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Cost-Effective LED Dimming Driver With Single Chip Design for Smart Lighting System

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ABSTRACT For smart lighting system, this paper presents a high-power (60V/1A) single-chip driver for LED dimming using TSMC high-voltage process. The main circuit included analog circuit, power driver and digital control circuit with mixing-mode design methodology. The proposed digital dimming controls LED brightness increasing or decreasing with only two switches. The switches can be controlled by the auto mode or manual mode for user selection. All digital control circuits are embedded to the chip. Because of without the need of micro-processor for LED dimming, this chip is cost-effective design that can save the components of interface. To keep high-stable LED lighting, the dimming techniques used current mode rather PWM (Pulse Width Modulation) to reduce flicker. The multi-level current approach used 16 steps for LED lighting control. The step resolution is 6.25% for smart lighting system. With variable constant current control, this approach can achieve better lighting efficiency, reduce noise radiation and prolong LED lifetime for smart lighting systems. The maximum driving efficiency of the proposed chip can achieve near 98% as driving for 60W LED dimming.

INDEX TERMS LED, multi-level current, power MOS, power driver, dimming control.

I. INTRODUCTION

Recently, the smart lighting system with LED devices is popular for energy efficiency. The main issue includes high efficiency LED driver and automatic smart control systems. The lighting level can be adjusted according to occupancy or daylight by automatic or manual method. Smart lighting is a fundamental system for smart cities [1] based on IoT (Internet of Things) platform. Current smart lighting systems employed with existing communication techniques to offer users to remote control the lamps. For smart lighting control, the wiring connection is widely used from the control panel to lamp with Dali standard system [2]. Power-Line Communication(PLC) can carry with the control signals through power network [3], but the high-power noise may interfere with the communication data. In order to save the wires, the wireless system with WIFI or Zigbee is used for smart lighting control [4]. The lighting control can employ the manual mode and auto mode for user selection. For the manual mode, the control panel generally had Lighting-Up, Lighting-Down and Power-ON on wall-switches [5] or cell-phone. For auto control, the simple method can adopt PIR (Pyroelectric Infrared) sensor to detect human activity for lighting control [6]. Closed-loop control algorithm [7] is proposed with feedback from a spectral sensor, and the light spectrum output is converged to the target spectrum. For complex multi-color lighting control, neural-network based is proposed to control each string color based on training approach [8].

LEDs are energy-efficient devices, exceeding 200 lumens/Watt since 2019 years. More and more applications used LED as lighting sources, for example, LCD backlight, traffic signals, street lighting or indoor illumination over large areas. Now the smart lighting system always used LED as lighting sources. Since LED is DC supplying component, a driver is required for LED lighting system [9]. Currently, LED drivers have two types: one is AC/DC driver [10]–[19] and the other is DC/DC driver [20]–[25]. For AC/DC converter, the main issue is for low harmonic distortion, high power factor correction (PFC) and high driving efficiency. For user friendly, the dimming function is embedded to LED driver generally. For LED dimming, the methods can utilize AM (amplitude-mode modulation), pulse width modulation (PWM) and multi-current level (MCL). Generally, AM approach is applied on AC/DC driver [18], such as

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flyback structure. However, its linearity is poor since the voltage vs LED current is exponential curve. The dimming range is limited about in the range of 20%∼100%, which cannot be applied for weak-lighting control. Currently, PWM is widely used to control the LED brightness by on-off duty cycle, which directly switches high-power LED devices [21], [22]. PWM method can achieve high dimming accuracy, but low lighting-efficiency, high noise and even to shorten LED lifetime [26]. Because LEDs lighting is switching with high-frequency, human eyes cannot detect lighting flicker. However, the high-frequency flicker possibly damages human eyes after a long time used. To reduce the disadvantages of PWM, a constant current driver [27] was used, but its dimming resolution is too low.

In this study, chip-level methodology is presented to design high-power LED dimming driver for smart lighting system. For LED dimming, the micro-processor was required to control the brightness in the past [7]. Our main intention is to develop a single chip, which does not use extra micro-processor for high-power LED dimming. This chip employed multi-current approaches rather than PWM method to reduce lighting flicker. Only two switches are used, where one switch can be pushed to increase LED brightness, and the other is to decrease. The switches can be controlled by manually or automatic for lighting adjustment. Efficient control circuit is embedded to an LED driver with 16-level currents for LED dimming. The step resolution is 6.25%, which is enough for smart lighting system. Our proposed method enables a stable LED driving current without the need for rapid switching to reduce the problem of EMI problem. The remainder of this paper is organized as follows. The chip architecture is outlined in Section II. Implementation and experiments are described in Section III. The proposed chip is applied on smart lighting system is depicted in Section IV, and conclusions are drawn in Section V.

