

HIGH EFFICIENCY CHARGE PUMP FOR 7 WLEDs WITH I²C INTERFACE

FEATURES

- 3.0-V to 6.0-V Input Voltage Range
- ×1 and ×1.5 Charge Pump
- Fully Programmable Current with I²C
 - 64 Dimming Steps with 25mA Maximum (Sub and Main Display Banks)
 - 4 Dimming Steps with 80mA Maximum (DM5 for Auxiliary Application)
- 2% Current Matching for Sub LEDs at Light Load Condition (Each 100µA)
- 750-kHz Charge Pump Frequency
- Continuous 230-mA Maximum Output Current
- Auto Switching Between ×1 and ×1.5 Mode for Maximum Efficiency
- Built-in Soft Start and Current Limit
- Hardware Enable/Disable
- Open Lamp Detection
- 24-Pin 4mm x 4mm QFN

APPLICATIONS

- Cellular Phones

- PDA, PMP, GPS (Up To 4 Inch Display)
- Multidisplay Handheld Devices

DESCRIPTION

The TPS60251 is a high efficiency, constant frequency charge pump DC/DC converter that uses a dual mode 1× and 1.5× conversion to maximize efficiency over the input voltage range. It drives up to five white LEDs for a main display and up to two white LEDs for a sub display with regulated constant current for uniform intensity. By utilizing adaptive 1×/1.5× charge pump modes and very low-dropout current regulators, the TPS60251 achieves high efficiency over the full 1-cell lithium-battery input voltage range.

Four enable inputs, ENmain, ENsub1, ENsub2, and ENaux, available through I²C, are used for simple on/off controls for the main, sub1, sub2, and DM5 displays, respectively. To lower operating current when using one sub display LED, the device provides independent operation in sub display LEDs.

The TPS60251 is available in a 24-pin 4mmx4mm thin QFN.

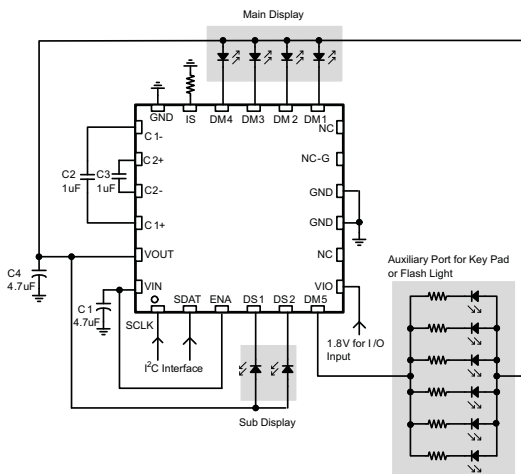


Figure 1. Typical Application for Sub and Main

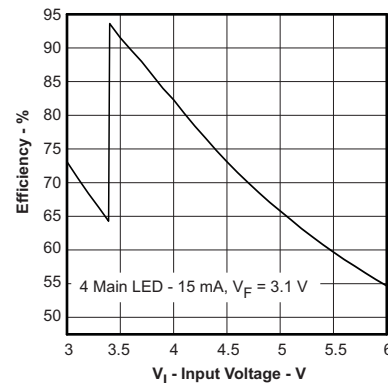


Figure 2. Efficiency vs Input Voltage

ORDERING INFORMATION⁽¹⁾

| PART NUMBER | PACKAGE | T _A |
|-------------|------------------------------|----------------|
| TPS60251RTW | 24 Pin 4 mm × 4 mm QFN (RTW) | –40°C to +85°C |

(1) For the most current package and ordering information, see the Package Option Addendum at the end of this document, or see the TI web site at www.ti.com.



Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

ABSOLUTE MAXIMUM RATINGS

over operating free-air temperature range (unless otherwise noted)⁽¹⁾

| | | VALUE | UNIT |
|-----------------|--|------------|------|
| V _I | Input voltage range (all pins) | –0.3 to 7 | V |
| | MAX Output current limit | 650 | mA |
| | HBM ESD Rating ⁽²⁾ | 2 | kV |
| | CDM ESD Rating ⁽³⁾ | 500 | V |
| | MM ESD Rating ⁽⁴⁾ | 200 | V |
| T _A | Operating temperature range | –40 to 85 | °C |
| T _J | Maximum operating junction temperature | 150 | °C |
| T _{ST} | Storage temperature | –55 to 150 | °C |

- (1) Stresses beyond those listed under *absolute maximum ratings* may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these or any other conditions beyond those indicated under *recommended operating conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) The Human body model (HBM) is a 100-pF capacitor discharged through a 1.5-kΩ resistor into each pin. The testing is done according JEDECs EIA/JESD22-A114.
- (3) Charged Device Model
- (4) Machine Model (MM) is a 200-pF capacitor discharged through a 500-nH inductor with no series resistor into each pin. The testing is done according JEDECs EIA/JESD22-A115.

DISSIPATION RATINGS

| PACKAGE | THERMAL RESISTANCE, R _{θJC} | THERMAL RESISTANCE, R _{θJA} | T _A ≤ 25°C POWER RATING | DERATING FACTOR ABOVE T _A = 25°C | T _A = 85°C POWER RATING |
|-------------|--------------------------------------|--------------------------------------|------------------------------------|---|------------------------------------|
| QFN 4×4 RTW | 57.9°C/W | 37.8°C/W | 2.646 W | 1.455 W | 1.058 W |

RECOMMENDED OPERATING CONDITIONS

| | | MIN | NOM | MAX | UNIT |
|---------------------------------|--------------------------------|-----|-----|-----|------|
| V _I | Input voltage range | 3.0 | | 6.0 | V |
| I _{O(max)} | Maximum output current | | 230 | | mA |
| C _I | Input capacitor | | 4.7 | | μF |
| C _O | Output capacitor | | 4.7 | | μF |
| C ₁ , C ₂ | Flying capacitor | | 1.0 | | μF |
| T _A | Operating ambient temperature | –40 | | 85 | °C |
| T _J | Operating junction temperature | –40 | | 125 | °C |
| C _{IS(MAX)} | Maximum capacitance on IS pin | | | 100 | pF |

ELECTRICAL CHARACTERISTICS

V_I = 3.5 V, T_A = –40°C to 85°C, R_{IS} = 562 kΩ, typical values are at T_A = 25°C (unless otherwise noted)

| PARAMETER | TEST CONDITIONS | MIN | TYP | MAX | UNIT | |
|-----------------------|---------------------------------------|---|-----|-----|------|---|
| SUPPLY VOLTAGE | | | | | | |
| V _I | Input voltage range | 3.0 | | 6.0 | V | |
| I _Q | Operating quiescent current | 750-kHz Switching in 1.5× Mode (I _{MAIN_LED} = 15 mA × 4, I _O = 60 mA) | | 6.7 | mA | |
| | | No switching in ×1 mode (I _O = 100 μA) | | 68 | μA | |
| I _{SD} | Shutdown current | Enable Control Register has 0x00 | | 1.3 | μA | |
| V _{UVLO1} | UVLO Threshold voltage ⁽¹⁾ | V _I falling | 2.2 | 2.4 | 2.6 | V |

- (1) Shut down charge pump and power stage and keep I²C content

ELECTRICAL CHARACTERISTICS (continued)

$V_I = 3.5\text{ V}$, $T_A = -40^\circ\text{C}$ to 85°C , $R_{IS} = 562\text{ k}\Omega$, typical values are at $T_A = 25^\circ\text{C}$ (unless otherwise noted)

| PARAMETER | | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|--|--|-------|-------------|-----------|----------|
| V_{UVLO2} | UVLO Threshold voltage ²⁽²⁾ | V_I falling | 1.2 | 1.3 | 1.5 | V |
| V_{hys} | Under-voltage lockout hysteresis | UVLO1 | | 210 | | mV |
| V_{ENA_H} | Enable high threshold voltage | | 1.5 | | V_I | V |
| V_{ENA_L} | Enable low threshold voltage | | | | 0.4 | V |
| T_S | Soft start time ⁽³⁾ | $V_I = 3\text{ V}$, $C_O = 1\ \mu\text{F}$, $I_{\text{MAIN_LED}} = 15\text{ mA} \times 4$ | | 0.5 | | ms |
| CHARGE PUMP | | | | | | |
| V_{out} | Overvoltage limit | | | 6.5 | | V |
| F_s | Switching frequency | | | 750 | | kHz |
| R_O | Open loop output impedance | $\times 1$ Mode, $(V_I - V_O)/I_O$ | | | 1.2 | Ω |
| | | $\times 1.5$ Mode, $(V_I \times 1.5 - V_O)/I_O$ $V_I = 3.0\text{V}$ ($I_O = 120\text{mA}$) | | 3.5 | 5.0 | |
| CURRENT SINK | | | | | | |
| K_{m_sub} | Current matching of sub LEDs at light load condition ⁽⁴⁾ | $I_{\text{SUB_LED}} = 100\ \mu\text{A} \times 2$, $V_{\text{DXX}} = 0.4\text{ V}$ | | 0 | $\pm 2\%$ | |
| K_{m_main} | LED to LED Current matching ⁽⁵⁾ | $I_{\text{MAIN_LED}} = 15\text{ mA} \times 4$, $3.0\text{ V} \leq V_I \leq 4.2\text{ V}$ | | $\pm 0.1\%$ | $\pm 5\%$ | |
| K_a | Current accuracy | $I_{\text{LED}} = 15\text{ mA}$ | | | $\pm 6\%$ | |
| I_{D_MS} | Maximum LED current of DM1-4 and DS1-2 | Main and Sub Display Current Register = $0 \times 01 \& 2(111111)$, $V_{\text{DXX}} = 0.2\text{ V}$ | | 25.5 | | mA |
| I_{D_DM5} | Maximum LED current of DM5 | Aux Display Current Register = 0×03 (XXXX11) | | 80 | | mA |
| V_{IS} | IS Pin voltage | $3.0\text{V} \leq V_I \leq 6.0\text{V}$ | 1.229 | 1.254 | 1.279 | V |
| I_{sub} | Output current to current set ratio sub LEDs | $I_{\text{LED}} = 100\ \mu\text{A}$ ⁽⁶⁾ | | 44.8 | | |
| | | $I_{\text{LED}} = 15\text{ mA}$ ⁽⁶⁾ | | 6722 | | |
| I_{main} | Output current to current set ratio main LEDs | $I_{\text{LED}} = 100\ \mu\text{A}$ ⁽⁶⁾ | | 44.8 | | |
| | | $I_{\text{LED}} = 15\text{ mA}$ ⁽⁶⁾ | | 6722 | | |
| I_{DM5} | Output current to current set ratio DM5 | $I_{\text{LED}} = 80\text{ mA}$ ⁽⁶⁾ | | 35853 | | |
| V_{DropOut} | LED Drop out voltage | See ⁽⁷⁾ | | 80 | 120 | mV |
| $V_{\text{TH_GU}}$ | $1 \times$ Mode to $1.5 \times$ mode transition threshold voltage ⁽⁸⁾ | V_{DXX} Falling, $15\text{ mA} \times 4$ measured on the lowest V_{DXX} | 85 | 100 | 120 | mV |
| $V_{\text{TH_GD}}$ | Input voltage hysteresis for $1.5 \times$ to $1 \times$ mode transition | Measured as $V_I - (V_O - V_{\text{DXX_MIN}})$, $I_{\text{MAIN_LED}} = 15\text{ mA} \times 4$ | | 550 | | mV |
| SERIAL INTERFACE TIMING REQUIREMENTS | | | | | | |
| f_{max} | Clock frequency | | | | 400 | kHz |
| $t_{\text{wH(HIGH)}}$ | Pulse duration, clock high time | | | 600 | | ns |
| $t_{\text{wL(LOW)}}$ | Pulse duration, clock low time | | | 1300 | | ns |
| t_r | DATA and CLK rise time | | | | 300 | ns |
| t_f | DATA and CLK fall time | | | | 300 | ns |
| $t_{\text{h(STA)}}$ | High time (repeated) START condition(after this period the first clock pulse is generated) | | | 600 | | ns |
| $t_{\text{su(STA)}}$ | Setup time for repeated START condition | | | 600 | | ns |
| $t_{\text{h(DATA)}}$ | Data input hold time | | | 0 | | ns |
| $t_{\text{su(DATA)}}$ | Data input setup time | | | 100 | | ns |

