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Invited Paper

Thermophotonics for ultra-high efficiency visible LEDs

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ABSTRACT

The wall-plug efficiency of modern light-emitting diodes (LEDs) has far surpassed all other forms of lighting and is expected to improve further as the lifetime cost of a luminaire is today dominated by the cost of energy. The drive towards higher efficiency inevitably opens the question about the limits of future enhancement. Here, we investigate thermoelectric pumping as a means for improving efficiency in wide-bandgap GaN based LEDs. A forward biased diode can work as a heat pump, which pumps lattice heat into the electrons injected into the active region via the Peltier effect. We experimentally 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 virtually no reduction in the wall-plug efficiency at bias $V < \hbar\omega/q$. This result suggests the possibility of removing bulky heat sinks in high power LED products. A review of recent high-efficiency GaN LEDs suggests that Peltier thermal pumping plays a more important role in a wide range of modern LED structures that previously thought – opening a path to even higher efficiencies and lower lifetime costs for future lighting.

INTRODUCTION

A large fraction of US electricity (12%) is consumed in residential and commercial lighting [1]. The deployment of LED-based solid state lighting (SSL) is reducing the energy burden of all forms of lighting. The blue LED is the central element of SSL. These LEDs, based on gallium nitride semiconductors, now have peak electrical to light power conversion efficiency (the wall plug efficiency, WPE) in the 70+% range at low current densities. At higher current densities, the efficiency diminishes due to the droop phenomena. As a balance between economics and thermal management, blue LEDs in SSL today typically operate at 50-60% WPE. This balance between efficiency and current density has favored the deployment of larger area LEDs in order to realize improved wall-plug efficiency.

This balance is one consequence of industry trends over many decades that favor more, and more efficient lighting. Haitz's Law [2] describes the dramatic reduction of LED cost over time. As can be seen from Figure 1, since 2005 the capital cost of lighting has been below the operating cost (assuming 50k hrs lifetime). The result has been an industry-wide push for higher efficiency even if that means producing a more expensive LED (for example larger area LEDs cost more but are more efficient because of the lower current density).

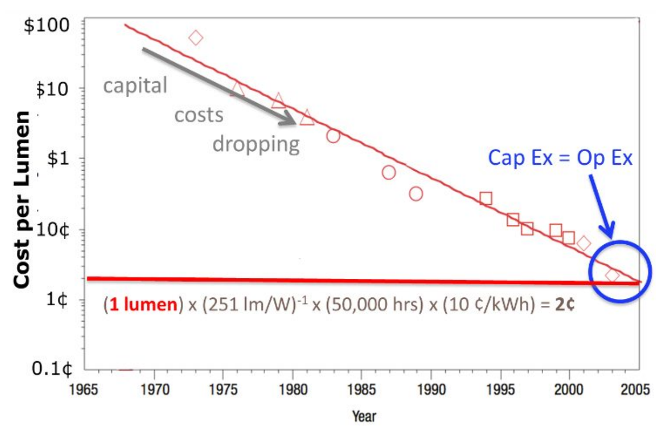

Figure 1. Capital and energy costs per lumnen [2]

The inefficiency of the LEDs used in SSL coupled with the thermal degradation of this efficiency necessitates the use of costly and physically bulky heat sinks. Today, the heat sink is the most expensive component in a SSL light bulb. Figure 2 shows a cost-breakdown, published by the US Department of Energy, which illustrates the increasing fraction of total lamp

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(A19 replacement) cost over time. This suggests that increasing efficiency not only reduces the lifetime cost of the lamp by reducing the cost of energy but also reduces the first cost of the lamp by reducing the heat that must be dissipated.

