Li-Ion Battery Charger Module (bq2057) - Notes

Introduction

This document is developed as a self guide in the process of designing a simple Li-Ion charger module. This is not a formal report.
Knowing how a simple battery charger module works is of vital importance as it allows to develop battery based devices like robots, drones, and wearable and portable devices. This is why I am developing a charging module myself. I could use my design and implement it in custom devices I make to eliminate the need of using other modules which may lack certain capabilities. For this project, I am using the battery charger ICs series bq2057 from Texas Instruments. Specifically I will be testing the charge process for a 3.7V and a 7.4V Li-Ion battery pack using the bq2057C and bq2057W ICs respectively. The purpose of the charge process is to safely charge the battery in the least time possible. I will also be testing what is the lowest battery voltage that leads similar performance as a fully charged battery in exchange for less charge time. For example, if charging the battery to 4.0V instead of 4.2V yields a battery life of lets say of 1h while the same battery at 4.2V yields 1.1 h and it takes about an hour to get from 4.0 V to 4.2 then I would say its worth it to charge the battery to 4 Volts instead. Finally but most importantly, I will be studying how the bq2057 series IC charger works to improve my understanding and future usage of such.

Topics of interest

1. How the series bq2057 IC work?
2. What is the best charge time for the Li-Ion batteries used?
3. What is the behavior of the Li-Ion battery during charge and discharge?

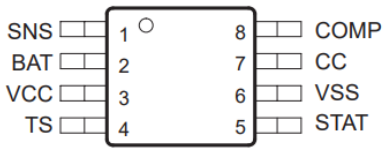
Implementation

1. How the series bq2057 IC work?

In this subsection I will be exploring the working of the series bq2057 IC battery charger, specifically the bq2057W in SOIC packing. I will be using the device’s data sheet to guide through the process of course. All pictures used in subsection 1 belong to such data sheet by Texas Instruments. Before starting with the circuit, let’s take a look at the characteristics including physical, MAX and MIN ratings for this product.

1.1 Physical Configuration and Pinout

bq2057xSN or bq2057xTS
SOIC (SN) or TSSOP (TS) PACKAGE
(TOP VIEW)



TERMINAL			I/O	DESCRIPTION
NAME	NO.			
	SOIC (SN) and TSSOP (TS)	MSOP (DGK)		
BAT	2	8	I	Voltage sense input
CC	7	5	O	Charge control output
COMP	8	6	I	Charge-rate compensation input (AutoComp)
SNS	1	7	I	Current sense input
STAT	5	3	O	Charge status output
TS	4	2	I	Temperature sense input
VCC	3	1	I	Supply voltage
VSS	6	4		Ground

This physical configuration and pinout will be useful when analyzing the sample circuit.

1.2 Characteristic charge regulation voltage table and MAX/MIN ratings

AVAILABLE OPTIONS

T_A	PACKAGE			
	CHARGE REGULATION VOLTAGE	SOIC (SN)	TSSOP (TS)	MSOP† (DGK)
−20°C to 70°C	4.1 V	Not available	bq2057TS	bq2057DGK
	4.2 V	bq2057CSN	bq2057CTS	bq2057CDGK
	8.2 V	Not available	bq2057TTS	Not available
	8.4 V	bq2057WSN	bq2057WTS	

† Note the difference in pinout for this package.

As seen, the charge regulation voltage for bq2057W is 8.4V. Therefore, I will be charging two 3.7V 18650 Li-Ion batteries in series for testing purposes. These batteries are of the make *Skywolfeye*, cheap yet not as good as other makes when it comes to charge storage capacity. As a matter of fact I will calculate charge storage capacity in Subsection 3.

