapphire/air}) \cdot (\text{air/polycarbonate}) \cdot (\text{polycarbonate/air})
\]

\[
= 0.5 \times 0.97 \times 0.92 \times 0.95 \times 0.95
\]

\[
= 40\%
\]

(2.2)

where the refractive indices used (at 450 nm) are \( n_{\text{Sapphire}} = 1.78 \), \( n_{\text{GaN}} = 2.49 \), \( n_{\text{Polycarbonate}} = 1.61 \), \( n_{\text{Air}} = 1.00 \), and the coefficient 0.5 appeared in front of the transmission is an approximation of the light ratio emitting towards bottom that can be ultimately collected by the photodetector. This calculation assumed a perfectly intimate contact between the sample LED die and the plane surface of the sapphire hemisphere, so no air gap exists (the actual test samples are not specifically backside polished, but appear to be smooth through the observation by an optical microscope). In addition, all light are assumed to have normal incidence at different interfaces. Note that here we have neglected the total internal reflection at the GaN/Sapphire interface which may occupy 70.0% of the total bottom emitting light if assuming an isotropic radiation from a point light source, as this part of the light is still considered extractable at the LED bottom interface after multiple internal reflections and scatterings. Therefore, the light collection efficiency calculated above only reflects an upper limit. A more accurate \( \eta_c \) requires a further calibration, which will be elaborated in the last section of this chapter. The total optical power \( P_{out} \) of the test LED can thus be calculated by the photo-current reading \( I_{PD} \) from a source meter biasing the photodetector (at \(-10 V\)) as,

\[
P_{out} = \frac{I_{PD}}{R_{sp} \eta_c}
\]

(2.3)

where \( R_{sp} = 0.13 A/W \) is the photodetector responsivity at 450 nm.
2.2.2 (b) Heating and Temperature Monitoring

In the initial experimental setup, the copper arm is hollow in the rear and has a cartridge heater inserted, as shown in Figure 2-1. Thus it also serves as a heating stage for the test sample. Thermal conducting cement is applied around the cartridge heater and also to the contact surface between the glass slip and the copper arm to enhance the thermal conduction. The entire copper arm is then tightly covered with a few layers of thermal insulating fabric (except for the area on which the test sample sits) in order to reduce the strong exposure of thermal radiation and convection when the temperature gets high, which is a necessary protection for most of other optical components in the setup (the thermal insulating fabric may be purchased long time ago and stored without any package, we can not source its exact type and model). It also helps the stage heat up and stabilize to a designated temperature more quickly. The heating power of the cartridge heater, thus the final temperature of the heating stage is controlled by a relay from Crydom of model 10PCV2415 (rating 15 $A - 90 A$). The relay gets a 110 $V$, 50 $Hz$ AC input, which is then delivered to the resistive load (i.e., the heater) with a modulated duty cycle proportionally controlled by another 2 $- 10 V$ DC input. The 110$V AC$ input is directly supplied by the wall outlet and the modulating signal is by an Agilent DC power supply. A thermocouple made of copper-constantan is attached to the front end of the copper arm near the glass slip, so that the temperature can be monitored real-time through a 16 channel thermocouple monitor SR630 from Stanford Research System.

The heating stage in the initial setup described above provided a basic function to the study of temperature variations of LED characteristics, but did not manage to meet the requirements previously set. First of all, the LED temperature is monitored (or inferred) by a single thermocouple, which is neither directly contact with the LED die itself, nor compared/calibrated with any other method/device measuring simultaneously. Together with the fact that the glass slide on which the sample sits has a thermal conductivity of 0.8 $W/m \cdot K$ which is much smaller than that of copper (385.0 $W/m \cdot K$), the temperature reading is potentially inaccurate. In addition, the
copper heating stage is supported by a thermal-insulating plastic post (otherwise the sample will never get hot, or the entire optical table gets heat up) made of polyether-ether-ketone (PEEK). PEEK has a maximum service temperature at around 150°C, which sets an upper limit of the test temperature for the entire setup. However, our goal is to extend the high temperature measurement up to 350°C. Therefore, some improvements must be done to facilitate the subsequent study.

In the second generation experimental setup, the support of the heating stage is replaced by another plastic rod (half an inch in diameter) made from a better thermal resistant material PolyBenzImidazole (PBI). PBI is a kind of high performance imidized thermoplastic, which offers the highest service temperature (glass transition at near 450°C) among all engineering plastics currently available. It is also an excellent thermal insulator and easy to machine, which make it our best (and actually the only) choice. An image of the PBI rod same as what we are using is shown in Figure 2-6. Instead of directly attaching the setup on the optical table, the PBI post supporting the LED characterization platform is now clamped onto a 3-axis adjustable opto-mechanical stage to provide some extra flexibility in position for a better optimization of the light collection efficiency.

![Figure 2-6: High performance thermal resistant PBI rod.](image)

As mentioned in the previous section of light collection sub-system, the new heating stage is made of a modified copper arm in order to fit the sapphire hemispherical lens newly employed. As shown in the schematic figure 2-2, it has a thinned (about
1 mm thick) long protruding copper finger welded onto the front of the copper arm (the heater). By using a ball head bit, a circular opening with 10 mm diameter is drilled vertically on its front end to hold the sapphire dome and match the curvature of its concave surface for a better contact (here I would like to thank Dr. William Herrington for his great help of machining the copper arm). The copper arm and the copper finger are again wrapped by layers of thermal insulating fabric, and the cartridge heater with a relay connected is still responsible for controlling the stage temperature. It is notable that, although the sapphire lens itself has no problem enduring a high temperature up to its melting point at 2000°C, it is not the case for a typical anti-reflection coating applied on it. The coating we used is of a special type only available at VisiMax Technologies Inc., which claims to remain functioning at a temperature up to 500°C. In addition, as the sapphire lens could be very hot (up to 350°C) during high temperature measurements while the polycarbonate CPC underneath only has a temperature rating up to 150°C, a small gap of about 5 mm is left in between intentionally. Furthermore, the outer surface of the CPC is also covered by a piece of thermal isolating fabric as another protection measure. In this manner, the CPC could remain undamaged when performing high temperature testing (proved to be so), and the photodetector underneath is always cool without any active cooling. In fact, with this improved setup, the copper arm & finger is even able to deliver thermal energy to the test sample more efficiently than previous, as the sapphire dome that holds the LED die has a far better thermal conductivity (23 ~ 25 W/m·K) compared to that of glass (0.8 W/m·K) used in the initial setup.

Regarding the accuracy of temperature control and monitoring for the second generation setup, apart from attaching a thermocouple to the copper finger near the sapphire lens, we added a thermister directly in contact with the sapphire lens for a verification of the temperature reading. The thermister used is from ThorLab of model TH100PT, which is made of Al₂O₃ substrate with fused glass cover, and has a lead diameter of 0.35 mm. Its working temperature ranges between −70 − 400°C and the temperature coefficient is 3.85 × 10⁻³/K. Furthermore, thermal images of the test sample were taken by a FLIR camera before conducting the actual
measurement to confirm the (roughly) even distribution of temperature across the substrate. Experiments were conducted only when the temperature readings from the three sensing devices got stabilized and converged to three degrees (Kelvin). In the subsequent measurements, this improved sub-system functioned as well as expected from the design, and proved to be robust enough at a temperature even higher than 350°C. It is also reasonably efficient – the test sample was able to reach and stabilize to a designated temperature in about 20 minutes with some fine tuning of the modulating signal to the control relay (the required DC voltage is actually between 2 – 5 V for a modulation from room temperature up to 350°C). A typical thermal image of a hot LED die is shown in Figure 2-7 below. Areas of lower temperature distributed on the die indicate the metal contacts or metal debris.

Figure 2-7: A thermal image of an heated LED die taken by a FLIR camera.

2.2.3 (c) Probing and Sourcing

The sample dies under test are small pieces of square-shaped transparent GaN substrate, with dimension around 5 mm by 5 mm and thickness less than 1 mm. An array of top-emitting LED mesa structures of 0.1 mm² in size (active region) are epitaxially grown on each of the substrates, as shown in Figure 2-8 with the cathode and anode labeled correspondingly. These samples are fabricated and provided by our
collaborators Yuji Zhao and Sang-Ho Oh from the Solid State Lighting & Energy Electronics Center (SSLEEC) at University of California, Santa Barbara (UCSB). More details about the LED structure and performance will be introduced in the next chapter, or refer to C.-C. Pan et al. [70]. In order to source these small LEDs for our subsequent study, either probing or wire-bonding is required. However the wire-bonding option is not viable here as the LED structure has a high density on the substrate. Hence the LED characterization platform designed above also needs a probe station integrated, with an optical microscope installed above. In our initial setup, a pair of probe holders of simple 3-axis adjustment function are utilized, with a source meter (Keithley 2400) connected for LED sourcing. A separate source meter (Keithley 2635) is used for photodetector sensing.

![Sample LED substrate and the structure.](image)

Since the LED metal contacts are fragile on these particular samples, it was found that probing at different positions of the contacts or with different loading forces could lead to a big difference in the contact resistance. Therefore, a single probe landing for each LED sample is preferred in a series of tests for more consistent results. However, the LED characterization includes temperature variations, thus the copper arm could elongate for up to tens of micrometers (according to the observation) during the heating process, which caused the LED sample to move together with it while the probe tips were still remaining at their original positions, pinning on the chip and scratching it (probe holders are fixed separately to the optical table). As a result, with the initial setup the LED metal contacts are easily damaged or even peeled off by
the probe tips, and are usually dead in a few measurements. In addition, as the LED and the photodetector are driven by two different source meters in the initial setup, the synchronization between sample sourcing and light detection was not excellent. However it is desirable that the LED is switched on only for a short duration for sampling its I-V and the light collection data (which requires good synchronization), as the LED junction could heat up quickly at high power operation, thus affecting the accuracy of the measurements.

Given these serious problems in the probing & sourcing part sub-system of the initial setup which not only led to inaccurate results but is also destructive to the test samples, a few changes were made for an overall upgrade of the system. First, we employed a pair of more advanced high precision probe holders from CascadeMicrotech (model: DPP105), as shown in Figure 2-9, which provides X, Y and Z displacement of 7 mm, 8 mm and 25 mm, respectively, with 25 μm resolution (coarse X-Y adjustment by its magnetic base). More importantly, it offers adjustable tip contact pressure from 5 grams to 20 grams, and a buffer design is employed such that the pre-specified contact pressure is unchanged within a short range of Z displacement. In addition, we used a pair of thicker tungsten probe tips from PicoProbe (model: ST-20-10) of 10 μm radius (the probe tips in the initial setup are unidentifiable, but appeared much thinner). With these better apparatus equipped, the probing procedure became much easier and the contact resistance was less position dependent. Although the thermal expansion of the heating stage is still inevitable here, the LED metal contacts could now survive longer. In addition, we replaced the two source meters used in the initial setup by one programmable dual-channel source meter from Keysight (model 2602), which could perform much faster I-V sweep and solved the synchronization issue as well.

Finally, a close image of the actual setup is shown in Figure 2-10 (initial version), and the upgraded version is shown in Figure 2-11. All key components are labeled within the figures.
Figure 2-9: The probe holder CascadeMicrotech DPP105 used in the second generation setup.
Figure 2-10: The initial construction of the LED characterization platform.
Figure 2-11: The upgraded version of the LED characterization platform.
2.3 Setup Calibration

One of the main purposes of constructing our own experimental platform is, of course, to facilitate the optical power measurement under different (or extreme) operating conditions specifically for our LED samples, thus the study objectives can be fulfilled. Typically, this could have been carried out by the direct employment of a commercially available integrating sphere, a commonly used optical characterization instrument earlier introduced in Chapter 1. However, the temperature under investigation could easily exceed the limit of any of such general-purpose instruments, and more importantly, chip probing is not feasible in an integrating sphere. In contrast, our specifically built experimental setup is capable of doing LED die characterization up to 350°C, but as a trade-off, the light collection is not as efficient due to the limitation of using additional instruments necessary for chip probing. With our setup, the total optical power of the test sample is measured by conducting a detection of the partial light emission (thus get a photo-current readout), and then performing a calculation involving the detector responsivity and collection efficiency, as indicated in the calculation of Equation 2.3. In the previous section, an upper limit of 40% was estimated for the light collection efficiency of our upgraded setup, but it is still necessary to further conduct a calibration in order to figure out its exact value. Here, an integrating sphere could finally serve this purpose by conducting some reference measurements – to achieve the actual total optical power of a sample and compare with the partial light collection from our setup for the same operating condition, thus the exact light collection efficiency could be obtained (i.e., their ratio).

