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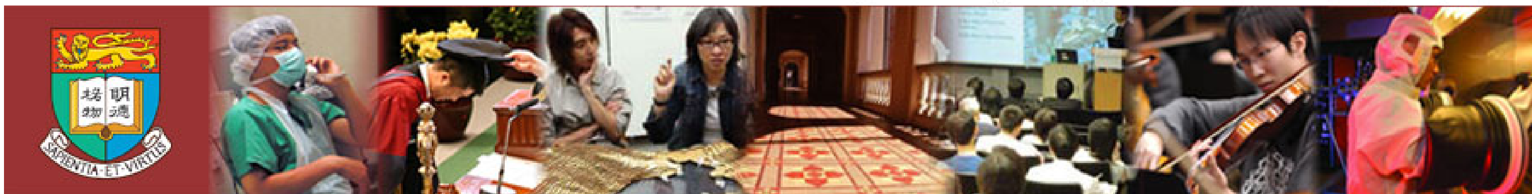

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Author(s)	Chen, H; Cheung, YF; Choi, HW; Tan, SC; Hui, SYR
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Reduction of Thermal Resistance and Optical Power Loss Using Thin-Film Light-Emitting Diode (LED) Structure

Huan Ting Chen, *Member, IEEE*, Yuk Fai Cheung, Hoi Wai Choi, *Senior Member*, *IEEE*, Siew Chong Tan, *Senior Member*, *IEEE* and S.Y.(Ron) Hui, *Fellow, IEEE*

***Abstract*—In this paper, a GaN-LED with sapphire structure and a thin-film LED without sapphire structure are characterized in the photo-electro-thermal (PET) modeling framework for comparison. Starting from the analysis and modeling of internal quantum efficiency as a function of current and temperature of blue LED, this work develops the thin-film LED device model and derives its optical power and the heat dissipation coefficient. The device parameters of the two LED devices with different structural designs are then compared. Practical optical power measurements are compared with theoretical predictions based on the two types of fabricated devices. It is shown that the thin-film LED device has much lower thermal resistance and optical power loss.**

***Index Terms*— Light-emitting diodes, Thin-Film, Photo-electro-thermal theory**

NOMENCLATURE

R_r radiative recombination rates, $m^{-3}s^{-1}$;
R_{nr} non-radiative recombination rates, $m^{-3}s^{-1}$;
s active layer area, m^2;
l active layer thickness , m;
q elementary charge, C;
h Planck's constant, J.s;
η_{int} internal quantum efficiency, dimensionless;
η_{ext} external efficiency, dimensionless;
η_{inj} injection efficiency, dimensionless;
η_{extr} light extraction efficiency, dimensionless;
$\eta_{int,0}$ internal quantum efficiency at reference point (T_0, I_0), dimensionless;
η_w wall plug efficiency, dimensionless;
P_{opt} optical power, W;
P_d electrical power,W;
I current, A;
I_0 reference current,A;
T_j junction temperature,℃;
T_1 characteristic temperature,℃;
T_0 reference temperature,℃;
T_a ambient temperature,℃;
N number of LED devices, dimensionless;
R_{jc} thermal resistance of LED device, ℃/W;
R_{hs} thermal resistance of heatsink, ℃/W;
k_h heat dissipation coefficient, dimensionless;
k_t slope for internal quantum efficiency over temperature change, ℃$^{-1}$;
k_i slope for internal quantum efficiency over current change, A^{-1};

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H. T. Chen, Y. F. Cheung, H. W. Choi and S. C. Tan are with the Department of Electrical & Electronic Engineering, The University of Hong Kong (e-mail: htchen23@gmail.com, yfcheung@eee.hku.hk, hwchoi@eee.hku.hk, sctan@eee.hku.hk).
S.Y.R. Hui is with the Departments of Electrical & Electronic Engineering, The University of Hong Kong (email: ronhui@eee.hku.hk) and Imperial College London (e-mail: r.hui@imperial.ac.uk).

I. INTRODUCTION

With the demands for high brightness, the driving power of the LED package increases continuously over the past few years. For LED technology, the luminous output and the junction's thermal stress of the LED device are conflicting factors. The droop effect of the luminous efficacy against increasing junction temperature is well reported [1]. Proper thermal design becomes crucial to the overall performance of an LED system including not only the LED package and the driver, but also the heatsink design [2]. In order to reduce the junction temperature, measures can be taken on the device packaging level and the device structure level. For device packaging, one can reduce the average junction's thermal resistance and thus temperature by using the multi-chip structure as explained in [3]. For the same power rating, a multi-chip structure consumes a lower power per chip, but has a larger total chip contact area for heat transfer than that of a single chip structure. This has led to LED packages with flat surfaces. In fact, a more effective measure would be to re-design the LED device structure in order to reduce the junction-to-case thermal resistance.