II. SYSTEM ARCHITECTURE FOR LED DRIVER

In this study, a single chip is proposed for LED dimming driver by mixing mode design. The chip embeds the digital control circuit, oscillator, multi-level current generator and power driving circuit. For LED dimming, the interface only adopts two switches instead of micro-processor, which can greatly save the cost of system implementation. The current dimming is controlled by a sensing resistor, and the sensing voltage is compared with a reference voltage, to control the driving current. A linear mode is an alternative to switched mode drivers in order to overcome the problem of premature degradation of LED devices and EMI.

A. CONTROL CIRCUIT DESIGN

Figure 1 shows the system architecture of the proposed single chip. The left side is the digital control circuit and oscillator. The right is for current dimming and high-power driving. In the digital control core, Up or Down singal is detected to control LED brightness increasing or decreasing respectively. The Up/Down singals are fed to control up/down counter.

TABLE 1. Truth table of dimming control.

Input					Output		
Clock	Up	Down	A_{03}	O_{03}	clk	u	d
↑	0	0	0	1	0	0	0
↑	0	1	0	1	↑	0	1
↑	1	0	0	1	0	0	0
↑	1	1	0	1	0	0	0
↑	0	0	1	0	0	0	0
↑	0	1	1	0	0	0	0
↑	1	0	1	0	↑	1	0
↑	1	1	1	0	0	0	0

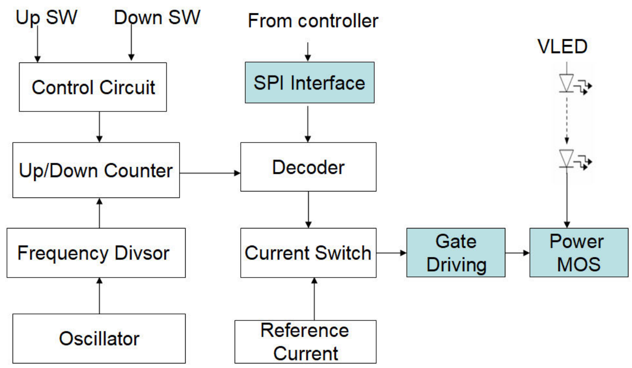


FIGURE 1. The system architecture of the proposed single chip for LED dimming driver.

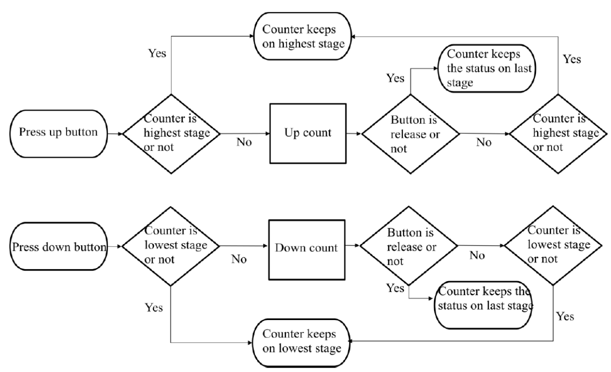


FIGURE 2. The dimming control flowchart.

The flowchart of dimming control is shown in Fig. 2. When pushing the Up switch, first checking whether the counter is at the highest level. If yes, the highest level is kept. Otherwise, the counting value increases by one per cycle until Up switch is released. Oppositely, when pushing the Down switch, the lowest level is kept if the counter is at the lowest level. Otherwise, the counting value decreases by one per cycle until Down switch is released. According to the control state, the truth table for state controller is listed in Table 1, where A_{03} and O_{03}. senses the maximum and minimum output respectively. The digital control circuit is desinged by using the state machine, as shown in Fig. 3. The design for up/down counter employs T-FF and AND/OR gates, as shown in Fig. 4. The chip included SPI interface. The lighting level

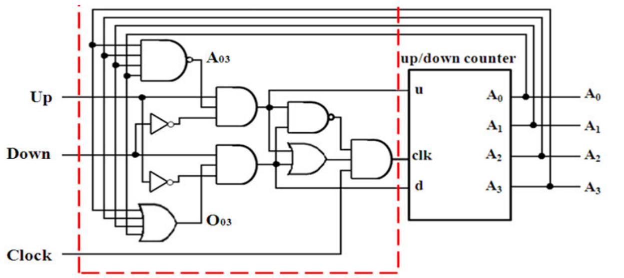


FIGURE 3. The up/down state controller for counter.

