Design and research of an LED driving circuit with accurate proportional current sampling mode*

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Abstract: An LED driving circuit in accurate proportional current sampling mode is designed and fabricated based on CSMC 0.5 μm standard CMOS technology. It realizes accurate sensing of sampling current variation with output driving current. A better constant output current characteristic is achieved by using an amplifier to clamp the drain voltage of both the sampling MOSFET and power MOSFET to the same value with feedback control. Small signal equivalent circuit analysis shows that the small signal output resistance in the accurate proportional current sampling mode circuit is much larger than that in a traditional proportional current sampling mode circuit, and circuit stability could be assured. Circuit simulation and chip testing results show that when the LED driving current is 350 mA and the power supply is 6 V with $\pm$10% variation, the stability of the output constant current of the accurate proportional current sampling mode LED driving IC will show 41% improvement over that of a traditional proportional current sampling mode LED driving IC.

Key words: LED driver; accurate proportional current sampling; constant current
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1. Introduction

White LEDs are being used as backlights for notebook PCs, medium and large size LCD TVs, colorful outdoor signs and lighting engineering because of their high energy efficiency and very long operation time. Various LED driver techniques are based on constant current driving to avoid violating the maximum current rating and comprising the reliability, to get predictable and matched luminous intensity and chromaticity from each LED[1]. In constant current driving mode LED driver ICs, a sampling resistance is always used to measure the driving current directly and produce sampling voltage. This sampling voltage keeps the LED driving current constant by negative feedback. As the power of the LED driving IC is increased, its driving current will reach several dozens of milliampere to several ampere. The increase in power dissipation on sampling resistance will cause a decrease in power efficiency of this driving IC and limit the practical applications. Although reducing the value of sampling resistance can decrease the sampling power dissipation accordingly, it will also degrade the accuracy of current sampling and controlling[2−4].

An improved circuit called traditional proportional current sampling (TPCS) mode is to sample the output current partially by a current mirror circuit. The small proportional sampling current can also produce enough sampling voltage to keep its sampling accuracy and reduce sampling power dissipation.

In this paper an accurate proportional current sampling (APCS) LED driving IC is designed based on TPCS mode and the equivalent circuit analysis on its constant output current characteristic is carried out. The APCS mode IC can increase both the equivalent output resistance and sampling accuracy to obtain better constant output current characteristics.

2. Circuit principle and equivalent output resistance analysis

The TPCS circuit is shown in Fig. 1. It is based on linear regulated constant current driving mode.

Current sensing MOSFET Ms and power driving MOSFET Mp provide a highly effective way of measuring load current with proportion sampling strategy. These devices split load current into power and sense components and thereby allow the signal level resistor Rsense to be used for sampling Vsense. The constant current feedback control is composed of a current sampling resistance, an error amplifier, a reference, a sensing MOSFET and a power MOSFET. If the output current increases, Vsense will be increased and the output voltage of the amplifier also increases. The driving source–gate voltage of the power MOSFET Mp will be decreased, causing the output load current to decrease. Vice versa, the output current is kept stable and constant. But there is still a drain voltage difference between Ms and Mp in the varied work region. The sensing current cannot reflect the changes of power current totally and it will reduce the constant current driving accuracy[5, 6].

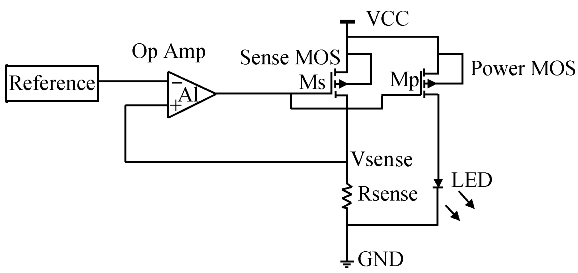

Fig. 1. TPCS mode LED driver circuit.

