Application Note
Intelligent LED Drivers For Portable Lighting
RTG 904 / 905 / 906 / 907

Portable LED lighting products use a diverse combination of LEDs and batteries. RTG has developed a line of products to match the batteries to the LEDs while giving the consumer unprecedented control over the brightness and functionality of the lighting product. This application note provides examples and explains how to get the most from the 904, 905, 906 and 907 parts. These parts are applicable to fixed-base and portable LED lighting products using boost, SEPIC, or buck topologies. Application boards are available to demonstrate each of these topologies.

V LED	ILED (mA)	# of LEDs	Pwr (W)	Battery (VBAT)	Topo-logy	Part	Ext FET	App Board	Ver
3.2	360	1	1.2	1.8 to 3.2	Boost	904		50804	01
				1.8 to 6.5	SEPIC	904		50808	01
3.3	720	1	2.4	5.4 to 15	Buck	907		50807	01
6.4	1000	2	6.4	5.4 to 15	SEPIC	906	●	50806	01
10.7	120	3	1.3	1.8 to 6.5	Boost	904		50804	02
12.8	360	4	4.6	2.7 to 6.5	Boost	904		50804	03
31.5	360	9	11.3	3.6 to 6.5	Boost	905	●	50805	01
	1000		31.5	10.8 to 15	Boost	906	●	50805	02

These products are intended for torch/flashlights, lanterns, barricade/warning lights, RV lighting, and other applications where the user wants to enable/disable the light, directly vary the brightness, or change the light from steady to flashing.

The 904 and 905 are intended for operation with low battery voltages, 1.8 to 6.5 volts and can be used in either a boost or SEPIC topology to match the LED voltage and current needs. The internal power FETs of the 904 have lower on-resistance and lower breakdown voltage than the 905 and 906. The 906 is similar to the 905 with a high-voltage regulator added to allow 3.6 to 35 volt battery operation. The 907 is a buck regulator and also features a high-voltage regulator for 4 to 40 volt batteries. All products feature internal power FETs as well as the ability to directly drive external power FETs for increased power and flexibility.

There are five applications boards, 50804, 50805, 50806, 50807 and 50808, for evaluating the 904 - 907 parts in boost, SEPIC, and buck topologies with various LED and battery combinations (LEDs and batteries not included). The 50808 board includes switches and jumpers for manipulating the brightness and modes; it can be configured as either a boost or an uncoupled SEPIC regulator. The other boards are configured for external control switches through an 8-pin header. A separate control board, 50802, can be connected to the 50804 / 5 / 6 / 7 boards through a ribbon cable to evaluate the many product features and facilitate temperature testing.

The application boards have been laid out for ease of modification to allow the designer to use different components or topologies that would be most suitable to their product. Material lists and measured data are provided as examples and are not considered lowest-cost approaches or guaranteed results. Careful consideration of your end-application requirements and the product datasheets should determine the design choices for your product.

Battery polarity is critical. Your product should provide a means to assure the correct polarity of voltage is applied at all times. Inadvertent reversal of battery polarity will damage the 904 - 907 parts. This issue has not been addressed on the application boards and reversal of the battery potential is easily done with disastrous consequences.

This application note is not a substitute for the product datasheet. The product datasheet should be used in conjunction with this application note to create your design.

Outline

This application note starts with the features common to all parts and suggests how to get the most from these features. Then detailed calculation examples are given to explain the part values found on the application boards.

While the calculation examples may be dry and tedious, they are intended to give the designer a feel for the trade-offs made in the application boards, as well as the ability to create a design that is specific to their needs. The design formulas are not intended to be rigorously correct; rather, they are simplified to quickly create working designs with an understanding of the trade-offs.

Finally, measured data is presented from the application boards to help select a good starting point for the designer's specific product.

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Enabling the Part:
EN, MO and Auto Shut-off

There are two ways to enable the product: Momentary contact closure (MO) or continuous contact closure (EN). Both MO and EN are active low with internal pull-up currents and have hysteretic line receivers with contact debouncing circuitry. The debouncing time is approximately 40 milliseconds and prevents inadvertent enabling. The internal pull-up current sources, hysteretic line receivers and contact debouncing circuitry make it easy to interface with a wide range of switching approaches, Figure 1.

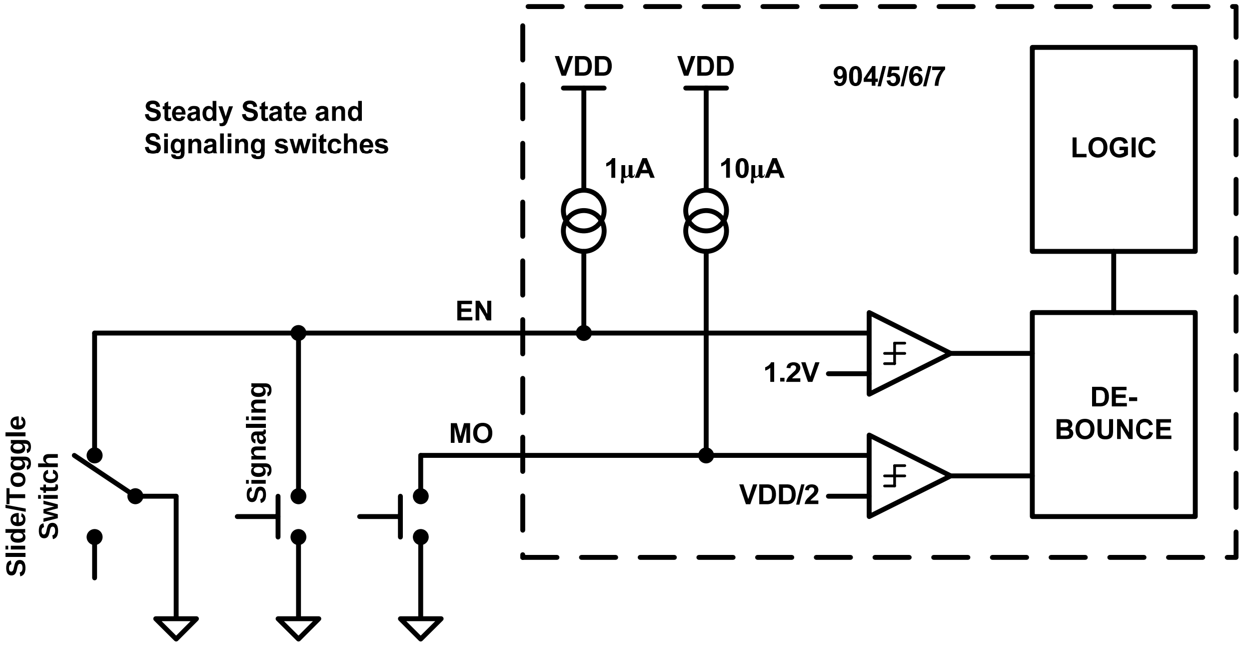


Figure 1: EN and MO Inputs
EN and MO pins have pull-up current sources, schmit buffers, and debouncing circuitry.
MO is used with momentary contact switch.

The typical toggle or slide switch found on most lighting products should be used to control EN rather than switching power. When the power is switched, the EN should be tied low to automatically enable the part when power is applied. By always applying power and using EN/MO to enable the part, the users' last settings are preserved. The 10 uA off-current allows for years of standby without significant loss of battery capacity.

EN and MO can be activated together or independently. There is no contention between MO and EN for control even with inputs skewed by 10 milliseconds. MO should not be connected to a slide or continuous contact switch because it will interfere with other shut-down features and limit the parts ability to completely shut-down.

EN enables the product when it is low and disables the product when it is high. MO acts as an electronic toggle switch to enable on the first activation and disable on the second activation. However, MO cannot disable the product when EN is low. If the product was enabled through MO, the EN pin can be used to disable the product by taking EN low and then high. This precedence provides unique switching capabilities.

The combination of MO and EN allows a lighting device to be quickly changed from a steady-on light source to a signaling device, by using momentary contact switches for both inputs, as shown in Figure 1. MO acts as the "steady-on" switch with only momentary contact needed to enable and disable the light, while EN receives the "signaling" input from the other momentary contact switch.

The MO input can be used to create single-wire, two-way switching or global / local switching for multiple light sources, Figure 2. The added pull-up resistors provide addition pull-up current to prevent enabling the lights when power is cycled from off to on. The capacitance of long leads must be charged within 25 ms, otherwise the MO pin will enable the part.

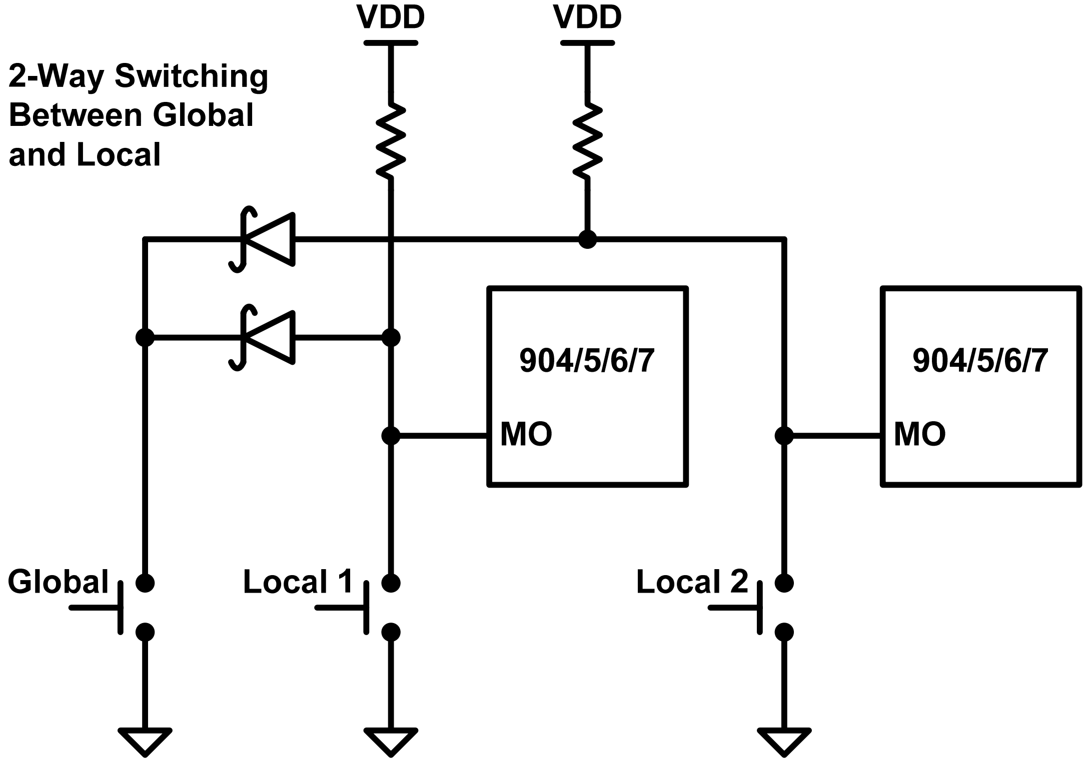


Figure 2: Single-wire Two-way Switching
MO pin has 10 uA pull-up current. External pull-up resistors and schottky diodes provide global and local switching for multiple sources.

Light sensitive switching is easily implemented with a photodiode and a resistor. The 1 uA pull-up current of EN is compatible with most photodiodes over a wide range of light.

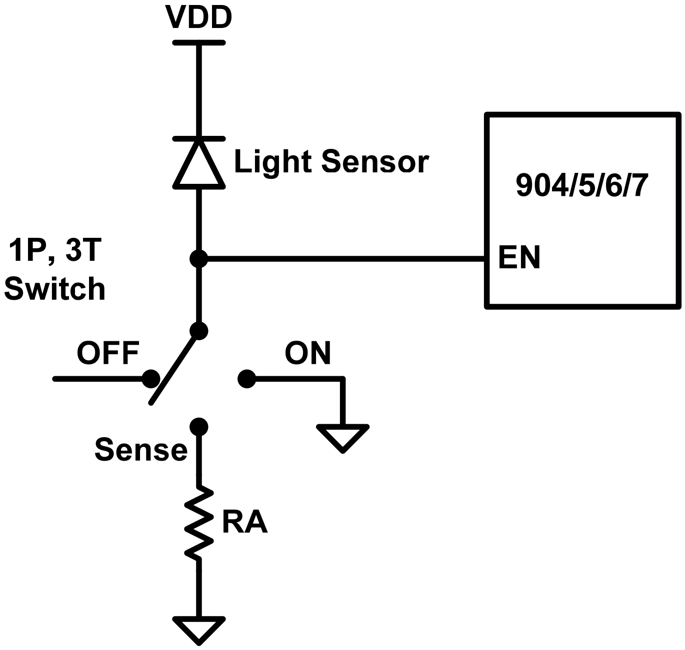


Figure 3: Enabling With Light Sensor
EN pin with 1 uA pull-up current source, compatible with photo diodes. The SP3P switch provides always-off, night-activation, and always-on settings.

The photodiode acts as an external pull-up current source. An open circuit on EN will hold the product off, Figure 3. Applying a short to EN will continuously enable the light. Connecting a resistor, RA, from EN to GND will enable the product at low light levels, and keep the light off when bright light causes higher current to flow in the photodiode. Hysteresis prevents flickering when transitioning from light to dark or dark to light.

With a TEPT5600 ambient light sensor and a 10K shunt resistor, RA, light levels below 50 lux will enable the product. The maximum daylight current is the battery voltage, VDD, divided by RA. A second series resistor can be added to the light sensor to reduce this current.

An automatic shut-off feature can be enabled through the U input and disabled through the D input. The automatic shut-off feature disables the product after 18 minutes of inactivity from U or D. Prior to shut-off, the LED light will modulate for two minutes to warn the user of the automatic shut-off (Figure 4a). Activating U or D will reset the timer without changing the brightness setting.

The EN or MO pin can be used to re-enable the part after an automatic shut-off has occurred. The EN pin must cycle high for more than 70 ms and then low again. The automatic shut-off feature will remain enabled until disabled by the D input or VDD is taken to less than 10 mV for more than 10 ms.

The low battery detection input (LBD) is used to shut-off the part when the battery reaches its end-of-life. If sufficient charge exists in the battery, cycling EN or MO will re-enable the part for less than 30 seconds while signaling a low battery condition (Figure 4a).

Controlling the Brightness:
U, D, and FB

The LED brightness is controlled through one of three inputs: U, D, and FB. All are active low and have active pull-up currents. The U and D have debouncing:

U	Increases brightness
D	Decreases brightness
FB	Switch to full brightness

There are 15 brightness settings from full brightness (100% LED duty) to minimum brightness (0.78% LED duty). The LED modulation rate is approximately 244 Hz and brightness steps are near logarithmic. For every two steps the brightness either doubles or decreases by half. By default, the LED is set four steps below full brightness (25%).

Holding U or D low will cause auto stepping of the brightness; this is similar to an audio volume control. When U or D are first activated, debouncing delays the first response for approximately 100 ms. If U or D remain active for another 260 ms, auto stepping will occur and continue every 260 ms until U or D becomes inactive; the full range of brightness control can be auto swept in a few seconds. However, it is also feasible to pulse U or D at approximately 10 times a second to sweep the full range in less than 2 seconds.

The FB input is used to immediately switch to full brightness. It can be used for dual intensity lighting when U and D are not available, or for signaling when the brightness is set below full brightness.

When designing the power converter section, operation at full brightness must be assumed.

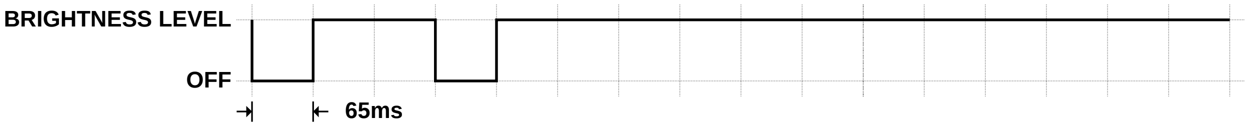
Controlling the Modes

The U and D inputs also control other modes of the device:

- Automatic Shut-Off
- Flashing / Beacon
- SOS

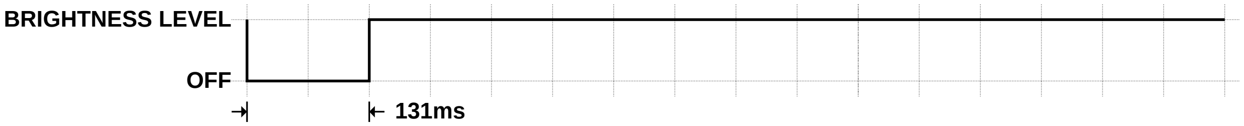
Enabling and disabling the part does not clear the last mode or brightness setting. Only removal of power to the VDD pin and shorting VDD to GND for more than 10 ms assures a reset of the mode and brightness to default settings. Figures 4a and b show the State and Mode patterns.

LOW BATTERY



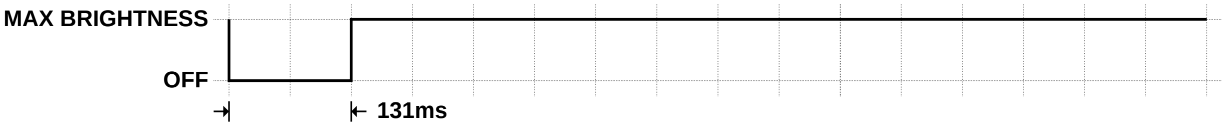
1 SECOND PATTERN
PATTERN REPEATED 4 TIMES UPON DETECTION OF LOW BATTERY, THEN SINGLE PATTERN EVERY 16 SECONDS AFTERWARDS

AUTO SHUT-OFF: WARNING



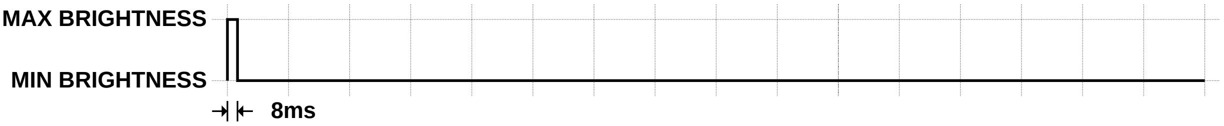
REPEATS PATTERN EVERY 4 SECONDS FOR 2 MINUTES UNTIL SHUT-OFF, OR BUTTON PRESS RESETS TIMER

AUTO SHUT-OFF: ENABLE



1 SECOND PATTERN
REPEATS 4 TIMES TO SIGNAL AUTO SHUT-OFF ENABLED

AUTO SHUT-OFF: DISABLE



1 SECOND PATTERN
REPEATS 4 TIMES TO SIGNAL AUTO SHUT-OFF DISABLED

Figure 4a: State and Mode Patterns

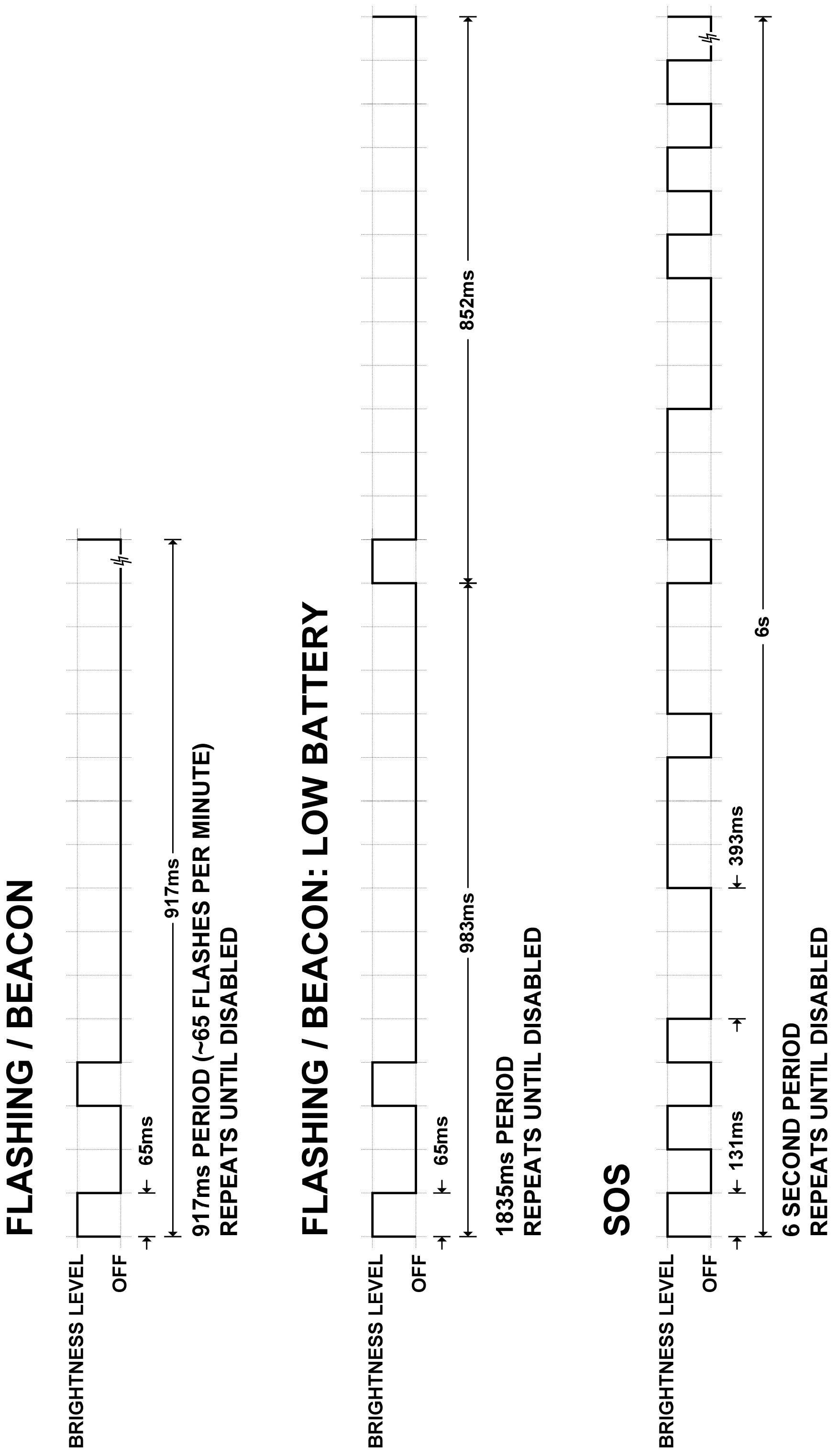


Figure 4b: State and Mode Patterns

Automatic Shut-off:

The automatic shut-off feature disables the product after 18 minutes. Prior to shut-off, the LED light will be modulated for two minutes to warn the user of the automatic shut-off. During automatic shut-off warning, activating U or D will reset the timer for an additional 16 minutes without changing the brightness. By default the automatic shut-off feature is disabled. The automatic shut-off feature is always disabled when in the Flashing / Beacon or SOS modes.

To enable automatic shut-off, the U input must be used to set the product to full brightness. The U input is then taken high for at least 1 second followed by low for at least 2 seconds. The LED will flash off periodically for a few seconds to indicate the automatic shut-off has been enabled.

To disable automatic shut-off, the D input must be used to set the product to minimum brightness. The D input is then taken high for at least 1 second followed by low for at least 2 seconds. The LED will flash to full brightness periodically for a few seconds to indicate the automatic shut-off has been disabled. Taking D immediately high then low again will stop the flashing pattern.

Flashing / Beacon:

A Flashing / Beacon mode can be enabled from any brightness setting by holding both U and D low for at least 2 seconds. The LED will flash approximately 65 flashes (doublet flashes) per minute. The automatic shut-off feature is disabled while in the Flashing / Beacon mode. A special flashing pattern is used to indicate a low battery condition. To exit the Flashing / Beacon mode, U and D are taken high for at least 700 ms followed by low for approximately 1 second.

To create a flashing beacon for warning / barricade products, the U and D pins are tied to GND. When enabled, the part will start in flashing mode. To change from low intensity to high intensity, tie the FB pin to GND. The EN pin can be controlled by a light sensing circuit.

When the batteries are low, the flashing pattern changes to an alternating doublet-singlet pulse train shown in Figure 4b. This lowers the average power while maintaining visual effectiveness before end of life.

To calculate the battery load, use the input power calculations from the converter design section as the starting point. The input current, I_{in}, for (full brightness) is reduced by the pattern duty cycle and the brightness factor. The high intensity flasher, HIF, has the full-brightness pin (FB) tied low and only the flashing pattern affects the supply current. The low intensity flasher, LIF, is at the default brightness.

HIF = $0.142 * I_{in} + 1.5$ mA (fresh battery)
= $0.106 * I_{in} + 1.5$ mA (low battery)
LIF = $0.035 * I_{in} + 1.5$ mA (fresh battery)
= $0.026 * I_{in} + 1.5$ mA (low battery)

Note that I_{in} is a function of the battery voltage. As the battery voltage decreases and the power converter attempts to maintain constant output power, the current from the battery will increase. Representative data is presented in the Measured Data section.

SOS:

In the SOS mode the product will modulate the LED to produce the Morse Code for SOS. To enter the SOS mode the product must first enter the Flashing / Beacon mode described above, then U and D inputs must be high for at least 700 ms. The U and D inputs are then held low for more than 4 seconds. The automatic shut-off feature is disabled while in the SOS mode; low battery is not indicated in this mode. To exit the SOS mode, U and D inputs must be high for at least 700 ms followed by low for approximately 1 second.

Low Battery Detection and Shut-off (LBD)

The low battery detection (LBD) function is implemented with a resistor divider from the battery to the LBD pin and the SW0 pin, Figure 5.

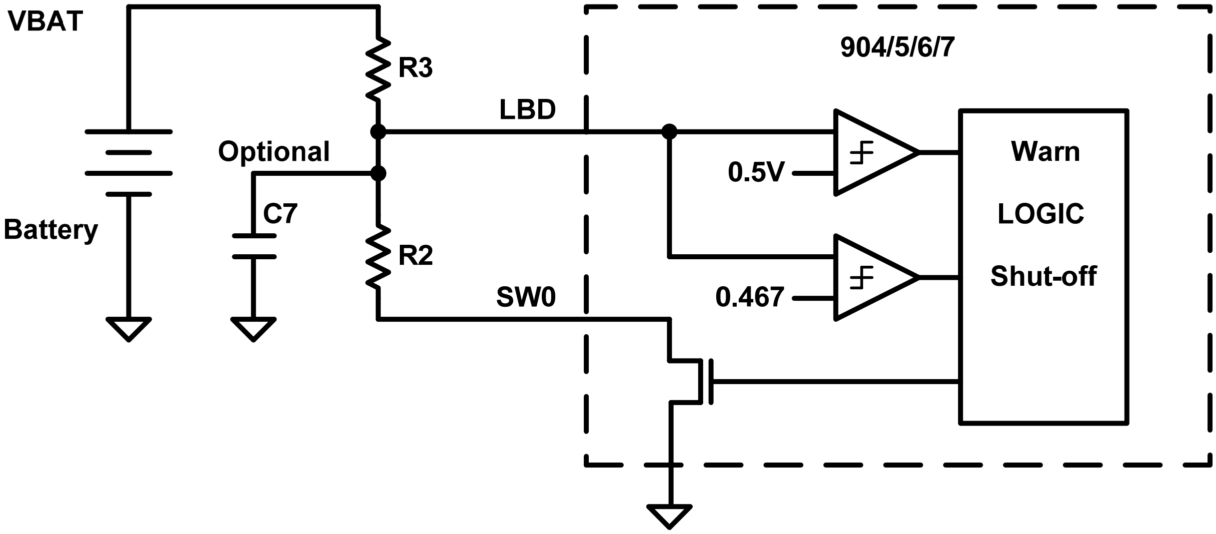


Figure 5: Low Battery Detection (VBAT <= 6.5V)
LBD pin has comparators for warning and shut-off. The shut-off function is delayed approximately 20 seconds. SW0 is an open circuit when the part is disabled.

The SW0 pin is a low impedance switch to GND when the part is enabled. When the part is disabled, the SW0 pin is an open circuit; this prevents battery discharge through the resistor network.

The LBD pin has two thresholds for warning and shutoff, 0.5 and 0.467 volts. Although the LBD pin has a very high impedance input, the shunt resistor from LBD and SW0 should be low enough to prevent coupling of switching signals into LBD. (An optional bypass capacitor C7 is available to aid in filtering the signal at the LBD pin and allows large values for R2.) Typically, R2 is 10K with 50 uA current at the warning threshold.

R2 = 10.0K assumed for approximately 50 uA current.

R3 = R2* (Vshutoff - 0.467) / 0.467
= 10K * (1.8 - 0.467) / 0.467 = 28.5 K
$\simeq$ 28.7K standard 1% value.

Vwarn = 0.5*(R3+R2)/R2
= 1.94 V warn at 1.94, shut off at 1.8

LBD Table: R2 and R3

VBAT (min)	R2	R3	V warn	V shutoff
1.8	10.0K	28.7K	1.94	1.81
2.7	10.0K	47.5K	2.88	2.68
3.6	10.0K	66.5K	3.83	3.57
5.4	10.0K	105K	5.78	5.37
10.3	10.0K	210K	11.00	10.27

When the battery voltage is greater than 6.5 volts (906 and 907 parts), an external FET is used to isolate the battery from the LBD and OVP pins (Figure 6 and 8). Without the external FET, the internal protection diodes will pull VDD up to the battery voltage when SW0 is open and may damage the part.

To eliminate this risk of exceeding the maximum voltage on VDD / VCC when the part is disabled, U1, with two FETs, is included on the 50805 and 50806 boards. Both boards have optional components for using a 904 / 905 part at lower battery voltage.

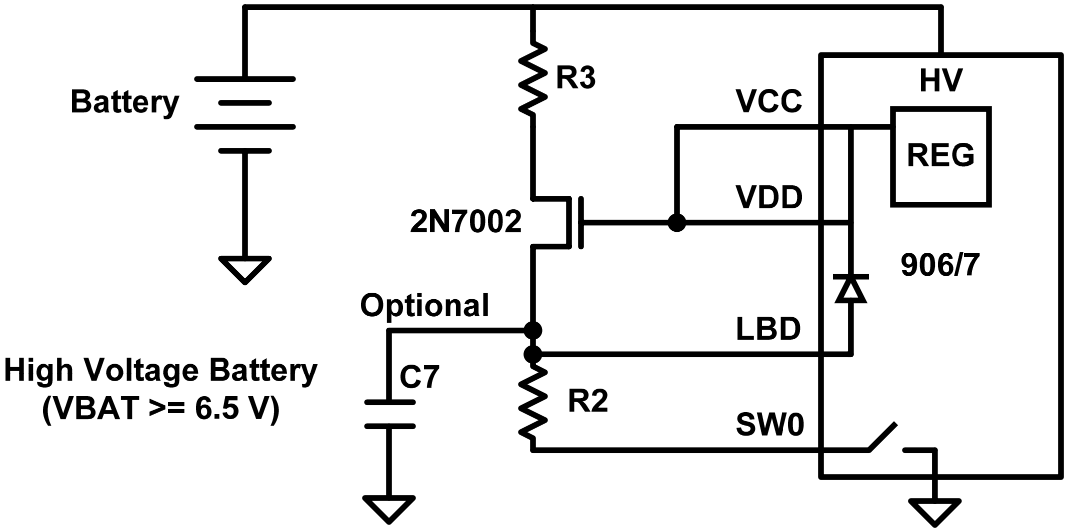


Figure 6: Low Battery Detection with High Voltage Battery (906/7)
LBD pin with high voltage battery (906/7) requires external FET in the middle of resistor network R2 and R3.