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Recently, high power LEDs with thin-film structures have attracted serious attention because of their excellent thermal properties [4]-[6]. Traditional GaN-LED structure is based on the metal-organic chemical vapor deposition (MOCVD) with the GaN LED epi-layer grown on sapphire substrate. Heat generated from the active layer region has to go through a layer of sapphire which has a high thermal resistance. Consequently, high junction temperature induced by heat accumulation reduces the internal quantum efficiency. Such limitations can be alleviated by adopting advanced chip architectures which include the flip-chip and thin-film solutions [7]. In the flip-chip approach the laterally-conducting LED chip is physically flipped upside-down and makes contact with the sub-mount via arrays of solder bumps. By doing so, heat generated from the active region is conducted to the heat sink without passing through the sapphire substrate, representing a significant improvement over conventional LEDs. As such the solder bumps serve as heat conduction (as well as current conduction) pathways, but their contact areas with the chip itself are invariably smaller than the size of the chip. The thin-film architecture, on the other hand, offers the ultimate heat-sinking solution by having the chip completely bonded to a carrier substrate via a metallic bonding layer, maximizing heat conduction from the chip to the heat-sink. The photometric, electrical, and thermal characteristics of LED systems are highly dependent on one another [9]-[11]. Increasing the junction temperature results in reduction of luminous efficacy. For such luminous efficacy droop, the effect of temperature on the light output of an LED is strongly dependent on the materials and structure of the chip [12]. The interactions of the photometric, electric and thermal aspects have been described mathematically in a photo-electro-thermal (PET) theory [13][14] for LED systems. The PET theory can be used to optimize the design of an LED system and to determine the operating point of the maximum luminous flux per Watt. It can also be used to set criteria for the optimal thermal design for the appropriate heatsink for a given application such as LED systems described in [22],[23].

In this paper, a GaN-LED with sapphire structure and a thin-film LED without sapphire structure are characterized in the PET modeling framework for comparison. In particular, the internal quantum efficiency as a function of current and temperature is incorporated into the framework to determine the optical power and the heat dissipation coefficient of two LED samples with different structures. The device parameters of the two structural designs are compared. These two low-power samples, rated at about 0.36W, are blue LEDs without phosphor coating, because the comparison focuses primarily on their thermal resistance and optical power losses. Practical optical power measurements are compared with theoretical predictions based on the two types of devices fabricated in the laboratory.

II. CHARACTERIZATION AND MODELING OF A GAN-LED DEVICE AND THIN-FILM LED DEVICE

A. Quantum Efficiency and Optical Power

The basic principle of the LED operation is the generation of light within the LED active region. The light generation occurs through the radiative recombination of the injection of electrons and holes into the active region. Any photons generated by radiative recombination may be trapped inside the LED die by total internal reflection, and then these parts of photons are absorbed by the materials. With the injection current I flowing into the LED die, the radiative recombination process occurs with non-radiative recombination. The radiative and non-radiative recombination rates can be represented by R_r, R_{nr}. Under steady state conditions, the total charges injected into the active region can be described as [15]:

$$\frac{I}{q} = R_{nr} sl + R_r sl \qquad (1)$$

where s and l are the area and thickness of the active layer respectively; q is the elementary charge magnitude, and $R_r sl$ is the total photon generation inside the LED.

The internal quantum efficiency η_{int} is the ratio of the radiative electron-hole recombination coefficient to the total (including radiative and non-radiative) recombination coefficient. It can be expressed as

$$\eta_{\text{int}} = \frac{R_r}{R_r + R_{nr}} \qquad (2)$$

Substituting (2) into (1), the radiative recombination can be expressed as

$$\frac{I}{q} = \frac{R_r sl}{\eta_{\text{int}}} \qquad (3)$$

Then, the optical power can be expressed as

$$P_{opt} = \eta_{ext} R_r slhv = \eta_{ext} \eta_{\text{int}} hv \frac{I}{q} \qquad (4)$$

where R_{nr} is dependent on the defect concentration, meaning that any change in defect concentration inside the device die can affect the balance between the injection current and the photon generation. Equation (4) indicates that the photon generation decreases as the defect concentration increases under the same injection current. Non-radiative recombination is a process in which charge carriers recombine with photons (opposite to photons generation), and the related recombination energy is dissipated as heat. The optical power P_{opt} of an LED is equal to the number of photon generation $R_r sl$ from the LED multiplied by the average photon energy hv and external efficiency η_{ext}.

The external efficiency η_{ext} for the LED can be mathematically expressed as:

$$\eta_{ext} = \eta_{extr} \eta_{inj} \qquad (5)$$

where η_{inj} is the injection efficiency and η_{extr} is the light extraction efficiency. The light extraction efficiency for LED is limited by the high refractive index of the semiconductor material, which imposes constraints for light to escape from the semiconductor. In general, η_{inj} is identical for the same bin of the wafers. Therefore, the light extraction efficiency for GaN LED with sapphire and thin-film LED without sapphire can be calculated using ray-trace simulation. The optical power and the quantum efficiency can be related in the following equation:

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$$P_{opt}=\eta_w P_d=\eta_w IV=\eta_{ext}\eta_{\text{int}}hv\frac{I}{q} \quad (6)$$

where P_d is the LED power.

B. Photo-Thermal Characteristics

The emission intensity P_I of LEDs decreases with increasing junction temperature. At room temperature, the emission intensity follows an exponential decay function [1], and is given as

$$P_I=P_{I_25^oC}\exp\left(-\frac{T_j-25^oC}{T_1}\right) \quad (7)$$

where T_1 is the characteristic temperature and T_j is the junction temperature of the LED. The exponential curve of (7) within its practical range of operating temperature is fairly linear. In photometric terms, this relationship is reflected in the temperature-dependent internal quantum efficiency η_{int} of LEDs and will be approximated as:

$$\eta_{\text{int}}=\eta_{\text{int},0}+k_t(T_j-T_0) \quad for \quad T_j\geq T_0 \quad and \quad \eta_{\text{int},0}\geq 0 \quad (8)$$

where T_0 is the reference temperature, k_t is the slope for internal quantum efficiency over the temperature change, and $\eta_{int,0}$ is the reference internal quantum efficiency at the reference temperature T_0.