In order to characterize an un-packaged LED die in an integrating sphere, the sample must be pre-processed and mounted on a particular metal header before becoming compatible with the sample holding stage in the sphere. Since the integrating sphere required and some other relevant equipment for GaN chip processing are only available at SSLEEC, this calibration measurement was conducted at UCSB with the help of our experienced collaborator Sang-Ho Oh. The preparation work including sample pre-processing and chip mounting were completed in two days. The proce-
dures are standardized and have been briefly summarized in Appendix A. It is notable that the final step of wire-bonding is very tricky as the metal contact peeled off easily together with the wire. As a result, only one processed device survived this step and was verified to be able to work as well as before. This successfully processed LED sample mounted on the header can be found in Figure 2-12 bellow. The epi-layer side of the processed LED faces upwards with two wires bonded and the substrate side is attached to the header with epoxy. The top surface of the metal header used has a silver color, but not perfectly mirror-like reflective. It is a bit diffusive instead. The detailed specifications of the header are confidential at UCSB thus not able to provide.

Once the sample was mounted on the header and confirmed to work properly, it was ready for the optical power measurement in the integrating sphere. The integrating sphere we adopted is of model ISP 500-100 from Instrument Systems, as shown in Figure 2-13. The diameter is 500 mm and the service temperature is up to 140°C. This is an open version sphere capable of 4π radiant power measurement. For the room temperature test, the sample was fixed on the central stage. A voltage sweep from 3 V to 4 V with 0.2 V interval was performed (six data points in total), and the total optical power was recorded. For higher temperature tests (80°C and 140°C), the sample was fixed at a side port with a heater integrated. The same
voltage sweep was performed when the temperature of the sample reached a steady state, and the total optical power was recorded. It is notable that, a coefficient of 1.32 needs to be manually imposed on the measured optical power (i.e., direct output reading from the integrating sphere) if the sample was fixed at a side port instead of the central stage. This coefficient had been verified to be necessary and correct by our examination prior to the tests (i.e., we tested a sample blue LED for the both central stage and side port fixture at room temperature and compared the measured optical power). The I-V sweeping data of the calibration sample at different temperatures are compared with those from earlier measurements conducted by our own LED characterization setup (for the same sample device), and they are found to be close. The comparison of I-V curves in both conditions is presented in Figure 2-14 below, with “W-Temperature” representing the data in wire-bonded condition (shown in solid lines) and “P-Temperature” for the probed condition (shown in dashed lines) in the legend. It indicates that both the probing and the wire bonding provided a firm electrical contact, and again verified that the sample was not damaged though the processing and mounting procedures. By directly comparing the total optical power measured by the integrating sphere on the wire-bonded LED sample and the collected power by our improved setup with the bare LED die, the light collection efficiency versus LED current density at three different temperatures are plotted and shown in Figure 2-15.

The figure is plotted against LED current density as we have assumed that the same LED sample would produce the same output power at a specific current density before/after the pre-processing and mounting procedures described above. From the figure, we can see that the calibrated collection efficiency at room temperature (in blue line) basically distribute around 35% to 36%, while those at higher temperature (80°C indicated with orange line & 140°C with red line) in general fall below 35%. This is somewhat expected as the optical alignment was only optimized for room temperature light collection in our second generation high temperature LED characterization platform, and the thermal expansion in different parts of the optical system at elevated temperatures could cause misalignment and thus reduce the effi-
Figure 2-13: (a) The integrating sphere ISP 500; (b) side view of the central stage for holding a mounted LED sample.

Figure 2-14: The comparison of calibration sample’s I-V sweeping data between the wire-bonded condition (tested by the integrating sphere, shown in solid lines) and the probed condition (tested by our own experimental platform, shown in dashed lines) for the same device at different temperatures.
Figure 2-15: The calibrated light collection efficiency of the second generation setup under different conditions.

Apart from this temperature related drift, variations or oscillations also exist in the calibration results of the same temperature, when the LED current density changes (so as the optical power). These small oscillations exhibited (except for the first data point at low current density in the blue line) are likely due to the mechanical vibration of the system which could also affect the optical alignment, or local temperature drift of the test sample. A single outlier is also noticed for the room temperature collection efficiency at low LED current density, but no good explanation was found for this relatively large deviation. Here, we consider these LED current density dependent oscillations and the outlier are unimportant and thus could be neglected, since the variation is relatively small and more importantly, other errors have already been introduced and make their contribution to the oscillations complicated. These errors include the actual change of L-I curve after the sample was processed and mounted (i.e., the previous assumption is not rigorously correct, but we do not have a better solution for calibration), the inaccuracy of integrating sphere measurements (it has
no guarantee to produce the perfectly accurate reference data, particularly at high
temperatures, as the integrating sphere itself is only calibrated in factory at room
temperature by a reference light source whose radiation pattern and emission wave-
length can both be different from our sample), etc. Furthermore, although the light
collection efficiency of this particular experimental setup is speculated and proved
to be temperature dependent, only one fixed value is required for all our subsequent
data extraction and analysis at all temperatures, as it is impossible to do the calibra-
tion for them all. Therefore, according to the calibration results available here, and
to be conservative for the sample characterization at high temperature, a fixed light
collection efficiency of 35.0% is adopted for future measurements at all temperatures.
Here by being conservative at high temperature LED characterization, we mean to
utilize a slightly larger collection efficiency for the estimation of a more conservative,
or smaller normalized optical power (further implication will be discussed in the next
chapter). Raw data corresponding to the calibration figure is also provided in the
tables below. $P_r$ indicates the total power measured by integrating sphere on the
mounted LED sample and $P_c$ indicates the power collected by our own experimental
setup with the bare LED die. $\eta_c$ is the calibrated setup collection efficiency.
### Table 2-1: Measurement Results at 20°C

<table>
<thead>
<tr>
<th>$V_{LED}$ (V)</th>
<th>$J_{LED}$ (A/cm²)</th>
<th>$P_r$ (W)</th>
<th>$P_c$ (W)</th>
<th>$\eta_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>15.7</td>
<td>9.37 $\times$ 10^{-3}</td>
<td>3.58 $\times$ 10^{-3}</td>
<td>38.3</td>
</tr>
<tr>
<td>3.2</td>
<td>27.0</td>
<td>16.86 $\times$ 10^{-3}</td>
<td>6.12 $\times$ 10^{-3}</td>
<td>36.3</td>
</tr>
<tr>
<td>3.4</td>
<td>39.9</td>
<td>25.08 $\times$ 10^{-3}</td>
<td>8.92 $\times$ 10^{-3}</td>
<td>35.6</td>
</tr>
<tr>
<td>3.6</td>
<td>54.3</td>
<td>33.19 $\times$ 10^{-3}</td>
<td>12.00 $\times$ 10^{-3}</td>
<td>36.2</td>
</tr>
<tr>
<td>3.8</td>
<td>69.9</td>
<td>42.91 $\times$ 10^{-3}</td>
<td>15.15 $\times$ 10^{-3}</td>
<td>35.3</td>
</tr>
<tr>
<td>4.0</td>
<td>86.8</td>
<td>52.36 $\times$ 10^{-3}</td>
<td>18.46 $\times$ 10^{-3}</td>
<td>35.3</td>
</tr>
</tbody>
</table>

### Table 2-2: Measurement Results at 80°C

<table>
<thead>
<tr>
<th>$V_{LED}$ (V)</th>
<th>$J_{LED}$ (A/cm²)</th>
<th>$P_r$ (W)</th>
<th>$P_c$ (W)</th>
<th>$\eta_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>22.9</td>
<td>14.30 $\times$ 10^{-3}</td>
<td>4.82 $\times$ 10^{-3}</td>
<td>33.7</td>
</tr>
<tr>
<td>3.2</td>
<td>35.4</td>
<td>21.66 $\times$ 10^{-3}</td>
<td>7.37 $\times$ 10^{-3}</td>
<td>34.0</td>
</tr>
<tr>
<td>3.4</td>
<td>48.8</td>
<td>28.44 $\times$ 10^{-3}</td>
<td>10.04 $\times$ 10^{-3}</td>
<td>35.3</td>
</tr>
<tr>
<td>3.6</td>
<td>62.6</td>
<td>37.55 $\times$ 10^{-3}</td>
<td>12.62 $\times$ 10^{-3}</td>
<td>33.6</td>
</tr>
<tr>
<td>3.8</td>
<td>76.7</td>
<td>47.26 $\times$ 10^{-3}</td>
<td>15.29 $\times$ 10^{-3}</td>
<td>32.4</td>
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<tr>
<td>4.0</td>
<td>91.3</td>
<td>55.47 $\times$ 10^{-3}</td>
<td>17.91 $\times$ 10^{-3}</td>
<td>32.3</td>
</tr>
</tbody>
</table>

### Table 2-3: Measurement Results at 140°C

<table>
<thead>
<tr>
<th>$V_{LED}$ (V)</th>
<th>$J_{LED}$ (A/cm²)</th>
<th>$P_r$ (W)</th>
<th>$P_c$ (W)</th>
<th>$\eta_c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>31.0</td>
<td>17.99 $\times$ 10^{-3}</td>
<td>5.98 $\times$ 10^{-3}</td>
<td>33.3</td>
</tr>
<tr>
<td>3.2</td>
<td>46.2</td>
<td>26.65 $\times$ 10^{-3}</td>
<td>8.78 $\times$ 10^{-3}</td>
<td>33.0</td>
</tr>
<tr>
<td>3.4</td>
<td>62.6</td>
<td>35.18 $\times$ 10^{-3}</td>
<td>11.68 $\times$ 10^{-3}</td>
<td>33.2</td>
</tr>
<tr>
<td>3.6</td>
<td>80.2</td>
<td>44.29 $\times$ 10^{-3}</td>
<td>14.66 $\times$ 10^{-3}</td>
<td>33.1</td>
</tr>
<tr>
<td>3.8</td>
<td>98.6</td>
<td>52.77 $\times$ 10^{-3}</td>
<td>17.65 $\times$ 10^{-3}</td>
<td>33.4</td>
</tr>
<tr>
<td>4.0</td>
<td>120.8</td>
<td>61.10 $\times$ 10^{-3}</td>
<td>21.08 $\times$ 10^{-3}</td>
<td>34.5</td>
</tr>
</tbody>
</table>
With the calibration implemented, although the concluded collection efficiency of 35.0% is not perfectly accurate in all conditions, it should serve the right purpose to generate normalized optical power of test samples under different conditions that are easy for us to compare with.
Chapter 3

Thermally Enhanced Blue LEDs - Experimental Results and Discussion

With the exclusive experimental setup we specifically designed and built for high temperature LED characterization as introduced in Chapter 2, a series of measurements at different temperatures were conducted for some blue LED samples of specially designed structures. So this Chapter serves as a section of data analysis and discussion, which aims to investigate the mechanism of thermoelectric pumping in these wide-bandgap GaN based LEDs and to understand how it is able to improve the WPE at useful output powers by taking advantage of their high junction temperature rather than avoiding the problem of temperature-induced efficiency droop by external cooling.

As a quick overview of the experimental results contained in this Chapter, here we demonstrate a thermally enhanced 450 nm GaN LED, in which nearly fourfold light output power is achieved at 615 K (compared to 295 K room temperature operation), with almost no reduction in the wall-plug efficiency at bias $V < \hbar \omega / q$. The LED is shown to work in a mode similar to a thermodynamic heat engine operating with charged carriers pumped into the active region by a combination of electrical work and Peltier heat (phonons) drawn from the lattice. In this optimal operating regime
at 615 K, the LED injection current (3.26 A/cm²) is of similar magnitude to the operating point of common high power GaN based LEDs (5 – 35 A/cm²).

### 3.1 Test Samples

In Chapter 1 & 2, we have stated why we primarily focus on blue emitters for the next-step study of heat-pump mechanism in LEDs. It is because they are the most important and widely used solid-state visible light sources today. In fact, their massive deployment also indicates another important motivation for us - the current maximum achievable IQE of blue LEDs has been very high (above 90%) after years of development, so has their EQE. In addition, GaN based LEDs also typically exhibit low turn-on voltage compared to their wide bandgaps. Therefore, according to Equation 3.1 below which we have previously introduced in Chapter 1, these two characteristics together make blue LEDs promising with potentially high WPE (even greater than unity) when operating at a bias below the bandgap, thus they are ideal samples for studying the thermoelectric pumping effect.

$$\eta_{wp} = \eta_{EQ} \times \frac{\hbar \omega}{qV}$$ (3.1)

The optimization of device EQE is the key for improving its WPE. The sample blue LEDs specifically prepared for this study are provided by our collaborator Yuji Zhao from UCSB and are designed to have high IQE (thus high EQE if the light extraction is also maximized) and low current-induced efficiency droop, which are typical design goals for high-power high-efficiency blue emitters. Specifically, these goals are achieved by a fourfold approach, i.e., utilizing (1) different growth orientation to reduce polarization-related internal electric fields; (2) a single QW structure to mitigate the issue of non-uniform electron/hole distribution; (3) increased thickness of QW to reduce the average carrier density under high bias; (4) growth of high-quality active region on native GaN substrate to reduce the undesirable SRH recombination rate. All these design techniques are implemented by growing the LED test samples on a free-standing (20\,2\,1) semi-polar GaN substrate [70].
For conventional GaN based hetero-structure LEDs grown on c-plane sapphire substrates, the [0001] growth direction inherently results in a large discontinuity of piezoelectric polarization density in the GaN/InGaN/GaN QW active region. The polarization discontinuity then induces an internal electrical field $\varepsilon_{pz}$ across the QW region, which is anti-parallel but much larger than the build-in field $\varepsilon_{bi}$ of an LED junction. This strong net field causes the band structure to tilt in the QW region, displaces the electron and hole wavefunctions to opposite sides of the well, and leads to a significant reduction of wavefunction overlap. For the semi-polar growth direction [20\overline{2}1] adopted by design approach (1), however, this effect is largely mitigated through reducing the strength of $\varepsilon_{pz}$ and make it partially cancel with $\varepsilon_{bi}$ under low-bias operating conditions. In this case, the wavefunction overlap is maximized in the flat QW region and hence the radiative recombination rate is high, so the device IQE improves. To better illustrate this effect, simulated band diagrams are plotted in Figure 3-1 and 3-2 respectively, for conditions of zero current density and high current density ($100 A/cm^2$) (simulation figures are provided by the UCSB collaborators). A more detailed band structure specifically for the sample studied in this work is depicted separately in Figure 3-3 below. Band tilting is exaggerated to illustrate the effect of polarization field in typical GaN based LEDs.