recommended operating conditions

	MIN	MAX	UNIT
Supply voltage, V_{CC}	4.5	15	V
Operating free-air temperature range, T_A	−20	70	°C

electrical characteristics over recommended operating free-air temperature range (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
$I_{(VCC)}$	V_{CC} Current	$V_{CC} > V_{CC(min)}$, Excluding external loads		2	4	mA
$I_{(VCCS)}$	V_{CC} Sleep current	For bq2057 and bq2957C, $V_{(BAT)} \geq V_{(min)}$, $V_{(BAT)} - V_{CC} \geq 0.8$ V		3	6	μA
		For bq2057T and bq2957W, $V_{(BAT)} \geq V_{(min)}$, $V_{(BAT)} - V_{CC} \geq 0.8$ V			10	μA
$I_{IB(BAT)}$	Input bias current on BAT pin	$V_{(BAT)} = V_{(REG)}$			1	μA
$I_{IB(SNS)}$	Input bias current on SNS pin	$V_{(SNS)} = 5$ V			5	μA
$I_{IB(TS)}$	Input bias current on TS pin	$V_{(TS)} = 5$ V			5	μA
$I_{IB(COMP)}$	Input bias current on COMP pin	$V_{(COMP)} = 5$ V			5	μA
BATTERY VOLTAGE REGULATION						
$V_{O(REG)}$	Output voltage	bq2057, See Notes 1, 2, 3	4.059	4.10	4.141	V
		bq2057C, See Notes 1, 2, 3	4.158	4.20	4.242	V
		bq2057T, See Notes 1, 2, 3	8.119	8.20	8.282	V
		bq2057W, See Notes 1, 2, 3	8.317	8.40	8.484	V

NOTES: 1. For high-side current sensing configuration
2. For low-side current sensing configuration, the tolerance is ±1% for $T_A = 25°C$ and ±1.2% for $-20°C \geq T_A \geq 70°C$
3. $V_{(BAT)}+0.3\text{ V} \leq V_{CC} \leq V_{CC(max)}$

As highlighted, this IC works within the range of 4.5-15V and the regulation voltage it uses to compare to the battery voltage is in the range of **8.317-8.484V**. This battery voltage regulation value is used to compare to the battery voltage. When the battery voltage falls within this range as measured through BAT (Pin 2), the charge is stopped, meaning the battery is fully charged. This process is shown in the operation flowchart in sub-subsection 1.3.

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT	
CURRENT REGULATION							
$V_{(SNS)}$	Current regulation threshold	bq2057 and bq2057C, High-side current sensing configuration	95.4	105	115.5	mV	
		bq2057T and bq2057W, High-side current sensing configuration	113.6	125	137.5	mV	
		bq2057 and bq2057C, Low-side current sensing configuration	100	110	121	mV	
		bq2057T and bq2057W, Low-side current sensing configuration	118.1	130	143	mV	
CHARGE TERMINATION DETECTION							
$I_{(TERM)}$	Charge termination current detect threshold	Voltage at pin SNS, relative to V_{CC} for high-side sensing, and to Vss for low-side sensing, $0°C \leq T_A \leq 50°C$	−24	−14	−4	mV	1
TEMPERATURE COMPARATOR							
$V_{(TS1)}$	Lower temperature threshold	TS pin voltage	29.1	30	30.9	$\%V_{CC}$	
$V_{(TS2)}$	Upper temperature threshold	TS pin voltage	58.3	60	61.8	$\%V_{CC}$	
PRECHARGE COMPARATOR							
$V_{(min)}$	Precharge threshold	bq2057	2.94	3	3.06	V	
		bq2057C	3.04	3.1	3.16	V	
		bq2057T	5.98	6.1	6.22	V	
		bq2057W	6.18	6.3	6.43	V	
PRECHARGE CURRENT REGULATION							
$I_{(PRECHG)}$	Precharge current regulation	Voltage at pin SNS, relative to V_{CC} for high-side sensing, and to V_{SS} for low-side sensing, $0°C \leq T_A \leq 50°C$		13		mV	2
		Voltage at pin SNS, relative to V_{CC} for high-side sensing, $0°C \leq T_A \leq 50°C$, $V_{CC} = 5$ V	3	13	22	mV	
V_{RCH} COMPARATOR (Battery Recharge Threshold)							
$V_{(RCH)}$	Recharge threshold	bq2057 and bq2057C	$V_{O(REG)}-$ 98 mV	$V_{O(REG)}-$ 100 mV	$V_{O(REG)}-$ 102 mV	V	3
		bq2057T and bq2057W	$V_{O(REG)}-$ 196 mV	$V_{O(REG)}-$ 200 mV	$V_{O(REG)}-$ 204 mV	V	
CHARGE-RATE COMPENSATION (AutoComp)							
$G_{(COMP)}$	AutoComp gain	$V_{(BAT)}+0.3\text{ V} \leq V_{CC} \leq V_{CC(max)}$, bq2057, bq2057C, bq2057T, bq2057W	1.87	2.2	2.53	V/V	
		$V_{(BAT)}+0.3\text{ V} \leq V_{CC} \leq V_{CC(max)}$, bq2057T and bq2057W in low-side sensing configuration	2.09	2.4	2.76	V/V	
STAT PIN							
$V_{OL(STAT)}$	Output (low) voltage	$I_{OL} = 10$ mA			0.7	V	
$V_{OH(STAT)}$	Output (high) voltage	$I_{OH} = 5$ mA	V_{CC}-0.5			V	
CC PIN							
$V_{OL(CC)}$	Output low voltage	$I_{O(CC)} = 5$ mA (sink)			1.5	V	
$I_{O(CC)}$	Sink current	Not to exceed power rating specification (P_D)	5		40	mA	