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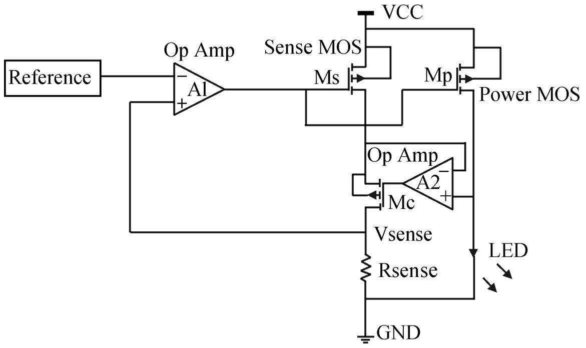

Fig. 2. APCS mode LED driver circuit.

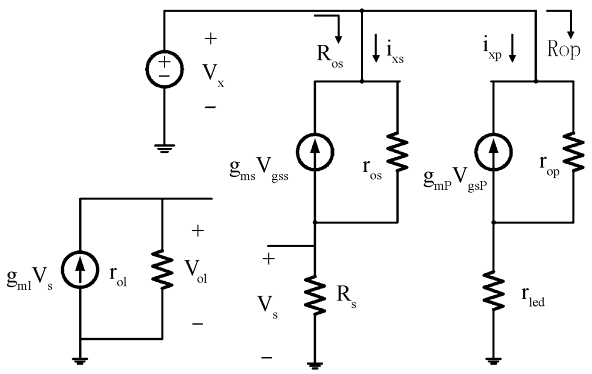

Fig. 3. Small signal equivalent circuit of TPCS.

An APCS LED circuit is proposed in Fig. 2. The op amp A2 is used to force the drain voltages of Ms and Mp to be equal to eliminate the non-idealities resulting from channel length modulation and working region variation[7]. Furthermore the feedback loop introduced by A2 helps to increase the equivalent output resistance of power MOSFET Mp and improve the constant current controlling characteristics.

According to circuit theory, the higher the equivalent output resistance[8], the smaller the current fluctuation which appears in the LED driving path under the LED power supply variation and process variations. It is used to improve the output resistance characteristics and constant current driving performance of the LED driving circuits.

The TPCS equivalent circuit is shown in Fig. 3. V_x is used as a test voltage source. The op amp A1 is modeled as the voltage controlled current source and the equivalent output resistance. V_{o1} is the op amp A1 output voltage. R_{os} is the equivalent small signal output resistance looking into the current sensing path and R_{op} is the equivalent small signal output resistance looking into the current power driving path. r_{os} and r_{op} are the small signal output resistance of the current sensing MOSFET and the current driving MOSFET.

In V_x loop V_x can be expressed as

$$V_x = \left[i_{xs} + g_{ms}V_{gss}\right] r_{os} + i_{xs}R_s, \tag{1}$$

and

$$V_x = \left[i_{xp} + g_{mp}V_{gsp}\right] r_{op} + i_{xp}r_{led}, \tag{2}$$

since V_{gss} can be expressed as

$$V_{gss} = V_{gsp} = V_{o1} - V_x = g_{m1}i_{xs}R_sr_{o1} - V_x. \tag{3}$$

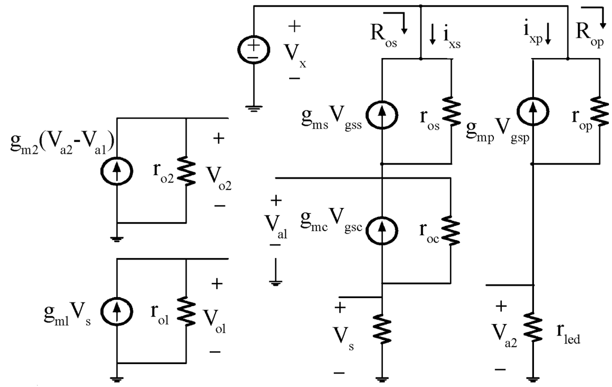

Fig. 4. Small signal equivalent circuit of APCS.

