Low-Flicker Lighting From High-Voltage LEDs Driven by a Single Converter-Free Driver

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***Abstract*— This letter reports the design and characterization of high-power flip-chip high-voltage light-emitting diodes (HVLEDs), driven by a single converter-free LED driver for a compact and low-flicker lighting system. The HVLED chips show small forward voltage variation, uniform light emission, good optical output linearity, and stable thermal performance. All these characteristics well satisfy the demanding requirements of the novel quasi-constant power control scheme adopted in the converter-free LED driver. After bonding 12 HVLED chips (60 LED cells in total) and a single driver onto a silicon carrier through metal bonding, a low lighting flicker of 15.2%∼17% was demonstrated, showing great potential for high-quality illumination applications that require low flicker, high light output, and good thermal stability.**

***Index Terms*— Converter-free driver, general illumination, high-voltage LED, low-flicker lighting.**

I. INTRODUCTION

RECENTLY, gallium nitride (GaN) based light-emitting diodes (LEDs) have been widely utilized in applications including display, signage and general illumination due to their high energy efficiency, long lifetime, and low cost of ownership [1]–[3]. Meanwhile, there has been a growing demand for improving the lighting quality of LED lighting systems. It has been found that long-time exposure to light with severe flickers may cause health problems including headaches and epileptic seizures [4], [5], among others. Recently, Gao *et al.* [6] reported a novel high-performance converter-free LED driver adopting a quasi-constant power control scheme to achieve low flicker without using bulky and expensive power inductors and short-lifetime electrolytic capacitors (E-caps) that are typically adopted in conventional LED drivers.

This specific LED driver design also sets special requirements, such as a large number of LEDs in a string configuration and small variation of the constituent LEDs' properties including forward voltage, wavelength, and energy efficiency. Although the above-mentioned LED string configuration can be obtained by integrating pre-sorted discrete LED chips through wire bonding, the accumulated variations of the whole LED string can be quite large and the pre-selection process for a large number of LEDs that meets all the electrical and optical requirements can be tedious and ineffective. Although additional regulated current sources or balancing resistors in the LED driver [7] can manage the variation to some extent, the complex LED driver circuitry, low reliability of the LED string and high package cost make this solution unfavorable.

A high-voltage LED (HVLED), which features a monolithically-integrated multi-junction LED configuration [8]–[13], can significantly reduce the fundamental variations among constituent LED cells. Because of their high-voltage low-current operation mode, HVLEDs can also mitigate the "efficiency droop" occurring in conventional single-junction high-power LEDs [13] and simplify the mains AC-to-DC driver design. Moreover, HVLEDs are reported to be more reliable, compact and inexpensive, compared with the chip-on-board (COB) packaging LEDs [9]. Thus, HVLEDs are a promising candidate compatible with LED drivers to achieve uniform and stable lighting.

In this paper, we report a compact and low-flicker lighting system using uniform and reliable high-power flip-chip HVLEDs driven by a single converter-free LED driver. HVLED chips with different numbers of junctions were designed and fabricated, and their suitability and compatibility with the converter-free driving scheme were discussed with regard to their electrical, optical, and thermal characteristics. An example system made of 60 LED cells and one converter-free LED driver demonstrated a low lighting flicker of 15.2%∼17%, showing great potential for illumination applications that require low flicker, high light output power and good thermal stability.

II. DEVICE DESIGN AND FABRICATION

Fig. 1 schematically shows the converter-free lighting system, which consists of an LED driver and an LED string. For the LED driver, a quasi-constant power (QCP) controller is used to apply a nearly-constant power. For each branch of LEDs, an individual current regulator with a fixed reference voltage is designed to control the current and voltage of the LEDs on that branch. When the input voltage increases, more LEDs on the LED string can be lit up, while the current flowing through each LED decreases, and vice versa.

For a 110 V_{AC} mains power input, a string of 60 LED cells with 10 branches is used. To achieve such a multi-branch

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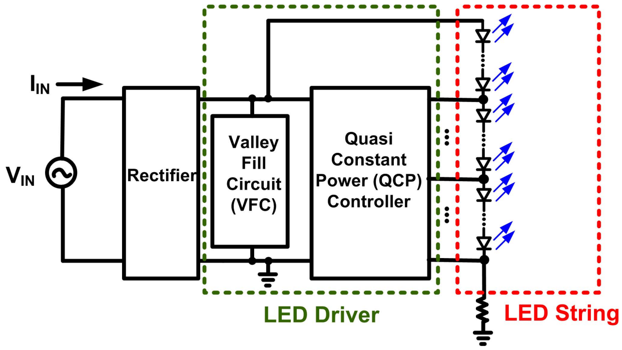

Fig. 1. Schematic of the converter-free LED lighting system.