![Figure 3-1: Simulated band diagrams for single QW InGaN Blue LEDs of different polarizations at zero current density.](image)

In addition, for conventional GaN LEDs grown on c-plane sapphire substrates,
Figure 3-2: Simulated band diagrams for single QW InGaN Blue LEDs of different polarizations at current density of $100 \, A/cm^2$.

Figure 3-3: Band diagram of the InGaN single QW LED under study, the mechanism of thermoelectric pumping is also illustrated.

the defect (mainly threading dislocation) density is on the order of $10^8 \, cm^{-2}$ \cite{111}, while this value can be as low as $10^5 \, cm^{-2}$ for those directly grown on free-standing GaN native substrates \cite{70}. Therefore, the high-quality growth of the LED active
region on a free-standing semi-polar GaN substrate as described in design approach (4) offers the possibility of reducing defect associated SRH recombination rate, which also directly improves the IQE of the sample devices. As for approaches (2) & (3), their effects can be briefly understood through the simple IQE model in Equation 3.2 previously introduced in Chapter 1,

\[ \eta_{IQ} = \frac{Bn^2}{An + Bn^2 + Cn^3} \]  

where the notations appeared are all consistent with those used in Chapter 1. It is also known that the bi-molecular radiative recombination coefficient \( B \) and the Auger coefficient \( C \) both scale with the magnitude of the overlap of the electron and hole wavefunctions [112]. Here, the device IQE is optimized at low-bias condition \( (V < \hbar \omega/q) \) in which the Auger recombination is not dominant. Hence the design technique (2) described above can be considered to have an overall effect of enhancing the radiative recombination coefficient \( B \) only, while (3) could apparently lead to a higher ratio in Equation 3.2 at high electrical injection conditions. More importantly, these design approaches employed not only optimized device IQE, but also made significant contributions in mitigating the current-induced droop effect, which have been extensively discussed in Chapter 1.

In the present work, a 450 nm small area \((0.1 \text{ mm}^2)\) indium gallium nitride (In-GaN) single-quantum-well LED die (epi no. S121216AL) specifically designed for high power and low current droop is studied. The epitaxial structure of the sample device is shown in Figure 3-4 below [70]. It consists of an n-type GaN layer \((1 \mu m \text{ thick with Si doping concentration of } 1 \times 10^{19} \text{ cm}^{-3})\), followed by 10 pairs of \( \text{In}_{0.01}\text{Ga}_{0.99}\text{N/GaN} \) \((3/3 \text{ nm})\) undoped buffer layers for the suppression of dislocation propagation, a GaN/\( \text{In}_{0.18}\text{Ga}_{0.82}\text{N/GaN} \) single QW \((10 \text{ nm GaN bottom barrier, } 12 \text{ nm InGaN QW and } 15 \text{ nm GaN upper barrier})\), a \( \text{Al}_{0.18}\text{Ga}_{0.82}\text{N} \) electron blocking layer \((\text{EBL, } 3 \text{ nm with Mg doping concentration of } 2 \times 10^{19} \text{ cm}^{-3})\), and a p-type GaN layer \((50 \text{ nm with Mg doping concentration of } 4 \times 10^{19} \text{ cm}^{-3})\).

Through the approach of high-quality semi-polar growth on native GaN substrates
and the design of single thick QW structure, this high-power LED sample exhibits low
current-induced efficiency droop as expected. An encapsulated sample with backside
roughening and a ZnO vertical-stand package has an EQE of 50.1%, 45.3%, 43.0%
and 41.2%, a light output power of 140 mW, 253 mW, 361 mW and 460 mW at
current densities of 100 A/cm², 200 A/cm², 300 A/cm² and 400 A/cm², respectively
(under pulse mode operation) [70]. In this work, to facilitate experiments over a wide
temperature range, the LED samples tested were on a bare die without packaging or
encapsulation, resulting in lower EQE and WPE measurement values than devices
optimized for high light extraction [15]. Nevertheless, the absolute magnitudes of
EQE is not crucial in the present study and only relative changes/trends of EQE for
samples running at different operating conditions are meaningful, as we can always
apply our findings on packaged blue LEDs with state-of-the-art EQE without loss of
generality. Therefore, we may use arbitrary units to present or plot EQE comparisons
of measured data in subsequent sections.

3.2 Measurement Results

All major measurements are performed on an LED specimen from a sample die with
epi no. S121216AL by conducting voltage sweeps between 2 – 5 V with 0.05 V stepsize
under ambient temperatures of 295 K, 375 K, 455 K, 535 K and 615 K, respectively. Measurements at each voltage step are taken with 1 ms delay in order for LED operation to reach steady state, but only last for 20 ms to avoid any possible over-heating issue. Data are also collected after the system reaches thermal equilibrium. An I-V and a L-I curve plotted for all different temperatures can be found below in Figure 3-5 and 3-6, respectively. The optical output powers shown in the figure have been normalized by the calibrated collection efficiency $\eta_c$ of the experimental setup.

Figure 3-5: I-V sweep of the specimen at different temperatures.

A spectral related study is also performed for this LED specimen, with the room temperature emission spectrum shown in Figure 3-7 (a) and the temperature dependence of central wavelength $\lambda_c$ (measured at fixed bias of 3.5 V) shown in Figure 3-7 (b). The measurement results indicate that the spectral shape of the LED at higher operating temperatures basically maintain the same Gaussian profile but broadens a bit, which is not shown here. If this temperature dependence of the LED central wavelength is converted to a dependence of the corresponding bandgap energy, which
is plotted separately in Figure 3-8, it is found that this result can be well described by the Varshni’s empirical expression,

$$ E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{3.3} $$

where the material parameters can be found by a curve fitting according to this relation (also shown in the figure), resulting in $E_g(0) = 2.79 \text{ eV}$, $\alpha = 5.55 \times 10^{-4} \text{ eV/K}$ and $\beta = 1285 \text{ K}$.

Since the above investigation on the temperature dependence of LED emission spectrum is carried out at fixed bias (3.5 V), it may introduce other interfering effects such as current crowding or high carrier density induced spectral shift, as the current density at the same bias would increase exponentially at elevated temperatures. Therefore, we would like to perform a cleaner temperature dependent spectral measurement at a fixed current density of $J = 5 \text{ A/cm}^2$. However, the initial LED specimen was damaged during the previous high temperature tests, thus this particu-
Figure 3-7: (a) Measured (room temperature) emission spectrum of an LED specimen from a sample die of epi no. S121216AL; (b) temperature dependence (in Celsius degree) of the central wavelength $\lambda_c$.

Figure 3-8: Temperature dependence (in Celsius degree) of the corresponding LED bandgap energy at the active QW region.
lar measurement was conducted on another specimen with exactly the same structure but from a different die with epi no. \textit{S130110AL}. The test results at five different operating temperatures are summarized in the table below. It may be noticed that

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>295</th>
<th>375</th>
<th>455</th>
<th>535</th>
<th>615</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias V (Volt)</td>
<td>3.91</td>
<td>3.53</td>
<td>3.21</td>
<td>3.03</td>
<td>2.78</td>
</tr>
<tr>
<td>Central $\lambda$ (nm)</td>
<td>435.74</td>
<td>439.42</td>
<td>443.36</td>
<td>447.82</td>
<td>452.02</td>
</tr>
<tr>
<td>Photon Energy (eV)</td>
<td>2.846</td>
<td>2.822</td>
<td>2.797</td>
<td>2.769</td>
<td>2.743</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>17.36</td>
<td>20.80</td>
<td>24.83</td>
<td>27.00</td>
<td>29.67</td>
</tr>
</tbody>
</table>

the central emission wavelength of this specimen at room temperature (436 nm) is slightly shorter than that of the previous one (450 nm). This is merely due to the lesser indium incorporation during the QW growth of this epi, not by any structural change. Except for this minor difference, the temperature dependence exhibited from this LED spectrum basically reflects the same trend – longer central wavelength at higher operating temperatures. In addition, the linewidth broadening of the LED mentioned above can be measured by examining the full width at half maximum (FWHM) in the spectral profile, and is also shown in the table. On the other hand, we want to find out what is the exact influence of different injection currents to the emission spectrum of our LED specimen. Therefore we measured its spectrum (also from epi no. \textit{S130110AL}) again at room temperature (295 K) across a wide range of current density. The key results are shown in the following table. in fact, no conspicuous difference was found from the spectral profiles in these different LED operating conditions. This result manifests that the mean photon energy is basically unaffected by the high carrier density in the QW region even at a current density as high as 100 A/cm$^2$, which also reflects the effectiveness of the LED design described in the previous sections.

<table>
<thead>
<tr>
<th>Current Density (A/cm$^2$)</th>
<th>0.05</th>
<th>0.1</th>
<th>0.5</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central $\lambda$ (nm)</td>
<td>435.21</td>
<td>434.95</td>
<td>435.74</td>
<td>435.47</td>
<td>435.74</td>
<td>435.21</td>
<td>435.21</td>
<td>435.21</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>18</td>
<td>16</td>
<td>19</td>
<td>20</td>
<td>18</td>
<td>19</td>
<td>18</td>
<td>19</td>
</tr>
</tbody>
</table>
An image of a probed and turned-on LED specimen emitting blue light is shown in Figure 3-9.

Figure 3-9: Image of a turned-on LED emitting blue light.

### 3.3 Discussion

Given the I-V and corresponding L-I data measured, device EQE and WPE in different conditions can be calculated by Equation 3.4 and 3.5, respectively,

\[
\eta_{EQ} = \frac{P_{out}/(\hbar \omega)}{A J/q} \tag{3.4}
\]

\[
\eta_{WP} = \frac{P_{out}}{A J V} \tag{3.5}
\]

where \(P_{out}\) is the total optical output power already normalized by the calibrated setup collection efficiency, \(\hbar \omega\) is the mean photon energy which can be easily converted by the 450 nm central emission wavelength, \(A\) is the area of LED active region, \(J\) is the injection current density, and \(V\) is the corresponding bias. The dependence of calculated EQE and WPE on LED current density at different temperatures are shown in Figure 3-10. As expected, EQE exhibits a small efficiency droop at high current density. It is notable that, although the peak EQE reduces with increasing temperature, the peak WPE has no apparent drop. In fact, since the light collection
of the experimental setup is optimized at room temperature only, thermal expansion of the heated sample holder (relative to the photodetector) and the resultant optical misalignment is likely responsible for the small roll-off in the measured WPE at higher temperatures, which was actually indicated in the setup calibration procedures described in Chapter 2.

The dependence of EQE and WPE on LED bias at different temperatures are also shown in Figure 3-11. It is observed that with the increase of temperature, peak WPE point gradually moves towards lower bias regime with virtually no reduction in value. As discussed in Equation 3.1 this is mainly because of the overall reduction in bias voltage at elevated temperatures. In addition, it seems that the relatively small drop in device EQE at large thermal excitation also had a decisive impact to it. A closer comparison for the two extreme cases at 295 K and 615 K is shown in Figure 3-12 with their corresponding light output power plotted together. As labeled in the figure, the bias voltage 3.35 V corresponding to peak WPE at 295 K
has moved to $2.5\,V$ at $615\,K$, with nearly fourfold increase in light output power and only $0.42\%$ reduction in WPE (not calibrated for thermal expansion). More detailed operating conditions for peak WPE at different temperatures are listed in the table of Figure 3-13 below. It clearly tracks the continuous change of peak WPE and the corresponding EQE, indicating a growing light output power and reduced forward bias at higher temperatures. Note that, the value of WPE starts to exceed EQE at $535\,K$, indicating the onset of low bias operation ($V < \hbar\omega/q$) and effective thermoelectric pumping. In addition, the injection current density in the case of $615\,K$ ($3.26\,A/cm^2$) is already close to the value of $5\,A/cm^2$, which is the operating point of common high power GaN based LEDs.