If N samples of the LED with single or multi-chip structure are mounted on a heatsink, the thermal model of the LED system can be shown in Fig 1. The junction temperature can be given by:

$$T_j=(R_{jc}+NR_{hs})k_h IV+T_a \quad (9)$$

where k_h is the heat dissipation coefficient, R_{hs} is the thermal resistance of heatsink, R_{jc} is the junction-to-case thermal resistance of the LED device, I is the electrical current, V is the forward voltage of the diode and T_a is the ambient temperature in degree Celsius.

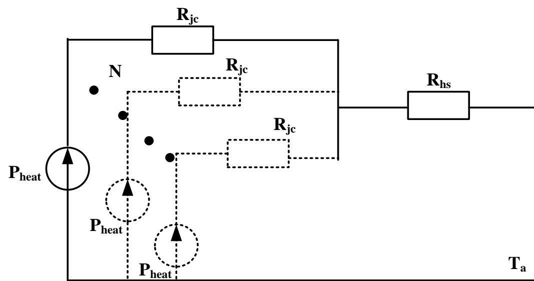

Fig 1 Thermal model of LED device with single or multi-chip structure mounted on a heatsink

C. Photo-Electro-Thermal Characteristics

In practice, the wall-plug efficiency η_w is a function of current and temperature [16]. If the external efficiency η_{ext} is assumed to be constant, the internal quantum efficiency is dependent on the current and temperature as suggested in (6). The internal quantum efficiency η_{int} can be expressed as a function of temperature and current as follows:

$$\eta_{\text{int}}=\left[k_t\left(T_j-T_0\right)+\eta_{\text{int},0}\right]\left[k_i\left(I-I_0\right)+1\right] \quad (10)$$

where I_0 is the reference current, k_i is slope for internal quantum efficiency over current change, and $\eta_{int,0}$ is the internal quantum efficiency at reference point (T_0, I_0).

Substituting (9) into (10), the internal quantum efficiency can be rewritten as:

$$\eta_{\text{int}}=\left\{k_t\left[\left(R_{jc}+NR_{hs}\right)k_h IV+T_a-T_0\right]+\eta_{\text{int},0}\right\}\left[k_i\left(I-I_0\right)+1\right] \quad (11)$$

Substituting (11) into (6), the optical power of LED can be expressed as:

$$\begin{aligned}P_{opt}&=\eta_w P_d=\eta_w IV\\&=\eta_{ext}\left\{k_t\left[\left(R_{jc}+NR_{hs}\right)k_h IV+T_a-T_0\right]+\eta_{\text{int},0}\right\}\left[k_i\left(I-I_0\right)+1\right]hv\frac{I}{q}\\&=\eta_{ext}\frac{hv}{q}\left\{k_t k_h\left(R_{jc}+NR_{hs}\right)I^2V+\left[k_t\left(T_a-T_0\right)+\eta_{\text{int},0}\right]I\right\}\left[k_i\left(I-I_0\right)+1\right]\end{aligned} \quad (12)$$

Several important observations are drawn from (12) :

(i) Equation (12) relates altogether the optical power P_{opt} to the injection current of the LED I, the thermal resistance of the heatsink R_{hs} and device R_{jc}, and the internal quantum efficiency η_{int}. It also builds up the framework that integrates the photometric, thermal, electrical and physical characteristics of the LED device altogether.

(ii) Because k_t and k_i are negative and less than 1, (12) is in the form of P_{opt}=($\alpha_1 I$- $\alpha_2 I^2$) (-$\alpha_3 I$+α_4)= $\alpha_1\alpha_4 I$-($\alpha_1\alpha_3$+$\alpha_2\alpha_4$) I^2+$\alpha_2\alpha_3 I^3$, where α_1,α_2, α_3 and α_4 are positive coefficients. As I is increased from zero, P_{opt} increases almost linearly because the second term is negligible when P_{opt} is small. As I increases, the second negative term, which is proportional to the square of I, will become increasingly dominant and will reduce P_{opt} significantly.

For a given heatsink, the operating point I at which the maximum P_{opt} occurs can be determined. It can be used for thermal design to optimize the size of the heatsink R_{hs} for a given LED device.

III. BLUE LED STRUCTURES

A Process to Remove Sapphire Layer

Fig.2(a) shows the structure of a traditional GaN LED with sapphire. The structure of the thin-film LED is shown in Fig.2(b). All thicknesses of the layers of the two LED samples are provided in Table I. The epitaxial structure of the blue LED is grown by metal-organic chemical vapor deposition (MOCVD) on c-plane crystalline sapphire. It consists of a

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3-μm-thick undoped GaN layer, a 3-μm-thick Si-doped GaN layer, 5 periods of InGaN (3 nm)/GaN (5 nm) quantum wells, capped with a 0.25-μm-thick Mg-doped GaN layer. Its sapphire substrate is detached by laser lift-off (LLO) with the collimated 266-nm beam from an Nd: YAG laser (Continuum Surelite). To assist with separation, the sample is heated on a hot-plate to melt the Ga droplets formed at the GaN/sapphire interface. The detached GaN film is immersed into diluted HCL for removal of residual droplets. The undoped GaN layer is then etched away to expose the n-GaN surface by inductively-coupled plasma (ICP) etching using BCl_3/He gas mixtures [17]. The CCD-captured images of the GaN LED with sapphire and the thin-film GaN LED fabricated in our laboratory are shown in Fig.3(a) and Fig.3(b), respectively.