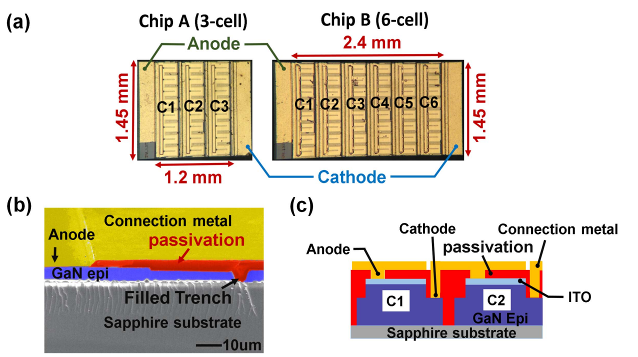

Fig. 2. (a) Microscope images of the two types of HVLED chips with current flowing from anode to cathode. (b) Pseudo color SEM image of the trench filling and metal interconnection. (c) Cross-session illustration of sub-LED cell-to-cell interconnection, taking C1 to C2 as an example.

LED string configuration, two types of HVLED chips: three cells in series (Chip A) and six cells in series (Chip B), are designed, as shown in Fig. 2 (a). Each constituent cell has the same mesa area of 0.38 mm^2 for both types of chips. In order to facilitate current spreading, an interdigitated p-n finger electrode is applied [10]. In the fabrication process, a 1.5 μm wide isolation trench was etched down to the sapphire substrate to isolate individual LED cells. A curable photoresist-filled-trench technique was also adopted to achieve side-wall passivation and trench filling [11]. As shown in Fig. 2 (b), the isolation trench is well filled, and good planarization and passivation have been achieved. Thus, a thin layer of connection metal (~400 nm) enabled good cell-to-cell interconnection.

III. Device Characterization

A. Electrical Characterization

Fig. 3 (a) shows the typical I-V characteristics of the two types of HVLED chips and a single constituent cell. At 20 mA, the forward voltages for the single cell, three-cell and six-cell HVLED are 2.90 V, 8.73 V and 17.3 V, respectively. The forward voltages of the multi-cell chips show good linearity with the forward voltage of the single constituent cell.

The distribution of forward voltages for 80 three-cell HVLEDs and 57 six-cell HVLEDs are displayed in Fig. 3(b). Using a Gaussian distribution model, we find that the average forward voltage values for Chip A and B are 8.8 V and 17.4 V

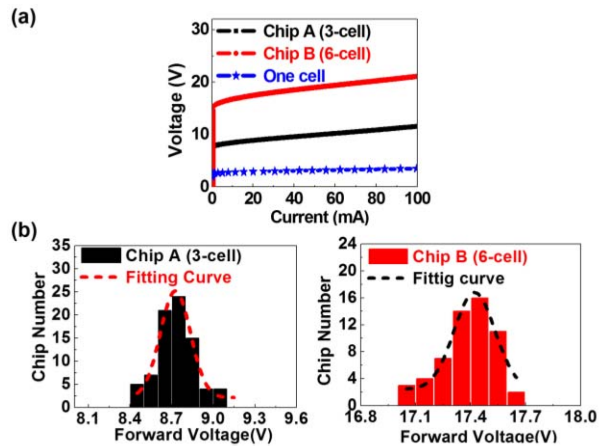

Fig. 3. (a) I-V characteristics of two types of HVLED chips and single constituent cell only. (b) V_F distribution for Chip A (three-cell) (left) and Chip B (six-cell) (right).

with standard deviations of 0.22 V and 0.23 V, respectively. For 84% of the three-cell HVLED chips and 80% of the six-cell HVLED chips, the forward voltages at 20 mA fall in the range of 8.8±0.2 V and 17.4±0.2 V. The small forward voltage variation observed in the HVLED chips is highly desirable because this guarantees a confirmative number of LEDs designed to be lit up by the LED driver and facilitates voltage or current control.

B. Optical Emission Characterization

Uniform light intensity distribution on the whole LED chip area and minimum peak wavelength variation among HVLED chips are essential elements in achieving highly efficient and stable light output when the LEDs are driven by Gao's driver. To characterize the light intensity uniformity at different injection currents, a Canon EOS500D camera with CMOS sensor area of 22.2 × 14.9 mm^2 was used for taking photos of the HVLEDs' light emission. Then the photos were converted into pseudo color images and normalized with their exposure times by using the Matlab image processing algorithm. As shown in Fig. 4 (a), both two types of HVLED chips can maintain evenly distributed light intensity under different current injections up to 100 mA. The uniform light emission can be attributed to the interdigitated p-n finger electrode design [10] and smooth current flow through the multiple cells [8].

