

TI Designs: TIDA-01008

温度センシング付きの光センス制御バックライトのリファレンス・デザイン



概要

この光制御バックライトのデザインは、周辺光レベルに応じてバックライトの輝度を調節して電力を削減し、液晶ディスプレイ(LCD)とバックライトの寿命を延長します。

CapTIvate™タッチ・マイクロコントローラ(MCU)スライダにより、望ましい設定に応じて輝度を微調整できます。リモート温度センサがLCDの敏感な熱要件を監視し、サーマル・シャットダウンによりシステムを保護できます。

リソース

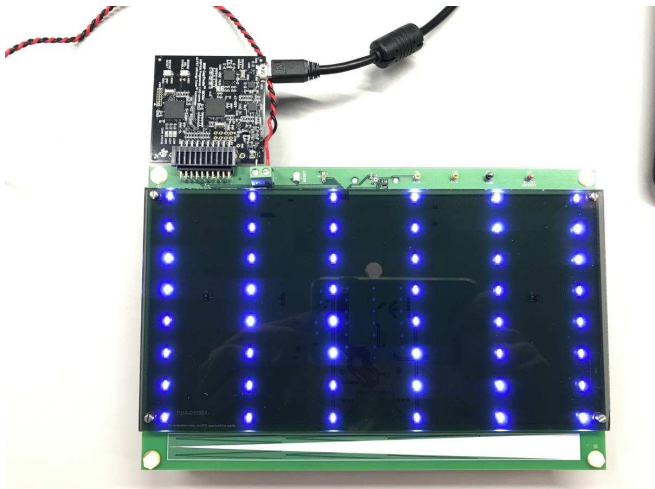
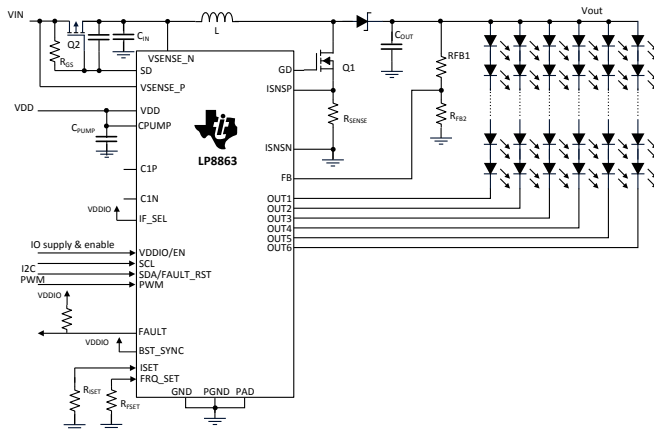
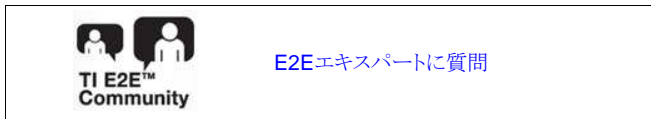
TIDA-01008	デザイン・フォルダ
LM74700-Q1	プロダクト・フォルダ
TPS22918-Q1	プロダクト・フォルダ
LP8863-Q1	プロダクト・フォルダ
MSP430FR2633	プロダクト・フォルダ
TPS7B69-Q1	プロダクト・フォルダ
OPT3001-Q1	プロダクト・フォルダ
TMP423-Q1	プロダクト・フォルダ

特長

- 人間の目と輝度の認識に基づいて、対数スケールを使用してバックライトの輝度を動的に調整
- 人間の目との非常に優れたスペクトル応答一致と、強力なIR除去(1%未満)
- 高電圧過渡およびバッテリー逆極性保護
- スタンバイおよびスリープ状態での低い I_Q
- 容量性タッチ・スライダによる手動の輝度調整
- サーミスタやフォトダイオードなしの、シングル・チップのセンシング・ソリューション

アプリケーション

- 車載用センター・スタック・ディスプレイ
- 車載用クラスタ・ディスプレイ
- 車載用統合ヘッド・ユニット・ディスプレイ
- 車載用電子ミラー
- その他の車載用ディスプレイ



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1 System Description

LCD based displays require an external light source to illuminate the image formed from the liquid crystals. Center stack, cluster, eMirror, head-unit, and other automotive displays implement this with LEDs located behind or on the edges of the LCD panels. An LED backlight driver controls the brightness of these LEDs. This reference design utilizes an ambient light sensor to calculate a brightness level relative to the ambient brightness in the vehicle. Implementation of this design enables a more comfortable viewing experience for the driver and ensures that the display avoids saturation during exposure to high sunlight or be overly bright during night driving. In turn, this design lowers the overall power and extends the lifetime of the system.

LCD panels have a sensitive temperature range of -20°C to 85°C . Due to the extreme temperature ranges to which vehicles are exposed, it is important to limit operation of the display outside of desired operating conditions. Panel temperature is sensed by a remote temperature sensor with diodes either embedded into the glass or placed behind the panel.

An end user of a display system may have their own personal preference for display brightness. This reference design has a capacitive touch slider that allows to fine tune the backlight brightness.

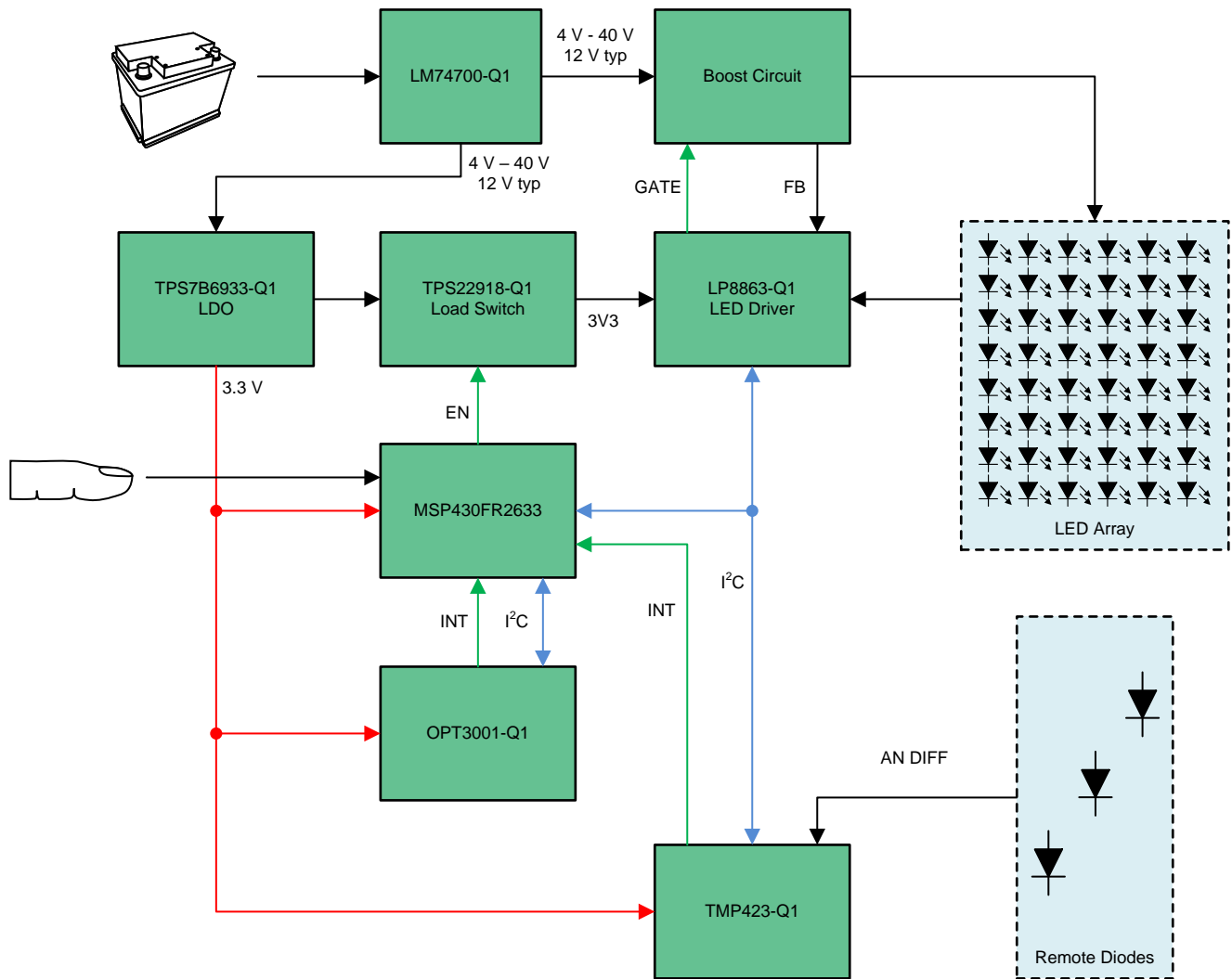
1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	Car battery (13.5 V _{typ} , 40 V _{MAX})	2.3.1.1
Operating temperature	-55°C to 105°C	2.2
Light sensitivity	> 83 klux	2.3.1.5
IR rejection	> 99%	2.3.1.5
Dimming ratio	32,000:1	2.3.1.5
Number of LED strings	6	2.3.3
Total number of LEDs	48	2.3.3
Max current per string	100 mA	2.3.3.4
LED driver boost frequency	2.2 MHz	2.3.3.5.2
LED PWM frequency	152 Hz	2.3.3.2.1
LED driver boost voltage	27.2 V	2.3.3.5.1
Board size	145 mm x 220 mm	3.1.1

2 System Overview

2.1 Block Diagram



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図 1. TIDA-01008 Block Diagram

2.2 Highlighted Products


2.2.1 LM74700-Q1

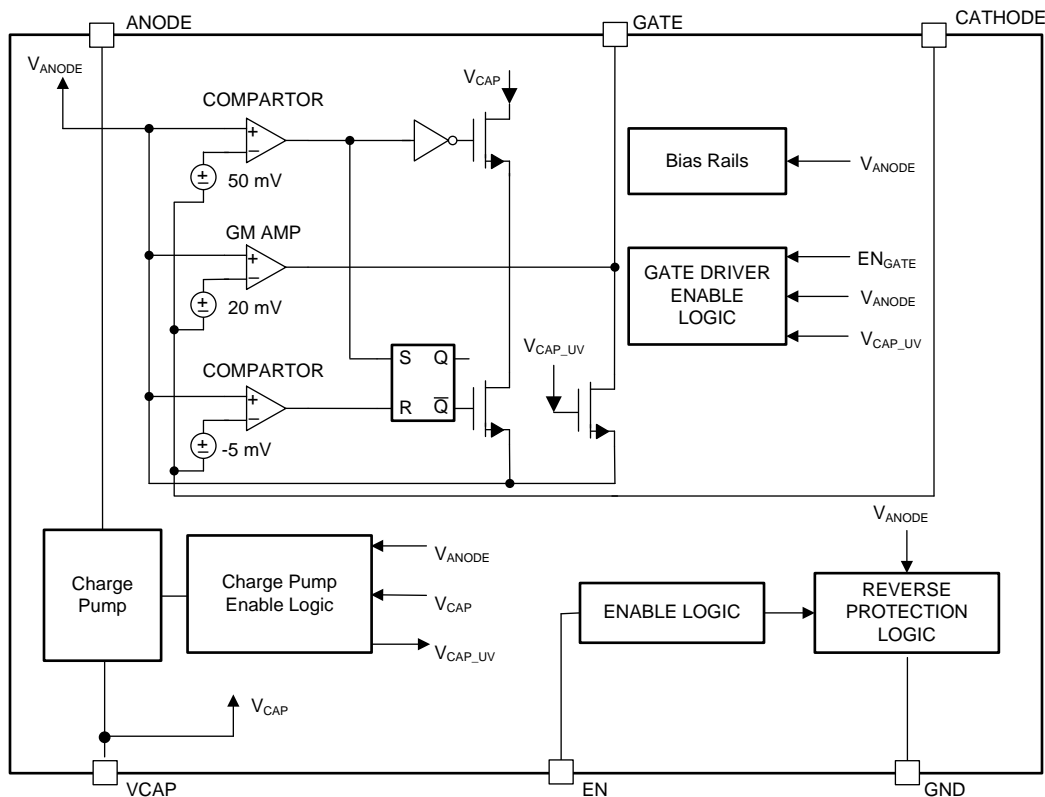
The LM74700-Q1 is a smart diode controller that operates in conjunction with an external N-channel MOSFET as an ideal diode rectifier for low-loss reverse polarity protection. The wide supply input range of 3 V to 65 V allows control of many popular DC bus voltages. The device can withstand and protect the loads from negative supply voltages down to -65 V. With a low $R_{DS(ON)}$ external N-channel MOSFET, this device can achieve a very-low forward voltage while minimizing the amount of power dissipated in the MOSFET. For low-load currents, the forward voltage is regulated to 20 mV to enable graceful shutdown of the MOSFET. TI recommends external MOSFETs with 5 V or lower threshold voltage. With the enable pin low, the controller is off and draws approximately 3 μ A of current.

The LM74700-Q1 controller provides a charge pump gate drive for an external N-channel MOSFET. The high voltage rating of the LM74700-Q1 helps to simplify system designs for automotive ISO7637 protection. Fast response to reverse current blocking makes the device suitable for systems with output voltage holdup requirements during ISO7637 pulse testing as well as power fail and brownout conditions. The LM74700-Q1 is also suitable for ORing applications or AC rectification.

Features:

- Qualified for automotive applications
- AEC-Q100 qualified with the following results:
 - Device temperature grade 1:
–40°C to +125°C ambient operating temperature range
 - Device human body model (HBM) electrostatic discharge (ESD) classification level 2
 - Charge device model (CDM) ESD classification level C4B
- 3-V to 65-V input range
- -65 V reverse voltage rating
- Charge pump for external N-Channel MOSFET
- 20-mV ANODE to CATHODE forward-voltage drop regulation
- Enable pin feature
- 3- μ A shutdown current (EN = low)
- 30- μ A operating quiescent current (EN = high)
- 1.5-A peak gate turnoff current
- Fast response to reverse current blocking:
< 2 μ s
- Meets automotive ISO7637 transient requirements with a suitable transient-voltage-suppression (TVS) diode
- -40 °C to $+150$ °C operating junction temperature
- 6-pin SOT 23-6 package (3 mm x 3 mm)

 2 shows the LM74700-Q1 functional block diagram.



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図 2. LM74700-Q1 Functional Block Diagram

2.2.2 TPS7B69-Q1

The TPS7B69xx-Q1 device is a low-dropout linear regulator (LDO) designed for up to 40-V V_I operations. With only 15- μ A (typical) quiescent current at light load, the device is suitable for standby microcontrol-unit systems, especially in automotive applications.

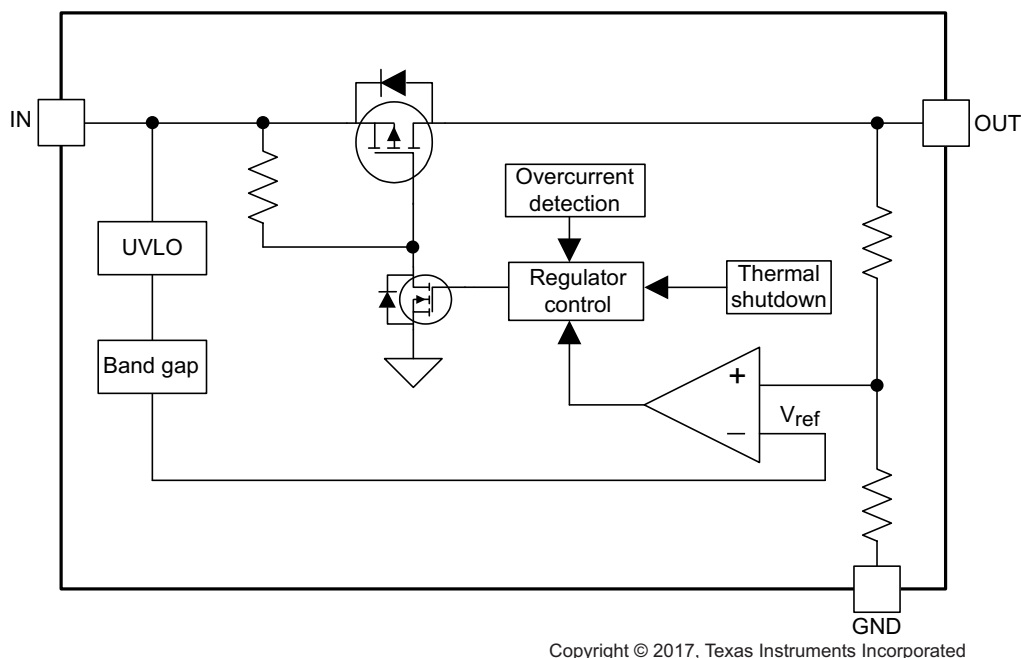
The devices feature an integrated short-circuit and overcurrent protection. The TPS7B69xx-Q1 device operates over a -40°C to 125°C temperature range. Because of these features, the TPS7B6925-Q1, TPS7B6933-Q1, and TPS7B6950-Q1 devices are well suited in power supplies for various automotive applications.

