

High Efficiency Switching Mode Battery Charger

General Description

The RT9535A is a PWM switch mode battery charger controller to fast charge single or multiple Li-Ion, NiMH and NiCd batteries, using constant current or constant voltage control. Maximum current can be easily programmed by external resistor. The constant voltage output can support up to 22V with 0.5% accuracy.

A third control loop limits the input current drawing from the adapter during charging. This allows simultaneous operation of the equipment and fast battery charging without over loading to the adapter.

The RT9535A can charge batteries from 2.5V to 22V with dropout voltage as low as 0.4V.

The RT9535A is available in the WQFN-16L 4X4 package.

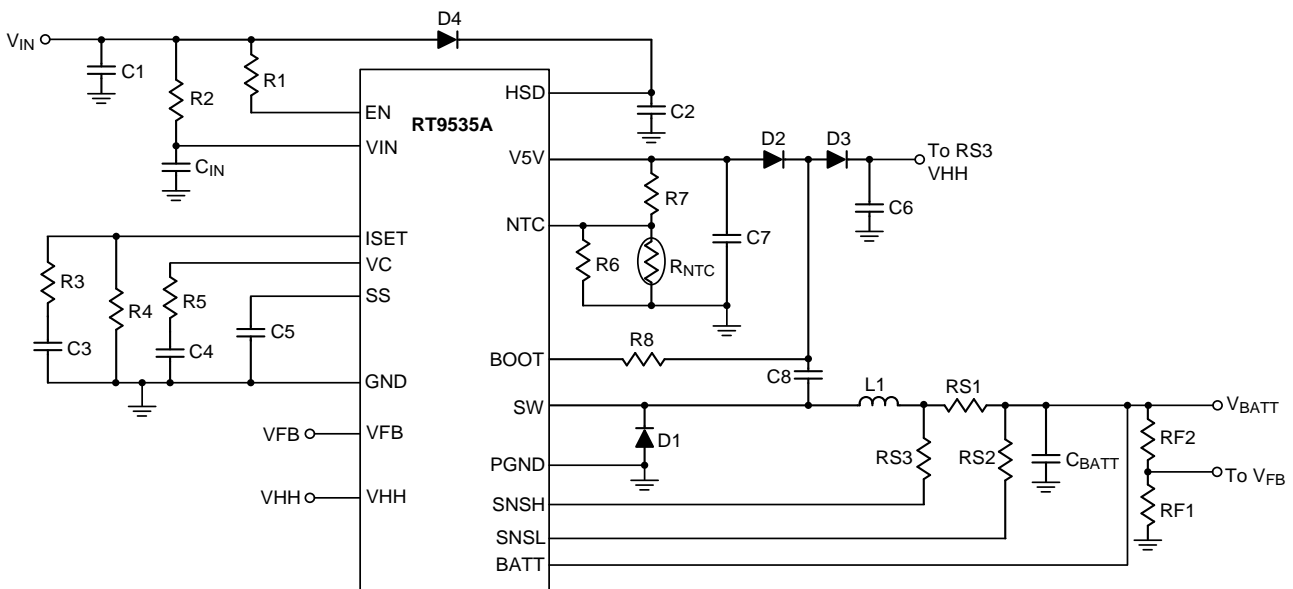
Features

- Fast Charging for Li-Ion, NiMH and NiCd Batteries
- Adjustable Battery Voltages from 2.5V to 22V
- High Efficiency : Up to 95%
- Charging Current Programmed by Resistor
- Precision 0.5% Charging Voltage Accuracy
- Provide 5% Charging Current Accuracy
- 500kHz Switching Frequency
- Auto Shutdown with Adapter Removal

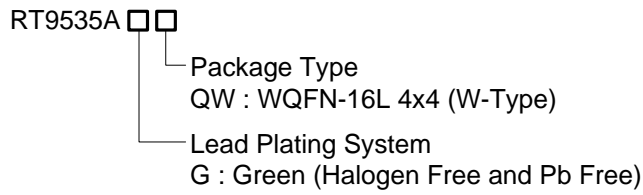
Applications

- Notebook Computers
- Portable Instruments
- Chargers for Li-Ion, NiMH, NiCd and Lead Acid Rechargeable Batteries

Simplified Application Circuit



Ordering Information

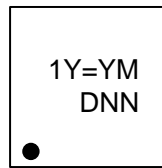


Note :

Richtek products are :

- ▶ RoHS compliant and compatible with the current requirements of IPC/JEDEC J-STD-020.
- ▶ Suitable for use in SnPb or Pb-free soldering processes

Marking Information

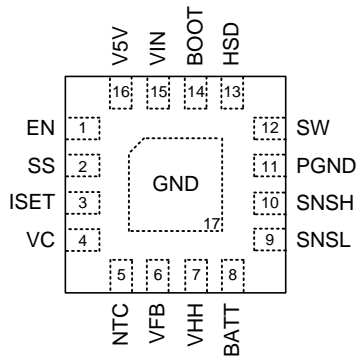


1Y= : Product Code

YMDNN : Date Code

Pin Configurations

(TOP VIEW)