(2) Shut down completely and come up with all 0's after device restart

(3) Measurement Condition: From enabling the LED driver to 90% output voltage after V_I is already up.

(4) LED current matching is defined as: $(I_{\text{SUB_LED_WORST}} - I_{\text{AVG_SUB}}) / I_{\text{AVG_SUB}}$

(5) LED to LED Current Matching is defined as: $(I_{\text{MAIN_LED_WORST}} - I_{\text{AVG_MAIN}}) / I_{\text{AVG_MAIN}}$

(6) See the *Setting the LED Current* section of the data sheet for details on calculating LED current given by dimming step and R_{IS} .

(7) Dropout Voltage is defined as V_{DXX} (WLED Cathode) to GND voltage at which current into the LED drops 10% from the LED current at $V_{\text{DXX}} = 0.2\text{ V}$, WLED current = $15\text{ mA} \times 4$.

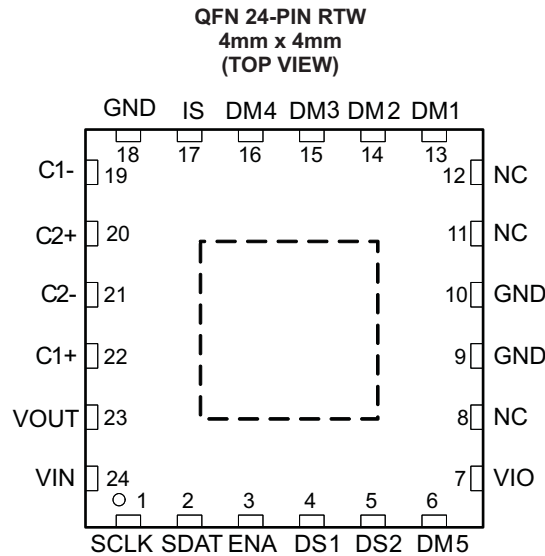
(8) As V_I drops, V_{DXX} eventually falls below the switchover threshold of 100mV, and TPS60251 switches to $1.5 \times$ mode. See the *Operating Principle* section for details about the mode transition thresholds.

ELECTRICAL CHARACTERISTICS (continued)

$V_I = 3.5\text{ V}$, $T_A = -40^\circ\text{C}$ to 85°C , $R_{IS} = 562\text{ k}\Omega$, typical values are at $T_A = 25^\circ\text{C}$ (unless otherwise noted)

| PARAMETER | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|--|---------------------------|--|----------------------|----------------------|------|
| $t_{su(STO)}$ | STOP condition setup time | | 600 | | ns |
| $t_{(BUF)}$ | Bus free time | | 1300 | | ns |
| I²C COMPATIBLE INTERFACE VOLTAGE SPECIFICATION (SCLK, SDAT, VIO) | | | | | |
| V_{IO} | Serial bus voltage level | | 1.4 | 4.5 | V |
| V_{IL} | Low-level input voltage | $3.0\text{V} \leq V_I \leq 6.0\text{V}$, $1.4\text{ V} < V_{IO} < 1.8\text{ V}$ | 0 | $0.37 \times V_{IO}$ | V |
| V_{IH} | High-level input voltage | $3.0\text{V} \leq V_I \leq 6.0\text{V}$ | $0.87 \times V_{IO}$ | | V |
| V_{OL} | Low-level output voltage | $I_{LOAD} = 2\text{ mA}$ | | 0.4 | V |

PIN ASSIGNMENTS



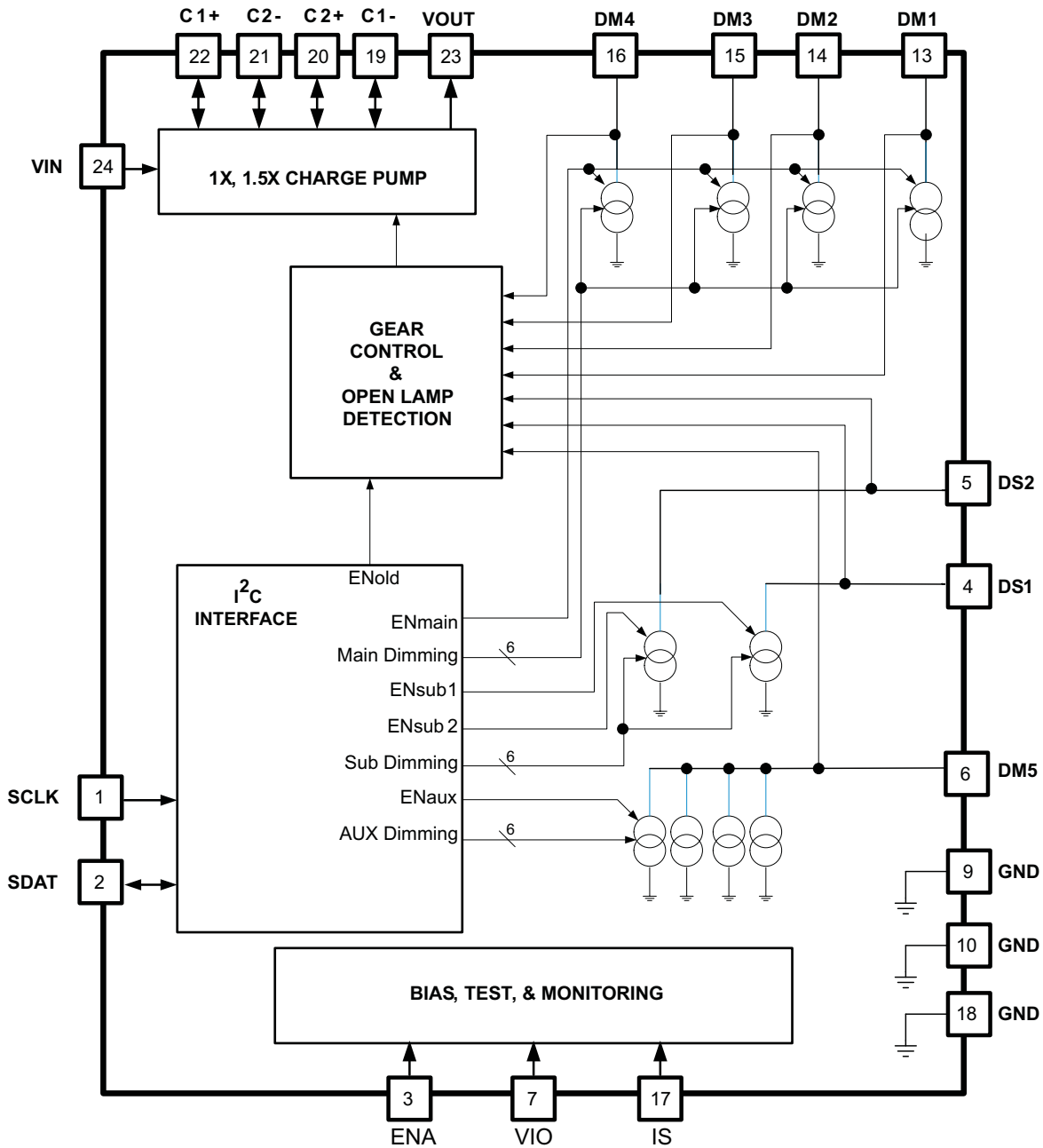
TERMINAL FUNCTIONS

| TERMINAL | | I/O | DESCRIPTION |
|----------|-----------|-----|---|
| NAME | NO. | | |
| SCLK | 1 | I | I ² C Interface |
| SDAT | 2 | I/O | I ² C Interface |
| ENA | 3 | I | Hardware enable/disable pin. Connect this pin high to enable the device. Connect this pin low to disable the device. Do not leave this pin unconnected. |
| DS1 | 4 | I | Current sink input. Connect the cathode of one of the sub display white LEDs to this pin. |
| DS2 | 5 | I | |
| DM5 | 6 | I | Current sink input. Connect the cathode of the aux display or the 5th main display white LED to this pin. |
| VIO | 7 | I | I/O Voltage input (1.8V). Connect an input voltage supply of 1.8V to VIN to set the logic levels for the I ² C interface. |
| NC | 8, 11, 12 | – | No connection |
| GND | 9, 10, 18 | – | Ground |
| DM1 | 13 | I | Current sink input. Connect the cathode of one of the main display white LED to this pin. |
| DM2 | 14 | I | |
| DM3 | 15 | I | |
| DM4 | 16 | I | |
| IS | 17 | I | Maximum LED current setting input. Connect a resistor (R_{IS}) between this pin and GND to set the full-scale white LED current for sub (DS1, DS2), main (DM1, DM2, DM3, DM4), and DM5 LEDs. See the <i>Setting the LED Current</i> section for details on selecting the correct value for R_{IS} . |