The low battery detection logic samples the comparator outputs at the end of the LED "on" portion of the PWM cycle (~4 ms). The battery voltage decreases during the "on" portion of the LED PWM cycle, and recovers during the "off" portion. At low brightness setting the battery voltage usually recovers before the next PWM cycle. By sampling at the end of the "on" portion, the LBD function uses the valley portion of the battery voltage. Capacitor C7 can be used to smooth or average the battery voltage at the LBD pin to minimize this effect.

The internal resistance of the battery and its connection resistance may cause excessive ripple voltage ripple at VDD. If the voltage at VDD drops below 1.6 volts the part may shut itself off. This threshold is typically 1.5 volts but is not well controlled. The values for R2, R3, C2 (across the battery), and C7 should take into account the expected ripple from the battery. If necessary, use an R-C filter between the battery and VDD.

Over Voltage Protection

The over voltage protection (OVP) function prevents the boost/SEPIC regulator from operating when the output voltage is above a set threshold and the LED current is below its target value. Its purpose is to protect the circuitry from damaging voltage that would occur if the LED became an open circuit and the boost/SEPIC regulator continued to provide energy to the output, Figure 7. Additionally, D1 protects the LD pin from electrical overstress that may be caused by lead inductance between the part and the LED.

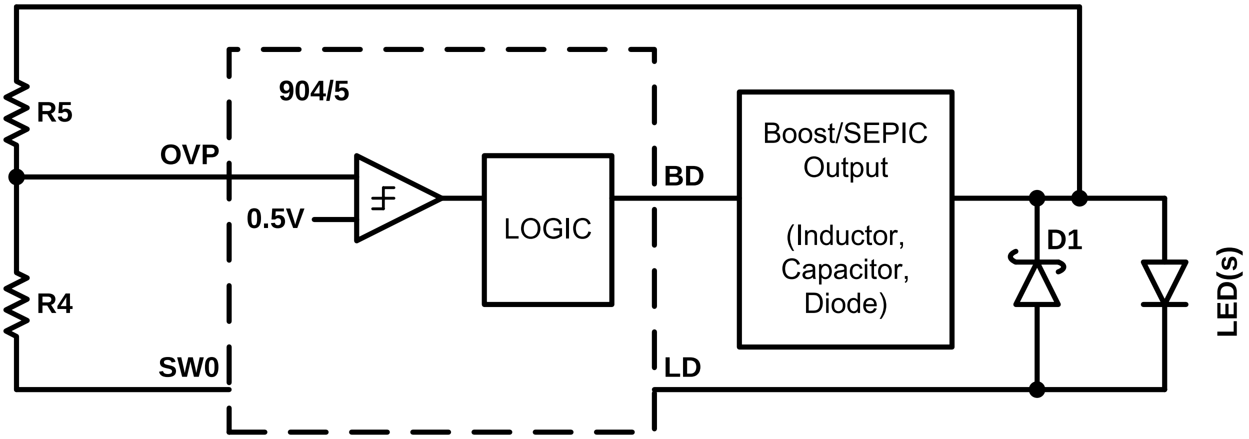


Figure 7: Over Voltage Protection with Low Voltage Battery (904/5)

OVP is implemented with a resistor divider from the output (anode of the LED) to the OVP pin and the SW0 pin. The threshold for the OVP pin is 0.5 V; and the threshold at the LED must be greater than the maximum LED voltage plus the drop across the LED FET and its sense voltage (~ 0.3 volts).

The current through this network must be kept low for two reasons. When the part is disabled and the output voltage is greater than the battery voltage, a current flows into the OVP internal protection diodes because SW0 is open; this current should be minimized for the 904 and 905 and must be eliminated for the 906 and 907 by using an external FET as shown in Figure 8.

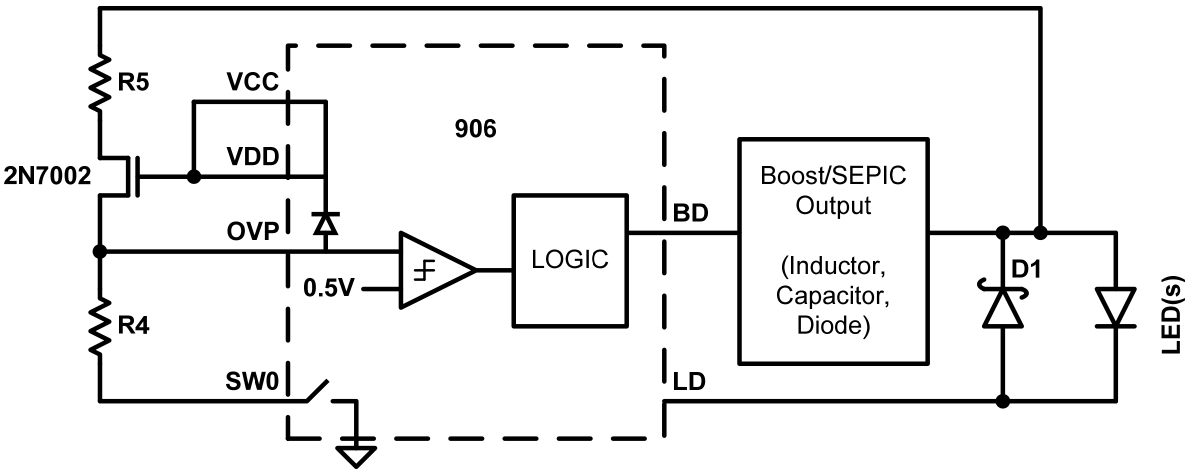


Figure 8: Over Voltage Protection – High Voltage Battery (906)
OVP pin with an external FET in the middle of resistor network (R4 and R5) to prevent current flowing into OVP pin when SW0 is open.

Unlike the 904 and 905 topologies that have VDD connected to the low impedance battery, the 906 and 907 series regulator output is a relatively high impedance that can be pulled up above the breakdown voltage for VDD and VCC. Current flowing into OVP is directed through internal protection diodes to VDD. It is necessary to prohibit voltages greater than 6.5 volts from appearing on the OVP or LBD pins. The FET in Figures 6 and 8 prevent the OVP and LBD pins from pulling VDD above the maximum voltage when the part is disabled.

The second reason for minimizing R5 current involves the beacon mode. When the part is at minimum brightness and in the Flashing / Beacon mode, the resistor network of R5 and R4 removes charge from C2 between flashes. If too much energy is removed between flashes, the first of a pair of flashes will appear dimmer than the second. If the current in R5 is less than ILED / 5000 the first flash is nearly the same as the second.

Assume the OVP threshold at the LED anode is 4.0 volts.

R5 $\underset{\sim}{}$ 5000*(OVP - 0.5)/ILED = 48.6K
= 48.7K standard 1% resistor.
R4 $\underset{\sim}{}$ 5000*(0.5)/ILED = 6.94K
= 6.98K standard 1% resistor.
OVP = 0.5*(R5 + R4)/R4 = 3.99 volts

Assume the OVP threshold at the LED anode is 12.5 volts.

R5 $\underset{\sim}{}$ 5000*(OVP - 0.5)/ILED = 500K
= 499K standard 1% resistor.
R4 $\underset{\sim}{}$ 5000*(0.5)/ILED = 20.8K
= 20.5K standard 1% resistor.
OVP = 0.5*(R5 + R4)/R4 = 12.7 volts

OVP Table: R4 and R5

VLED	ILED	R4	R5	OVP
3.2	360	6.98K	48.7K	4.0
3.3	720	3.48K	24.3K	4.0
6.4	1000	2.49K	37.4K	8.0
10.7	120	20.5K	499K	12.7
12.8	360	6.98K	205K	15.2
31.5	360	6.98K	464K	33.7
31.5	1000	2.49K	165K	33.6

An over-voltage protection feature can also be implemented with the 907 buck converter, Figure 9. The purpose is to limit the in-rush energy into the LED if it is intermittently connected to the output.

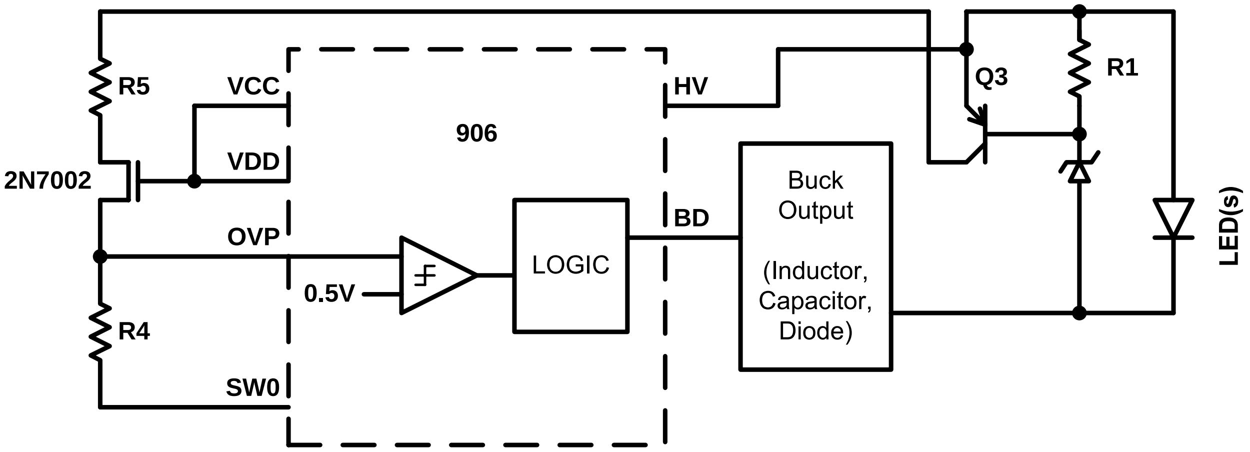


Figure 9: Over Voltage Protection – High Voltage Buck 907
OVP pin with level translator and high voltage battery (907) to protect LED from intermittent open circuit.

Temperature and Supply Effects

Both temperature and the voltage at VDD affect the comparator thresholds for LBD shut-off, LBD warn, OVP, BS and LS. The low battery shut-off threshold is the controlling threshold. All other thresholds are slaved to this value. The tables below give the typical values as a function of supply voltage and temperature.

LBD Shut-off Threshold (mV) Table:

	Temperature C			
VDD	**-20**	**25**	**70**	**110**
1.6	455	456	459	464
1.8	470	467	466	471
3.0	475	471	472	480
5.0	479	475	478	493
6.5	489	485	490	515

Comparator Thresholds (mV) Table:

VDD	**LBD Shut-off**	**LBD Warn**	**OVP**	**BS**	**LS**
1.6	456	488	488	196	196
1.8	465	498	498	199	199
3.0	467	500	500	200	200
5.0	468	501	501	201	201
6.5	475	509	509	205	205

The prior LBD and OVP resistor tables did not account for the temperatures and voltage shifts. If greater accuracy is required, the resistor values should be recalculated using the voltage values given above. The use of thermistors in parallel with the resistors can create temperature compensating networks.

To measure the internal operating temperature of the 904 - 907, the internal protection diode on the FB pin is used. There are two diodes internally connected to the FB pin, one from VDD to FB and the other from DAP to FB. The diode from VDD is located near the thermal center of the device. Since the forward diode voltage is proportional to the temperature when a constant current source is applied, the diode between VDD and FB can be used to sense the temperature of the device. A 100 uA current source may be used to pull FB above VDD.

The complete circuit path is from FB to VDD, not to GND, as shown in Figure 10. This makes the circuit path independent of the VDD to GND current. The current source can be a source/measure instrument (such as a Keithley 2600 series) or as simple as a 100K ohm resistor and a 10 volt supply. Note that the current source is floating with respect to GND, GNDG, and DAP.

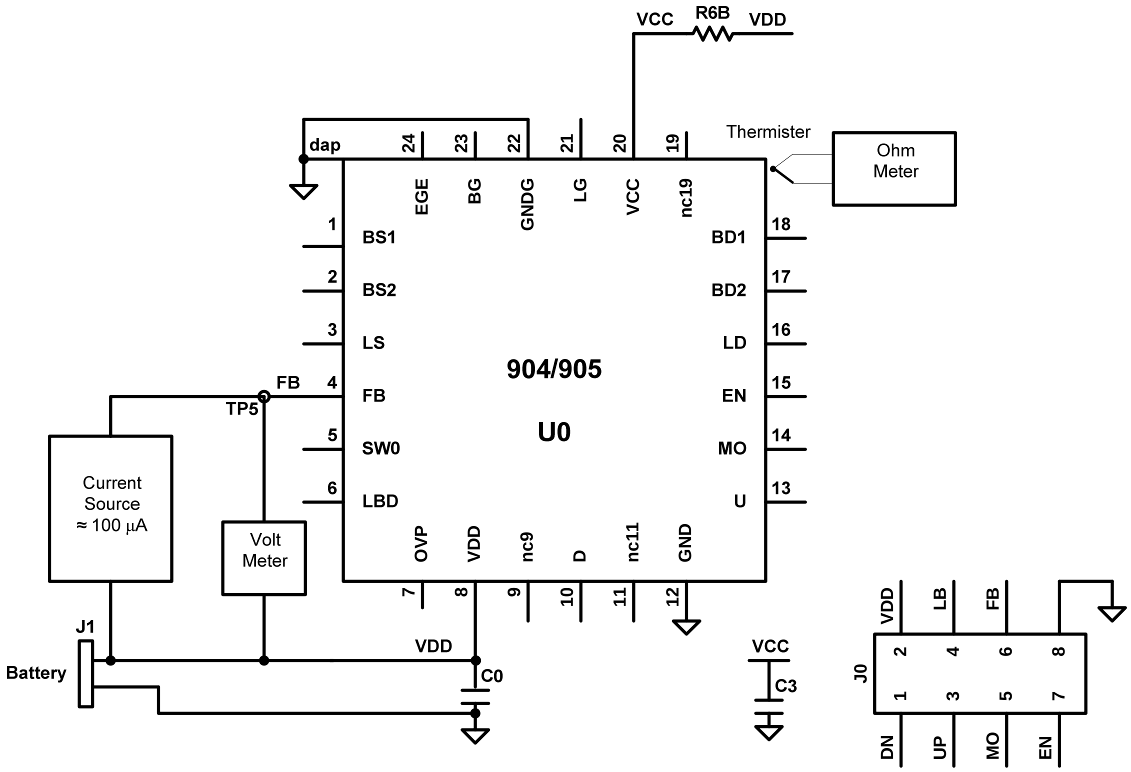


Figure 10: Temperature Measurement
Current source from FB to VDD is 100 µA. Voltage from FB to VDD is approximately linear function of temperature. C0 and C3 must be greater than 33 nF each. R6B is a wire-short add between VCC and VDD.

First the voltage from FB to VDD needs to be calibrated as a function of temperature. The calibration is performed with at least 1.8 volts applied to VDD (904 / 5) or at least 4 volts applied to HV (906 / 7), and the device in the "disabled" state (EN and MO pins tied to VDD). For consistency, it is recommended to use the expected operating voltage at either VDD or HV. A thermistor (e.g., Murata NCP15WF104F03RC) is attached to the back of the board on pads provided near the part.

With the device powered and disabled, a temperature chamber is used to vary the temperature while recording the thermistor resistance and FB to VDD voltage. The thermistor resistance values are converted to temperature. (A thermocouple can be used instead of the thermistor; however it needs to be thermally connected as close as possible to the device DAP as possible.)

The FB to VDD voltage as a function of temperature should be nearly linear so that one can easily extrapolate to higher or lower temperatures.

With this data, the part can now be placed in its normal operation and the internal device temperature measured with the current source from FB to VDD. The specified case temperature assumes a 25 C rise from the case to the internal device. The measured device temperature should be below 125 C for long-term operation.

Battery Voltage Considerations

When the battery voltage may be greater than 6.5 volts, the 906 and 907 parts must be used to reduce VDD and VCC below 6.5 volts.

The 906/7 parts incorporate a regulator to step down the battery voltage to approximately 5 volts. The parts internally shorts VCC and VDD together through a small trace, thus an external short (R6B) is recommend when using the 906 or 907 part.

The step-down regulator works in conjunction with the capacitors C0 and C3 by switching an internal current source from the HV pin to VCC until the voltage at VCC is above its regulation point as shown in Figure 10. C0 and C3 should be at least 47 nF each typically 1 μF total. The VCC pin provides the gate drive voltage for the power FET's. VDD supplies the internal logic.

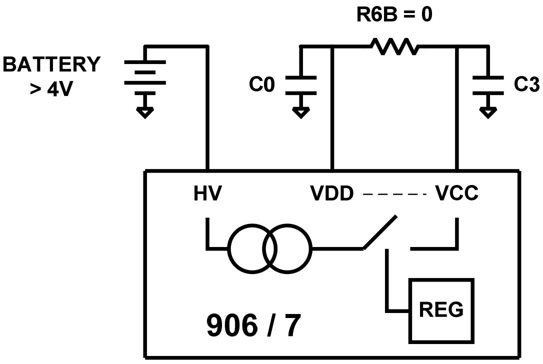


Figure 11: Internal Step-Down Regulator
C0 and C3 must be greater than 33 nF each. R6B is a wire short add between VCC and VDD.

The 906 part can be used with a battery voltage down to 3.8 volts. Below this value, the VCC voltage may drop below 3.5 volts and the on resistance of the power FETs will increase.

Bootstrap

When operating the 904/5 parts with VDD with less than 3.0 volts, it is recommended that a bootstrap approach be used to supply VCC, Figure 11. The optional bootstrap circuit couples the inductor L0 output voltage back to VCC pin. This will minimize the on resistance of the FET's and is especially important when batteries are near end-of-life and provide less than 2 volts; the end-of-life battery voltage will not be sufficient to drive the power FET's for high current operation, but will be sufficient for the bootstrap start up.

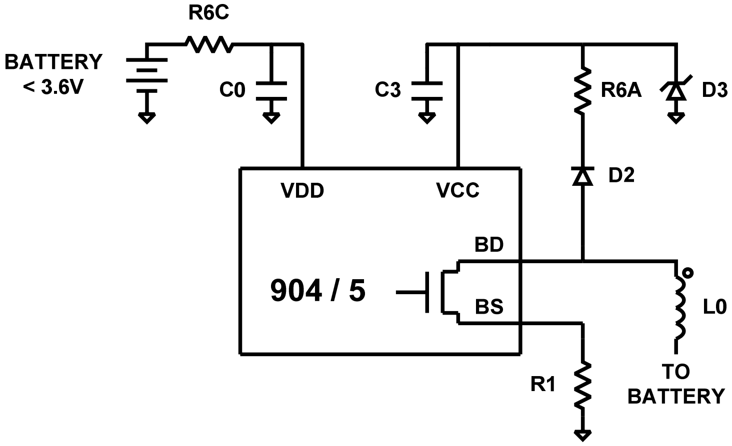


Figure 12: Boot-strap VCC circuit

The optional bootstrap circuit is comprised of D2, R6A, D3, and C3. (Only use the bootstrap circuit with the 904 and 905 parts; it is incompatible with the 906 part.) D2 couples the output of L0 back to VCC. R6A limits the current and forms a low pass filter with C3 on the VCC pin. The gate drive to both internal and optional external power FETs is provided by VCC. The internal power FETs require approximately 2 mA from VCC. To prevent VCC from exceeding 6.5 volts, the zener diode D3 clamps VCC at 6.2 volts. D3 is optional when using the boost topology and the OVP (over voltage protection) limit is set below 5 volts.

When the open-circuit battery voltage is greater than 6 volts, the zener diode D3 may act as a discharge path. By selecting a low tolerance zener for D3 and a standard (not schottky) diode for D2, the additional voltage drop from D2 will reduce the current to acceptable levels. The use of a schottky diode for D2 is recommended when driving a single white LED.

R6B, shown in Figure 11, must be removed from the application boards when using the bootstrap option. R6B allows direct connection between VDD and VCC. The 50805 and 50806 boards were designed to accommodate either 904, 905, or 906 parts. R6C provides the option to bypass the high voltage regulator and connect a low-voltage battery (<6.5 volts) directly to the VDD pin.

R6C must be removed when using the 906 part and R6B must be included.

R6A sets the maximum current through D2. It must allow enough charge to flow during the inductor discharge time to charge VCC. Excess charge will be absorbed by D3 to clamp the VCC voltage below 6.5 volts. When the boost topology is used and the OVP (over voltage protection) limit is set below 5 volts, R6A can be shorted and D3 can be removed.

When the boost regulator is operating in the PWM mode, the period is fixed at 1.5 μs and the discharge time varies from 1.25 to 0.5 μs. When the inductor charge time is greater than 1.0 μs, the boost regulator is operating in the PFM mode and the inductor discharge time is fixed at 0.5 μs.

PWM
$T_P = 1.5\ \mu s$
$0.5\ \mu s \le T_{off} \le 1.25\ \mu s$

PFM
$1.5\ \mu s \le T_P \le 11.5\ \mu s$
$T_{off} = 0.5\ \mu s$

The internal circuitry of VCC appears like a 300 pF capacitor. So the maximum charge required for the internal circuitry is

Q_{INT} = 300 pF * 6.5 Volts (maximum permitted VCC voltage)
= 1.95 nC

In addition to the internal charge, there may be an external power FET connected to BG and LG pins. As an example, the NTD3055L104T4G from ON Semiconductor requires 7.4 nano-coulombs to switch the device on. The total charge required is

$$Q_{TOTAL} = 1.95 + 7.4 = 9.35\ nC$$

This charge must be delivered during the inductor discharge time, which may be as short as 0.5 μs.

$$I_{R6A} \geq Q_{TOTAL} / 0.5\ \mu s = 18.7\ mA$$

For example, if the output voltage is 27 volts and an external power FET is used, then

$$R6A \simeq (27 - 6.5) / 18.7\ mA \simeq 1096\ ohms$$

The value for R6A is not critical. Values less than this, or when the inductor discharge time is greater than 0.5 μs, will result in greater charge than needed. The excess charge will be absorbed by the zener diode D3. If R6A is much larger, the VCC voltage will be less than the zener voltage of D3. Note the average current flowing is much less, since the current only flows during the discharge time. When only the internal power FETs are used the following simple formula will give good results:

$$R6A \simeq (VLED - 3.5) / 2\ mA$$

For LED voltages below 5 volts, R6A is shorted.

Critical Components

D0, D1 and C9 (SEPIC) are critical components for the survival of the 904 / 5 / 6 part. (See the application schematics section.) The internal power FETs are very fast switching devices. Parasitic inductance and switching delays must be minimized on the BD and LD circuits to prevent inadvertent over-voltage. Use schottky diodes for both D0 and D1. Without D1, the combination of LED lead inductance and current can cause over-voltage damage to the internal FET.

The physical area of the loop through C1 and C2 should be minimized to reduce parasitic inductance. A ground plane is highly recommended. The gate drive currents are fed through pin 22, GNDG and the exposed pad, DAP, on the bottom of the package. Pin 12, GND, is used to sense the ground reference voltage for the internal voltage comparators.

Setting the LED Current: R0

The 904, 905 and 906 parts use a FET that is separate from the power converter circuit to modulate the LED brightness. The LED brightness is controlled by pulse-width modulation of a constant current. The 907 part combines the LED brightness FET with the power converter FET in a buck topology. In all topologies, R0 sets the nominal LED current.

In the boost / SEPIC topologies, R0' is the total resistance in the source circuit of the LED FET and senses the LED current when the LED is on. As shown in Figure 13, there is an internal resistance, RLs, between the LS pin and the internal sense point where the FET current is sensed. RLs is typically 66 milli-ohms and forms a resistor divider network with the external resistor R0 and reduces the apparent threshold seen at the LS pin.

$$R0' = R0 + RLs$$

When the LED is on and its sense point (at the FET) is below 0.2 volts, the boost / SEPIC regulator is enabled, which provides additional charge to C1 and the LED circuit. (See the application schematic section.) When the sense point is above 0.2 volts the boost / SEPIC regulator is shut off and C1 supplies the current to the LED. If the value for C1 is small, the larger ripple voltage can greatly reduce the average operating point by coupling through the low impedance of the LED and FET to the sense point; the peak of the ripple voltage may start to dominate the control of the boost / SEPIC regulator. When the ripple voltage is small, the value for R0' and R0 are given by:

$$R0' = 0.2 / ILED \qquad \text{and} \qquad R0 = 0.2 / ILED - RLs$$

If the LED current doubles due to a fault, the LED duty factor is reduced to less than 1% with a 1 µsec on time. It will remain in this mode until the sense point is less than 0.4 volts when the LED is on. A fault may occur when one of a series of LEDs is shorted, an intermittent open circuit over charges C1, or the battery voltage exceeds the LED voltage in the boost configuration.

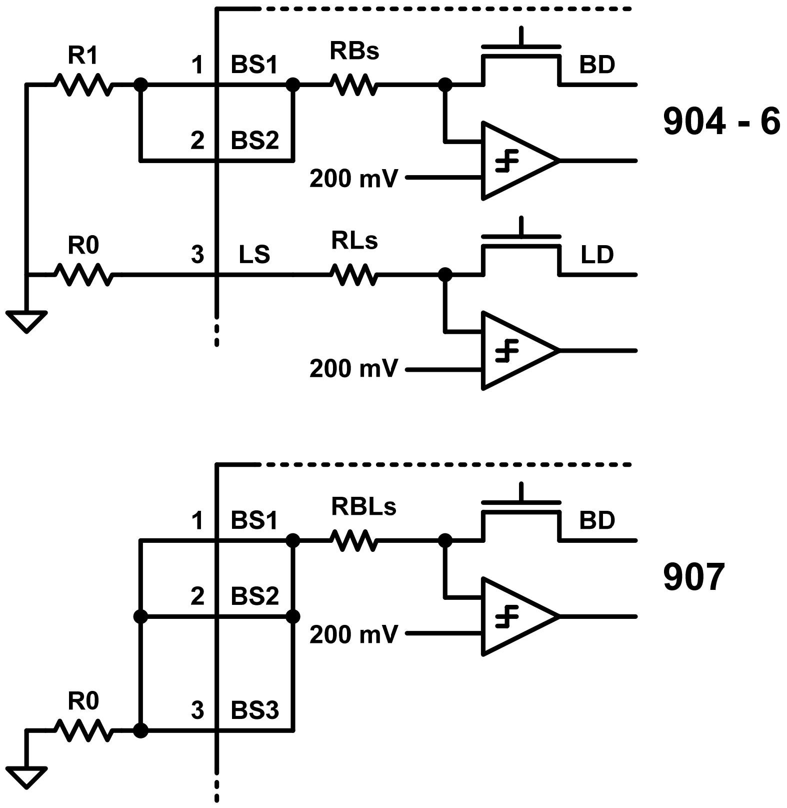


Figure 13: Sense resistance circuit

R0' and R1' are the total resistance. R0 = R0' – RLs and R1 = R1' – RBs for 904 – 906, and R0 = R0' – RBLs for 907.

In the buck topology (907), the converter operates in the discontinuous / critical conduction mode. The FET is on until its source is above 0.2 volts and then opens to discharge the inductor L0. The discharge of L0 is sensed at the drain of the internal FET by the drain voltage dropping below the supply voltage. The time to sense and restart the charge is approximately 200 ns.

The internal resistance, RBLs, is typically 22 milli-ohms and forms a resistor divider network with the external resistor R0 (Figure 13). The average LED current is slightly less than 1/2 the peak current in R0 and L0. Two factors contribute to lower LED current: (1) there is approximately 200 ns dead time between the end of the discharge and the beginning of the charge phase; and (2) magnetic losses in the inductor. Both factors are more pronounced when the charge time is shortened by increasing input voltage. It is recommended that the R0 value be reduced by 5 to 10 % to account for these factors as shown in the R0 Table below. C1 smoothes the current into the LED. (See application schematic 50807.)

R0 Table

ILED (mA)	Boost / SEPIC R0 = 0.2 / ILED - RLs		Buck R0 = 0.2 / (2*ILED) - RBLs	
	R0 (cal)	R0 (part)	R0 (cal)	R0 (part)
120	1.60	1.62	0.811	0.75
360	0.489	0.51	0.255	0.24
720	0.212	0.20	0.117	0.11
1000	0.134	0.27 || 0.27	0.078	0.15 || 0.15

Buck Converter Design Equations

The buck converter decreases the battery voltage to match the voltage needs of the LED by supplying a current that ramps from 0 to twice the desired LED current. C1 is in parallel with the LED and smoothes the current. (See application schematic 50807.)

The buck converter operates very near critical conduction, so the LED current is approximately 1/2 the peak inductor current. L0 and C1 are chosen to preserve constant-current pulse-width modulation (PWM) of the LED. Two factors contribute to lower LED current: (1) there is approximately 200 ns dead time between the end of the discharge and the beginning of the charge phase; and (2) magnetic losses in the inductor.

The maximum charge time is 15 µsec followed by a 1 µsec minimum off time: 16 µsec maximum period, 0.94 maximum duty. At this extreme it is possible to operate in the continuous conduction mode, which will increase the average current in the LED and cause the LED current to become a function of the input voltage, i.e., out of regulation.

The minimum charge time should be approximately 0.35 µsec to avoid the 220 ns fault detection threshold. Also note that short charge times cause greater magnetic loss in the inductor and increase the significance of the dead time from discharge to charge. Both contribute to lower LED current.

The battery voltage needs to be greater than the maximum LED voltage by at least twice the loss in the driving circuit. The loss is the sum of the voltage for current sensing at BS and the voltage drop across BD and BS. The available voltage to charge the inductor is reduced by the losses of the buck sense resistor, R0, and the drain to source resistance, BRdson, which includes the sense resistance RBLs.

Example 1: 50807-01

Buck
VLED = 3.3 (max 3.75)
ILED = 0.72
$5.4 \leq$ VBAT ≤ 15 volts

The R0 value was calculated in the prior section with an approximate 10% correction for the dead time and inductor losses. The peak current, Ipk, is

$Ipk = 0.2 / R0' = 0.2 / (0.11 + 0.022)$ Note R0 = 0.11, RBLs = 0.022

$= 1.52A$

The peak voltage loss across R0 and the FET:

$Vloss \simeq Ipk*(R0 + BRdson)$
$= 1.52 * (0.11 + 0.19) = 0.456$

The voltage across the inductor will decrease by 0.46 volts as the current in the inductor increases. This will lengthen the charge time and increase the duty factor. The minimum battery voltage at maximum LED voltage:

$VBAT \geq VLED_{MAX} + 2*Vloss$
$\geq 3.75 + 2*0.456 = 4.66$ volts

Below this voltage, calculating the inductor current and charge time becomes more complicated than assuming constant voltage across the inductor.