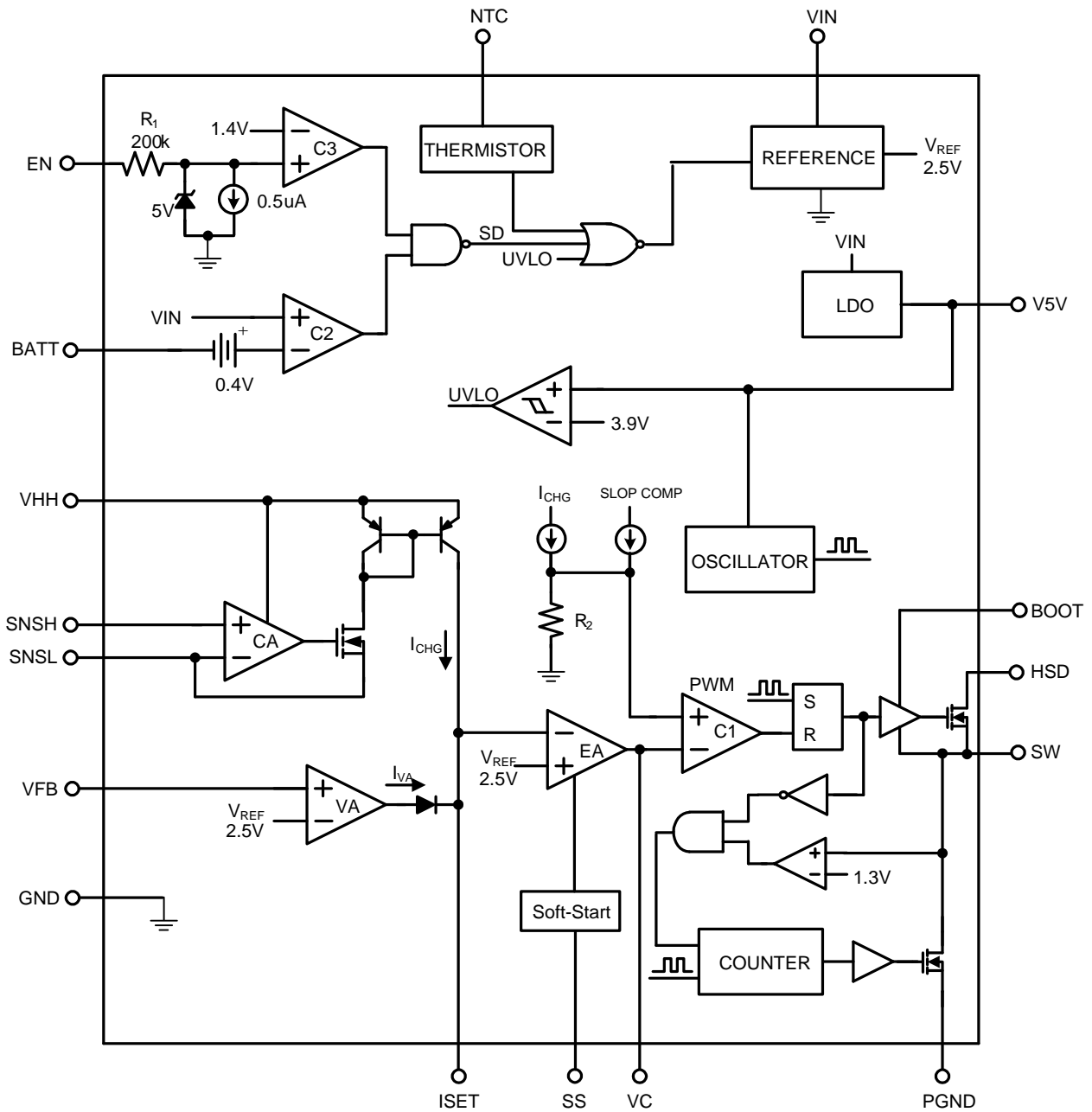


WQFN-16L 4x4

Functional Pin Description

Pin No.	Pin Name	Pin Function
1	EN	Enable Control Input (Active High). It must be connected to a logical voltage or pulled up to VIN with a 100kΩ resistor.
2	SS	Soft-Start Control Input. SS controls the soft-start time. Connect a capacitor from SS pin to GND to set the soft-start time.
3	ISET	Charge Current Setting and System Loop Compensation Pin. Connect a resistor from this pin to ground to set the charge current.
4	VC	Control Signal of the Inner Loop of the Current Mode PWM. A capacitor of at least 0.1μF with a serial resistor to GND filters out the current ripple.
5	NTC	Input for an external NTC thermistor for battery temperature monitoring.
6	VFB	Battery Voltage Feedback. Using an external resistor divider to set battery full charge voltage.
7	VHH	To supply the current sense amplifier CA for very low dropout condition. It must be connected as shown in the typical application circuit or connected to VIN if VIN is always larger than BATT by at least 1.8V.
8	BATT	Battery Voltage Sensing Input. A 10μF or larger X5R ceramic capacitor is recommended for filtering charge current ripple and stability purpose.
9	SNSL	Negative Terminal for Sensing Charge Current.
10	SNSH	Positive Terminal for Sensing Charge Current.
11	PGND	Power Ground.
12	SW	Switch Node. This pin switches between ground and VIN with high dv/dt rates. Care needs to be taken in the PCB layout to keep this node from coupling to other sensitive nodes.
13	HSD	Drain of Internal High-Side Power N-MOSFET Switch. Connect a low ESR capacitor of 10μF or higher from this pin to ground for good bypass.
14	BOOT	Bootstrap Supply for the High-Side Power Switch Gate Driver and Control Circuitry. In normal operation, $V_{BOOT} \approx V_{SW} + 5V$.
15	VIN	Input Power Supply. Connect a low ESR capacitor of 10μF or higher from this pin to ground for good bypass.
16	V5V	Output of Internal 5V LDO. Connect a 1μF ceramic capacitor from this pin to GND for stability.
17 (Exposed Pad)	GND	Exposed Pad. Connect the exposed pad to PGND.

Function Block Diagram



Operation

The RT9535A is a current mode PWM step-down switching charger controller. The battery DC charge current is programmed by a resistor R4 at the ISET pin and the ratio of sense resistor RS2 over RS1 in the typical application circuit. Amplifier CA converts the charge current through RS1 to a much lower sampled current I_{CHG} ($I_{CHG} = I_{BATT} \times RS1 / RS2$) fed into the ISET pin. Amplifier EA compares the output of CA with 2.5V reference voltage and drives the PWM loop to force them to be equal. Note that I_{CHG} has both AC and DC components. High DC accuracy is achieved with averaging filter R3 and C3 at ISET pin. I_{CHG} is mirrored to go through R4 and generates a ramp signal that is fed to the PWM control comparator, forming the current mode inner loop. An internal LDO generates a 5V to power high-side MOSFET gate driver. For batteries like lithium that require both constant current and constant voltage charging, the 0.5% 2.5V reference and the voltage amplifier VA reduce the charge current when battery voltage reaches the normal charge voltage level. For NiMH and NiCd, VA can be used for over-voltage protection.

Absolute Maximum Ratings (Note 1)

- VHH, BOOT to GND----- -0.3V to 36V
- VIN, EN, SW, HSD to GND ----- -0.3V to 30V
- ISET, VC, VFB, V5V SS, NTC to GND ----- -0.3V to 6V
- BATT SNSH, SNSL to GND----- -0.3V to 28V
- Power Dissipation, P_D @ T_A = 25°C
 - WQFN-16L 4x4 ----- 3.5W
- Package Thermal Resistance (Note 2)
 - WQFN-16L 4x4, θ_{JA} ----- 28.5°C/W
 - WQFN-16L 4x4, θ_{JC} ----- 7°C/W
- Lead Temperature (Soldering, 10 sec.)----- 260°C
- Junction Temperature----- 150°C
- Storage Temperature Range----- -65°C to 150°C
- ESD Susceptibility (Note 3)
- HBM (Human Body Model) ----- 2kV
- MM (Machine Model)----- 200V

Recommended Operating Conditions (Note 4)

- Supply Input Voltage ----- 4.5V to 28V
- Battery Voltage, V_{BAT} ----- 2.5V to 22V
- Ambient Temperature Range----- -40°C to 85°C
- Junction Temperature Range ----- -40°C to 125°C