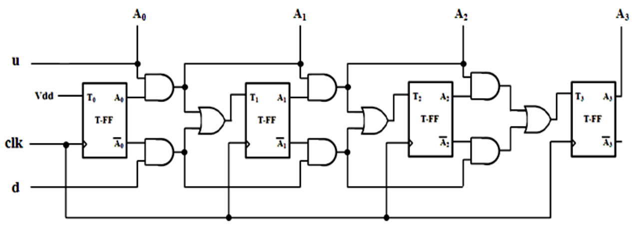


FIGURE 4. The up/down counter using T-FF.

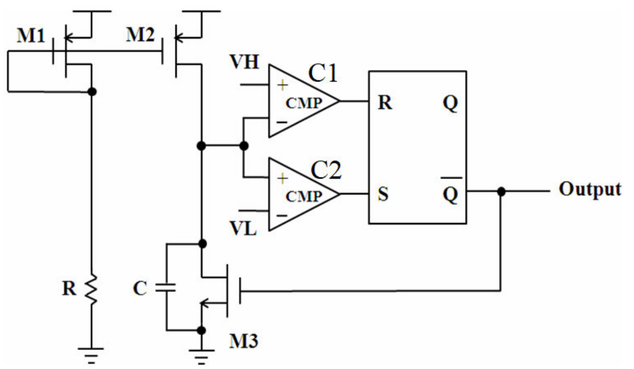


FIGURE 5. The architecture of system oscillator.

can be controlled by SPI interface to specify the address and data for each lamp lighting control [28].

Since the counter requires clock, an oscillator and frequency divisor are embedded into the chip. Figure 5 shows the architecture of system oscillator. M1 and M2 is the pair of current mirror. M1 and R produce a reference current and then mirrors to M2. The M2 current is I2 that charges the capacitor C. The voltage of the capacitor Vc successively increases following to the time. As the Vc >VH, the C1 comparator(CMP) becomes high, where VH is a high-level threshold. MOS M3 turns on, then the capacitor C is discharged. Now the Vc successively decreases until to Vc <VL, where VL is a low-level threshold. Then C2 comparator(CMP) becomes high, and M3 turns off. Once and again, the current I2 repeats to charge the capacitor. The clock signal is from Q pin of RS flip-flop. Generally the clock frequency of the oscillator is several KHz in minimum. For user dimming control, only several Hz is required for the lighting step control. Hence a frequency divisor is employed to reduce the frequency of oscillator.

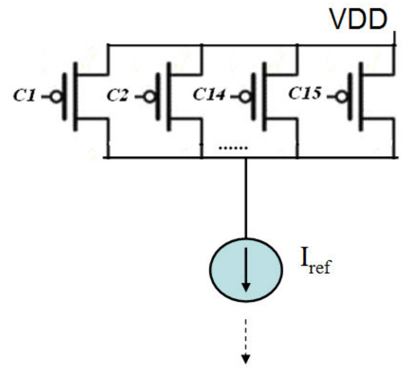


FIGURE 6. The PMOS current switch array for LED dimming.

B. POWER CONTROL

For multi-current LED dimming, the current switches are adopted to control the driving current. The n-bit results of the up/down counter input to a decoder that decodes the n-bit to 2^n signals for control the current switches. The decoding value corresponds to the driving current. When the counting value is high, the decoding value corresponds to high. While more current switches turn on, the driving current increases to make LED higher brightness. The current switches can use PMOS device. The switch array is as shown in Fig. 6. One PMOS can generate the constant current as

$$I_P = \frac{1}{2}\mu_p \ C_{OX}\frac{W}{L}(V_{GS}-V_{TH})^2. \tag{1}$$

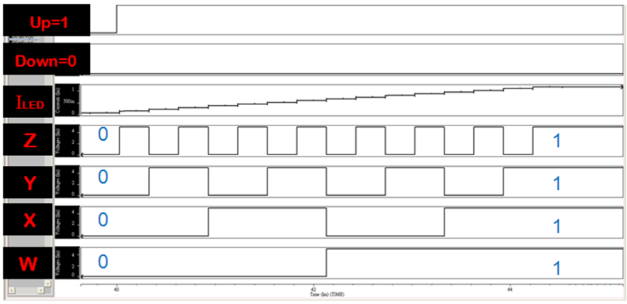
The parameters u_p, C_{ox} *and* V_{TH} are mobility, thin oxidized capacitor and threshold respectively, which are fixed in the chip process. The channel width (W) and length (L) of MOS are used to adjust the current. For LED dimming, 16 PMOS parallel are employed to generate 16-level currents. When there are M current switches on, the driving current increase M times of Ip. The switch is controlled by the Ch pin. If Ch=0, the h^{th} PMOS turns on, such that the reference current can be expressed as

$$I_{ref} = \bar{C}_o I_{p0} + \bar{C}_1 I_{p1} + \bar{C}_2 I_{p2} + \ldots\ldots + \bar{C}_{14} I_{p14} + \bar{C}_{15} I_{p15}. \tag{2}$$