Substituting Eq. (3) into Eq. (1), R_{os} can be solved as

$$R_{os} = \frac{V_x}{i_{xs}} = \frac{r_{os} + R_s + g_{ms}r_{os}g_{m1}r_{o1}R_s}{1 + g_{ms}r_{os}} \approx g_{m1}r_{o1}R_s. \tag{4}$$

Since $V_{gsp} = V_{gss}$, $i_{xs} = V_x/R_{os}$, R_{op} is solved as

$$R_{op} = \frac{V_x}{i_{xp}} = \frac{r_{op} + r_{led}}{1 + \left(1 - g_{m1}r_{o1}\dfrac{R_s}{R_{os}}\right) g_{mp}r_{op}}. \tag{5}$$

Using Eqs. (4), (5) and $g_{m1}r_{o1}R_s \gg 1$,

$$R_{op} = \frac{r_{op} + r_{led}}{1 + \left(1 - \dfrac{g_{m1}r_{o1}R_s}{g_{m1}r_{o1}R_s + \dfrac{R_s}{1 + g_{ms}r_{os}}}\right) g_{mp}r_{op}} \approx r_{op} + r_{led}. \tag{6}$$

The equivalent small signal output resistance R_{os} of the TPCS sensing path is very large due to the large open loop gain of A1[9]. The equivalent small signal output resistance R_{op} of the TPCS power driving path is much smaller than R_{os} and as low as dozens of ohm because there is no feedback loop in the power MOSFET path of TPCS. A low equivalent output resistance means a large current variation, causing poor constant current control when the power supply varies.

The APCS equivalent small signal circuit is shown in Fig. 4. The feedback control is introduced into the power MOSFET Mp path with the help of Op amp A2 in Fig. 4.

It is similar to the TPCS circuit that V_x and V_{gsp} can be also written respectively as follows.

$$V_x = \left[i_{xp} + g_{mp}V_{gsp}\right] r_{op} + i_{xp}r_{led}, \tag{7}$$

$$V_{gsp} = V_{gss} = V_{o1} - V_x = g_{m1}i_{xs}R_sr_{o1} - V_x. \tag{8}$$

Substituting Eq. (8) into Eq. (7) gives

$$V_x\left[1 + g_{mp}r_{op}\right] = \left[g_{mp}r_{op}g_{m1}r_{o1}R_s\right] i_{xs} + \left(r_{led} + r_{op}\right) i_{xp}. \tag{9}$$

The relationship between $i_{\rm xs}$ and $i_{\rm xp}$ should be derived to obtain the equivalent small signal output resistance $R_{\rm op}$. From the sensing MOSFET Ms path, $V_{\rm x}$ can also be expressed as

$$V_{\rm x} = \left[i_{\rm xs} + g_{\rm ms}V_{\rm gss}\right] r_{\rm os} + \left[i_{\rm xs} + g_{\rm mc}V_{\rm gsc}\right] r_{\rm oc} + i_{\rm xs}R_{\rm s}. \quad (10)$$

As a feedback function of A2, the voltage loops for the control voltage $V_{\rm gsc}$, $V_{\rm o2}$ are shown below as Eqs. (11) and (12).

$$V_{\rm gsc} = V_{\rm o2} - \left[(i_{\rm xs} + g_{\rm mc}V_{\rm gsc})r_{\rm oc} + i_{\rm xs}R_{\rm s}\right], \quad (11)$$

$$\begin{aligned} V_{\rm o2} &= g_{\rm m2}r_{\rm o2}(V_{\rm a2} - V_{\rm a1}) \\ &= g_{\rm m2}r_{\rm o2}\left\{i_{\rm xp}r_{\rm led} - \left[(i_{\rm xs} + g_{\rm mc}V_{\rm gsc})r_{\rm oc} + i_{\rm xs}R_{\rm s}\right]\right\}. \end{aligned} \quad (12)$$