$I_{IND} = Ipk * (VBAT-VLED)/Vloss * [1 - \exp(-t*Vloss/(Ipk*L))]$

To estimate the duty factor and inductor charge time, the average loss (Vloss / 2) will be used since the battery voltage is well above the minimum.

$D \simeq (VLED + Vdiode) / (VBAT + Vdiode - Vloss/2)$
$Dmin \simeq (3.3 + 0.5) / (15 + 0.5 - 0.228) = 0.242$
$Dmax \simeq (3.3 + 0.5) / (5.4 + 0.5 - 0.228) = 0.620$

The maximum duty factor of 0.62 is less than the 0.94 limit. The minimum charge time should be greater than 0.35 µsec to avoid the 250 ns fault threshold. The minimum LED voltage and its temperature effects need to be considered when calculating the minimum charge time. The minimum LED voltage may be 200 mV less than typical and decrease as much as 300 mV as its temperature rises.

$Lmin \geq 0.35 * (VBAT - (VLED - 0.2 - 0.3) - Vloss/2) / Ipk$
$\geq 0.35 * (15 - 2.8 - 0.228) / 1.52$
$\geq 2.76\ \mu H$

L0 $= 4.7\ \mu H$ standard value with margin for tolerances.

$Ton \simeq Ipk * L0 / (VBAT - VLED - Vloss/2)$
$\simeq 5.02\ \mu sec$ at min battery, max LED
$\simeq 0.60\ \mu sec$ at max battery, min LED

$Toff \simeq Ipk * L0 / (VLED + Vdiode)$
$Toff_{min} \simeq 1.52 * 4.7 / (3.75 + 0.5) = 1.68\ \mu sec$
$Toff_{max} \simeq 1.52 * 4.7 / (2.8 + 0.5) = 2.16\ \mu sec$

$Tp = Ton + Toff + Tdead$ where $Tdead \simeq 200$ ns
$= 6.9\ \mu sec$ at min battery, max LED
$= 2.96\ \mu sec$ at max battery, min LED

The average LED current at full brightness:

ILED = Ipk*(Ton + Toff)/(2*Tp)
= 738 mA at min battery, max LED
= 709 mA at max battery, min LED

The average input current at full brightness:

Iin = Ipk/2 * Ton/Tp
= 0.553 A at min battery, max LED
= 0.154 A at max battery, min LED

Note these average currents do not account for inductor losses. Inductor losses will have the effect of increasing Ton and reducing Toff. At high input voltage the charge time, Ton, is shorter for the same magnetic flux change. This will result in greater losses in the core material. The overall effect will be to increase the input current and reduce the average LED current.

Boost Converter Design Equations

The boost converter increases the battery voltage to match the voltage needs of the LED at the current set by R0. When the LED current is below its set point, the boost converter is enabled until the LED current rises above the set point. This on/off control of the boost converter is averaged by C1 to match the current needs of the LED. (See the application schematic section.)

The boost converter operates either in a fixed period (1.5 µsec) or a fixed discharge time (0.5 µsec) with variable period. The transition occurs when the charge time exceeds 1 µsec.

L0 and R1

R1 senses the current in the boost FET and sets the peak current in inductor L0. The 0.2 volt threshold, VBs, refers to the internal sense point as shown in Figure 12. R1' is the sum of RBs and R1, and sets the peak current. The value of L0 and the input to output voltage determine whether the boost regulator is operating in the discontinuous, critical, or continuous conduction mode. Larger L0 values reduce the input ripple current but can adversely effect output ripple.

Selection of L0 is constrained by the minimum and maximum battery voltage, VBAT, and the degree of continuous conduction mode. If the peak current is reached in less than 0.25 µsec, the soft start or fault mode is entered. When battery voltage VBAT is maximum, the time to charge the inductor must be greater than 0.25 µsec. When the battery input is lowest, the recommended operating point is near critical conduction. Inductor saturation current should be significantly greater than the peak operating current. Losses in the inductor greatly increase as the peak current approaches the saturation current, which will result in reduced output power and excessive heating.

Example 2: 50804-01

Boost
VLED = 3.2
ILED = 0.36
1.8 ≤ VBAT ≤ 3.2 volts

VBD ≃ VLED + VLS + Vdiode Output voltage plus the diode drop
= 3.2 + 0.2 + 0.5
= 3.9
Po = 3.9 * 0.36 power to the output section including D0.
= 1.4 watts
Pin = Po/0.9 assumes 10% loss at input
= 1.56 watts
Iin = Pin/VBAT average current at minimum battery voltage
= 1.56/1.8
= 0.866 A average at low battery

The term Iin is used to calculate the inductance and sense resistor values. It represents an "instantaneous" average over the boost regulator cycle. The "long-term" average current from the battery will decrease with increasing battery voltage or decreasing LED brightness since the LED is regulating the number of boost cycles required.

The available voltage to charge the inductor is reduced by the losses of the boost sense resistor, R1, and the drain to source resistance, BRdson, which includes the sense resistance RBs. (The 904 part has the lowest BRdson.) At the peak current, the voltage across R1' is 0.2 volts. At this point, assume the peak current is twice the average input current.

Vloss ≃ 0.2 + 2*Iin*(BRdson-RBs) Note Ipk = 2* Iin
= 0.2 + 0.34 = 0.54

The voltage across the inductor will decrease from 1.8 to 1.3 as the current in the inductor increases. This will lengthen the charge time and increase the duty factor. We will use the average loss (Vloss / 2) to modify the calculation for duty factor.

D = (VBD - VBAT) / (VBD - Vloss / 2)
= (3.9 - 1.8) / (3.9 - 0.54 / 2)
= 0.579
D is less than 0.67, so the PWM mode will be used, Tp = 1.5 μsec.

Ton = D*1.5 = 0.87 μsec
Toff = (1-D)*1.5 = 0.63 μsec

For critical conduction the peak inductor current is twice the input current and is completely discharged each cycle. During inductor discharge the full input voltage is available. The minimum inductor value to supply the output current:

ΔI = 2*Iin = 1.733 A
L ≥ (VBD - VBAT)*Toff/ ΔI
≥ (3.9 - 1.8)*0.63/1.7333 = 0.763 μH

Inductor values less than this will result in decreasing output at low battery voltage. However, as the input voltage increases, ΔI decreases and the conduction mode transitions from critical conduction to continuous conduction. Values much larger than those calculated above should be avoided for better regulation at higher battery voltage.

L0 = 1.0 µH a widely available inductance value.

ΔI = (VBD - VBAT) * Toff/L0
= 1.32 A
Ipk = Iin + ΔI / 2
= 1.53 A

R1 = 0.2 / Ipk - RBs
= 0.131 - 0.033 ≃ 0.1 ohms Resultant Ipk = 1.50 A

Iin = (2*Ipk - ΔI)/2 = 0.84 A

P_{R1} = D * R1 * [Ipk^2 + (Ipk - ΔI)^2 + Ipk*(Ipk-ΔI)] / 3
= 0.579 * 0.100 * [2.34 + 0.04 + 0.32] / 3
= 0.052 watts

Example 3: 50804-02

Boost
VLED = 10.7
ILED = 0.12
1.8 ≤ VBAT ≤ 6.5 volts

VBD ≃ VLED + VLS + Vdiode Output voltage plus the diode drop
= 10.7 + 0.2 + 0.5
= 11.4
Po = 11.4 * 0.12
= 1.4 watts
Pin = Po/0.9 assumes 10% loss at input
= 1.56 watts
Iin = Pin/VBAT at minimum battery voltage
= 1.56/1.8
= 0.866 A average at low battery

Vloss ≃ 0.2 + 2*Iin*(BRdson - RBs)
= 0.2 + 0.34 = 0.54

D = (VBD - VBAT) / (VBD - Vloss / 2)
= (11.4 - 1.8) / (11.4 - 0.27)
= 0.863

D is greater than 0.67, so the PFM mode will be used, Tp > 1.5 µsec and Toff = 0.5 µsec.

Ton = 0.5*D/(1-D) = 3.14 µsec

For critical conduction the peak inductor current is twice the input current and is completely discharged each cycle. During inductor discharge the full input voltage is available. The minimum inductor value to supply the output current:

$Ipk = 2 * Iin = \Delta I$

$= 2 * 0.866 = 1.733\text{ A}$

$L \geq (VBD - VBAT) * Toff / \Delta I$

$\geq (11.4 - 1.8) * 0.5 / 1.7333 = 2.77\ \mu H$

Inductor values less than this will result in decreasing output at low battery voltage. However, as the input voltage increases, ΔI decreases and the conduction mode transitions from discontinuous conduction to continuous conduction. For this example the value for L0 will be chosen less than 2.77 µH to demonstrate these effects. Also, an inductor greater than 2.77 µH at 1.73 A requires the next physically larger package.

L0 = 2.2 µH with 1.8A saturation

Assume the same peak current as the prior example, 1.50 A.

R1 $= (0.2 / Ipk) - RBs$ and $R1' = 0.133$

$= 0.10$ ohms Resultant $Ipk = 1.50$

When the battery is at 1.8 volts, the output current will be reduced:

$Tdischarge = Ipk * L0 / (VBD - VBAT)$

$= 1.50 * 2.2 / (11.4 - 1.8) = 0.344\ \mu sec$

$Ton = Ipk * L0 / (VBAT - Vloss / 2) = 2.16\ \mu sec$

$Tp = Ton + 0.5 = 2.66\ \mu sec$

$Iout = (Ipk/2) * Tdischarge / Tp$

$= 97\text{ mA}$ about 20% below the target of 120 mA

$Iin = (Ipk/2) * (Ton + Tdischarge) / Tp = 0.71\text{ A}$

When the battery voltage increases more than 18%, approximately 120 mA can be supplied to the LED. Assume VBAT = 2.12 volts.

$Tdischarge = 1.50 * 2.2 / (11.4 - 2.12) = 0.356\ \mu sec$

$Ton = 1.50 * 2.2 / (2.12 - 0.27) = 1.78\ \mu sec$

$Tp = Ton + 0.5 = 2.28\ \mu sec$

$Iout \simeq (1.50/2) * 0.356 / 2.28 = 117\text{ mA}$

The minimum charge time, from fully discharged, must be larger than 250 ns with at least 30% margin for component tolerances. This occurs at maximum battery voltage, VBAT = 6.5 volts.

$L > VBAT * 0.25\mu s * 1.3 / Ipk = 1.41\ \mu H$

The 2.2 uH inductor chosen for this example is large enough. However, the 1.0 µH inductor of example 2 would be too small for this application.

Example 4: 50804-03

Boost
VLED = 12.8
ILED = 0.36
2.7 ≤ VBAT ≤ 6.5 volts

VBD ≃ VLED + VLS + Vdiode Output voltage plus the diode drop
 = 12.8 + 0.2 + 0.5
 = 13.5
Po = 13.5 * 0.36 power to the output section including D0.
 = 4.86 watts
Pin = Po/0.9 assumes 10% loss at input
 = 5.4 watts
Iin = Pin/VBAT average current at minimum battery voltage
 = 5.4/2.7
 = 2.0 A average at low battery

Without an external FET, the peak current must be limited to less than 2.67 A peak. The 2.0 average current restriction applies at minimum input voltage. At higher input voltages the boost converter is intermittently operating to provide the output energy; this lowers the rms current through the device when the LED is on.

Ipk = 2.67 A peak current limited by part spec.

Iavg ≤ 2.00 A average current limited at min voltage.

R1 = 0.2 / 2.67 - RBs = 0.042
 ≃ 0.043 standard value

Ipk ≃ 2.63

Since this example is operating at the limit of the device without an external FET, the peak current and average current are fixed and the maximum inductance is calculated from these limits. The inductor current will increase from 1.37 to 2.63 A (2.0 average).

Vloss ≃ 0.2 + Ipk*(BRdson - RBs)
 = 0.2 + 2.63*(0.197)= 0.72 Average 0.75*Vloss ≃ 0.54

The voltage across the inductor will decrease from 2.33 to 1.98 as the current in the inductor increases.

VInductor ≃ VBAT - I*(R1 + BRdson) where I varies from 1.37 to 2.63

This will lengthen the charge time and increase the duty factor. The average loss of 0.75*Vloss and will be used to calculate charge and discharge times.

D = (VBD - VBAT) / (VBD - 0.75 * Vloss)
 = 0.833

It is apparent that at minimum battery voltage it will not supply full current to the LED with the constraints on peak and average current.

Iout = Iin * (1-D)
 = 2 * (0.166)
 = 333 mA (Maximum Ipk = 2.63 A and Iavg = 2.0 A)

D is greater than 0.67, so the PFM mode will be used, Tp > 1.5 µsec and

Toff = 0.5 µsec.

Ton = 0.5*D/(1-D) = 2.51 µsec

ΔI = 2*(Ipk - Iavg)

= 2*(2.63 - 2.0) = 1.26 A

L ≤ (VBD - VBAT)*Toff/ ΔI

≤ (13.5 - 2.7)*0.5/1.26 = 4.3 µH

L0 = 3.3 µH next lower value in NR5040 package

The reduced inductance will increase ΔI (since the off time is fixed at 0.5 µsec) and reduce the average input current (since Ipk is fixed at 2.63 A).

ΔI = (VBD - VBAT)*Toff/ L = 1.64 A

Ton = ΔI*L/(VBAT - 0.75*Vloss) = 2.51 µsec

Tp = Ton + 0.5 = 3.01 µsec

D = Ton/Tp = 0.834

Iout ≃ (2*Ipk - ΔI)/2 * 0.5/Tp = 301 mA

Iin = (2*Ipk - ΔI)/2 = 1.81 A

When the battery voltage increases 15%, the 360 mA output current can be supplied to the LED. Assume VBAT = 3.1 volts.

ΔI = (13.5 - 3.1)*0.5 / 3.3 = 1.58 A

Ton = 1.59*3.3/(3.1 - 0.75*0.72) = 2.04 µsec

Tp = 2.04 + 0.5 = 2.54 µsec

Iout ≃ (2*2.63 -1.58)/2 * 0.5/2.54 = 362 mA

Iin = (2*2.63 - 1.58)/2 = 1.84 A

Since we are operating close to the 904 current limits, the heat dissipation ability of the circuit board may be critical.

R1 power is maximum at minimum VBAT, 2.7 V, since increasing VBAT reduces the duty factor more rapidly than it increases the mean squared current. Also, the average operating time of the boost converter is reduced by LED feedback with increasing VBAT.

P_{R1} = D * R1 * [(Ipk- ΔI)^2 + Ipk*(Ipk- ΔI) + Ipk^2] / 3
= 0.834 * 0.043* [1.10 + 2.76 + 6.92] / 3 = 0.129 watts

The power in the 904 part is also maximum at this operating point.

P_{904} ≃ P_{R1} * BRdson / R1 + ILED^2 * LRdson = 0.746 watts

Example 5: 50805-01

Boost
VLED = 31.5
ILED = 0.36
3.6 $\le$ VBAT $\le$ 6.5 volts

VBD $\simeq$ VLED + VLS + Vdiode   Output voltage plus the diode drop
= 31.5 + 0.2 + 0.5
= 32.2
Po = 32.2 * 0.36 power to the output section including D0.
= 11.6 watts
Pin = Po/0.9   assumes 10% loss at input
= 12.9 watts
Iin = Pin/VBAT   average current at minimum battery voltage
= 12.9/3.6
= 3.58 A   average at low battery

The peak current in the 905 part must be limited to less than 2.67 A peak. The 2.0 average current restriction applies at minimum input voltage. At higher input voltages the boost converter is intermittently operating to provide the output energy; this lowers the rms current through the device when the LED is on. An external power FET must be added to achieve the 3.58 A average current. The current sharing between the external and internal power FETs is governed by the on resistance of each FET.

ID = Ipk * XRdson / (XRdson + BRdson)   where ID is through the 905.

The chosen external FET is NTD3055L104T4G by ON Semiconductor. Its on resistance, XRdson, is typically 89 milli-ohms with 5 volt gate drive. The bootstrap circuit for VCC (see Figure 11 and application schematic) is used to assure at least 5 volt gate drive when the battery voltage is at its minimum. At this point assume the combined peak current through the devices is twice the average input current.

Ipk = 2 * Iin   peak current is twice Iin at minimum battery voltage.
= 7.16 A

ID = 7.16 * 89 / (89 + 310)   Portion of current in 905 device.
= 1.59 A   Within limit for 905 device.

Vloss $\simeq$ 0.2 + ID*(BRdson - RBs)   Internal in parallel with external FET
= 0.2 + 1.59*(0.310 - 0.033)
= 0.64

The voltage across the inductor will decrease from 3.6 to 2.96 as the current in the inductor increases. This will lengthen the charge time and increase the duty factor. We will use the average loss (Vloss/2) to modify the calculations for duty factor.

D = (VBD - VBAT) / (VBD - Vloss/2)
= 0.897

D is greater than 0.67, so the PFM mode will be used, Tp > 1.5 µsec and

Toff = 0.5 µsec.

Ton = 0.5*D/(1-D)   = 4.36 µsec

Tp = 4.86 µsec.

For critical conduction the peak inductor current is twice the input current and is completely discharged each cycle. During inductor discharge the full input voltage is available. The minimum inductor value to supply the output current:

ΔI = 2*Iin
= 2*3.58 = 7.16 A

L ≥ (VBD - VBAT)*Toff/ ΔI
≥ (32.2 - 3.6)*0.5/7.16 = 2.0 µH

Inductor values less than this will result in decreasing output at low battery voltage. Higher inductor values will lower the peak current and reduce the ripple current at the input. Significantly increasing the inductance value result in poorer regulation at the output due to the excess energy initially stored in the inductor. The next higher value in DR125 package is chosen:

L0 = 3.3 µH

ΔI = (VBD - VBAT)*Toff/ L = 4.33 A

Ipk = Iin + ΔI/2 = 5.74 A

ID = Ipk * XRdson / (XRdson + BRdson)
= 5.74 * 89 / (89 + 310) = 1.28 A

ΔID = ΔI * XRdson / (XRdson + BRdson)
= 4.33 * 0.223
= 0.966 A

The sense resistor, R1, is divided into 3 resistors, R1A, R1B and R1C. The internal sense voltage is 0.2 volts. The apparent voltage seen at the BS pins, VBS, is the internal sense voltage reduced by voltage drop across the internal resistance, RBs.

VBS = 0.2 - ID * RBs
= 0.2 - 1.28 * 0.033
= 0.157 volts

R1 = VBS / Ipk
= 0.157 / 5.74
= 0.0274 ohms Three resistors each 0.082 ohms

R1A = **R1B** = **R1C** = 0.082 ohms

Iin =(2*3*VBS/R1A - ΔI)/2 = 3.58 A

P_{R1} = D * R1 * [Ipk^2 + (Ipk - ΔI)^2 + Ipk*(Ipk-ΔI)] / 3
= 0.897 * 0.0274 * [32.95 + 1.99 + 8.09] / 3
= 0.353 watts Three resistors each 0.118 watts

The power in the 905 part is also maximum at this operating point.

P_{905} ≃ D * BRdson * [ID^2 + (ID - ΔID)^2 + ID*(ID-ΔID)] / 3
+ ILED^2 * LRdson = 0.405 watts

The assumption made at the beginning of the example was a 10% loss input power or 1.3 Watts. Now we calculate the power losses to determine if our initial assumption of 10% power loss was correct:

Losses due to Mosfet and sense resistor:

R_{eq} = (XRdson * BRdson) / (XRdson + BRdson) + R1
= (0.089 * 0.310) / (0.089 + 0.310) + 0.0273 = 0.09645

$P_{loss} = Ipk^2 * R_{eq}/3$
$= 5.74^2 * 0.09645/3 = 1.059$ Watts

Inductor winding losses due to dc resistance for inductor being used:

$P = Ipk^2 * R_{DC}/3$
$= 5.74^2 * 0.0068/3 = 0.075$ Watts

Inductor core losses using datasheet graph or using derived equation from graph:

$P = k*(V\text{-}S/F)^2 * T^{-1.32}$

Where k = 0.2615, V-S = (VBD – VBAT) *Toff, F is from the data sheet "V-S" column for chosen inductor (Cooper-Coiltronics DR series), and T is the period for which it’s applied.

$P = k*\{((VBD - VBAT) * Toff /F)^2 * Toff^{-1.32} + (VBAT*Ton/F)^2 * Ton^{-1.32}\}$

$P = 0.2615 * \{(14.3V\text{-}us/9.10V\text{-}us)^2 0.5us^{-1.32} + (15.7V\text{-}us/9.10V\text{-}us)^2 4.36us^{-1.23})\}$
= 1.725 Watts

Losses due to diode:

P = V * (Ipk-ΔI/2) * Toff/Tp
= 0.6 * (5.74 – 7.16/2)*.5/4.36 = 0.5753

Summing up all power losses we get 3.4 Watts, which means we need an input power of:

Pin = Ploss + Po
= 3.4 + 11.6 = 15 Watts

The initial input power used to calculate component values is not sufficient to provide the power needed by the LED and the power losses. As a result, the LED current will regulate below the desired current. In order to boost the current we can either increase the peak current by decreasing the R1 resistance, or increase the average current per output cycle by increasing the inductance, which reduces the ripple current, ΔI. Decreasing R1 will increase the peak current and the core power losses. Increasing the inductance will lower core losses but increase winding losses. Increasing the inductance is recommended to increase the output power since the inductor power loss is significant.

We can calculate an inductor value to yield enough input current.

Iin = Pin/Vbat-min
Iin = 15/3.6 = 4.17A

Since R1 resistor(s) are not being changed, the peak current is the same as calculated before. Inductor current is calculated as:

$\Delta I = 2(Ipk - Iin)$
$= 2(5.74 - 4.17) = 3.14A$

We can then calculate the minimum inductor size:

$L \geq (V_{BD} - V_{BAT})*Toff/\ \Delta I$
$\geq (32.2 - 3.6) * (.5us) / 3.14 = 4.55uH$

Due to 20% inductor tolerance:

L'= L / (1 - 0.2)
= 4.55uH/0.8 = 5.69uH

We choose a standard value of **L0** = 6.8uH

Additionally, the temperature rise of the components should be considered. Since we are operating well below the 905 current limits, the heat dissipation ability of the circuit board needs is not that critical. The 905 power dissipation is primarily the sum of the two power FET dissipation.

$P_{905} \simeq D * BRdson * [ID\^{}2 + (ID - \Delta ID)\^{}2 + ID*(ID-\Delta ID)] / 3 + ILED\^{}2 * LRdson$

$\simeq 0.897 * 0.310 * [1.28\^{}2 + (1.28 - 3.14*0.223)\^{}2 + 1.28*(1.28 - 3.14*0.223)] / 3 + 0.36\^{}2 * 0.62$

$\simeq$ 0.332 Watts

Printed circuit boards with power planes typically have thermal resistance of 60 C/W. Locally, the 905 part is expected to be 20 C above the ambient temperature:

$\Delta T \simeq P_{905} * 60 \simeq 20$ C

Example 6: 50805-02

Boost
VLED = 31.5
ILED = 1
10.8 $\leq$ VBAT $\leq$ 15

VBD $\simeq$ VLED + VLS + Vdiode Output voltage plus the diode drop
= 31.5 + 0.2 + 0.5
= 32.2

Po = 32.2 * 1 power to the output section including D0.
= 32.2 watts
Pin = Po/0.9 assumes 10% loss from input to output
= 35.8 watts
Iin = Pin/VBAT average current at minimum battery voltage
= 35.8/10.8
= 3.314 A average at low battery

The peak current in the 906 part must be limited to less than 2.67 A peak. The 2.0 average current restriction applies at minimum input voltage. At higher input voltages the boost converter is intermittently operating to provide the output energy; this lowers the rms current through the device when the LED is on. An external power FET must be added to achieve the 3.31 A average current. The current sharing between the external and internal power FETs is governed by the on resistance of each FET.

ID = Ipk * XRdson / (XRdson + BRdson) where ID is through the 906.

The chosen external FET is NTD3055L104T4G by ON Semiconductor. Its on resistance, XRdson, is typically 89 milli-ohms with 5 volt gate drive. At this point assume the combined peak current through the devices is twice the average input current for complete discharge of the inductor with each cycle.

Ipk = 2 * Iin peak current is twice Iin at minimum battery voltage.
= 6.63 A

ID = 6.63 * 89 / (89 + 310) Portion of current in 905 device.
= 1.49 A Within limit for 905 device.

Vloss $\underline{\sim}$ 0.2 + ID*(BRdson - RBs) Internal in parallel with external FET
= 0.2 + 1.49*(0.310 - 0.033)
= 0.610

The voltage across the inductor will decrease from 10.8 to 10.19 as the current in the inductor increases. This will increase the charge time and duty factor. We will use the average loss (Vloss/2) to modify the calculations for duty factor.

D = (VBD - VBAT) / (VBD - Vloss/2)
= 0.671

D is greater than 0.67, so the PFM mode will be used, Tp > 1.5 µsec, and

Toff = 0.5 µsec.

Ton = 0.5*D/(1-D) = 1.02 µsec

Tp = 1.52 µsec.

For critical conduction the peak inductor current is twice the input current and the inductor is completely discharged each cycle. During inductor discharge the full input voltage is available. The minimum inductor value to supply the output current:

ΔI = 2*Iin

= 2*3.31 = 6.63 A

L ≥ (VBD - VBAT)*Toff/ ΔI

≥ (32.2 – 10.8)*0.5/6.63 = 1.6 µH

Inductor values less than this will result in decreasing output at low battery voltage. Higher inductor values will allow a lower peak current with reduced ripple current at the input. Let's assume a much larger value to reduce the ripple current:

L0 = 4.7 µH

Due to a 20% tolerance in inductance the ripple current could be as high as:

ΔI = (VBD - VBAT)*Toff/ (L*0.8) = 2.85A

Ipk = Iin + ΔI/2 = 4.74 A

ID = Ipk * XRdson / (XRdson + BRdson)
= 4.74 * 89 / (89 + 310) = 1.057 A

ΔID = ΔI * XRdson / (XRdson + BRdson)
= 0.636 A

The sense resistor, R1, is divided into 3 resistors, R1A, R1B and R1C. The internal sense voltage is 0.2 volts. The apparent voltage seen at the BS pins, VBS, is the internal sense voltage reduced by voltage drop across the internal resistance, RBs.

VBS = 0.2 - ID * RBs
= 0.2 – 1.06 * 0.033
= 0.165 volts

R1 = VBS / Ipk
= 0.165 / 4.74
= 0.035 ohms Three resistors each 0.105 ohms

R1A = **R1B** = **R1C** = 0.1 ohms

Iin =(2*3*VBS/R1A - ΔI)/2 = 3.18 A

P_{R1} = D * R1 * [Ipk^2 + (Ipk - ΔI)^2 + Ipk*(Ipk-ΔI)] / 3
= 0.7 * 0.035 * [22.5 + 3.57 + 8.96] / 3
= 0.286 watts Three resistors each 0.095 watts

The power in the 906 part is also maximum at this operating point.

P_{906} $\simeq$ D * BRdson * [ID^2 + (ID - ΔID)^2 + ID*(ID-ΔID)] / 3
+ ILED^2 * LRdson

= 0.671 * 0.31 * [1.057^2 + (1.057 - 0.636)^2 + 1.057*(1.057 - 0.636)] / 3
+ 1.0 * 0.62

= 0.741 watts

The printed circuit board with internal ground power plane has a typical thermal resistance of 60 C/W for the 906 part. Locally, the 906 part is expected to be 52 C above the ambient temperature:

ΔT_{BA} $\simeq$ P_{906} * 60 $\simeq$ 44 C

T_C $\simeq$ $T_A + \Delta T_{BA}$ $\simeq$ 69 C where ambient, T_A , is typically 25C.

However, the other components on the board are adding heat to the circuit board as well, so the effective starting temperature, T_A , will be higher than the typical 25C.

The upper limit case temperature of 85C is based on maximum operating conditions of for both the boost converter and the LED modulator, which results in slightly more than 2 watts power dissipation. (The temperature coefficient of resistance for the power FET resistance is approximately +1200 ppm/C.) At this power level the internal die temperature is approximately 25 C above the exposed device pad (DAP). For long term reliability, the die temperature should be maintained below 125 C. To measure the die temperature, refer to the **Temperature and Supply Effects** section. Heat sinks and/or a fan are recommended if operating at high temperatures or in an enclosure.

Tables for Boost Designs:

L0 Table

ILED (mA)	VLED	VBAT min	VBAT max	Pin	Vloss	L0 (cal)	L0 (part)	Ton	Toff	App Board	Ver
360	3.2	1.8	3.2	1.56	0.54	0.76	1.0	0.87	0.63	50804	01
120	10.7	1.8*	6.5	1.56*	0.54	2.8	2.2	2.16	0.34*	50804	02
360	12.8	2.7	6.5	5.4*	0.72	4.3	3.3	2.51*	0.5	50804	03
360	31.5	3.6	6.5	12.9	0.64	2.0	3.3	4.36	0.5	50805	01
1000	31.5	10.8	15.0	35.8	0.61	1.6	4.7	1.02	0.5	50805	02

R1 Table

ILED (mA)	VLED	VBAT min	VBAT max	Iin	ΔI	Ipk (part)	R1 (cal)	R1 (part)	App Board	Ver
360	3.2	1.8	3.2	0.87	1.32	1.50	0.098	0.10	50804	01
120	10.7	1.8*	6.5	0.71*	1.50	1.50	0.098	0.10	50804	02
360	12.8	2.7	6.5	1.81*	1.64*	2.63*	0.042	0.043	50804	03
360	31.5	3.6	6.5	4.17	3.14	5.74	0.0274	0.082(x3)	50805	01
1000	31.5	10.8	15.0	3.18	2.85	4.74	0.035	0.1 (x3)	50805	02

*Does not supply full current to LED at minimum battery voltage. Discharge time less than 0.5 μsec at minimum VBAT or restricted by FET current. Input current increases with battery voltage up to the regulation point and then decreases.

SEPIC Converter Design equations

The application boards use two types of SEPIC (single-ended primary-inductor converter) topologies. The 50806 uses coupled inductors (1:1 transformer) whereas the 50808 uses uncoupled inductors. With coupled inductors, the SEPIC topology could be thought of as a modified flyback topology. When the FET switch is closed, the input voltage appears across both inductors (windings) as if they were in parallel and charges the inductors. When the FET switch opens, both inductors "see" the output voltage and feed current to the output. C5 is the coupling mechanism and has the battery voltage as its steady-state voltage.