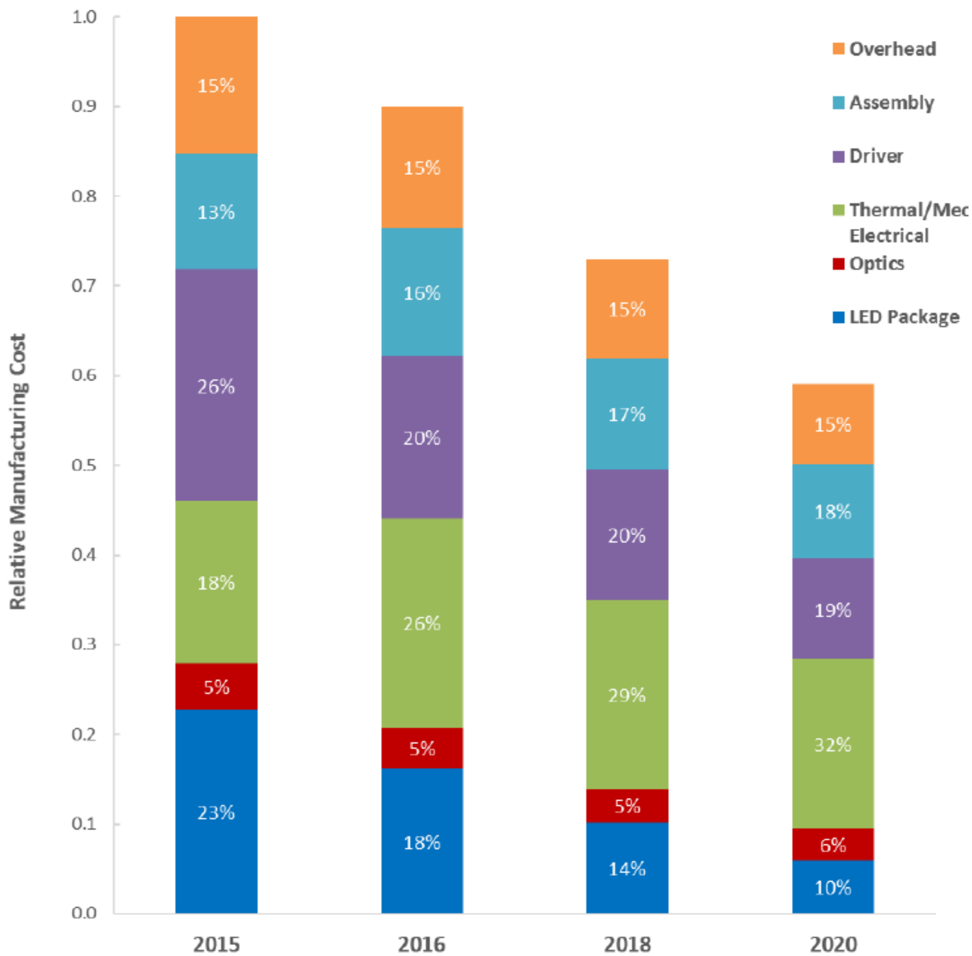

Figure 2. Cost Breakdown Projection for a Typical A19 Replacement Lamp [3]

The WPE (η_{WPE}) of LEDs is the product of the internal quantum efficiency (IQE) η_{IQE}, the fraction of emitted photon per injected electron hole pair in the active layer, the light extraction efficiency $\eta_{extract}$, the fraction of emitted photons that escape the LED chip, and the electrical efficiency η_{elec}: the ratio of the energy (*hv*) of the e-h pairs injected in the active layer to the energy supplied to the LED *qV*:

$$\eta_{WPE} = \eta_{IQE}\ \eta_{extract}\ \eta_{elec}. \tag{1}$$

The quantity that is easily measured is the EQE which is given as $\eta_{EQE} = \eta_{IQE}\ \eta_{extract}$ and is determined from the emitted power (e.g., measured in an integrating sphere) and the injected current. The IQE is often described by the 'ABC' model:

$$\eta_{IQE} = \frac{BN^2}{AN + BN^2 + CN^3} \tag{2}$$

where A, B, and C are the Shockley-Read-Hall (SRH) or defect-mediated non-radiative recombination, radiative (desired), and Auger (3 carrier) non-radiative recombination rates, respectively, and *N* is the injected carrier density in the emitting quantum wells. Typically, the peak EQE of blue LEDs is realized at current densities on the order of 1–10 A cm^{-2}. At higher current densities, the LED efficiency decreases via efficiency droop by Auger recombination. Typically LEDs in SSL lamps are operated at current densities on the order of 5 - 35 A cm^{-2} where droop already impacts efficiency.

Not every injected e-h pair will result in a useful photon that escapes the LED –the external quantum efficiency (EQE) is not 100%. The WPE can be expressed in a simple form: the energy supplied from the power supply is *IV*, the number of emitted photons per second is $\eta_{EQE}\, I/q$, and they carry out an optical power $h\nu(\eta_{EQE}\, I/q.)$. The ratio of emitted and supplied power is WPE and is simply given by

$$\eta_{WPE} = (h\nu/qV)\eta_{EQE}. \quad (3)$$

100% WPE, i.e WPE = 1, is achieved if $\eta_{EQE} = qV/h\nu$. Usually in practice $qV > h\nu$. If the operating voltage (qV) is reduced below the photon energy ($h\nu$) there is a dramatic reduction in both the EQE and current density, the factor $h\nu/qV$ in WPE, does not typically compensate for the decreased η_{EQE}.