Substituting Eqs. (8, 11, 12] into Eq. (10) gives

$$\begin{aligned} V_{\rm x}[1 + g_{\rm ms}r_{\rm os}] = &\Big[r_{\rm os} + r_{\rm oc} + R_{\rm s} + g_{\rm ms}r_{\rm os}g_{\rm m1}r_{\rm o1}R_{\rm s} \\ &- \frac{(1 + g_{\rm m2}r_{\rm o2})(r_{\rm oc} + R_{\rm s})g_{\rm mc}r_{\rm oc}}{1 + (1 + g_{\rm m2}r_{\rm o2})g_{\rm mc}r_{\rm oc}}\Big]i_{\rm xs} \\ &+ \frac{g_{\rm mc}r_{\rm oc}g_{\rm m2}r_{\rm o2}r_{\rm led}}{1 + (1 + g_{\rm m2}r_{\rm o2})g_{\rm mc}r_{\rm oc}}i_{\rm xp}. \end{aligned} \quad (13)$$

Op amp A2 with large open loop gain senses the drain voltages of Mp and Ms and keeps the drain voltages equal. Because $g_{\rm m2}r_{\rm o2} \gg 1$, Equation (13) can be simplified as

$$V_{\rm x}\left[1 + g_{\rm ms}r_{\rm os}\right] = \left[r_{\rm os} + g_{\rm ms}r_{\rm os}g_{\rm m1}r_{\rm o1}R_{\rm s}\right]i_{\rm xs} + i_{\rm xp}r_{\rm led}. \quad (14)$$

Since $V_{\rm x}$ in Eqs. (9) and (14) is the same small signal voltage in parallel path, the ratio of the small signal current $i_{\rm xs}$ and $i_{\rm xp}$ can be derived.

$$\begin{cases} i_{\rm xs} = Ki_{\rm xs}, \\ K = \dfrac{(g_{\rm mp}r_{\rm op} - g_{\rm ms}r_{\rm os})g_{\rm m1}r_{\rm o1}R_{\rm s} - g_{\rm mp}r_{\rm op}r_{\rm os}}{(g_{\rm mp}r_{\rm op} - g_{\rm ms}r_{\rm os})r_{\rm led} - g_{\rm ms}r_{\rm os}r_{\rm op}}. \end{cases} \quad (15)$$

Substituting Eq. (15) into Eq. (9), the equivalent small signal output resistance $R_{\rm op}$ of APCS mode can be calculated as

$$\begin{aligned} R_{\rm op} &= \frac{V_{\rm x}}{i_{\rm xp}} \\ &= \frac{\left[g_{\rm mp}r_{\rm op}g_{\rm m1}r_{\rm o1}R_{\rm s}\right]\dfrac{1}{K} + \left(r_{\rm led} + r_{\rm op}\right)}{1 + g_{\rm mp}r_{\rm op}} \\ &\approx \frac{1}{K}g_{\rm m1}r_{\rm o1}R_{\rm s}. \end{aligned} \quad (16)$$

$R_{\rm op}$ will be large if K is small and $g_{\rm m1}r_{\rm o1} \gg 1$. With the same biasing voltage for the current sensing MOSFET and power driving MOSFET, a useful relationship is

$$g_{\rm mp}r_{\rm op} = g_{\rm ms}r_{\rm os}. \quad (17)$$

Applying Eq. (17) to Eq. (15), K is given by

$$K = \frac{r_{\rm os}}{r_{\rm op}} = \frac{I_{\rm DP}}{I_{\rm DS}} = \frac{(W/L)_{\rm Mp}}{(W/L)_{\rm Ms}}. \quad (18)$$

This means that the current ratio of two transistors is the same as the W/L ratio. As the W/L ratio K increases, the dissipation of the sensing MOSFET Ms path decreases. But the accuracy of the circuit decreases and the equivalent small signal output resistance of the power MOSFET path degrades. To improve the LED constant current driving characteristic, an appropriate K and a high gain for both op amps are needed to obtain a large, thousands of kΩ equivalent small signal output resistance.