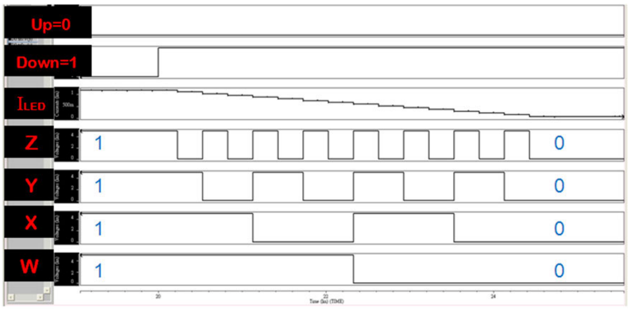
The symbols Ip0, Ip1 and Ip15 denote the current of the 1st,2nd and 16th PMOS, respectively. The I_{ref} current is higher and higher when more and more PMOSs turned on. Switch control pins C1 to C16 are set by digital signals that decodes from the results of up/down counter. Next, the current of power MOS refers to the I_{ref} current for LED driving.

III. LED DRIVER CHIP IMPLEMENTATION AND DEMONSTRATION

To verify chip function, first the SPICE simulation tool is employed to realize physical circuit using TSMC 0.25*um* high-voltage process. To achieve better cost-efficiency, 60v and 5v MOS devices are used to design high-power driver and low-power control circuit, respectively. The relative-ship



(a) The simulations of LED driving current increase as Up



(b) The simulations of LED driving current increase as Down=1

FIGURE 7. (a) The simulations of LED driving current increase as Up=1. (b) The simulations of LED driving current increase as Down=1.

of digital control and LED driving current is presented by mixing-mode simulations for LED dimming. When push "Up" switch, Fig 7(a) shows I_{LED} successively increasing if the counting value is less than the maximum. The symbols Z, Y, X and W are corresponded to the counting values, A0, A1, A2 and A3 of Fig.4 respectively. Oppositely, when push "Down" switch, I_{LED} is successively decreasing until to the counting value arrives at the minimum one, as shown in Fig 7(b). Since the 4-bit counter is designed, 16-step currents are achieved for LED dimming. The chip layout is designed by using full custom methodology, which had been verified through layout-Vs-schematic (LVS) and design rule check (DRC). The parameters of layout are extracted, and to verify the linear current for LED dimming with the post simulation. Figure 8 shows the linear-curve of the control step vs LED driving current, which can keep good linearity. The size of the chip with I/O pads is only $0.9 \times 1.101 mm^2$. This chip included one power MOS that can drive 60V/1A LED at the maximum specification. A prototyping chip had been fabricated through CIC(Chip Implementation Center, Taiwan) MPC project using the TSMC (Taiwan Semiconductor Manufacture Company) process. Figure 9 shows the photo die of the proposed chip.

A. CHIP MEASUREMENT

The chip samples are measured with one PCB(print circuit board), which consists of off-chip passive components. The test circuit is shown in Fig. 10. Since a single chip design for LED dimming, the interface is very simply, where only one capacitor, three resistors and two push switches are used.

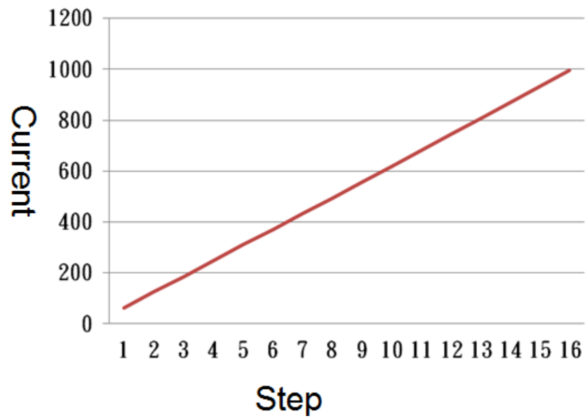


FIGURE 8. The linear current control for LED driving in each step.