Features:

- Qualified for automotive applications
- EC-Q100 qualified with the following results:
 - Device temperature grade 1: -40°C to 125°C ambient operating temperature range
 - Device HBM ESD classification level 2
 - Device CDM ESD classification level C4B
- 4-V to 40-V wide V_I input voltage range with up to 45-V transient
- Maximum output current: 150 mA
- Low quiescent current (I_Q):

- 15- μ A typical at light loads
- 25- μ A maximum under full temperature
- 450-mV typical low dropout voltage at 100-mA load current
- Stable with low equivalent series resistance (ESR) ceramic output capacitor (2.2 μ F to 100 μ F)
- Fixed 2.5-V, 3.3-V, and 5-V output voltage options
- Integrated fault protection:
 - Thermal shutdown
 - Short-circuit protection
- Packages:
 - 4-pin SOT-223 package
 - 5-pin SOT-23 package

Figure 3 shows the TPS7B69-Q1 functional block diagram.



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Figure 3. TPS7B69-Q1 Functional Block Diagram

2.2.3 TPS22918-Q1

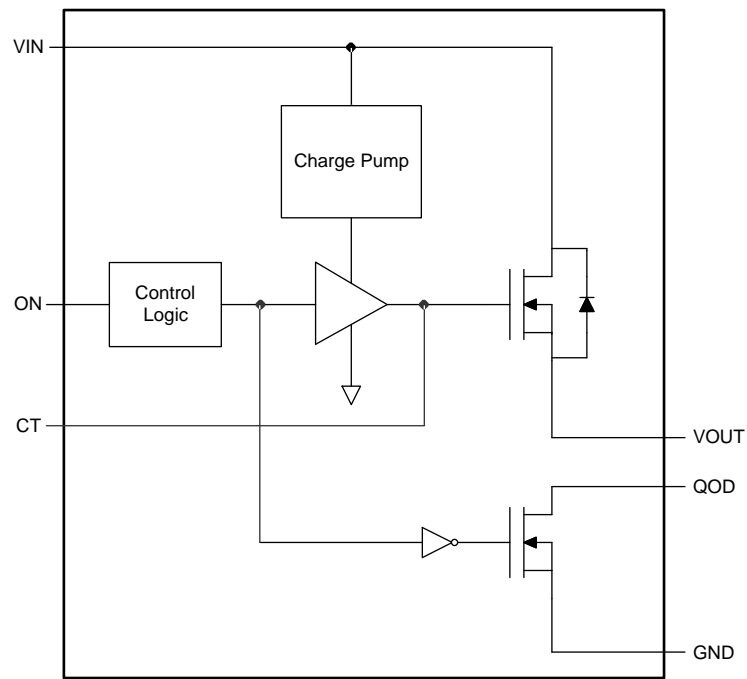
The TPS22918-Q1 is a single-channel load switch with both configurable rise time and configurable quick-output discharge. The device contains an N-channel MOSFET that can operate over an input voltage range of 1 V to 5.5 V and can support a maximum continuous current of 2 A. The switch is controlled by an ON and OFF input, which is capable of interfacing directly with low-voltage control signals.

The configurable rise time of the device reduces inrush current caused by large bulk load capacitances, thereby reducing or eliminating power supply droop. The TPS22918-Q1 features a configurable quick output discharge (QOD) pin, which controls the fall time of the device to allow design flexibility for power down and sequencing.

The TPS22918-Q1 is available in a small, leaded SOT-23 package (DBV) which allows to visually inspect solder joints. The device is characterized for operation over the free-air temperature range of -40°C to $+105^{\circ}\text{C}$.

- AEC-Q100 qualified
- Integrated single-channel load switch
- Qualified for automotive applications:
 - Device temperature grade 2: -40°C to $+105^{\circ}\text{C}$ ambient operating temperature range
- Input voltage range: 1 V to 5.5 V
- Low ON-resistance (R_{ON})
 - $R_{\text{ON}} = 52 \text{ m}\Omega$ (typical) at $V_{\text{IN}} = 5 \text{ V}$
 - $R_{\text{ON}} = 53 \text{ m}\Omega$ (typical) at $V_{\text{IN}} = 3.3 \text{ V}$
- 2-A maximum continuous switch current
- Low quiescent current
 - $8.3 \mu\text{A}$ (typical) at $V_{\text{IN}} = 3.3 \text{ V}$
- Low-control input-threshold enables use of 1 V or higher general-purpose input/output (GPIO)
- Configurable quick-output discharge (QOD)
- Configurable rise time with CT pin
- Small SOT23-6 package (DBV)
 - $2.9 \text{ mm} \times 2.8 \text{ mm}$, 0.95-mm pitch,
1.45-mm height (with leads)
- ESD performance tested per AEC Q100
 - $\pm 2\text{-kV}$ HBM and $\pm 750\text{-V}$ CDM

☒ 4 shows the TPS22918-Q1 functional block diagram.



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図 4. TPS22918-Q1 Functional Block Diagram

2.2.4 LP8863-Q1

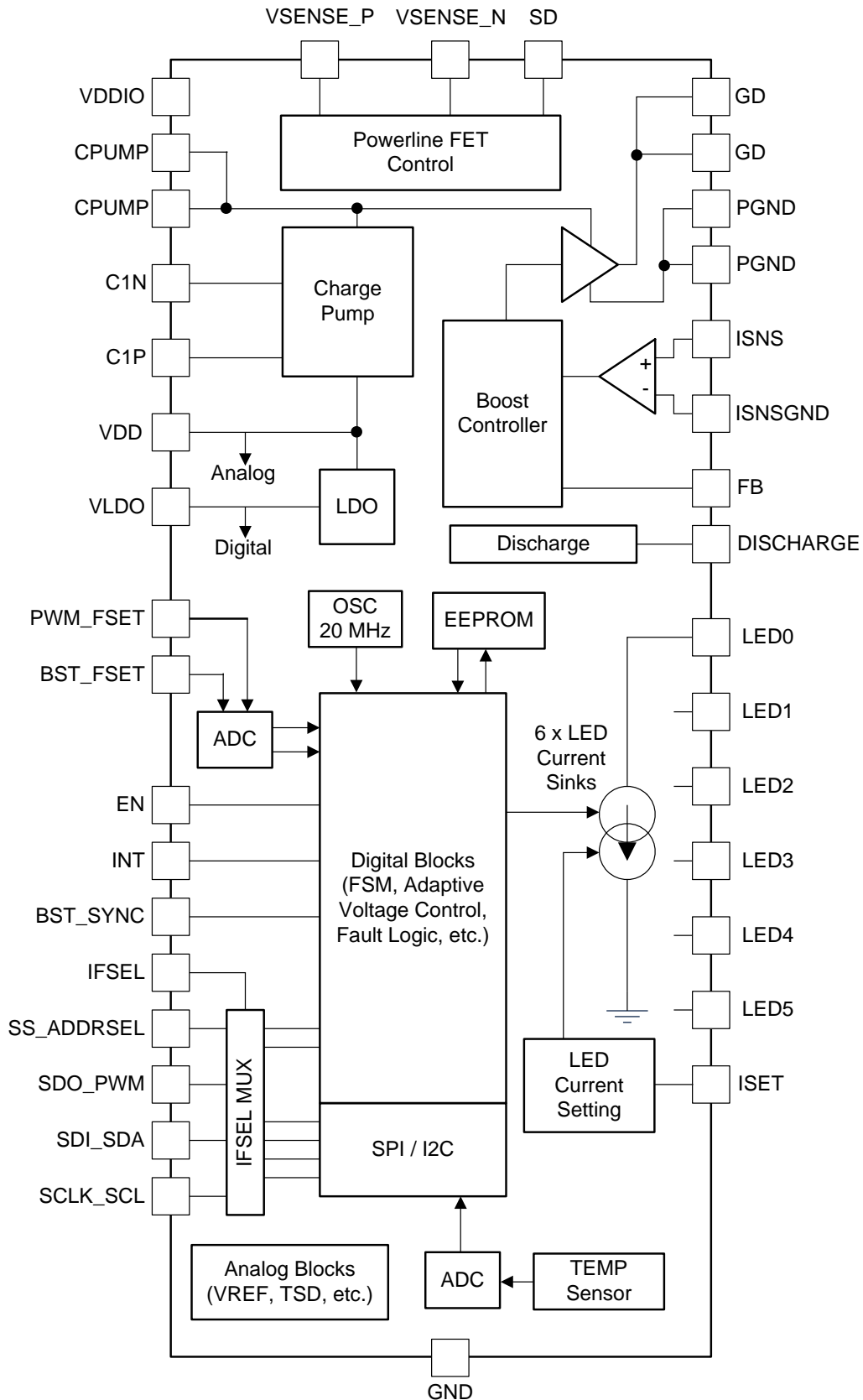
The LP8863-Q1 is an automotive, high-efficiency, light-emitting diode (LED) driver with boost controller. The six, high-precision current sinks support phase shifting which is automatically adjusted based on the number of channels in use. Control the current sink brightness individually and globally through the serial peripheral interface (SPI) or I²C interface; global control of the brightness is also available through the pulse-width modulation (PWM) input.

The boost controller has adaptive output voltage control based on the headroom voltages of the LED current sinks. This feature minimizes the power consumption by adjusting the voltage to the lowest sufficient level in all conditions. A wide-range adjustable frequency allows the LP8863-Q1 to avoid disturbance for the AM radio band.

The LP8863-Q1 supports built-in, hybrid PWM and current dimming, which reduces EMI, extends the LED lifetime, and increases the total optical efficiency.

- Qualified for automotive applications
- AEC-Q100 qualified with the following results:
 - Device temperature grade 1: –40°C to +125°C ambient operating temperature
- Input voltage operating range 3 V to 48 V
- Six high-precision current sinks
 - Current matching 1% (typical)
 - Dimming ratio 32 000:1 using 152-Hz LED output PWM frequency
 - Up to 16-bit LED dimming resolution with SPI, I²C, or PWM input
 - Automatically detects used LED strings and adjusts LED-channel phase shift
 - Independent current control for each channel
- Hybrid PWM and current dimming
- Up to 47-V V_{OUT} boost or single-ended primary-inductor converter (SEPIC) DC/DC controller
 - Switching frequency 300 kHz to 2.2 MHz
 - Boost spread spectrum for reduced EMI
 - Boost sync input to set boost switching frequency from an external clock
 - Integrated charge pump supports low V_{IN} conditions such as cold crank
 - Output voltage automatically discharged when boost is disabled
- Extensive fault diagnostics

Figure 5 shows the LP8863-Q1 functional block diagram.



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図 5. LP8863-Q1 Functional Block Diagram

2.2.5 MSP430FR2633

The MSP430FR263x and MSP430FR253x are ultra-low-power MSP430™ microcontrollers (MCUs) for capacitive touch sensing that feature [CapTIvate touch technology](#) for buttons, sliders, wheels, and proximity applications. MSP430 MCUs with CapTIvate technology provide the most integrated and autonomous capacitive-touch solution in the market with high reliability and noise immunity at the lowest power. TI's capacitive touch technology supports concurrent self-capacitance and mutual-capacitance electrodes on the same design for maximum flexibility. MSP430 MCUs with CapTIvate technology operate through thick glass, plastic enclosures, metal, and wood with operation in harsh environments including wet, greasy, and dirty environments.

TI capacitive touch sensing MSP430 MCUs are supported by an extensive hardware and software ecosystem with reference designs and code examples to get your design started quickly. Development kits include the [MSP-CAPT-FR2633 CapTIvate technology development kit](#). TI also provides free software including the [CapTIvate Design Center](#), where engineers can quickly develop applications with an easy-to-use GUI and [MSP430Ware™ software](#) and comprehensive documentation with the [CapTIvate technology guide](#).

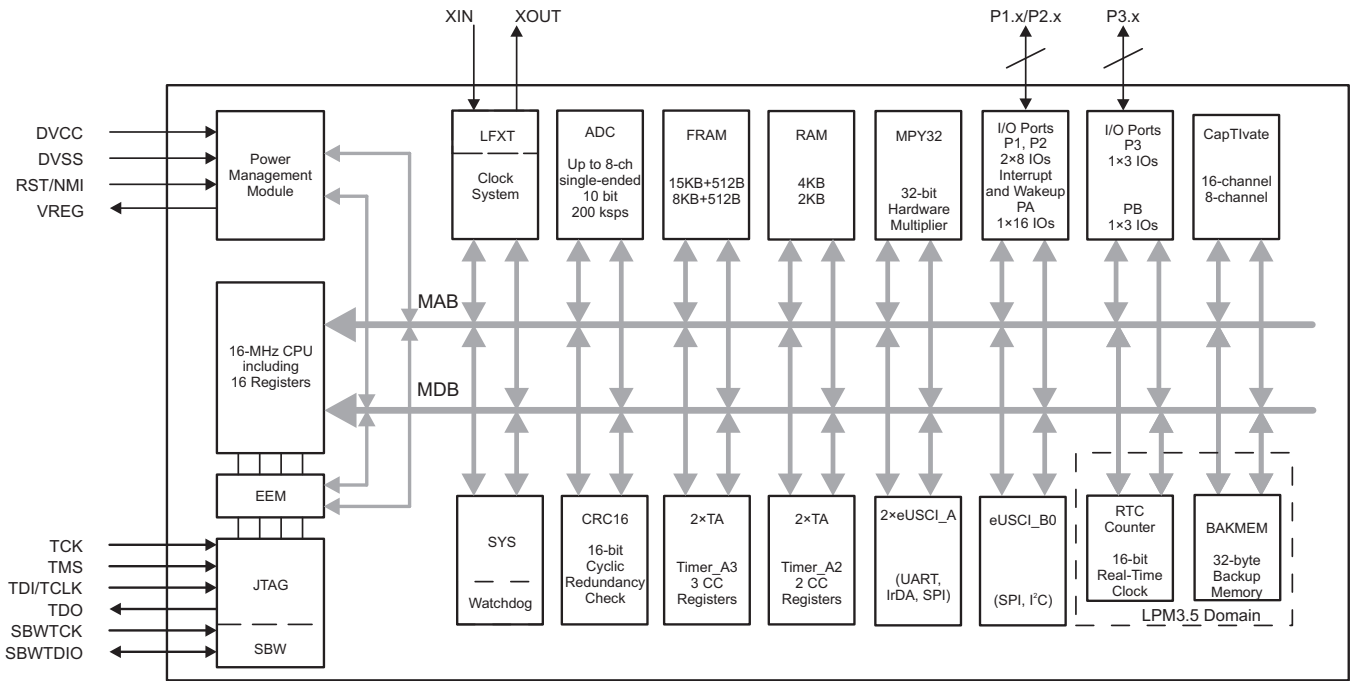
TI's MSP430 ultra-low-power (ULP) FRAM microcontroller platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatility of flash.

- [CapTIvate Technology](#) – Capacitive Touch
 - Performance
 - Fast electrode scanning with four simultaneous scans
 - Support for high-resolution sliders With > 1024 points
 - 30-cm proximity sensing
 - Reliability
 - Increased immunity to power line, RF, and other environmental noise
 - Built-in spread spectrum, automatic tuning, noise filtering, and debouncing algorithms
 - Enables [reliable touch solutions](#) with 10-V RMS common-mode noise, 4-kV electrical fast transients, and 15-kV electrostatic discharge, allowing for IEC-61000-4-6, IEC-61000-4-4, and IEC-61000-4-2 compliance
 - Reduced RF emissions to simplify electrical designs
 - Support for metal touch and water rejection designs
 - Flexibility
 - Up to 16 self-capacitance and 64 mutual-capacitance electrodes
 - Mix and match [self- and mutual-capacitive electrodes in the same design](#)
 - Supports multitouch functionality
 - Wide range of capacitance detection, wide electrode range of 0 to 300 pF
 - Low power
 - <0.9 μ A/button in wake-on-touch mode, where capacitive measurement and touch detection is done by hardware state machine while CPU is asleep
 - Wake-on-touch state machine allows electrode scanning while CPU is asleep

- Hardware acceleration for environmental compensation, filtering, and threshold detection
- Ease of use
 - [CapTivate Design Center](#), PC graphical user interface (GUI) allows engineers to design and tune capacitive buttons in real time without having to write code
 - CapTivate Software Library in ROM provides ample FRAM for customer applications
- Embedded microcontroller
 - 16-bit reduced instruction set computer (RISC) architecture
 - Clock supports frequencies up to 16 MHz
 - Wide supply voltage range from 1.8 V to 3.6 V ⁽¹⁾
- Optimized ultra-low-power modes
 - Active mode: 126 μ A/MHz (typical)
 - Standby
 - 1.7 μ A/button average (typical) (16 self-capacitance buttons, 8-Hz scanning)
 - 1.7 μ A/button average (typical) (64 mutual-capacitance buttons, 8-Hz scanning)
 - LPM3.5 real-time clock (RTC) counter with 32768-Hz crystal: 730 nA (typical)
 - Shutdown (LPM4.5): 16 nA (typical)
- High-performance analog
 - 8-Channel 10-bit analog-to-digital converter (ADC)
 - Internal 1.5-V reference
 - Sample-and-hold 200 ksps
- Enhanced serial communications
 - Two enhanced universal serial communication interfaces (eUSCI_A) support universal asynchronous receiver and transmitter (UART), IrDA, and SPI
 - One eUSCI (eUSCI_B) supports SPI and I²C
- Intelligent digital peripherals
 - Four 16-bit timers
 - Two timers with three capture/compare registers each (Timer_A3)
 - Two timers with two capture/compare registers Each (Timer_A2)
 - One 16-Bit Timer Associated With CapTivate™ Technology
 - One 16-bit counter-only RTC
 - 16-bit cyclic redundancy check (CRC)
- Low-power ferroelectric RAM (FRAM)
 - Up to 15.5KB of nonvolatile memory
 - Built-in error correction code (ECC)
 - Configurable write protection
 - Unified memory of program, constants, and storage
 - 10¹⁵ write cycle endurance

⁽¹⁾ Minimum supply voltage is restricted by SVS levels (see V_{SVSH-} and V_{SVSH+} in section regarding PMM, SVS, and BOR in [MSP430FR263x, MSP430FR253x Capacitive Touch Sensing Mixed-Signal Microcontrollers](#) .