TERMINAL FUNCTIONS (continued)

| TERMINAL | | I/O | DESCRIPTION |
|----------|-----|-----|---|
| NAME | NO. | | |
| C1- | 19 | - | Connect to the flying capacitor C1 |
| C2+ | 20 | - | Connect to the flying capacitor C2 |
| C2- | 21 | - | Connect to the flying capacitor C2 |
| C1+ | 22 | - | Connect to the flying capacitor C1 |
| VOUT | 23 | O | Connect the anodes of the sub, main, and aux display white LEDs to this pin. Bypass VOUT to GND with a 4.7- μ F or greater ceramic capacitor. |
| VIN | 24 | I | Supply voltage input. Connect to a 3-V to 6-V input supply source. Bypass VIN to GND with a 4.7- μ F or greater ceramic capacitor. |

FUNCTIONAL BLOCK DIAGRAM



TYPICAL CHARACTERISTICS

TABLE OF GRAPHS

| | DESCRIPTION | REF |
|--|--|-----------|
| Efficiency | Efficiency vs Input Voltage, 4 Main LED - 15mA, 25mA | Figure 3 |
| | Efficiency vs Input Voltage, 2 Sub LED with Light Load Condition, $\times 1$ Mode Operation | Figure 4 |
| Output Impedance of $\times 1$ and $\times 1.5$ Mode | Switch Resistance vs Free-Air Temperature, $\times 1$ Mode, $I_{LED} = 230$ mA | Figure 5 |
| | Switch Resistance vs Free-Air Temperature, $\times 1$ Mode, $I_{LED} = 100$ mA | Figure 6 |
| | Switch Resistance vs Free-Air Temperature, $\times 1.5$ Mode Charge Pump Open-Loop, $I_{LED} = 230$ mA | Figure 7 |
| | Switch Resistance vs Free-Air Temperature, $\times 1.5$ Mode Charge Pump Open-Loop, $I_{LED} = 100$ mA | Figure 8 |
| Shutdown Current | Shutdown Current vs Input Voltage | Figure 9 |
| Input Current | Input Current vs Supply Voltage, 4 Main LED | Figure 10 |
| DM5 with Maximum 80 mA | DM5 Current vs Input Voltage, Programmed with 80 mA | Figure 11 |
| Current Accuracy | WLED Current vs Input Voltage, 4 Main LED with 15 mA | Figure 12 |

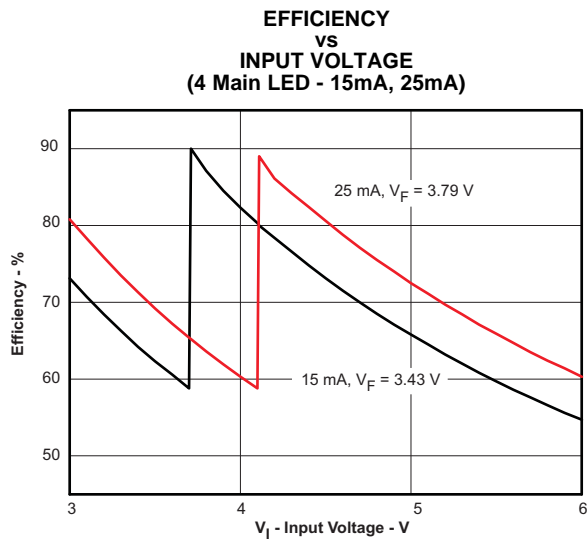


Figure 3.

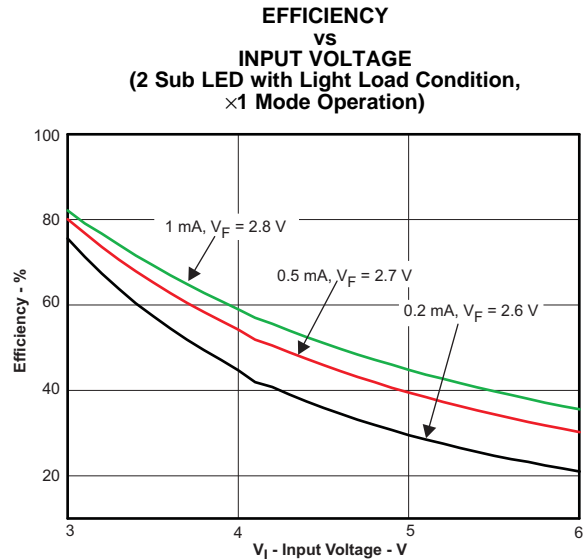


Figure 4.

**SWITCH RESISTANCE
 vs
 FREE-AIR TEMPERATURE
 (×1 Mode)**

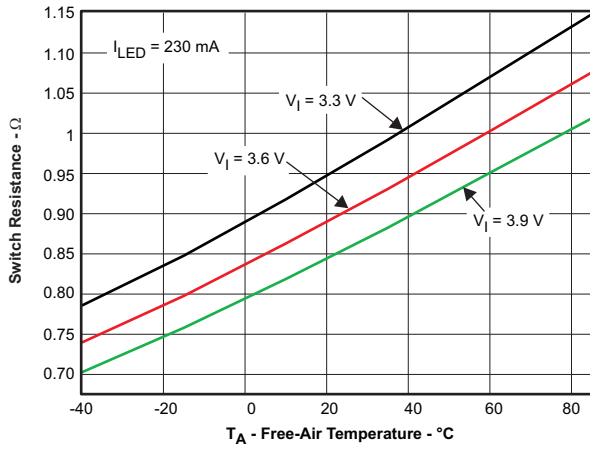


Figure 5.

**SWITCH RESISTANCE
 vs
 FREE-AIR TEMPERATURE
 (×1 Mode)**

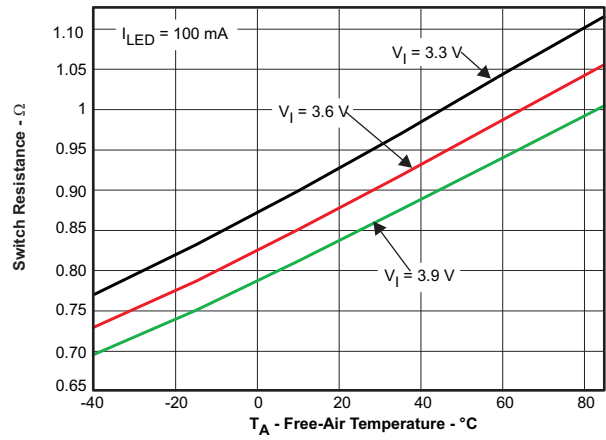


Figure 6.

**SWITCH RESISTANCE
 vs
 FREE-AIR TEMPERATURE
 (×1.5 Mode Charge Pump Open-Loop)**

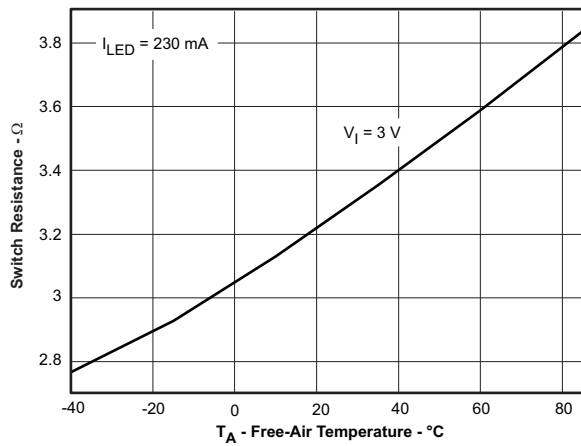


Figure 7.

**SWITCH RESISTANCE
 vs
 FREE-AIR TEMPERATURE
 (×1.5 Mode Charge Pump Open-Loop)**

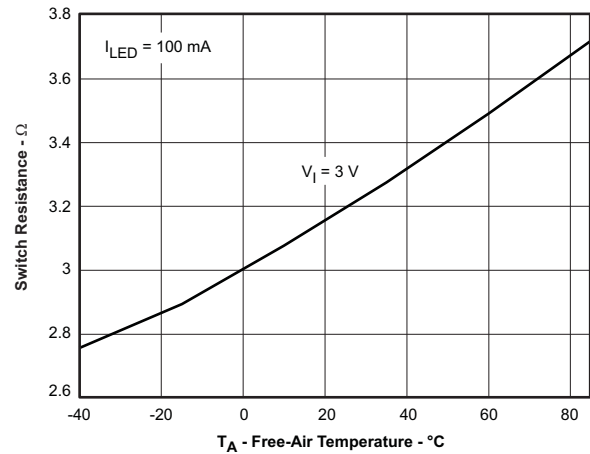


Figure 8.