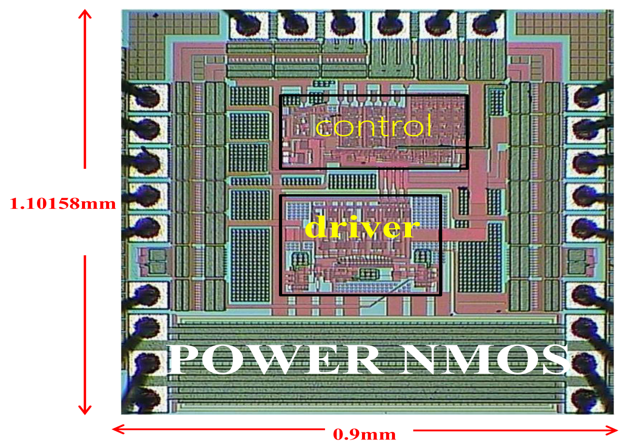


FIGURE 9. The photo die of the proposed chip.

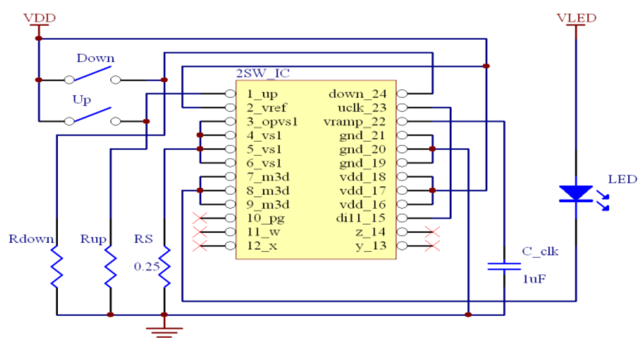


FIGURE 10. The system testing circuit of the proposed single chip for LED dimming driver.

First, the oscillation after frequency divisor is measured. Figure 11 shows the output for a square waveform. The cycle time is 250ms (about 4Hz) that is suitable for user to adjust LED lighting step. The cycle time can be changed by the capacitor. Figure 12 (a) and (b) shows the demo system for the proposed single chip to control LED dimming in the lowest and highest driving current, respectively. The system is designed to drive $12 \times 3W$ white LEDs within one PCB. The system is very simple for user to adjust LED brightness by

TABLE 2. The features of the proposed chip.

Technology	TSMC 0.25 UM CMOS HV BCD 1P5M SALICIDE 2.5/5/60V
Chip Size	0.9 mm ×1.10158mm
Transistor/Gate Count	977 Transistors
Chip Power Dissipation(max)	0.9W
Max. Driving Efficiency	98%
Max. Driving Current	1A
#Dimming Step	16
Dimming Control	Two switches

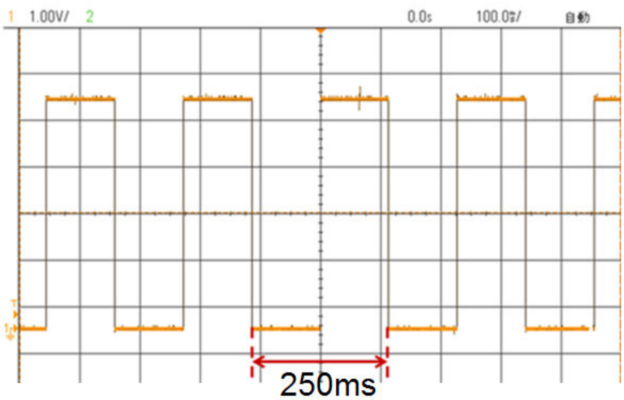


FIGURE 11. The measured up/down control frequency.

two switches. Hence this chip is cost-effective for the smart lighting system.

Table 2 lists the chip features of the proposed LED driving chip. The prototype is implemented using TSMC 0.25*um* high-voltage 60v/5v process. The chip size contained I/O pads is about the silicon area of 1 mm^2. The chip only employed 976 low-voltage transistors and one 60V power MOS. The maximum power dissipation of the internal circuit is about 0.9W when driving 60W LED. The maximum driving current can achieve 1A with enabling 16-step dimming. The dimming control only employed two switches without extra micro-processor required.