Example 7: 50806-01

SEPIC
VLED = 6.4
ILED = 1.0
5.4 ≤ VBAT ≤ 15
external FET
coupled inductors
906 part:

The internal boost FET is in parallel with an external FET to increase the peak current above 2.67 A. The boost FET voltage, VBD, has the battery voltage added to its output voltage, Vout (Note Vout = VBD from the boost converter design):

Vout = VLED + VLS + Vdiode
= 6.4 + 0.2 + 0.5 = 7.1
VBD = Vout + VBAT

VBD_{max} = 22.1

VBD_{min} = 12.5

Po = Vout * ILED
= 7.1 * 1.0 power to the output section including D0.
= 7.1 watts

Pin = Po/0.9 assumes 10% loss at input as initial guess.
= 7.9 watts

Iin ≃ Pin/VBAT estimated average current at minimum battery voltage
= 7.9/5.4
= 1.46 A estimated average at low battery

The available voltage to charge the inductors is reduced by the losses of the sense resistor, R1, and the drain to source resistance, BRdson. The FET current, Id, is the sum of the input and output currents plus the ripple current from charging and discharging the inductors.

Ipk = 2 * (Iin + ILED) Critical Conduction mode.
= 4.93 A

The peak current in the 906 part must be limited to less than 2.67 A peak and 2.0 A average current at minimum input voltage. At higher input voltages the SEPIC converter is intermittently operating to provide the output energy; this lowers the rms current through the device when the LED is on. An external power FET must be added to achieve the 5.1 A peak current. The current sharing between the external and internal power FETs is governed by the on resistance of each FET.

ID = Ipk * XRdson / (XRdson + BRdson) where ID is through the 906.

The chosen external FET is NTD3055L104T4G by ON Semiconductor. Its on resistance, XRdson, is typically 89 milli-ohms with 5 volt gate drive.

ID = 4.93 * 89 / (89 + 310) Portion of current in 906 device.
= 1.10 A Within limit for 906 device.

Vloss $\simeq$ 0.2 + ID*(BRdson - RBs) Internal in parallel with external FET
= 0.2 + 1.10*(0.310 - 0.033)
= 0.50

The voltage across the inductor will decrease from 5.4 to 4.9 as the current in the inductor increases. This will lengthen the charge time and increase the duty factor. We will use the average loss (Vloss/2) to modify the calculations for duty factor.

D = Vout / (VBD - Vloss/2)

D_{min} = 0.325 15 volt battery

D_{max} = 0.580 5.4 volt battery

Since D_{max} is less than 0.667, the regulator will be operating in the PWM mode with the time period fixed at 1.5 µsec.

Ton = 1.5 * D_{max} = 0.87 µsec

Toff = 1.5 * (1 - D_{max}) = 0.63 µsec

At D_{max}, the coupled inductor must be large enough to continuously supply current to the output (critical or continuous conduction).

Iout = ILED/(1-D) = 2.38 A

The coupled inductor has two equal windings around a common core. If the coupling capacitor, C5, had infinite capacitance, each winding would supply half of the output current during the first cycle. However, at the end of the first cycle there would be a charge imbalance on C5 that would lower its voltage and result in lower current in the secondary due to the finite winding resistance and coupling. The steady-state input current will become:

Iin = ILED * D_{max} /(1- D_{max}) = 1.38 A (which is Iout - ILED)

The losses are less than estimated. The secondary current is ILED, which may be the limiting factor that determines the minimum required inductance. By assuming 100% ripple current at the secondary, the minimum value for L0:

L0 $\geq$ Vout * Toff / (2 * ILED)
$\geq$ 7.1 * 0.63 / 2
$\geq$ 2.2 µH

The inductor also must be large enough to prevent a fault at maximum battery voltage. The minimum charge time should be approximately 0.35 μsec to avoid the 250 ns fault threshold.

$L0 \geq 0.35*VBAT_{max}/(Iout)$
$\geq 0.35 * 15 / 2.38$
$\geq 2.21\ \mu H$

During the first cycle, C5, is charging the secondary while the battery is charging the primary. Each winding will charge to Iout for a total of 2*Iout in the core for 100% ripple current. The limiting factor is at maximum battery voltage; however this is not always the case. Pick a standard value large enough that it will be greater than the minimum calculated values with tolerances.

L0 $= 3.3\ \mu H$ standard inductor value, parallel windings.

$\Delta I_0 = Vout * Toff/L0$ inductor L0 ripple current per winding
$= 1.36$ A

$Iip = Iin + \Delta I_0/2$ peak input (primary) current
$= 2.05$ A

$Iop = ILED + \Delta I_0/2$ peak secondary current
$= 1.68$ A

$Ipk = Iip + Iop$
$= 3.73$ A

$ID = Ipk * XRdson / (XRdson + BRdson)$ where ID is through the 906.
$= 3.73 * 89 / (89 + 310)$
$= 0.832$ A

$\Delta ID = 2* \Delta I_0 * ID/Ipk = 0.607$

The sense resistor, R1, is divided into 2 resistors, R1A, and R1B. The internal sense voltage is 0.2 volts. The apparent voltage seen at the BS pins, VBS, is the internal sense voltage reduced by voltage drop across the internal resistance, RBs.

$VBS = 0.2 - ID * RBs$
$= 0.2 - 0.832 * 0.033$
$= 0.173$ volts

$R1 = VBS / Ipk$
$= 0.173 / 3.73$
$= 0.0463$ ohms Two ideal resistors, each 0.0926 ohms

R1A = **R1B** = 0.091 ohms Two standard value resistor

$Ipk = 2*VBS/R1A = 3.80$ A

$Iin = Ipk - \Delta I_0 - ILED = 1.44$ A

Note the peak current and input current are higher than necessary because the standard value resistors are lower than the ideal. The LED regulator circuitry will cycle the SEPIC converter off and on to achieve the needed power. The worst case power is

$P_{\mathbf{R1}} = D_{max} * R1 * [Ipk\hat{}2 + (Ipk - \Delta I)\hat{}2 + Ipk*(Ipk-\Delta I)] / 3$
$= 0.58 * 0.0455 * [14.44 + 1 + 3.8] / 3$

= 0.169 watts Two resistors each 0.085 watts

The power in the 906 part is also maximum at this operating point.

P_{906} $\underset{\sim}{}$ ~ D_{max} * BRdson * [ID^2 + (ID - ΔID)^2 + ID*(ID-ΔID)] / 3

+ ILED^2 * LRdson = 0.837 watts

As the input voltage increases the peak current remains the same while the power to the output increases. Increasing the input voltage will increase the average output current per cycle due to longer off time. The voltage across C1 and the LED current will increase. When the LED current is above its set point, the SEPIC converter is shut-off until the LED current drops below the set point.

The coupling capacitor C5 sees the average input current when the FET is off. This is the same charge that was removed when the FET was on. Assuming 25 mV per battery volt for the ripple voltage and D_{max}:

C5 $\geq$ Iin * Toff / (0.025*VBAT) = 6.7 µF (135 mVp-p ripple)

C5 = 10 uF a standard value that results in ~ 90 mVp-p ripple

Example 8: 50808-01

SEPIC
VLED = 3.2
ILED = 0.36
1.8 $\leq$ VBAT $\leq$ 6.5 volts
uncoupled inductors
904 part

The boost FET voltage, VBD, has the battery voltage added to its output voltage, Vout. (Note Vout = VBD from the boost converter design):

Vout = VLED + VLS + Vdiode
= 3.2 + 0.2 + 0.5 = 3.9
VBD = Vout + VBAT

VBD_{max} = 10.4

VBD_{min} = 5.7

Po = Vout * ILED
= 3.9 * 0.36 power to the output section including D0.
= 1.4 watts
Pin = Po/0.9 assumes 10% loss at input as initial guess.
= 1.56 watts
Iin ~ Pin/VBAT estimated average current at minimum battery voltage
= 1.56/1.8
= 0.866 A estimated average at low battery

The available voltage to charge the inductor is reduced by the losses of the sense resistor, R1, and the drain to source resistance, BRdson. The FET current, Id, is the sum of the input and output currents plus the ripple current from charging and discharging the inductors. The maximum peak current without an external FET is 2.67 A.

$Idpk \le 2 * (Io + Iin) = 2 * (0.36 + 0.866) = 2.45$

This rough guess is used to estimate the losses of the sense resistor and FET on resistance. (See Figure 12 for internal resistance, BRs, and R1 relationship.)

$$Vloss \simeq 0.2 + Idpk*(BRdson - BRs)$$
$$= 0.2 + 2.45*(0.23 - 0.033) = 0.68$$

The voltage across the inductor will decrease from 1.8 to 1.12 as the current in the inductor increases. This will lengthen the charge time and increase the duty factor. We will use the average loss (Vloss / 2) to modify the calculation for duty factor.

$D = Vout / (VBD - Vloss/2)$

$D_{min} = 0.388$ 6.5 volt battery

$D_{max} = 0.728$ 1.8 volt battery

Since D_{max} is greater than 0.667, the regulator will be operating in the PFM mode with the discharge time, Toff, fixed at 0.5 µsec.

$Toff = 0.5$ µsec

$Ton = 0.5 * D_{max} / (1 - D_{max}) = 1.34$ µsec

At D_{max}, the inductors must be large enough to continuously supply current at the input and output (critical or continuous conduction). The input current flows through L0, whereas the output current is supplied by both L0 and L1. With D_{max}, the output current from L0 and L1 can be found.

$Iout = ILED/(1-D) = 1.324$

The input current is revised based on the duty factor.

$Iin = ILED * D/(1-D) = 0.964$ (Which is Iout - ILED)

The losses are greater than originally estimated. This process can be iterated for better accuracy after choosing the inductor values.

The minimum value for L0 is found assuming 100% ripple current at minimum battery voltage. The duty factor, D, is set to D_{max}.

$$L0 \ge VBAT_{min} * [Toff*D/(1-D)] / (2*Iin)$$
$$\ge 1.8 * [0.5 * 0.728/(.272)] / (2*0.964)$$
$$\ge 1.25 \mu H$$

The inductors also must be large enough to prevent a fault at maximum battery voltage. The minimum charge time should be approximately 0.35 µsec to avoid the 250 ns fault threshold.

$$L0 \ge 0.35*VBAT_{max}/(2*Iin)$$
$$\ge 1.18 \mu H$$

Note the limiting factor is at minimum battery voltage; however this is not always the case. Pick a standard value large enough that, with tolerances, it will be greater than the minimum values calculated above.

L0 = 2.2 µH standard inductor value.

ΔI_0 = Vout * Toff/L0 inductor L0 ripple current
= 0.886 A

Iip = Iin + $\Delta I_0/2$ peak input (and L0) current
= 1.369 A

The output inductor, L1, supplies the difference between L0 and Iout, which is the LED current ILED.

L1 $\geq$ Vout * Toff / (2 * ILED)
$\geq$ 2.71 µH

Pick a standard value that is proportionately larger than the value pick for L0.

L1 = 4.7 µH $\simeq$ 2.71 * 2.2 / 1.18 ($L1_{min}$ scaled by $L0/L0_{min}$)

ΔI_1 = Vout * Toff/L1 inductor L1 ripple current
= 0.415 A

Iop = ILED + $\Delta I_1/2$ peak current for L1
= 0.568

Ipk = Iip + Iop
= 1.937

R1' = 0.2 / Ipk
= 0.103 ohms

R1 = R1' - BRs = 0.103 - 0.033 = 0.070 ohms
$\simeq$ 0.068 Standard value resistor.

resultant peak FET current = 1.98 A

(See Figure 12 for internal resistance, BRs, and R1 relationship.)

Note the peak current must be less than 2.67A when an external FET is not used.

As the input voltage increases the currents in the inductors remain the same; however, the period decreases and eventually reaches 1.5 µsec where the off time begins to increase. The decreasing time period increases the average output current and voltage across C1, which increases the LED current. When the LED current is above its set point, the SEPIC converter is shut-off until the discharging of C1 decreases the LED current below its set point.

The coupling capacitor C5 sees the average input current when the FET is off. This is the same charge that was removed when the FET was on. Assuming 25 mV per battery volt for the ripple voltage and D_{max}:

C5 $\geq$ Iin * Toff / (0.025*VBAT) = 10.3 µF (45 mVp-p ripple)

C5 = 10 uF a standard value that results in ~ 50 mVp-p ripple

Filter Capacitors C1 and C2

The boost / SEPIC output capacitor, C1, plays an important part in the LED current regulation control loop. Ripple voltage at the output is coupled to the current sense resistor, R0, through the dynamic resistance of the LED and the power FET. The dynamic resistance of an LED is typically less than 1 ohm as shown in Figure 14 below. The power FET resistance is typically less than 0.5 ohms.

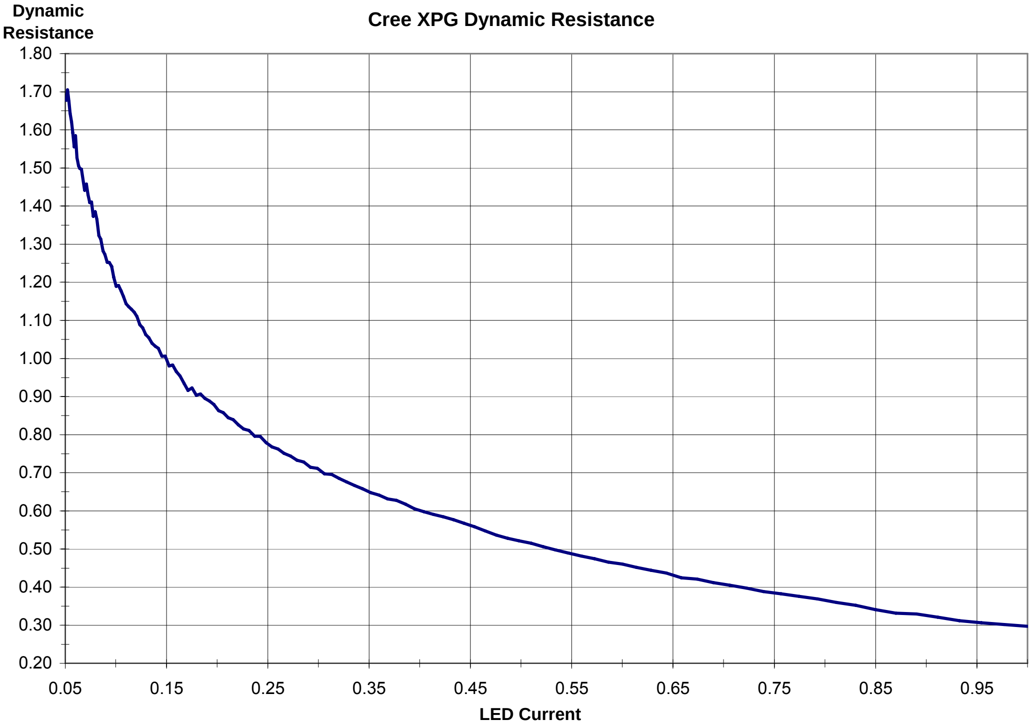


Figure 14. LED Dynamic Resistance, Cree XPG

The LED ripple current is approximately:

$$\Delta I_{LED} = V_{RIPPLE} / (R_{LED} + Rdson + 0.2/I_{LED})$$

For an LED operating at 350 mA with 100 mV of ripple:

$$\Delta I_{LED} = 0.1 / (0.65 + 0.5 + 0.2/0.35)$$

$$= 58 \text{ mA}$$

The frequency and shape of this ripple is dependent upon the input battery voltage. The internal digital control loop enables the boost / SEPIC regulator to operate when the LED current is below the target value. And shuts-off the boost / SEPIC regulator when the LED current is above its target value. There is a delay from the time the current drops below its target value until the inductor is fully charged, which allows the LED to drop further below its target regulation point. Typically the regulation point is near the peak of the LED current. Consequently, the average LED current can be reduced by a sizeable portion of the ripple current, ΔI_{LED}. As the input voltage varies, it changes the timing relationship between the start of the boost / SEPIC regulator and when the peak

LED current is reached. This in turn can vary the sampling point for the regulation loop and results in changing the average current in the LED.

In addition to the capacitance value of C1, the equivalent series impedance of the type of capacitor is an important factor. Ceramic chip capacitors have very low equivalent series resistance and inductance. Although aluminum electrolytic capacitors are very inexpensive on a per unit of capacitance, their equivalent series resistance and inductance may offset any benefit of the added capacitance. Aluminum-polymer capacitor address this issue but at significantly higher cost. Consequently, the value for C1 is often an economic choice.

The component placement of C1, C2, R0 and R1 is important. The goal is to minimize return inductances. The application boards feature a ground plane to assist with minimizing the return impedances. However, note that in some of the application boards the ripple current in the boost inductor is greater than 2 amperes and occurs over a 0.5 μs time. This high rate of change makes even the smallest inductances in the return paths important. With as little as 5 nH of inductance a 20 mv "noise" component can be added to the "ground" reference plane. This "noise" will interact with the control loop for both the LED current and boost / SEPIC current.

Fortunately, these factors are relatively constant for a given layout and component selection. Adjustments to the calculated R0 and R1 values can offset some of these factors and may be the most economical solution to low performance. The application boards do not have any of these adjustments.

The values used for C1 and C2 are sometimes much larger than the calculated values. Often the cost for a 10 μF is lower than the cost for an intermediate value between 1 and 10 μF. Additionally, larger capacitance will reduce ripple currents. Both the calculated and part values are shown for clarity.

Assume the LED ripple current is 10%. Then the voltage at the LED sense point will vary 20 mV. Using the dynamic resistance of the LED, and the power FET on resistance, (LRdson - RLs), the effective ripple voltage, ΔV, at the output can be found.

$$\Delta V = 0.1 * ILED * (R_{LED} + LRdson - RLs) + 20\ mV$$

Where R_{LED} is the total dynamic resistance of the LED string.

Note that LRdson included the sense offset resistance, RLs, which was already accounted for in the 20 mV ripple of the sense voltage. Therefore RLs must be subtracted from LRdson.

The ripple voltage, ΔV, has two components. When the LED current first transitions below its target regulation point, the boost / SEPIC converter starts to charge the inductor from a fully discharged state after a delay of approximately 0.1 μs. During the time it takes the inductor to charge, the LED current is continuing to drop below the regulation point. Conversely, when the LED finally transitions above its target regulation point, the inductor may still have current flowing, which will further drive the LED above its target regulation point. Combine the worst case for both of these to find the total charge:

$$Q_{ripple} = T_{charge} * ILED + T_{off} * Ipk/2$$

And

$C = Q_{ripple} / \Delta V$

The boost and SEPIC output capacitors, C1 and C4, filter the current going to the LED and play an important part in the LED current regulation control loop.. For example, 50804-01

$\Delta V = 0.1 * ILED * (R_{LED} + LRdson - RLs) + 20\ mV$
$= 0.1 * 0.360 * (0.64 + 0.46 - 0.066) + 0.02$
$= 57.2\ mV$

$Q_{ripple} = T_{charge} * ILED + T_{off} * Ipk/2$
$= 0.87 * 0.36 + 0.63 * 1.53/2$
$= 0.795$ micro Coulombs (μC)

$C > Q_{ripple} / \Delta V$
$> 0.795\ \mu C / 57.2\ mV$
$> 13.9\ \mu F$
$C1 = 10\ \mu F$ a widely available capacitance value.

However, the average LED current for the buck convert (50807-01) is not dependent upon C1 and C4 filtering. The LED almost always receives current through the inductor and the ripple voltage across the LED does not effect the control point since the inductor is in series with the LED. The filtering provided by C1 and C4 are primarily for EMI considerations. However, the same approach can be used by assuming a desired ripple voltage, ΔV, and using the total time period as the worst case for either charge or discharge time. For the 50807-01 the assumed ripple was 50 mV.

$C \sim \Delta I / 4 * Tp / \Delta V$ Note $Q \sim \Delta I / 4 * Tp$
$\sim 1.52 / 4 * 6.9 / 0.05 = 52.4\ \mu F$
$C1 = 47\ \mu F$ a widely available capacitance value.

The input capacitors C2 and C6 need to provide a low impedance source for the inductor L0, internal FET switch, and output section of D0 and C1. These component should be laid out in a tight loop of minimum area. The purpose of C2 and C6 is to be the primary source of ripple energy during a regulator cycle. Use the largest combined value to minimize the impedance. For the purpose of this calculation, an arbitrary value of 25 mV of ripple per battery volt is used: (50804-01)

$C \sim \Delta I / 4 * Tp / (0.025 * VBAT)$
$\sim 1.32 / 4 * 1.5 / 0.045 = 11.0\ \mu F$
$C2 = 10\ \mu F$ a widely available capacitance value.

However, the input for the buck convert (50807-01) only provides current during the charge time.

$C > [(2 * Ipk - \Delta I)/2 - Iin] * Ton / (0.025 * VBAT)$
$> [(2 * 1.54 - 1.54)/2 - 0.52] * 3.85 / 0.135$
$> 7.1\ \mu F$

C2 = 10 µF a widely available capacitance value.

EMI requirements may require greater capacitance values and the addition of pi networks.

The battery internal resistance causes the voltage to decrease when under load. At low brightness settings, the battery "sees" a pulsed load every 4 ms with a duty factor proportional to the brightness. To minimize the effects of battery internal resistance when low brightness settings are used, increase C2 capacitance as much as possible. C2 will provide the energy to "ride" through the load pulses at low brightness setting and extend the useful battery time. This is highly recommended if the product is intended to use alkaline battery technology since they have much higher internal resistance than other battery technology.

When making laboratory measurements with a power supply substituted for a battery, the dynamic output impedance of the power supply may be too high for useful measurements. Additional bypass capacitance will be required. Voltage from a battery will sag under dynamic load; but, the voltage from a power supply may overshoot above its open circuit value when insufficient bypass capacitance is used.

C1 Table: Combined Output Capacitors C1 and C4

App Board	Ver	ILED	VLED	#	Rdson	RLED	Ton	Toff	Ipk	ΔV (mv)	Q (μC)	C1 (calc)	C1 (part)
50804	01	360	3.2	1	0.39	0.64	0.87	0.63	1.53	57	0.80	13.9	10
50804	02	120	10.7	3	0.39	1.05	2.16	0.34*	1.50	63	0.51	8.2	10
50804	03	360	12.8	4	0.39	0.64	2.51	0.5	2.63	126	1.56	12.4	20
50805	01	360	31.5	9	0.55	0.64	4.36	0.5	5.74	247	3.00	12.1	10
50805	02	1000	31.5	9	0.49	0.30	1.02	0.5	4.74	339	2.21	6.5	10
50806	01	1000	6.4	2	0.49	0.30	0.87	0.63	3.73	129	2.04	15.8	20
50807	01	720	3.3	1	0.18	0.41	4.63	2.01	1.41	50	2.62	52.4	47
80508	01	360	3.2	1	0.39	0.64	1.34	0.5	1.94	57	0.97	16.9	10

*Discharge time for inductor at minimum battery voltage is less than minimum off time. Higher battery voltage will increase the discharge time to 0.5 µs. Use 0.5 µs to calculate C1.

C2 Table: Combined Input Capacitors C2 and C6

VBAT (min)	Iin (part)	ΔV (mV)	Ipk (part)	ΔI	Ton	C2 (cal)	C2 (part)	Board	Ver
1.8	0.84	45	1.53	1.32	0.87	11.0	10	50804	01
1.8*	0.71*	45	1.50	1.50	2.16*	22.2	20	50804	02
1.8	0.96	45	1.93	0.89	1.34	9.1	10	50808	01
2.7*	1.81*	68	2.63	1.64	2.51	18.3	20	50804	03
3.6	3.58	90	5.74	3.36	4.36	45.8	94	50805	01
5.4	1.44	90	3.73	1.36	1.09	8.0	10	50806	01
5.4	0.52	135	1.41	1.41	4.63	16.2	10	50807	01
10.8	3.31	270	4.74	2.85	1.05	4.2	10	50805	02

*Does not supply full current to LED at minimum battery voltage. Discharge time is less than 0.5 µsec at minimum VBAT or restricted by FET current. Input current increases with battery voltage up to the regulation point and then decreases.

App. Schematics and Material List

50802 – Control Board for 50804-50807 Application Boards

50804 – 904 Boost Topology for 1.8 to 6.5 Volt Batteries and 3 to 13 Volt LEDS

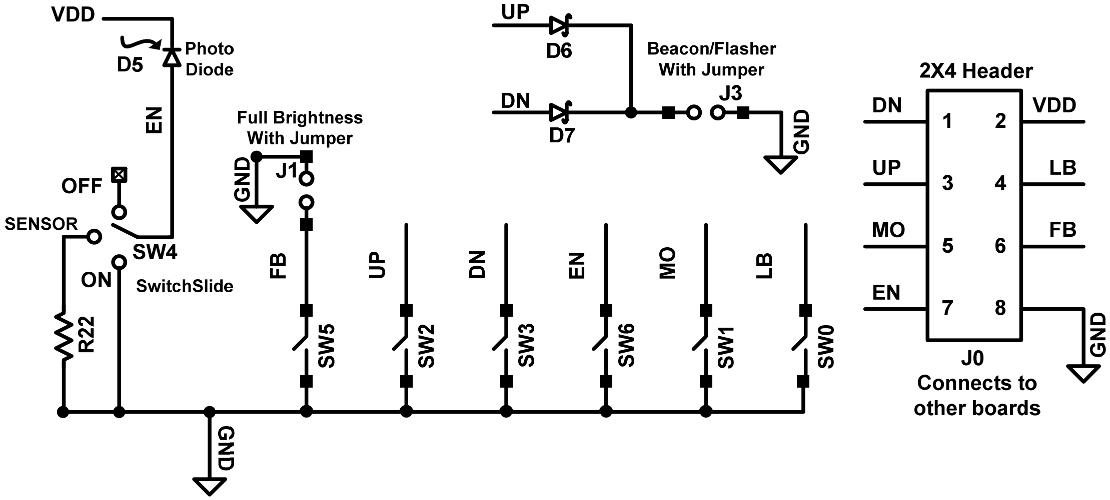
50805 – 905 & 906 Boost Topology with External FET

50806 – 906 SEPIC Topology with External FET

80807 – 907 Buck Topology

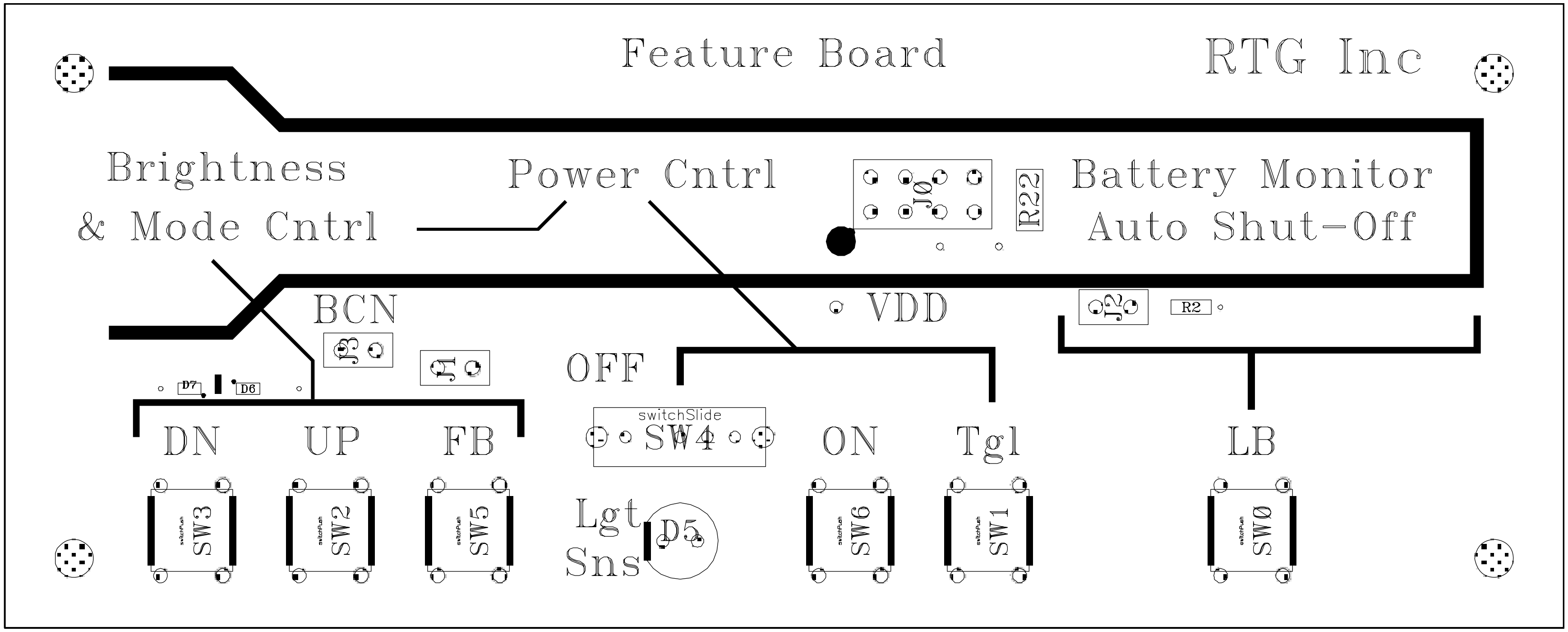
50808 – SEPIC Topology with Uncoupled Inductors and Self-contained Switches

50802 Application Board – Control Board for 50804-50807 Application Boards



50802 Schematic

50802 Application Board



50802
4.5 x 1.8 inches
Scale 2x

ML-50802-01

Feature Control Board
Applicable to 50804 - 50807 boards

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board	50802B	RTG		
D5		Diode, Ambient Light Sensor, 20mA, 5V, LED5mm	TEPT5600	Vishay	1957	250
D6		Diode, Schottky, 200mA, 30V, SOD523	BAT54WX-TP	Micro Commercial	957	690
D7		Diode, Schottky, 200mA, 30V, SOD523	BAT54WX-TP	Micro Commercial	1117	690
J0		Connector, IDC8	67996-108HLF	FCI	2650	1250
J1		Header, 2 pos, Straight, head 0.230, tail 0.120	90120-0122	Molex	450	750
J3		Header, 2 pos, Straight, head 0.230, tail 0.120	90120-0122	Molex	1000	800
R22		Resistor, 10K Ohms, 1%, 250mW, Thick Film	ERJ-8ENF1002V	Panasonic	2958	1234
SW0		Switch, Tact MOM 100g	B3F-1000	Omron	3600	280
SW1		Switch, Tact MOM 100g	B3F-1000	Omron	2840	280
SW2		Switch, Tact MOM 100g	B3F-1000	Omron	890	280
SW3		Switch, Tact MOM 100g	B3F-1000	Omron	1290	280
SW4		Switch, Slide, SP3T, Termination: pin	OS103011MS8QP1	C&K	1949	550
SW5		Switch, Tact MOM 100g	B3F-1000	Omron	490	280
SW6		Switch, Tact MOM 100g	B3F-1000	Omron	2440	280

