TEXAS INSTRUMENTS
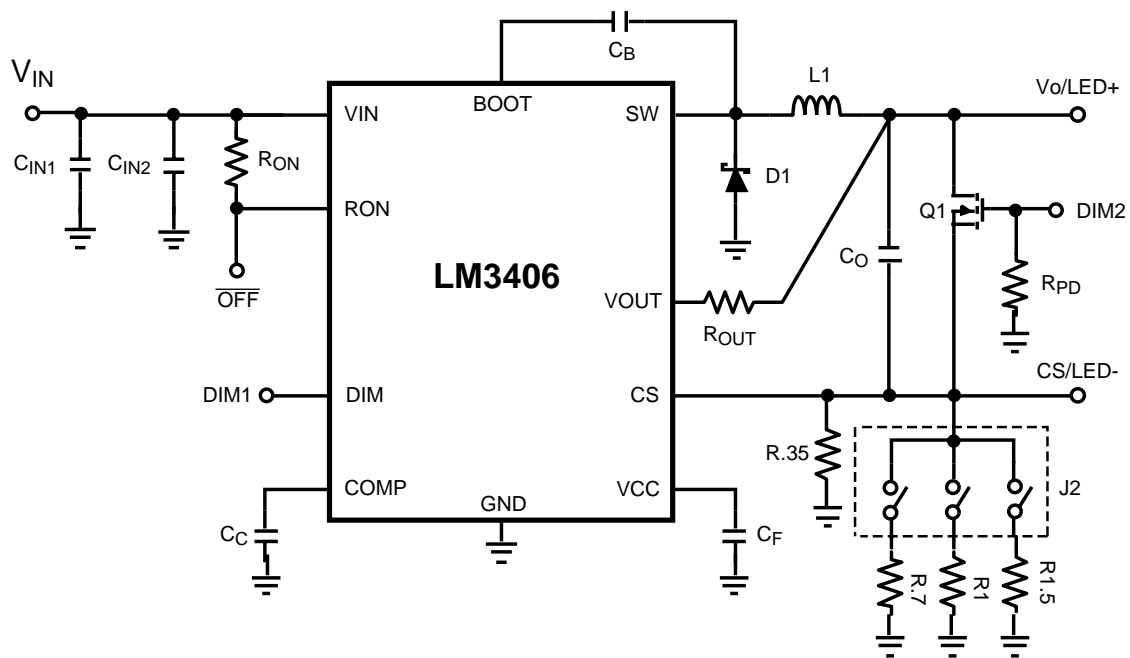
AN-1750 LM3406 Evaluation Board

1   Introduction

The LM3406 is a buck regulator controlled current source designed to drive a series string of high power, high brightness LEDs (HBLEDs) such as the Luxeon™ K2 Emitter at forward currents of up to 1.5A. The converter's output voltage adjusts as needed to maintain a constant current through the LED array.

Figure 1. Complete Circuit Schematic

2   Circuit Performance

The LM3406 circuit and BOM that come pre-installed on the evaluation board are optimized to run from an input voltage of 24V, but the circuit can operate from a wide input voltage range of 6.0V to 42V. The current output ranges from 0.35A to 1.5A. Figure 2 shows the program jumper settings used to program currents of 0.35A, 0.7A, 1A, and 1.5A.
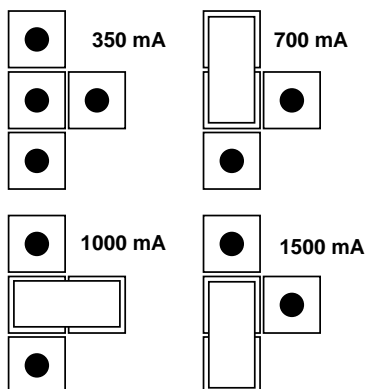