Electrical Characteristics

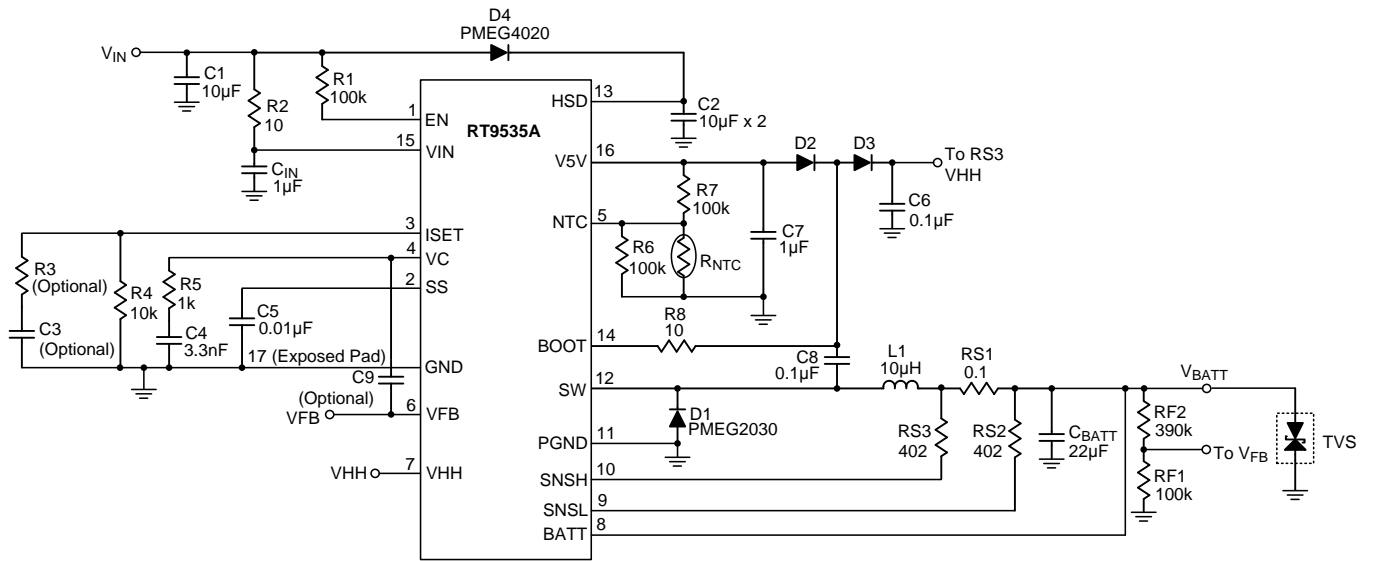
(V_{IN} = V_{BAT} + 3V, V_{BAT} is the full charge voltage, pull-up EN to V_{IN} with 100kΩ resistor, T_A = 25°C, unless otherwise specified)

Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
Overall						
Supply Quiescent Current	I _Q	No Charge Current	0.5	1.3	2	mA
Supply Shutdown Current	I _{SD}	V _{EN} = 0	--	--	12	μA
Reverse Current from Battery	I _{REV}	V _{IN} Floating, V _{EN} = 0 V _{BATT} = V _{SW} = V _{SNSH} = V _{SNSL} = 20V	--	--	10	μA
VIN Under-Voltage Lockout	V _{UVLO}		3.6	3.8	4.3	V
VIN Under-Voltage Lockout Hysteresis	V _{UVLO_HYS}		--	300	--	mV
Reference						
Reference Voltage	V _{FB}		2.486	2.5	2.514	V
FB Bias current	I _{FB}	V _{FB} = 2.5V	--	--	0.1	μA

Parameter	Symbol	Test Conditions	Min	Typ	Max	Unit
Charge Current						
Full-Scale Charge Current Sense Voltage	V _{ICHG}	Measure the Voltage Drop Across RS1	95	100	105	mV
ISET Output Current	I _{SET}		-1	--	--	mA
SNSL Bias Current	I _{SNSL}	No Charge Current	-36	-12	-6	μA
SNSH Bias Current	I _{SNSH}	No Charge Current	-36	-12	-6	μA
Battery Voltage						
V _{HH} Minimum Voltage with Respect to BATT	ΔV _{HH}		--	--	2	V
V _{IN} Minimum Voltage with Respect to BATT	V _{DROP}	(Note 5)	--	0.3	0.4	V
V _{HH} Input Current	I _{VHH}	V _{HH} = 28V	40	95	150	μA
BATT Bias Current	I _{BATT}	V _{EN} = 0, V _{BATT} = V _{SW} = V _{SNSH} = V _{SNSL} = 20V	--	--	10	μA
VC Pin Current	I _{VC}	V _{VC} = 0V	-25	-15	-1	μA
Switch Characteristics						
Switching Frequency	f _{OSC}		430	500	545	kHz
High-Side Switch On-Resistance	R _{ON}		--	150	--	mΩ
High-Side Switch leakage Current	I _{HSD}	V _{HSD} = 28V, V _{EN} = 0V	--	--	10	μA
BOOT Leakage Current	I _{BOOT}	V _{BOOT} = 30V, V _{EN} = 0V (Note 5)	--	1	--	μA
Maximum Duty		V _{VC} = 0V	95	--	--	%
SW Leakage Current	I _{LKGL}	V _{SW} = 28V, V _{EN} = 0V	--	--	10	μA
Regulator and Logic Characteristics						
LDO Output Voltage	V _{LDO}	50mA Load at V5V, V _{VC} = 0V	4	5	6	V
EN Input Voltage	Logic-High	V _{ENH}	2.5	--	--	V
	Logic-Low	V _{ENL}	--	--	0.6	
EN Input Current	I _{EN}	0V ≤ V _{EN} ≤ 5V	--	--	10	μA
Soft-Start Sourcing Current	I _{SS}		1.5	3.3	6	μA
Thermal Comparator and Protection						
NTC Threshold, Cold	V _{COLD}	NTC Voltage Rising, 1% Hysteresis	73.5% × V _{V5V}	75% × V _{V5V}	76.5% × V _{V5V}	V
NTC Threshold, Hot	V _{HOT}	NTC Voltage Rising, 1% Hysteresis	31% × V _{V5V}	32.5% × V _{V5V}	34% × V _{V5V}	V
NTC Disable Threshold	V _{DISNTC}	NTC Voltage Rising, 1% Hysteresis	0.2% × V _{V5V}	1.7% × V _{V5V}	3.2% × V _{V5V}	V
NTC Bias Current	I _{NTC}		--	2	10	μA
Thermal Shutdown Temperature	T _{SD}	(Note 5)	--	160	--	°C
Thermal Shutdown Hysteresis	ΔT _{SD}	(Note 5)	--	30	--	°C

- Note 1.** Stresses listed as the above "Absolute Maximum Ratings" may cause permanent damage to the device. These are for stress ratings. Functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may remain possibility to affect device reliability.
- Note 2.** θ_{JA} is measured at $T_A = 25^\circ\text{C}$ on a high effective thermal conductivity four-layer test board per JEDEC 51-7. θ_{JC} is measured at the exposed pad of the package.
- Note 3.** Devices are ESD sensitive. Handling precaution recommended.
- Note 4.** The device is not guaranteed to function outside its operating conditions.
- Note 5.** Guaranteed by design, not subjected to production test.