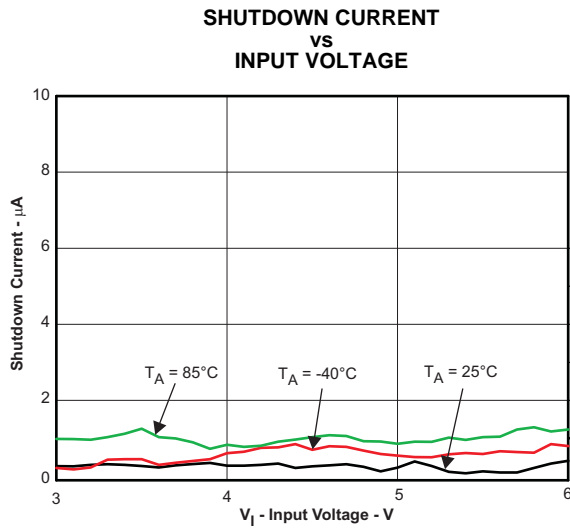


Figure 9.

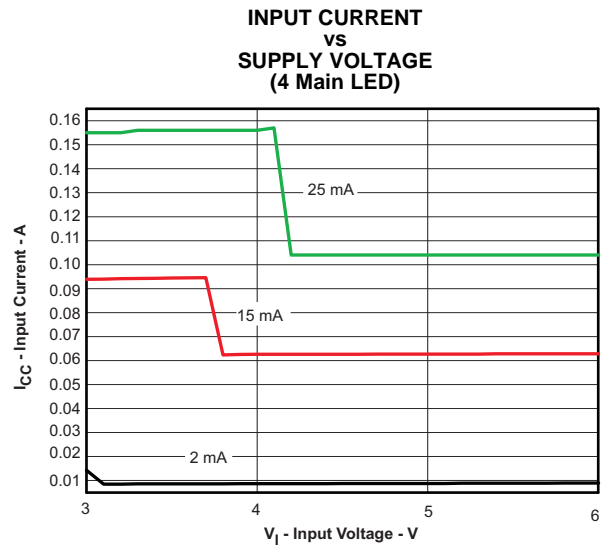


Figure 10.

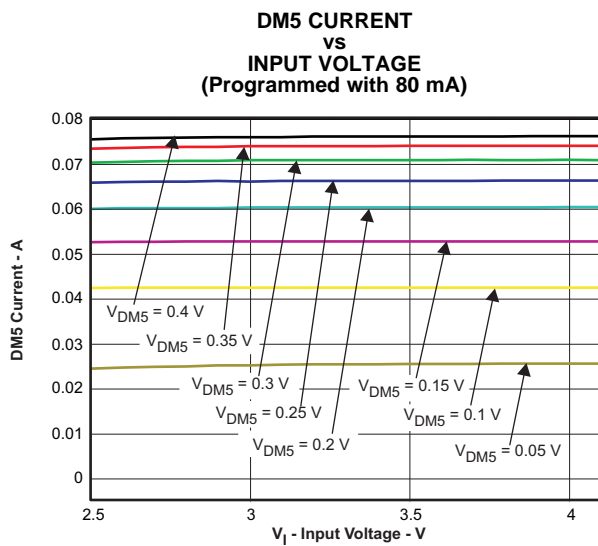


Figure 11.

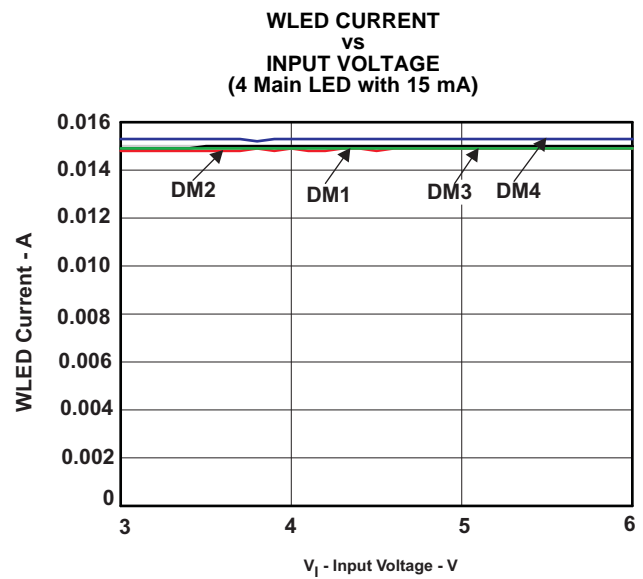


Figure 12.

APPLICATION INFORMATION

APPLICATION OVERVIEW

Most of the current handsets fall into one of three categories. First is the clamshell design, with a main display on the inside, a secondary display on the outside and a keypad backlight. Second is the bar design, with a main display and a keypad backlight. Third is the slide type (slide-up and slide-down) design, with a main display and two keypad banks (inside and outside). The TPS60251 is well suited for use in these three major phone designs because it has 7 individually regulated white LED current paths for driving up to five white LEDs in main display and up to two white LEDs in sub display with regulated constant current for uniform intensity. The main and sub display LED channels drive up to 25mA and an auxiliary LED output (DM5) drives up to 80mA that can be assigned for keypad backlight, torch light or low cost/weak camera flash application using the I²C interface.

The TPS60251 circuit uses only 5 external components: the input/output capacitors, 2 chargepump flying capacitors, and one resistor that sets the maximum WLED current. The few external components combined with the small 4mm×4mm QFN package provide for a small total solution size. By combining independent control of three separate banks of backlight LEDs with low cost and weak flash capability, the TPS60251 helps designers minimize power consumption especially in light load conditions while reducing component count and package size.

OPERATING PRINCIPLE

Charge pumps are becoming increasingly attractive in battery-operated applications where board space and maximum height of the converter are critical constraints. The major advantage of a charge pump is the use of only capacitors as storage elements. The TPS60251 chargepump provides regulated LED current from a 3-V to 6-V input source. It operates in two modes. The 1× mode, where the input is connected to the output through a pass element, and a high efficiency 1.5× charge pump mode. The IC maximizes power efficiency by operating in 1× and 1.5× modes as input voltage and LED current conditions require. The mode of operation is automatically selected by comparing the forward voltage of the WLED plus the voltage of current sink for each LED with the input voltage. The IC starts up in 1× mode, and automatically transitions to 1.5× if the voltage at any current sink input (DM_or DS_) falls below the 100-mV transition voltage. The IC returns to 1× mode as the input rises. [Figure 13](#) provides a visual explanation of the 1× to 1.5× transition.

In 1.5× mode, the internal oscillator determines the charge/discharge cycles for the flying capacitors. During a charge cycle, the flying capacitors are connected in series and charged up to the input voltage. After the on-time of the internal oscillator expires, the flying capacitors are reconfigured to be in parallel and then connected in series to the input voltage. This provides an output of 1.5× the input voltage. After the off-time of the internal oscillator expires, another charge cycle initiates and the process repeats.

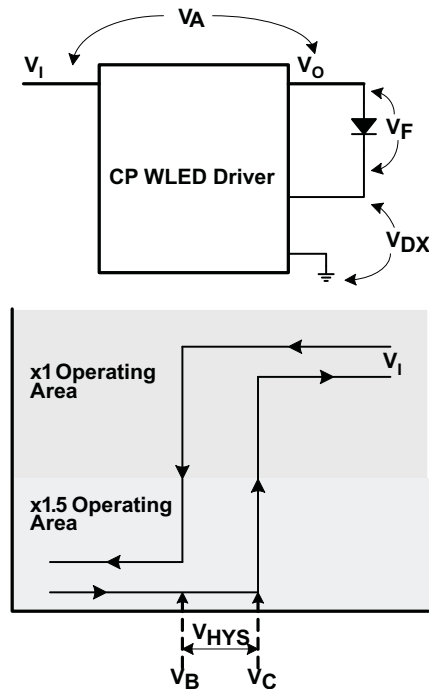


Figure 13. Input Voltage Hysteresis Between $\times 1$ and $\times 1.5$ Mode

As shown in Figure 13, there is input voltage hysteresis voltage between $1\times$ and $1.5\times$ mode to ensure stable operation during mode transition. For the 1 cell Li-Ion battery input voltage range, the TPS60251 operates in $1\times$ mode when a fully charged battery is installed. Once the battery voltage drops below the V_B level, which is the mode transition voltage from $1\times$ to $1.5\times$, the WLED driver operates in $1.5\times$ mode. Once in $1.5\times$ mode, the battery voltage must rise to the V_C level in order to transition from $1.5\times$ to $1\times$. This hysteresis ensures stable operation when there is some input voltage fluctuation at the $1\times/1.5\times$ mode transition. The WLED driver provides a typical 280mV hysteresis voltage (V_{HYS}) that changes based on LED current, to prevent oscillating between modes.

The transition voltage, V_B , depends on V_{DX} (the mode transition threshold voltage), V_F (WLED forward voltage drop) and V_A (the drop out voltage of the charge pump stage) and is calculated as follows:

$$V_B = V_A + V_F + V_{DX}$$

$$V_A = R_{OUT1X} \times I_{LEDTOTAL}$$

Where R_{OUT1X} is the $1\times$ mode output impedance of the IC. See the Electrical Characteristics table for output impedance specifications.

The TPS60251 switches to $1.5\times$ mode when the input voltage is below V_B and remains in $1.5\times$ mode as long as the input is lower than V_C . $1.5\times$ Mode is exited when the input voltage rises above V_C . V_C is calculated as:

$$V_C = V_F + 550 \text{ mV}$$

The input voltage mode transition hysteresis voltage (V_{HYS}) between $1\times$ and $1.5\times$ is calculated using the following equation.

$$V_{HYS} = V_C - V_B = 550 \text{ mV} - V_{DX} - V_A, \text{ where } V_{DX} = 100 \text{ mV}$$

Note that V_A is the key factor in determining V_{HYS} and is dependant on the $1\times$ mode charge pump output impedance and WLED current.