Figure 2. Setting Output Current, J2

The LM3406 is a step-down regulator with an output voltage range extending from a $V_{O\text{-}MIN}$ of 200 mV (the reference voltage) to a $V_{O\text{-}MAX}$ determined by the ratio of the minimum off time (typically 230 ns) to the switching frequency. The regulator can maintain the output current through any number of LEDs as long as the combined forward voltage of the array does not exceed $V_{O\text{-}MAX}$. $V_{O\text{-}MAX}$ can be calculated with the following formula:

$$V_{O\text{-}MAX} = V_{IN\text{-}MIN} \times (1 - f_{SW} \times t_{OFF\text{-}MIN}) \tag{1}$$

For example, if V_{IN} is 24V ±10%, then $V_{IN\text{-}MIN}$ is 21.6V. For a switching frequency of 500 kHz the maximum output voltage for the converter is 21.6 x [1 - (5 x 10^5) x (230 x 10^{-9}) = 19.1V. Output voltage is calculated with the following formula:

$$V_O = n \times V_F + 0.2V \tag{2}$$

Where 'n' is the number of series-connected LEDs, V_F is the forward voltage of each LED, and 0.2V represents the voltage across the current sense resistor. For InGaN LEDs (white, blue, blue-green) V_F is typically 3.5V, and with a limit of (19.1 - 0.2) = 18.9V the LM3406 could drive as many as five in series. For AlInGaP LEDs (red, orange, amber) V_F is typically 2.5V, so a $V_{O\text{-}MAX}$ of 18.9V would allow as many as seven to be driven in series.

3   Connecting the LED Array

The LM3406 Evaluation Board includes a female 6-pin SIP connector, **J1**, as well as two standard 94mil turrets for the cathode and anode connections of the LED array. Figure 3 shows the pinout of **J1**. Solid 18 or 20 gauge wire with about 1 cm of insulation stripped away makes a convenient, solderless connection to **J1**.
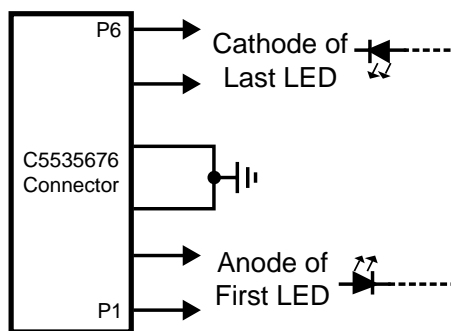
Figure 3. 6-Pin LED Connector, J1

## 4   Setting the LED Current

The default forward current I_F delivered to the LED array when no program jumper is installed on **J2** is 0.35A, set by resistor **R.35**. The higher LED currents are set when the program jumper puts resistors **R.7**, **R1** or **R1.5** in parallel with **R.35**. For users that wish to program a current other than one of the four default levels, or for users who want the best accuracy at a given current, the program jumper **J2** should be removed, and **R.35** changed according to the following equation:

$$R.35 = 0.2 / I_F \tag{3}$$

This resistor should be rated to handle the power dissipation of the LED current. For example, the closest 5% tolerance resistor to set an LED current of 0.35A is 0.56Ω. In steady state this resistor will dissipate $(0.35^2 \times 0.56) = 69$ mW, indicating that a resistor with a 1/8W rating is more than capable of dissipating the power.

5   Pulse Width Modulation (PWM) Dimming

The **DIM1** terminal on the PCB provides an input for a logic-level pulse width modulation signal for dimming of the LED array. In order to fully enable and disable the LM3406 the PWM signal should have a maximum logic low level of 0.8V and a minimum logic high level of 2.2V. Graphical representations of minimum and maximum PWM duty cycle are illustrated in Figure 4. The interval t_D represents the delay from a logic high at the DIM pin to the rise in output current. The quantities t_{SU} and t_{SD} represent the time needed for the output current to slew up to steady state and slew down to zero, respectively. It is important to note that t_D is a property of the LM3406 and remains fixed in all applications. The slew rates t_{SU} and t_{SD} are a function of the external circuit parameters V_{IN}, V_O, I_F, inductance (L) and the LM3406 parameter $t_{OFF-MIN}$. Response times for a circuit driving three white LEDs at 1A from 24V are shown in the Typical Performance Characteristics section, but the user should test every new circuit to determine the actual PWM dimming response.