- Radiation resistant and nonmagnetic
 - High FRAM-to-SRAM ratio, up to 4:1
 - Clock system (CS)
 - On-chip 32-kHz RC oscillator (REFO)
 - On-chip 16-MHz digitally controlled oscillator (DCO) with frequency-locked loop (FLL)
 - $\pm 1\%$ accuracy with on-chip reference at room temperature
 - On-chip very low-frequency 10-kHz oscillator (VLO)
 - On-chip high-frequency modulation oscillator (MODOSC)
 - External 32-kHz crystal oscillator (LFXT)
 - Programmable MCLK prescaler of 1 to 128
 - SMCLK derived from MCLK with programmable prescaler of 1, 2, 4, or 8
 - General input and output and pin functionality
 - Total of 19 I/Os on TSSOP-32 package
 - 16 interrupt pins (P1 and P2) can wake MCU from low-power modes
 - Development tools and software
 - Ease-of-use ecosystem
 - CapTIvate design center – code generation, customizable GUI, real-time tuning
 - 12-KB ROM library includes CapTIvate touch libraries and driver libraries
 - Family members (also see *Device Comparison* section in [MSP430FR263x](#), [MSP430FR253x](#) *Capacitive Touch Sensing Mixed-Signal Microcontrollers*)
 - MSP430FR2633: 15KB of program FRAM + 512B of information FRAM + 4KB of RAM up to 16 self-capacitive or 64 mutual-capacitive sensors
 - MSP430FR2533: 15KB of program FRAM + 512B of information FRAM + 2KB of RAM up to 16 self-capacitive or 16 mutual-capacitive sensors
 - MSP430FR2632: 8KB of program FRAM + 512B of information FRAM + 2KB of RAM up to 8 self-capacitive or 16 mutual-capacitive sensors
 - MSP430FR2532: 8KB of program FRAM + 512B of information FRAM + 1KB of RAM up to 8 self-capacitive or 8 mutual-capacitive sensors
 - Package options
 - 32-pin: VQFN (RHB)
 - 32-pin: TSSOP (DA)
 - 24-pin: VQFN (RGE)
 - 24-pin: DSBGA (YQW)
 - For Complete module descriptions, see the [MSP430FR4xx and MSP430FR2xx Family User's Guide](#)
- ☒ 6 shows the MSP430FR2633 functional block diagram.



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図 6. MSP430FR2633 Functional Block Diagram

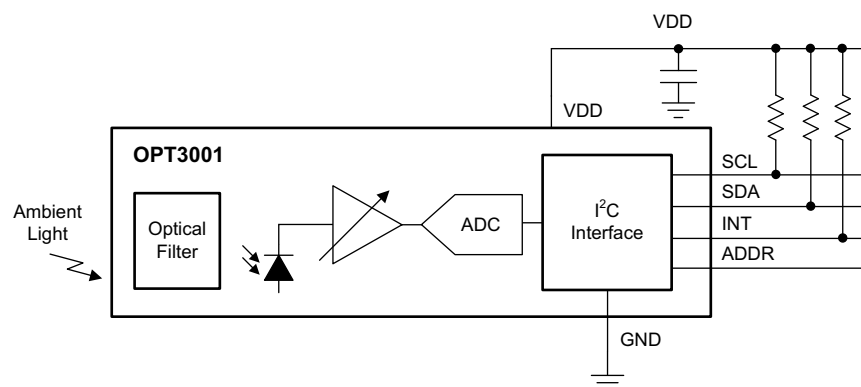
2.2.6 OPT3001-Q1

The OPT3001 device is a sensor that measures the intensity of light. The spectral response of the sensor is tightly matched to the photopic response of the human eye and includes significant infrared rejection. The OPT3001 is a single-chip lux meter, measuring the intensity of light as seen by the human eye. The precision spectral response and strong IR rejection of the device enables the OPT3001 to accurately measure the intensity of light regardless of its source. The strong IR rejection also aids in maintaining high accuracy when industrial design calls for mounting the sensor under dark glass for aesthetics. The OPT3001 is designed for systems that create light-based experiences for humans and is an ideal, preferred replacement for photodiodes, photoresistors, or other ambient light sensors with less human eye matching and IR rejection. The small form factor (2.0 × 2.0 × 0.65 mm) allows the device to fit almost anywhere.

Features:

- Precision optical filtering to match human eye
 - Rejects >99% (typ) of IR
- Automatic full-scale setting feature simplifies software and ensures proper configuration
- Measurements: 0.01 lux to 83k lux
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted full-scale range settings: <0.2% (typ) matching between ranges
- Low operating current: 1.8 μ A (typ)
- Operating temperature range: -40°C to 85°C
- Wide power-supply range: 1.6 to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system
- Small-form factor: 2.0 × 2.0 × 0.65 mm

☒ 7 shows the OPT3001 functional block diagram.



☒ 7. OPT3001 Functional Block Diagram

2.2.7 TMP423-Q1

The TMP42x-Q1 family of devices are single, dual, and triple remote, automotive-qualified temperature sensor monitors with a built-in local temperature sensor. The remote temperature sensor diode-connected transistors are typically low-cost, NPN- or PNP-type transistors or diodes that are an integral part of microcontrollers, microprocessors, or field-programmable gate arrays (FPGAs).


Remote accuracy is $\pm 1^{\circ}\text{C}$ for multiple device manufacturers, with no calibration required. The two-wire serial interface accepts SMBus write byte, read byte, send byte, and receive byte commands to configure the device.

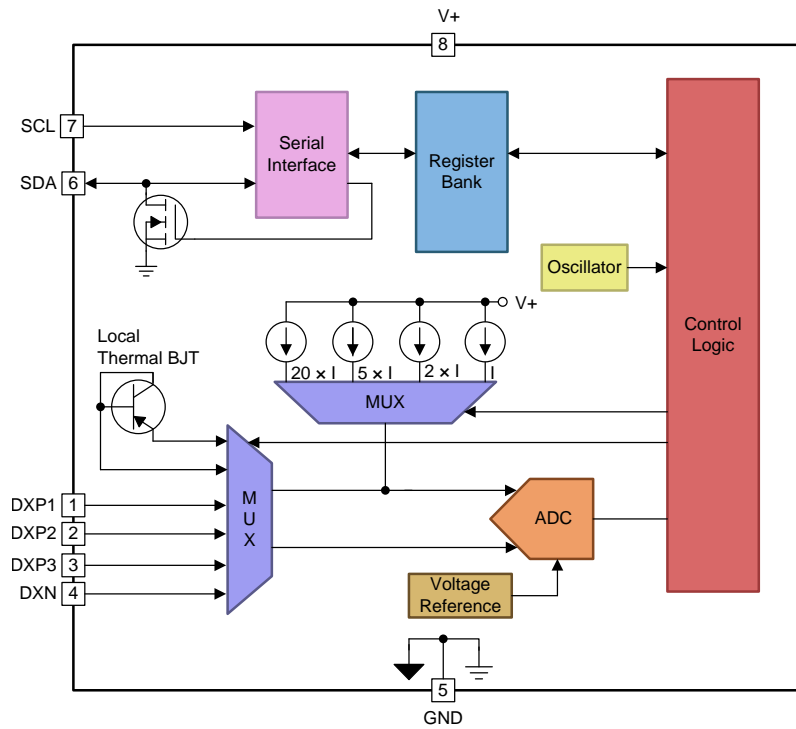
The TMP423-Q1 includes series resistance cancellation, programmable non-ideality factor, wide remote temperature measurement range (up to $+150^{\circ}\text{C}$), and diode fault detection.

The TMP42x-Q1 are all available in an 8-pin SOT-23 package.

Features:

- AEC-Q100 qualified with the following results
 - Temperature grade 1: -40°C to $+125^{\circ}\text{C}$
 - Device HBM ESD classification level 2
 - Device CDM ESD classification level C5
- SOT23-8 package
- $\pm 1^{\circ}\text{C}$ remote diode sensor (maximum)
- $\pm 1.5^{\circ}\text{C}$ local temperature sensor (maximum)
- Series resistance cancellation
- n-factor correction
- Two-wire I²C or SMBus™ compatible serial interface
- Multiple interface addresses
- Diode fault detection
- RoHS compliant and No Sb/Br

 8 shows the TMP423-Q1 functional block diagram.



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図 8. TMP423-Q1 With Three Remote Diode Inputs

2.3 System Design Theory

This reference design consists of the following three subsystems:

- Power management
- MCU and sensors
- Backlight driver, boost circuit, and LED array

2.3.1 Power Managements Overview

2.3.1.1 Reverse Battery Protection

Reverse battery protection is a requirement for every electronic subsystem in a vehicle recognized by original equipment manufacturer (OEM) standards as well as load dump protection standards ISO 16750-2. The LM74700 is used to control the negative-channel field-effect transistor (NFET) to protect the load in a negative polarity condition. This device is used to emulate an ideal diode by using an NFET in series with the battery supply. This configuration has the advantage of a highly effective and efficient substitute for reverse battery protection to the traditional rectifier. The LM74700 device has a low typical I_Q of 30 μA and standby current of 3 μA that is drawn from the battery. Additionally, the voltage drop across the field-effect transistor (FET) is so inconsequential that it allows the system to operate at even lower battery input voltages. This property is an advantage for scenarios such as cold crank when the battery voltage temporarily drops to as low as 3.5 V. A traditional diode solution usually has a 700-mV voltage drop, so the LDO would not be able to maintain the minimum 3-V system voltage. With the smart diode solution, the LDO and boost converter still receive close to 5 V during this condition and can continue to operate.

2.3.1.2 MOSFET and TVS Diodes

[LM74700-Q1 Low I_Q Always ON Smart Diode Controller](#) details the MOSFET selection for the LM74700-Q1. The following items are important characteristics to design around:

- Continuous drain current (I_D)
- Maximum drain-to-source voltage ($V_{DS(MAX)}$)
- Gate-to-source threshold voltage ($V_{GS(TH)}$)
- Drain-to-source on resistance ($R_{DS(ON)}$)

Additionally, the rating for I_D must exceed the system current ($I_D > I_{LOAD}$), which is less than 2.5 A in this system. This ideal diode controller is paired with a SQJ412EP-T1 MOSFET.

表 2 lists the TVS diode parameters.

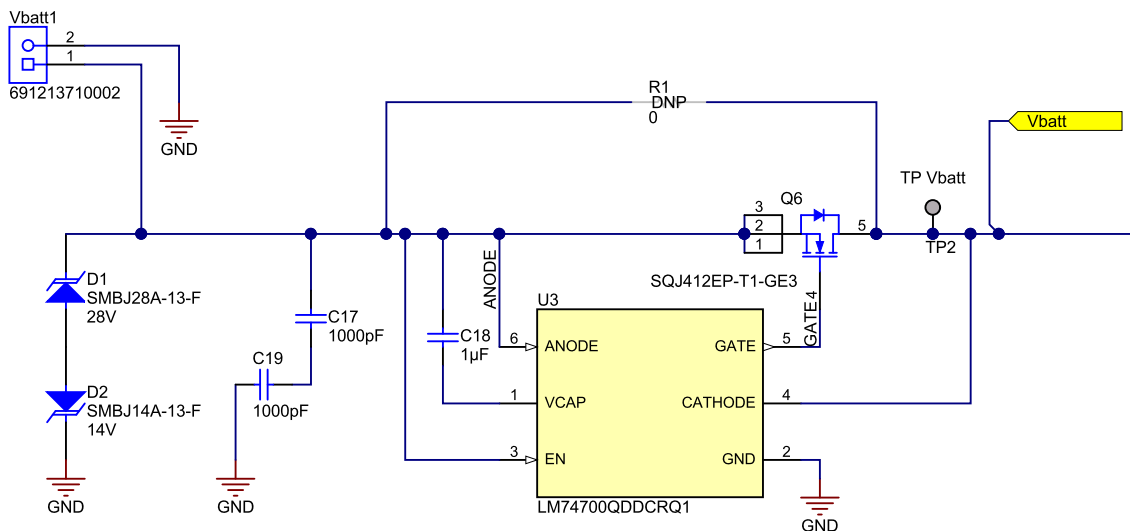
表 2. TVS Diode Parameters

PARAMETER	COMMENTS	MIN	TYP	MAX	UNIT
D1SMBJ28A					
V_{RWM}	Reverse standoff voltage	—	28.0	—	V
V_C	Clamping voltage	—	—	45.4	V
V_{BR}	Breakdown voltage	31.1	—	35.8	V
D2SMBJ14A					
V_{RWM}	Reverse standoff voltage	—	14	—	V
V_C	Clamping voltage	—	—	23.2	V
V_{BR}	Breakdown voltage	15.6	—	17.9	V

The diode breakdown voltages must be chosen such that the transients are clamped at the voltages that protect the MOSFET and the remainder of the system. In 表 2 , the positive clamping diode D1 clamps above the double battery (jump-start) and clamped load dump voltages, but lower than the maximum operating voltage of the downstream devices. In this case, the positive clamping diode starts to clamp around 28 V, but has a maximum clamp voltage just below 40 V (ideally, somewhere around 36 V), which is why D1 is chosen for its maximum clamping voltage (see 図 9).

The reverse clamping diode D2 must clamp all negative voltages greater than the battery voltage so that it does not short out during a reverse-battery condition. Because the battery voltage is likely to be 14 V, D2 is selected to block all negative voltages greater than this voltage.

Regarding the power levels for the TVS diodes, the particular package used is SMBJ, which supports 600-W peak power levels. This package is sufficient for ISO 7637-2 pulses and suppressed load dump case (ISO-16750-2 pulse B). Unsuppressed load dumps (ISO-16750-2 pulse A) may require higher-power TVS diodes such as SMCJ or SMDJ. For more information about designing the TVS diodes for this application, see [LM74700-Q1 Low I Q Always ON Smart Diode Controller](#).



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図 9. TIDA-01008 Schematic: Input Protection

2.3.1.3 LC Filter and Input Capacitors

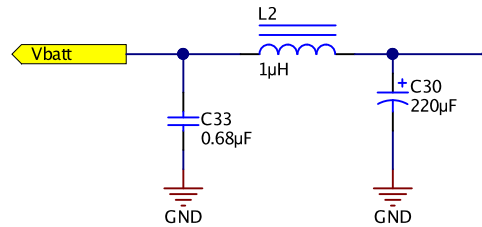
After the LM74700 setup, an LC filter is used for two main functions: prevent EMI and prevent high-frequency voltage on the power line from passing through to the power supply of the regulator.

For EMI filter designs, determining the attenuation and appropriate cutoff frequency is important to properly calculate the capacitor and inductor values. For further clarification, see [AN-2162 Simple Success With Conducted EMI From DC-DC Converters](#).

The regulator performs switching at 2.2 MHz; therefore, TI recommends to set the cutoff frequency to be approximately 1/10 f_{sw} . The cutoff frequency is set as follows in 式 1.

$$f_c = 220 \text{ kHz} = 1 / (2 \pi L C) \quad (1)$$

The values chosen for C33 and L2 are 0.68 μF and 1 μH , respectively, for a cutoff frequency of 190 kHz. Place C30 after the filter to increase the impedance of the PI filter and prevent stability problems between the filter and converter (see 図 10).

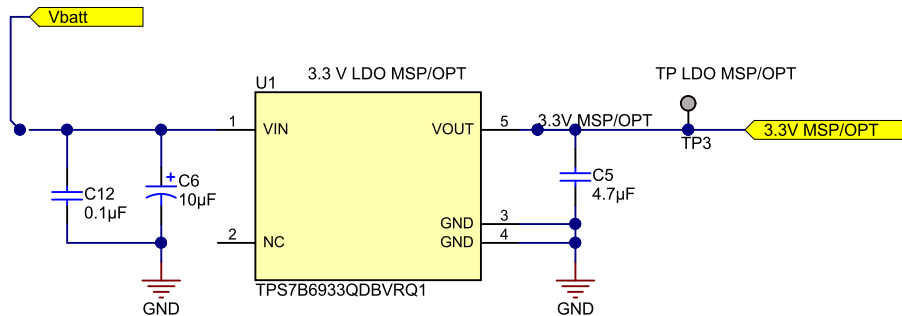


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図 10. TIDA-01008 Schematic: PI Filter

2.3.1.4 OFF-Battery LDO

Use an OFF-battery LDO to convert the battery voltage to the 3.3-V system voltage. The TPS7B6933 is a low-dropout linear regulator that operates up to 40-V input voltage, which make it capable of handling the clamped transient levels experienced after the TVS diodes during spikes (see 図 11). The OFF-battery LDO provides the VDD for all the devices in the system. The protected battery voltage directly supplies the input to the boost converter, instead of sourcing from the LDO. TI recommends adding an electrolytic capacitor with a value of 10 µF and a ceramic bypass capacitor at the TPS7B69xx device input when the input supply is located more than a few inches away.