The spectrum uniformity of the HVLED chips was also characterized. As shown in Fig. 4. (b), the peak wavelengths for the three-cell and six-cell HVLED, and single-constituent cell are all located at 451 nm because the HVLEDs are made of identical epitaxial materials. The single peak wavelength, even with an up-scaled number of LEDs that increased the total active area, makes a uniform spatial color temperature [14] possible when the LEDs are coated with phosphor powders to emit white light.

C. Output vs Input Power Density Characterization

One important and unique feature of Gao's LED driver is the quasi-constant power control scheme, in which a higher input

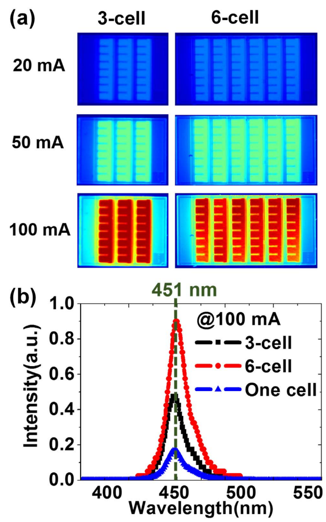

Fig. 4. (a) Pseudo color images of the light intensity distribution for two types of HVLED chips pumped at 20 mA, 50 mA and 100 mA. (b) Comparison of spectra from a three-cell HVLED, a six-cell HVLED and a single constituent cell at 100 mA current injection.

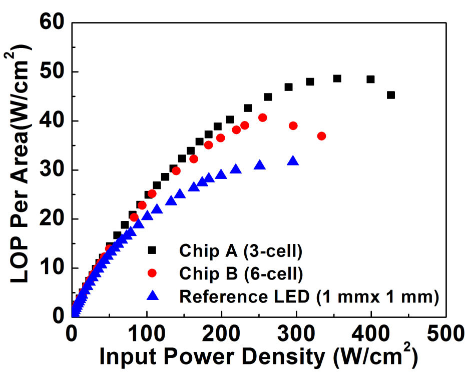

Fig. 5. Light output power density vs the input power density for three types of LED chips: three-cell HVLED chip, six-cell HVLED chip and single-junction high-power LED (1 mm^2 active area) as a reference.

voltage will power up more LED cells on the string, but will decrease the current through each LED cell. In order to create a stable optical output, and thus lower flicker, the light output power of the constituent LED chips, must have good linearity with the input power. It is well known that a single-junction chip cannot meet this requirement due to the efficiency droop phenomenon. The HVLED chips in this work, with their high-voltage/low-current operational mode, can greatly mitigate the efficiency droop issue and provide excellent optical power linearity up to 125 W/cm^2 for either three-cell chips or six-cell chips, as shown in Fig. 5. It is also noted that the three-cell and six-cell chips have almost the same energy efficiency within the measured range of 0$\sim$ 125 W/cm^2. Thus, driven by the quasi-constant power scheme, the HVLEDs will maintain nearly constant optical power, which is independent of the number of lit LED cells, and achieve a low-flicker lighting system within the measured range of 0$\sim$ 125 W/cm^2, corresponding to the input power range of 0$\sim$ 28.85 W. Such a wide input power range not only satisfies the demand of our current LED driver's design with the maximum LED input power of 6 W, but also allows for further upscaling of the LED driver's input power in future.

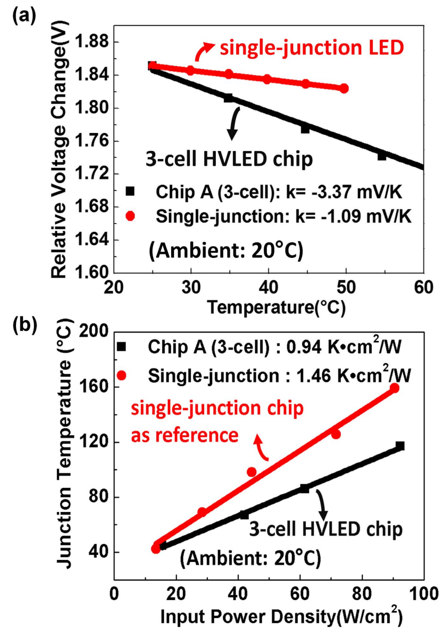

Fig. 6. Thermal performance comparison of a three-cell HVLED and single-junction high-power LED as a reference: (a) k-factor. (b) Junction temperature vs input power density. The lines are the linear fitting of the experimental data.