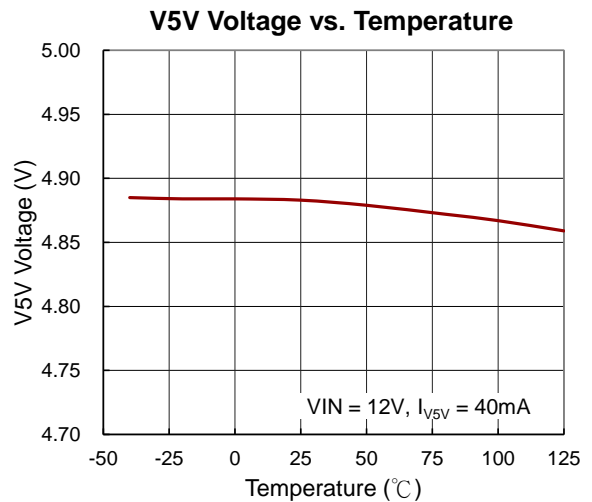
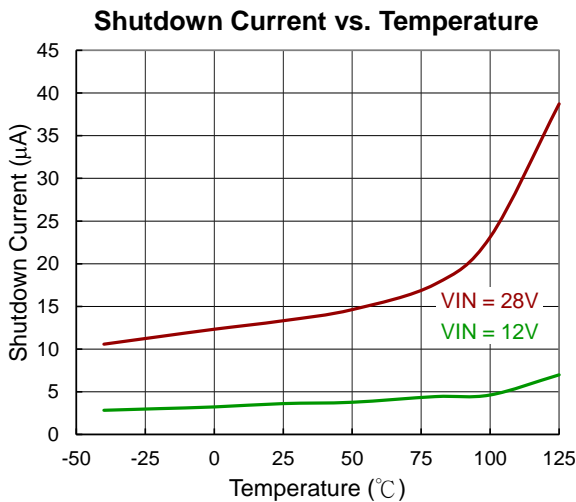
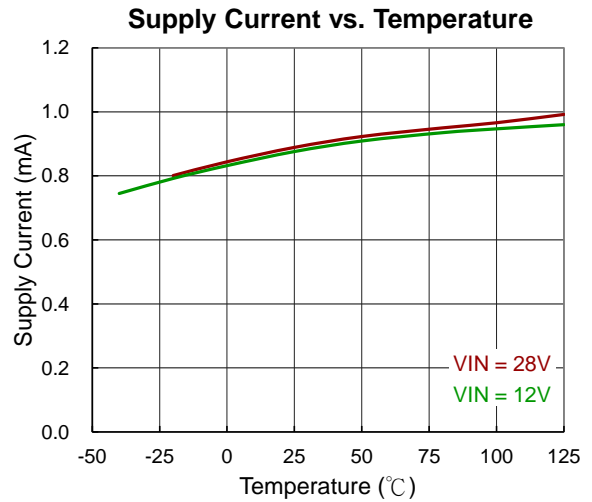
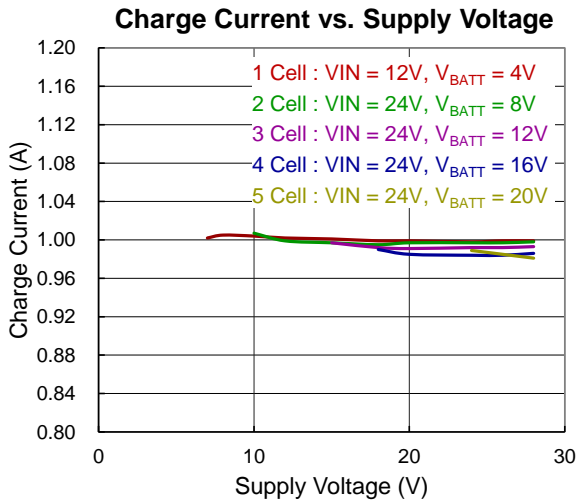
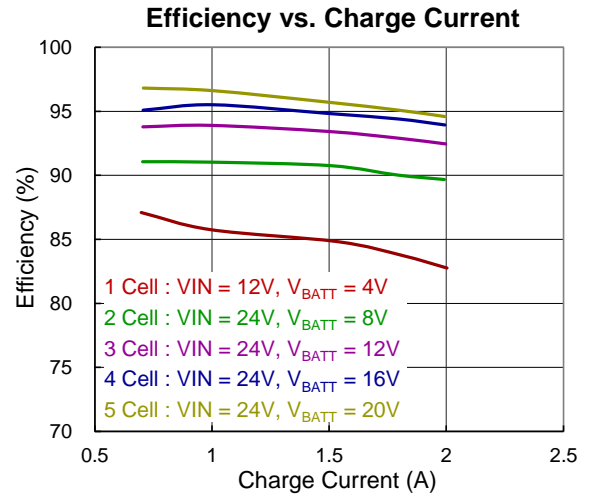
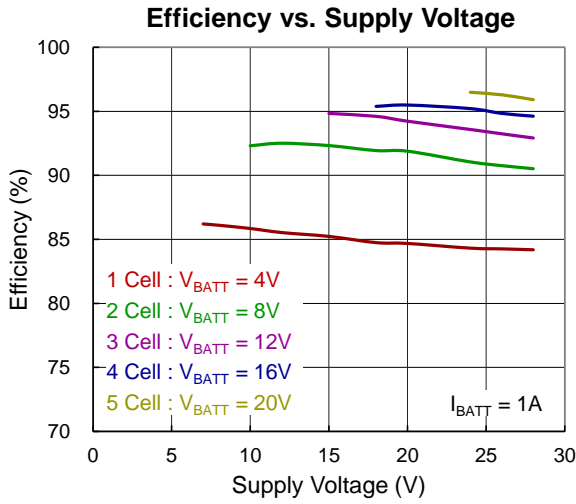
Typical Application Circuit