LED CURRENT SINKS (DM_, DS_)

The TPS60251 has constant current sinks which drive seven individual LED current paths. Each current sink regulates the LED current to a constant value determined by the I²C interface. The internal register addressing allows the LED main channels DM1~DM5 to be controlled independently from the LED sub channels DS1~DS2. The maximum current is programmable by the user (see the *Setting the LED Current* section). All the LED channels sink up to 25mA of current except DM5 which has an 80-mA maximum current when configured as an

auxiliary output. Using the I²C interface, the user may assign DM5 to the main display bank with up to 25-mA current or as an auxiliary output for torch or keypad light or low/weak camera flash with 80-mA current. DM5 has 64 dimming steps which is the main and sub display banks when assigned to the main display. However, it has its own current programming register and enable control. When assigned as an auxiliary, DM5 has 4 dimming steps (full scale, 70%, 40%, 20%).

These optimized current sinks minimize the voltage headroom required to drive each LED and maximize power efficiency by increasing the amount of time the controller stays in 1× mode before transitioning to 1.5× mode.

OPEN LAMP DETECTION

In system production it is often necessary to leave LED current paths open depending on the phone model. For example, one phone may use 2 LEDs to backlight the main display while another uses 4 LEDs. Rather than use two different ICs for these different phone applications, the TPS60251 may be used in both applications with no additional efficiency loss in the 2 LED applications. In traditional LED driver applications when an LED current path is open, the current sink voltage falls to ground and the current regulation circuitry drives the output to a maximum voltage in an attempt to regulate the current for the missing LED path. This severely reduces the system efficiency. The TPS60251 uses 7 internal comparators to detect when an open LED condition occurs and shut down the open current sink. The open lamp detection is enabled/disabled using the I²C interface.

ENABLING THE DEVICE

The TPS60251 contains a hardware enable input for situations where the IC cannot be disabled using the I²C interface. Connect the EN input high to enable the device for normal operation. Connect EN low to disable the device and place it in a low power shutdown. The hardware enable overrides the I²C enable. When EN is pulled low, the TPS60251 is completely disabled (shutdown mode) and all internal registers are set to 0x00h while the software shutdown using I²C keeps all internal registers.

ENABLING THE LED BANKS

The I²C interface is used to enable/disable the LED banks. The MAIN, SUB, and AUX LEDs are individually controlled. Additionally, the two SUB LEDs (DS_) can be enabled independently.

CAPACITOR SELECTION

The TPS60251 is optimized to work with ceramic capacitors with a dielectric of X5R or better. The two flying capacitors must be the same value for proper operation. The 750-kHz switching frequency requires that the flying capacitor be less than 4.7μF. Use of 1-μF ceramic capacitors for both chargepump flying capacitors is recommended.

For good input voltage filtering, low ESR ceramic capacitors are recommended. A 1-μF ceramic input capacitor is sufficient for most of the applications. For better input voltage filtering this value can be increased to 4.7 μF.

The output capacitor controls the amount of ripple on the output. Since small ripple is undetectable by the human eye, a 4.7-μF output capacitor works well. If better output filtering and lower ripple is desired, a larger output capacitor may be used.

I/O INPUT

The input logic low and high threshold voltage for I²C interface is changed by supplying voltage to VIO. The voltage range of VIO is 1.8V to V_I. This allows the user to optimize the input logic low and high I²C threshold voltages for the TPS60251 to cover different voltage levels for I²C interface for the various phone models.

SETTING THE LED CURRENT

The maximum LED current is user programmable using the IS input. Connect a resistor from IS to GND to set the maximum LED current. The resistor value is calculated using the following equation between 2mA and 25.5mA:

$$I_{LED}(\mu A) = \left[\left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{\text{Step} \times 500}{3.5 \times 10^{-6}} \right] - \left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times 1714.29 \times 10^6 \tag{1}$$

Where R_{IS} is the resistor from IS to GND, I_{LED} is the LED current in μA and Step is the dimming step set by the I²C interface (1 to 63). I_{LED} may be set up to 25mA ($R_{IS} = 562 \text{ k}\Omega$).

R_{IS} has an effect on the current steps that are programmed using the I²C. When the current is programmed below 1.5mA, the current is determined by the following equation:

$$I_{LED}(\mu A) = \left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{\text{Step} \times 100}{3.5 \times 10^{-6}} \tag{2}$$

This equation provides a greater resolution in current steps at lower currents.

| STEP | I _{LED} | STEP | I _{LED} | STEP | I _{LED} | STEP | I _{LED} |
|------|------------------|------|------------------|------|------------------|------|------------------|
| 1 | 100 μ A | 17 | 2.5mA | 33 | 10.5mA | 49 | 18.5mA |
| 2 | 200 μ A | 18 | 3.0mA | 34 | 11.0mA | 50 | 19.0mA |
| 3 | 300 μ A | 19 | 3.5mA | 35 | 11.5mA | 51 | 19.5mA |
| 4 | 400 μ A | 20 | 4.0mA | 36 | 12.0mA | 52 | 20.0mA |
| 5 | 500 μ A | 21 | 4.5mA | 37 | 12.5mA | 53 | 20.5mA |
| 6 | 600 μ A | 22 | 5.0mA | 38 | 13.0mA | 54 | 21.0mA |
| 7 | 700 μ A | 23 | 5.5mA | 39 | 13.5mA | 55 | 21.5mA |
| 8 | 800 μ A | 24 | 6.0mA | 40 | 14.0mA | 56 | 22.0mA |
| 9 | 900 μ A | 25 | 6.5mA | 41 | 14.5mA | 57 | 22.5mA |
| 10 | 1.0mA | 26 | 7.0mA | 42 | 15.0mA | 58 | 23.0mA |
| 11 | 1.1mA | 27 | 7.5mA | 43 | 15.5mA | 59 | 23.5mA |
| 12 | 1.2mA | 28 | 8.0mA | 44 | 16.0mA | 60 | 24.0mA |
| 13 | 1.3mA | 29 | 8.5mA | 45 | 16.5mA | 61 | 24.5mA |
| 14 | 1.4mA | 30 | 9.0mA | 46 | 17.0mA | 62 | 25.0mA |
| 15 | 1.5mA | 31 | 9.5mA | 47 | 17.5mA | 63 | 25.5mA |
| 16 | 2.0mA | 32 | 10.0mA | 48 | 18.0mA | | |

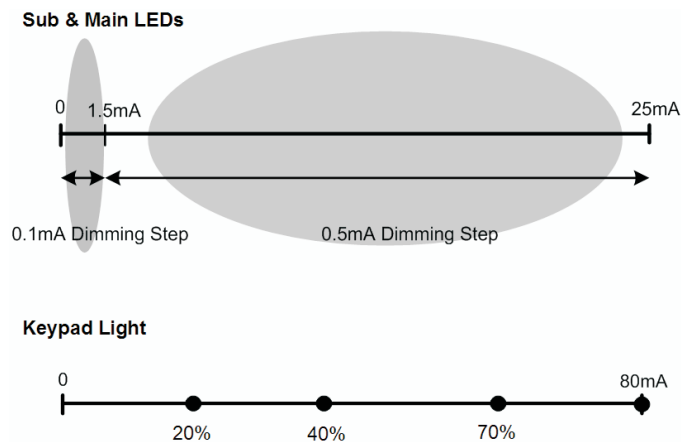


Figure 14. Dimming Steps for Sub, Main, and Keypad Backlight

Figure 14 shows the dimming steps for sub, main, and auxiliary display banks in the 25mA maximum current application. To satisfy today’s requirements on LED current, the TPS60251 covers low LED current area from 100 μ A to 1.5mA with 100- μ A dimming step (total 16 steps for 25-mA maximum current) for the new LCD panels which have improved transparency rates. For LED currents in the range from 2mA to 25mA, the device uses 48 dimming steps with 0.5mA step. Also, DM5 has 4 dimming steps once the current path is assigned for auxiliary applications with maximum 80-mA current.

R_{IS} also affects the current for the auxiliary application. The four current levels (20%, 40%, 70%, and 100%) are determined by the following equations:

$$I_{AUX}(100\%) = \left[\left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{8000}{3.5 \times 10^{-6}} \right] \times 10 \quad (3)$$

$$I_{AUX}(70\%) = \left[\left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{6000}{3.5 \times 10^{-6}} \right] \times 9.333 \quad (4)$$

$$I_{AUX}(40\%) = \left[\left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{4000}{3.5 \times 10^{-6}} \right] \times 8 \quad (5)$$

$$I_{AUX}(20\%) = \left[\left(\frac{1.254}{R_{IS}} + 1.276 \times 10^{-6} \right) \times \frac{2000}{3.5 \times 10^{-6}} \right] \times 8 \quad (6)$$

SERIAL INTERFACE

The serial interface is compatible with the standard and fast mode I²C specifications, allowing transfers at up to 400 kHz. The interface adds flexibility to the WLED driver solution, enabling most functions to be programmed to new values depending on the instantaneous application requirements. Register contents remain intact as long as V_{CC} remains above UVLO2 (typical 1.3V) and ENA is high.

For normal data transfer, DATA is allowed to change only when CLK is low. Changes when CLK is high are reserved for indicating the start and stop conditions. During data transfer, the data line must remain stable whenever the clock line is high. There is one clock pulse per bit of data. Each data transfer is initiated with a start condition and terminated with a stop condition. When addressed, the TPS60251 device generates an acknowledge bit after the reception of each byte. The master device (microprocessor) must generate an extra clock pulse that is associated with the acknowledge bit. The TPS60251 device must pull down the DATA line during the acknowledge clock pulse so that the DATA line is a stable low during the high period of the acknowledge clock pulse. Setup and hold times must be taken into account. During read operations, a master must signal the end of data to the slave by not generating an acknowledge bit on the last byte that was clocked out of the slave. In this case, the slave TPS60251 device must leave the data line high to enable the master to generate the stop condition.