D. Thermal Performance Characterization

The thermal performance of the HVLED chips was characterized, as shown in Fig. 6. The k factor describing the rate of forward voltage drop with the increase of junction temperature was calibrated as −3.37 mV/K for a three-cell HVLED. Since the voltage drop of a three-cell HVLED chip is the sum of the voltage drops of its three junctions, the average forward voltage drop rate for each LED cell is −1.12 mV/K, comparable with the k factor of −1.09 mV/K for a single-junction high-power LED. Fig. 6 (b) shows the input power density-dependent junction temperature of a three-cell HVLED in comparison with a 1 mm × 1 mm single-junction LED chip after being bonded to the same type of silicon carriers. The junction temperature increase rate of the three-cell HVLED chip was measured to be 0.94 K•cm^2/W, which is 35% lower than that of its conventional single-junction LED reference. The low junction temperature of the HVLEDs can greatly ease thermal management of the system. Thus, a compact and long-lifetime lighting system can be expected, as the risk of heat-induced premature failure of the driver and LEDs is greatly mitigated.

E. System Integration

Fig. 7 (a) shows the images of a printed circuit board (PCB) and the mounted silicon carrier with the LED string (four three-cell HVLED chips and eight six-cell chips) and the converter-free LED driver which works with 110 V_{AC}, 60 Hz mains power. The PCB was connected with other off-chip components (rectifier and valley fill circuit) for system testing. As shown in Fig. 7 (b), as the voltage exerted on the LED

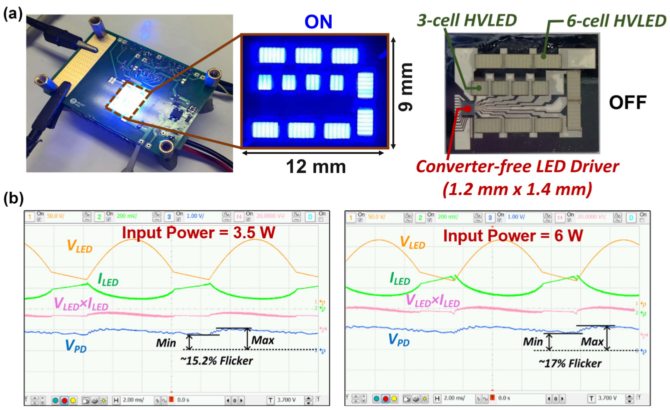

Fig. 7. System integration demonstration: (a) PCB with mounted silicon carrier. (b) Measured waveforms of the voltage, current applied on the LED string and output voltage of the photodiode for flicker monitoring at 3.5 W and 6 W.

TABLE I
DRIVER PERFORMANCE COMPARISON WITH OTHER WORKS

	[16]	[15]	[5]	This work
Year	2012	2013	2016	2017
Chip Area	0.75 mm^2	9.6 mm^2	NA	1.85 mm^2
Off-chip Switch	800 V MOSFET	NA	600V MOSFET	NA
Transformer	1.8 mH	NA	Yes	NA
Inductor	NA	NA	150 μH	NA
Capacitor	Electrolytic 470 μF	NA	Film caps 11.2/20 μF	MLCC 15 μF×4
Power	6-12 W	22 W	20 W	3.5- 6 W
Input (V_{AC})	180-260	110/220	100-260	110
Flicker	~30%	~100%	~8%	17%

(MLCC: Multi-layer Ceramic Capacitor.)

string was increased, the current flowing through the lit-up LED cells decreased, and vice versa. As a result, the input power at any given point in time was almost constant. A stabilized optical power output from the 60-cell LED string was obtained at different input powers without using any power inductors or electrolytic capacitors.

According to [15], for a time-varying luminance with maximum and minimum values of $L_{\max}$ and $L_{\min}$, the percent flicker can be defined as:

$$\text{Percent Flicker} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \times 100\%$$

As shown in Fig. 7 (b), the flicker of the LED strings was measured to be 15.2% and 17% at 3.5 W and 6 W input power, respectively, much smaller than the results of 100% [15] and 30% [16] for the AC driver design. Compared with the flicker value in [5], as shown in Table I, our LED driver eliminates two switching converters (fly-back and buck) with bulky and expensive components (transformer and inductor). Thus, the LED system presented here has significant advantages in terms of cost, size and life-time.

IV. CONCLUSION

A compact illumination system that consists of HVLED chips and a single LED driver is demonstrated, featuring a low flicker without using bulky power inductors and electrolytic capacitors. The design, fabrication, and characterization of the tailor-made HVLED chips are reported. Uniform electrical and optical characteristics, and stable thermal performance of the HVLEDs are analyzed and their compatibility with the quasi-constant power scheme of the driver design are discussed. The integrated system reported here paves a practical path for applications where compact, large area, and low-flicker lighting is needed.

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