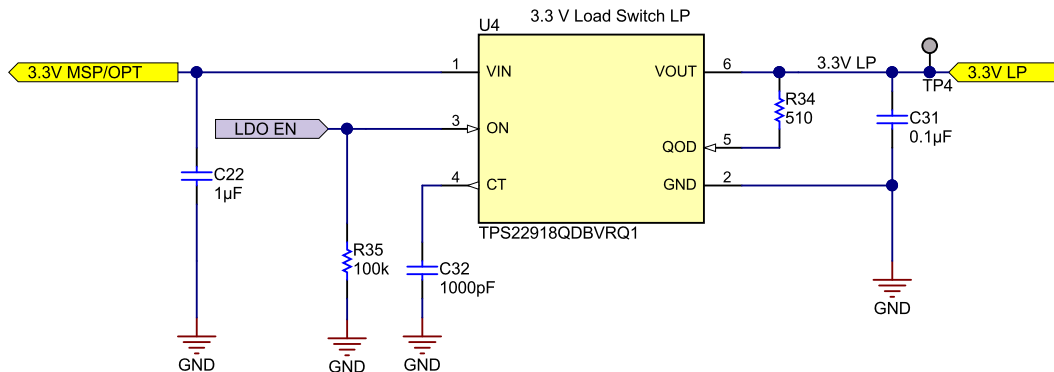


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図 11. TIDA-01008 Schematic: TPS7B69-Q1

2.3.1.5 Load Switch for Low-Power States

This reference design uses a low ON-resistance load switch which turns off the LED driver VDD voltage when the backlight is not required or is in standby mode. The LP8863-Q1 has an I_Q up to 300 µA (max) when in standby mode; for this reason, the load switch must completely cut the input power to the LED driver to mitigate this quiescent current.



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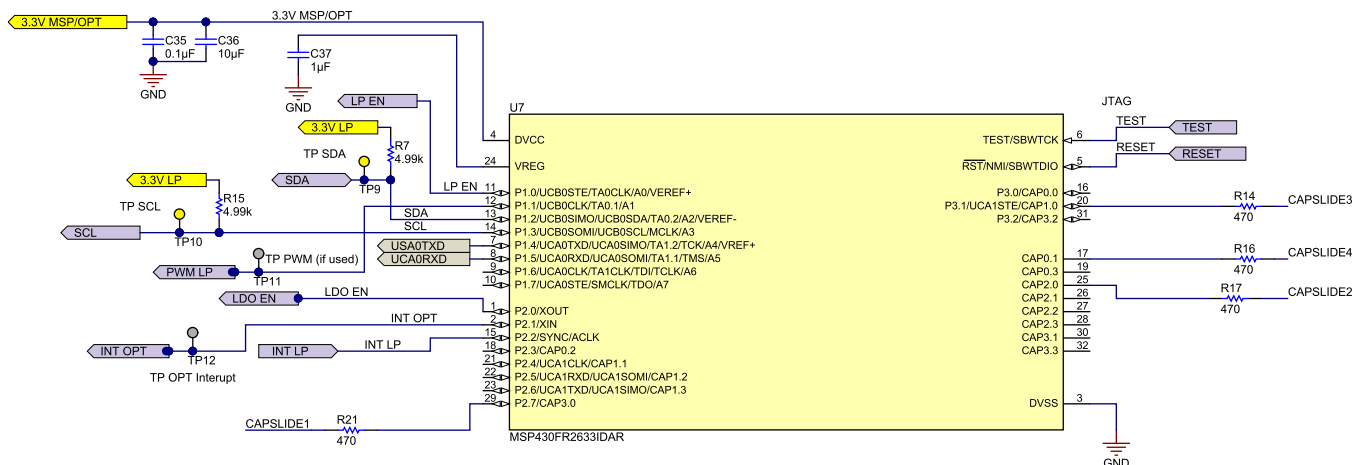
図 12. TIDA-01008 Schematic: TPS22918-Q1

2.3.2 Overview of Sensors and MCU

This reference design utilizes an MCU to execute the smart backlight algorithm and interface with the various user inputs, sensors, and power devices.

2.3.2.1 MCU

This design has few MCU requirements because the rest of the devices are easy to control through one I²C bus and GPIO pins. The minimum requirements for the MCU include one I²C bus to communicate to the optical sensor, temperature sensor, and LED driver, as well as a GPIO for enabling devices and interrupts. The MSP430FR2633 is used in this design to implement a CapTIvate touch slider for brightness adjustment. The MSP430FR2633 is an ultra-low power, FRAM-based MCU that meets the I²C interface and GPIO pin requirements, while also supporting high-resolution sliders with greater than 1024 points through its mutual and self-capacitance solution (see 図 13). An advantage to using this MCU is its ability to use the CapTIvate module while the MSP430 is in LPM3, which saves the system power.



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図 13. TIDA-01008 Schematic: MSP430FR2633

2.3.2.1.1 I²C Device Addresses

All devices that communicate on the I²C bus in this design have their own unique I²C address. 表 3 lists the device addresses for the I²C bus.

表 3. Device I²C Addresses

DEVICE	ADDRESS	CONFIGURATION
MSP430™	Master	N/A
OPT3001	100 0100	ADDR pin LOW
TMP423	100 1100	N/A (Hardset)

2.3.2.2 Optical Sensing

The OPT3001 ambient light sensor is used to measure the ambient light level exposed to the display. The only hardware recommendations for the OPT3001 sensor is a bypass capacitor on the VDD pin to ensure stable, low-noise input power. The digital interface pins require pullup resistors. The OPT3001 has an open-drain interrupt and interrupt reporting system that allows the processor connected to the I²C bus to enter sleep mode, or otherwise ignore the device results, until a user-defined event occurs that requires possible action. Two major interrupt reporting modes are available: latched-window comparison mode and transparent hysteresis-style comparison mode. This reference design has the interrupt connected to the MCU but does not use these interrupt modes. I²C read calls are used to read the data from the device. For more information on the modes and use of the interrupt pin, see [OPT3001 Ambient Light Sensor \(ALS\)](#).

The light level is read from a 16-bit register that has two fields: a 4-bit exponent(E[3:0]) and 12-bit mantissa (R[11:0]). The exponent field is based on the full-scale range and sets the least significant bit (LSB) size for one lux. This design used the auto-scaling feature of the device and calculated the resulting lux in 式 2.

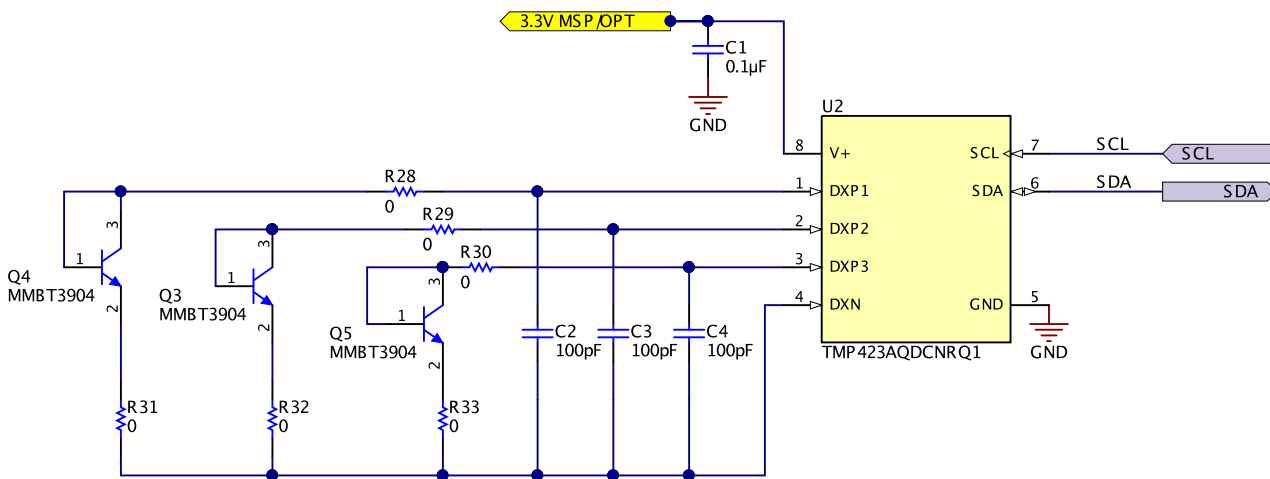
$$\text{Lux} = 0.01 \times (2^{E[3:0]}) \times R[11:0] \quad (2)$$

2.3.2.3 Temperature Sensing

This reference design uses a digital temperature sensor and remote transistors to sense the temperature at different locations around the board (see 図 14). Alternative to using a thermistor network and sequential ADC, the TMP423 device allows temperature monitoring through an I²C bus. This design measures four total locations using the TMP423 sensor: one local die measurement channel and three remote junction temperature measurement channels.

The use of either NPN or PNP transistors is permissible as long as the base-emitter junction is used as the remote temperature sense. The designer can connect the remote transistors to the temperature sensor in two different configurations: diode connected and transistor connected. The diode-connected configuration provides better settling time. The transistor-connected configuration provides better series resistance cancellation. NPN transistors must be diode-connected. PNP transistors can either be transistor or diode-connected.

In this example, the reference design uses NPN transistors in the diode configuration.



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図 14. TIDA-01008 Schematic: Remote Temperature Sensor

2.3.2.4 CapTivate™ Touch Slider

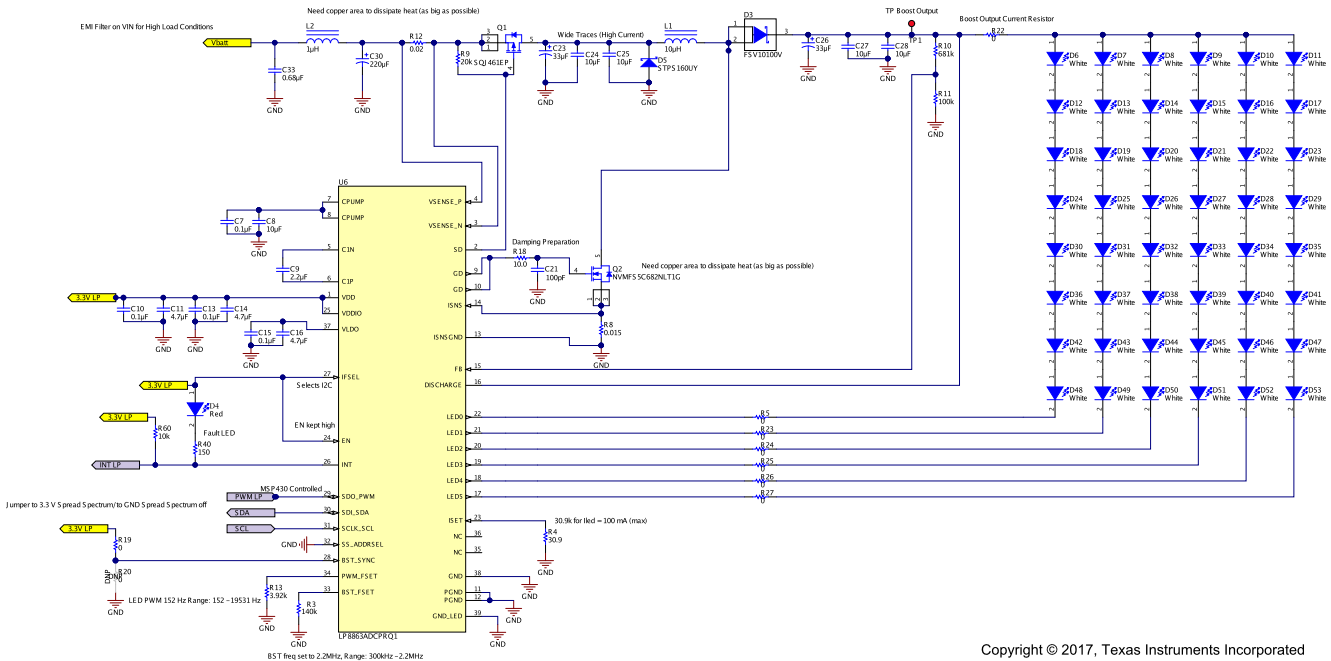
CapTivate technology uses copper as an electrode and measures the change in capacitance whenever a finger touches the electrode. A capacitive touch slider comprises three or more electrodes placed sequentially together. When a person touches a slider, the MCU senses an absolute position representing the point along the slider where the touch occurred. This absolute position is used to further tune the ambient adjusted backlight brightness based on the user's brightness preference.

For more information on CapTivate technology and implementation, see [CapTivate Technology Guide](#).

2.3.3 Backlight Driver, Boost Circuit, and LED Array Overview

Because LEDs typically have a forward voltage of a few volts, the voltage must be boosted to allow for a larger number of LEDs per string. Accomplish this boosting with a backlight driver and boost circuitry. The LP8863-Q1 is an automotive, high-efficiency LED driver with booster controller and six high-precision current sinks. The LED driver supports one to six LED strings with a max current of 150 mA and boost voltage of 47 V.

Figure 15 shows the schematic for the backlight driver, boost, and LED circuitry.



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Figure 15. TIDA-01008 Schematic Backlight, Boost, and LED

2.3.3.1 LED Configurations Array

2.3.3.1.1 LED Configurations

Display backlight LED configurations have two main types of configurations. The more common of the two, the edge-lit configuration, has the LEDs placed around the edge of the display and uses a light guide to channel and distribute the light upward through the liquid-crystal display (LCD) panel. The direct-lit configuration consists of an array of LEDs that are directly behind the LCD panel in an array configuration. This reference design has the LEDs configured as a direct-lit array due to the easier mechanical design and demonstration. The edge-lit configuration is also acceptable for this design and would only change the physical location and orientation of the LEDs and require additional optical light guides.

The LED array in this design consists of six strings of eight LEDs. The LED array spans the entire top side of the board, which is sized to be comparable to a 12-in display.

2.3.3.1.2 LED Selection

The LEDs in this design are the OSRAM KW DPLS32.EC compact LED from the OSRAM SYNIOS E4014 family. These LEDs have a low-profile and compact design of 4.0 × 1.4 × 0.65 mm. The LEDs also have a typical forward voltage of 3.15 V, max forward current of 180 mA, and typical optical efficiency of 110 lm/W with a color temperature of 5700 K.

For information on setting the LED driver and boost configuration for these LEDs, see [2.3.3.4](#).

2.3.3.2 Backlight Driver and Boost Converter

2.3.3.2.1 Dimming Ratio and LED Output PWM

The LED PWM frequency is generated from the internal 20-MHz oscillator and can be set to eight discrete frequencies from 152 Hz to 19.531 kHz by setting the PWM_FSET resistor. The dimming ratio depends on the selected PWM frequency and the minimum output pulse of the LED driver. The LP8863 has an LED output minimum pulse of 200 ns. This reference design demonstrates the maximum dimming ratio with a LED PWM frequency of 152 Hz. The theoretical dimming ratio can be calculated using [式 3](#).

$$\text{Theoretical dimming ratio} = 1 \text{ PWM Freq.} \times 200 \text{ ns} \quad (3)$$

2.3.3.2.2 Brightness Level Interface

The LP8863-Q1 backlight driver has three available brightness-level interfaces compatible with the MCU, which are I²C, SPI, and PWM. This design selects the I²C interface because it generates less noise and does not require a constant signal, such as the PWM.

This design provides MCU-to-LED driver connections for both PWM and I²C; the user can implement the desired interface through software.

2.3.3.3 Output Discharge and Voltage Bleeder

During a correct shutdown sequence, the LED driver discharges the output when the device is disabled. The discharge pin, hooked up to the boost output, sinks 30 mA of current to quickly discharge the output voltage.

During an atypical shutdown, such as input power being removed, the output voltage remains high due to the residual voltage in the capacitors. This voltage discharges slowly through the feedback network and ESR of the output capacitors. Bench testing revealed that this residual voltage interferes with the string detection during initialization after a fast shutdown and restart. Two such cases where the shutdown and start-up profile resulted in incorrect string detection were pressing the reset button on the board or programming the MSP430™ MCU.

To mitigate this behavior, the LP8863-Q1 device is enabled then quickly disabled to activate the quick discharge functionality. Subsequently, the load switch is then toggled off then back ON to allow the LED driver to restart in the correct state. This start-up sequence takes approximately 200 ms; see [3.2.3.3](#) to observe the sequence. While the boost converter does switch momentarily, the device is still in its initialization mode; therefore, no backlight flicker is present.