$$T = \frac{1}{f_{PWM}}$$

$$D_{MIN} = \frac{t_D + t_{SU}}{T}$$

$$D_{MAX} = \frac{T - t_{SD}}{T}$$
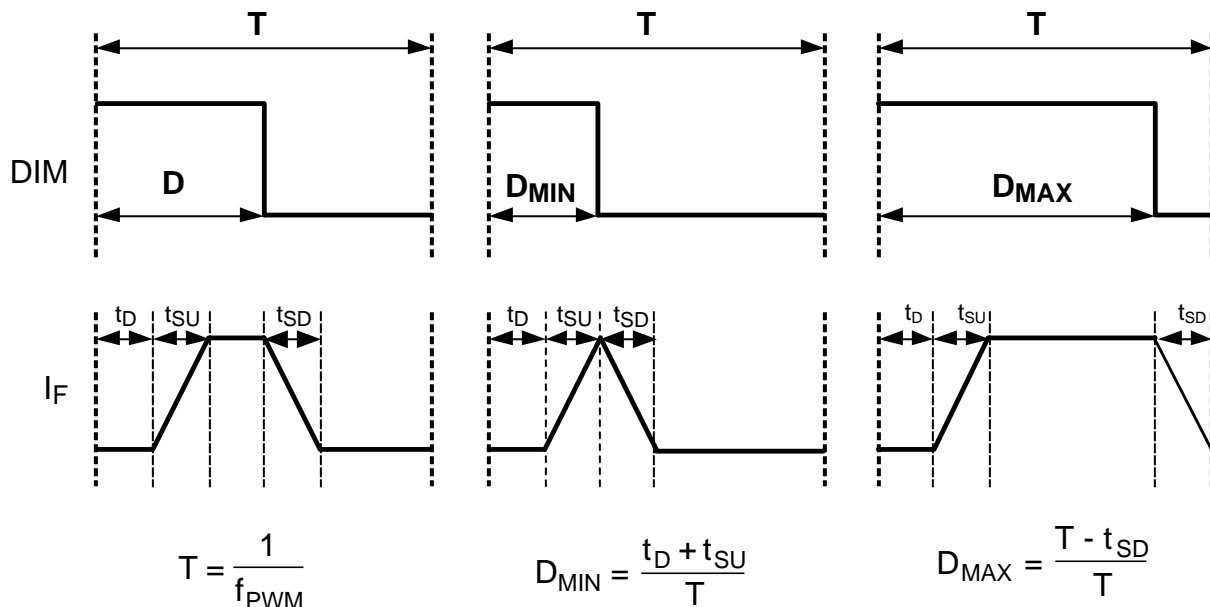
Figure 4. PWM Dimming Limits

The logic of **DIM1** is active low, hence the LM3406 will deliver regulated output current when the voltage at **DIM1** is high, and the current output is disabled when the voltage at **DIM1** is low. Connecting a constant logic low will disable the output. Note that an internal pullup esnures that the LM3406 is enabled if the DIM pin is open-circuited. The **DIM1** function disables only the power MOSFET, leaving all other circuit blocks functioning to minimize the converter response time, t_D.

The **DIM2** terminal provides a second method for PWM dimming by connecting to the gate of MOSFET **Q1**. **Q1** provides a parallel path for the LED current. Shunting the output current through a parallel MOSFET reduces the PWM dimming delays because the inductor current remains continuous, providing faster response time for higher frequency and/or greater resolution in the PWM dimming signal. The trade-off in this method is that the full current flows through **Q1** while the LED is off, resulting in lower efficiency. The standard BOM of the LM3406 evaluation board includes an output capacitor to reduce output current ripple, but the drawback of this output capacitor is that it causes significant delays when using parallel MOSFET dimming. The output capacitor should be removed to take full advantage of parallel MOSFET dimming.

The logic of **DIM2** is active high, hence the regulated output current flows through the LED array when the voltage at **DIM2** is low, and the current flows through the shunt FET when the voltage at **DIM2** is high. Connecting a constant logic high to the **DIM2** will turn off the LED but will not shut down the LM3406.