Note that the WPE can theoretically exceed 100% when $\eta_{EQE} > qV/h\nu$. While η_{EQE} is bounded at 100%, the bound for $h\nu/qV$ is set by the Carnot limit for energy conversion [4,5]. The challenge is is to realize blue LEDs which would have the following properties:

(i) a high η_{EQE} at voltages such that $qV < h\nu$;

(ii) at these low voltages, the LED should be driven at a current density of at least 1 A cm^{-2} to yield emitted areal powers such that final SSL lamp costs are competitive.

This paper reviews previous work exploring low-bias ($qV < h\nu$) operation of LEDs starting with a brief survey of the early work (starting in 1952), recent experimental results exploring the fundamental limits to LED performance (2012) and to the existing state-of-the-art for low-bias GaN LEDs in the blue and violet (2015-).

HISTORICAL PERSPECTIVE

Since the early days of LEDs, light emission could be observed at photon energies ($h\nu$) higher than the injected electron-hole pair energy given product of the electron charge q and applied voltage on the diode V (qV) [6]. In fact, the first demonstration of light emission in a diode structure was reported by Lehovec, et al. in 1953. Their paper, "Light Emission Produced by Current Injected into a Green Silicon-Carbide Crystal," included a report of light emission where applied voltage across the contacts was 1.8 V but the energy of the light quanta was 2 eV [6]. Over the subsequent decades, low-bias operation was observed in various material systems ranging from GaAs [7, 8], ZnS [9], and even early GaN [10]. In each of these early experiments, a unique mechanism was postulated to explain the emission of photons when $qV < h\nu$.

These early theories attempted to explain the difference in the observed defect between the energy supplied by the battery and the energy of the photon ($\Delta E = qV - h\nu$). The earliest papers by Lehovec (SiC) and Dousmanis (GaAs) suggested that "any excess of energy emitted over energy supplied by the battery must have been taken up by lattice vibrations. This should lead to a cooling effect, as in the case of the well-known Peltier effect" [6]. Nathan, et al. later postulated that the higher energy photons were the result of Auger process near the GaAs active region that were populating high lying energy states [8]. A similar mechanism was proposed by Bitter, et al. where they suggested that tunneling assisted impact ionization was responsible for populating these high lying states [9]. Finally, Pankove postulated that the low bias emission observed in GaN (2.9 eV photons from a bias as low as 1.62 V) was the result of simultaneous two-electron impact ionization that resulted again in the population of high energy states [10]. As we can see, low-bias operation was easily observed over a wide range of materials and structures, however, after 20 years of experiments the origins of low-bias (or anti-Stokes) emission were under debate with the various theories falling into two broad categories:

(a) phonon absorption by the injected electrons in a process similar to Peltier cooling, or
(b) two-electron processes which allowed for high energy states to be populated.

Two-electron processes necessarily require two injected electrons for every emitted photon and hence the EQE must be below 50% during low bias emission. These early LED experiments could not easily distinguish between the various theories as the WPE and EQE were low under low bias operation ($qV < h\nu$). Low voltage operation necessary results in lower carrier density and hence the radiative recombination processes (B) struggle to compete with defect assisted non-radiative recombination (A). Clear experimental evidence demonstrating that low-bias photon emission could be achieved at high EQE (>50%) would not be published until 2015 [11]!

However, over the subsequent decades, the phonon absorption process came to be viewed as a more likely explanation for light emission at low voltage ($qV < h\nu$). For one, multi-electron processes such as Auger were not expected to be dominant for low voltages where the carrier densities were small. Secondly, a body of theoretical work established the thermodynamic argument showing that heat (phonon) absorption in an LED was consistent with both the First and Second Law of thermodynamics [4,12]. The physical process that conserves total energy is that the electrons and holes absorb thermal energy before they emit light. Heat (and its associated entropy) can be absorbed because the emission of the LED light increases entropy (due to a broad optical spectrum, low coherence). The entropy in the emitted light is greater than the entropy of the e-h pair and the heat absorbed by the e-h pair – as required by the 2nd Law. Early thermodynamic analysis of an LED recognized the potential for wall-plug efficiency greater than 100%, but this was not realized experimentally until 2012 [13].

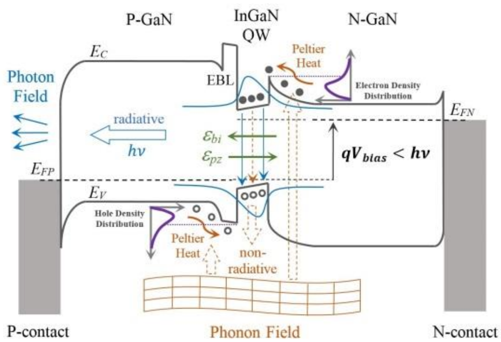

Figure 3. Forward biased nitride LED showing the carrier injection and recombination for $qV < hv$. Note that the electron and hole high energy thermal tails provide the "missing energy" (hv - qV).