The driving efficiency was devised using the ratio of input power to output power, as follows:

$$Efficiency = \frac{Output\ LED\ Power}{Input\ Power} = \frac{I_{LED} \times NV_d}{VLED \times I_{LED} + V_{DD} \times I_{VDD}} \quad (3)$$

The output power can be measured according to the practical voltage drop across all LED devices (N×Vd) and their driving currents (ILED), where V_d is one LED drop voltage and the string number of LED is N. The input power is measured by the summation of the internal control circuit with $V_{DD} \times I_{VDD}$ and the high-voltage power for LED driver with

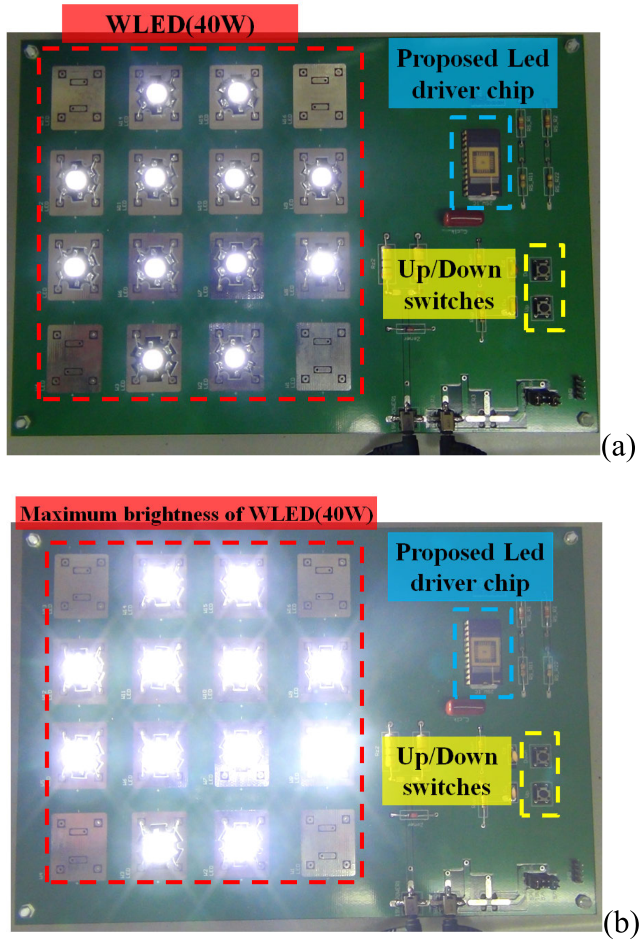


FIGURE 12. The demo system for the proposed single chip LED dimming driver in lowest driving current with 62mA in (a), and the highest driving current with 992mA in (b).

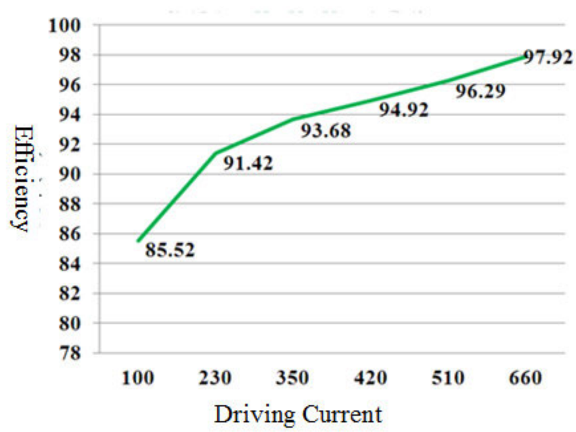


FIGURE 13. The driving efficiency in various current.

VLED $\times I_{LED}$, where VLED supplies the high-voltage to be connected to the anode of LED. Figure 13 shows the driving efficiency under various output currents. When the driving current increases, the efficiency is higher. The maximum efficiency can achieve about 98% as the driving current is over 660mA.

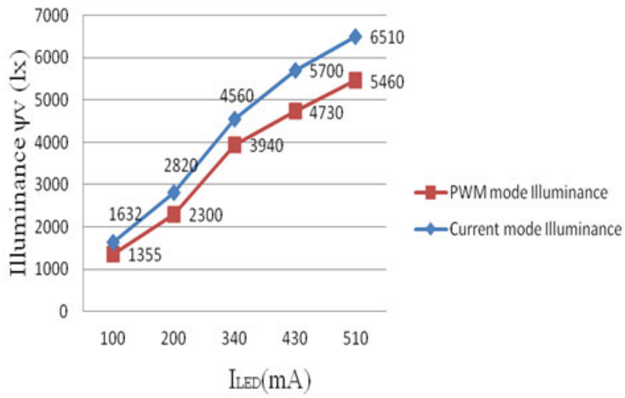


FIGURE 14. Comparison of luminance flux vs the currents.