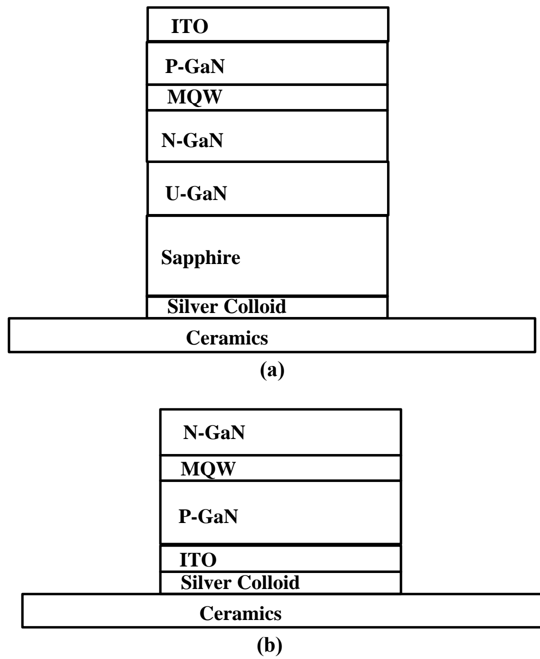
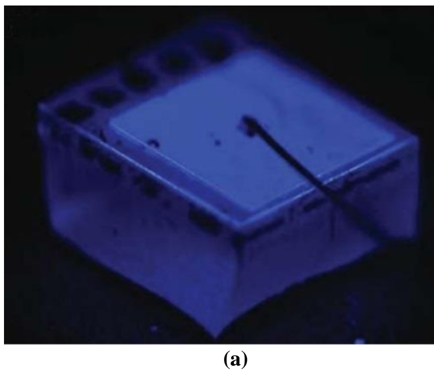
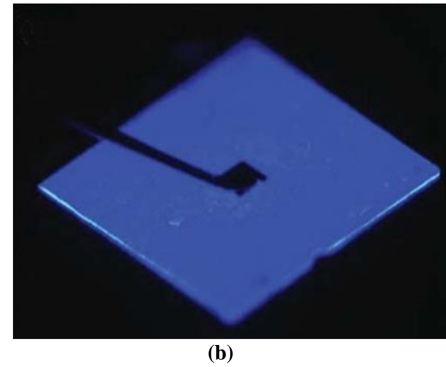


Fig. 2 (a) GaN LED with sapphire and (b) thin-film LED



(a)



(b)

Fig 3 CCD-captured images of the (a) GaN LED with sapphire (b) thin-film LED

IV. PRACTICAL EVALUATION AND COMPARISON

A. Experiment Process

The GaN LED with sapphire and thin-film LED have been used for practical evaluation. The optical measurements of the LED samples are obtained under steady-state thermal and electrical conditions using the PMS-50 spectro-photocolorimeter with an integrating sphere (measured after 20 minutes of system operation at different electrical power levels and at an ambient temperature of 20 ℃). The voltage changes of the LED devices with temperature variation are captured with the Transient Thermal Tester (T3Ster). Besides the combined thermal and optical measurements, the temperature dependence of the optical power and the wall-plug efficiency η_w of the LED are also recorded. The T3ster captures the thermal transient response in real time, records the cooling/heating curves, and then evaluates the cooling/heating curves for plotting the thermal characteristics. The heating current for the samples is 0.02 A and the heating/cooling time is 20 minutes. The measured current is 1 mA. For voltage-temperature-sensitive parameter calibration, a small current of 1 mA is applied to a temperature-controlled heatsink (at different ambient temperature values: 25 ℃, 35 ℃, 45 ℃, and 55 ℃) under a pulsed-current injection mode with a small duty cycle. The thermal resistance of the LED package could be extracted using the thermal structure function, which is based on the distribution RC networks [18].

B. GaN LED with Sapphire

The light extraction efficiency of the LED samples has to be estimated from their respective structures. This is done using the commercial software TracePro. The two structures in Fig.2 are used in the simulation. The thicknesses of the layers of Indium tin oxide (ITO), P-GaN, MQW, N-GaN, U-GaN, sapphire, silver colloid and ceramics are 200 nm, 0.25 μm, 40 nm, 3 μm, 3 μm, 400 μm, 20 μm, 400μm respectively. The refractive indices of GaN and sapphire are 2.5 and 1.7, respectively. The absorption coefficient of GaN and sapphire are 200 cm^{-1} and 0.0053 cm^{-1}. The areas of the two wafers and ceramics are 600 μm x 600 μm and 1.2 cm x 1.2 cm, respectively. The emission surface of upward and downward MQW layers are set as a Lambertian plane source with 0.1W with a total number of rays equal to 500000. In the simulations, the LED samples are placed inside a sphere, which collects their ray emissions. The ray trace

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of the structure of the GaN LED with sapphire are also simulated using TracePro. The simulation results are shown in Fig 4, which shows that a significant amount of emitted rays are trapped inside the device and are absorbed by the sapphire. Red rays represent light emission without reflection inside LED device, which indicates no energy loss. Blue rays represent light reflected and/or refracted inside LED device, which means some energy loss and absorption. The light extraction efficiency for the GaN LED with sapphire η_{extr} is 16.8 %.