Options		
	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

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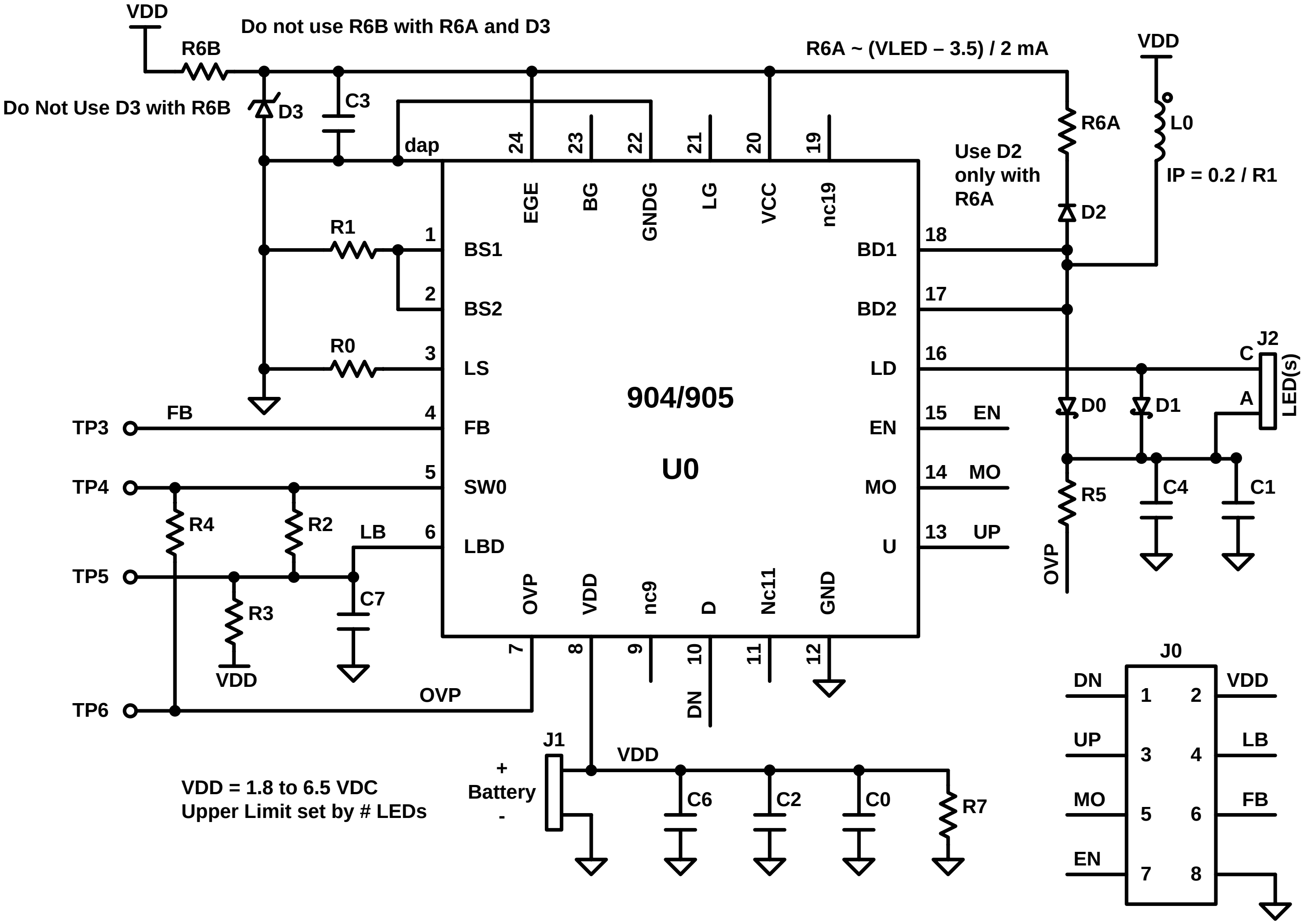
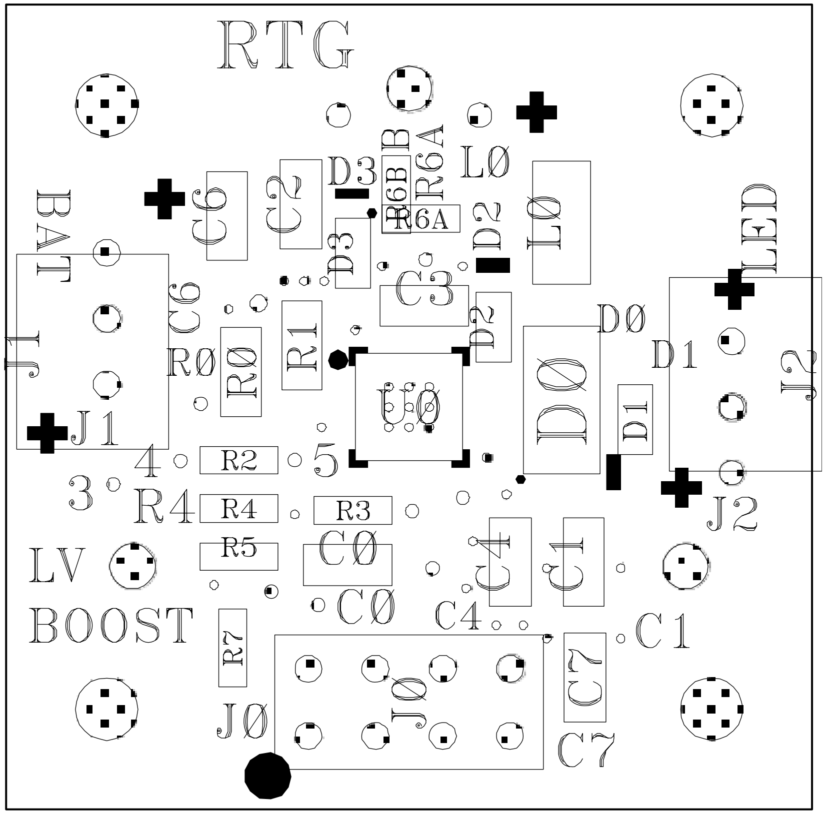
50804 Application Board – 904 Boost Topology



50804 Schematic

50804 Application Board



50804 Board
1.2 x 1.2 inches
Scale 3.5x

ML50804-01

904 part, Boost topology VBAT 1.8 to 3.2 1 LED, 3.2 V, 360 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board 1.2 x 1.2 inches	50804C	RTG		
C0		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-91	-236
C1A		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	264	-231
C2		Capacitor, 10uF, 10%, 10V, X5R, 0805	GRM21BR61A106KE19L	Murata	-271	285
C3		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	23	151
C4		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	151	-231
C6	NI	Capacitor, 10uF, 10%, 10V, X5R, 0805 / "Can use 1210"	GRM21BR61A106KE19L	Murata	-161	302
C7	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	262	-403
D0		Diode, Schottky, 2A, 40V, SMA / "Can use SMB"	B240A	Diodes Inc.	227	10
D1		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	336	-19
D2		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	126	119
D3	*	Diode, Zener, 6.2V ±2% 200MW SOD-323F	MM3Z6V2B	Fairchild	-84	229
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	-150	-490
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-450	132
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	480	1
L0		Inductor, 1.0u, 20%, 2.4A, 0.043 Ohms, 1210 / "up to 4mm"	BRL3225T1R0M	Taiyo Yuden	227	275
R0		Resistor, 500m Ohms, 1%, 250 mW, 0805	RL1220S-R50-F	Susumu	-250	52
R1		Resistor, 100m Ohms, 1%, 250 mW, 0805	RL1220S-R10-F	Susumu	-160	92
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-253	-79
R3		Resistor, 28.7K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2872V	Panasonic	-83	-154
R4		Resistor, 6.98K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6981V	Panasonic	-253	-151
R5		Resistor, 48.7K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4872V	Panasonic	-253	-223
R6A		Resistor, 100 Ohms, 1%, 100 mW, 0603	ERJ-3EKF1000V	Panasonic	21	284
R6B	N/A	"Do Not Use"			-19	317
R7	*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-262	-359
U0		Boost Reg, LV input, LV output, Low Rdson	904	RTG	0	0

Options	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

ML-50804-02

904 part, Boost topology VBAT 1.8 to 6.5 3 LED, 10.7 V, 120 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board, 1.2 X 1.2 inches	50804C	RTG		
C0		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-91	-236
C1A		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	264	-231
C2		Capacitor, 10uF, 10%, 10V, X5R, 0805	GRM21BR61A106KE19L	Murata	-271	285
C3		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	23	151
C4		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	151	-231
C6		Capacitor, 10uF, 10%, 10V, X5R, 0805	GRM21BR61A106KE19L	Murata	-161	302
C7	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	262	-403
D0		Diode, Schottky, 2A, 40V, SMA / "Can use SMB"	B240A	Diodes Inc.	227	10
D1		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	336	-19
D2		Diode, Standard, 75V, 100 mA, SOD323	1N4448WS	Fairchild	126	119
D3		Diode, Zener, 6.2V ±2% 200MW SOD-323F	MM3Z6V2B	Fairchild	-84	229
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	-150	-490
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-450	132
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	480	1
L0		Inductor, 3.3u, 20%, 2.3A, 0.055 Ohms, 4mm	NRS4018T3R3MDGJ	Taiyo Yuden	227	275
R0		Resistor, 1.62 Ohms, 1%, 100 ppm, 125mW, 0805	CRCW08051R62FKEA	Vishay/Dale	-250	52
R1		Resistor, 100m Ohms, 1%, 250 mW, 0805	RL1220S-R10-F	Susumu	-160	92
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-253	-79
R3		Resistor, 28.7K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2872V	Panasonic	-83	-154
R4		Resistor, 20.5K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2052V	Panasonic	-253	-151
R5		Resistor, 499K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4993V	Panasonic	-253	-223
R6A		Resistor, 976 Ohms, 1%, 100 mW, 0603	ERJ-3EKF9760V	Panasonic	21	284
R6B	N/A	"Do Not Use"			-19	317
R7	*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-262	-359
U0		Boost Reg, LV input, LV output, Low Rdson	904	RTG	0	0

Options		
	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

ML-50804-03

904 part, Boost topology VBAT 2.7 to 6.5 4 LED, 12.8 V, 360 mA

Ref Des	Opt (*)	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board	50804C	RTG		
C0		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-91	-236
C1		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	264	-231
C2		Capacitor, 10uF, 10%, 10V, X5R, 0805	GRM21BR61A106KE19L	Murata	-271	285
C3		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	23	151
C4		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	151	-231
C6		Capacitor, 10uF, 10%, 10V, X5R, 0805	GRM21BR61A106KE19L	Murata	-161	302
C7	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	262	-403
D0		Diode, Schottky, 2A, 40V, SMA / "Can use SMB"	B240A	Diodes Inc.	227	10
D1 (D2)		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	336	-19
D2 (D1)		Diode, Standard, 75V, 100mA, SOD323	1N4448WS	Fairchild	126	119
D3		Diode, Zener, 6.2V ±2% 200MW SOD-323F	MM3Z6V2B	Fairchild	-84	229
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	-150	-490
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-450	132
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	480	1
L0		Inductor, 3.3u, 30%, 3.8A, 27m Ohms, 5mm	NR5040T3R3N	Taiyo Yuden	227	275
R0		Resistor, 500m Ohms, 1%, 250 mW, 0805	RL1220S-R56-F	Susumu	-250	52
R1		Resistor, 43m Ohms, 1%, 250 mW, 0805	ERJ-6BWFR043V	Panasonic	-160	92
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-253	-79
R3		Resistor, 47.5K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4752V	Panasonic	-83	-154
R4		Resistor, 6.98K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6981V	Panasonic	-253	-151
R5		Resistor, 205K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2053V	Panasonic	-253	-223
R6A		Resistor, 1.74K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1581V	Panasonic	21	284
R6B	N/A	"Do Not Use"			-19	317
R7	*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-262	-359
U0		Boost Reg, LV input, LV output, Low Rdson	904	RTG	0	0

Options		
	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

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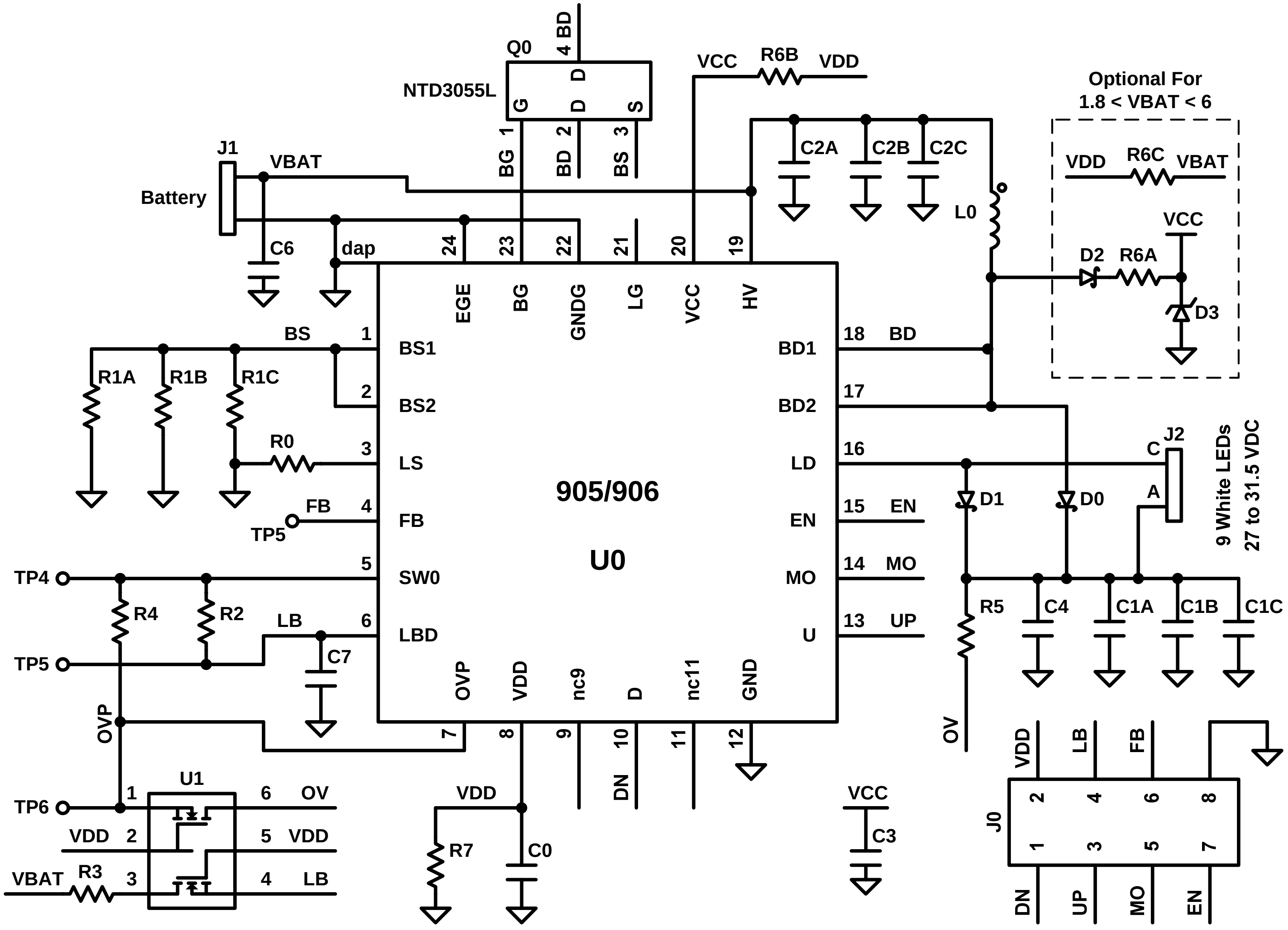
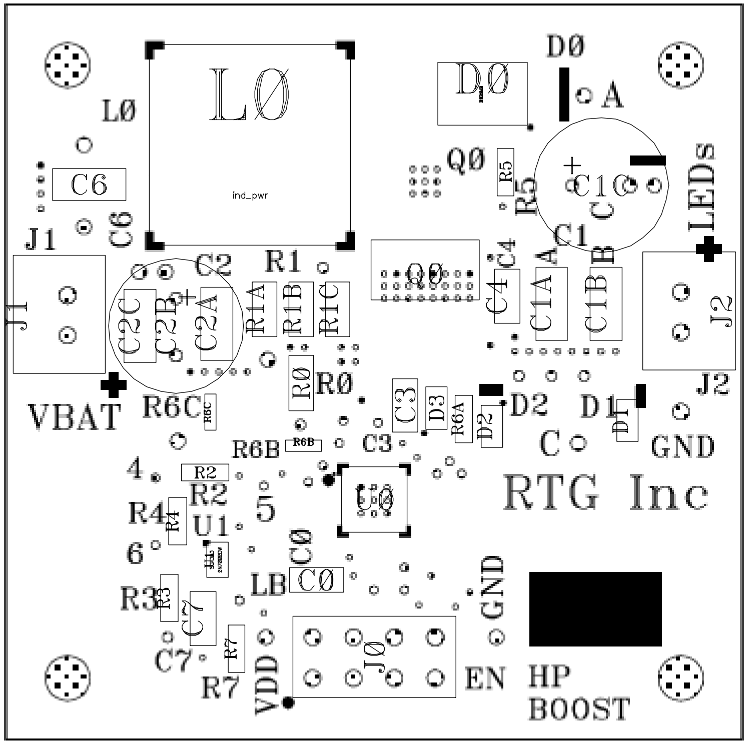
50805 Application Board – 905 & 906 Boost Topology with External FET



50805 Schematic

50805 Application Board



50805
1.8 x 1.8 inches
Scale: 2.125x

ML-50805-01

905 part, Boost w Ext FET VBAT 3.6 to 6.5 9 LED, 31.5 V, 360 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board	50805C	RTG		
C0 (C2)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-325	-80
C1A (C1)		Capacitor, 10uF, 10%, 35V, X5R, 1206 / "Can use 1210"	GMK316BJ106KL-T	Taiyo Yuden	434	164
C1B (C2)	NI	Capacitor, 10uF, 10%, 35V, X5R, 1206 / "Can use 1210"	GMK316BJ106KL-T	Taiyo Yuden	568	164
C2A (C5)		Capacitor, 47uF, 20%, 10V, X5R, 1206 / "Can use 1210"	GRM31CR61A476ME15L	Murata	-386	129
C2B	NI	Capacitor, 680 uF, 20%, 10V, Alum, 330 mil Dia, Radial	EEU-FM1A681L	Panasonic	-485	110
C2C (C3)	?NI	Capacitor, 47uF, 20%, 10V, X5R, 1206 / "Can use 1210"	GRM31CR61A476ME15L	Murata	-574	129
C3 (C6)		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	76	-84
C4		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	326	183
C6		Capacitor, 47uF, 20%, 10V, X5R, 1206 / "Can use 1210"	GRM31CR61A476ME15L	Murata	-711	457
C7		Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	-409	-606
D0		Diode, Schottky, 3A, 40V, SMB / "Can use SMC"	B340B	Diodes Inc.	230	679
D1		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	608	409
D2		Diode, Standard, 75V, 100mA, SOD323	1N4448WS	Fairchild	288	-136
D3		Diode, Zener, 6.2V ±2% 200MW SOD-323F	MM3Z6V2B	Fairchild	152	-91
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	0	-700
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-771	38
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	771	146
L0		Inductor, 3.3u, 20%, 15A, 4.5m Ohms, 12.5mm sq	DR125-2R2-R	Cooper	-304	554
Q0		NFET, 12A, 60V, 104m Ohms, Logic Level, DPAK	NTD3055L104T4G	ON Semi	124	247
R0		Resistor, 500m Ohms, 1%, 250 mW, 0805	RL1220S-R50-F	Susumu	-179	-23
R1A		Resistor, 82m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR082	Rohm	-269	141
R1B		Resistor, 82m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR082	Rohm	-179	141
R1C		Resistor, 82m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR082	Rohm	-89	141
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-414	-249
R3		Resistor, 66.5K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6652V	Panasonic	-481	-557
R4		Resistor, 6.98K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6981V	Panasonic	-481	-368
R5		Resistor, 464K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4643V	Panasonic	353	519
R6A (R11)		Resistor, 1.1K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1372V	Panasonic	219	-118
R6B (D4R)	N/A	"Do Not Use"			-173	-181
R6C (R10)		Jumper, 0402	RMCF0402ZT0R00	Stackpole	-400	-102
R7	?*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-338	-680
U0		Boost Reg, LV input, HV output	905	RTG	0	-315
U1		NFET, Dual, 115mA, 60V, 2V Vgs, SOT-363	2N7002DW	Fairchild	-384	-463

Options		
	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

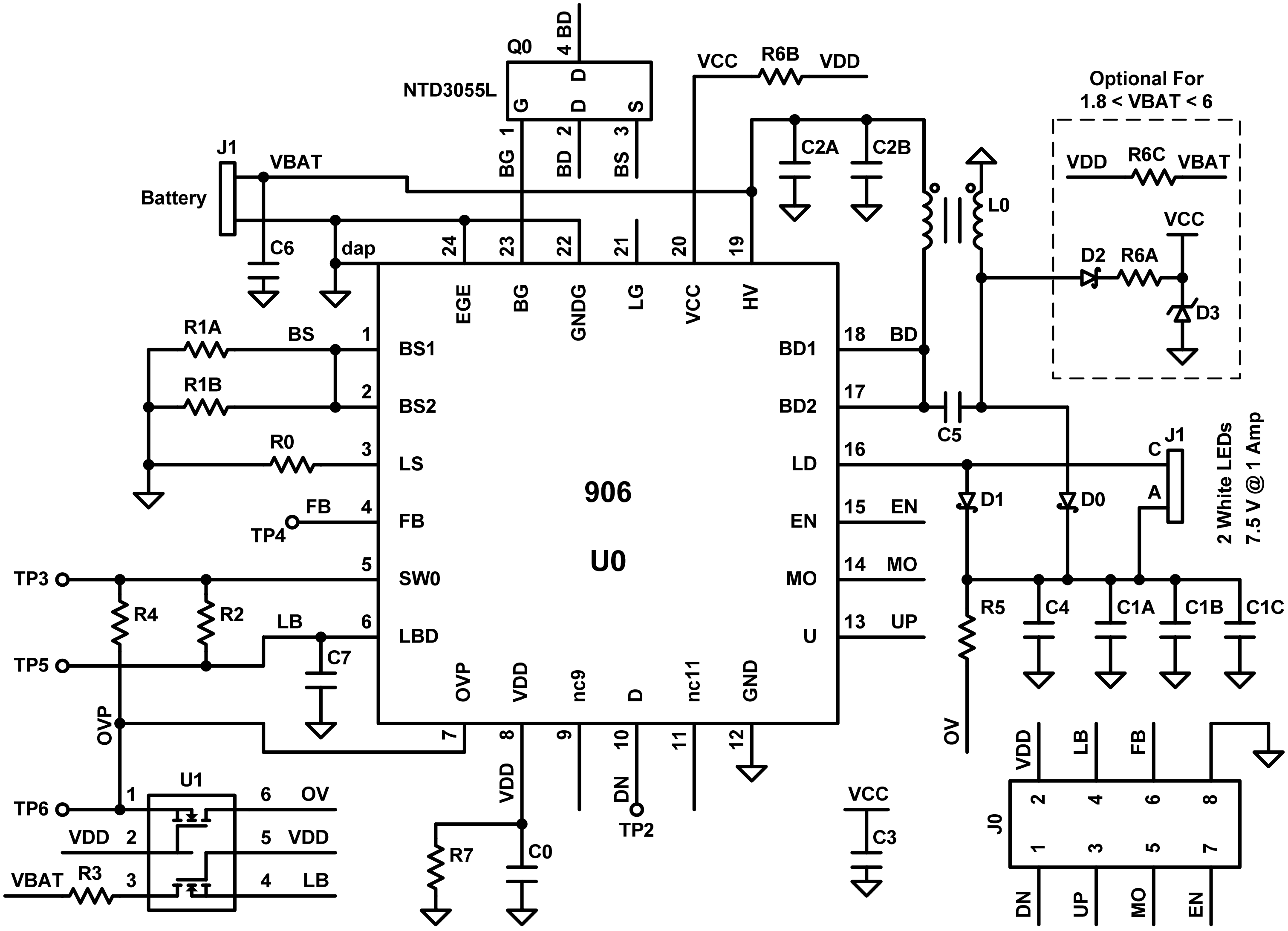
ML-50805-02

906 part, Boost w Ext FET VBAT 10.8 to 15 9 LED, 31.5 V, 1000 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed circuit board	50805C	RTG		
C0 (C2)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-325	-80
C1A (C1)		Capacitor, 10uF, 10%, 35V, X5R, 1206 / "Can use 1210"	GMK316BJ106KL-T	Taiyo Yuden	434	164
C1B (C2)	NI	Capacitor, 10uF, 10%, 35V, X5R, 1206 / "Can use 1210"	GMK316BJ106KL-T	Taiyo Yuden	568	164
C1C		Capacitor, 150uF, 20%, 50V,ELECT,10mm	EEU-FM1H151	Panasonic		
C2A (C5)	NI	Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	-386	129
C2B		Capacitor, 220 uF, 20%, 20V, Al, Polymer, 8m D, 3.5m Sp	PLV1DZZ1	Nichicon	-485	110
C2C (C3)	NI	Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	-574	129
C3 (C6)		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	76	-84
C4	*	Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	326	183
C6		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	-711	457
C7	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	-409	-606
D0		Diode, Schottky, 3A, 40V, SMB / "Can use SMC"	B340B	Diodes Inc.	230	679
D1		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	608	409
D2	N/A	"Do Not Use"			288	-136
D3	N/A	"Do Not Use"			152	-91
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	0	-700
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-771	38
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	771	146
L0		Inductor, 4.7u, 20%, 9.71A, 10.5m Ohms, 12 mm sq	DR125-4R7-R	Cooper	-304	554
Q0		NFET, 12A, 60V, 104m Ohms, Logic Level, DPAK	NTD3055L104T4G	ON Semi	124	247
R0		Resistor,130m Ohms, 1%, 250 mW, 0805	RL1200S-R13F	Susumu	-179	-23
R1A		Resistor, 100m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR100	Rohm	-269	141
R1B		Resistor, 100m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR100	Rohm	-179	141
R1C		Resistor, 100m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR100	Rohm	-89	141
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-414	-249
R3		Resistor, 210K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2103V	Panasonic	-481	-557
R4		Resistor, 6.98K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6981V	Panasonic	-481	-368
R5		Resistor, 464K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4643V	Panasonic	353	519
R6A (R11)	N/A	"Do Not Use"			219	-118
R6B (D4R)		Jumper, 0402	RMCF0402ZT0R00	Stackpole	-173	-181
R6C (R10)	N/A	"Do Not Use"			-400	-102
R7	?*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-338	-680
U0		Boost Reg, HV input, HV output	906	RTG	0	-315
U1		NFET, Dual, 115mA, 60V, 2V Vgs, SOT-363	2N7002DW	Fairchild	-384	-463

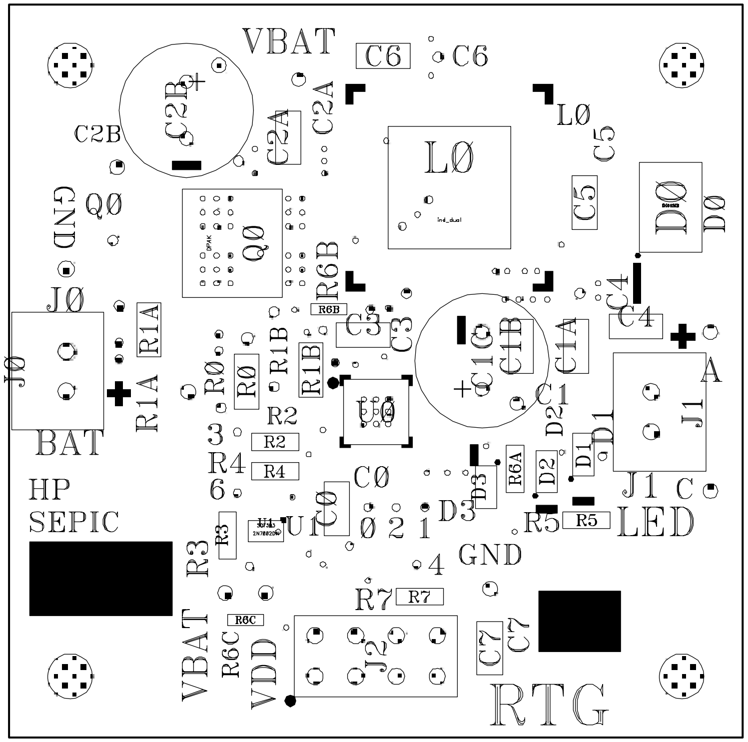
Options	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

50806 Application Board – 906 SEPIC Topology with External FET



50806 Schematic

50806 Application Board



50806
1.8 x 1.8 Inches
Scale: 2.125x

ML-50806-01

906 part, SEPIC w Ext FET, coupled inductor
VBAT 5.4 to 15 2 LED, 6.4 V, 1000 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed Circuit Board, 1.8 X 1.8 inches	50806D	RTG		
C0		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-96	-338
C1A		Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can use 1206"	GRM21BR61C106KE15L	Murata	491	61
C1B		Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can use 1210"	GRM21BR61C106KE15L	Murata	356	61
C1C	NI	Capacitor, 100uF, 20%, 16V, Al Polymer, 8m D, 3.5m Sp	RR71C101MDN1	Nichicon	260	25
C2A		Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can use 1210"	GRM21BR61C106KE15L	Murata	-215	572
C2B	NI	Capacitor, 100uF, 20%, 16V, Al Polymer, 8m D, 3.5m Sp	RR71C101MDN1	Nichicon	-465	640
C3		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	-31	88
C4		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	638	109
C5		Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can use 1206"	GRM21BR61C106KE15L	Murata	512	413
C6	NI	Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can use 1210"	GRM21BR61C106KE15L	Murata	18	774
C7	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	279	-681
D0		Diode, Schottky, 2A, 40V, SMA / "Can use SMB or SMC"	B240A	Diodes Inc.	723	402
D1		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	508	-205
D2	N/A	"Do Not Use"			419	-247
D3	N/A	"Do Not Use"			270	-285
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	-781	-1
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	696	-100
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	0	-700
L0		Inductor, dual, 3.3u, 20%, 2.7A, 36.6m Ohms, 7.6mm sq	DRQ74-3R3-R	Cooper	180	450
Q0		NFET, 12A, 60V, 104m Ohms, Logic Level, DPAK	NTD3055L104T4G	ON Semi	-353	313
R0		Resistor, 130m Ohms, 1%, 250 mW, 0805	RL1220S-R13-F	Susumu	-317	-26
R1A		Resistor, 91m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR091	Rohm	-557	101
R1B		Resistor, 91m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR091	Rohm	-160	2
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-248	-174
R3		Resistor, 105K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1053V	Panasonic	-364	-403
R4		Resistor, 2.49K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2491V	Panasonic	-248	-246
R5		Resistor, 37.4K Ohms, 1%, 100 mW, 0603	ERJ-3EKF3742V	Panasonic	517	-366
R6A	N/A	"Do Not Use"			341	-241
R6B		Jumper, 0402	RMCF0402ZT0R00	Stackpole	-115	151
R6C	N/A	"Do Not Use"			-320	-611
R7	*	Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	107	-554
U0		Boost Reg, HV input, HV output	906	RTG	0	-100
U1		NFET, Dual, 115mA, 60V, 2V Vgs, SOT-363	2N7002DW	Fairchild	-270	-393