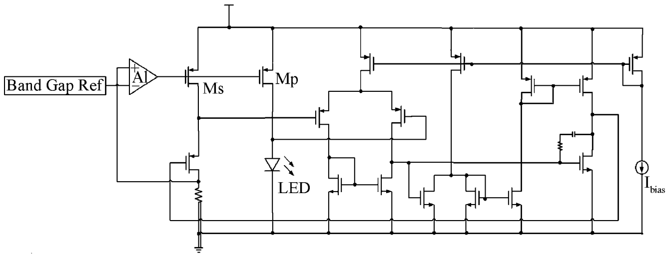

Fig. 5. Circuit topology.

Compared with the single negative feedback loop in TPCS mode, there are a negative feedback loop and a positive feedback loop in APCS mode. To avoid oscillation resulting in an unstable state, the negative feedback loop gain should be larger than the positive feedback loop gain. The negative feedback loop gain of APCS mode is

$$A\beta_{\rm N} = \frac{A_1R_{\rm s}\left[g_{\rm ms}r_{\rm os} + (A_2 + 1)\,g_{\rm mc}r_{\rm oc}g_{\rm ms}r_{\rm os}\right]}{R_{\rm s} + r_{\rm oc} + r_{\rm os} + (A_2 + 1)\,g_{\rm mc}r_{\rm oc}r_{\rm os}} \approx A_1R_{\rm s}g_{\rm ms} \quad (19)$$

and the positive feedback loop gain of the APCS circuit is

$$\begin{aligned} A\beta_{\rm P} &= \frac{A_1A_2g_{\rm mc}r_{\rm oc}g_{\rm mp}\left(r_{\rm op}//r_{\rm led}\right)R_{\rm s}}{R_{\rm s} + r_{\rm oc} + r_{\rm os} + (A_2 + 1)\,g_{\rm mc}r_{\rm oc}r_{\rm os}} \\ &\approx \frac{A_1R_{\rm s}g_{\rm mp}\left(r_{\rm op}//r_{\rm led}\right)}{r_{\rm os}}. \end{aligned} \quad (20)$$

According to Eq. (17) and the fact that the LED has a smaller $r_{\rm led}$, it can be improved to $A\beta_{\rm N} \gg A\beta_{\rm P}$, so the APCS circuit is stable.

3. Circuit simulation and test results

The circuit topology is shown in Fig. 5. The circuit is simulated using Cadence Spectre and a 0.5 μm CSMC CMOS mixed signal process model.

The W/L of the sampling MOSFET is set to 2 × 8 μm/0.8 μm, the W/L of the power MOSFET is set to 250 × 51.6 μm/0.8 μm, and the LED driving currents are set to 350 mA in each circuit mode.

The simulation result in Fig. 6 shows that the equivalent small signal output resistance is about 75 Ω in TPCS mode and 44 kΩ in APCS mode. The equivalent small signal output resistance has been greatly improved in APCS mode.

The simulation current waveforms in Fig. 7 show improvement of the constant current control characteristics. The output current of TPCS mode is between 336.3 and 355.8 mA, and the current change is about 3.9% when the supply voltage is 6 V and varies ±10%. The output current of APCS mode is between 354.3 and 347.2 mA, and the current change is smaller than 1.2% when the supply voltage is 6 V and varies ±10%.

The results indicate that, compared to the TPCS mode, the equivalent small signal output resistance in APCS mode is 586