6   Low Power Shutdown

The LM3406 can be placed into a low power shutdown (typically 240 µA) by grounding the **OFF*** terminal. During normal operation this terminal should be left open-circuit.

7   Output Open Circuit

The LM3406 will begin to operate as soon as VIN is greater than 6V and the DIM and RON pins are not grounded. If the regulator is powered and enabled but no LED array is connected, the output voltage will rise to V_{IN}. The output of the circuit is rated to 50V (beyond the maximum input voltage) and will not suffer damage, however care should be taken not to connect an LED array if the output voltage is higher than the target forward voltage of the LED array in steady state.

If the LEDs are disconnected or one of the LEDs fails open-circuit while the LM3406 is operating, the output voltage will experience a surge as the current in the output inductor seeks a discharge path. The output capacitor (if present) can absorb some of this energy, however circuits with little or no output capacitance can experience a voltage spike that exceeds the rating of the VOUT pin. The evaluation board uses a 10 kΩ resistor in series with the VOUT pin to limit current flowing into the pin. Alternatively, a diode connected from V_{IN} to V_O as shown in Figure 5 will clamp the spike to V_{IN} plus a diode drop.
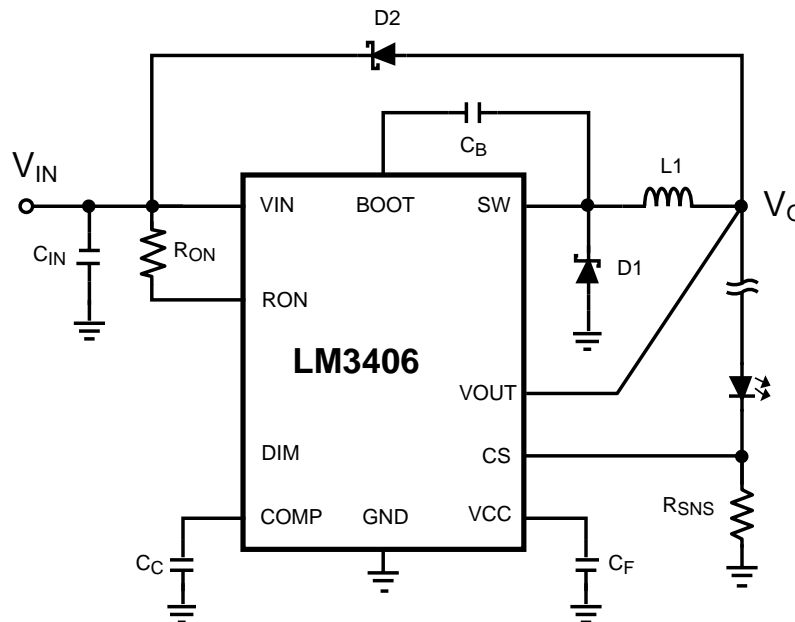
Figure 5. Schottky Diode Protection for Open-Circuit

8   Bill of Materials

Table 1. Bill of Materials

ID	Part Number	Type	Size	Parameters	Qty	Vendor
U1	LM3406	Buck LED Driver	TSSOP-14	42V, 1.5A	1	NSC
Q1	Si3458DV	N-MOSFET	SOT23-6	60V, 2.8A	1	Vishay
D1	CMSH2-60M	Schottky Diode	SMA	60V, 2A	1	Central Semi
L1	VLF10045T-330M2R3	Inductor	10 x 10 x 4.5mm	33 µH, 2.3A, 70 mΩ	1	TDK
Cin1 Cin2	C4532X7R1H685M	Capacitor	1812	6.8 µF, 50V	2	TDK
Co	C3216X7R1H474M	Capacitor	1206	470 nF, 50V	1	TDK
Cf ,Cc	VJ0603Y104KXXAT	Capacitor	0603	100 nF 10%	2	Vishay
Cb	VJ0603Y223KXXAT	Capacitor	0603	22 nF 10%	1	Vishay
R3.5	ERJ6RQFR56V	Resistor	0805	0.56Ω 1%	1	Panasonic
R.7	ERJ6RQFR62V	Resistor	0805	0.62Ω 1%	1	Panasonic
R1	ERJ6RQFR30V	Resistor	0805	0.3Ω 1%	1	Panasonic
R1.5	ERJ6RQFR16V	Resistor	0805	0.16Ω 1%	1	Panasonic
Ron	CRCW08051433F	Resistor	0805	143kΩ 1%	1	Vishay
Rpd Rout	CRCW06031002F	Resistor	0603	10 kΩ 1%	2	Vishay
OFF* DIM1 DIM2	160-1512	Terminal	0.062"		3	Cambion
VIN GND CS/LED- Vo/LED+	160-1026	Terminal	0.094"		2	Cambion