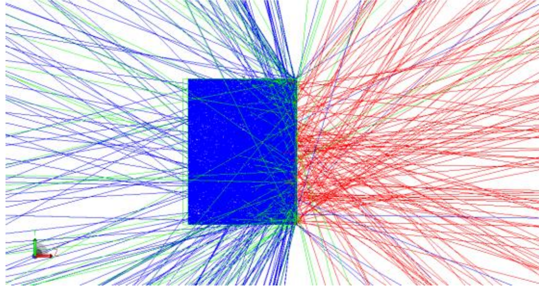

Fig 4 Ray-trace for GaN LED with sapphire

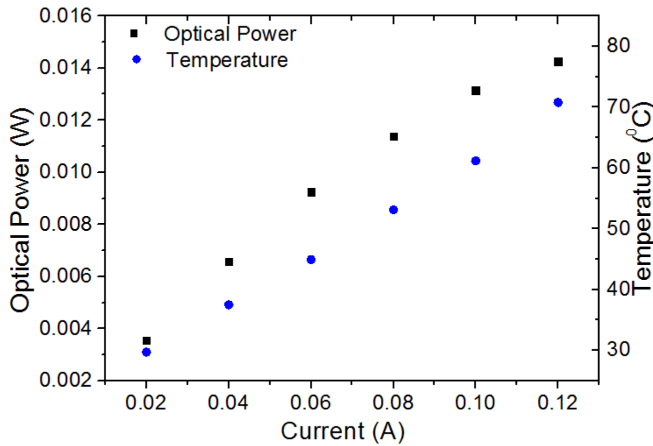

Fig 5 Measured optical power and temperature of GaN LED with sapphire with current

The measured optical power and temperature values of the GaN LED with sapphire for a range of LED currents are recorded in Fig.5. Using such measured data and the simulated value of η_{extr} from eqn (4), the internal quantum efficiency as a function of current can be calculated and plotted as shown in Fig 6.

The optical power and wall plug efficiency for the GaN LED with sapphire are measured at different current levels. The parameters required for (12) can be found as follows. The reference point (T_0, I_0) is set as (25 °C, 0.02 A). The values of k_t and k_i are -0.0024 $^oC^{-1}$and -0.63 A^{-1}, respectively [19]. Based on (7) and the results in Fig 6, the internal quantum efficiency $\eta_{int,0}$ at the reference value of (T_0, I_0) could be determined as 0.394. It should be noted that k_t and k_i are negative coefficients. Based on these parameters, the theoretical and measured heat dissipation coefficients are recorded and shown in Fig.7. The theoretical curves of k_h are in good agreement with the measured ones. It is important to note that at a controlled current of 0.02 A, k_h is about 0.615. When the current is 0.12 A, k_h increases to 0.793. This practical result highlights the important fact that, even with the same LED power, k_h increases with an increasing operating current. The thermal design of LED systems are therefore critical to their performance. The minimum error is about 1.4 %, and the average error is about 2.8 %. It is indicated that the reasonably good agreement between these measured and calculated values confirm the validity of the proposed estimation methods for the heat dissipation coefficient for the GaN LED with sapphire.

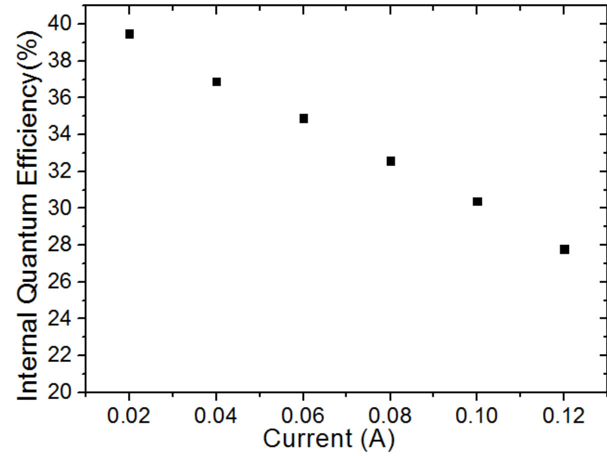

Fig 6 Internal quantum efficiency versus current

As I is increased from zero, P_{opt} increases almost linearly when I is small. As I continues to increase, the negative item $k_t k_h(R_{jc}+NR_{hs})I^2$ will reduce P_{opt} significantly. After reaching the maximum optical power, P_{opt} will drop with increasing I. The optical power function is approximately a parabola and therefore has a maximum optical power I^*. This I^* will shift to lower value with an increasing thermal resistance or heat dissipation, which indicates the dependency of the operating point I^* of the LED device on the junction temperature. The theoretical and measured optical power curves in Fig.8 agree reasonably well. The operating point I^* of the LED with maximum optical power is about 0.12 A. The minimum error is about 1.4 %, and the average error is about 4.3 %. As shown in Fig 9, the theoretical and measured luminous efficacy versus current are in good agreement. With injection currents of 0.02 A to 0.12A, the temperature variation is about 55.1 °C and the luminous efficacy variation is about 3.95 lm/W. Therefore, the temperature sensitivity of the luminous efficacy of the GaN-LED with sapphire is around -0.072 lm/W.°C.