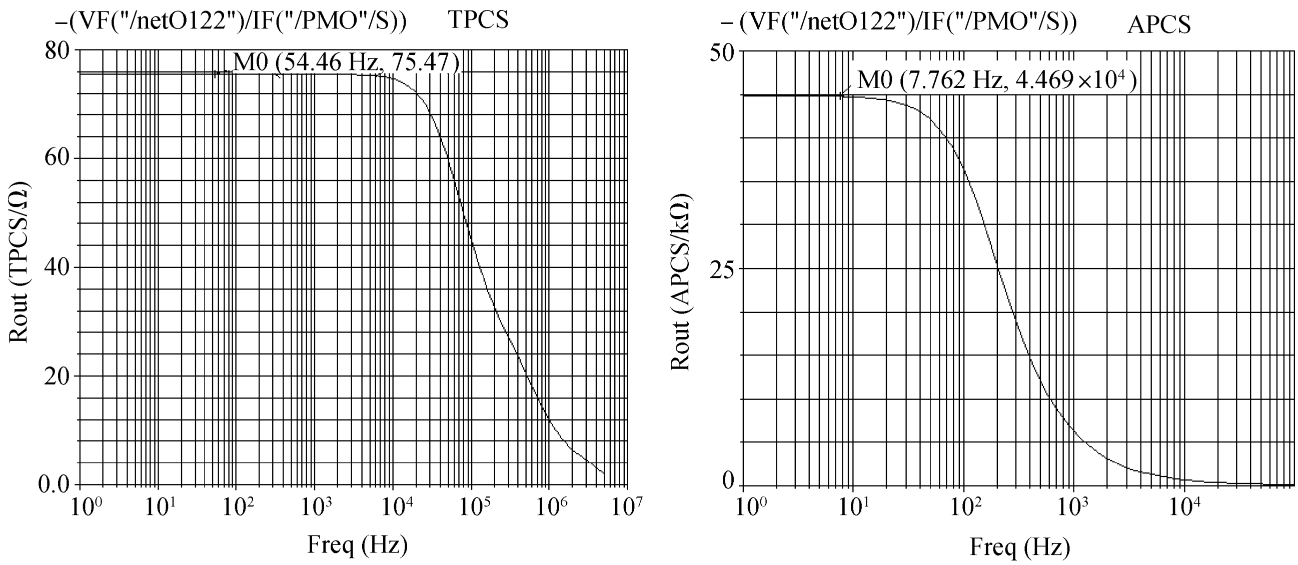

Fig. 6. Simulation results of the equivalent small signal output resistance of two circuit modes.

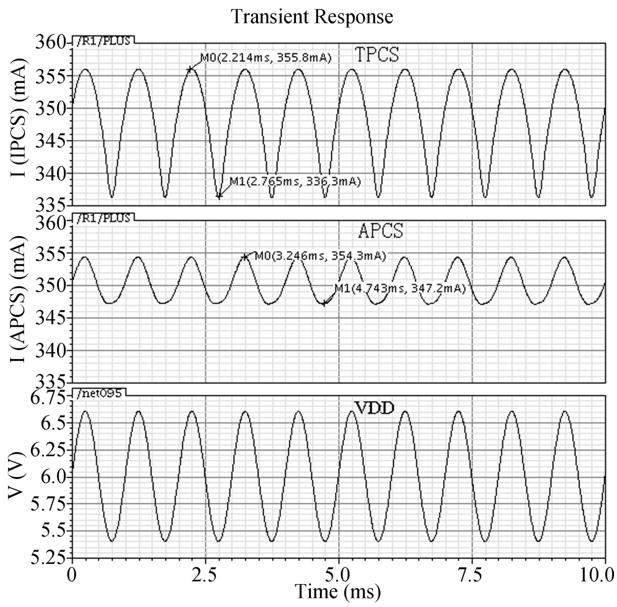

Fig. 7. Simulation results of TPCS and APCS output current characteristics.

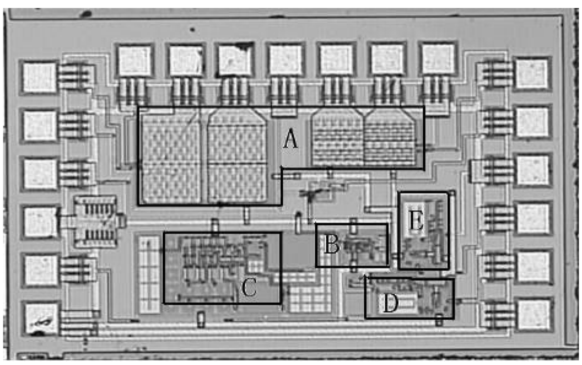

Fig. 8. Micrograph of APCS mode chip.

times higher and the stability of the constant current shows 2.7% improvement. The results of small signal equivalent circuit analysis and circuit simulation confirms that the constant current characteristic has been developed with improvement of the output resistance by using APCS mode instead of TPCS mode.