Figure 3-11: EQE and WPE versus LED bias voltage at different temperatures. The bias voltage corresponding to the photon energy is indicated.

To further look into the role that Peltier effect plays at different operation conditions, the total LED heating power (per unit area) $Q_{\text{total}}$ generated from all sources including Peltier heating (intra-band phonon emission or absorption) $Q_{\text{Peltier}}$, non-
Figure 3-12: EQE (dashed lines) and WPE (solid lines) versus LED bias voltage at two extreme temperatures cases. All blue lines correspond to 295 K room temperature operation, and red lines correspond to 615 K high temperature operation. The bias voltage corresponding to the photon energy is indicated.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>V (V)</th>
<th>J (A/cm²)</th>
<th>P_OUT at Max WPE (W/cm²)</th>
<th>η_EQE (%)</th>
<th>η_WPE_MAX (%)</th>
<th>Q_Peltier (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>295</td>
<td>3.35</td>
<td>0.61</td>
<td>2.40</td>
<td>14.31</td>
<td>11.77</td>
<td>3.46 × 10⁻¹</td>
</tr>
<tr>
<td>375</td>
<td>3.10</td>
<td>1.00</td>
<td>3.61</td>
<td>13.07</td>
<td>11.61</td>
<td>3.12 × 10⁻¹</td>
</tr>
<tr>
<td>455</td>
<td>2.95</td>
<td>2.11</td>
<td>7.01</td>
<td>12.06</td>
<td>11.26</td>
<td>3.43 × 10⁻¹</td>
</tr>
<tr>
<td>535</td>
<td>2.75</td>
<td>2.94</td>
<td>9.06</td>
<td>11.19</td>
<td>11.21</td>
<td>−9.83 × 10⁻²</td>
</tr>
<tr>
<td>615</td>
<td>2.50</td>
<td>3.26</td>
<td>9.24</td>
<td>10.30</td>
<td>11.35</td>
<td>−9.02 × 10⁻¹</td>
</tr>
</tbody>
</table>

Figure 3-13: Conditions of reaching peak WPE at different temperatures.

radiative carrier recombination $Q_{\text{non-rad}}$ and Joule heating $Q_{\text{Joule}}$ arising from series
resistance can be analyzed and expressed as:

$$Q_{total} = Q_{Peltier} + Q_{non-rad} + Q_{Joule} = JV \times (1 - \eta_{wp})$$  \hspace{1cm} (3.6)$$

An approximate magnitude for the Peltier heating component $Q_{Peltier}$ can be determined from:

$$Q_{Peltier} = (V - IR_s - \frac{\hbar \omega}{q}) \times J$$  \hspace{1cm} (3.7)$$

where $R_s$ is the total series resistance of the LED. Simple calculations for the asymptotic inverse gradient of the I-V curves at high bias side (refer to Figure 3-5) show that $R_s$ has a value of 44.3Ω, 33.1Ω, 15.4Ω, 9.7Ω and 6.6Ω at 295K, 375K, 455K, 535K and 615K, respectively. It can be observed that the total heating power $Q_{total}$ is always positive so long as the wall-plug efficiency is below 100%, while the total Peltier heating component could become negative at low bias regime ($V < \frac{\hbar \omega}{q}$), indicating a transition from Peltier heating to Peltier cooling. For instance, a plot of $Q_{total}$ and $Q_{Peltier}$ versus LED bias at 295K and 615K is shown in Figure 3-14. A clear comparison in the relative magnitude of Peltier cooling power for the two temperature cases shows its dependence on the junction temperature: the Peltier effect is greatly enhanced at larger thermal excitation (i.e., higher junction temperature), mainly due to the exponential increase of injection current $J$, according to Equation 3.7. Note that the reduced series resistance of LEDs at higher temperature seems to have a negative impact on enhancing the Peltier cooling effect, according to Equation 3.7. But in fact it is not, since the Peltier effect is only relevant to the region near LED junction where a potential barrier exists, and the external bias $V$ will always compensate the voltage drop at the contact resistance, no matter how large it is (e.g., at $V = 2.76\, V$, $IR_s$ is $0.97\, mV$ at 295K and $51\, mV$ at 615K). Thus the change of term $IR_s$ at different temperatures only affects the magnitude of $Q_{Joule}$ (and $Q_{total}$), never for $Q_{Peltier}$. The Peltier heating power (per unit area) for peak WPE operation at different temperatures is also listed in the Table of Figure 3-13. Again the change of sign of these values indicates the initiation of effective thermoelectric pumping.
Based on the observation of the maximum WPE at bias $V < \frac{h\omega}{q}$ and the analysis of $Q_{Peltier}$ demonstrated above, we can conclude that the LEDs enhanced high temperature performance is fundamentally attributed to the thermoelectric pumping mechanism as we expected. In the low bias regime that we are interested, thermal excitation due to Peltier effect is necessary for a considerable amount of carrier injection. In other words, the LED works in a mode similar to a thermodynamic heat engine operating with charged carriers pumped into the active region by a combination of electrical work and Peltier heat (phonons) drawn from the lattice [41], as depicted in Figure 3-3. The absorption of Peltier heat near junction area can be
better understood from the perspective of statistical mechanics: only carriers at the high energy tail of Boltzmann distribution can be thermionically emitted above the diodes built-in potential barrier into the active region, with the remaining carriers absorbing heat from lattice (i.e., electron-phonon scattering) to restore the quasi-equilibrium distribution. If lattice temperature increases, carrier temperature also increases and thus the corresponding distribution profile moves towards higher energy. In this case the thermionic emission can happen more easily and the Peltier effect is more conspicuous.

However, it is found that, although the thermoelectric pumping mechanism introduces an additional pathway of input energy, the improvement of LED WPE at the low bias, high temperature regime is still conditional since fewer injected carriers could result in radiative recombination — EQE reduces at elevated temperatures. In other words, the optimal regime proposed for thermoelectric pumping does not universally exist for common GaN based LEDs. The successful demonstration of the specimen studied in this work is not only attributed to its property of low current-induced droop, but more importantly, also to the low thermal-induced droop. To achieve low thermal droop, reducing the density of defect states in LED active region is crucial, as the trap assisted SRH non-radiative recombination dominates the temperature dependence at low-bias \[111\].

By assuming that traps capture electrons and holes at the same rate, the SRH recombination lifetime \(\tau_{SRH}\) has approximately the following temperature dependence \[2\]:

\[
\tau_{SRH} = \tau_0 (1 + \cosh \frac{E_{Trap} - E_{Fi}}{k_B T})
\]

where \(\tau_0\) is a constant dependent on defect density and carrier capture rates. Increasing the density of defect states results in smaller \(\tau_0\). \(E_{Trap}\) and \(E_{Fi}\) are the trap energy level and intrinsic Fermi level within the energy bandgap, respectively. According to the temperature dependence of Equation \[3.8\], we can see that a higher temperature LED junction results in an exponentially shorter SRH lifetime and thus a lower IQE.

An empirical relation describing LED light output power at different temperatures
(for a constant current density) is given by [111]:

\[
P_{\text{out}}(T) = P_{\text{out,}300K} \times \exp\left(-\frac{T - 300K}{T_c}\right) \quad (3.9)
\]

where \(T_c\) is the device characteristic temperature, with higher value indicating better thermal droop performance. At a current density around 10 A/cm\(^2\), compared to the \(T_c\) values of less than 200 K for typical GaN based LEDs grown on c-plane sapphire substrates [111], the samples we studied here exhibit a much higher value of 869 K, indicating a lower decay rate in IQE with increasing temperature. According to the theory in Equation 3.8, this is likely due to the reduced defect density in the active region of our sample LEDs, which is realized by the high-quality growth on native GaN substrates.

All the above discussions about the LED thermal enhancement are based on the experimental results extracted from the LED specimen from epi no. S121216AL (LED1). We can also examine and compare this performance for the other specimen from epi no. S130110AL (LED2), which has an exactly the same device structure but with slightly shorter central emission wavelength (the same LED introduced in the previous section of spectral analysis). After obtaining the I-V and L-I sweeping data, the measurement results are processed in a similar way for an EQE and a WPE plot in Figure 3-15 and 3-16, respectively, at two extreme temperatures of 295 K and 615 K. The bias voltage corresponding to the photon energy of LED1 is also indicated by a vertical line in both figures (the photon energy of LED2 corresponds to a slightly larger bias of 2.84 V). From the EQE plot, it is found that both LED specimens actually exhibit a similarly non-significant thermal-induced droop effect, but LED2 somehow has lower EQE at small injections. This is likely due to the more significant SRH recombination, according to the rate equation model in 3.2.

Therefore, different from LED1, LED2 effectively presents a much reduced EQE in the low bias regime \(V < \hbar\omega/q\) at 615 K, which directly leads to a conspicuous reduction in the maximum achievable WPE at this high temperature, according to Figure 3-16. It is also notable that, the transition of LED bias conditions corresponding to the
The WPE\textsubscript{max} point between the two extreme operating temperatures crosses the bandgap voltage for LED1, but not for LED2, as indicated by the green arrows in the figure. In this case, the lower high temperature performance exhibited by LED2 is still likely due to the increase of defect density in the LED active region, which led to a lower device EQE at small injections as mentioned above and this might be originated by the lesser indium incorporation in the QW growth processes (it typically requires higher growth temperature).

![Figure 3-15: EQE calculated for LED1 (i.e., the specimen from epi no. S121216AL) and LED2 (i.e., the specimen from epi no. S130110AL) are plotted in blue and red lines, respectively. Solid lines indicate the LED operation at 295 K room temperature and dashed lines are for 615 K high temperature. The bias voltage corresponding to the photon energy of LED1 is indicated.](image-url)

A similar comparison of the high temperature performance with commercial LEDs is also made here. The I-V and L-I characteristics of conventional blue LEDs grown on c-plane sapphire substrates are extracted and adapted from the experimental results in Meynard \textit{et al.} \[32\]. A calculation of their EQE and WPE is performed and a
Figure 3-16: WPE calculated for LED1 (i.e., the specimen from epi no. S121216AL) and LED2 (i.e., the specimen from epi no. S130110AL) are plotted in blue and red lines, respectively. Solid lines indicate the LED operation at 295 K room temperature and dashed lines are for 615 K high temperature. The bias voltage corresponding to the photon energy of LED1 is indicated.

Comparison with the device studied in this work are plotted in Figure 3-17 and 3-18 respectively (here the efficiency of each device have been normalized in the figures for a clearer comparison). In both plots, the legend “Chip1” refers to the LED specimen from epi no. S121216AL (i.e., LED1). The bias voltage corresponding to the photon energy of conventional 440 nm blue LEDs is indicated by a vertical line. Compared to our specially made device, EQE of the conventional blue LEDs drops dramatically at low injections. In addition, they present a much more severe thermal droop effect at the elevated temperature of 450 K. Therefore, these undesirable characteristics of the conventional blue LEDs together lead to a significant reduction in the WPE at higher temperatures, which is indicated in Figure 3-18. This is also why the heat sinks are necessary components for the commercial high-power blue/white LEDs. On
the contrary, the proposed low-bias high-temperature operating regime is ideal for our device to achieve a better thermally enhanced performance. Again, this is essentially due to the unique property of low thermal droop of our device, which is ultimately realized by the high-quality growth on native semi-polar substrates to reduce the density of defect states in the LED active region.

Figure 3-17: Comparison of EQE for our device (in red lines) and conventional commercial blue LEDs (in green lines). Dashed lines represent the measurement data at 330 K and solids lines are for 450 K operation. The bias voltage corresponding to the photon energy of conventional 440 nm blue LEDs is indicated.

In summary, by taking advantage of the thermoelectric pumping effect, we are able to demonstrate a thermally enhanced 450 nm high power GaN LED, in which nearly fourfold light output power is achieved at 615 K (compared to 295 K room temperature operation), with nearly no reduction in the wall-plug efficiency. Under this 615 K maximum WPE operating condition at $V < \hbar \omega/q$, the LED injection current ($3.26 \text{ A/cm}^2$) is found to be close to the value of $5 \text{ A/cm}^2$, which is the operating point of common high power GaN based LEDs. This result suggests the
Figure 3-18: Comparison of WPE for our device (in red lines) and conventional commercial blue LEDs (in blue lines). Dashed lines represent the measurement data at 330 K and solids lines are for 450 K operation. The bias voltage corresponding to the photon energy of conventional 440 nm blue LEDs is indicated.

possibility of removing bulky heat sinks in commercial high power LED products, bringing a considerable reduction in the cost for general illumination. In addition, this demonstration also indicates that in order for an blue emitter to realize an effective thermal enhancement of the performance at the proposed operating regime, the maintenance of a relatively high device IQE is a necessary condition, which in turn requires the device to have the properties of low thermal-induced droop as well as low current-induced droop.
Chapter 4

Thermodynamics of Efficient Visible Lighting

In the literature, researchers have studied the thermodynamic bound of energy conversion efficiency on LEDs, which mainly focused on the methodology including model construction, derivation, and validation of assumptions. Such models as reviewed in Chapter 1 (Section 1.3.2) are not specific for visible LEDs, but apply generally for incoherent electroluminescent emitters at all wavelengths. Here in this chapter, in order to better understand the potential of visible LEDs for further efficiency improvement at useful light intensities, we present a thermodynamic analysis discussing the characteristics and criteria for efficient visible lighting in sections 4.1, 4.2 and 4.3. This thermodynamic framework allows us to estimate the Carnot limit for the WPE of a visible LED at different operating conditions. We find that the theoretical efficiency limit drops at higher light intensities but can still be well above unity even at 10 $W/cm^2$. Ideally, realizing such high efficiency at useful output powers requires the device to possess an EQE close to unity. Here we are able to introduce dissipation into the thermodynamic model and thus determine a minimum EQE required for an LED to achieve unity WPE. In addition, the thermodynamic study for visible LEDs yields one surprising result, suggesting that the electroluminescent emitters of shorter wavelength are actually more suitable for high-power solid-state cooling.