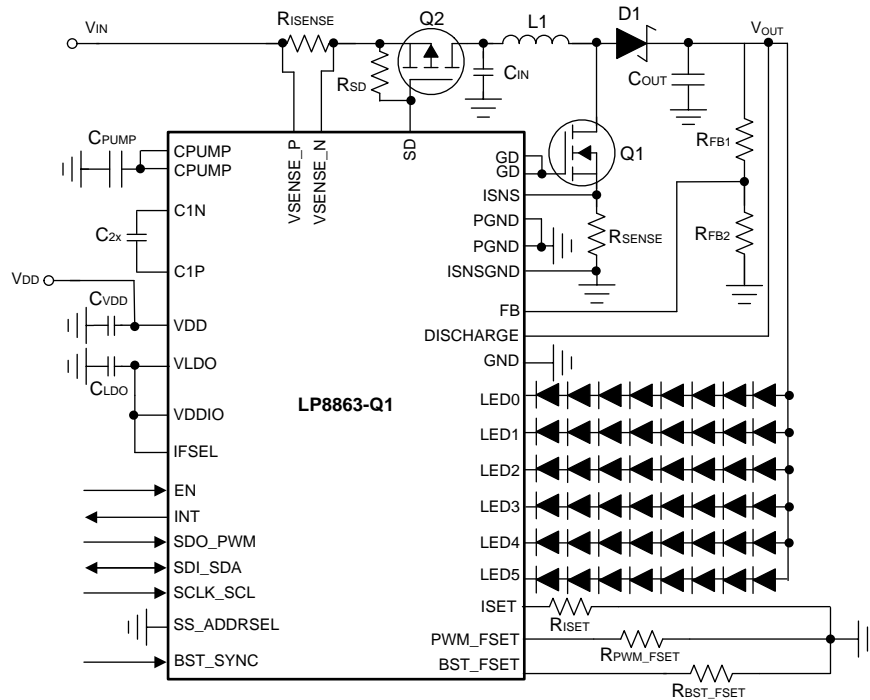
2.3.3.4 Boost Voltage and LED Current

The LEDs forward voltage characteristics and number per string determine the boost voltage required to drive the LEDs. When setting V_{MAX} , the designer must add at least 30% margin to the worst-case boost voltage. The LED drive voltage should theoretically be 27.2 V across the eight LEDs based on the worst-case forward voltage of 3.4 V.

The max LED current per string that each current sink can pull is set by the R_{ISET} resistor. The KW DPLS32.EC LEDs used in this design have a max current capability of 180 mA, while the LED driver can support up to 150 mA. The string current is set to 100 mA, which is chosen due to the high temperature rise of the LEDs when operating at 150 mA and measuring at 100°C.

2.3.3.5 Boost Controller and Circuitry

The LP8863-Q1 current-mode-controlled boost DC/DC controller generates the bias voltage for the LEDs (see [Figure 16](#)).



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Figure 16. LED Driver and Boost Circuit

Table 4 lists the boost converter and LED driver parameters per the reference design components.

Table 4. LED Driver and Boost Parameters

PARAMETER	SPECIFICATIONS	COMPONENT OR PIN	DETAILS
Boost frequency	2.2 MHz	BST_FSET	2.3.3.5.2
V_{OUT_MAX}	35 V	$R_{FB1} = 681 \text{ k}\Omega$	2.3.3.5.1
		$R_{FB2} = 100 \text{ k}\Omega$	
Boost current limit	13.3 A	$R_{SENSE} = 15 \text{ m}\Omega$	2.3.3.5.5
LED string current limit	100 mA	$R_{ISET} = 30.9 \text{ k}\Omega$	2.3.3.4
Output configuration	LED0 to LED5, display mode (phase shift 60°)		2.3.3.1.1
Charge pump	Enabled		

表 4. LED Driver and Boost Parameters (continued)

PARAMETER	SPECIFICATIONS	COMPONENT OR PIN	DETAILS
Spread spectrum	Enabled		2.3.3.5.2
Discharge function	Enabled	V _{BOOST} tied to discharge pin	2.3.3.3
BOOST COMPONENT	VALUE AND PART NO	DESCRIPTION	DETAILS
Input capacitance	33 μF	Polmyer hybrid, 20%, 50 V, 40 Ω	2.3.3.5.6
	10 μF (x2)	CERM, 50 V, 10%, X7R	
Power line FET	SQJ461EP	P-Ch, 60 V,30 A, SO-8L	2.3.3.5.3
Switch FET	NVMFS5C682NLT1G	N-CH, 60 V, 25A, SO-8FL	2.3.3.5.5
Inductor	10 uH	I _{SAT} 15.5 A, 0.0164 Ω	2.3.3.5.4
Diode	FSV10100V	100 V, 10 A, TO-277A	2.3.3.5.7
Output capacitance	33 μF	Polmyer hybrid, 20%, 50 V, 40 Ω	2.3.3.5.6
	10 μF (x2)	CERM, 50 V, 10%, X7R	

2.3.3.5.1 Maximum Output Voltage

The recommended maximum boost voltage is 30% higher than the expected maximum LED string voltage. A maximum output voltage of 35 V is chosen because the maximum LED string voltage is approximately 27 V for this design. Feedback resistors R_{FB1} and R_{FB2} determine the maximum boost output level. Calculate the output voltage as shown in 式 4:

$$V_{OUT_MAX} = \left(\frac{V_{BG}}{R_{FB2}} + I_{SEL_MAX} \right) \times R_{FB1} + V_{BG} \quad (4)$$

where,

- V_{BG} = 1.21 V,
- I_{SEL_MAX} = 38.7 μA,
- R_{FB2} = 100 kΩ (recommended for boost mode).

The bottom resistor in the feedback network (R_{FB2}) is set to the recommended value of 100 kΩ. For a maximum output voltage of 35 V, the top resistor in the feedback network (R_{FB1}) is set to 681 kΩ.

2.3.3.5.2 Boost Frequency

The LP8863-Q1 LED driver supports a wide range of switching frequencies from 300 kHz to 2.2 MHz. The R_{BST_FSET} resistor sets the boost switching frequency. A value of 140 kΩ is chosen to set the frequency at 2.2 MHz. Spread spectrum is enabled in this design for its benefits in damping noise at the fundamental frequency of the boost. For more details about the boost controller and boost frequency selection, see the boost controller section in [LP8863-Q1 Automotive Display LED-Backlight Driver With Six 150-mA Channels](#).

2.3.3.5.3 Power-Line FET and Sense

A power-line FET is used to disconnect the input power from the boost input to protect the LP8863-Q1 device and boost components in the case of an overcurrent event. A P-type MOSFET is used for the power-line FET. The voltage rating must be at least 25% higher than the maximum input voltage level. A low R_{DS(ON)} is important to reduce the power loss on the FET; TI recommends less than 20 mΩ. The current rating for the FET must be at least 25% higher than input peak current. The gate-to-source voltage (V_{GS}) for the open transistor must be less than the minimum input voltage; use a 20-kΩ resistor between the p-FET gate and source.

2.3.3.5.4 Inductor Selection

Be sure to consider the inductance, current rating, and DC resistance when choosing an inductor. The section regarding inductor selection in the LP8863 data sheet recommends inductance values for a range of switch frequencies. The LP8863-Q1 device automatically sets internal boost compensation controls depending on the selected switching frequency. Thus, the recommended value of 10 μH is used in the design.

2.3.3.5.5 Switching FET and Boost Sense Resistor

The switching FET is a critical component for determining the power efficiency of the boost converter. Consider several mandatory aspects when selecting a switching FET, such as the voltage and current rating, $R_{\text{DS(ON)}}$, power dissipation, thermal resistance, and rise and fall times. An N-type MOSFET with a voltage rating at least 25% higher than the maximum output voltage must be used. The current rating of the switching FET must be equal to or higher than the inductor rating. $R_{\text{DS(ON)}}$ must be as low as possible; TI recommends less than 20 $\text{m}\Omega$. The thermal resistance ($R_{\theta\text{JA}}$) must also be low to dissipate heat from any power loss on the switching FET. The NVMFS5C682NLT1G N-Channel FET is used in the design. This FET has a 60-V voltage rating and 25-A current rating.

The R_{SENSE} resistor determines the boost overcurrent limit and is sensed every boost switching cycle. A high-power 20- $\text{m}\Omega$ resistor can be used for sensing the boost SW current and setting the maximum current limit at 10 A (typical). The designer can increase R_{SENSE} to lower this limit, which can be calculated using 式 5; however, do so with care because this change may also affect the stability. The boost overcurrent limit must not be set below 4 A; therefore, R_{SENSE} must not exceed 50 $\text{m}\Omega$. Calculate the power rating from the inductor current and sense resistor resistance value.

$$R_{\text{SENSE}} = \frac{200 \text{ mV}}{I_{\text{BOOST_OCP}}} \quad (5)$$

where,

- R_{SENSE} : boost sense resistor ($\text{m}\Omega$),
- $I_{\text{BOOST_OCP}}$: boost overcurrent limit.

A value of 15 $\text{m}\Omega$ is used in this design to set the boost overcurrent limit to 13.3 A.

2.3.3.5.6 Input and Output Capacitors

The output capacitance value determines the voltage ripple and boost stability. Ensure that enough effective capacitance is on the output after DC-derating. TI recommends a capacitance of at least 50 μF on the output. A 33- μF polymer hybrid and two 10- μF ceramics are used for the output capacitance in this reference design.

TI also recommends to match the input capacitance to the output capacitance. Although the input capacitance is not quite as critical to the boost operation, minimizing the input capacitance too much limits the amount of input power filtering. For this design, the 33- μF and two 10- μF capacitors are use for the input capacitance.

2.3.3.5.7 Boost Diode

A Schottky diode must be used for the boost output diode. The current rating must be at least 25% higher than the maximum output current; TI recommends a 12-A current rating for most applications. Schottky diodes with a low forward drop and fast switching speeds are ideal for increasing efficiency. At maximum current, the forward voltage must be as low as possible; less than 0.5 V is recommended. Reverse breakdown voltage of the Schottky diode must be significantly larger than the output voltage; 25% higher voltage rating is recommended. TI does not recommend using ordinary rectifier diodes because slow switching speeds and long recovery times cause efficiency and load regulation to suffer. The diode used in this design is the FSV10100V, a 100-V, 10-A Schottky diode with a forward drop of less than 500 mV when I_F is below 5 A.

2.3.3.5.8 Gate Resistor and Capacitor

A gate resistor and capacitor is placed between the gate drive pin and the gate of the boost FET to decrease the switch transition speed. This placement reduces the ringing on the switch node, which improves the noise and EMI performance of the boost converter (see [Figure 17](#)).

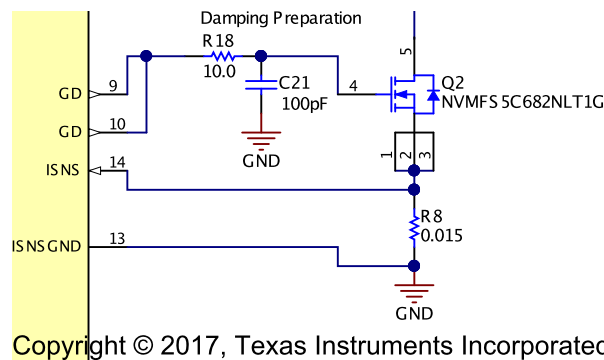
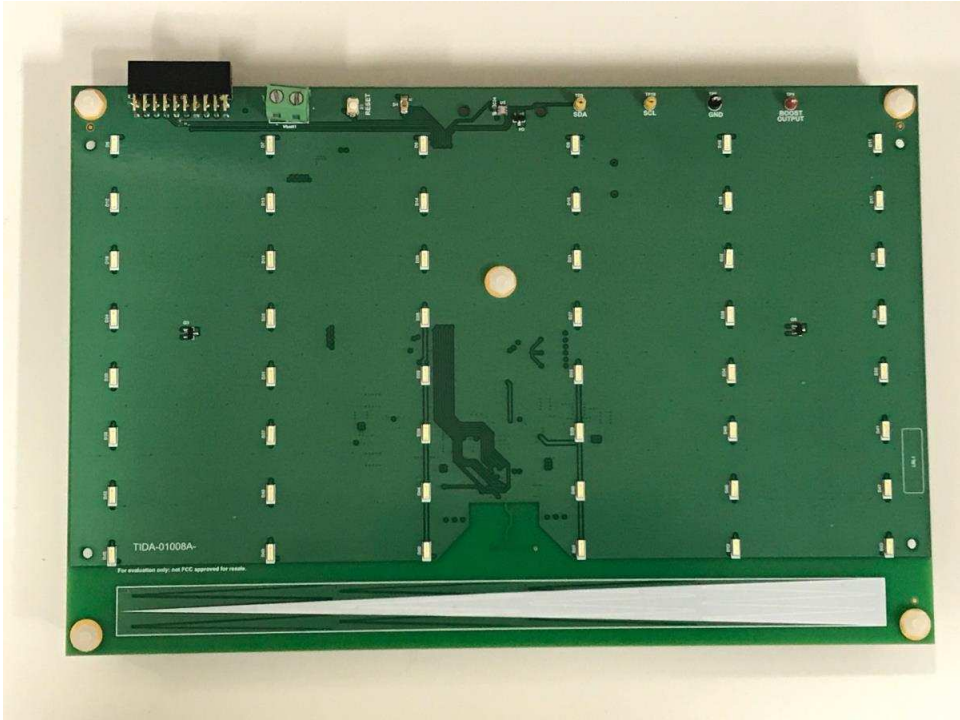


Figure 17. TIDA-01008 Schematic: Gate Resistor and Capacitor

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The LED array, connectors, sensors, and touch slider are located on the top side of the board. All other integrated circuits (ICs) and passive components are located on the back side of the board.  18 shows the top side of the design board.

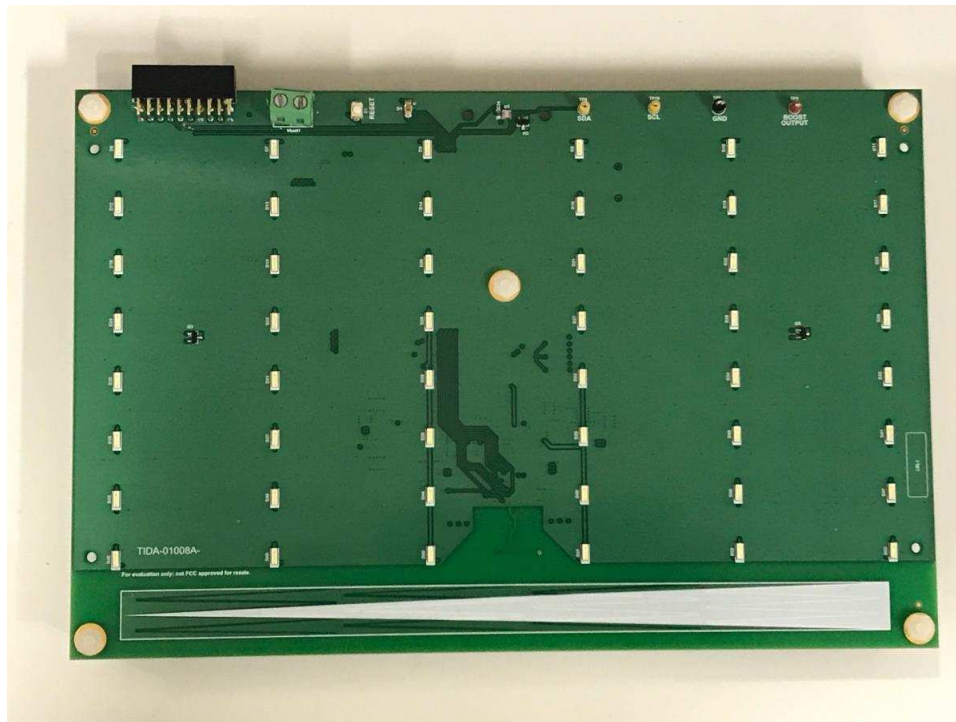


図 18. TIDA-01008 Board Top

The 48 LEDs are evenly distributed in eight columns across the top side of the board. Each column of LEDs is connected the LEDx pin on the LED driver. The ambient light sensor is placed on the top side of board at the top of the LED array, or where the display would be. Three remote transistors for temperature sensing are placed on the left and right side of the board within the LED array and an additional transistor is placed beside the OPT3001 sensor. The touch slider is also on the top side of the board and located beneath the LED array. The debug port, power connector, and I²C and V_{BOOST} test pins are placed on the top side of the board.

Aside from the sensors and LEDs, all ICs and circuitry are located on the bottom side of the board (see [Figure 19](#)).