Options	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

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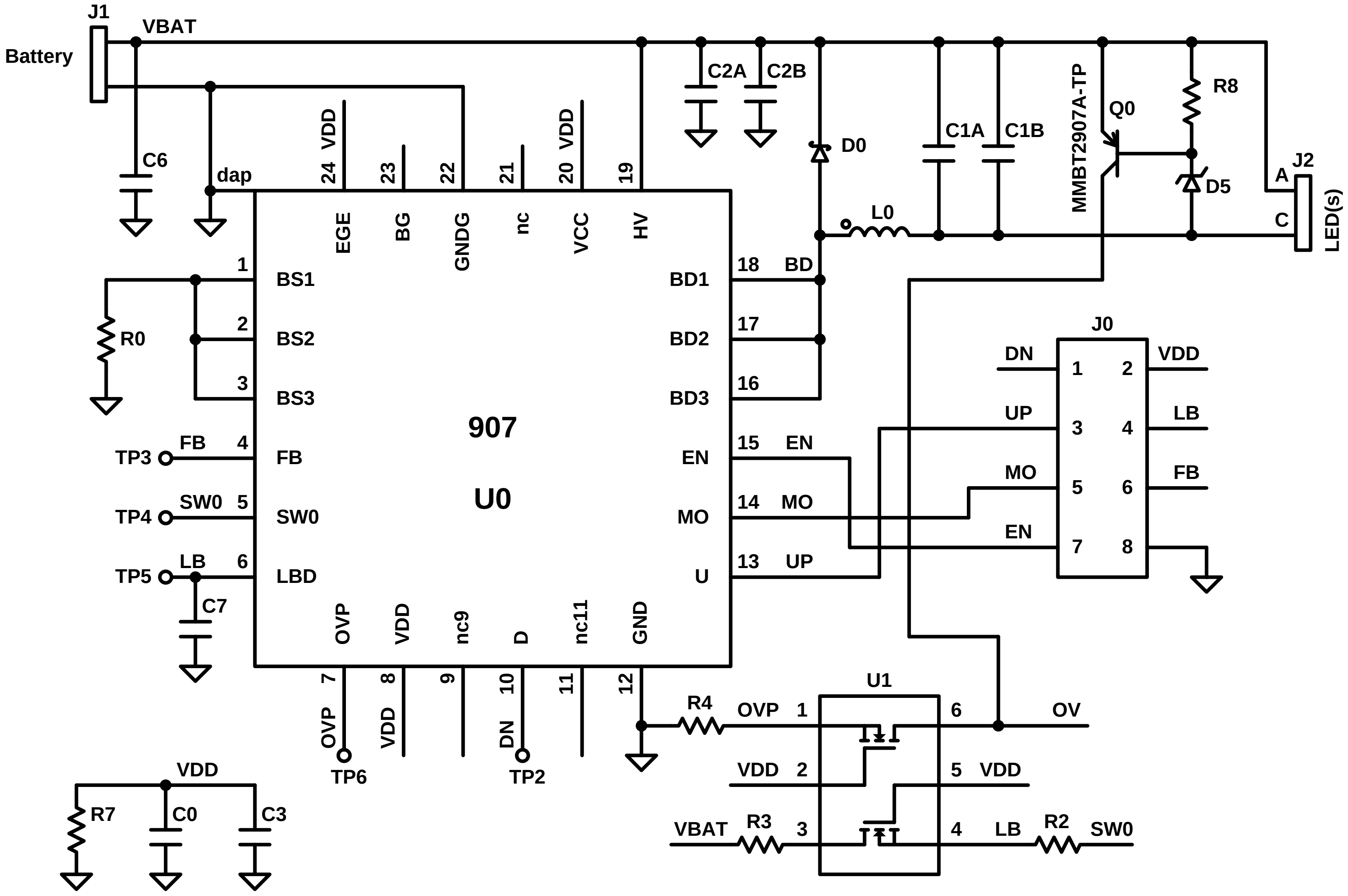
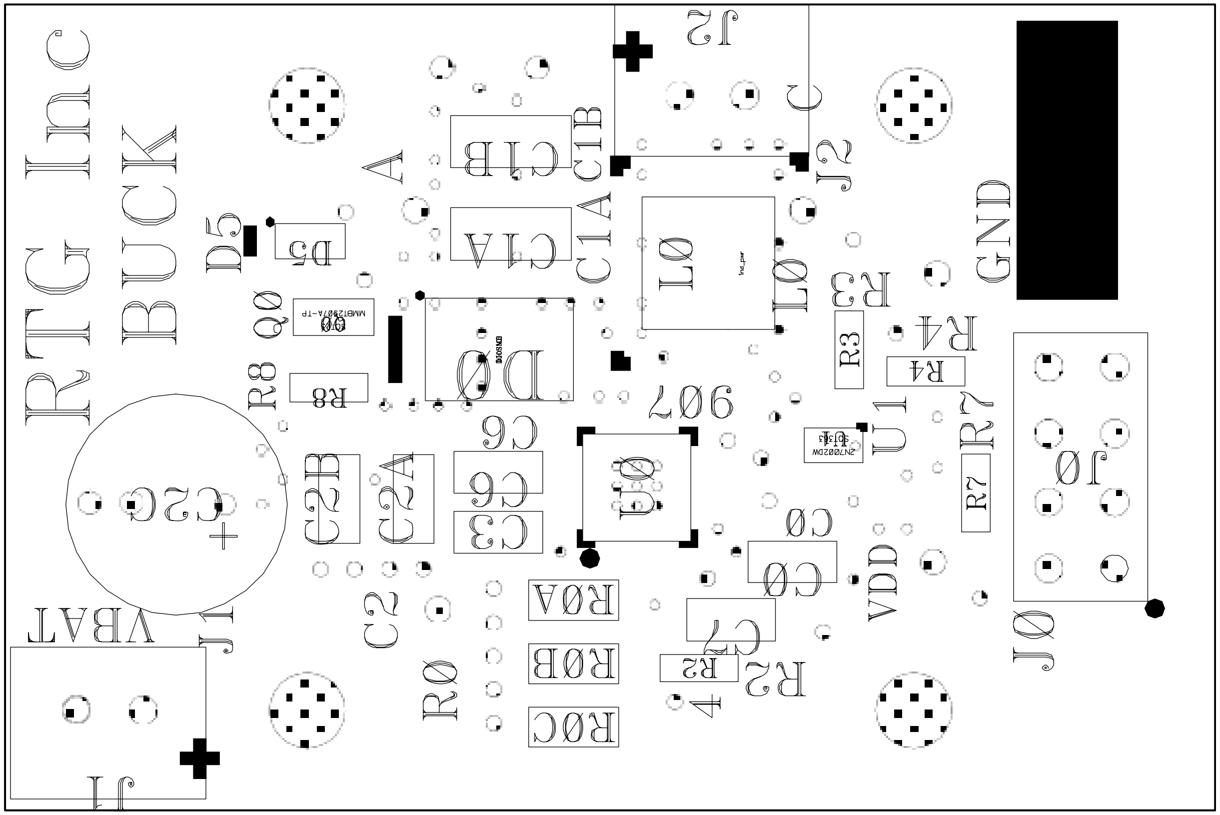
50807 Application Board – 907 Buck Topology



50807 Schematic

50807 Application Board



50807
1.2 x 1.8 Inches
Scale 3.5x

ML-50807-01

907 part, Buck
VBAT 5.4 to 15 1 LED, 3.3 V, 720 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed Circuit Board, 1.2 X 1.8 inches	50807C	RTG		
C0 (C6)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-231	-271
C1A (C1)		Capacitor, 47uF, 20%, 10V, X5R, 1206 / "Can Use 1210"	GRM31CR61A476ME15L	Murata	258	147
C1B	NI	Capacitor, 47uF, 20%, 10V, X5R, 1206 / "Can Use 1210"	GRM31CR61A476ME15L	Murata	478	-185
C2A (C3)		Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can Use 1206"	GRM21BR61C106KE15L	Murata	-137	282
C2B	NI	Capacitor, 10uF, 10%, 16V, X5R, 0805 / "Can Use 1210"	GRM21BR61C106KE15L	Murata	-137	398
C3 (C0)		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	-186	156
C6 (C5)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-97	156
C7 (R2/C6)	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	-317	-181
D0		Diode, Schottky, 3A, 40V, SMB	B340B-13-F	Diodes Inc.	86	165
D5		Diode, Zener, 1mA, 5.1V, SOD323	MM3Z5V1C	Fairchild	247	446
J0	*	Header, 8 pos, 2 row, 0.1 spc / "Required for ext cntrl brd"	67996-108HLF	FCI	-90	-700
J1	NI	Connector, XH-2, Top	B2B-XH-A	JST	2	656
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	471	159
L0		Inductor, 4.7u, 30%, 0.29 Ohms, 3.3A, 5mm / "Up to 7.6 mm"	NR5040T4R7N	Taiyo Yaun	242	-148
Q0		Transistor, PNP, 60V, 600 mA, SOT23	MMBT2907A-TP	Micro	134	411.5
R0		Resistor, 110m Ohms, 1%, 250 mW, 0805	RL1220S-R11-F	Susumu	-287	54
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-389	-133
R3		Resistor, 105K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1053V	Panasonic	86	-356
R4 (R6)		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	53	-470
R7 (C6)		Resistor, 10.0M Ohms, 1%, 100 mW, 0603	CRCW060310MKFEA	Vishay/Dale	-128	-544
R8 (R1)		Resistor, 1K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1001V	Panasonic	29	418
U0		Buck Reg, HV input, HV output	907	RTG	-120	-40
U1		NFET, Dual, 115mA, 60V, 2V Vgs, SOT-363	2N7002DW	Fairchild	-57	-332.4

Options		
	*	Included, but not necessary
	NI	Not Included, optional part
	N/A	NOT ALLOWED in this configuration

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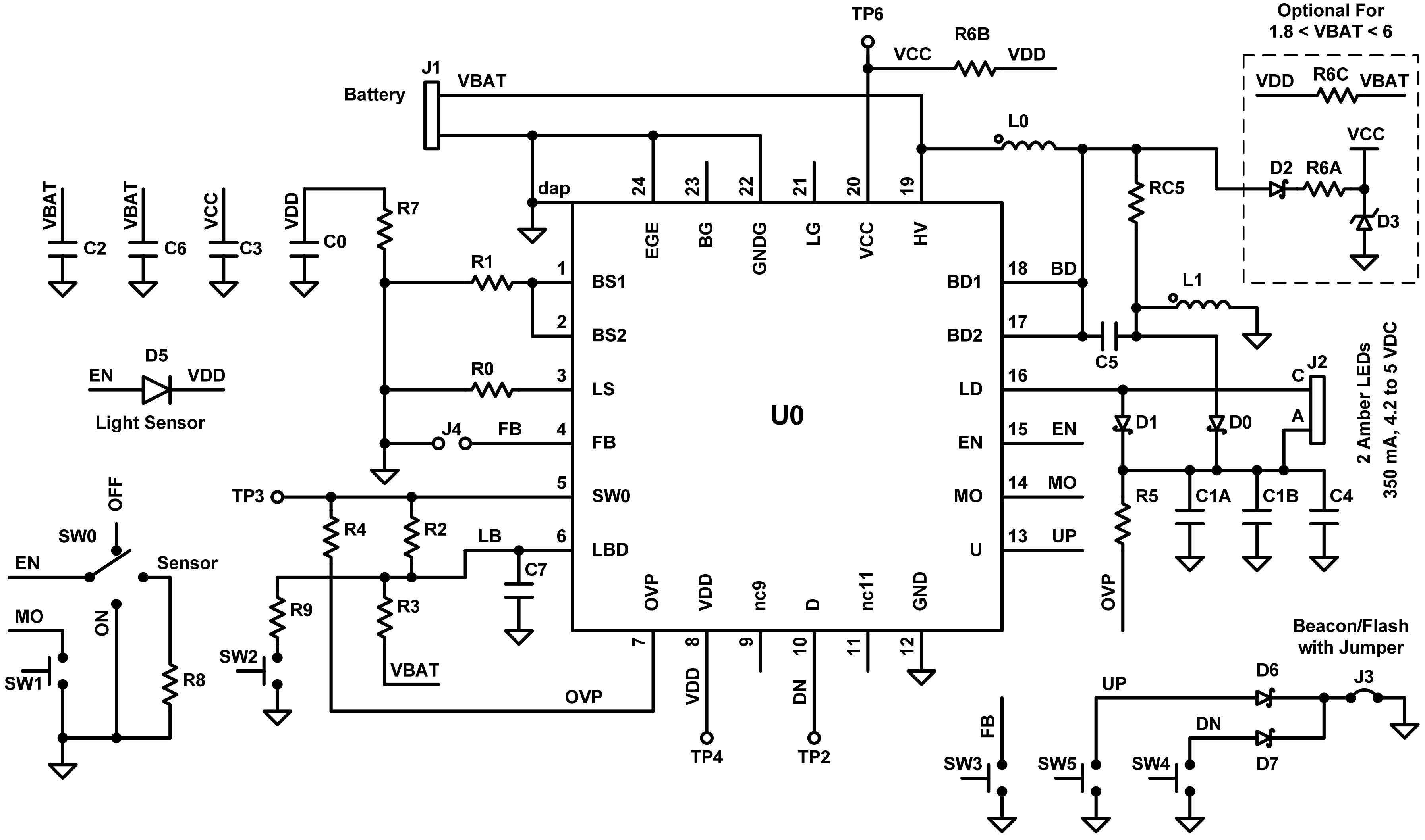
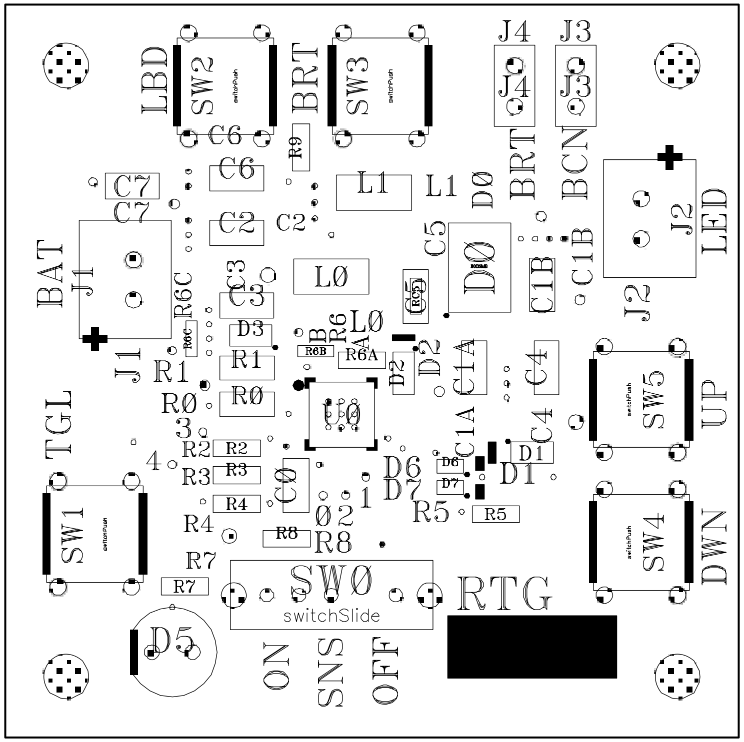
50808 Application Board - SEPIC Topology



50808 Schematic

50808 Application Board



50808
1.8 x 1.8 Inches
Scale: 2.125x

ML-50808-01

904 part, SEPIC, w uncoupled inductors VBAT 1.8 to 6.5 1LED, 3.2V, 360 mA

Ref Des	Opt	Part Description / Comment	Part Number	Manufacture	X	Y
		Printed Circuit Board, 1.8 X 1.8 inches	50808C	RTG		
C0 (C8)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	-186	-281
C1A (C1)		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	251	9
C1B (C4)	NI	Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	417	211
C2 (C5)		Capacitor, 10uF, 10%, 10V, X5R, 0805 / "Can use 1210"	GRM21BR61A106KE19L	Murata	-332	339
C3 (C6)		Capacitor, 100nF, 10%, 50V, X7R, 0805	GRM21BR71H104KA01L	Murata	-307	161
C4 (C2)		Capacitor, 10nF, 10%, 50V, X7R, 0805	08055C103KAT2A	AVX	363	9
C5 (C3)		Capacitor, 10uF, 10%, 16V, X5R, 0805	GRM21BR61C106KE15L	Murata	107	184
C6 (C7)	NI	Capacitor, 10uF, 10%, 10V, X5R, 0805 / "Can use 1210"	GRM21BR61A106KE19L	Murata	-332	473
C7 (C0)	*	Capacitor, 10nF, 10%, 50V, X7R, 0805 / "fltrs LBD pin"	08055C103KAT2A	AVX	-589	454
D0		Diode, Schottky, 3A, 40V, SMB	B340B	Diodes Inc.	263	254
D1 (D3)		Diode, Schottky, 40V, 1A pulsed, SOD323	NSR0240HT1G	ON Semi	387	-201
D2 (D4)		Diode, Standard, 75V, 100mA, SOD323	1N4448WS	Fairchild	78	-5
D3 (D5)		Diode, Zener, 6.2V ±2% 200MW SOD-323F	MM3Z6V2B	Fairchild	-298	87
D5 (D1)	*	Diode, Ambient Light Sensor, 20mA, 5V, LED5mm	TEPT5600	Vishay	-483	-690
D6	*	Diode, Schottky, 200mA, 30V, SOD523	BAT54WX-TP	Micro Commercial	192	-234
D7	*	Diode, Schottky, 200mA, 30V, SOD523	BAT54WX-TP	Micro Commercial	192	-286
J1	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	-606	224
J2	NI	Connector, XH-2, Top	B2B-XH-A(LF)(SN)(P)	JST	681	374
J3	*	Header, 2 pos, Straight, head 0.230, tail 0.120	90120-0122	Molex	500	700
J4	*	Header, 2 pos, Straight, head 0.230, tail 0.120	90120-0122	Molex	350	700
L0		Inductor, 2.2u, 20%, 150M, 0.065 Ohms, 1.85 A	BRL3225T2R2M	Taiyo Yuden	-100	233
L1		Inductor, 4.7u, 20%, 120M, 0.18 Ohms, 1.3 A	BRL3225T4R7M	Taiyo Yuden	5	450
R0		Resistor, 500m Ohms, 1%, 250 mW, 0805	RL1220S-R50-F	Susumu	-306	-82
R1		Resistor, 68m Ohms, 1%, 250 mW, 0805	MCR10EZHFSR068	Rohm	-306	8
R2		Resistor, 10.0K Ohms, 1%, 100 mW, 0603	ERJ-3EKF1002V	Panasonic	-332	-190
R3		Resistor, 28.7K Ohms, 1%, 100 mW, 0603	ERJ-3EKF2872V	Panasonic	-332	-256
R4		Resistor, 6.98K Ohms, 1%, 100 mW, 0603	ERJ-3EKF6981V	Panasonic	-332	-326
R5		Resistor, 48.7K Ohms, 1%, 100 mW, 0603	ERJ-3EKF4872V	Panasonic	303	-351
R6A (R10)		Resistor, 475 Ohms, 1%, 100 mW, 0603	ERJ-3EKF4750V	Panasonic	-25	26
R6B (DR2)	N/A	"Do Not Use"			-138	49
R6C (R13)		Jumper, 0402	RMCF0402ZT0R00	Stackpole	-444	79
R7	*	Resistor, 10.0M Ohms, 1%, 100.00mW, Thick Film	CRCW060310MKFEA	Vishay/Dale	-460	-529
R8		Resistor, 10.0K Ohms, 1%, 250mW, Thick Film	ERJ-3EKF1002V	Panasonic	-209	-411
R9		Resistor, 100 Ohms, 1%, 250mW, Thick Film	ERJ-3EKF1000V	Panasonic	-174	549
RC5 (C3R)	N/A	"Do Not Use"		Stackpole	107	184
SW0		Switch, Slide, SP3T, Termination: pin	OS103011MS8QP1	C&K	-99	-550
SW1		Switch, Tact MOM 100g	B3F-1000	Omron	-680	-400
SW2		Switch, Tact MOM 100g	B3F-1000	Omron	-360	715
SW3		Switch, Tact MOM 100g	B3F-1000	Omron	20	715
SW4		Switch, Tact MOM 100g	B3F-1000	Omron	660	-420
SW5		Switch, Tact MOM 100g	B3F-1000	Omron	660	-70
U0		Boost Reg, LV input, LV output, Low Rdson	904	RTG	-75	-106

Options

*	Included, but not necessary
NI	Not Included, optional part
N/A	NOT ALLOWED in this configuration

Measured Data

This section presents measured data from the application boards with discussion of the features of the 904-907 products and the representative topologies. Some measurements are taken at varying component values to show design trade-offs. Measurements taken at more than one component value are indicated in the corresponding graph. Measurement groups are ordered by board number as follows: 80804-01, 80804-02, 80804-03, 80805-01, 80805-02, 80806-01, 80807-01, and 80808-01.

Measurements are presented in the following order:

- Log(Input Current) vs Brightness Setting
- Beacon Supply Current Measurements
- Input Current vs V_{BAT} at Maximum Brightness
- LED Current vs V_{BAT} at Maximum Brightness
- Bootstrapped V_{CC} and V_{BS} vs Time

Log(Input Current) vs Brightness Setting

Current measurements were taken with an Agilent 34401A. The battery voltage was measured at the application board. Measurements were taken across all brightness settings with 1 being the lowest and 15 being the highest brightness setting. Graph below has input current plotted in a logarithmic scale.

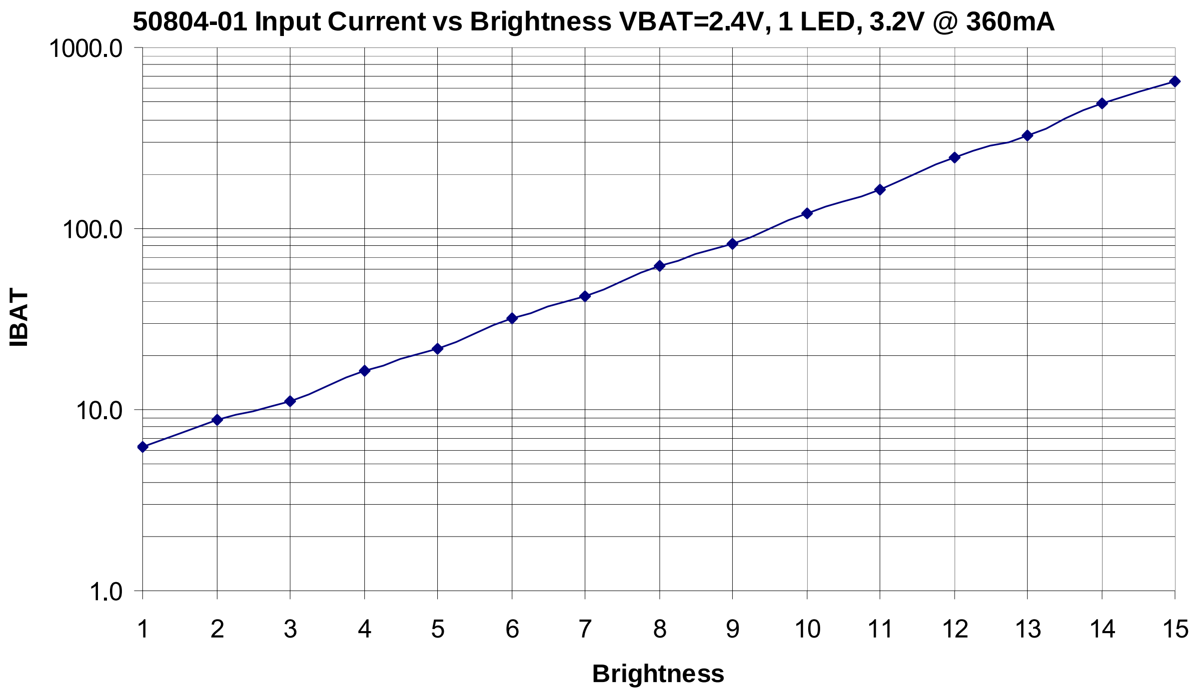


Table with Input Current vs Brightness setting for each application board:

	App Brd	50804-01 VBAT = 2.4	50804-02 VBAT = 2.4	50804-03 VBAT = 4.8	50805-01 VBAT = 4.8	50805-02 VBAT = 12	50806-01 VBAT = 4.8	50807-01 VBAT = 6.5	50808-01 VBAT = 4.8
Input Current (mA) vs Brightness Setting	1	6.3	6.0	8.7	20	240	6.5	4.8	4.4
	2	8.8	8.5	12.3	30	250	9.9	6.3	5.6
	3	11.3	11.0	16.4	40	270	12.7	8.1	6.9
	4	16.3	16.0	23.2	50	300	18.9	11.6	10.0
	5	21.9	21.0	30.8	70	320	25.0	15.3	12.5
	6	31.9	31.0	45.5	110	350	37.0	22.9	18.8
	7	41.9	41.0	60.0	140	400	49.0	30.5	23.1
	8	61.9	60.0	89.2	220	480	69.0	46.3	34.4
	9	83.1	80.0	117.5	280	560	98.0	63.3	45.0
	10	123.0	120.0	176.5	430	730	146.0	87.9	66.3
	11*	163.0	160.0	234.5	540	870	192.0	114.1	90.0
	12	245.0	241.0	348.8	860	1230	287.0	169.3	134.4
	13	325.0	320.0	464.8	1140	1530	375.0	223.4	175.0
	14	490.0	480.0	697.3	1710	2170	566.0	330.8	261.3
	15	648.0	640.0	921.5	2280	2750	735.0	436.7	350.6

* Default brightness

Beacon Supply Current Measurements

Beacon supply current for each application board at maximum and default brightness was calculated and measured. Measurements for high intensity flashing (HIF) and low intensity flashing (LIF) are compared to calculated values using the equations from the Flash / Beacon section and shown below:

HIF $= 0.142 * I_{in} + 1.5$ mA (fresh battery)
$= 0.106 * I_{in} + 1.5$ mA (low battery)
LIF $= 0.035 * I_{in} + 1.5$ mA (fresh battery)
$= 0.026 * I_{in} + 1.5$ mA (low battery)

Supply current measurements were taken across a 0.01 ohm resistor going to an amplifier with a low pass filter that has a 68 second time constant. Additional filtering is provided by 10,000 uF capacitors that were placed on either side of the 0.01 ohm sense resistors. The large capacitors are mainly to prevent power supply transients induced by the beacon flash. A 15 minute stabilization time is required before measurement .