Previous work studying the thermodynamic models and efficiency limits of pho-
toluminescence and electroluminescence are all in the case of reversible limit \[16, 21, 43–46, 109\]. In section 4.4 of this chapter, we also propose a tighter bound of the efficiency as a further step by considering a thermodynamic irreversibility associated with optical extraction, which is already known as radiance constraints in the context of passive optical systems and is often described in terms of etendue of the light \[106\].

If we consider the steady-state photon extraction process from within the LED to the far-field of the LED being a passive optical system, we show that the thermodynamic temperature of the internal radiation field within the LED is higher than that in the far-field. This higher temperature demands more work to be done by the power supply to sustain the electroluminescence, and hence lowers the WPE compared to ideal reversible case. In this chapter, an irreversible thermodynamic model for energy conversion in an LED will be constructed by considering and comparing the temperatures of the internal and far-field radiation fields.

### 4.1 Carnot Limit of LED Efficiency

#### 4.1.1 Wavelength Dependence

In Chapter 1, we have briefly introduced the mechanism of the LED as heat pump, and reviewed the thermodynamic bound of its wall-plug efficiency. This efficiency bound typically depends on the exact operating condition of an LED, including detailed information of the electroluminescent radiation field, as well as the operating lattice temperature, according to the following expression previously derived,

\[
\eta_{wp} = \frac{I_r}{JV} \leq \frac{I_r}{I_r - T_l\Phi_r}
\]  

(4.1)

With the analytical solution available here, and combining the calculation methods for \(\Phi_r\) introduced in Chapter 1(Section 1.3.2), let us briefly examine the thermodynamic bound of WPE for visible LEDs of different wavelengths operating with useful output power. In the following calculations, steady-state electroluminescent radiation produced by different LEDs are all assumed to have Gaussian spectral profile
with fixed 20 nm linewidth (full width at half maximum) regardless of the exact LED operating condition. This is close to the typical spectral width for visible LEDs [2]. In Figure 4-1 below, the efficiency limits of LEDs with different colors are plotted against a wide range of optical intensity \(i.e., I_r\). This plot indicates that LEDs could be more efficient at lower optical intensity or longer emission wavelength, since the corresponding electroluminescence contains more entropy per unit optical power, allowing a higher ratio of heat influx to participate in carrier excitation for radiative recombination. This trend has an exception at high brightness, where intersections appear and the efficiency limits of all LEDs asymptotically approach unity. It is reasonable since the thermal energy \(k_B T_l\) available in the lattice becomes increasingly insufficient at higher optical power when more carriers are electrically pumped by the higher voltage. Also, the WPE is theoretically unbounded when the output intensity diminishes. As for the case of indoor-light-level LED brightness, the efficiency limits all reach 120% or higher, which are significantly higher than the conventional limit of unity. Even for emerging high-power applications requiring output of hundreds watt per centimeter square, the maximum optical power achievable by LEDs could still surpass the electrical input by more than 5%, with the remaining energy drawn from the lattice as heat. In such an operating regime with WPE over unity, the LED indeed works as a light-emitting refrigerator.

### 4.1.2 Temperature Dependence

According to Equation 4.1, the maximum achievable WPE not only varies with different LED color and brightness, but also has a strong dependence on the lattice temperature. In Figure 4-2, efficiency limit is plotted for a 415 nm blue LED operating at different temperatures. As expected, high lattice temperature tremendously improves the upper bound of WPE while other conditions remain the same. This is because the amount of heat absorbed per unit entropy from the lattice increases linearly with the increasing of local temperature, thus reducing the necessary amount of electrical input. In addition, it is not surprising that the actual LED efficiency in practical cases may also follow this theoretical prediction of the bound, as increased
thermal energy available in the LED lattice could further improve carrier excitation. But in reality, the enhancement of WPE at elevated temperatures requires the device EQE to remain relatively stable (i.e., does not drop significantly at higher temperatures). Such an effect of thermal enhancement is recently reported with experimental results on a high-power blue LED die [64], with its details discussed in Chapter 3. As a straightforward comparison, the performance of a state-of-the-art device of the same spectral profile is also shown in Figure 4-2 with a dashed line in grey [15]. We can see there is still room for efficiency improvement (more than 30%) under room temperature operation. It also suggests that temperature manipulation could be an effective method to further enhance the WPE since the bound is extended at the same time.
Figure 4-2: Efficiency limit versus intensity are plotted in solid lines for an LED with 415 nm central wavelength operating at 300K (blue), 400K (green), 500K (orange), and 600K (red), respectively. Dashed line in grey represents the experimental result published by Hurni et al. for the 300K measurement [15].

4.1.3 Inference on Current-Voltage Relation

A fundamental restriction imposed on the current-voltage (J-V) relation of all LEDs is also implied from the above thermodynamic analysis. Assuming the EQE of an LED is constantly unity, the current density of the device can be simply converted from its optical intensity $I_r$ by dividing the photon energy and multiplying the electron charge. Besides, the minimum input power corresponding to the same optical intensity can be derived from the efficiency bound previously calculated, so would the minimum bias required, i.e.,

$$ J = \frac{qI_r}{\hbar\omega} \quad (4.2) $$

$$ V_{\text{min}} = \frac{I_r}{J \cdot \text{WPE}_{\text{max}}} \quad (4.3) $$
In this manner, a J-V relation indicating the minimum bias requirement for LEDs operating at specific output power can be established. This is a fundamental result directly imposed by the Second Law of Thermodynamics, thus completely independent of the electrical property of any particular device. In Figure 4-3, J-V relations (at 300K) for the same group of visible LEDs are plotted with solid lines in their corresponding colors. Dashed lines of the same color indicate the asymptotic behavior for each of them, which also reflect the bandgap energy matching the LED central wavelength. By observing the J-V curves at low current density, we can see thermal energy may play an important role in assisting the electrical excitation to inject each carrier into the LED active region. However at high current density, it implies a full electrical excitation, which agrees well with the efficiency trend in Figure 4-1. In addition, Figure 4-3 indicates that even in the thermodynamic perspective, J-V relation of LEDs should also approximately follows the exponential diode law in order to operate efficiently.

4.2 Unity-Efficiency EQE of LEDs

According to the derivation shown, the thermodynamic efficiency limit of LEDs is independent of device EQE, which means that an efficient operation with \( \eta_{\text{wep}} > 1 \) is possible even at very low EQE as long as the device electrical property allows a large enough current being produced in an LED by a small bias. This is because the maximum WPE condition at a given \( I_r \) only requires a constant minimum input power \( JV_{\min} \), and if EQE reduces, \( J \) must increase with a smaller \( V_{\min} \) in order to maintain the original output power and the high efficiency. This unconventional case could be achieved under certain conditions (e.g., extremely low power operation) [62, 63], but typically for LEDs with useful output intensities, high WPE directly associates with high device EQE – i.e., in most cases, the thermodynamic efficiency limit of an LED corresponds to the unity EQE condition only. That is why the pursuit and maintenance of high EQE is still the most common goal for the design of high-power high-efficiency LEDs in the industry. To be more specific, the main objective
Figure 4-3: The minimum voltage required versus current density produced at 300K for LEDs with central wavelength at 400 nm (violet), 500 nm (cyan), 600 nm (orange) and 700 nm (red) are shown with solid lines in their corresponding colors, respectively. Unity EQE is assumed. Dashed lines represent the asymptotic behaviors of J-V curves in the same color.

of current research focusing on the optimization of high-power LED structures is to overcome the problem of efficiency droop (i.e., EQE reduction) at high current density or high temperature, as introduced in Chapter 1. Therefore, understanding that the achievement and maintenance of unity EQE is difficult, it is then important to know the minimum EQE required for an LED to achieve unity WPE, in which case no incoming electrical power is lost as waste heat, and thus the heat sink is no longer necessary.

Assuming the LED operation at the WPE limit corresponds to the condition of unity device EQE and the LED also has a monotonic increasing I-V relation, we can write an expression for LED output intensity $I_r$ under two different operating conditions, i.e., the maximum WPE condition (with unity EQE) and the unity WPE
condition (with EQE below unity), respectively,

\[ I_r = J_0 \cdot V(J = J_0) \cdot (\eta_{wp})_{max} = \frac{J_0}{\eta_{EQ}} \cdot V(J = J_0) \cdot 1 \]  \hspace{1cm} (4.4)

where \( J_0, V(J = J_0) \) are the current density and bias voltage when the LED achieves the thermodynamic efficiency limit \((\eta_{wp})_{max}\), respectively, for producing \( I_r \), while \( \frac{J_0}{\eta_{EQ}} \), \( V(J = \frac{J_0}{\eta_{EQ}}) \) are the correspondingly increased values for the same device when the original unity EQE drops to a value of \( \eta_{EQ} \), which is the minimum EQE possible for the LED to achieve a unity WPE. If diode law is further assumed for Equation 4.4 and after simple transformations, we have,

\[ \frac{\ln(J_s J_0) + 1}{\ln(J_0 + 1)} = \eta_{EQ} (\eta_{wp})_{max} \]  \hspace{1cm} (4.5)

where \( J_s \) is the saturation current density of the device with a typical value of \( J_s = 10^{-6} A/cm^2 \). According to Equation 4.5, \( \eta_{EQ} \) can be numerically solved for a given output condition. This result is general and independent of device ideality factor. In Figure 4-4 below, calculated values of \( \eta_{EQ} \) (at 300K) are plotted with dashed lines for the same group of visible LEDs. Though the curves are not simply monotonic, \( \eta_{EQ} \) decrease with the decreasing of optical intensity approximately within the range of interest for lighting purpose, namely above 0.1mW/cm². Also as expected, LEDs with shorter wavelengths need higher EQE.

Consider a case in which an LED is driven by a constant current density and initially operates at room temperature with WPE lower than unity. As a result of self-heating, the lattice temperature rises after some time, which could lead to a thermally induced WPE enhancement as explained in the previous section (i.e., in the case that the device EQE does not decrease dramatically at higher temperatures). This efficiency improvement would in turn reduce the self-heating power of the LED, and thus the lattice temperature would grow slower and slower, and finally stabilize. In the ultimate steady state, the WPE should be near unity if the LED package is well-designed for thermal isolation (i.e., in order for the LED to maintain at the elevated temperature with a small self-heating power), in which case the device EQE
Figure 4-4: The upper bound of WPE for LEDs operating at room temperature (300K) with central wavelength at 400nm (violet), 500nm (cyan), 600nm (orange) and 700nm (red), are shown with solid lines in their corresponding colors, respectively. Dashed line in the same color represents the minimum EQE required to achieve unity WPE.

is approximately the value of $\eta_{EQ}$ at the current elevated temperature. In Figure 4-5 below, $\eta_{EQ}$ is calculated and plotted for visible LEDs of different central wavelengths operating at 300K and 600K, respectively. It is apparent that the high temperature LED operation, which requires a good thermally isolated LED packaging if no external heating is provided, is crucial for the relief of the stringent EQE requirement to achieve unity WPE.

### 4.3 ELC in Different Regimes

The first observation of above-unity WPE (i.e., ELC) was on a heated 2.2 µm infrared LED [62], and the subsequent demonstration at room temperature necessarily required a longer-wavelength 3.4 µm device in order to realize sufficient carrier injec-
Figure 4-5: Minimum values of EQE required to achieve unity WPE are plotted for visible LEDs operating at 300K (solid lines) and 600K (dashed lines), respectively. Lines corresponding to LEDs with central wavelength at 400nm, 500nm, 600nm, and 700nm are shown in violet, cyan, orange and red, respectively for both temperatures.

However, our thermodynamic analysis indicates that at useful optical powers—and hence useful cooling powers—visible LEDs of shorter wavelength are expected to show stronger cooling capability at a lower current density.