B. COMPARSIONS

For comparisons, LED luminance is measured at various driving currents compared with PWM method. The PWM duty cycle can be controlled for a specified LED driving current. For test, the input current of PWM driver is adjusted by the duty cycle, to equal with that of our multi-level current driver. The average input current can be measured from the current meter of the power supply. Then the integrating sphere was employed to measure the luminous flux of LEDs under various input currents. Figure 14 presents the curves of the driving currents vs LED luminance for each test. The luminous flux increases as corresponding to the current increasing. The multi-level current driver can achieve higher efficiency than PWM types due to without switching lost. Results show that the lighting efficiency of the proposed chip can be improved to be approximately 20% higher than a conventional PWM driver. Since PWM controls LED with fast on/off, the lighting energy is lost during the switching periods. The averaged of two power levels based on duty cycle PWM control gives a lower averaged luminous output than using a continuous point. When the driving current is higher and higher, the switching lost is more and more. This causes the lighting efficiency of PWM method is not appropriated as applied on the high-power LED system.

Table 3 lists the results of comparison between the proposed chip and the state-of-the art LED drivers [29]–[31]. Liu et. al. presented synchronous buck chip for LED driver [29], which the maximum driving power and current is 26W and 700mA. For LED dimming, this chip requires PWM pulse to trigger the control logic. The micro-processor (μP) must be used to generate PWM duty cycle. A wide voltage range for LED driving chip is presented with HV process [30]. This chip is suitable to drive high-voltage LED device with low current. The maximum current is 350mA to drive 5V$\sim$115V LED. The analog dimming for LCD backlight was presented in [31]. This technique is for high accuracy dimming, but applied on low-power system. The proposed chip employs high-voltage process for high-power LED driving chip, providing the maximum power of 60W with VLED=60V and I_{LED} =1A. The proposed chip not only can achieve

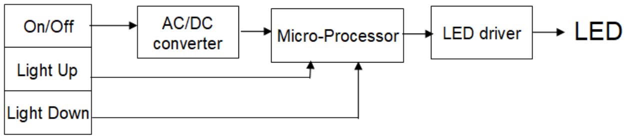
TABLE 3. Performance Comparisons with state-of-the-art LED chips.

Features	[29]'15	[30]'16	[31]'19	Proposed
Max. Supply Voltage	45V	115V	5.5V	60V
Max. LED Driving Power (Current)	31.5W (700mA)	40W (350mA)	1W (20mA)	60W (1A)
Core Size(mm^2)	6.6	9.4	1.16	0.99
Process	0.35 μm 50 V CMOS process	0.5 μm 120 V CMOS process	0.18μm, *BCD* process	TSMC 0.25μm HV G2 process
Dimming Method	PWM Pulse	PWM Pulse	Analog Voltage	16-Level Current
Dimming Interface	μP	μP	μP	Switch or μP
Dimming Freq.	20kHz	20k	20k	4Hz
Switching Freq.	<4MHz	<2.2MHz	0	0
EMI Problem	Serious	Serious	Little	None
Flicker	Yes	Yes	Free	Free
Max. Driving Efficiency	97%	94%	-	98%
LED Lighting Efficiency*	1	1	1.2	1.2

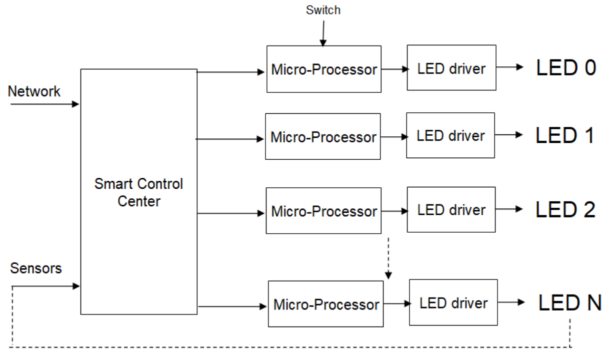
The conventional buck requires high PWM frequency for feedback control and also external PWM signal for LED dimming. The high-energy switching used for the LED devices would produce RF noise, and EMI problems in practical lighting systems. The micro-processor is required controlling PWM duty for LED dimming. The proposed chip employs 16-level currents for LED dimming with a stable current source and no need fast current switching. The step current is easily controlled by using two switches, where only 4Hz is used to adjust LED brightness. Hence the proposed chip is no EMI interference and flicker free. Our efficiency is higher than PWM type because of no switching lost. The lighting efficiency can be better 20% than PWM dimming in experiments. The maximum driving efficiency of the proposed chip can achieve about 98% as driving for 60W LED system. It is worthy notice that the color changing by the different magnitude of driving current is higher than PWM. The LED lighting color only produces little deviation using multi current driver in our experiments, which the differential does not be sensed by human eyes. Besides, by the digital dimming, the discrepancy can be corrected by a digital table if color deviation is visible.