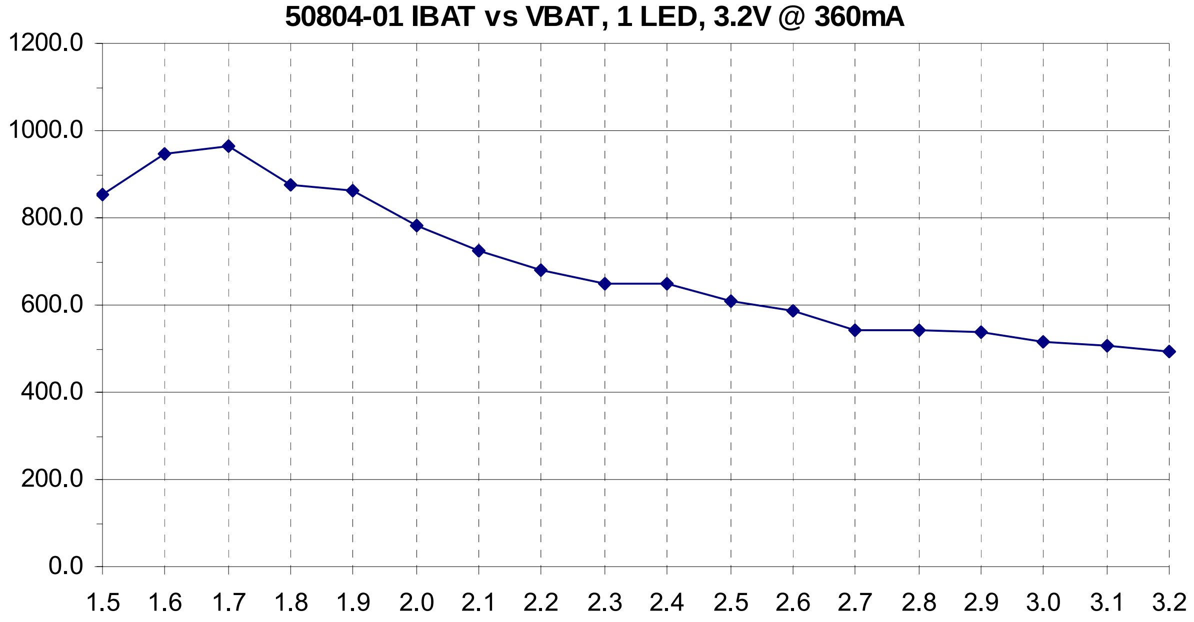
Flashing Beacon Supply Current

Application Board	Full Brightness Measured No Flash	LIF Calculated Flash	LIF Measured Flash	HIF Calculated Flash	HIF Measured Flash
50804-01, VBAT = 2.4	660	25	25	95	95
50804-02, VBAT = 2.4	770	28	29	111	111
50804-03, VBAT = 4.8	1020	37	38	146	148
50805-01, VBAT = 4.8	2520	90	93	359	360
50805-02, VBAT = 12	2930	104	110	418	420
50806-01, VBAT = 12	746	28	29	107	107
50807-01, VBAT = 12	233	10	11	35	36
50808-01, VBAT = 4.8	360	14	14	53	54

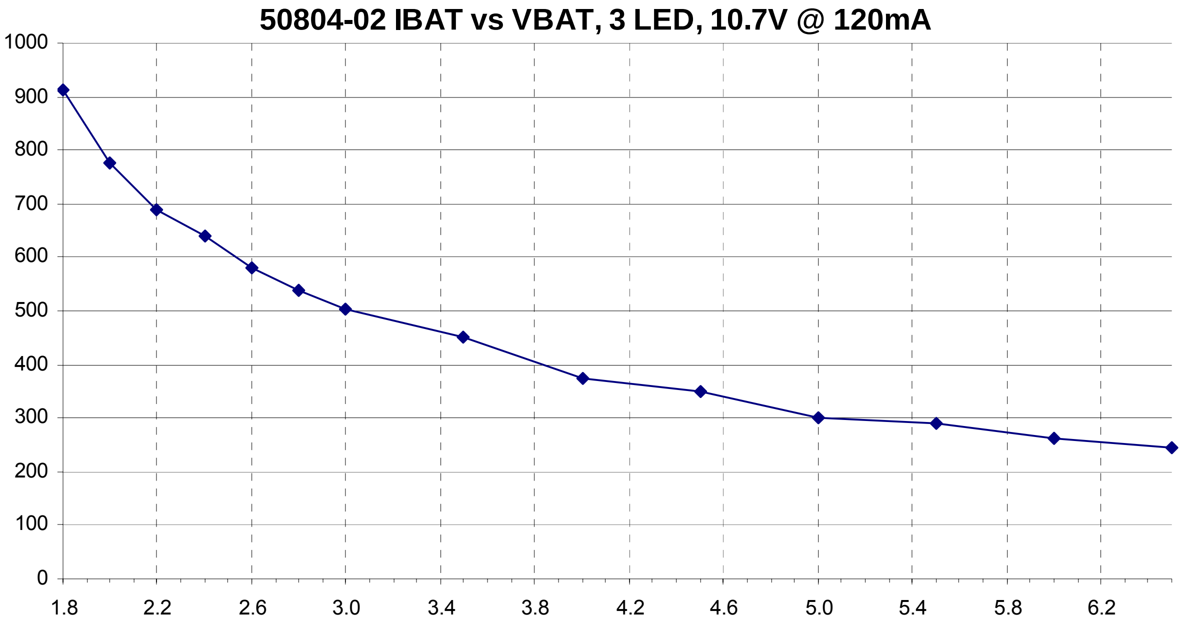
Input Current vs VBAT at Maximum Brightness

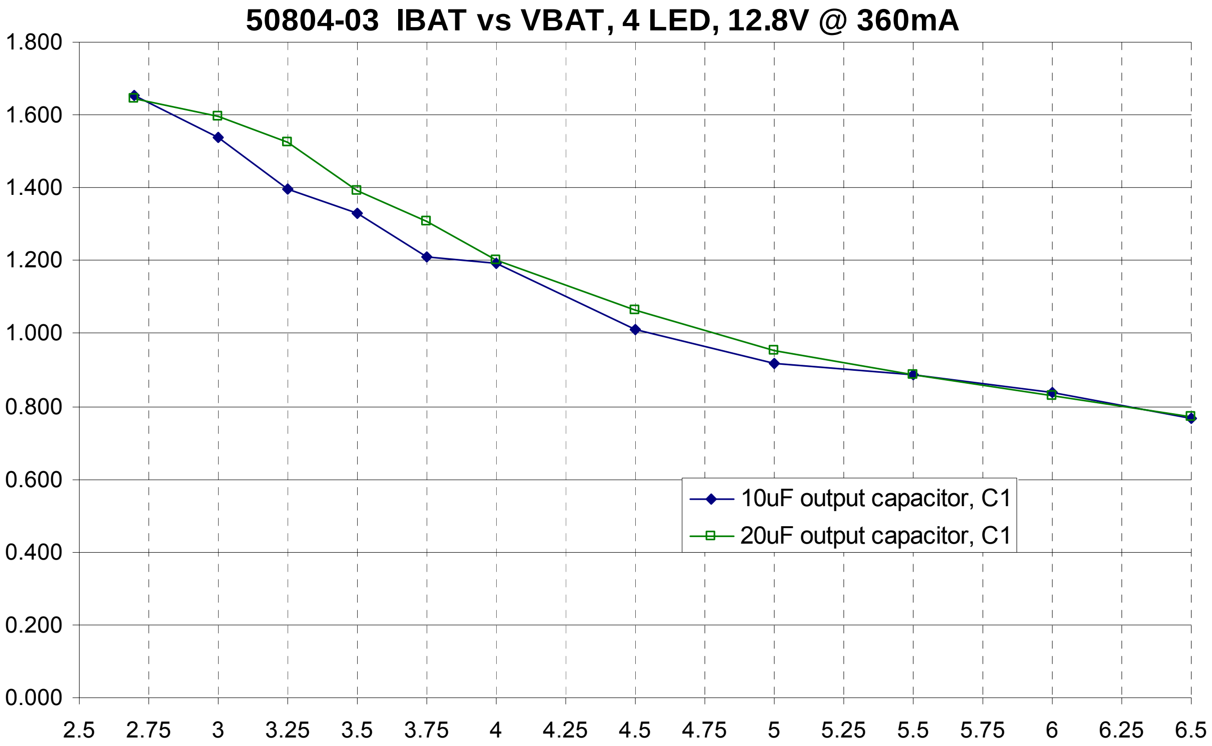
These measurements were made with the low battery warning and shut-off feature disabled by tying the LBD pin to VDD. Transient response of the power supply may require a large bypass capacitor to be added to the input pins of the application board.

The 50804-01 board has measurements below the specified operating range to show the effects of insufficient battery voltage.

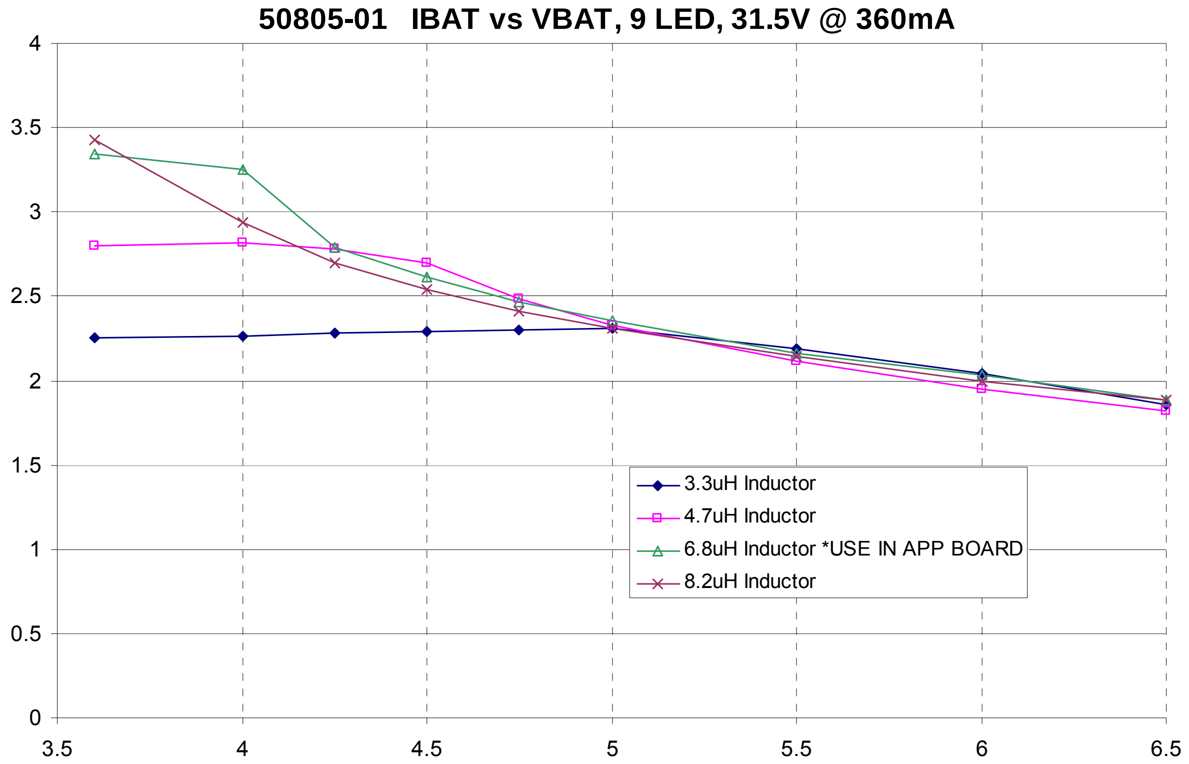


In the 50804-01 graph above the input current drops when VBAT is below 1.7V. This is because the boost regulator is not capable of providing enough current at these lower battery voltages. The LED current drops below the regulation point, the output power is reduced and the input power drops. See 50804-01 LED current vs VBAT (shown later).

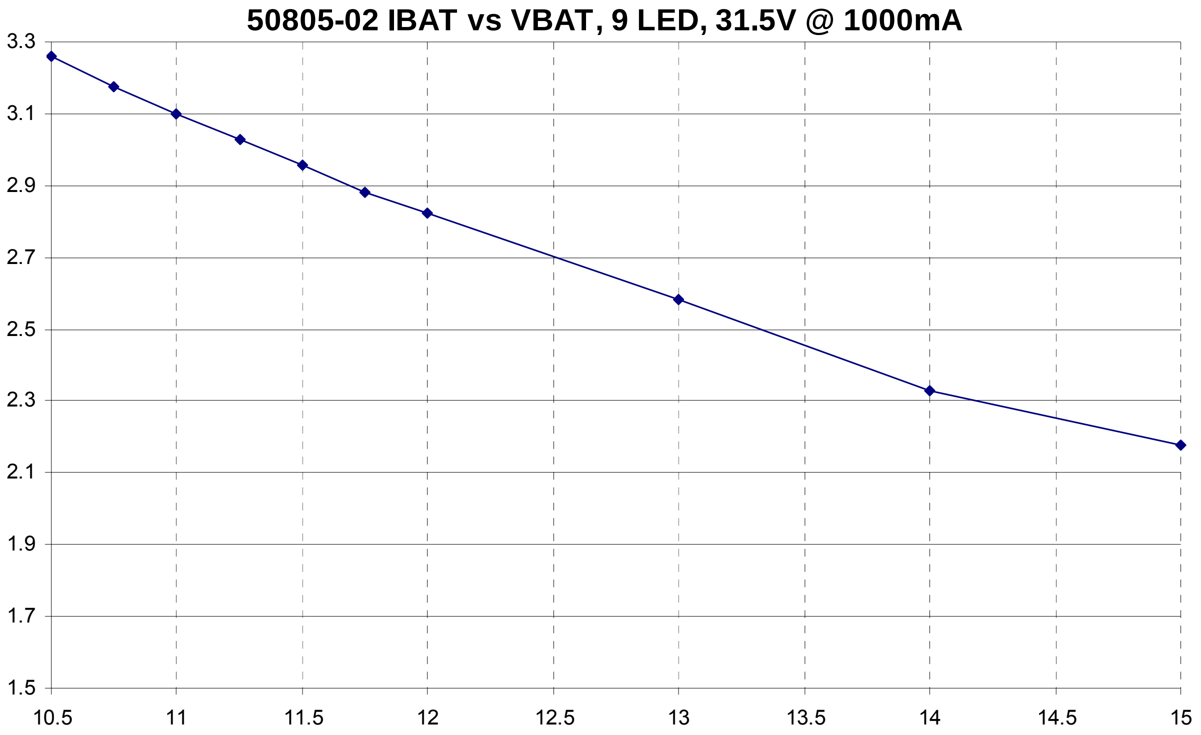




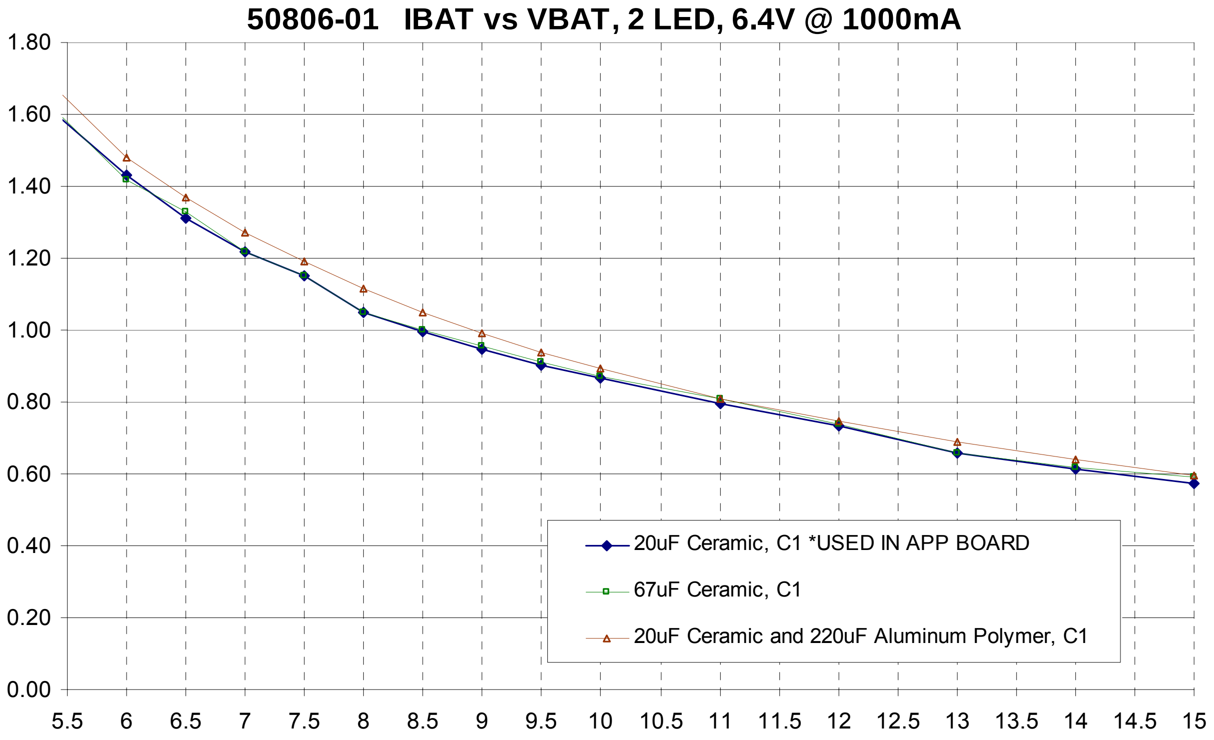
The 50804-03 graph above compares a C1 output capacitance of 10uF to 20uF.



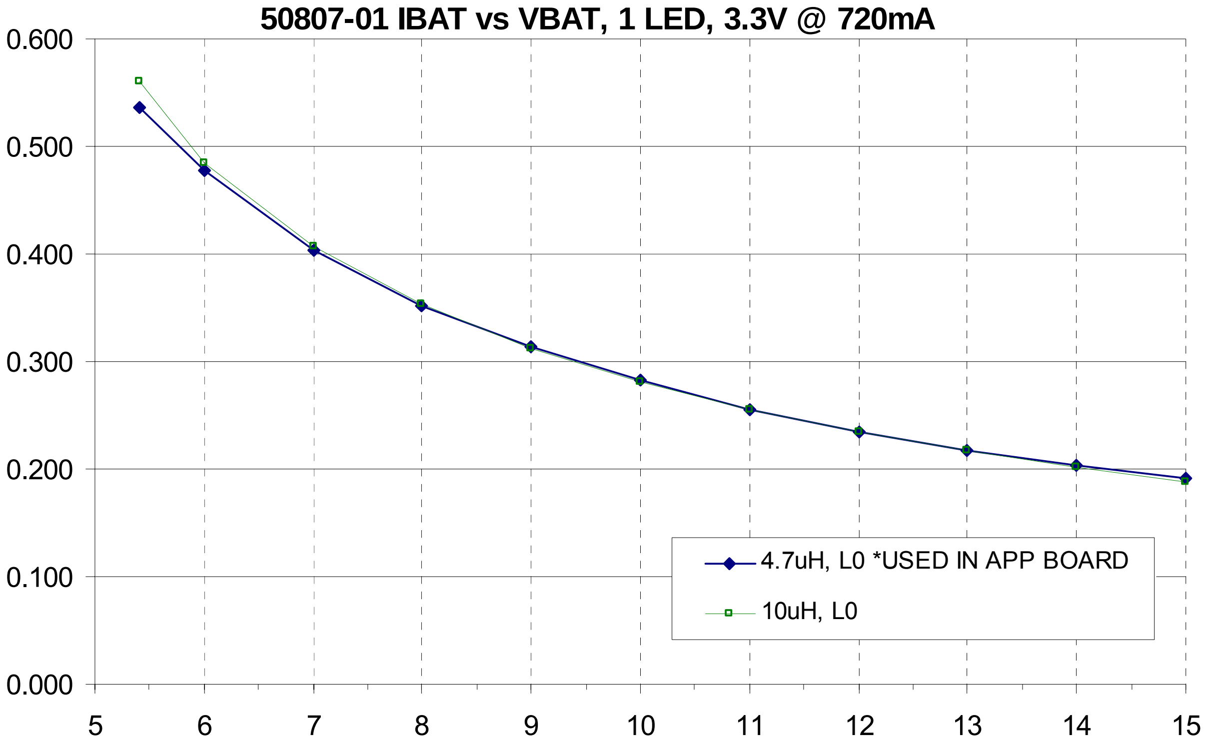
The 50805-01 graph above shows battery current with respect to different inductor values, L0. For the values of 3.3uH and 4.7uH, the battery current levels off below 5V and 4.5V respectably. This is because these inductor values do not provide enough input power for the circuit losses and LED output (see design Example 5: 50805-01 discussion for more details). The 6.8uH inductor is used for the 50805-01 application board. The small rise at 4V for the 6.8uH inductor is the transition point between the boost converter running continuously and the boost intermittently running to regulate the LED current. The 8.2uH inductor provides the best overall performance.

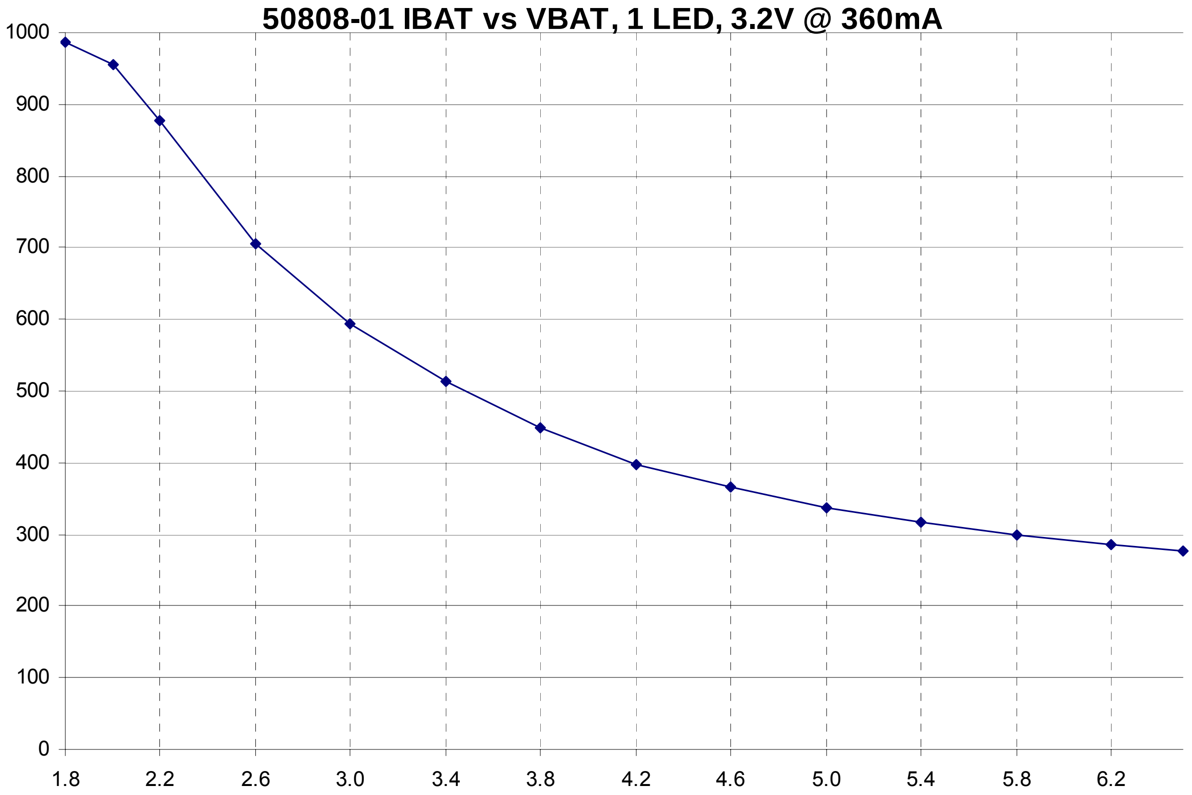


50805-02 IBAT vs VBAT, 9 LED, 31.5V @ 1000mA



50806-01 IBAT vs VBAT, 2 LED, 6.4V @ 1000mA

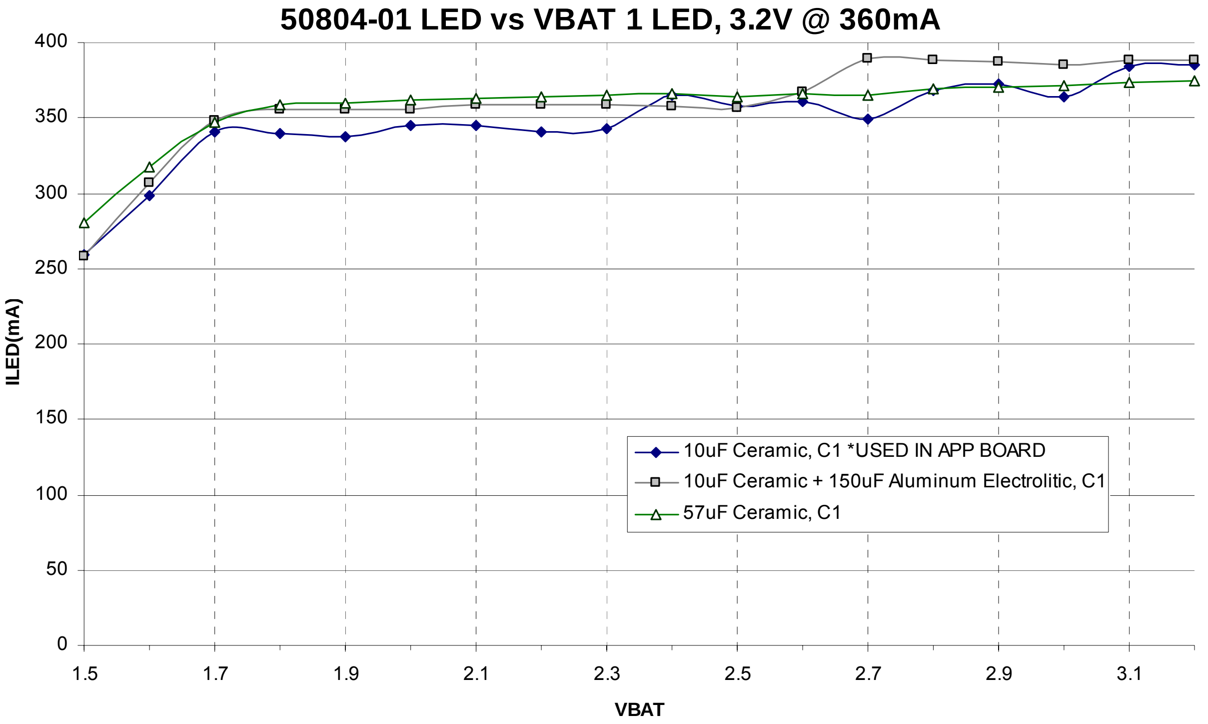




In the 50808-01 graph above the input current drops when VBAT is at 1.8V and below. This is because the boost regulator is not capable of providing enough current at these lower battery voltages.

ILED vs VBAT at Maximum Brightness

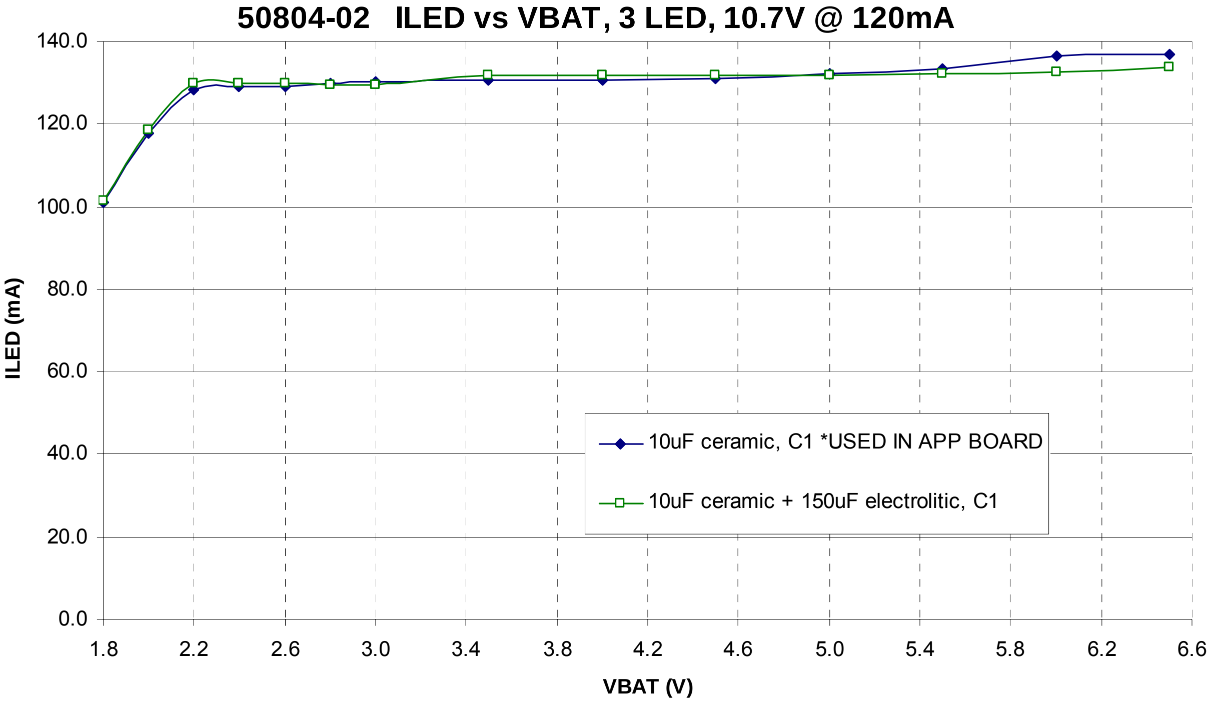
These measurements were made with the low battery warning and shut-off feature disabled by tying the LBD pin to VDD. Board 50804-01 has measurements below the operating range.



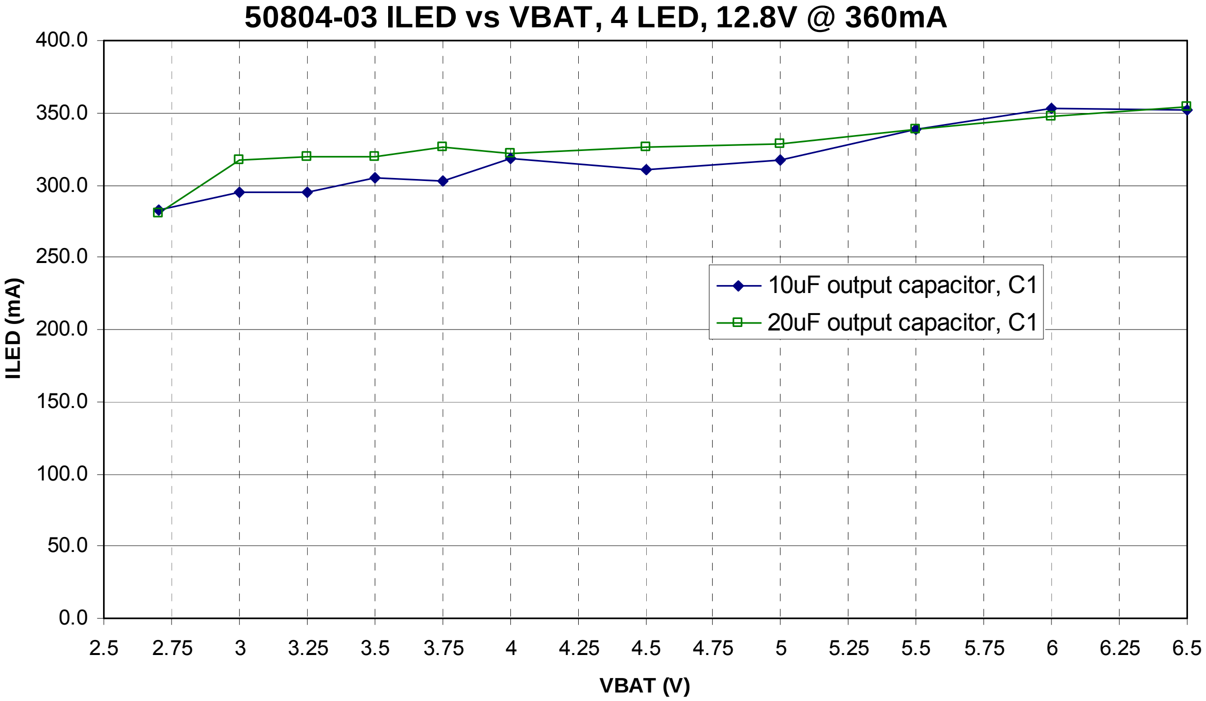
The graph above shows the LED current variation with three different output capacitors for C1. The variation is due to the ripple voltage at C1 coupling to the current sense point for the LED. Current through the LED is controlled using a comparator. When the current through the LED is above the regulation point, the boost circuit turns off and when it is below the threshold the boost circuit is on. The rate at which the inductor charges and discharges is dependent on VBAT. As VBAT increases the time it takes to charge up the inductor (and cycle period) decreases. If the LED current is sampled slightly below the comparator threshold the boost regulator will continue to run, causing the LED current to be higher than the regulation point. Similarly, if the LED current is sampled just above the comparator threshold the LED current will be lower. As the period varies with VBAT, there is a clock period rounding error which would make a period slightly longer or shorter, causing the LED current to slightly fluctuate as a function of VBAT.

Another issue to consider is that at high LED and inductor currents the voltage drop through the series Impedance on the output capacitors may be significant enough to affect the sense voltage at the LED comparator, which only has a 200mV reference. For example, the addition of a 150 µF aluminum electrolytic capacitor did not perform as well as the addition of a 47 µF ceramic capacitor (57 µF total). Although the total capacitance was less, the all ceramic capacitor filter capacitor resulted in less variation in the LED current.