The maximum cooling power of an LED, $P_{\text{cool}}$, is the difference between its optical power, $P_{\text{opt}}$, and electrical input power in the condition of maximum WPE:

$$P_{\text{cool}} = \left( \frac{\eta_{wp}}{\eta_{wp}} \right)_{\text{max}} - 1 \frac{P_{\text{opt}}}{\eta_{wp}}$$

The maximum cooling power density at different levels of LED brightness is plotted in Figure 4-6 below, which shows to grow exponentially with optical intensity at very low bias, but saturates at high intensity. LEDs of longer wavelength are found to have higher thermodynamic bounds for cooling at low optical intensity, but the situation
reverses at high intensity instead. This wavelength associated cross-over shown in Figure 4-6 is actually originated from the similar phenomenon exhibited in Figure 4-1. To further exploit this result, it in fact reveals two distinct cooling regimes of LEDs: (1) the low-power regime, suitable for LEDs of long wavelength operating at low EQE; (2) the high-power regime, suitable for LEDs of short wavelength operating at high EQE. Limited by the current fabrication techniques and material quality, only the former case was experimentally demonstrated for now, as mentioned in the beginning of this section [62, 63].

Figure 4-6: Maximum cooling power at 300\(K\) for LEDs with central wavelength at 400\(nm\) (violet), 700\(nm\) (red), 1550\(nm\) (green) and 3500\(nm\) (grey) are shown with solid lines, respectively.

4.4 Irreversible Thermodynamic Modeling

The above thermodynamic discussions are all based on an idealized LED model in the reversible limit. In practice, all kinds of irreversibilities may enter into the system.
and the efficiency limit will decrease correspondingly. In this section, one of the most essential irreversibilities associated with passive optical extraction is introduced in the thermodynamic LED modeling by considering the entropy and temperature of the internal and far-field radiation fields.

In the following, basic rate equations for energy and entropy change will be revisited for the LED electronic system in order to derive an upper bound of WPE in the reversible limit within a newly built thermodynamic framework. After converting the upper bound to a form associated with the temperature of far-field radiation, we see that an ideal forward-biased LED can be interpreted as a reversed Carnot engine. Then through an analysis revealing the imbalance of the temperatures for the radiation field inside and outside an LED, an irreversible thermodynamic model is further developed for an LED in steady-state operation, as well as a tighter bound of the WPE.

Consider an LED die with a planar top-emitting structure. We investigate an open system consisting of the electrons within the device (i.e., the LED electronic system). In forward-biased, steady-state operation, the system is electrically pumped by entropy-free input work at the rate \( JV \) per unit area (where \( J \) is the current density and \( V \) is the bias voltage), and emits electromagnetic energy through spontaneous radiative recombination at the net rate (per unit area) \( R_{sp} \) from active region to the surrounding, where the radiation is assumed to be distributed isotropically within the LED, as shown in Figure 4-7. We further assume there is no internal loss, thus the net radiation power leaving the LED from its internal radiation field through the top emitting surface (per unit area), denoted as \( I_r \), must equal to \( h\bar{\nu}R_{sp} \) in the steady state, i.e.,

\[
\frac{1}{A} \frac{dE_{r,i}}{dt} = h\bar{\nu}R_{sp} - I_r = 0 \tag{4.7}
\]

where \( h \) is Plank's constant, \( \bar{\nu} \) is the mean photon frequency, \( A \) is the emitting area of the LED die, and \( E_{r,i} \) is the total energy of the internal radiation field. However, according to the Second Law of Thermodynamics, the net rate of entropy leaving the
Figure 4-7: Block diagram showing the irreversible thermodynamic model of an LED.

Electronic system carried by $h\nu R_{sp}$, denoted as $\Phi_{sp}$, must be less or equal to that leaving the LED from the internal radiation field, denoted as $\Phi_r$, i.e., in the steady state,

$$\frac{1}{A} \frac{dS_{ri}}{dt} = \Phi_{sp} + \Delta \Phi_i - \Phi_r = 0$$  \hspace{1cm} (4.8)$$

where $S_{ri}$ is the total entropy of the internal radiation field, and $\Delta \Phi_i$ is a non-negative entropy generation rate of the internal radiation field (per unit projected area) corresponding to any irreversible processes. In such a configuration, if ignoring all boundary effects between the LED emitting surface and the ambient, the far-field
radiation pattern from the LED would be Lambertian and the optical intensity scales with the inverse square law as the distance increases from observer to the LED. In the analysis presented here, all the radiation power and associated entropy refer to the electroluminescence only. Effects from the background thermal radiation of the LED, are negligible due to detailed balance with the ambient.

Along with the process of minority carrier injection, the electronic system also absorbs heat from the lattice at the net rate $Q$ per unit area due to Peltier effect at the diode junction. This heat transfer process is related to the restoration of the carrier distribution, and is assumed to take place sufficiently close to the quasi-neutral regions of the LED, where carrier temperature can be considered the same as that of the lattice due to fast electron-phonon scattering processes. The energy band diagram for a typical single quantum well LED depicting this process is shown in Figure 4-8. The LED lattice serves as a phonon reservoir with temperature $T_l$. Thus the net entropy transfer rate into the electronic system carried by $Q$ is approximately $Q/T_e|_{inj} \approx Q/T_l$, where $T_e|_{inj}$ is the electron temperature during injection process. We can write two rate equations, in the steady state, for the $E_{el}$ and $S_{el}$ be the total internal energy and entropy of the electronic system described above,

$$\frac{1}{A} \frac{dE_{el}}{dt} = JV + Q - \hbar \nu R_{sp} = 0 \quad (4.9)$$

$$\frac{1}{A} \frac{dS_{el}}{dt} = \frac{Q}{T_l} + \Delta \Phi - \Phi_{sp} = 0 \quad (4.10)$$

where $\Delta \Phi$ is the internal entropy generation rate (per unit area) in the electronic system, which is also non-negative due to irreversible processes associated with non-ideal LED operation such as non-radiative recombination, Joule heating, etc. Combining Equation 4.7 to 4.10 with the Second Law of Thermodynamics, we arrive the following inequality,

$$\Delta \Phi + \Delta \Phi_i = \Phi_r - \frac{I_r - JV}{T_l} \geq 0 \quad (4.11)$$
Figure 4-8: Energy band structure of a typical single quantum-well LED. Temperatures of different fields are labeled.

Thus the WPE of an LED, denoted as $\eta_{wp}$, must satisfy,

\[
\eta_{wp} = \frac{I_r}{JV} \leq \frac{I_r}{I_r - T_i \Phi_r}
\] (4.12)

According to Equation [4.12], the WPE of an LED has an upper bound that is dependent on the specific operating condition, and the bound is always greater than unity. This result is essentially because the incoherent electroluminescence of LEDs contains finite entropy, but the input electrical work does not. The Second Law of Thermodynamics then allows the LED electronic system to absorb some heat (with entropy accompanied) from the lattice as an extra input. In the extreme case in which the entropy influx carried by the heat absorbed exactly balances the quota imposed by that of the output electroluminescence, the upper bound of WPE is achieved.

A calculation of $\Phi_r$ is required to determine this bound for a given $I_r$. Assume $f_i(\nu)$ to be the mean value of photon occupancy per mode at frequency $\nu$ for the internal radiation field. The distribution of $f_i$ over the frequency range of interest depends on the LED emission spectrum and the total radiation power leaving the
where $g_i(\nu)$ is the density of optical modes per unit volume for the internal radiation field, $c$ is the vacuum light speed, and $n$ is the refractive index of relevant material. Since the internal radiation field is assumed isotropic, the coefficient $1/4$ is introduced from an integration related to the apparent area of emitting surface viewed by optical modes in different directions, similar to the case of poking a hole on the cavity of an ideal radiator [110]. This coefficient is subject to change if there is an index difference across the emitting interface, in which case the light escape cone shrinks. Then, given the entropy formula of an ideal Bose gas [20,108], the net rate of entropy leaving the LED carried by $I_r$ can be written as,

$$\Phi_r = \frac{c}{4n} \int k_B[(f_i(\nu) + 1) \ln(f_i(\nu) + 1) - f_i(\nu) \ln(f_i(\nu))]g_i(\nu) \, d\nu$$

(4.14)

where $k_B$ is the Boltzmann constant. Combining Equation 4.13 and 4.14, $\Phi_r$ can be obtained for any given $I_r$ and its spectral information. It is notable that the above construction of $\Phi_r$ assumes that all photons in a small frequency interval are uniformly distributed among all the optical modes available, i.e., all photons (of the same frequency) have the same probability to occupy any of the modes despite of the number of photons already in that mode. This assumption is very similar to the thermal equilibrium condition of the internal radiation field within each small frequency interval, thus $\Phi_r$ is maximized for a given $I_r$ together with its relative intensity spectrum. This assumption can be further extended such that the total incoherent electroluminescence produced by an LED has an intensity distribution of $I_r(\nu)$ over a given spectral interval close to that of a blackbody radiation. Given the above assumptions, a temperature definition for the electroluminescent radiation field naturally arises.

Assigning a temperature to the external radiation field (i.e., far-field) of the LED
has engendered much discussion in the literature \[21, 44, 46\]. Unlike the internal field, the external field itself is comprised of a ballistic ensemble of photons moving away from the device, and is not in quasi-equilibrium with the electrons and holes in the LED active region. Several authors have introduced a temperature definition for this external radiation field by considering the ratio between the energy and entropy flux leaving the LED, which is physically more like a characterization of heat transfer (i.e., the radiation close to the LED emitting surface) rather than a direct description of a thermal equilibrium system:

\[
T_f(\nu) = \frac{I_r(\nu)}{\Phi_r(\nu)}
\]  

(4.15)

For convenience, we can define a collective temperature to cover the entire spectrum of the far-field in a similar way, denoted as \(T_r\),

\[
T_r = \frac{I_r}{\Phi_r}
\]

(4.16)

This collective far-field temperature does not necessarily equal the result in Equation \[4.15\] for each small frequency interval. In fact, the ratio in such a form is commonly used in entropy balance equations for open systems to describe the temperature at the point of a heat flow \[113\]. In the literature studying thermodynamics of light, it was also referred to as “effective temperature” \[21\] or “flux temperature” \[46\]. Weinstein argued that \(I_r(\nu)/\Phi_r(\nu)\) is very nearly equal to the temperature of a blackbody which would have the same emission power in the band, and physically interpreted it as a “brightness temperature” \[21\]. Here in this work, a simple modeling of the LED far-field with the assumption of isotropic emission had been attempted in order to reach the same results as in Equation \[4.15\] and \[4.16\], but the proof turned out to be incorrect as it failed to consider the additional entropy generated during the isotropic photon redistribution process. Details of this modeling and the reason to abandon it can be found in Appendix B.
Apply definition 4.16 to Eq. 4.12, we have,

\[ \eta_{wp} \leq \frac{T_r}{T_r - T_l} \]  

(4.17)

which is consistent with the result previously published by Weinstein [21]. In addition, we found the inequality in Equation 4.17 matches the expression of the coefficient of performance for a classical heat pump operating between a cold and a hot reservoir with temperature \( T_l \) and \( T_r \), respectively. Therefore, in the thermodynamic perspective, a forward-biased LED operating in the reversible limit can be considered equivalently as a reversed Carnot engine with its electronic system being the working fluid, lattice structure (i.e., the phonon field) being the low temperature reservoir and far-field radiation (i.e., the photon reservoir described above) being the high temperature reservoir. The four-step reversed Carnot cycle leads to a net effect by which charged carriers consumes external electrical work to pump heat from the LED lattice and release electroluminescence to the ambient.

So far, we have constructed and inspected the reversible thermodynamic model for an LED in the steady state. However, we have to be cautious and check whether the reversible limit is theoretically achievable, which requires (quasi-) thermal equilibrium between the internal and external radiation fields, since the internal field serves as an intermediate photon reservoir between the LED electronic system and the far-field. And even if it is valid, we still need to check whether a practical LED far-field truly has a temperature given in Equation 4.16, as it was previously proposed in the literature.

The following is an examination of the spectral temperature of the internal radiation field, which is denoted as \( T_i(\nu) \) and defined by,

\[
T_i(\nu) = \frac{\frac{d[u(\nu)]}{d[s(\nu)]}}{\frac{d[h\nu f_i(\nu)g_i(\nu)\Delta \nu]}{d[k_B((f_i(\nu) + 1)\ln(f_i(\nu) + 1) - f_i(\nu)\ln(f_i(\nu)))g_i(\nu)\Delta \nu]}} = \frac{dI_r(\nu)}{d\Phi_r(\nu)}
\]  

(4.18)
where \( u(\nu) \) and \( s(\nu) \) are the spectral energy and entropy density of the internal radiation field, respectively. Alternatively, \( T_i(\nu) \) can be directly calculated from \( f_i(\nu) \) by the Bose-Einstein distribution (with zero chemical potential) as well, which is equivalent to Equation 4.18. A simple numerical comparison shows that \( T_i(\nu) \) from Equation 4.18 is always larger than \( T_f(\nu) \) from Equation 4.15 for the same frequency, and the ratio between them increases with increasing \( I_r(\nu) \). A simple way to think about this mechanism is that, for the internal radiation field, only photons contained in modes directed towards the emitting surface can escape from the LED cavity and become distributed in the far-field. Therefore, together with the increased density of optical modes and conserved photon flux after the emission, the mean photon occupancy in the far-field of the LED is always smaller than that inside. If considering the ballistic transport nature of the external radiation flux, the far-field can thus be assigned a lower temperature as defined in Equation 4.16. The photon redistribution also justifies the entropy generation (or entropy maximization) during the optical extraction process, which may be caused by randomized scattering due to interactions with a roughened dielectric interface. Hence, the etendue of the radiation can increase after being extracted from the LED due to enlarged solid angle, and thus the output radiance reduces, which matches the argument of temperature reduction in the far-field. More importantly, in this situation the exact physical correspondence of \( I_r(\nu)/\Phi_r(\nu) \) to an (effective) temperature or how a practical LED far-field reaches this temperature no longer matters, since the intermediate photon reservoir — the internal radiation field has a higher occupancy (temperature) and is better approximated as a system in quasi-equilibrium with the distribution of electrons and holes in the LEDs active region.