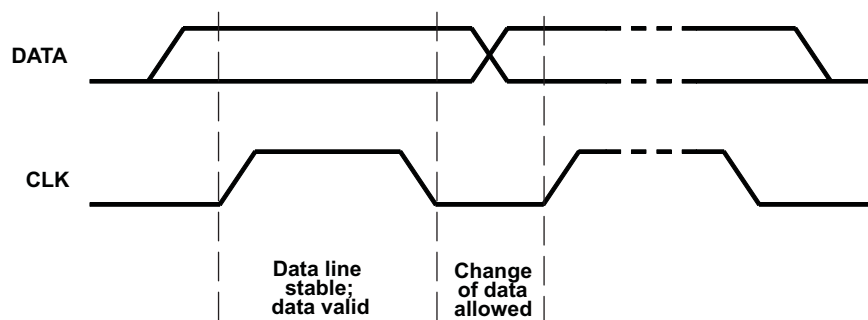


Figure 15. Bit Transfer on the Serial Interface

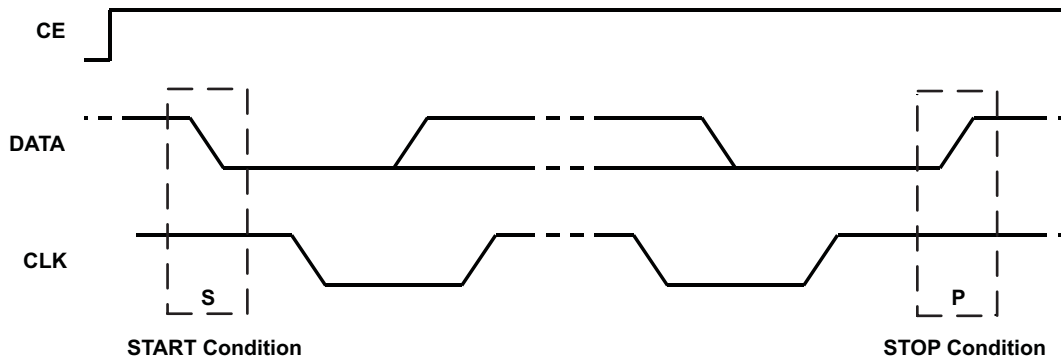


Figure 16. START and STOP Conditions

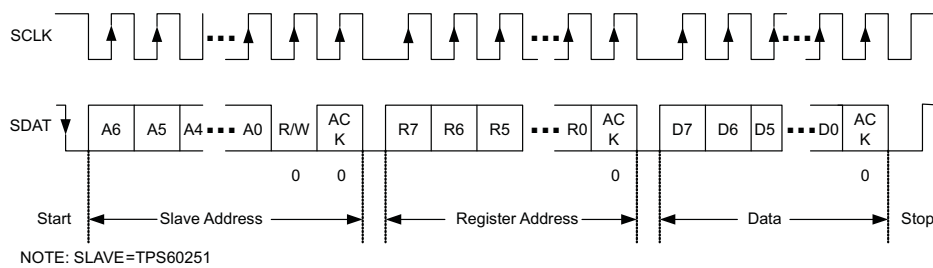


Figure 17. Serial I/F READ From TPS60251: Protocol A

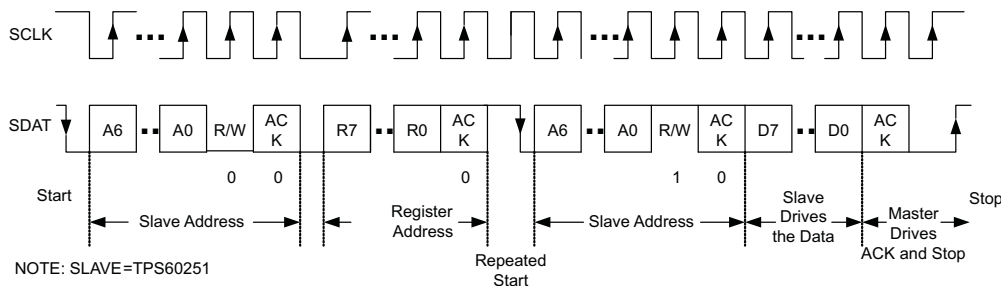


Figure 18. Serial I/F READ From TPS60251: Protocol B

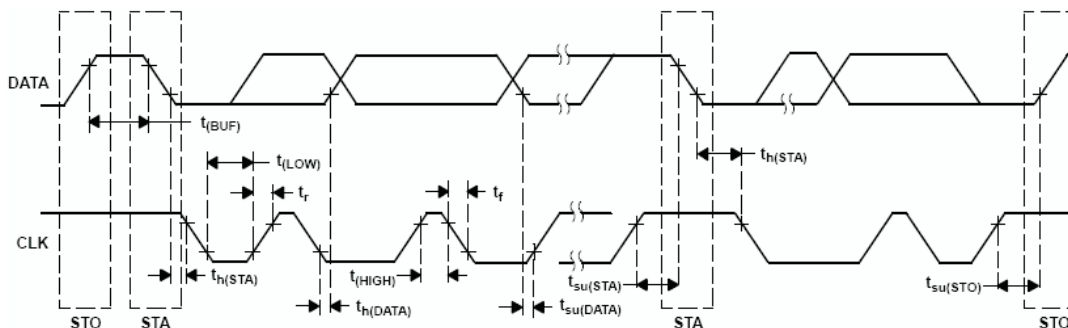


Figure 19. Serial I/F Timing Diagram

The I²C interface uses a combined protocol in which the START condition and the Slave Address are both repeated. The TPS60251 provides 2 I²C Slave Address using internal EEPROM in case more than 1 device is used in the system. The primary I²C Slave Address is **1110111**. For the alternative I²C address, contact the factory.

Enable Control Register (Address: 0x00h)

| ENABLE | B7 | B6 | B5 | B4 | B3 | B2 | B1 | B0 |
|-----------------|----|-------|--------|--------|--------|-------|------|------|
| BIT NAME | X | ENold | ENmain | ENsub2 | ENsub1 | ENaux | DM5H | DM5L |

Bit 6 ENold (Enable Open Lamp Detection)
 1: Open Lamp Detection Enabled
 0: Open Lamp Detection Disabled

Bit 5 ENmain
 1: Enable Main Display LEDs (DM1-DM4)
 0: Disable Main Display LEDs

Bit 4 ENsub2
 1: Enable Sub Display LED 2 (DS2)
 0: Disable Sub Display LED 2

Bit 3 ENsub1
 1: Enable Sub Display LED 1 (DS1)
 0: Disable Sub Display LED 1

Bit 2 ENaux
 1: Enable Aux Display LED (DM5)
 0: Disable Aux Display LED

Bits 1,0 DM5H, DM5L

| DM5H (B1) | DM5L (B0) | DM5 Mode and Shutdown Mode |
|-----------|-----------|---|
| 0 | 0 | Shutdown mode. All outputs disabled, all internal registers set to 0x00h |
| 0 | 1 | Enable the IC and Group DM5 as main display with maximum current of 25mA |
| 1 | 0 | Enable the IC and set as Aux output with maximum current of 80mA. Dimming steps determined by laux0 and laux1 bits. |
| 1 | 1 | Shutdown mode. All outputs disabled, all internal registers set to 0x00h |

Sub Display Current Control Register (Address: 0x01h)

| SUB DISP CURRENT | B7 | B6 | B5 | B4 | B3 | B2 | B1 | B0 |
|------------------|----|----|-------|-------|-------|-------|-------|-------|
| BIT NAME | X | X | lsub5 | lsub4 | lsub3 | lsub2 | lsub1 | lsub0 |

Bits 5 - 0 lsub5 - lsub0 (total 64 steps)
 6-Bit command (64 steps) to these bits sets the current for DS1 and DS2.
 For LED currents between 0 and 1.5mA, one step = 0.1mA increment
 For LED currents between 1.5 and 25.5mA, one step = 0.5mA increment

Main Display Current Control Register (Address: 0x02h)

| MAIN DISP CURRENT | B7 | B6 | B5 | B4 | B3 | B2 | B1 | B0 |
|-------------------|----|----|--------|--------|--------|--------|--------|--------|
| BIT NAME | X | X | lmain5 | lmain4 | lmain3 | lmain2 | lmain1 | lmain0 |

Bits 5 - 0 lmain5 - lmain0 (total 64 steps)
 6-Bit command (64 steps) to these bits sets the current for DM1-DM4.
 For LED currents between 0 and 1.5mA, one step = 0.1mA increment
 For LED currents between 1.5 and 25.5mA, one step = 0.5mA increment

Aux Output Brightness and Operation Mode Control Register (Address: 0x03h)

| | | | | | | | | |
|-------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| AUX DISP CURRENT | B7 | B6 | B5 | B4 | B3 | B2 | B1 | B0 |
| BIT NAME | iaux5 | iaux4 | iaux3 | iaux2 | iaux1 | iaux0 | Mode1 | Mode0 |

Bits 7 - 2 (DM5 set to Main Display Mode)

iaux5 - iaux0 (total 64 steps)

6-Bit command (64 steps) to these bits sets the current for DM5.