LOW BIAS OPERATION OF VISIBLE LEDS

Realizing the potential for ultra-high efficiency requires the development of new LEDs optimized for low-bias operation where conventional mechanisms of current and thermal droop are not dominant.

The first experimental observation of low-bias photon emission in GaN in 1975 resulted in exceedingly low WPE of only 0.0003 (or 0.03%) [10]. Exactly 40 years later the WPE efficiency at low bias ($qV < hv$) is 0.82 (82%) – an improvement of 2700x. It is also worth noting that, today, low-bias operation represents the highest WPE demonstrated for an electrically pumped LED. Much of the improvement in low-bias performance is a direct result of industry-wide improvements that have been made in GaN performance. These include dramatic improvements in material quality (which suppresses SRH recombination at low-bias), quantum well structures which maintain a high electron-hole wavefunction overlap even at low bias, low resistance contact structures, and high-efficiency optical extraction structures. All of these broad improvements have allowed us (and others) to exploit low-bias operation for enhanced efficiency. Let us look more closely at one of these structures.

The challenge is to realize blue LEDs which would have the following properties:

(i) a high η_{EQE} at voltages such that $qV < hv$ which requires ensuring that SRH recombination is minimized and radiative recombination (B) is optimal;

(ii) at these low voltages, the LED should be driven at a current density of at least 1 A cm^{-2} to yield emitted areal powers such that final SSL lamp costs are competitive – this requires structures with low diode 'turn-on' voltages.

Recently, our group and others [11,14] have explored low-bias operation in semipolar GaN. This material system offers potentially low SRH recombination (by virtue of active region growth on a matched GaN substrate) and high radiative recombination (B) rates (by virtue of reduced piezofields which would otherwise reduce the electron-hole wavefunction overlap).

In 2015, we presented preliminary experiments illustrating that thermal pumping can be observed in semipolar GaN emitting at 450 nm [14]. We used a 450 nm small area (0.1 mm^2) InGaN single-quantum-well LED. An encapsulated sample with backside roughening and a ZnO vertical-stand package has an EQE of 50.1% and a light output power of 140 mW at 100 A/cm^2. [15] To study LED behavior over a wide temperature range, the LEDs tested are bare dies without packaging or encapsulation, resulting in lower EQE and WPE measurement values than devices optimized for high light extraction. [11] We performed pulse-mode voltage sweeps from 2 - 5 V under ambient temperatures from 20-300C.

This device exhibits essentially zero thermal efficiency droop for the maximum WPE. We experimentally demonstrate 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. This enhanced high temperature performance is attributed to thermoelectric pumping as the maximum WPE is observed at a bias $V < h\nu/q$. In this low bias regime, 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, as depicted in Figure 3. In this optimal operating regime at 615 K, the LED injection current (3.26 A/cm^2) is found to be close to the value of 5 A/cm^2, which is the operating point of common high power GaN based LEDs (5 - 35 A/cm^2).

The dependence of EQE and WPE versus LED current density at different temperatures was measured. 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 significant drop. It is observed that with the increase of temperature, peak WPE point gradually moves towards lower bias regime with virtually no reduction in value. This is mainly because of the reduction in bias voltage, and more importantly for the minimal drop in EQE for large thermal excitation. The bias voltage 3.35 V corresponding to peak WPE at 20C has moved to 2.5 V at 300C, with nearly fourfold increase in output power and only 0.42% reduction in WPE (not calibrated for thermal expansion). It clearly tracks the continuous change of peak WPE.

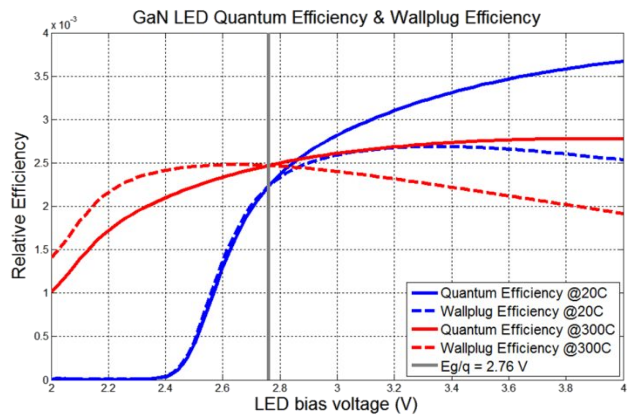

Figure 4. EQE (dashed lines) and WPE (solid lines) versus LED bias voltage at two extreme temperatures cases. All blue lines correspond to 295 K room temperature operation, and red lines correspond to 615 K high temperature operation. The bias voltage corresponding to the photon energy is indicated.