Since \( T_f(\nu) \neq T_i(\nu) \) for any frequency, the reversible limit and the efficiency bound in Equation 4.17 cannot be achieved. As a result, similar to the treatment of an endo-reversible heat engine (Novikov engine or Curzon-Ahlborn engine, to be more specific) [114–116], the electronic system of the LED must operate against \( T_i(\nu) \) rather than \( T_f(\nu) \) during the radiative recombination process, which is interpreted as the introduction of an irreversibility into the ideal reversible model. In other words,
this semi-ideal thermodynamic configuration still consists of a fully reversible Carnot-like cycle in which the LED electronic system pumps heat from lattice temperature (low) to the temperature of the internal field (high). With the LED emitting surface being an effective heat exchanger, the internal field is then coupled irreversibly with the far-field of lower temperature to achieve a finite radiation power. This is reasonable as any useful LED must have a finite output, and its electronic system should directly interact with the internal radiation field, not any far-field. Besides, higher LED output intensity $I_r$ always corresponds to (or driven by) larger temperature difference between the internal and the external radiation fields, which can be viewed as a stronger irreversibility. This is consistent with the basic characteristics of endo-reversible engines. Therefore, a collective temperature definition covering the entire spectrum for the internal radiation field is defined as,

$$T_i = \frac{d\left[\int u(\nu) \, d\nu\right]}{d\left[\int s(\nu) \, d\nu\right]} = \frac{d\left[\int h\nu f_i(\nu)g_i(\nu) \, d\nu\right]}{d\left[\int k_B((f_i(\nu) + 1) \ln(f_i(\nu) + 1) - f_i(\nu) \ln(f_i(\nu)))g_i(\nu) \, d\nu\right]}$$  \hspace{1cm} (4.19)

Substituting for the temperature of hot reservoir in Equation 4.17, now we have,

$$\eta'_wp = \frac{I_r}{J\nu} \leq \frac{T_i}{T_i - T_l}$$  \hspace{1cm} (4.20)

Since $T_i > T_r$, Equation 4.20 provides a tighter and also more realistic bound than that in Equation 4.17. It is notable that, different from a typical Curzon-Ahlborn efficiency which is obtained from a similar thermodynamic configuration (heat engine rather than the heat pump model in this case) but specifically corresponds to a system condition of maximum output power, here $\eta'_wp$ does not carry this meaning, as $T_i$ is determined by the actual rate of heat transfer (i.e., $I_r$ and $\Phi_r$) rather than being optimally chosen. In this case, different LED outputs yield different $\eta'_wp$ according to Equation 4.20. In addition, we can plot a temperature-entropy diagram for the above
LED model to identify each thermodynamic process it implements, which is shown below in Figure 4-9.

Figure 4-9: The temperature-entropy diagram indicating the complete thermodynamic cycle implemented by an LED: (1) is an isothermal heat absorption process based on the Peltier effect; (2) is an isentropic process, in which the internal energy of the electronic system increases through electrical pumping, and the corresponding carrier temperature rises from $T_i$ to $T_i$ (note, to characterize the excited state of carriers at $T_i$, the term “carrier temperature” was sometimes specified as “apparent radiant temperature” in the literature [16]); (3) is another isothermal process describing the photon emission taking place at the LED active region where injected carriers are in quasi-equilibrium with the internal radiation field (a proof of the quasi-equilibrium status can be found in Appendix C); (4) is another isentropic process describing carrier recombination following the spontaneous photon emission, in which carriers relax from $T_i$ back to $T_i$.

Although we have used the collective temperature as defined in Equation 4.16, we could have obtained a similar limit by considering the temperature of the far-field for each frequency component, $T_f(\nu)$. The reversible limit of WPE can be derived for each small frequency interval within the spectral range of interest through the monochromatic version of Equation 4.17. If we replace $T_f(\nu)$ with $T_i(\nu)$ in the equation, the irreversible limits at those frequencies would be obtained, whose weighted average by the LED spectral profile could lead to an overall upper bound of the WPE similar to Equation 4.20. Therefore, given the radiation flux density of an LED (i.e., $I_r$) being properly measured for a $2\pi$ solid angle close to the emitting surface, the irreversible limit calculated by Equation 4.20 should serve as a good approximation for the upper bound of WPE. Also, the isotropic assumption of the internal radiation field, which allows us to assume a maximum entropy for the electroluminescent radi-
ation, justifies the definition of temperature. However, the key part of the arguments should still remain valid without this assumption as long as the gradient of photon occupancy exists between the optical modes of internal and far-field radiation fields. For the special cases of anisotropic internal radiation field, such as LEDs with strong Purcell effect or of small dimension compared to the photon wavelength, the total entropy of the output electroluminescence would be overestimated by this model, as would the upper bound of WPE. In principle, Equation 4.12 is universally applicable as long as the rate of total radiation entropy can be properly estimated.

It is necessary to clarify that, by indicating the internal radiation field, we refer to the electromagnetic field distributed within the entire solid structure of the LED die. If any packaging maternal (e.g., solid immersion lens) is attached to the LED die, it could also be counted towards the internal volume, but in this case the photon field within the packaging material will be characterized by the same internal temperature $T_i$ according to the model. Otherwise, if the LED package has very different structure or material properties, an intermediate radiation field may be further introduced accordingly, so as another irreversible process of photon coupling. By indicating far-field, we refer to the ambient (typically being vacuum or air).

Finally, let us examine the thermodynamic bound of WPE for typical LEDs operating with useful output powers. Here, the steady-state electroluminescence produced by LEDs are assumed to have Gaussian spectral profile regardless of the exact LED operating condition, which is close to the actual case. For any given (or measured) optical intensity $I_r$ with Gaussian spectrum, we can first use Equation 4.13 to retrieve the occupancy function $f_i(\nu)$ for the internal radiation field, and then put it into Equation 4.14 to calculate the associated entropy flux $\Phi_r$ of the total output. By applying Equation 4.16 and 4.17, a corresponding reversible bound of WPE is thus obtained, and the same for the irreversible bound by applying Equation 4.19 and 4.20. In Figure 4-10 shown below, the upper bound of WPE for LEDs of different spectral profiles are plotted against a wide range of optical intensity as it is a major dependence of the LED efficiency both empirically and theoretically. This plot indicates that LEDs could be much more efficient at lower optical intensity or longer emission.
wavelength, since the corresponding electroluminescence contains more entropy per unit optical power, allowing a higher ratio of heat influx to participate in carrier excitation. This trend has an exception at extremely high brightness. In addition, the maximum of WPE is unbounded when the intensity diminishes. For typical visible or infrared LEDs, the WPE in the reversible case can be as high as 130% to 250% at moderate brightness close to the indoor lighting condition, which is significantly higher than the conventional efficiency limit of unity. Even in the extremely high power condition near $100\, W/cm^2$, the output intensity could still non-trivially surpass the electrical input power by more than 5%, with the remaining energy drawn from the LED lattice. More importantly, the irreversible limit, as expected from our model, is always lower than the reversible one of the same condition. This correction to the theoretical upper bound of WPE becomes increasingly more conspicuous and necessary at longer wavelength.

In this Chapter, we have conducted a thermodynamic analysis for visible LEDs to discuss the characteristics and criteria for efficient visible lighting. A theoretical upper limit for the wall-plug efficiency is also obtained through a thermodynamic modeling of the LED in both the ideal reversible limit and the practical irreversible case by considering the passive optical coupling effect in the device. The purpose of this theoretical investigation is to better understand the potential of visible LEDs for a further efficiency improvement at useful light intensities, and hopefully some of the results can also serve as a guidance or direction for the future development.

Recalling the experimental study previously discussed in Chapter 3, we now understand better why an enhanced LED performance could be achieved at a higher temperature. If we plot the WPE versus Intensity curves based on the experimental results in Figure 4-2, we will find that the curves at higher temperatures simply translate to the right hand side compared to those at lower temperatures. This translation actually follows the change of efficiency limit curves of different temperatures shown in the figure. We also know that if the LED sample exhibits better droop characteristic, the higher temperature curves could even move upwards, which justifies our previous conclusion – the temperature manipulation could be an effective method to further
enhance the WPE of an LED, since the theoretical bound is extended at the same time. In addition, the section of ELC analysis also tells us that the large-bandgap GaN based blue LEDs are not only superior for visible lighting purposes, but also more suitable for the high-power electroluminescent cooling applications compared to the longer-wavelength emitters.
Chapter 5

Conclusion and Future Work

In this conclusive chapter, a summary of the thesis work will be provided first, followed by a discussion of possible future work.

5.1 Conclusion

In this thesis, a thermophotonic method based on the heat-pump mechanism is proposed to potentially enhance the efficiency of visible LEDs for high-power operation. By leveraging this special mode of incoherent electroluminescence and with the focus on GaN technologies, we experimentally demonstrate a thermally enhanced blue LED operating in the low bias regime, and theoretically investigate the characteristics and criteria for efficiency visible lighting based on a thermodynamic study.

This thesis work primarily consists of three parts: (1) preparation of the high temperature LED characterization platform, (2) demonstration and discussion of thermally enhanced blue LEDs, and (3) thermodynamic modeling and analysis of LEDs for efficient visible lighting. These three parts, corresponding to the discussions in Chapter 2, 3 and 4, respectively, will be summarized individually in the following sub-sections.
5.1.1 Preparation of Experimental Platform

In the present thesis work, experimental investigations pertinent to high temperature LED characterization are conducted. As the conventional method with the employment of standard integrating spheres is not feasible in our case due to the limitation of their maximum service temperature and the difficulty in sample probing, we constructed and calibrated our own setup in order to facilitate the experimental studies and ensure the measurement accuracy for our specially designed LED samples. This experimental platform consists of three major sub-systems: (a) light collection, (b) heating & temperature monitoring, and (c) probing & sourcing. With continuous optimization in the design and two-generation developments from the initial setup, the final upgraded version of the high temperature LED characterization platform meets all the requirements of the study objectives, and has proven to be efficient and robust in the subsequent tests.

5.1.2 Demonstration of Thermally Enhanced Blue LEDs

Researchers have been actively investigating the origins and remedies for the current droop problem of GaN based high-power LEDs for years. However, other than the passive cooling, a specific solution to the temperature induced efficiency droop (thermal droop) was not reported. In the present thesis, we investigate the possibility of thermoelectric pumping in wide-bandgap GaN based LEDs to take advantage of high junction temperature rather than avoiding the problem of thermal droop through external cooling. We experimentally demonstrate a thermally enhanced 450 nm high power GaN emitter, in which a nearly fourfold enhancement in light output power is achieved at 615 K (compared to 295 K room temperature operation), with virtually no reduction in the wall-plug efficiency. In this optimal operating regime at 615 K, the LED injection current (3.26 A/cm²) is of similar magnitude to the operating point of common high power GaN based LEDs (5 ∼ 35 A/cm²). This result suggests the possibility of removing the bulky heat sinks in current commercial high power LED products, thus realizing significant cost reduction and improved design flexibility. In
addition, this demonstration also indicates that in order for an blue emitter to realize an effective thermal enhancement of the performance at the proposed operating regime, the maintenance of a relatively high device IQE is a necessary condition, which in turn requires it to have the properties of low thermal-induced droop as well as low current-induced droop.

5.1.3 Thermodynamics of Efficient Visible Lighting

Other researchers have studied the thermodynamic efficiency limit of LEDs mainly focusing on the methodology (model construction and detailed derivation procedures, etc.) and is general for incoherent electroluminescence of all wavelengths. To better understand the potential of visible LEDs for further efficiency improvement at useful light intensities, in this thesis we present a comprehensive thermodynamic analysis investigating the characteristics and criteria for efficient visible lighting, which includes the study of wavelength dependence and temperature dependence of the LED efficiency limit, the finding about current-voltage restriction, the derivation of unity-efficiency EQE, and the analysis of different regimes of ELC.