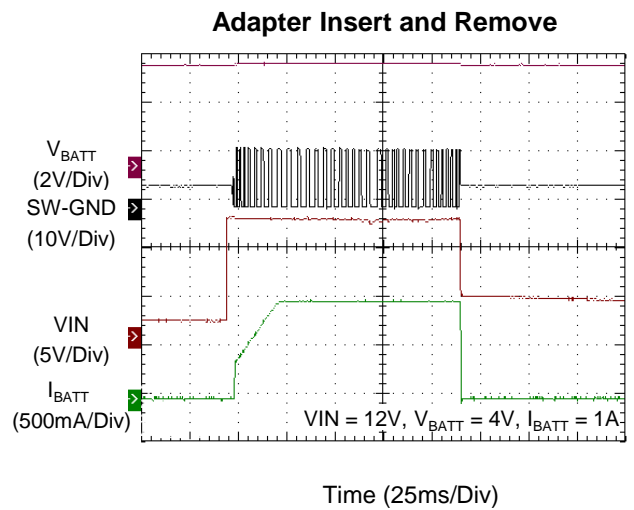
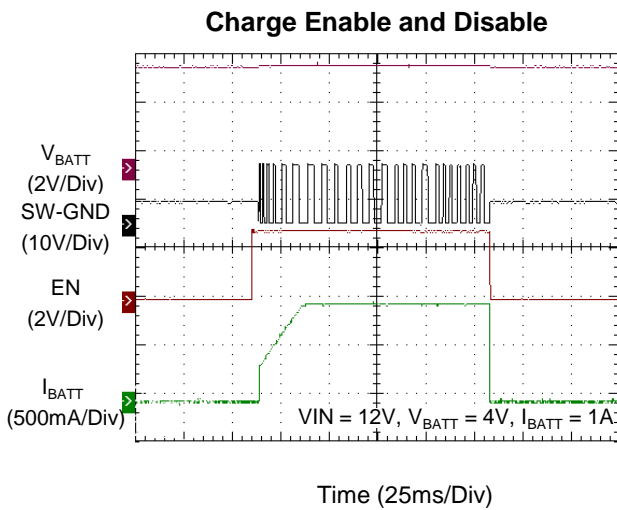
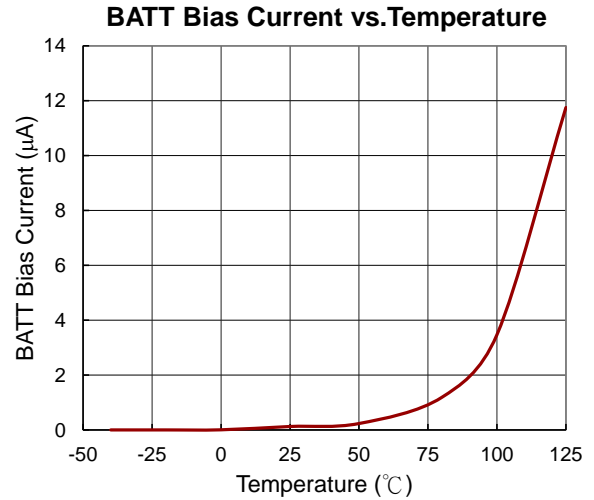
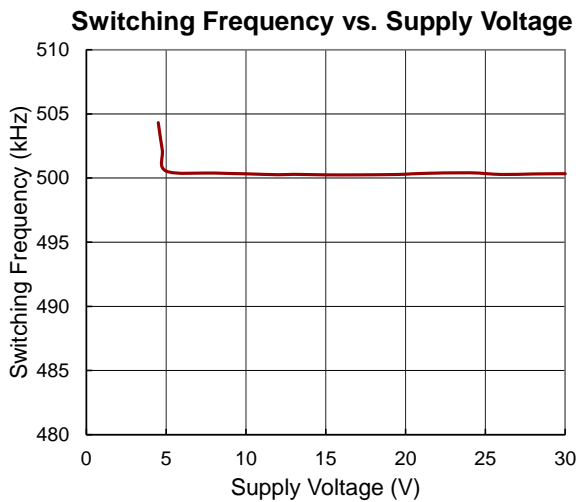
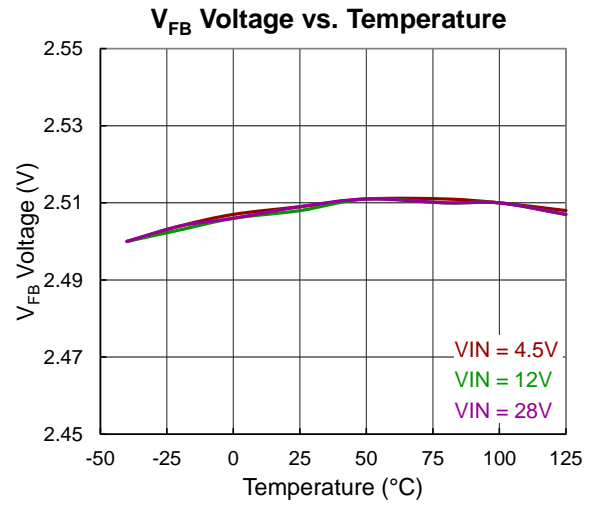
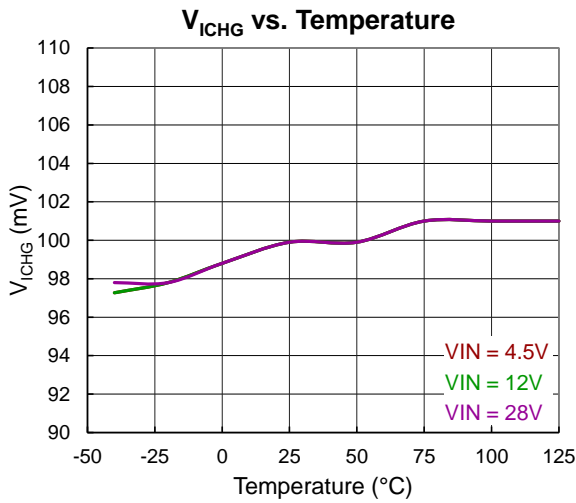


Note :

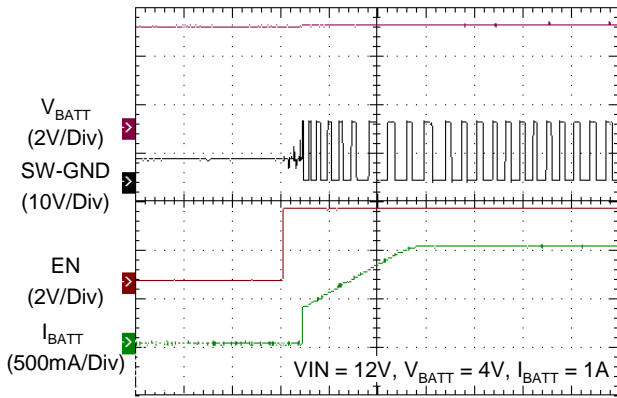
- (1). For application with removable battery, a TVS with appropriate rating is required as shown above.
- (2). $V_{IN} = 15V$ to $28V$, 3 – cell, $I_{CHARGE} = 1A$

Typical Operating Characteristics



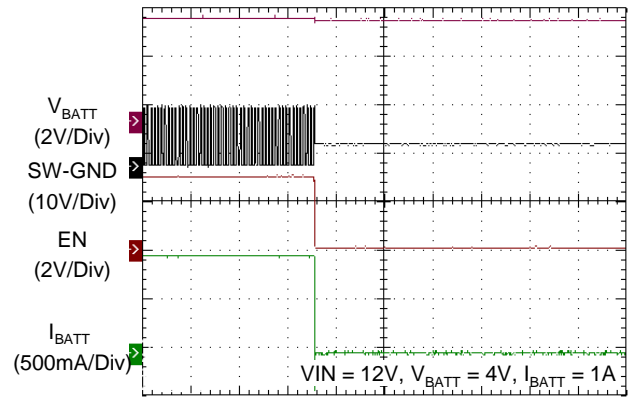


Charge Enable



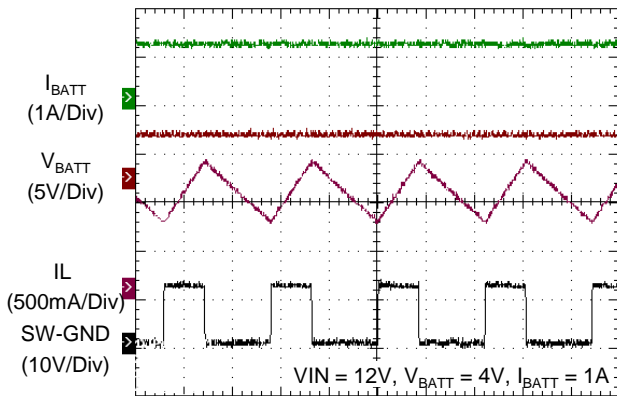
Time (10ms/Div)