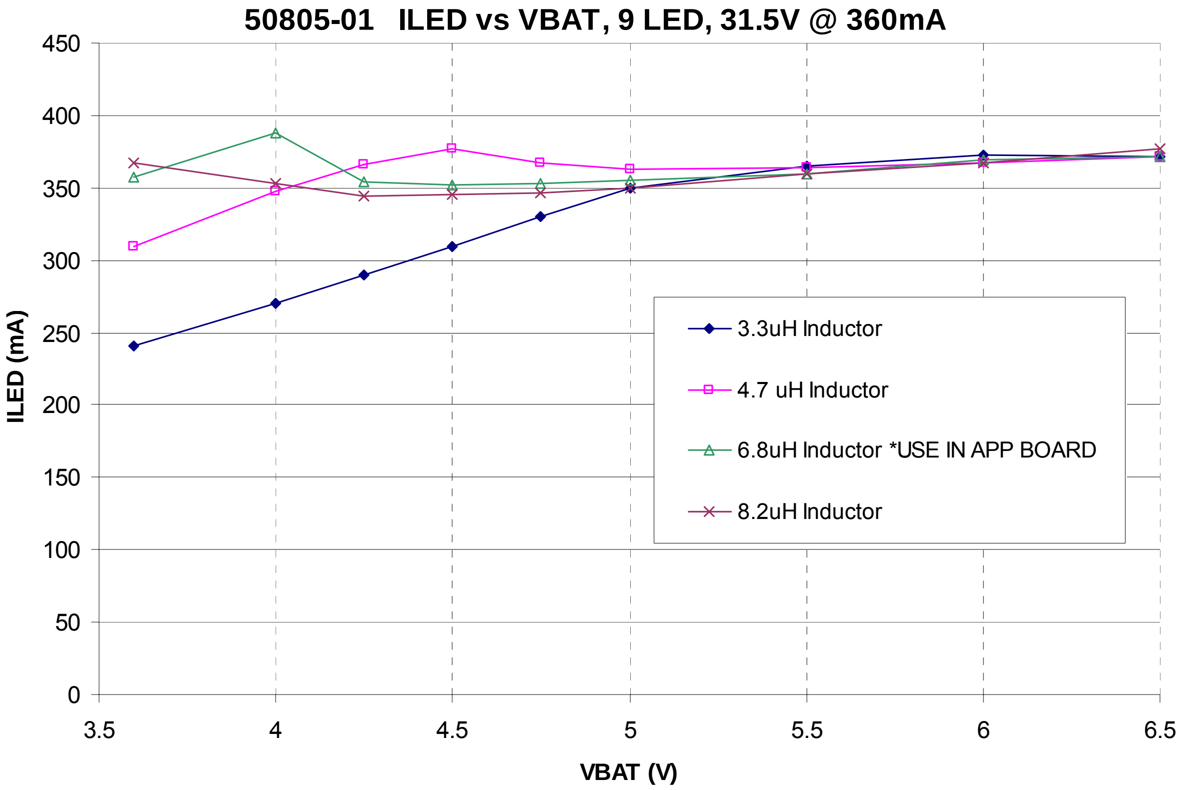
During testing, changes in LED brightness were not visible by the human eye. If changes in LED current are considered significant, increasing the capacitance at the output capacitor will smooth out the LED current and bring the current regulation point higher at the lower battery voltages.



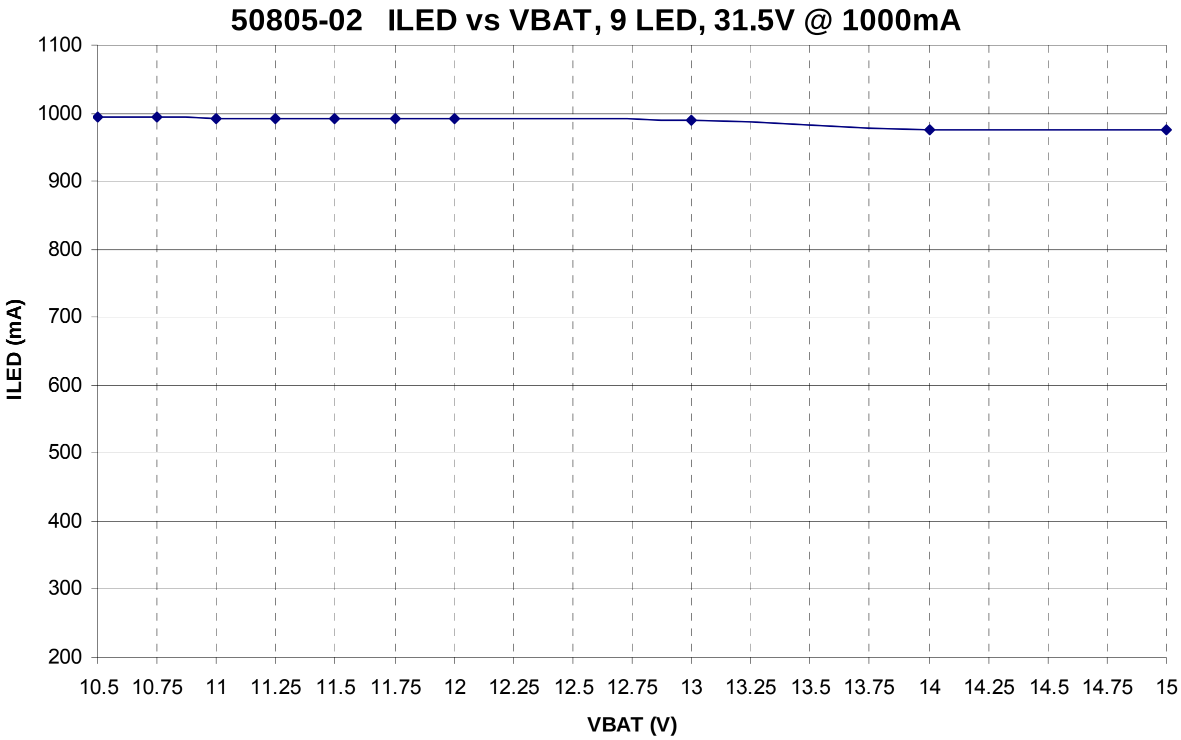
In the 50804-02 graph above the input current drops when VBAT is below 2.2V. This is because the boost regulator is not capable of providing enough current at these lower battery voltages.



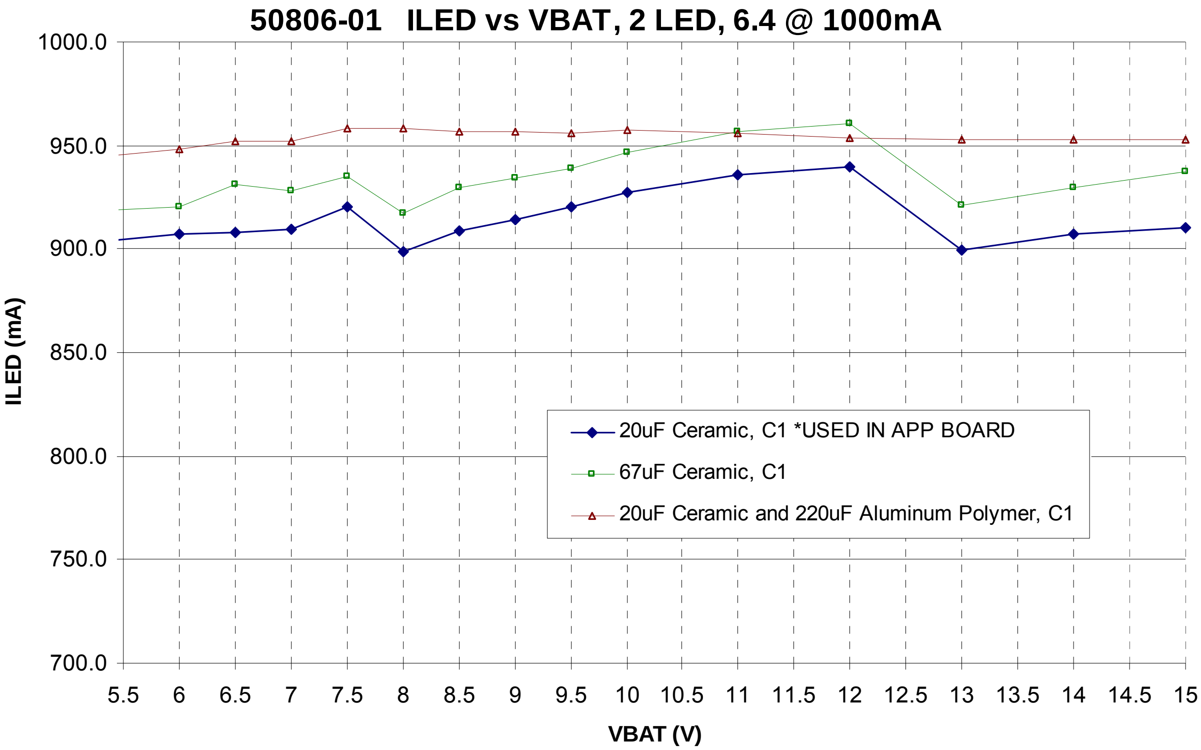
In the graph above, 50804-03, LED current is below regulation at lower battery voltages because we are limiting the peak current and average current in design (see design example 4: 50804-03). A 20uF capacitor at the output, C1, is used to smooth and raise the led current at lower battery voltages by lowering the ripple current though the LED into R0.



The 50805-01 graph above shows LED current with respect to different inductor values. For the values of 3.3uH and 4.7uH, the LED current drops off below 5V and 4.5V respectably. This is because these inductor values do not provide enough input power to accommodate for the circuit losses and LED output (see design Example 5: 50805-01 for more details). The 6.8uH inductor is used for 50805-01 application board. The small rise at 4V for the 6.8uH inductor is the transition point between the boost converter running continuously and the boost intermittently running to regulate the LED current. The 8.2uH inductor provides the best overall performance.

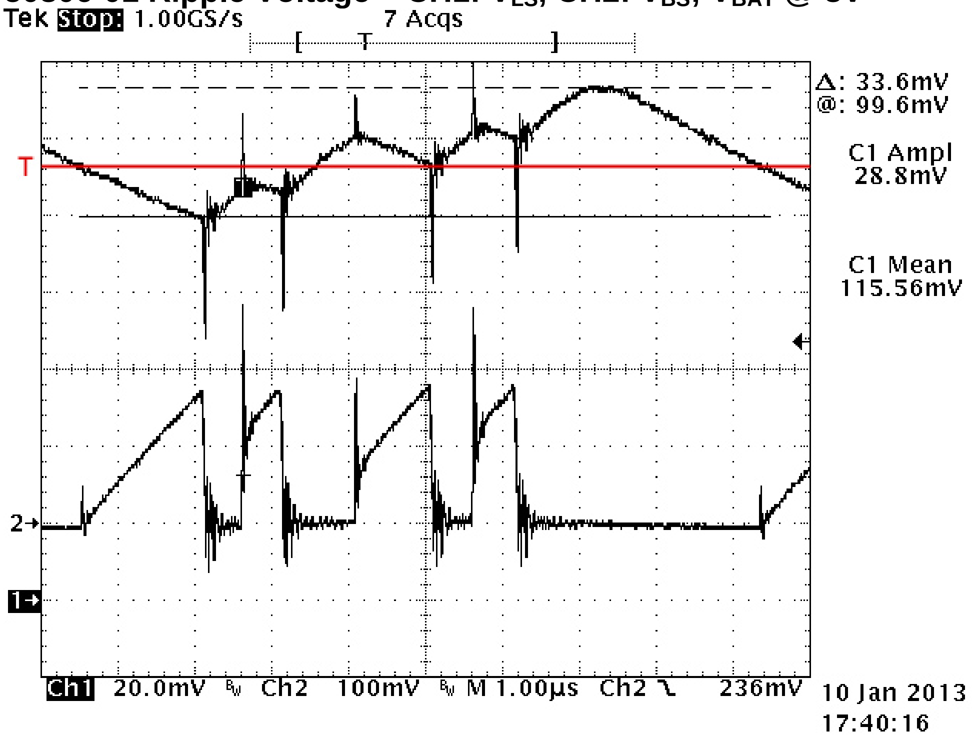


In the 50805-02 graph above, there is a small dip of 2%. This is due to the output ripple changing as a function of the boost cycle frequency. As VBAT increases the period frequency increases. Adding a larger output capacitor, C1 can decrease the output ripple. Losses associated with the inductor and FET also increase as VBAT increases.



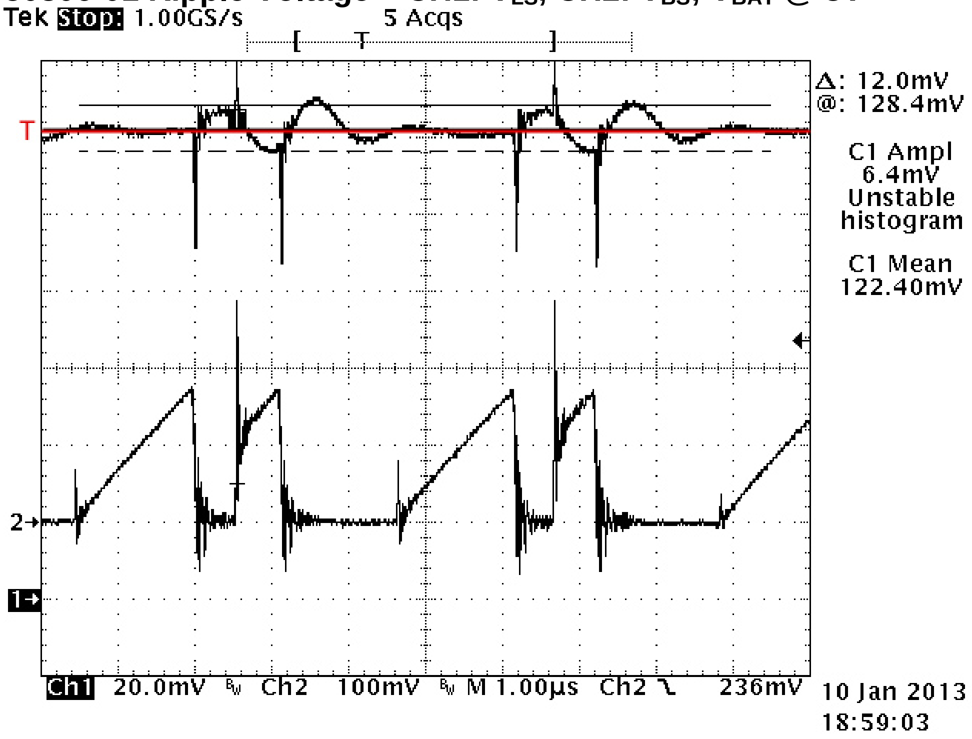
In the 50806-01 graph above, we can see fluctuations in LED current for the 20uF output capacitance. Fluctuations in LED current are caused by the SEPIC converter running intermittently due to output ripple voltage feeding though to the led current control circuit. An example of the ripple voltage with two different output capacitances is shown in the two figures below for comparison. If deemed significant, changes in LED current can be reduced by increasing the output capacitance as shown if the figure above. If LED current fluctuation over the operating voltage is acceptable, compensating for lower current regulation can be done by decreasing the value of R0.

50806-01 Ripple Voltage – CH1: V_{LS}, CH2: V_{BS}; V_{BAT} @ 8V

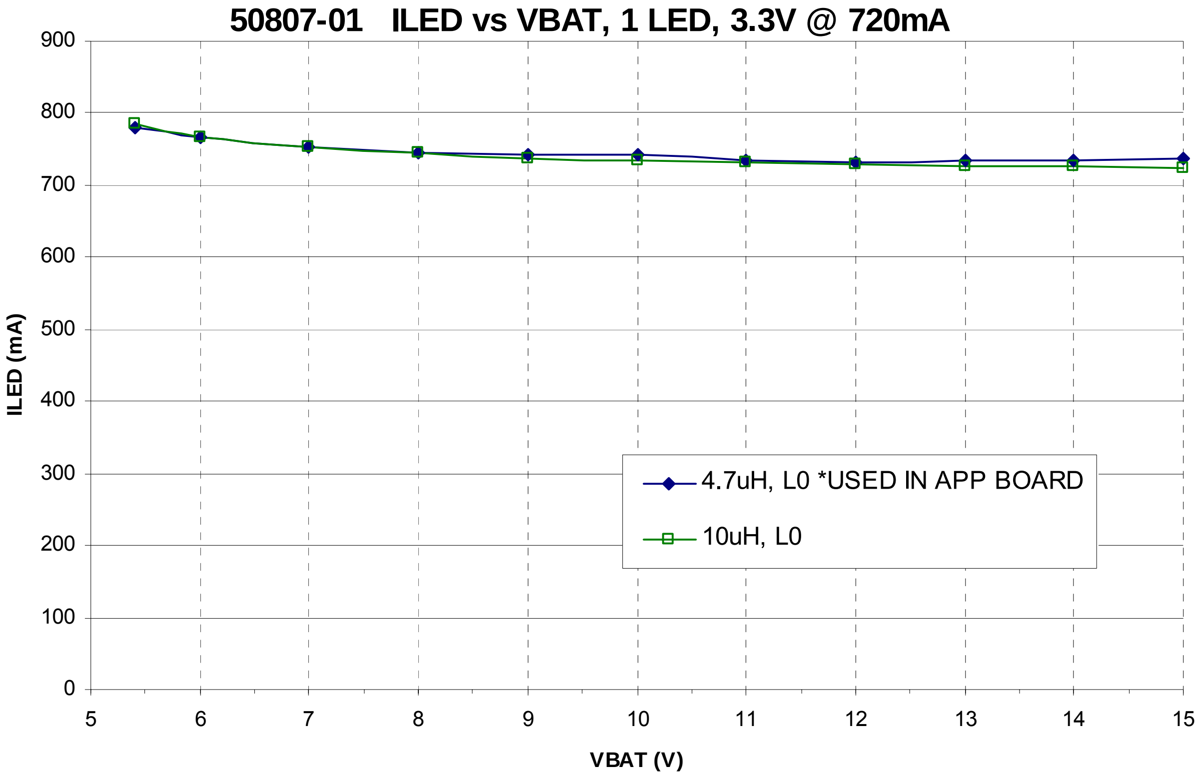


Ripple voltage at the LED anode with a 20uF ceramic output capacitor causes the ripple current at the sense point, LS, as shown in Channel 1. The marker line labeled T is an estimate of the threshold where the SEPIC regulator is turned on and off. The LED current (Channel 1) continues to fall below the threshold as the inductor is charged. The inductor charging is sensed at the BS pin and is shown in Channel 2. (Inductor discharge current is not shown since the Power FET is open during discharge.) At the end of the fourth SEPIC cycle, when the LED current is above the threshold, the LED current continues to rise as the inductor discharges into C1 and brings the LED current higher. Ripple voltage LS is 33.6mV.

50806-01 Ripple Voltage – CH1: V_{LS}, CH2: V_{BS}; V_{BAT} @ 8V

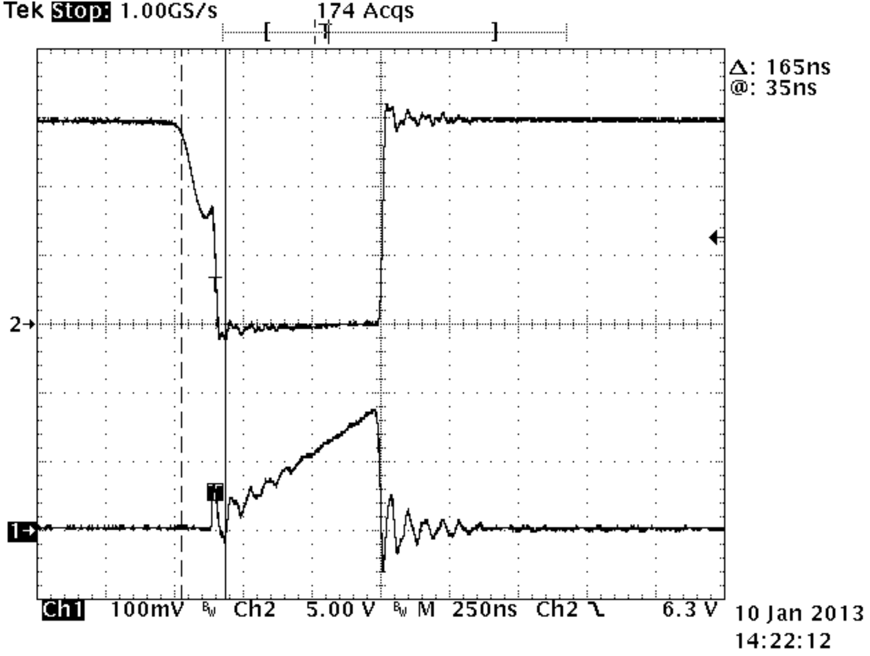


Ripple voltage at the LED anode with a 20uF ceramic plus a 220uF aluminum polymer capacitor causes the ripple current at the sense point, LS, as shown in Channel 1. The inductor charging is sensed at the BS pin and is shown in Channel 2. Channel 2 shows the SEPIC converter cycles. The marker line labeled T is an estimate of the threshold where the SEPIC regulator is turned on and off. The LED ripple current (Channel 1) is significantly reduced by the increased capacitance and as a result regulates the LED current closer to its regulation point. The ripple voltage at LS is only 12mV.

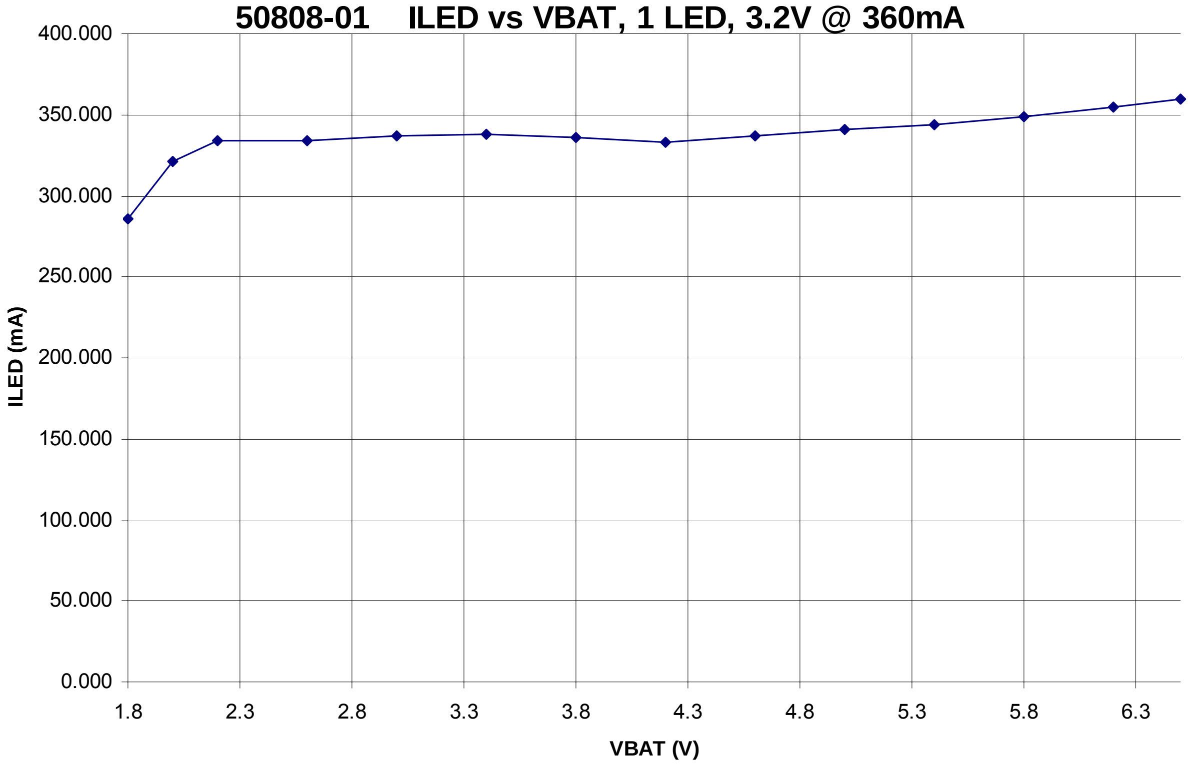


In the 50807-01 graph above, we see a drop in LED current. This is caused by magnetic losses associated with the inductor that go up as a function of the buck converter frequency. There is also a dead-band of approximately 165ns in the buck cycle shown in the figure below. As the battery voltage increases the buck converter period decreases and the dead time becomes more significant causing a drop in LED current.

50807-01 Dead-band – CH1: V_{BS}, CH2: V_{BD}; V_{BAT} @15V



165ns dead-band shown above

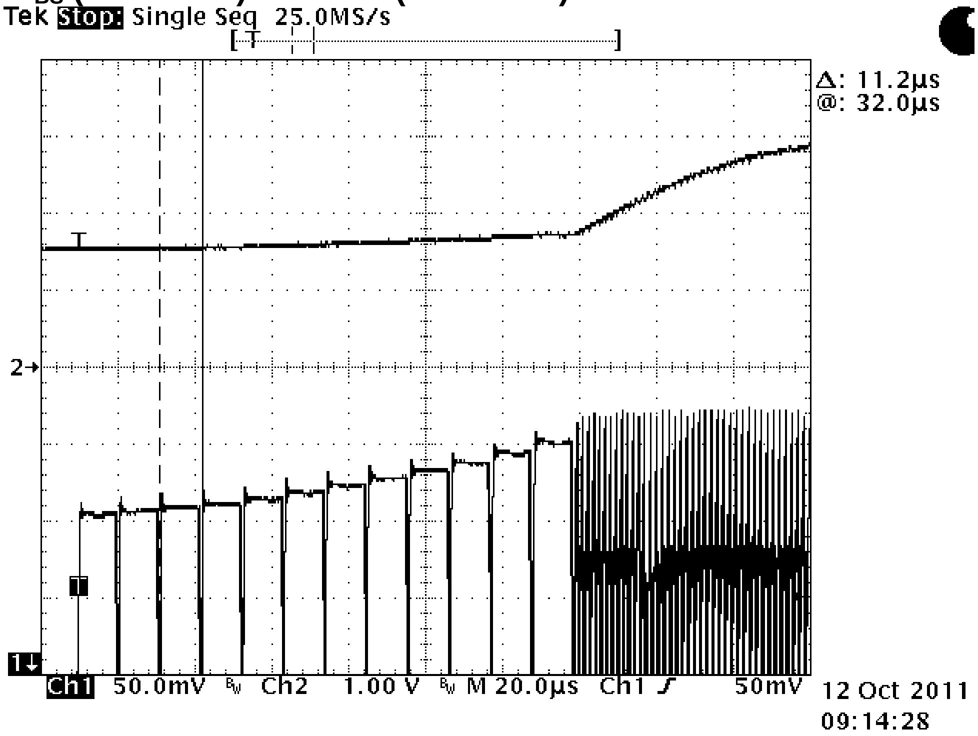


In the 50808-01 graph above, we can see fluctuations in LED current. This is due to ripple voltage being too large. Calculations of the output capacitance C1 call for a larger capacitor than that used in application board. See the discussion for graph 50804-01 ILED vs VBAT for more information.

Bootstrapped V_{CC} and V_{BS} vs Time

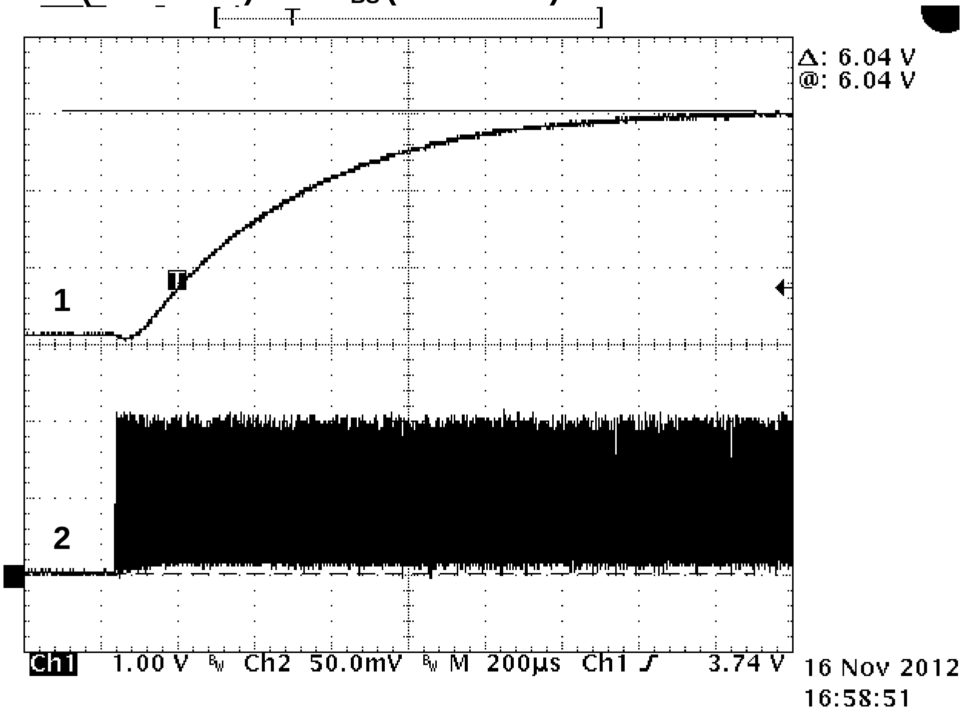
At low battery voltage, VCC does not provide enough gate drive voltage to the internal FET without bootstrap feedback. The figures below show the start-up sequence of VCC and the sense voltage at the BS pin. Notice that at 1.6 volts, the gate drive is insufficient to "switch" the power FET and causes it to act like a current source instead of a switch. The FET initially charges the inductor as a constant current and then discharges it at the maximum 11.5 μs period. The inductor charge increases the voltage at VCC and VA, the anode of the LED. (The resistive loads at these two points, VCC and VA, must be very high to allow the voltage to increase.) As the VCC voltage increases, the FET can supply more current and the inductor current increases until it reaches its regulation point. Once the inductor reaches its regulation point, the period is reduced and the VCC voltage rapidly increases.

V_{BS} (Channel 1) and VCC (Channel 2) vs Time:



The graph above shows VCC, (Channel 2) initially starting at 1.6 voltages. When the part is enabled we can see V_{BS} (Channel 1) initially does not reach its regulation point, and results in a maximum period of 11.5 μs. As VCC slowly rises the voltage at V_{BS} rises until sufficient gate drive at VCC allows it to reach its regulation point as shown by the change to a much shorter period.

VCC (Channel 1) and V_{BS} (Channel 2) vs Time:



The graph above shows VCC initially sitting at 3.1 volts. When the part is enabled we can see V_{BS} regulating and the bootstrap circuit pulling VCC to 6V. The VCC voltage is limited by the lower of the LED or Zener (D3) voltage. A single white LED will provide sufficient bootstrap voltage at VCC. In this example, the Zener is limiting VCC to a safe value.