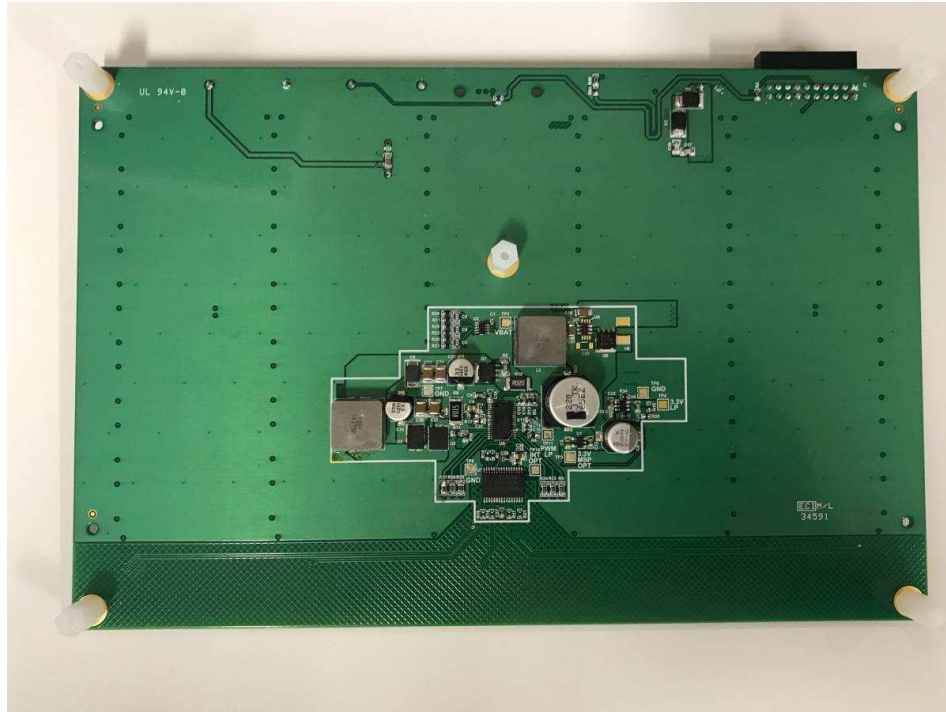


Figure 19. TIDA-01008 Board Bottom

[Figure 20](#) shows the input to output power path. The boost circuit is located on the right half of the circuit, the MSP is on the bottom, the LDO and load switch are to the right, and the ideal diode and PI filter are to the upper right.

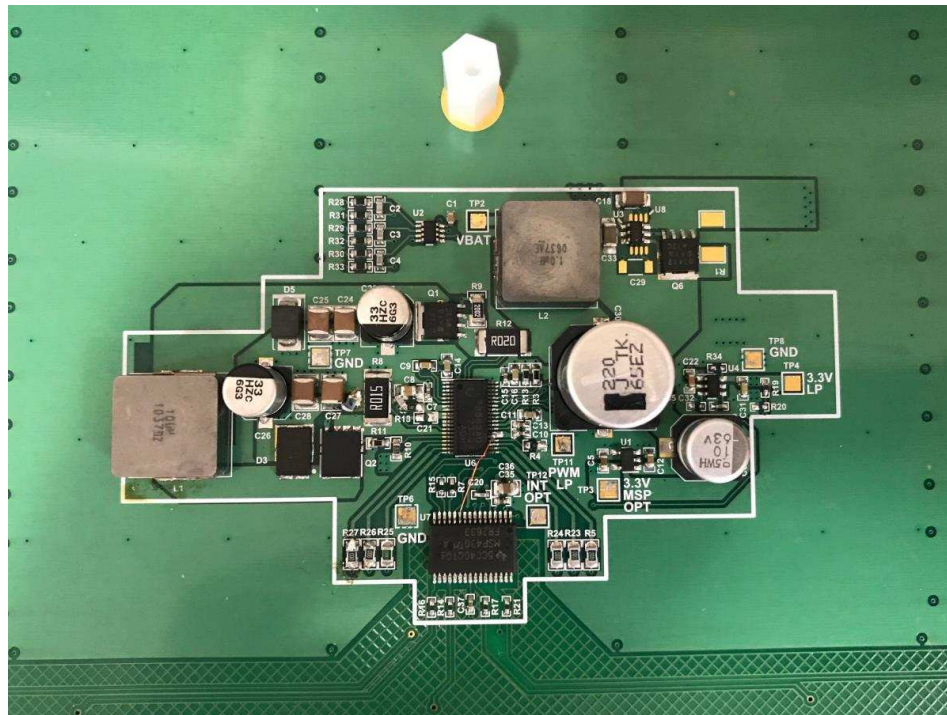
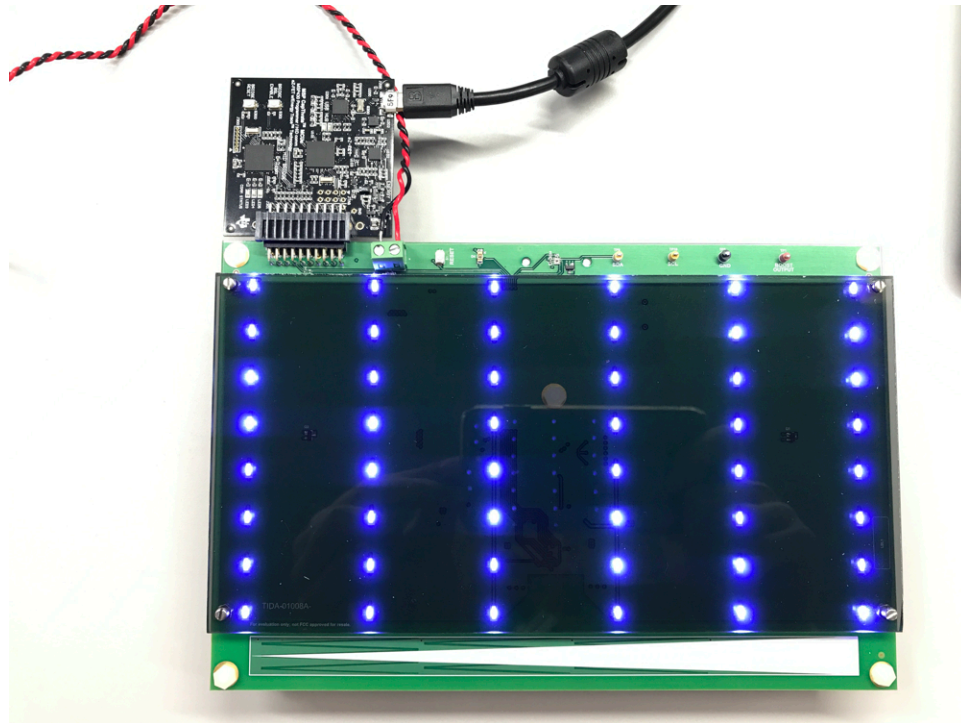


図 20. TIDA-01008 Board Bottom Zoom

3.1.1.1 LED Brightness Attenuation

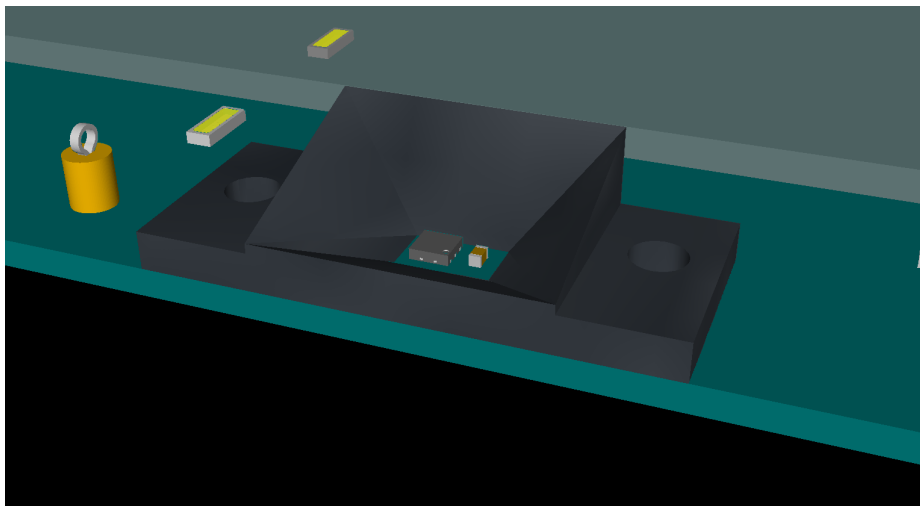
In this reference design, the backlight does not have a LCD panel, diffuser, or the rest of the LCD stack-up. For the purpose of testing and demonstration, a piece of tinted acrylic is mounted above the LED array to attenuate some of the illumination of the backlight. 図 21 shows the acrylic mounted on the board.



☒ 21. TIDA-01008 With Acrylic Light Attenuator

3.1.1.2 Light Sensor Shield

The optical sensor is placed on the top side of the board and is therefore flush with the LED array. To prevent the emitted light from the LEDs from interfering with the lux reading, place a light shield over the top of the sensor to block the emitted light. The light shield is constructed using a 3D printer and acrylonitrile butadiene styrene (ABS) plastic. ☒ 22 shows the fabricated light shield.



☒ 22. TIDA-01008 Light Shield

3.1.1.3 CAPTIVATE-PGMR Programmer PCB Overview

The CAPTIVATE-PGMR PCB provides debug services. The software includes an eZ-FET with EnergyTrace and a human interface device (HID) bridge for bringing UART and I²C into a host PC (see [23] and [24]).

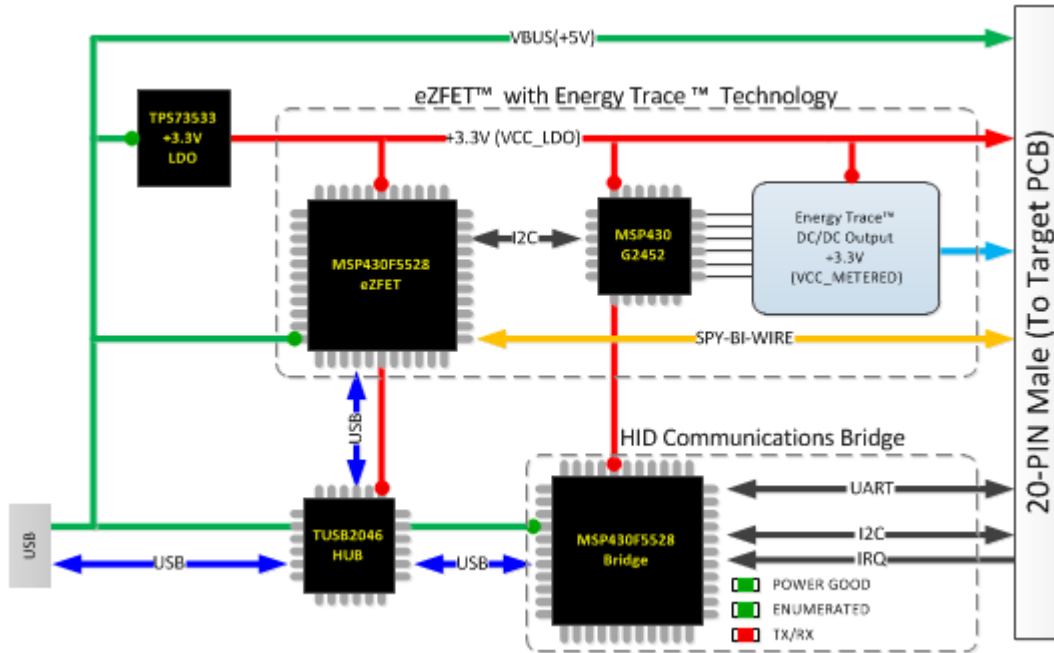


図 23. CAPTIVATE-PGMR PCB Block Diagram

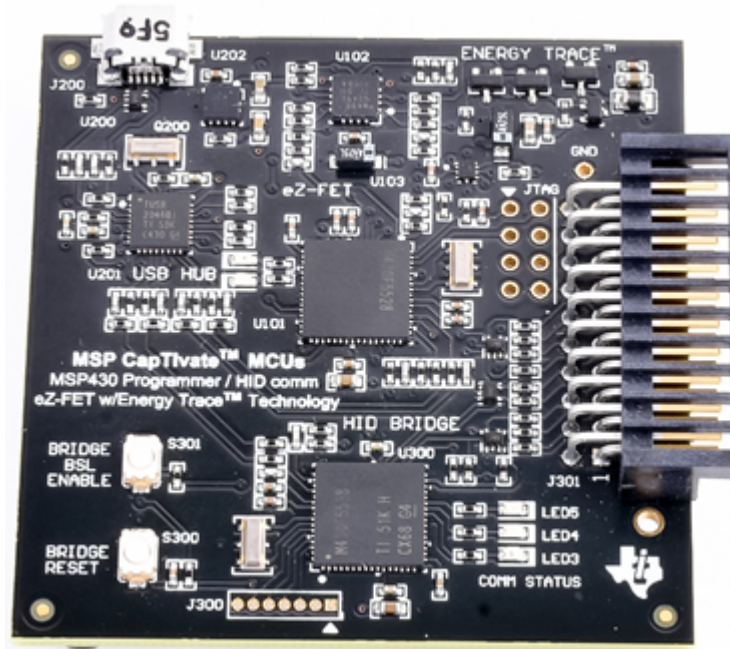



図 24. CAPTIVATE-PGMR PCB Hardware

Features:

- eZFET™ with EnergyTrace™ software
- Simple Spy-Bi-Wire target MCU programming
- Can be used to program any MSP430
- Separate +3.3-V outputs available for MCU
 - EnergyTrace™
 - Dedicated LDO
- 20-pin programmer, power, and communications connector
 - Spy-bi-wire interface
 - UART and I²C serial communication with target
 - +5-V USB
 - Two +3.3-V supply rails
- USB HID serial bridge
 - Provides interface between CapTivate™ Design Center and target MCU
 - Supports UART and I²C
 - HID: No drivers to install
 - Supports up to 250k baud
 - Easy update through bootstrap loader (BSL)

3.1.1.3.1 Programming, Power, and Communications Connector (20-Pin Male)

The male connector that the following  25 shows is designed to connect with the CAPTIVATE-FR2633 MCU PCB. This connector provides power, programming, and communications between the two PCBs. The programmer can be used to program a user's target PCB directly if the PCB has the mating connector or it is possible to connect only the required signals, power, and ground using wires. Note that the wires must be kept as short as possible, typically less than 20 cm. As an example of a typical "wired" connection scheme, the highlighted yellow boxes show the typical connections, such as:

- +3.3 V
- Ground
- SBWTCK_TST
- SBWDIO_RST
- UART-TXD
- UART-RXD

By using only these few signals, a smaller connector can be used on the user's PCB.

The SBWTCK_TST and SBWDIO_RST Spy-By-Wire signals are used for programming and debug, while the UART-TXD and UART-RXD are used to communicate with the CapTivate Design Center during development and the sensor tuning process. Optionally, the I²C communication signals SDA, SCL, and IRQ are provided on the connector and may be used instead of the UART signals.

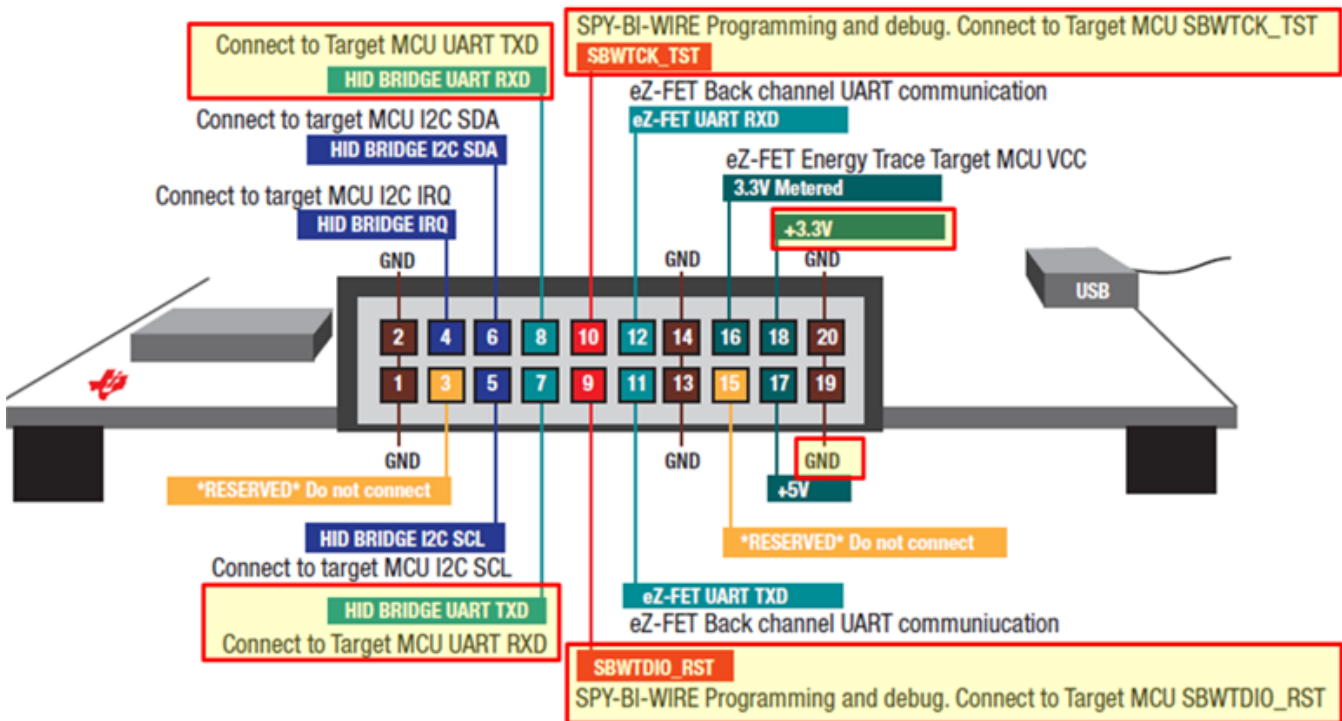


図 25. Programmer Connector Pinout

3.1.1.3.1.1 Power

The USB connector provides the power to the CAPTIVATE-PGMR PCB at approximately 5-V DC. A TI TPS73533 3.3-V, 500-mA LDO provides power for all the devices on the CAPTIVATE-PGMR. This 3.3-V output is referred to as VCC_LDO and is made available to the MSP430FR2633 target MCU on the CAPTIVATE-FR2633 PCB when attached. The eZFET™ with EnergyTrace™ technology also provides a DC/DC 3.3-V output. This output is referred to as VCC_METERED and is available only to the target MCU for energy measurements. A jumper on the CAPTIVATE-FR2633 PCB selects between the two sources for the MSP430FR2633.