Previous work investigating the thermodynamic bound of energy conversion efficiency for photoluminescence and electroluminescence are all in the case of reversible limit. Here, we also propose a tighter bound of the efficiency for a further step by considering a thermodynamic irreversibility associated with the mechanism of passive optical extraction. In the present thesis, an irreversible thermodynamic model for energy conversion in an LED is developed by considering and comparing the temperatures of the internal and far-field radiation fields. A new efficiency limit is then derived, and shown to be tighter and more realistic than the reversible case.

5.2 Future Work

As the thermal enhancement of blue LEDs has been conceptually and experimentally demonstrated in the present work, the next-step study shall aim to develop an actually useful device which is based on the same mechanism but is truly superior than the
current commercially available products – i.e., combining the design and fabrication techniques of the state-of-the-art devices with our proposed thermoelectric pumping mechanism for a realization of GaN based blue emitters with unity WPE.

To be more specific, this proposed future work is to demonstrate visible LEDs that operate at significantly lower voltage ($V < h\omega/q$) and higher energy conversion efficiency (approaching 100%). The goal is to obtain a heat sink-free 100% WPE blue LED. The technical goals are therefore to reach an IQE in the range of 90+% at low current (as operating at low voltage) and high temperature (in order to have enough current density at the chosen low voltage), and 90+% extraction efficiency. The overall EQE should be around 90%. The theoretical requirements on the device EQE to achieve unity WPE at different operating temperatures are discussed and derived in Chapter 4, which is considered as a good guidance for the design goals. The table below compares the expected performance of proposed devices to the performance of today’s state-of-the-art 450 nm blue LEDs (based on the 2015 DOE SSL RDP).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State-of-the-art</th>
<th>Proposed technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage</td>
<td>2.95 V</td>
<td>~2.5 V</td>
</tr>
<tr>
<td>$J$</td>
<td>5-50 A cm$^{-2}$</td>
<td>1-10 A cm$^{-2}$</td>
</tr>
<tr>
<td>IQE</td>
<td>80%</td>
<td>95%</td>
</tr>
<tr>
<td>$\eta_{\text{ext}}$</td>
<td>80%</td>
<td>95%</td>
</tr>
<tr>
<td>Source brightness</td>
<td>12-120 W/cm$^2$</td>
<td>2.75 W/cm$^2$</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20-85 °C</td>
<td>80-300 °C</td>
</tr>
<tr>
<td>WPE</td>
<td>60%</td>
<td>~100%</td>
</tr>
</tbody>
</table>

In the following, three specific tasks are listed for the proposed future work for achieving unity-efficiency blue LEDs.

5.2.1 Characterization of Blue LEDs with Different Polarizations

The primary task here is to make calibrated measurements of visible LEDs at voltages below the photon energy. To date, we have found limited published data on the quantum efficiency and wall-plug efficiency for low-bias voltages. These measurements will allow us to investigate fundamental recombination and transport processes in
nitride devices at low-carrier density where the influence of Auger recombination will be reduced.

We have already received several semi-polar and polar InGaN/GaN blue LED samples from our collaborators at UCSB. Complementing the electrical (I-V) and optical measurements we will use a suite of techniques to characterize recombination processes:

a) photoluminescence excitation
b) frequency impedance measurement
c) temperature-dependent I-V curve measurement

5.2.2 Model Building

Simulating the measurements obtained in Task 1 will require careful numerical modeling of the LEDs. Previously we have developed accurate numerical models of infra-red LEDs operating in both conventional and low-bias operating regimes. The agreement between numerical simulation and measurements is over four-orders of magnitude of operating current and light power. The models utilized a state-of-the-art engine (Synopsys Sentaurus Device) with only 3 experimentally derived fitting parameters for the full measurement range.

Nitride LEDs exhibit low-bias phenomena that are different from infrared LEDs. Chief among these are (1) the existence of large piezo-fields due to the built-in strain and highly polarized bonds between nitride layers and (2) alloy fluctuations which lead to large variations in the in-plane band parameters and dramatically lower the operating voltages. We will build a carrier transport model for InGaN/GaN blue LEDs based on the parameters we measured. This model will be a 3D drift-diffusion equation solver for carriers which takes piezoelectric fields, local strain and alloy fluctuation into account. We should will simulate the I-V and the IQE-I curves over a wide range of operating voltages.
5.2.3 Optimization for low bias LEDs

We will use the verified model to design InGaN/GaN blue LEDs with nearly 100% WPE. Possible ways to enhance the LED performance in the low bias regime include:

a) Optimal design of the single-quantum well active region thickness and barrier and doping.

b) We can decrease the contact layer doping level (p contact especially) of the device to enhance the extraction efficiency as we are operating at 10x lower current density.

c) The role of the electron blocking layer (EBL) in the carrier transport process is still under debate. Researchers have reported that the EBL might fail to confine the electrons and even decrease the hole injection rate. It is desired to investigate these effects and design the EBL for our low injection devices.

d) Optimize growth direction such that the IQE is minimally affected (or improved) by a combination of factors including the indium fluctuation, strain-induced/spontaneous polarization fields, etc at low bias condition.

e) Design of an LED packaging method with good thermal insulation property while maintaining the high transparency and light extraction, in order for the device to operate in the proposed regime at a higher temperature, which corresponds to a higher efficiency limit according to the thermodynamic study of this work.
Appendix A

Standard Procedures of LED Mounting

In order to characterize an un-packaged LED die in an integrating sphere, the sample must be pre-processed and mounted on a particular metal header before becoming compatible with the sample holding stage in the sphere. A standardized LED mounting procedure is briefly shown in Figure A-1 and the details are summarized in the following steps:

Step 1. Get the sample LED die ready once processed/fabricated.
Step 2. Mount the sample on a sapphire sub-mount, and on its top mount it with

Figure A-1: Standardized procedures for LED mounting.
a metal plate with silicon pieces. Coarsely lap the mounted sample (on the substrate side) with sand paper (#400-600) in a figure eight pattern repeatably.

Step 3. Mount the sample on the polishing metal plate and then mount the metal plate to the polisher. Polish the sample (in polisher) for 30 to 45 cycles. Do a solvent clean after the polishing.

Step 4. Conduct a photolithography on the polished backside with a roughening mask. Use ICP dry etch to clean the photoresist. Remove the sample from the sub-mount and clean it with solvent. Backside roughening pattern should appear.

Step 5. Carefully attach the sample on an adhesive tape and scribe the sample along the cut mark. Singulate and put the devices into different marked containers.

Step 6. Mount a diced single LED sample on a particular metal header (UCSB confidential) with Silverpaste/Epoxy/Silicone. Cure in the oven for a required duration of time. Make wire-bonding between the sample and the header. Check if the LED works with the header mounted.
Appendix B

Modeling of the LED Far-field

Here in this work, a simple modeling of the LED far-field with the assumption of isotropic emission had been attempted in order to reach the same results as in Equation 4.15 and 4.16 of Chapter 4. Details of the derivation are shown below.

Let us consider the radiation outside the LED emitting surface (i.e., the far-field) as a large photon reservoir with a fixed volume $V_r$ which absorbs all the photons emitted from the LED internal radiation field. At some instant, the number of photons in the reservoir is $N_r(\nu)$ within a small frequency interval $\Delta \nu$. The corresponding internal energy and entropy in the reservoir are $U_{r,f}(\nu)$ and $S_{r,f}(\nu)$, respectively. If all the radiation power and accompanying entropy flux leaving the LED enters this photon reservoir, the increasing rates of energy and entropy in the reservoir are,

$$ AI_r(\nu) = h\nu \frac{dN_r(\nu)}{dt} $$

$$ A\Phi_r(\nu) = \frac{dS_{r,f}(\nu)}{dt} $$

In addition, if the extracted far-field radiation in the photon reservoir is also isotropically distributed, and the energy distribution can be described by the Bose-Einstein statistics with a spectral temperature $T_f(\nu)$, then the mean photon occu-
pancy per mode in the far-field, denoted by \( f_f(\nu) \), can be written as,

\[
f_f(\nu) = \frac{1}{\exp\left(\frac{\hbar \nu}{k_B T_f(\nu)}\right) - 1}
\]  

(B.3)

Note that, by explicitly relating the occupancy function \( f_f(\nu) \) with a temperature quantity \( T_f(\nu) \) as in Equation B.3, \( T_f(\nu) \) has been made consistent with the thermodynamic definition of temperature:

\[
T_f(\nu) = \frac{\partial U_{r,f}(\nu)}{\partial S_{r,f}(\nu)} |_{V_r, N_r(\nu)}
\]

The number of photons in the reservoir within the frequency interval is

\[
N_r(\nu) = f_f(\nu)g_f(\nu) \Delta \nu V_r
\]  

(B.4)

where \( g_f(\nu) \) is the density of optical modes per unit volume in the photon reservoir. Therefore the corresponding entropy is,

\[
S_{r,f}(\nu) = k_B \left[ \ln\left(\frac{N_r(\nu)}{g_f(\nu) \Delta \nu V_r}\right) + 1 \right] - \frac{N_r(\nu)}{g_f(\nu) \Delta \nu V_r} \ln\left(\frac{N_r(\nu)}{g_f(\nu) \Delta \nu V_r}\right) g_f(\nu) \Delta \nu V_r
\]  

(B.5)

Bring to Equation B.2, thus we have,

\[
A \Phi_r(\nu) = \frac{dS_{r,f}(\nu)}{dt} = \frac{dN_r(\nu)}{dt} \frac{dN_r(\nu)}{dN_r(\nu)}
\]

\[
= k_B \ln(f_f(\nu)^{-1} + 1) \frac{dN_r(\nu)}{dt}
\]

\[
= \frac{\hbar \nu}{T_f(\nu)} \frac{AI_r(\nu)}{h \nu} = A \frac{I_r(\nu)}{T_f(\nu)}
\]  

(B.6)

The above result shows that for a small frequency interval, the temperature of the far-field radiation can be re-written as,

\[
T_f(\nu) = \frac{\partial U_{r,f}(\nu)}{\partial S_{r,f}(\nu)} |_{V_r, N_r(\nu)} = \frac{I_r(\nu)}{\Phi_r(\nu)}
\]  

(B.7)

The photon reservoir is assumed to be large enough such that \( T_f(\nu) \) is approximately
constant throughout the time of interest. For convenience, we can define a collective
temperature for the far-field radiation in the reservoir in a similar way to cover the
entire spectrum, denoted as $T_r$,

\[
T_r = \frac{I_r}{\Phi_r}
\]  

(B.8)

This collective far-field reservoir temperature does not necessarily equal the result in
Equation [B.7] for each small frequency interval.

Now the expressions of $T_f(\nu)$ and $T_r$ seem to be obtained in the exact forms we
want. However, a problem is revealed after a careful examination of the derivation
process – Equation [B.2] failed to consider the additional entropy generated during the
isotropic photon redistribution process (i.e. a corresponding term should be added
on the left side of this equation).
Appendix C

Radiative Recombination in Quasi-Equilibrium

Suppose that the electron and hole density in the LED active region under bias voltage $V$ and current density $J$ is $n$ and $p$, respectively, as shown in Figure 4-8. Instead of treating the LED being electrically pumped to achieve high carrier density, if these hot carriers are imagined to be solely thermally excited by a high junction temperature $T_j$, we have,

$$np = N_c N_v \exp\left(-\frac{E_c - (E_i + \frac{1}{2}qV)}{k_B T_i}\right) \exp\left(-\frac{(E_i - \frac{1}{2}qV) - E_v}{k_B T_i}\right)$$

$$= N_c N_v \exp\left(-\frac{E_c - E_i}{k_B T_j}\right) \exp\left(-\frac{E_i - E_v}{k_B T_j}\right)$$

(C.1)

where $N_c$ and $N_v$ are the effective density of states at conduction and valence band edge, respectively. $E_c$ and $E_v$ are the energy level of conduction and valence band edge, respectively. $E_i$ is intrinsic Fermi level, and $q$ is electron charge. Equation [C.1] has assumed an undoped active region of the LED, which is a common case. Solving Equation [C.1] with relation $E_c - E_i = E_i - E_v = \frac{1}{2} \hbar \tilde{v}$, where $\tilde{v}$ is the mean frequency.
of emitted photons, we have an expression of the LED bias voltage,

\[ V = \frac{h\nu}{q} \left(1 - \frac{T_i}{T_j}\right) \]  \hspace{1cm} (C.2)

Combining Equation C.2 with current density \( J = qI_r/(h\nu) \), the wall-plug efficiency of the LED can be calculated by its definition in this alternative manner, and is found to reduce to the exact same form as in Equation 4.20 if \( T_j = T_i \). This condition is not unreasonable since the hot carriers in the LED active region interact directly with the internal radiation field rather than the far-field. This result manifests that the quasi-equilibrium status could be maintained between the internal radiation field and the hot carriers of a certain density (determined by the LED bias as in Equation C.1), and justifies the isothermal process (3) depicted in Figure 4-9 of Chapter 4.
Bibliography