IV. CHIP APPLIED ON SMART LIGHTING

Figure 15(a) shows the conventional smart lighitng with manual switches. The control panel includes the power On/Off,



(a) The conventional smart lighitng with manual switch

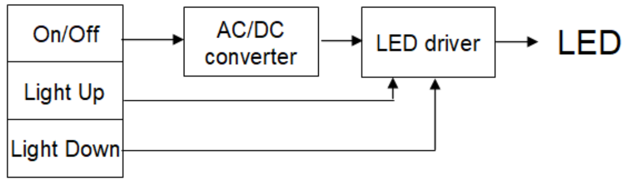


(b) The conventional smart lighitng with close loop for automatic control

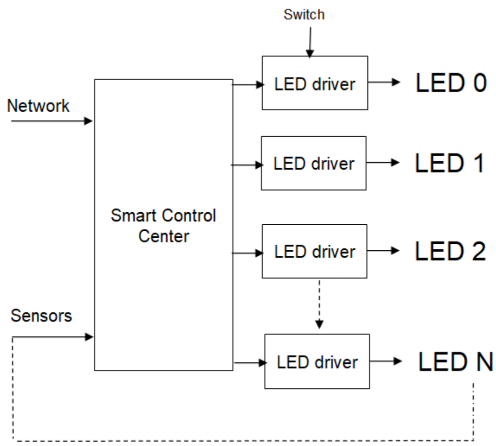
FIGURE 15. (a) The conventional smart lighitng with manual switch. (b) The conventional smart lighitng with close loop for automatic control.

lighting Up and Down [5]. The power switch can directly switch the AC line power of AC/DC converter to turn on or off the LED lighitng. The lighting Up and Down switches input to the micro-processor. When push the lighting Up, the micro-processor increase the PWM duty to LED driver, and the LED lighitng increases. Oppositely, the lighitng is down when PWM duty reducing. Figure 15(b) shows the conventional smart lighitng with close loop for automatic control. The LED lighitng is controlled by sensors. The lighitng level can be keep a suitable condition by photo sensing. When the lamp is close to a window in the day, the LED lighting can be reduced to save power energy while keeping enough lighitng. The human sensor can be detect whether peoples in the space. If there are no peoples, the lighting level can be reduced to save the energy. The signals of sensors input to the smart control center that can decide the PWM vlaues for each lamp. According to the current sensor status, the smart control center sends the desired PWM vlaue to the micro-processor of each lamp. The micro-processor generates PWM waveform to LED driver to control the lighitng level of each lamp. The lighting level can be controlled by remote device thorugh the networks, such as ethernet, WiFi, Zigbee, and so on. Of course, the user can direcltly adjust the lighting level by switches to control PWM value for the micro-prcoessor.

Figure 16(a) shows the proposed chip for smart lighitng with manual switches. The chip had been designed for the inputs of lighting Up and Down, which can be direcltly connected to the switches of control panel whithout the need of micro-processor. For a close-loop smart lighting system, the smart control center can be according to the current sensing status to control the lighting Up or Down by sending pulse signal to the proposed chip. Also, the control for the proposed chip with SPI signal is acceptable. The SPI protocol included address and data. Each lamp can be defined with



(a) The proposed chip for smart lighitng with manual switch



(b) The proposed chip for smart lighitng with close loop for automatic control

FIGURE 16. (a) The proposed chip for smart lighitng with manual switch. (b) The proposed chip for smart lighitng with close loop for automatic control.

own address [28]. The smart control center can send the lighting step to a specified lamp by the address through the serial port to adjust the brightness. After a long time using, due to LED aging, the lighting of the n^{th} lamp may be lower than the desired value by the feedback photo sensor. The smart control center can increase the lighting level to the relative address of the proposed chip with SPI signal to raise the LED current by the close-loop control.

V. CONCLUSION

This paper presents a single chip LED driver with mixing-mode design. Only two switches are employed to adjust LED brightness increasing or decreasing, without the need of micro-processor. Also, this chip supports SPI interface for remote control. Testing samples were successfully implemented using the TSMC G2 high-voltage process, where the chip size was only $1mm^2$. The cost-effective chip can provide simple use, small system area, high efficiency, and accurate dimming for LED smart lighting control. This chip is appropriated for high-power LED dimming, which can be applied in smart lighting systems as connecting to the Internet of Things (IOT).

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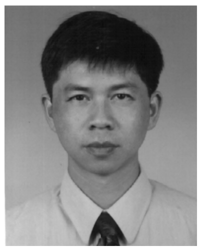

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