For LED currents between 0 and 1.5mA, one step = 0.1mA increment

For LED currents between 1.5 and 25.5mA, one step = 0.5mA increment

Bits 7 - 2 (DM5 set to Aux Display Mode)

| iaux5 (B7) | iaux4 (B6) | iaux3 (B5) | iaux2 (B4) | iaux1 (B3) | iaux0 (B2) | Aux Dimming Step |
|------------|------------|------------|------------|------------|------------|------------------|
| X | X | X | X | 0 | 0 | 20% |
| X | X | X | X | 0 | 1 | 40% |
| X | X | X | X | 1 | 0 | 70% |
| X | X | X | X | 1 | 1 | 100% |

Bits 1,0 Mode1, Mode0

| Mode1 (B1) | Mode0 (B0) | TPS60251 Mode |
|------------|------------|---|
| 0 | 0 | Auto-Switchover Mode. The TPS60251 selects 1x/1.5x mode as described in the <i>Operating Principle</i> section. |
| 0 | 1 | 1x Mode. TPS60251 remains in 1x mode regardless of the input voltage. LED current may not regulate at lower input voltages when in this mode. |
| 1 | 0 | 1.5x Mode. TPS60251 remains in 1.5x mode regardless of the input voltage. |
| 1 | 1 | Auto-Switchover Mode. The TPS60251 selects 1x/1.5x mode as described in the <i>Operating Principle</i> section. |

APPLICATION CIRCUITS

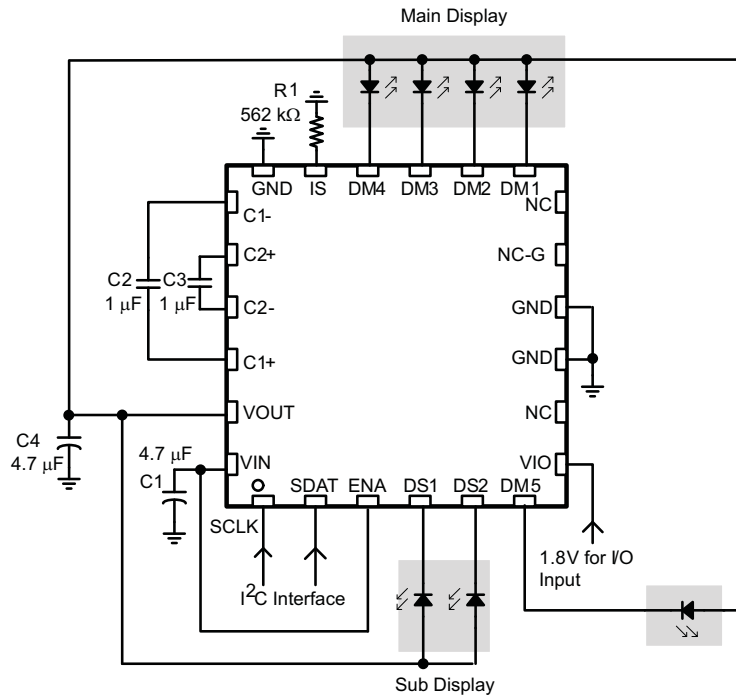


Figure 20. The Typical Application Circuit for Sub and Main Display

As shown in [Figure 20](#), this is a typical application circuit for a clam shell phone with 5 main LEDs and 2 sub LEDs. Recently, the LCD panel makers have developed a new panel that has improved the transparency rate which makes system efficiency with a 100-μA LED current a critical load point. To meet system efficiency requirements with the light load conditions for the new LCD operating panel, the TPS60251 has a maximum 55-μA operating current with the 100-μA output load condition. In this application, the controller always operates in 1× mode due to the WLED's low forward voltage drop (about 2.6V_F with a 100-μA WLED current). Thus, the total efficiency at a light load condition is determined using [Equation 7](#):

$$\eta_{\text{Light}} = \frac{I_O \times V_F}{V_{\text{in}} \times (I_O + I_{\text{op}})} \quad (7)$$

Where:

- I_O: Output Load (WLED) Current
- V_F: Forward Voltage Drop of WLED
- V_{in}: Input Voltage
- I_{op}: Operating Current of LED Driver

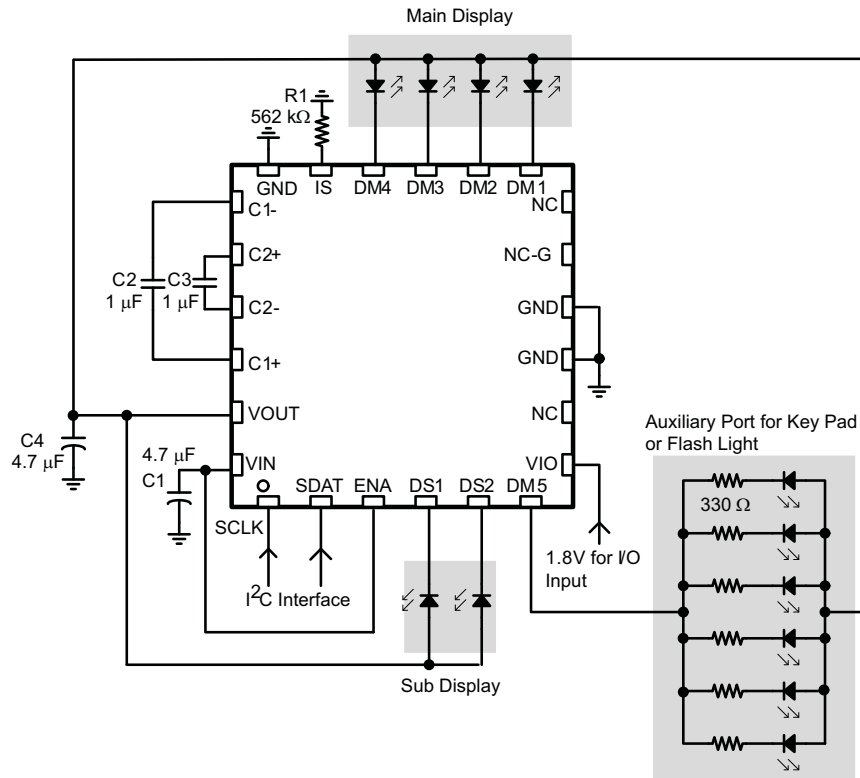


Figure 21. The Typical Application Circuit for Sub, Main, and Keypad Backlight

Figure 21 shows the typical application circuit for sub, main, and keypad backlight. In this application, DM5 is assigned as the auxiliary input for the keypad lighting application.

LAYOUT GUIDELINES

There are several points to consider when laying out a PCB for charge pump based solutions. In general, all capacitors should be as close as possible to the device. This is especially important when placing the flying capacitors (C2, C3 in Figure 20 and Figure 21). To provide accurate WLED current, the current path with the current setting resistor must be short to avoid any interference from other switching components. In cases where DM5 is assigned for torch/flash applications, with a maximum 80-mA WLED current, this current path must be kept wide to reduce the trace resistance.

Revision History

| Changes from Revision B (October 2007) to Revision C | Page |
|---|------|
| • Changed LED to LED Current matching typ value from $\pm 1\%$ to $\pm 0.1\%$ | 3 |

PACKAGING INFORMATION

| Orderable Device | Status ⁽¹⁾ | Package Type | Package Drawing | Pins | Package Qty | Eco Plan ⁽²⁾ | Lead/Ball Finish | MSL Peak Temp ⁽³⁾ |
|------------------|-----------------------|--------------|-----------------|------|-------------|-------------------------|------------------|------------------------------|
| TPS60251RTWR | ACTIVE | QFN | RTW | 24 | 3000 | Green (RoHS & no Sb/Br) | CU NIPDAU | Level-2-260C-1 YEAR |
| TPS60251RTWRG4 | ACTIVE | QFN | RTW | 24 | 3000 | Green (RoHS & no Sb/Br) | CU NIPDAU | Level-2-260C-1 YEAR |
| TPS60251RTWT | ACTIVE | QFN | RTW | 24 | 250 | Green (RoHS & no Sb/Br) | CU NIPDAU | Level-2-260C-1 YEAR |
| TPS60251RTWTG4 | ACTIVE | QFN | RTW | 24 | 250 | Green (RoHS & no Sb/Br) | CU NIPDAU | Level-2-260C-1 YEAR |

⁽¹⁾ The marketing status values are defined as follows:

ACTIVE: Product device recommended for new designs.

LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

PREVIEW: Device has been announced but is not in production. Samples may or may not be available.

OBSOLETE: TI has discontinued the production of the device.

⁽²⁾ Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check <http://www.ti.com/productcontent> for the latest availability information and additional product content details.

TBD: The Pb-Free/Green conversion plan has not been defined.

Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.

Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.

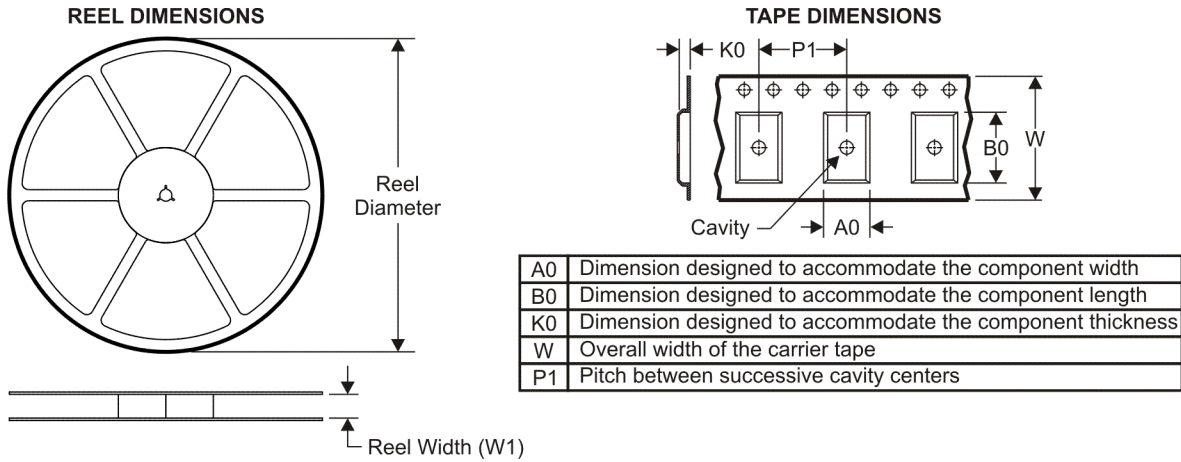
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