Charge Disable



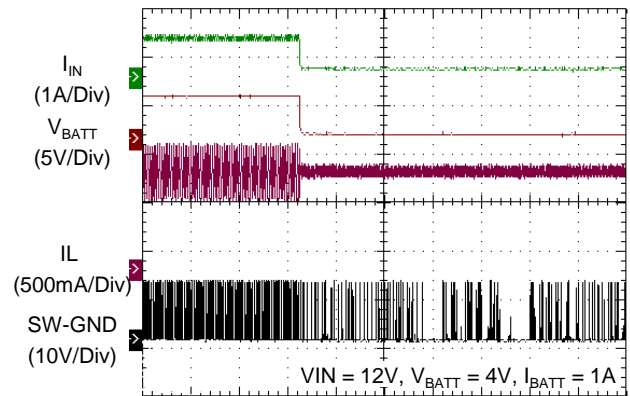
Time (10ms/Div)

Switching



Time (1μs/Div)

BATT to GND Short Response



Time (10ms/Div)

Application Information

Input and Output Capacitors

In the typical application circuit, the input capacitor (C2) is assumed to absorb all input switching ripple current in the converter, so it must have adequate ripple current rating. Typically, at high charging currents, the converter will operate in continuous conduction mode. In this case, the RMS current I_{RMSIN} of the input capacitor C2 can be estimated by the equation :

$$I_{RMSIN} = I_{BATT} \times \sqrt{D-D^2}$$

Where I_{BATT} is the battery charge current and D is the duty cycle. In worst case, the RMS ripple current will be equal to one half of output charging current at 50% duty cycle. For example, $I_{BATT} = 2A$, the maximum RMS current will be 1A. A low-ESR ceramic capacitor such as X7R or X5R is preferred for the input-decoupling capacitor and should be placed to the drain of the high-side MOSFET and source of the low-side MOSFET as close as possible. The voltage rating of the capacitor must be higher than the normal input voltage level. Above 20 μ F capacitance is suggested for typical of 2A charging current.

The output capacitor (C_{BATT}) is also assumed to absorb output switching current ripple. The general formula for capacitor current is :

$$I_{RMSCB} = \frac{V_{BATT} \times \left(1 - \frac{V_{BATT}}{V_{VIN}}\right)}{2 \times \sqrt{3} \times L1 \times f_{osc}}$$

For example, $V_{VIN} = 19V$, $V_{BATT} = 8.4V$, $L1 = 10\mu H$, and $f_{OSC} = 500kHz$, $I_{RMS} = 0.15A$.

EMI considerations usually make it desirable to minimize ripple current in the battery leads. Beads or inductors may be added to increase battery impedance at the 500kHz switching frequency. Switching ripple current splits between the battery and the output capacitor depending on the ESR of the output capacitor

and the battery impedance. If the ESR of C_{OUT} is 0.2 Ω and the battery impedance is raised to 4 Ω with a bead or inductor, only 5% of the ripple current will flow in the battery.

Inductor

The inductor value will be changed for more or less current ripple. The higher the inductance, the lower the current ripple will be. As the physical size is kept the same, typically, higher inductance will result in higher series resistance and lower saturation current. A good tradeoff is to choose the inductor so that the current ripple is approximately 30% to 50% of the full-scale charge current. The inductor value is calculated as :

$$L1 = \frac{V_{BATT} \times (V_{VIN} - V_{BATT})}{V_{VIN} \times f_{OSC} \times \Delta I_L}$$

Where ΔI_L is the inductor current ripple. For example, $V_{VIN} = 19V$, choose the inductor current ripple to be 40% of the full-scale charge current in the typical application circuit for 2A, 2-cell battery charger, $\Delta I_L = 0.8A$, $V_{BATT} = 8.4V$, calculate L1 to be 12 μ H. So choose L1 to be 10 μ H which is close to 12 μ H.

Soft-Start and Under-Voltage Lockout

The soft-start is controlled by the voltage rise time at SS pin. There are internal soft-start and external soft-start in the RT9535A. With a 0.01 μ F capacitor, time to reach full charge current is about 20ms and it is assumed that input voltage to the charger will reach full value in less than 20ms. The capacitor can be increased if longer input start-up times are needed.

For the RT9535A, it provides Under-Voltage Lockout (UVLO) protection. If 5V5LDO output voltage is lower than 3.5V, high-side internal power MOSFET. This will protect the adapter from entering a quasi "latch" state where the adapter output stays in a current limited state at reduced output voltage.

Full-Scale Charge Current Programming

The basic formula for full-scale charge current is (see Block Diagram) :

$$I_{BATT} = \left(\frac{V_{REF}}{R_4} \right) \times \left(\frac{RS_2}{RS_1} \right)$$

Where R4 is the total resistance from ISET pin to ground. For the sense amplifier CA biasing purpose, RS3 should have the same value as RS2 with 1% accuracy. For example, 2A full-scale charging current is needed. For low power dissipation on RS1 and enough signal to drive the amplifier CA, let RS1 = 100mV/2A = 50mΩ. This limits RS1 power to 0.2W. Let R4 = 10kΩ, then :

$$RS_2 = RS_3 = \frac{I_{BATT} \times R_4 \times RS_1}{V_{REF}} = \frac{2A \times 10k \times 0.05}{2.5V} = 400\Omega$$

Note that for charge current accuracy and noise immunity, 100mV full scale level across the sense resistor RS1 is required. Consequently, both RS2 and RS3 should be 402Ω. The R4 should be set to between 5kΩ and 15kΩ for the best operation.

It is critical to have a good Kelvin connection on the current sense resistor RS1 to minimize stray resistive and inductive pickup. RS1 should have low parasitic inductance (typical 3nH or less). The layout path from RS2 and RS3 to RS1 should be kept away from the fast switching SW node. A 1nF ceramic capacitor can be used across SNSH and SNSL and be kept away from the fast switching SW node.

Battery Voltage Regulation

The RT9535A uses high-accuracy voltage bandgap and regulator for the high charging-voltage accuracy. The charge voltage is programmed via a resistor divider from the battery to ground, with the midpoint tied to the VFB pin. The voltage at the VFB pin is regulated to 2.5V, giving the following equation for the regulation voltage:

$$V_{BATT} = 2.5 \times \left(1 + \frac{RF_2}{RF_1} \right)$$

where RF2 is connected from VFB to the battery and RF1 is connected from VFB to GND.

Charging

The 2A Battery Charger (typical application circuit) charges lithium-ion batteries at a constant 2A until battery voltage reaches the setting value. The charger will then automatically go into a constant voltage mode with current decreasing to near zero over time as the battery reaches full charge.

Dropout Operation

The RT9535A can charge the battery even when VIN goes as low as 2V above the combined voltages of the battery and the drops on the sense resistor as well as parasitic wiring. This low VIN sometimes forces 100% duty cycle and high-side power switch stays on for many switching cycles. While high-side power switch stays on, the voltage VBOOT across the capacitor C8 drops down slowly because the current sink at BOOT pin. C8 needs to be recharged before VBOOT drops too low to keep the topside switch on.