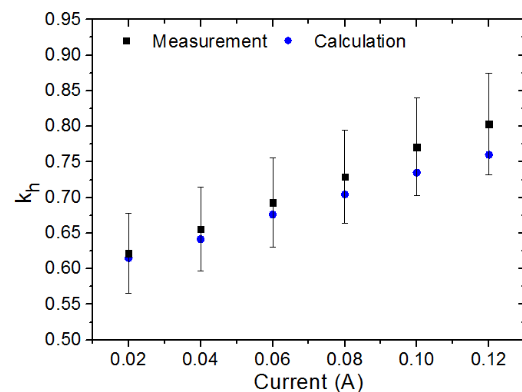

Fig 7 Measured and calculated k_h versus current for GaN-LED with sapphire

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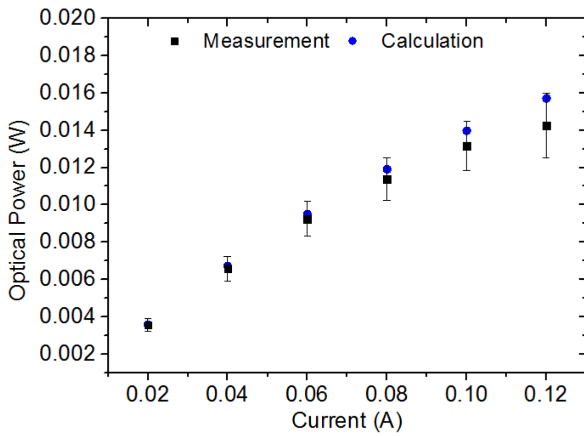

Fig 8 Measured and calculated optical power versus current for GaN-LED with sapphire

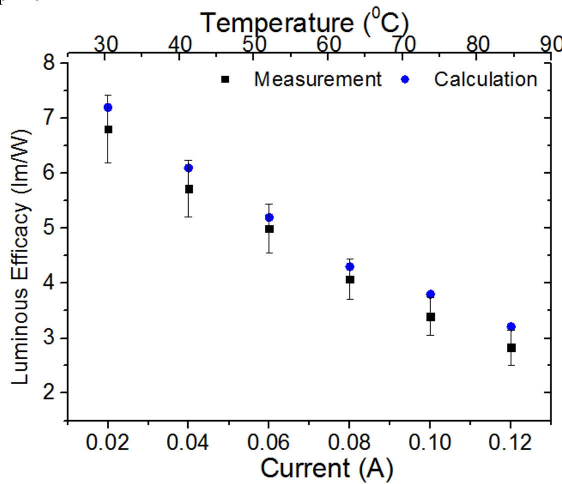

Fig 9 Measured and calculated luminous efficacy versus current for GaN-LED with sapphire [Note: this luminous efficacy is for a blue LED without phosphor]

C. Thin-Film LED

Thin-film LED with the sapphire substrate removed has a low device's thermal resistance. Based on T3Ster system, the measured thermal resistance for the thin-film LED is 110 ºC/W, as compared to the thermal resistance of the GaN LED with sapphire which is at 170 ºC/W. The temperature and current effect on the internal quantum efficiency of the thin-film LED is the same as that of the GaN LED with sapphire due to their identical MQW. The theoretical and measured heat dissipation coefficients of the thin-film LED are recorded and shown in Fig. 10. The theoretical curves of k_h are in good agreement with the measured ones. It is important to note that at a controlled current of 0.02 A, k_h is about 0.52. When the current is 0.12 A, k_h increases to 0.65. Compared to GaN LED with sapphire, the generated heat inside the thin-film LED are reduced clearly because of the high performance of the heat path. The minimum error is about 1.1 % and the average error is about 3.4 %. It is indicated that the reasonably good agreement between these measured and calculated values confirm the validity of the proposed estimation methods for the heat dissipation coefficient of the thin-film LED.

The theoretical and measured optical power curves of the thin-film LED in Fig.11 agree reasonably well. Even after the injection current reaches 0.12 A, the optical power still changes linearly with the current. The minimum error is about 1.1%, and the average error is about 2.5 %. As shown in Fig 12, the theoretical and measured luminous efficacy versus current are in good agreement. With injection currents of 0.02 A to 0.12 A, the temperature variation is about 30.5 ºC and the luminous efficacy variation is about 1.5 lm/W. Therefore, the temperature sensitivity of luminous efficacy of the GaN-LED with sapphire is around -0.049 lm/W.ºC.