⁽³⁾ MSL, Peak Temp. -- The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

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TAPE AND REEL INFORMATION



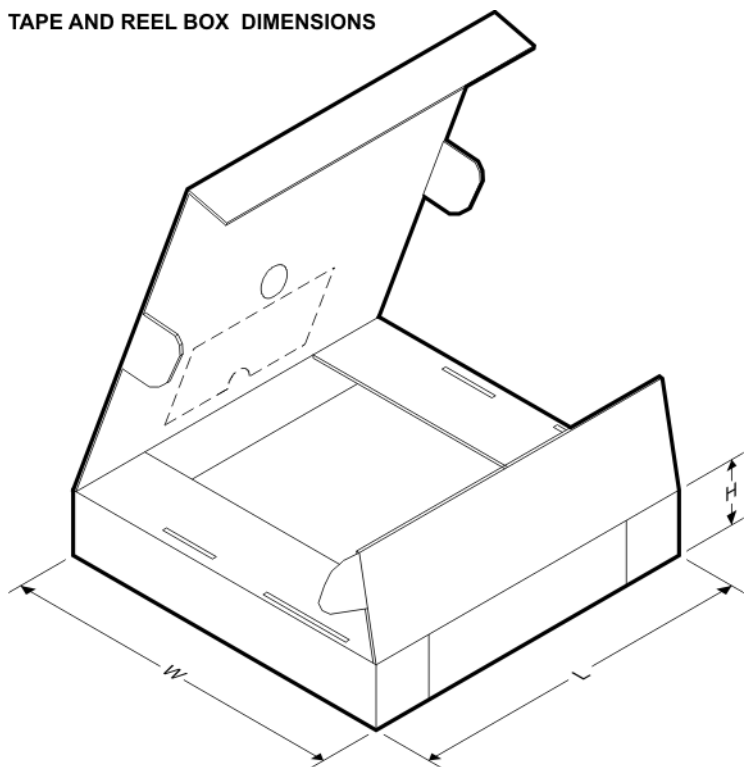
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

| Device | Package Type | Package Drawing | Pins | SPQ | Reel Diameter (mm) | Reel Width W1 (mm) | A0 (mm) | B0 (mm) | K0 (mm) | P1 (mm) | W (mm) | Pin1 Quadrant |
|--------------|--------------|-----------------|------|------|--------------------|--------------------|---------|---------|---------|---------|--------|---------------|
| TPS60251RTWR | QFN | RTW | 24 | 3000 | 330.0 | 12.4 | 4.3 | 4.3 | 1.5 | 8.0 | 12.0 | Q2 |
| TPS60251RTWT | QFN | RTW | 24 | 250 | 180.0 | 12.4 | 4.3 | 4.3 | 1.5 | 8.0 | 12.0 | Q2 |

TAPE AND REEL BOX DIMENSIONS

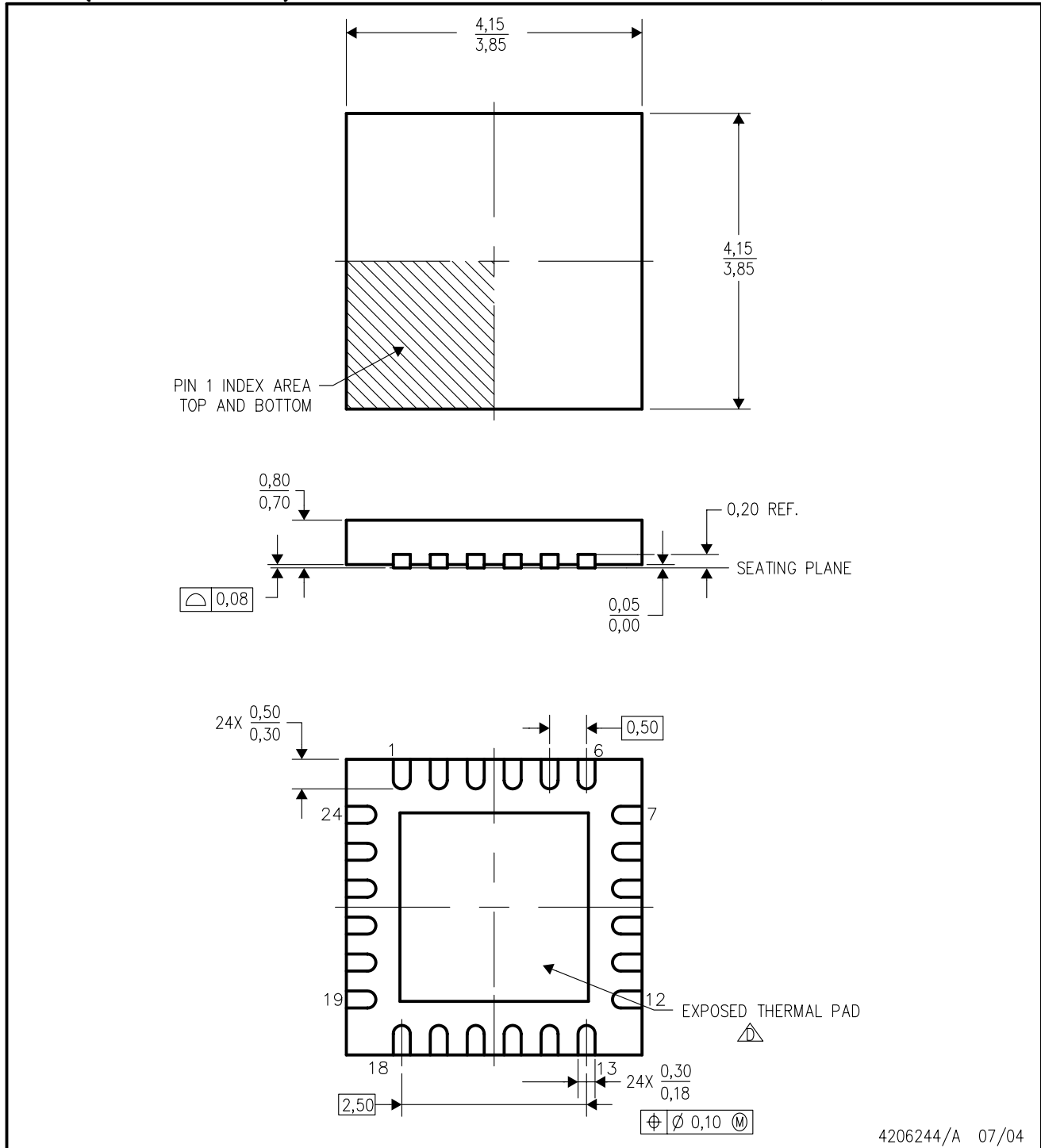



*All dimensions are nominal

| Device | Package Type | Package Drawing | Pins | SPQ | Length (mm) | Width (mm) | Height (mm) |
|--------------|--------------|-----------------|------|------|-------------|------------|-------------|
| TPS60251RTWR | QFN | RTW | 24 | 3000 | 346.0 | 346.0 | 29.0 |
| TPS60251RTWT | QFN | RTW | 24 | 250 | 346.0 | 346.0 | 31.8 |

RTW (S-PQFP-N24)

PLASTIC QUAD FLATPACK



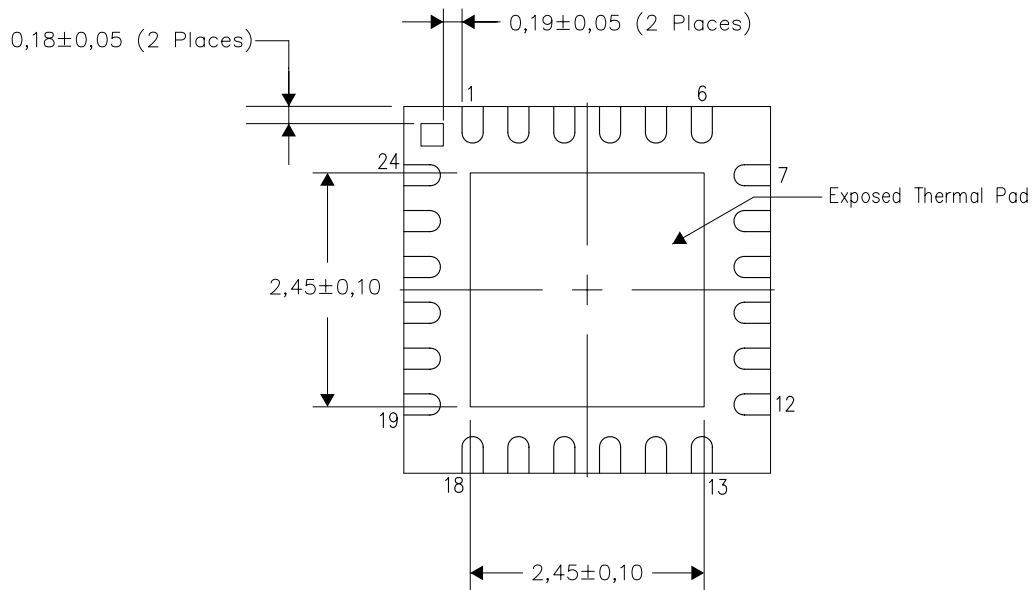
- NOTES:
- A. All linear dimensions are in millimeters. Dimensioning and tolerancing per ASME Y14.5-1994.
 - B. This drawing is subject to change without notice.
 - C. Quad Flatpack, No-Leads (QFN) package configuration.
 - D.  The package thermal pad must be soldered to the board for thermal and mechanical performance. See the Product Data Sheet for details regarding the exposed thermal pad dimensions.
 - E. Falls within JEDEC MO-220.

THERMAL INFORMATION

This package incorporates an exposed thermal pad that is designed to be attached directly to an external heatsink. The thermal pad must be soldered directly to the printed circuit board (PCB). After soldering, the PCB can be used as a heatsink. In addition, through the use of thermal vias, the thermal pad can be attached directly to the appropriate copper plane shown in the electrical schematic for the device, or alternatively, can be attached to a special heatsink structure designed into the PCB. This design optimizes the heat transfer from the integrated circuit (IC).

For information on the Quad Flatpack No-Lead (QFN) package and its advantages, refer to Application Report, QFN/SON PCB Attachment, Texas Instruments Literature No. SLUA271. This document is available at www.ti.com.

The exposed thermal pad dimensions for this package are shown in the following illustration.



Bottom View

NOTE: All linear dimensions are in millimeters

Exposed Thermal Pad Dimensions

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