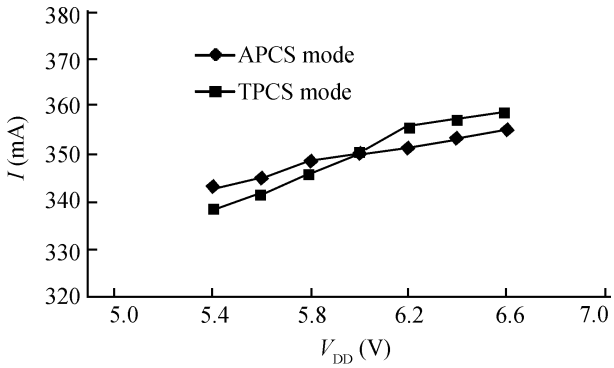

Fig. 9. Current variation measurement result with 6 V ±10% supply variation.

The chip is fabricated using the CSMC 0.5 μm standard CMOS process. Figure 8 shows a photograph of the APCS mode chip.

In Fig. 8, part A is the power MOSFET and sensing MOSFET, part B is the gate-driving control circuit, part C is the band gap reference, part D is the amplifier A1, and part E is the amplifier A2. Due to the insulating nature of sapphire substrate, electrostatic discharge (ESD) is still a problem for GaN-based LEDs, a customized GGNMOS and GGPMOS ESD structure is designed to connect the drain pad of the power driving MOSEFT Mp. The large capacitance to the ground at the drain of Mp also helps degrade the loop gain of the positive feedback and improve the system stability.

Test results (Fig. 9) indicate that the output current changes from 338 to 358.6 mA, less than 3.4% when the supply voltage (V_{DD} = 6 V) changes from 5.4 to 6.6 V in TPCS mode IC while the output current changes from 343 to 355 mA, less than 2% in APCS mode IC. The stability of the output constant current in APCS mode is 41% higher than TPCS's stability.

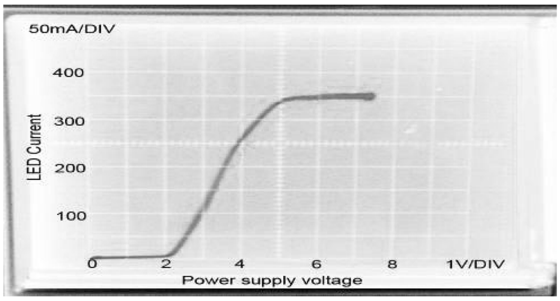

Fig. 10. Constant current characteristics of the APCS mode LED driver.

Figure 10 presents the constant current I–V characteristics of the APCS mode IC tested by Graphic Instrument XJ4810. It shows a quite flat current curve (I_{LED}: 345–355 mA when V_{DD} = 5–7 V).

It is measured that the A2 input pad connected with the LED can safely dissipate ESD strikes of 14 kV (HBM).

4. Conclusion

An accurate proportional current sampling (APCS) LED driving IC is designed and fabricated. The small signal equivalent circuit analysis and circuit simulation results indicate that the equivalent small signal output resistance in APCS mode is much larger than that in traditional proportional current sampling (TPCS) mode, thus obtaining a better constant current performance, and assuring circuit stability. Chip testing results show that when supply voltage varies ±10% around 6 V, APCS mode has a better constant current characteristic at 350 mA than TPCS mode, the maximum current deviation is 7 mA, the stability of the output current is less than 2%, which is 41% higher than TPCS. ESD protection structure of 14 kV (HBM) works well.

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