9   Typical Performance Characteristics

V_{IN} = 24V, I_F = 1A, T_A = 25°C, and the load consists of three InGaN LEDs in series unless otherwise noted.

Efficiency Vs. Number of InGaN LEDs in Series

Efficiency Vs. Output Current

I_F vs V_{IN}

I_F vs T_A

Switching Frequency vs Number of InGaN LEDs in Series

Switching Frequency vs V_{IN}

Switch Node and Output Current (DC Coupled)

Output Current (AC Coupled)

DIM1 Response (Rising)

DIM1 Response (Falling)

Start Up using OFF Terminal

Shutdown using OFF Terminal
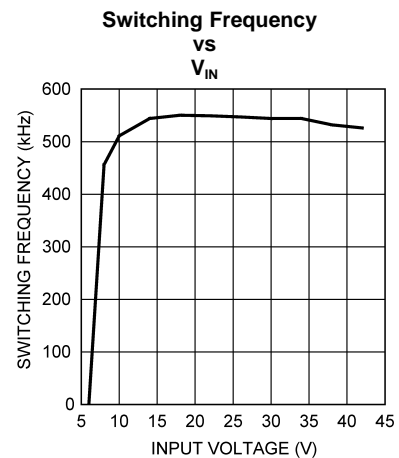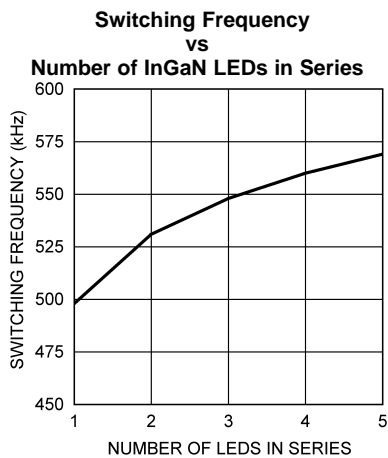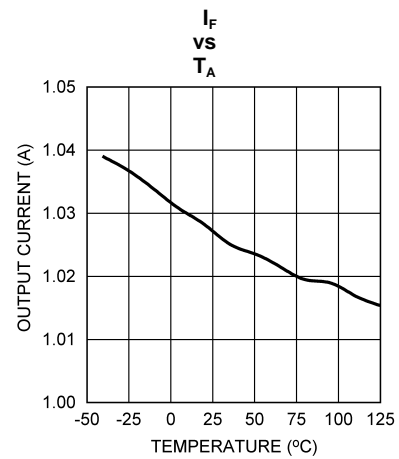