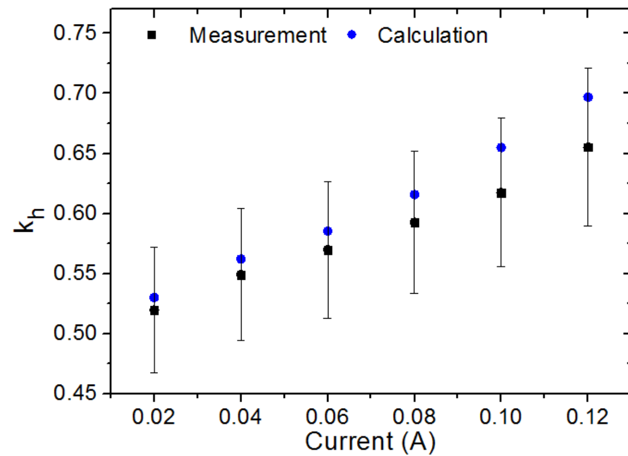

Fig 10 Measured and calculated k_h versus current for thin-film LED

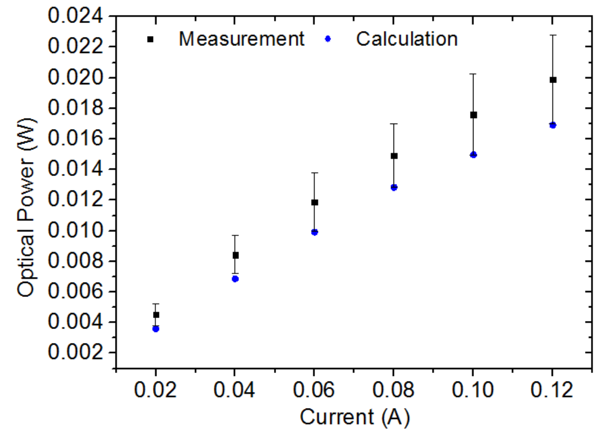

Fig 11 Measured and calculated optical power versus current for thin-film LED

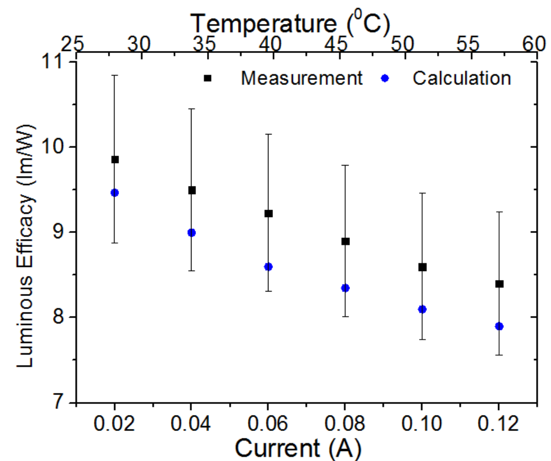

Fig 12 Measured and calculated luminous efficacy versus current for thin-film LED [Note: this luminous efficacy is for a blue LED without phosphor]

D. Comparison of LED with Sapphire and Thin-Film LED

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Table II summarizes the performance of the two LED samples based on the PET framework. For low-power blue LED with sapphire substrate, our fabricated sample has a thermal resistance of 170 ºC/W, which is slightly lower than conventional ones that are typically around 220 ºC/W [8]. With the removal of the sapphire layer, the thin-film LED has a thermal resistance of 110 ºC/W, which is a significant (35 %) reduction from 170 ºC/W. The reduction in thermal resistance affects other important parameters. The optical power of the thin-film LED of 20 mW is 43 % higher than that of the LED with sapphire, indicating that the thin-film LED has much less optical power loss. The internal quantum efficiency of the thin-film (0.308) is 39 % higher than that of the LED with sapphire. Comparison of the heat dissipation coefficients indicates that 66% of the input power of the thin-film LED ends up as heat, but the LED with sapphire has 73 % of its input power dissipated as heat. This difference in heat dissipation is also reflected in the difference in the luminous efficacy, which shows that the luminous efficacy is three times of that of the LED with sapphire. With a lower thermal resistance, the thin-film LED is also found to be less sensitive to junction temperature change.

V. CONCLUSION

This paper gives a comparative study on a conventional LED structure with sapphire and a thin-film LED without sapphire based on the PET framework. An estimation method for the optical power and heat dissipation coefficient of thin-film LED devices based on the general PET theory is presented. The proposal consists of a practical procedure for the required electrical and device parameters measurements. The parameters obtained in the procedure are applied to the original PET theory to predict the optical power and heat dissipation coefficients that cannot be easily accessed in practice. The estimation method extends the original PET theory to studying thin-film LED devices. LED manufacturers are encouraged to include more technical information such as internal quantum efficiency as a function of operating temperature and current in the data sheets as basic parameters for thin-film LED system designs. The comparative study shows that the removal of the conventional sapphire layer can greatly reduce the thermal resistance and the optical power loss. Such improvements in the thermal characteristics are linked to advantageous features such as improved luminous efficacy and internal quantum efficiency as well as reduction in thermal sensitivity. Since commercial LED devices still predominantly consist of the substrate structure, the thin-film structure offers better thermal and luminous performance. The propsed thin-film LED structure will be particularly suitable for compact LED systems such as those repored in [20] and [21].

VI. APPENDIX

TABLE I: ALL THICKNESSES OF THE LAYERS OF THE TWO LED SAMPLES.

	LED with Sapphire	Thin-film LED
ITO	200 nm	200 nm
P-GaN	0.25 μm	0.25 μm
MQW	40 nm	40 nm
N-GaN	3 μm	3 μm
U-GaN	3 μm	-
Sapphire	400 μm	-
Silver Colloid	20 μm	20 μm
Ceramics	400 μm	400 μm

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TABLE II: COMPARISON OF THE TWO LED SAMPLES BASED ON THE PET FRAMEWORK.

	LED with Sapphire	Thin-film LED	Comment
Wafer area	600μm x 600μm	600μm x 600μm	Identical
Thermal resistance	170 °C/W	110 °C/W	R_{jc} for the LED with sapphire is slightly lower than that of conventional low-power blue LEDs [8]. But the elimination of the sapphire can reduce the thermal resistance of the LED device significantly.
Optical power @ 0.12A	14 mW	20 mW	Thin-film LED has higher optical power and thus less optical power loss.
Internal quantum efficiency	0.221	0.308	Thin-film LED has higher internal quantum efficiency and thus higher optical power.
Heat dissipation coefficient @ 0.12A	0.73	0.66	Thin-film LED has a lower heat dissipation coefficient, meaning that it has less heat loss.
Luminous efficacy @ 0.12A	2.8 lm/W	8.45 lm/W	Note that the samples are monochromatic blue LEDs and should not be compared with white LEDs with phosphor coating. The results indicate that thin-film LED has better luminous efficacy than LED with sapphire.
Sensitivity of luminous efficacy with junction temperature from 0.02A to 0.12A	-0.072 lm/W/°C	-0.049 lm/W/°C	Thin-film LED is less sensitive to temperature change.