注: The CAPTIVATE-PGMR is considered a low-power USB device and therefore should draw at most 100 mA. The CAPTIVATE-PGMR PCB draws a nominal 60 mA, which allows any target to draw up to 40 mA.

3.1.1.3.1.2 Programming and Debug

The eZFET™ provides programming and debugging through its Spy-Bi-Wire interface.

The eZFET™ back-channel UART feature is available on this PCB; however, the CAPTIVATE-FR2633 does not support this feature.

3.1.1.3.1.3 Using Spy-Bi-Wire (SBW) Programming CAPTIVATE-ISO PCB

See the [JTAG and SBW limitations](#).

3.1.1.3.2 Target Communication Through USB HID Serial Bridge

The CAPTIVATE-PGMR PCB features a HID bridge which enumerates as a USB HID device and does not require any drivers to be installed on the PC. The HID device supports both I²C and UART interfaces and is factory programmed with a compact communications protocol for sending sensor data and status between the target MCU and the CapTlvate™ Design Center. For detailed information regarding the communications protocol, see the [HID bridge section](#).

The key features include:

- Supports UART and I²C interfaces
- Factory programmed with CapTlvate™ protocol
- No USB drivers required
- Easy firmware updates using USB BSL
- For more information, see the [HID bridge section](#).

The MSP430F5528 bridge MCU supports firmware updates using the USB BSL. To update the existing firmware or load a user-defined firmware image, use the “Python Firmware Upgrade” utility provided with the MSP430Ware™ software. Depending on the source installation folder for MSP430Ware, navigate to the “...MSP430ware...\usb430\Host_USB_Software\Python_Firmware_Updater” directory.

1. Place the MSP430F5528 into BSL mode:
 - a. Press and hold RESET button (S300)
 - b. Press BSL button (S301)
 - c. Release RESET button
 - d. Release BSL button
2. Launch the firmware upgrade utility:
 - a. Double-click on the utility icon (the utility scans the USB bus looking for a specific VID/PID combination of the MSP430F5528 in BSL mode)
 - b. If no device is found, repeat the previous steps to place the MSP430F5528 into BSL mode and select *File* → *Rescan Bus* in the utility menu
 - c. When ready, select *File* → *Open user firmware* from the utility menu to select the firmware image and begin the update process

3.1.2 Software

The MSP430 software is written in the Code Composer Studio™ (CCS) integrated development environment v6.

3.1.2.1 Software Overview

 26 shows a simple block diagram of the software for this design.

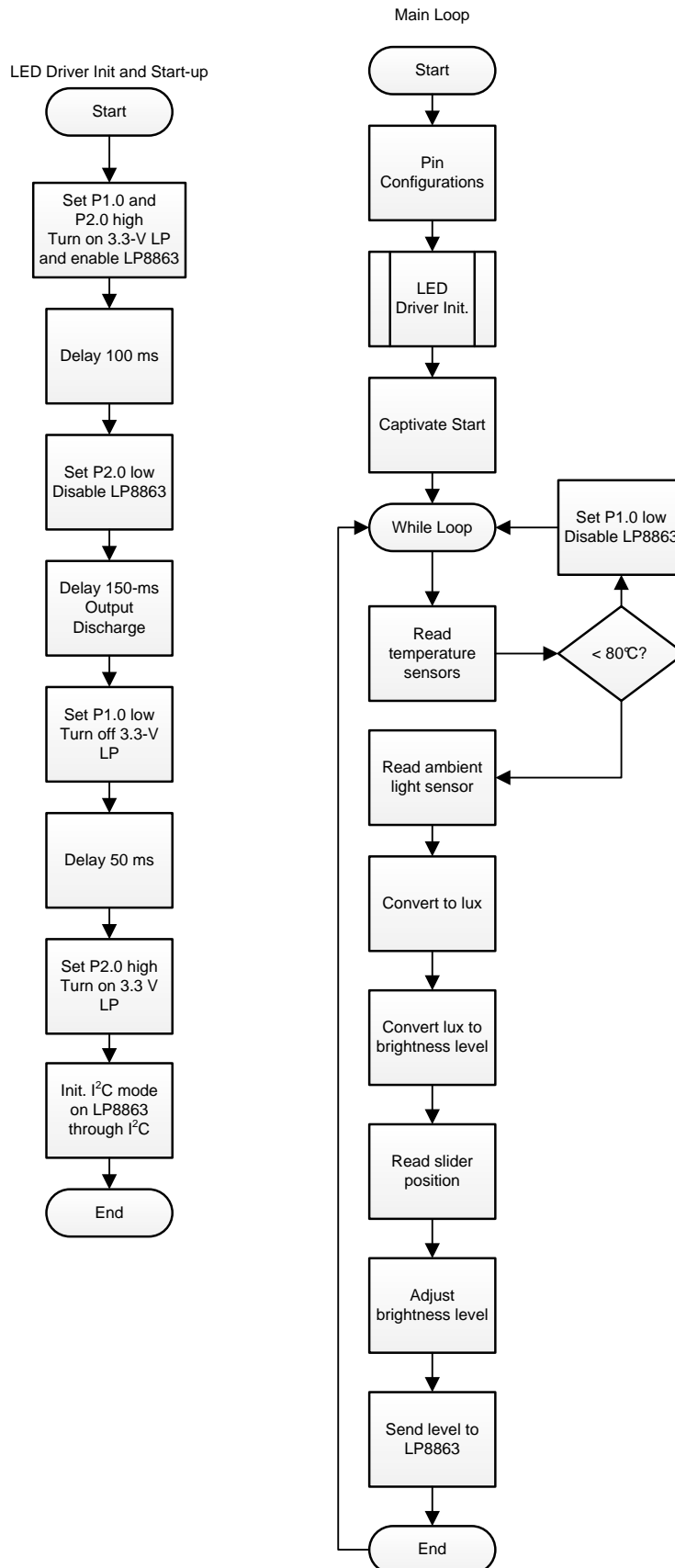
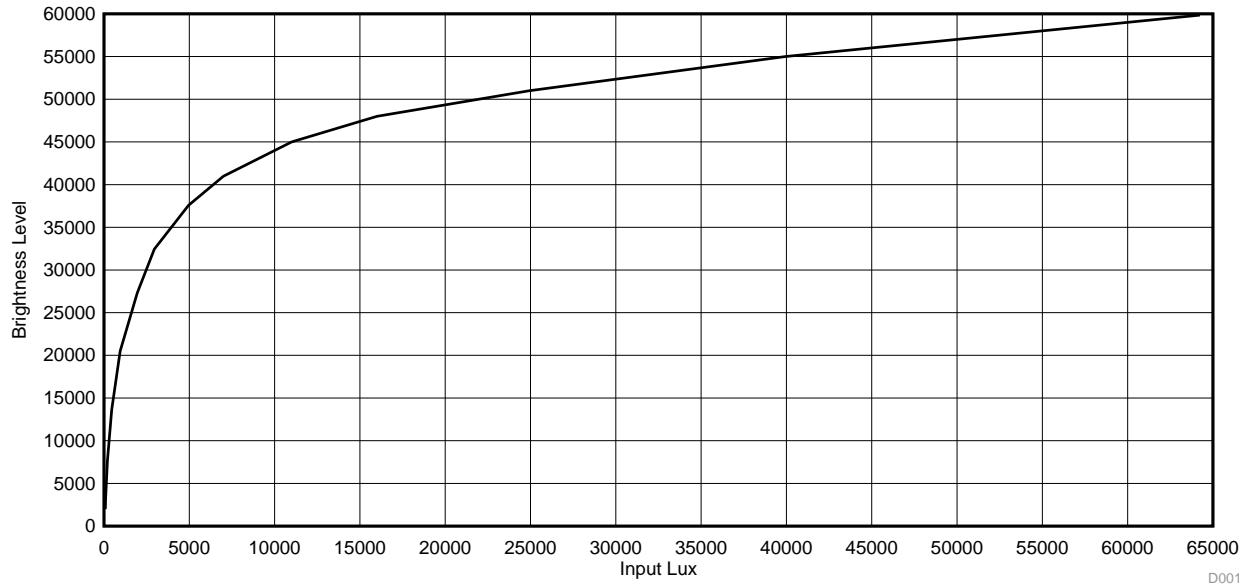


図 26. TIDA-01008 Software Overview

3.1.2.2 Input Lux to Backlight Brightness

Determining the best backlight brightness based on ambient light levels can vary from personal preference and application. The backlight levels of this design are based on a study completed by Microsoft, [Understanding and Interpreting Lux Values](#), which discusses how humans perceive ambient light in an almost logarithmic function.

☒ 27 shows the ambient input lux to backlight brightness curve used for this design.



☒ 27. TIDA-01008 Ambient Lux to Backlight Brightness

3.1.2.3 Sensor Sampling and Frequency

Both of the sensors communicate on the same I²C line, but each have their own unique addresses. Simple read and writes are employed to configure and read data from each of the sensors, then adjust the brightness as necessary. Temperature is checked to ensure that the system temperature is within the safe operating temperature.

3.2 Testing and Results

Testing was performed on the major sensing and power components in the system, including the LP8863-Q1 backlight driver, OPT3001 ambient light sensor, TMP423 temperature sensor, and touch slider output.

3.2.2 describes the test setup and procedures for the tests performed. View the test results in 3.2.3.

3.2.1 Test Equipment

The following equipment was used during the testing of this reference design.

3.2.1.1 Light Meter

An Extech Instruments model #407026 light meter is used as a reference measurement for the ambient light sensor during testing (see [Figure 28](#)). This light sensor can measure lux in the ranges of 0 to 2000, 0 to 20000, and 0 to 50000, with a max resolution of 1, 10, and 100, respectively. The accuracy is $\pm 4\%$.



Figure 28. Extech Light Meter

3.2.1.2 Dark Chamber

A 3x3x18-ft anechoic chamber was re-purposed as a pseudo dark room to test the illuminance of the design and the sensing capability of the OPT3001 sensor (see [Figure 29](#)). This chamber completely blocks out external light. The walls consist of a black foam and all reflective or white surfaces are covered with a light-absorbing fabric. Possible error could have been introduced from the light reflecting off the walls due to the relatively narrow and short enclosure size as compared to the amount of light emitted.




Figure 29. Anechoic Chamber—Pseudo Dark Room

3.2.2 Test Setup

The following subsections explain the test setup for the illuminance and outdoor or in-car brightness testing. [3.2.3.7](#) and [3.2.3.8](#) show the results, respectively. [3.2.3](#) shows the results of other tests that have a more intuitive setup, such as voltage and current testing, temperature testing, and touch slider testing.

WARNING



Hot surface. Contact may cause burns. Avoid touching to minimize the risk of burns.

3.2.2.1 Illuminance Sensing Testing

To demonstrate the illuminance capability of the design, a brightness sweep test was performed in a pseudo-dark chamber (see [Figure 30](#)). Two light meters are used to measure the data during the brightness sweeps: the first is the Extech light meter and the second is the OPT3001 evaluation module. The OPT3001 data demonstrates the ability of the ambient light sensor to measure illuminance and brightness.



Figure 30. TIDA-01008 Illuminance Sensing Testing

The light meter and the OPT3001 EVM were attached to a PVC pole that is connected to a sliding caster on the floor of the chamber (see [Figure 31](#)). This setup allowed the testers to collect the data with the light sensors at multiple distances from the backlight.



図 31. TIDA-01008 Light Meter and OPT3001 EVM Test Setup

3.2.2.2 *Outdoor Light Testing*

Ambient light levels were tested in outdoor and in-car environment to demonstrate the ability of the OPT3001 device to measure sunlight and ambient light conditions. The three locations tested were center stack console, on top of the dash in front of the vehicle, and outdoors in direct sunlight. Because all of these measurements were taken at the same time of day with the same environmental and weather conditions, the results provide insight to the relative brightness of each location compared to the outdoor brightness.

These tests were performed in Dallas on a clear, fall afternoon with the vehicle facing south. 図 32 demonstrates the use of the reference design in the area of the center stack display. Ambient light largely consists of reflected sunlight throughout the vehicle.



図 32. TIDA-01008 Outdoor Brightness—Center Stack Display in Vehicle

図 33 shows the process of measuring the brightness in the front dash of the vehicle, which is another common place to find a light sensor. Sunlight was only attenuated by the windshield in this test condition.



図 33. TIDA-01008 Outdoor Brightness—Front Dash of Vehicle

図 34 shows the process of measuring the direct sunlight when the reference design is placed on the roof of the vehicle. This measurement was taken as a benchmark for the other two test locations inside the vehicle.

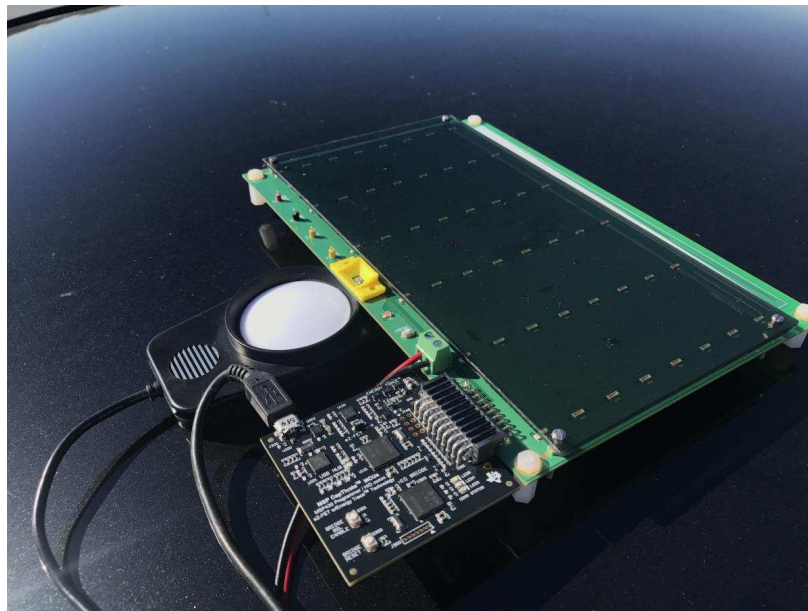


図 34. TIDA-01008 Outdoor Brightness—Outdoors (Top of Vehicle)

3.2.3 Test Results

3.2.3.1 Boost Switch Node

図 35 shows the switch node of the boost converter.

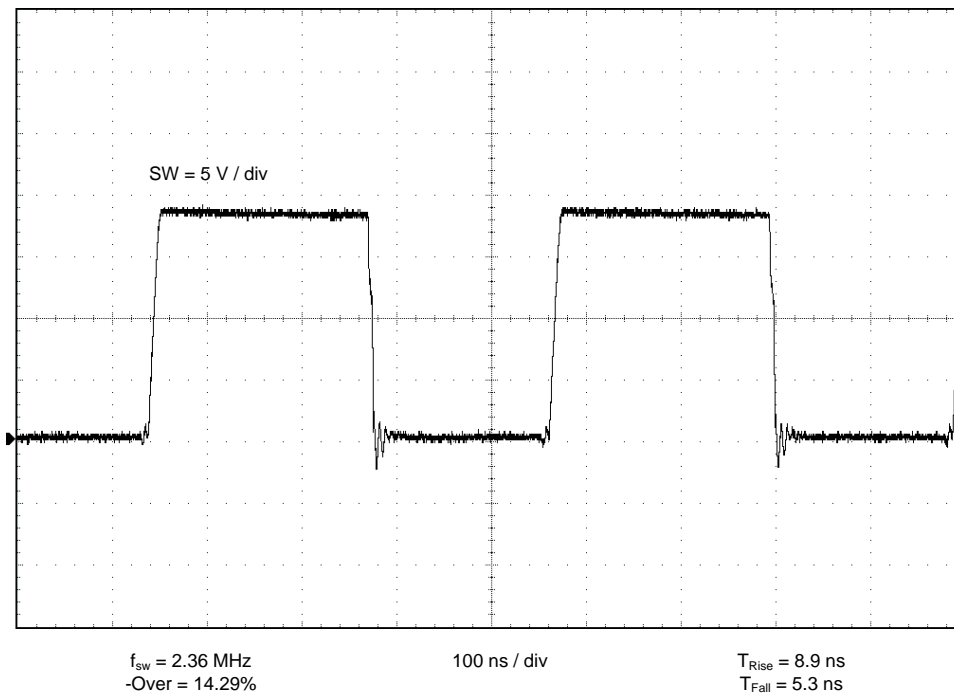


図 35. TIDA-01008 Switch Node

3.2.3.2 Boost Spread Spectrum

Figure 36 shows the spread spectrum mode by using the persistence mode of an oscilloscope.