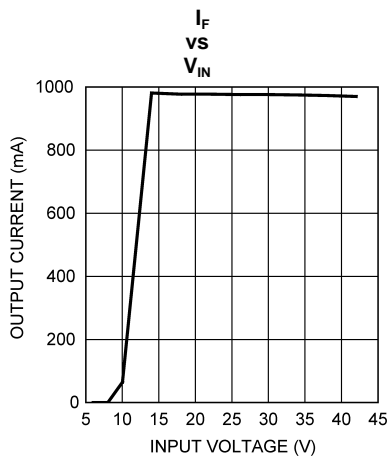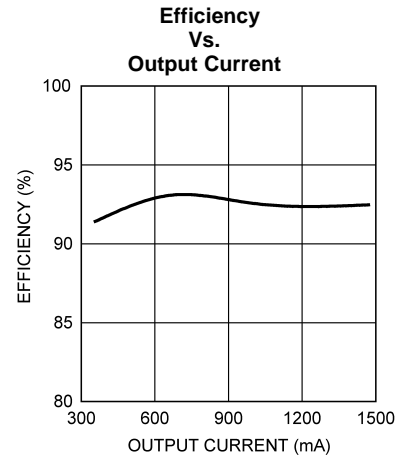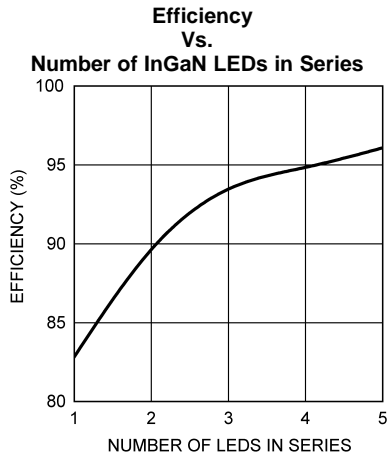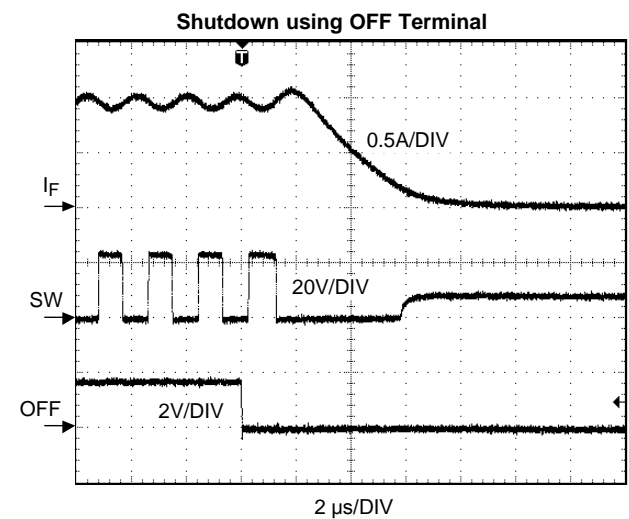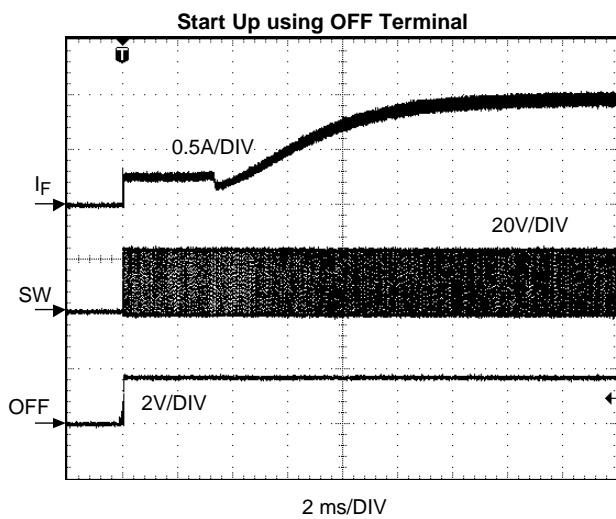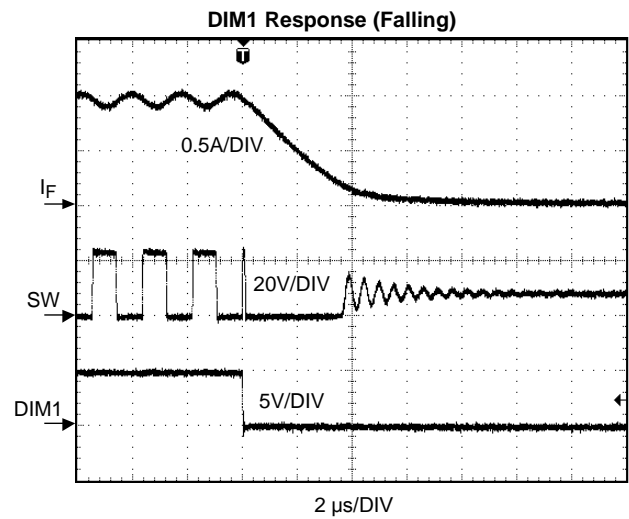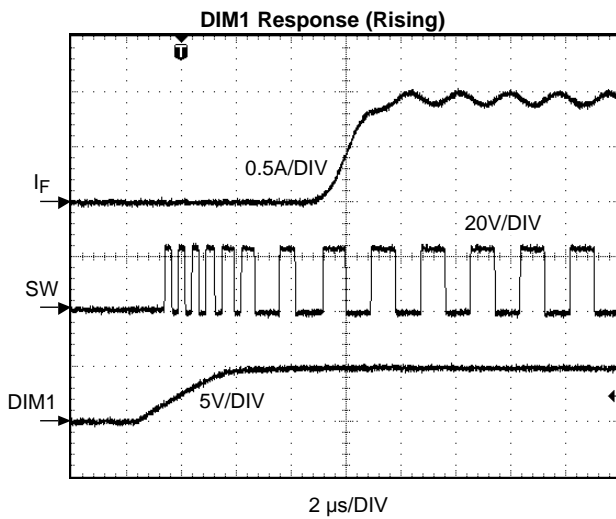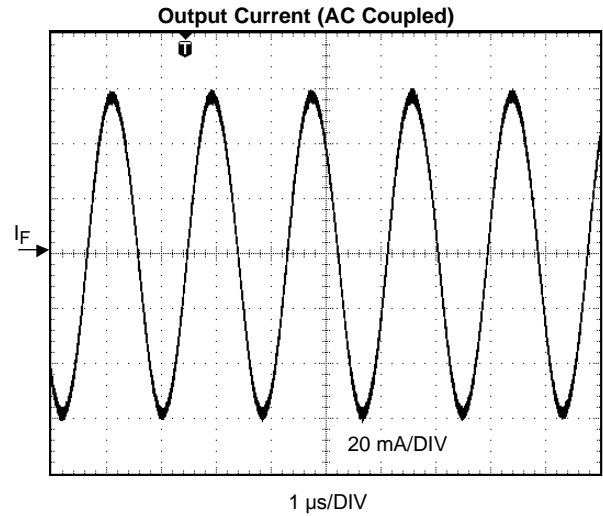