A unique design allows the RT9535A to operate under these conditions. If SW pin voltage keeps larger than 1.3V for 32 oscillation periods, high-side power MOSFET will be turned off and an internal MOSFET will be turned on to pull SW pin down. This function refreshes VBOOT voltage to a higher value. It is important to use 0.1μF to hold VBOOT up for a sufficient amount of time.

Shutdown

When adapter power is removed, VIN will drift down. As soon as VIN goes down to 0.1V above VBATT, the RT9535A will go into sleep mode drawing only ~10μA from the battery. There are two suggest ways to stop switching: pulling the EN pin low or pulling the VC pin low. Pulling the EN pin low will shut down the whole

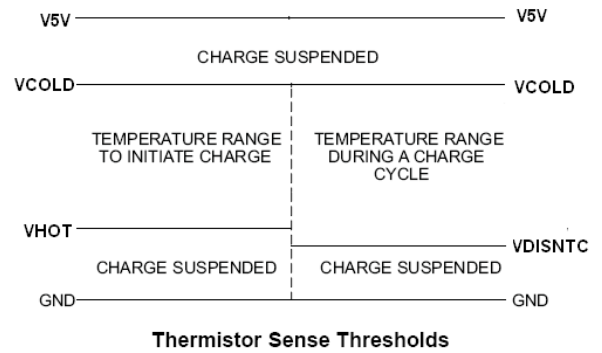
chip. Pulling the VC pin low will only stop switching and 5V5LDO stays active. Make sure there is a pull-up resistor on the EN pin even if the EN pin is not used, otherwise internal pull-down current will keep the EN pin low to shut down mode when power turns on.

Charger Protection

Note that the RT9535A will operate even when VBATT is grounded. If VBATT of typical application circuit charger gets shorted to ground very quickly from a high battery voltage, slow loop response may allow charge current to build up and damage the high-side internal N-MOSFET. A small diode from the EN pin to VBATT will shut down switching and protect the charger.

Temperature Qualification

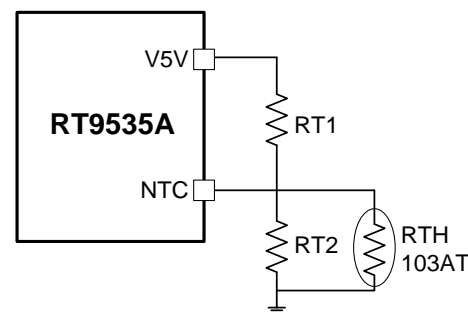
The controller RT9535A continuously monitors battery temperature by measuring the voltage between the NTC pin and GND. A negative temperature coefficient thermistor (NTC) and an external voltage divider typically generate this voltage. The controller compares this voltage against its internal thresholds to determine if charging is allowed. To initiate a charge cycle, the battery temperature must be within the VCOLD. If battery temperature is outside of this range, the controller suspends charge and the safety timer and waits until the battery temperature is within the VCOLD to VHOT range. During the charge cycle, the battery temperature must be within the VCOLD and VDISNTC thresholds. If the battery temperature is outside of this range, the controller suspends charge and waits until the battery temperature is within the VCOLD to VHOT range. The controller suspends charge by turning off the PWM charge MOSFETs.



Assuming a 103AT NTC thermistor on the battery pack as shown in the below, the values of RT1 and RT2 can be determined by using the following equations :

$$RT2 = \frac{V_{V5V} \times R_{THCOLD} \times R_{THHOT} \times \left(\frac{1}{V_{COLD}} - \frac{1}{V_{HOT}} \right)}{R_{THHOT} \times \left(\frac{V_{V5V}}{V_{HOT}} - 1 \right) - R_{THHOT} \times \left(\frac{V_{V5V}}{V_{COLD}} - 1 \right)}$$

$$RT1 = \frac{\frac{V_{V5V}}{V_{COLD}} - 1}{\frac{1}{RT2} + \frac{1}{R_{THCOLD}}}$$



TS Resistor Network

Where RTHCOLD and RTHHOT which have defined in the spec of the 103AT NTC thermistor.

Thermal Considerations

For continuous operation, do not exceed absolute maximum junction temperature. The maximum power dissipation depends on the thermal resistance of the IC package, PCB layout, rate of surrounding airflow, and difference between junction and ambient temperature. The maximum power dissipation can be calculated by the following formula :

$$P_{D(MAX)} = (T_{J(MAX)} - T_A) / \theta_{JA}$$

where $T_{J(MAX)}$ is the maximum junction temperature, T_A is the ambient temperature, and θ_{JA} is the junction to ambient thermal resistance.

For recommended operating condition specifications, the maximum junction temperature is 125°C. The junction to ambient thermal resistance, θ_{JA} , is layout dependent. For WQFN-16L 4x4 package, the thermal resistance, θ_{JA} , is 28.5°C/W on a standard JEDEC 51-7 four-layer thermal test board. The maximum power dissipation at $T_A = 25^\circ\text{C}$ can be calculated by the following formula :

$$P_{D(MAX)} = (125^\circ\text{C} - 25^\circ\text{C}) / (28.5^\circ\text{C/W}) = 3.5\text{W for WQFN-16L 4x4 package}$$

The maximum power dissipation depends on the operating ambient temperature for fixed $T_{J(MAX)}$ and thermal resistance, θ_{JA} . The derating curve in Figure 1 allows the designer to see the effect of rising ambient temperature on the maximum power dissipation.

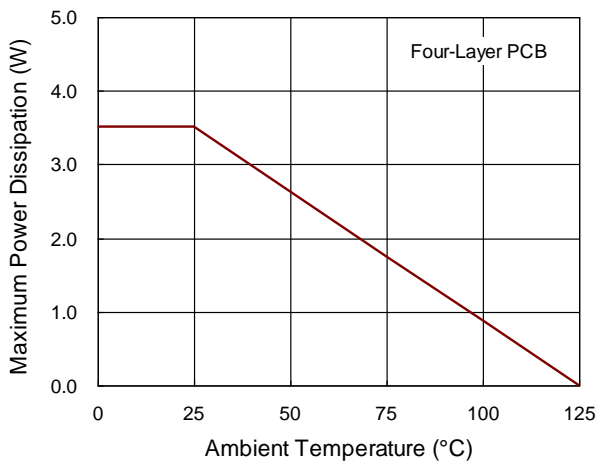


Figure 1. Derating Curve of Maximum Power Dissipation

Layout Consideration

Switch rise and fall times are under 20ns for maximum efficiency. To prevent radiation, the SW pin, the rectifier Schottky diode D1 and input bypass capacitor leads should be kept as short as possible. A ground plane should be used under the switching circuitry to prevent inter-plane coupling and to act as a thermal spreading path. Note that the rectifier Schottky diode D1 is probably the most heat dissipating device in the charging system. The voltage drop on a 2A Schottky diode can be 0.5V. With 50% duty cycle, the power

dissipation can go as high as 0.5W. Expanded traces should be used for the diode leads for low thermal resistance. Another large heat dissipating device is probably the inductor. The fast switching high current ground path including the MOSFETs, D1 and input bypass capacitor C2 should be kept very short. Another smaller input bypass (1 μ F ceramic or larger paralleled with C_{IN}) should be placed to VIN pin and GND pin as close as possible.