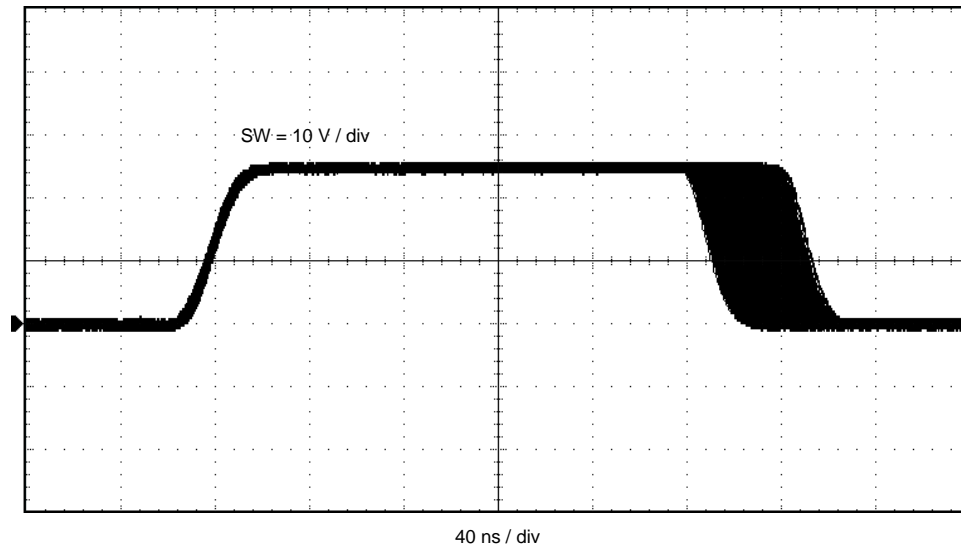


Figure 36. TIDA-01008 Switch Node Spread Spectrum

3.2.3.3 Boost Startup Voltage

Figure 37 shows the boost start-up waveform for the LP8863-Q1 LED driver. Figure 38 and Figure 39 show the start-up sequence and discharge routine described in 2.3.3.3.

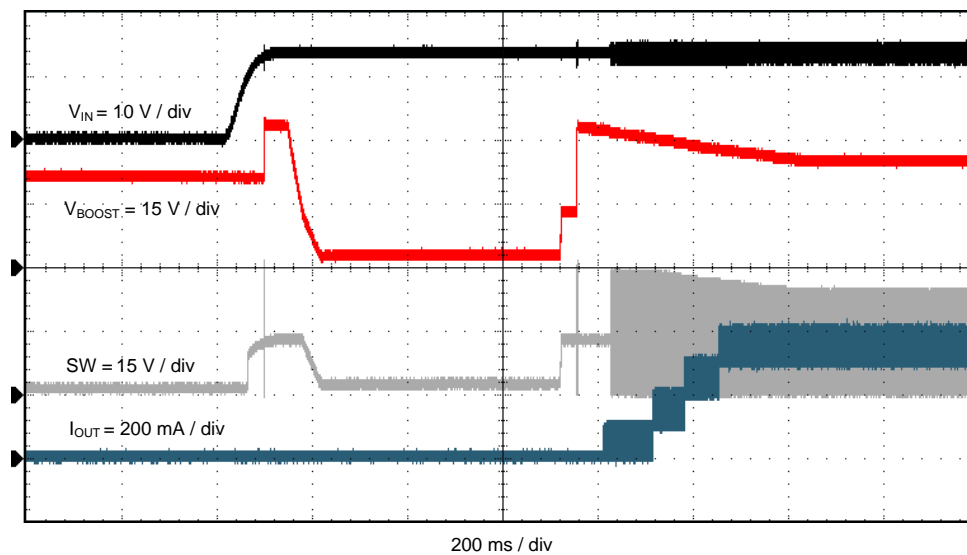


Figure 37. TIDA-01008 Start-Up

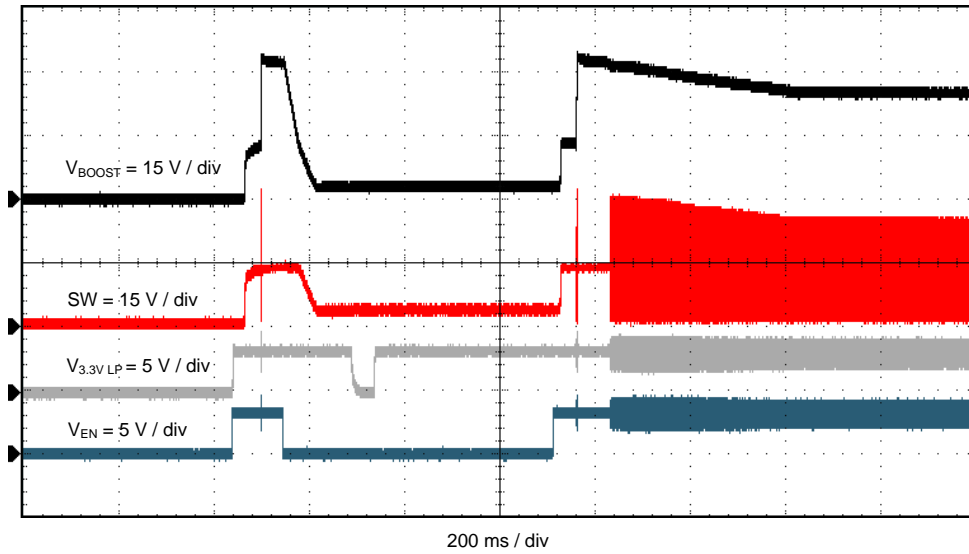


図 38. TIDA-01008 Start-Up Sequence

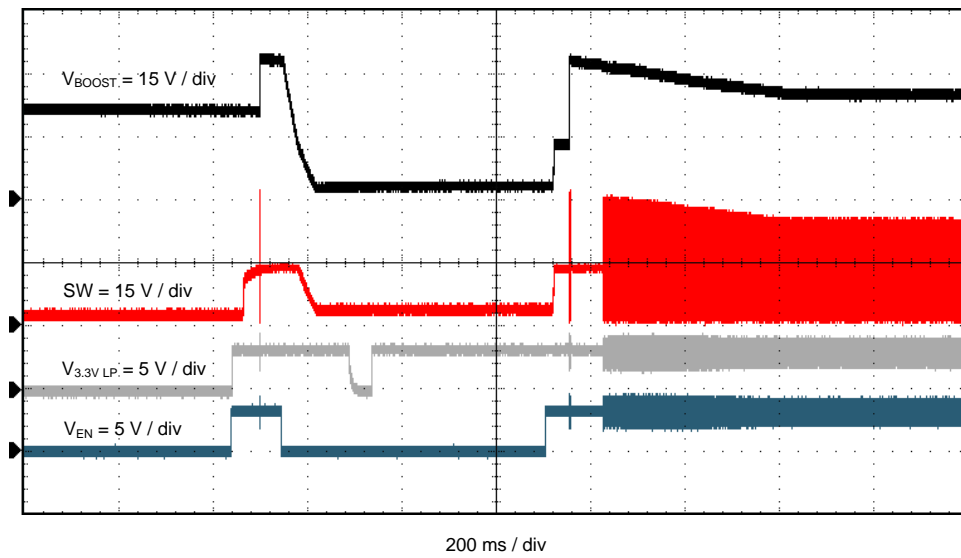


図 39. TIDA-01008 Start-Up Sequence With Residual Voltage

3.2.3.4 LED Current

Figure 40 shows the string LED current through LED0, LED6, and the boost output.

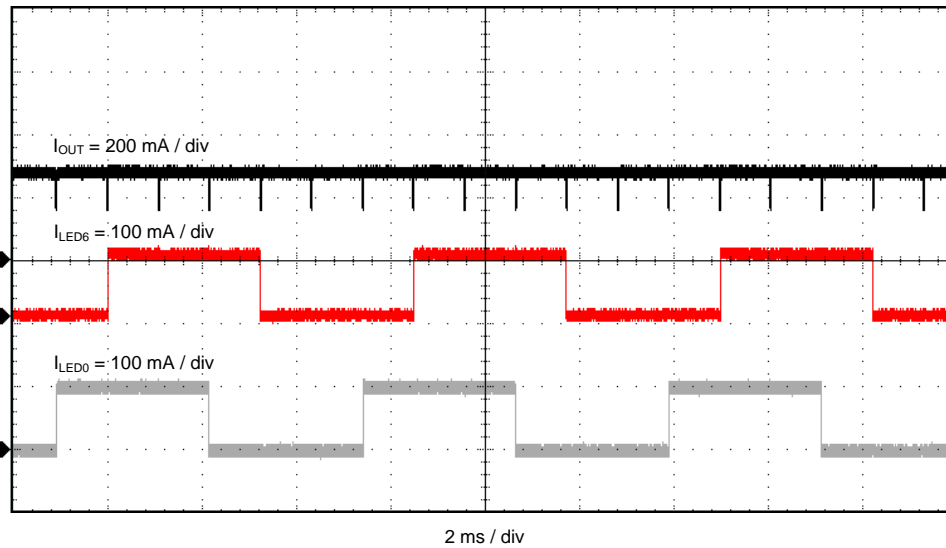


Figure 40. TIDA-01008 LED Current

3.2.3.5 Temperature Testing

Table 5 shows temperature test results of the four sensing locations at various temperatures.

Table 5. Temperature Sensing Tests

OVEN TEMP	LOCAL (HEX °C)	REMOTE 1 (HEX °C)	REMOTE 2 (HEX °C)	REMOTE 3 (HEX °C)
0°C	0x00 0°C	0xFF -1°C	0xFE -2°C	0xFF -1°C
25°C	0x1B 27°C	0x19 25°C	0x19 25°C	0x19 25°C
50°C	0x33 51°C	0x31 49°C	0x31 49°C	0x31 49°C
85°C	0x55 85°C	0x53 83°C	0x54 84°C	0x53 83°C

3.2.3.6 Capacitive Touch Slider Testing

Figure 41 shows a simple three-point touch test performed on the slider to ensure proper sensing values. The slider was touched at the beginning, middle, and end of the strip, after which the values were recorded.

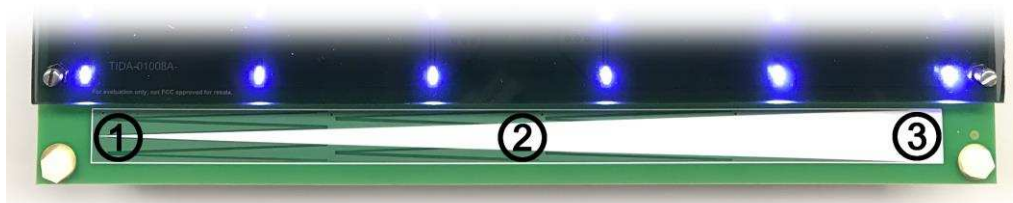


Figure 41. TIDA-01008 CapTivate™ Slider Test

Table 6. Capacitive Touch Slider Testing

LOCATION	1	2	3
VALUE	2	498	997

3.2.3.7 Backlight Illuminance Testing

Figure 42 shows the illuminance of the backlight driver measured from the OPT3001 EVM and Extech light meter. The backlight configuration for this test did not have the acrylic sheet to attenuate brightness and the max LED string current was the maximum at 150 mA.

A few possible reasons could explain the error for the discrepancy between the light meter and the OPT3001 EVM. The first reason is that the sensors have optomechanical builds which vary from one another. The light meter has a light receptor that is much larger than the OPT3001, which means it may not match the OPT3001 at all angles of light. The second possible source of error is from the positioning of both the light meter and EVM. As the previous Figure 31 shows, the OPT3001 and light meter have a slight offset between the placement.

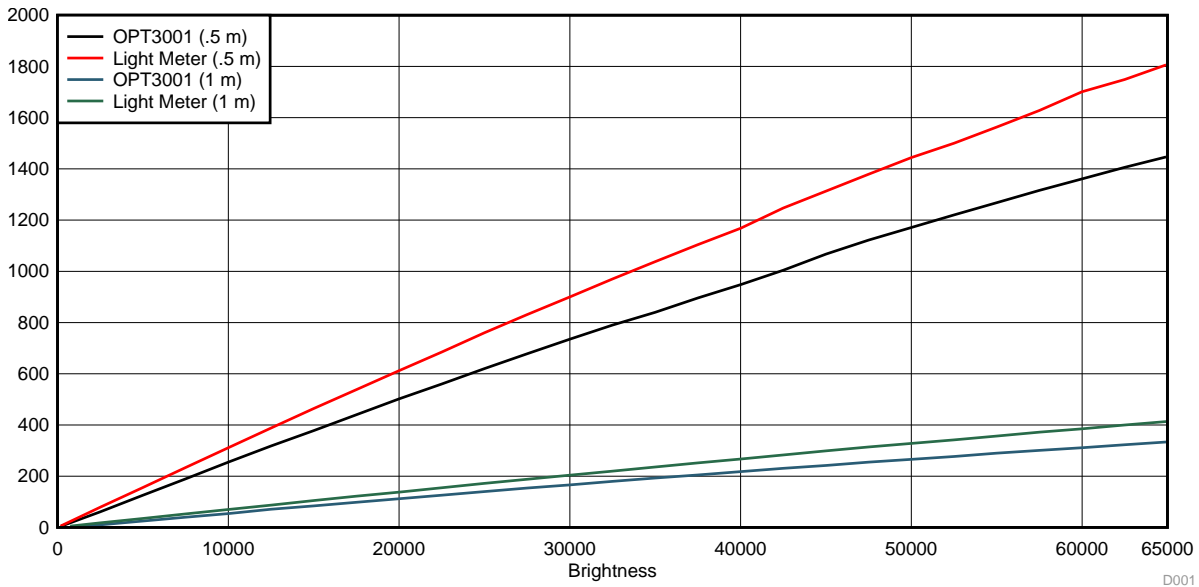


Figure 42. TIDA-01008 Backlight Illuminance Testing

3.2.3.8 Outdoor Light Testing

Table 7 shows the lux readings from the reference design and Extech light meter.

Table 7. Outdoor Light Testing

LOCATION	OPT3001	Extech Light Meter
CENTER STACK CONSOLE	544 lux	539 lux
FRONT DASH	45000 lux	43300 lux
OUTDOORS	61400 lux	64700 lux

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01008](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01008](#).

4.3 PCB Layout Recommendations

This reference design has a 1-oz copper for all four copper layers. Four layers allow routing on the internal layers and also an internal ground layer, which improves noise and thermals. Careful consideration was taken with the component placement in this design. All bypass capacitors are placed as close to the device pins as possible.

Placement of the MSP430 is important to maximize the effectiveness of the CapTivate slider. The slider was placed at the bottom of the PCB. The distance between the slider and the MSP430 must be short to minimize the parasitic capacitance between the electrodes and the sense pins. Therefore, the MSP430 was placed close to the bottom of the PCB. Other ICs in the system were then placed around the MSP430.

The positive and negative traces for each remote temperature channel were kept on the same layer and ran parallel to one another. The LED string traces were routed on the internal layer to help mitigate noise.

For layout recommendations on the LP8863-Q1 and boost circuit, see [PCB Layout Guideline for Automotive LED Drivers](#).

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01008](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01008](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01008](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01008](#).

5 Software Files

To download the software files, see the design files at [TIDA-01008](#).

6 Related Documentation

1. Microsoft.com, [Understanding and Interpreting Lux Values](#)
2. Texas Instruments, [LP8863-Q1 External Component Selection Guide](#)
3. Texas Instruments, [PCB Layout Guideline for Automotive LED Drivers](#)
4. Texas Instruments, [LP8863-Q1 Automotive Display LED-Backlight Driver With Six 150-mA Channels](#)
5. Texas Instruments, [TMP42x-Q1 \$\pm 1^\circ\text{C}\$ Remote and Local Temperature Sensor](#)
6. Texas Instruments, [OPT3001-Q1 Ambient Light Sensor \(ALS\)](#)
7. Texas Instruments, [TPS22918-Q1, 5.5-V, 2-A, 52-m \$\Omega\$ On-Resistance Load Switch](#)
8. Texas Instruments, [MSP430FR263x, MSP430FR253x Capacitive Touch Sensing Mixed-Signal Microcontrollers](#)
9. Texas Instruments, [TPS7B69xx-Q1 High-Voltage Ultra-Low IQ Low-Dropout Regulator](#)
10. Texas Instruments, [LM74700-Q1 Low IQ Always ON Smart Diode Controller](#)

6.1 商標

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7 About the Author

LOGAN CUMMINS is a systems engineer at Texas Instruments. Logan earned his bachelor of science in electrical engineering from Valparaiso University in 2016. As a member of the Automotive Systems Engineering team at Texas Instruments, he is responsible for developing reference design solutions for the Automotive Infotainment and Cluster segment focusing on Displays .

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