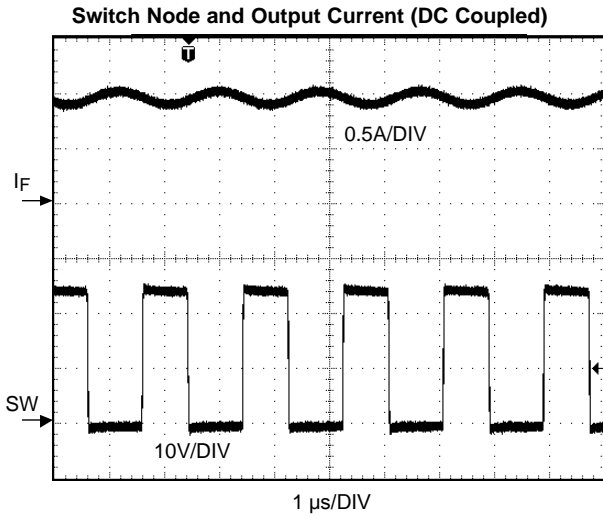
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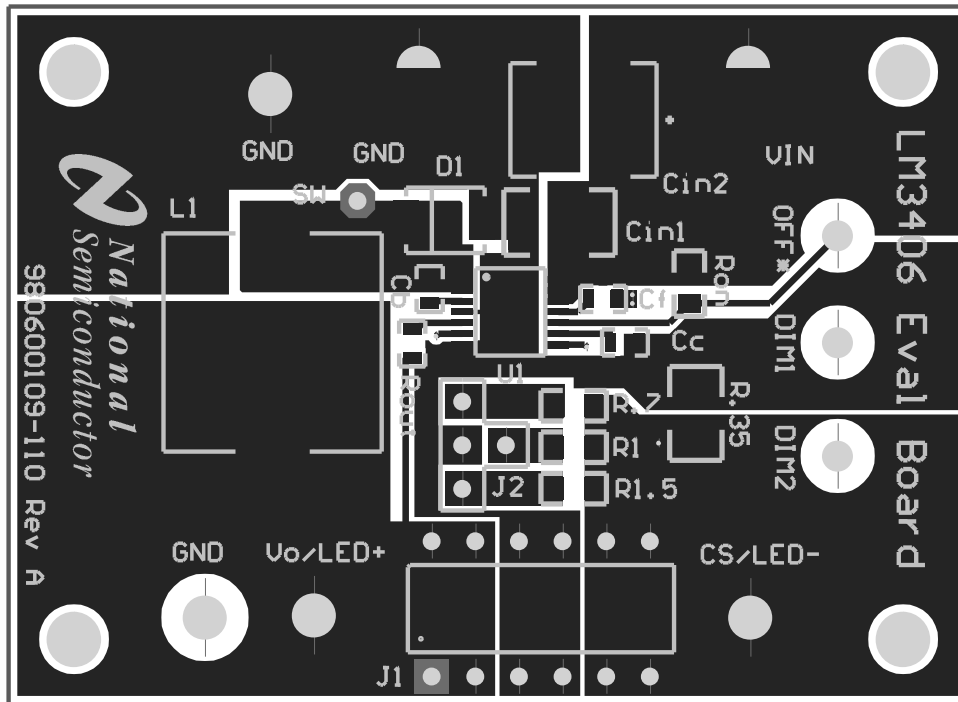
Figure 6. Top Layer and Top Overlay
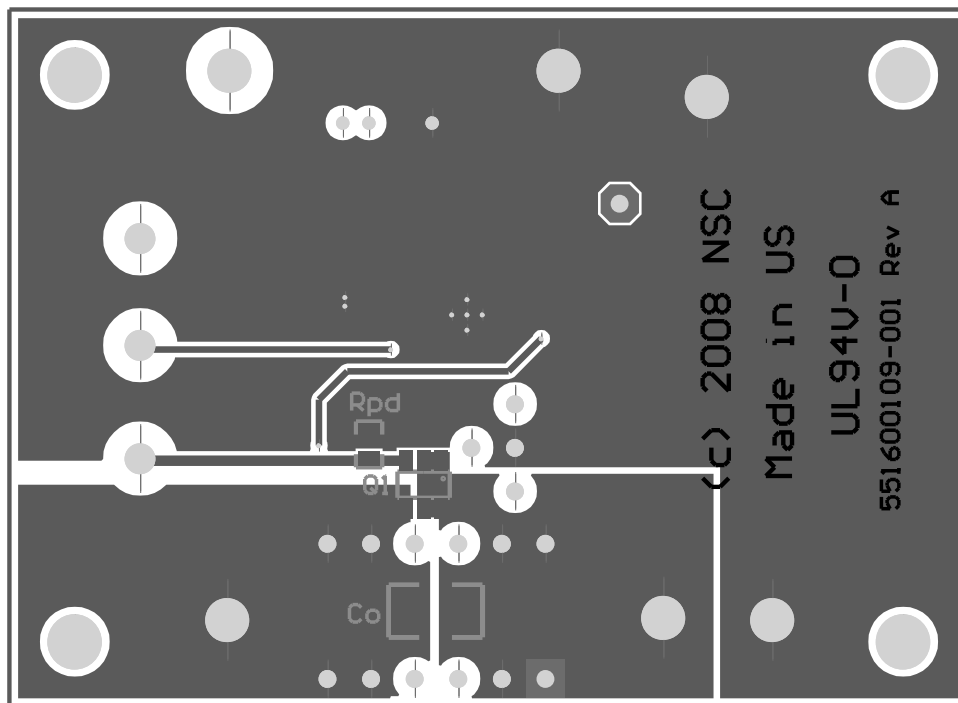
Figure 7. Bottom Layer and Bottom Overlay

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