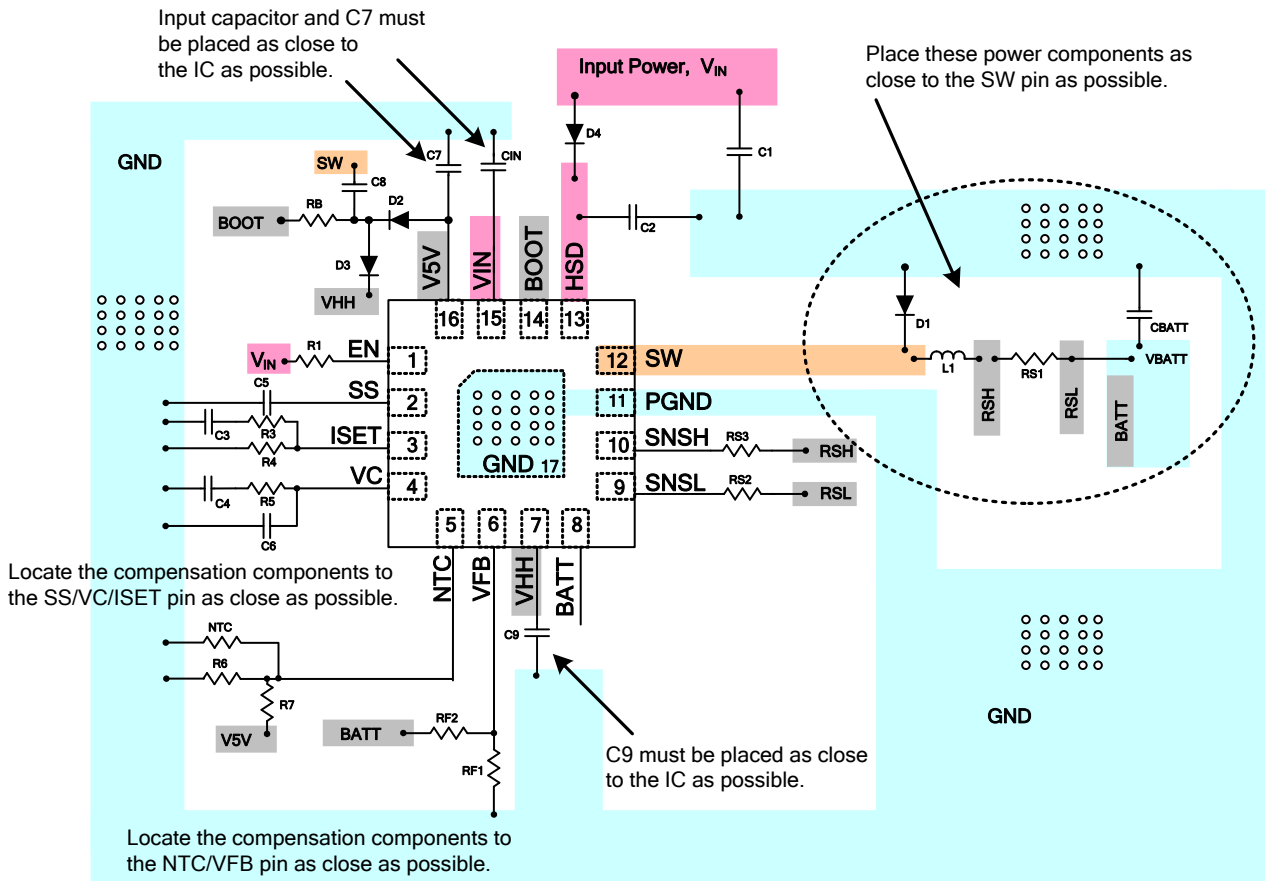
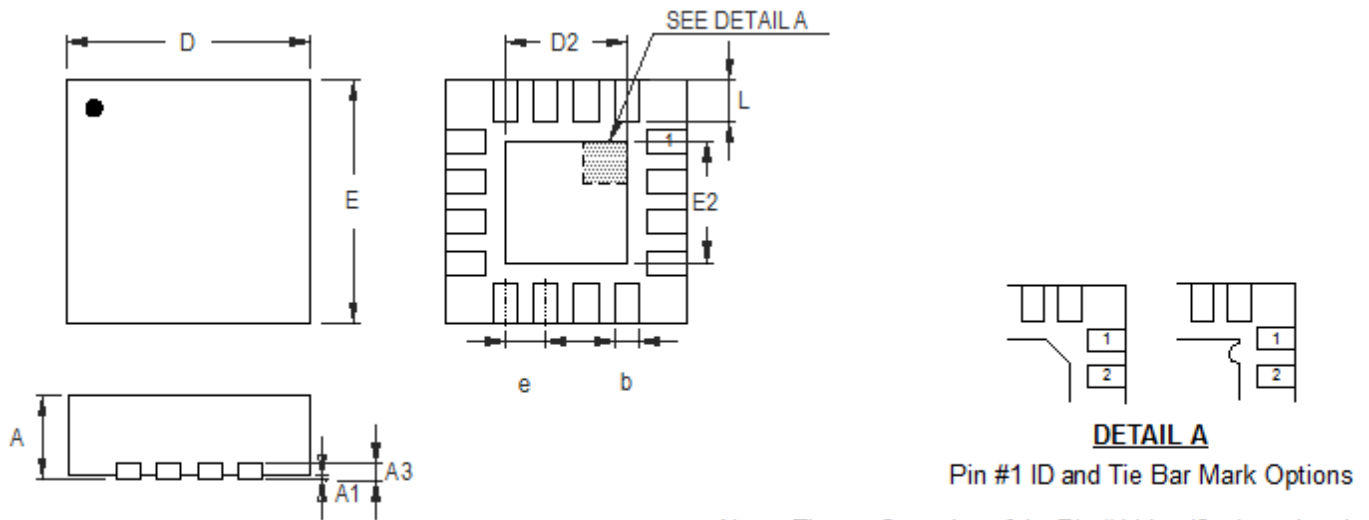


Figure 2. PCB Layout Guide

Outline Dimension



Note : The configuration of the Pin #1 identifier is optional, but must be located within the zone indicated.

Symbol	Dimensions In Millimeters		Dimensions In Inches	
	Min	Max	Min	Max
A	0.700	0.800	0.028	0.031
A1	0.000	0.050	0.000	0.002
A3	0.175	0.250	0.007	0.010
b	0.250	0.380	0.010	0.015
D	3.950	4.050	0.156	0.159
D2	2.000	2.450	0.079	0.096
E	3.950	4.050	0.156	0.159
E2	2.000	2.450	0.079	0.096
e	0.650		0.026	
L	0.500	0.600	0.020	0.024

W-Type 16L QFN 4x4 Package

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