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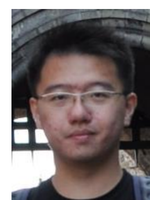
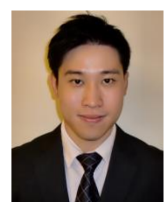
Huan Ting Chen (M'13) received the Ph.D degree in radio physics from Xiamen University, Xiamen, China, in 2010. He was a Joint Ph.D student at the Light & Lighting Laboratory, Catholic University College Gent, Belgium, from November 2009 to May 2010. He was a Senior Research Associate in the Department of Electronic Engineering, City University of Hong Kong, Hong Kong, in 2011. He is currently Postdoctoral Fellow in Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong. His research interests include solid-state lighting theory and technology.



Yuk Fai Cheung received his MPhil degree from the University of Hong Kong in 2013. With research based on Gallium Nitride light emitting diodes (GaN LEDs), his research focuses particularly on laser processing, device characterization and packaging. His current research projects mainly include colour tunable LEDs to achieve remarkable colour homogeneity and thin-film vertical LEDs to boost device performance.

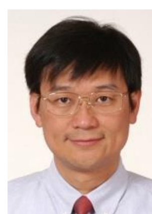
Hoi Wai Choi (SM'09) is associate professor with the Department of Electrical and Electronic Engineering at The University of Hong Kong. Dr. Choi received his PhD from the National University of Singapore and completed his postdoctoral training at the University of Strathclyde, Glasgow, where he contributed to pioneering development work on III-Nitride emissive micro-light-emitting diode arrays. Currently, Dr. Choi leads a team of researchers investigating topics in applied physics which include solid-state lighting, optical resonance and micro-cavities, nanophotonics, and laser processing of materials at the Semiconductor Lighting and Display Laboratory which he founded.



Siew Chong Tan (S'00–M'06–SM'11) received the B.Eng. (Hons.) and M.Eng. degrees in electrical and computer engineering from the National University of Singapore, Singapore, in 2000 and 2002, respectively, and the Ph.D. degree in electronic and information engineering from the Hong Kong Polytechnic University, Hong Kong, in 2005.

From October 2005 to May 2012, he worked as Research Associate, Postdoctoral Fellow, Lecturer, and Assistant Professor in Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hong Kong. From January to October 2011, he was Senior Scientist in Agency for Science, Technology and Research (A*Star), Singapore. He is currently an Associate Professor in Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong. Dr. Tan was a Visiting Scholar at Grainger Center for Electric Machinery and Electromechanics, University of Illinois at Urbana-Champaign, Champaign, from September to October 2009, and an Invited Academic Visitor of Huazhong University of Science and Technology, Wuhan, China, in December 2011. His research interests are focused in the areas of power electronics and control, LED lightings, smart grids, and clean energy technologies.

Dr. Tan serves extensively as a reviewer for various IEEE/IET transactions and journals on power, electronics, circuits, and control engineering. He is an Associate Editor of the IEEE Transactions on Power Electronics. He is a coauthor of the book *Sliding Mode Control of Switching Power Converters: Techniques and Implementation* (Boca Raton: CRC, 2011).



S. Y. (Ron) Hui (M'87-SM'94-F'03) received his BSc (Eng) Hons at the University of Birmingham in 1984 and a D.I.C. and PhD at Imperial College London in 1987. He has previously held academic positions at the University of Nottingham (1987–90), University of Technology Sydney (1991-92), University of Sydney (92-96), City University of Hong Kong (1996-2011). Presently, he holds the Chair Professorships at the University of Hong Kong and Imperial College London.

He has published over 200 technical papers, including more than 170 refereed journal publications and book chapters. Over 55 of his patents have been adopted by industry. He has been an Associate Editor of the IEEE Transactions on Power Electronics since 1997 and an Associate Editor of the IEEE Transactions on Industrial Electronics since 2007. He has been appointed twice as an IEEE Distinguished Lecturer by the IEEE Power Electronics Society in 2004 and 2006. He served an AdCom member of the IEEE Power Electronics Society and was the Chairman of its Constitution and Bylaws Committee from 2002-2010. He received the Excellent Teaching Award in 1998 and the Earth Champion Award in 2008. He won an IEEE Best Paper Award from the IEEE IAS Committee on Production and Applications of Light in 2002, and two IEEE Power Electronics Transactions Prize Paper Awards for his publications on Wireless Charging Platform Technology in 2009 and on LED system theory in 2010. His inventions on wireless charging platform technology underpin key dimensions of Qi, the world's first wireless power standard, with freedom of positioning and localized charging features for wireless charging of consumer electronics. In Nov. 2010, he received the IEEE Rudolf Chope R&D Award from the IEEE Industrial Electronics Society, the IET Achievement Medal (The Crompton Medal) and was elected to the Fellowship of the Australian Academy of Technological Sciences & Engineering and the recipient of the 2015 IEEE William E. Newell Award.

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