The data above show that thermal pumping – light emission when there is a deficit in energy supplied by the battery - is evident in low-bias GaN devices. Our preliminary results exploit this effect to eliminate the reduction of WPE with temperature. However, the maximum WPE for the packaged room-temperature device was 50% and for the unpackaged device over temperature was 11%.

Hurni, et al. have demonstrated significantly higher efficiency in semipolar GaN devices that exhibit peak WPE at low bias ($V < h\nu/q$) [11]. While also employing the same bulk GaN substrate as above, this device significantly improves on the performance of the device discussed above by employing triangular volumentric flip-chip for high extraction efficeincy (~90%). As in the above the bulk GaN substrate provides a low-defect density active region that achieves a 92% internal quantum efficiency (IQE) and an improved current spreading and contact geometry. With these improvements, they report a peak WPE of 84% at 85C. Most notably for our discussion, the peak WPE efficiency occurs in the low-bias limit where $V \approx 0.91 \times h\nu/q$. This device demonstrates a few important insights:

As the authors have pointed out, low-bias operation can be realized at high current density; WPE of 84% at approximately 4 A/cm^2 but low-bias ($V < h\nu/q$) is realized up to current densities of 75 A/cm^2. Because the low-bias WPE and EQE in this device is well-above 50%, this device also clearly illustrates that low-bias emission (or anti-Stokes emission) is not the result of multi-electron processes as suggested in [8,9,10].

Both of the above results relied on active regions grown on bulk GaN substrates to realize but as we point out at the beginning of this paper, low-bias emission is readily observed in a wide-range of materials. Next, we briefly examine the evidence for thermal pumping in widely used GaN-on-sapphire LEDs. Meyaard, et al have measured the performance of a 5 QW GaN-on-sapphire LED emitting at 440nm [16]. This data set was used to explore efficiency droop at high temperature and current injection. Here, we replot the experimental results from this paper with a particular focus on device performance at low-bias. Figure 5 shows the EQE and WPE for this device plottes as a function of voltage for operation at 200K, 330K, and 450K. The peak WP efficiency at 200K occurs at a bias point where essentially all of the energy for photon emission is supplied by the battery ($V \sim h\nu/q$). As the temperature rises to 330 K the bias for peak WPE shifts to the low-bias limit ($V < h\nu/q$) where a fraction of the emitted photon energy comes from the absorption of lattice vibrations during current injection. At yet higher temperatures, the IQE of the LED drops and while the optimal WPE still occurs in the low-bias regime, increased phonon absorption is unable to compensate for increased non-radiative recombination.

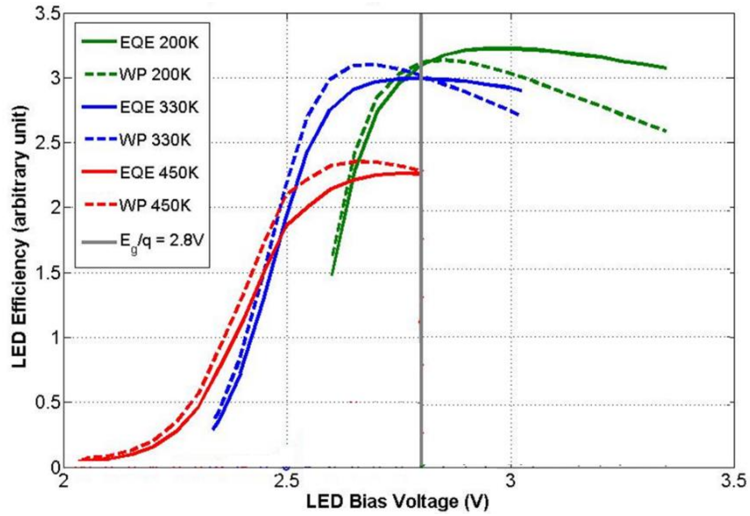

Figure 5. External quantum efficeincy (EQE) and wall-plug efficeincy (WP) for the GaN-on-sapphire MQW LED reported in [16]

The observation of peak WPE 100's of mV below the photon energy – an operating regime that was outside the design targets for this device – suggests that there is significant room for improvement in these devices. A research program focused on the optimization of GaN LEDs for operation at low-bias would likely result in higher efficeincy LEDs that by virtue of their phonon-assisted injection would experience essentially zero thermal droop over a wide operating range.

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