From what I understand in the table above, the voltage across the sense resistor V(SNS) for high-side current sensing - which means the sense resistor is placed before the charge transistor- should normally be between **118.1-143 mV** as maintained by the IC by means of charge-current feedback applied through the SNS pin. V(SNS) is independent of the resistor being placed at least during the current regulation phase, therefore this allows the user to set the desired charge current IO(REG) by using different resistor values for R(SNS). And so, IO(REG) = V(SNS)/R(SNS). Also, something very important is the fact that the IC constantly monitors the voltage of the battery with respect to V(min) to determine if the battery needs a pre-charge phase or not. Having a faulty two-battery pack in which one of the batteries has a voltage of almost zero may result in the IC always staying in pre-charge mode, charging the good battery for a very long time but never indicating the end of the charge phase. This may result in the overcharge of the good battery, let's be aware of that.

Below, I am covering each of the enumerated rows in the table above:

1. For the IC to detect when it's time to start charge termination current phase, V(SNS) - VCC should be in the range of **(-24) - (-4)mV**. Basically, this means that as the battery charges V(SNS) will increase with the battery and when V(SNS) falls in the range (-24) - (-4)mV with respect to VCC, the charge termination phase will kick in. Now, this is what I understand, however, if the previous is true then if I use 9V to charge my two 18650 Li-Ion series battery pack which will charge up to 8.4V, V(SNS) - VCC = -0.6V which is out of the threshold range. Does this mean VCC should be 8.4 + 24mV for the IC to terminate charge successfully? Also, if this is true the regulation voltage which is in the range **8.317-8.484V** may end the charge before the charge termination phase kicks in. Well, after looking at the operation flowchart, I can see that I(TERM) is check before comparing battery voltage to V(RCH), nevertheless I don't see how the IC overcomes the I(TERM) condition when V(SNS) - VCC is beyond the range even though the battery is charged. To my understanding this results in the IC never indicating the end of charge phase. Therefore, I should use a different resistor or set VCC to around 8.4 + 24mV. I will further start tests to measure the voltage at the pin SNS and will play with the value of R(SNS) to see the results.

TESTING:

Previously, I was using a faulty battery pack to test the IC. The problem with this battery pack is that one of the batteries didn't fully charge, therefore the two batteries in series will never reach the regulation voltage the IC is checking (at least ~8.2 V) these would stay somewhere in between 8.1-8.17V. Now, I will make a new battery pack using two new 18650 Li-Ion batteries of the make Skywolfeye. I expect the charge to reach an end since now the batteries can get to the regulation voltage. If the charge reaches the end then I know there is no problem with the I(TERM) condition. I will not change my circuit (See circuit in sub-subsection 1.4), my current R(SNS) is very small to allow for maximum current to charge the battery, if this does not result then I will change R(SNS) to 0.2 or 0.4 Ohms. I would know when the charge is done using an LED in the STAT pin, when the LED comes off, the charge is done. Also, I will measure the voltage at pin SNS with respect to VCC to verify the IC is working as expected.

RESULTS

The charge process was unsuccessful when I used a very small value for R(SNS) (**< 0.1 Ohms**). The battery was charged, but the charge process never finished due to the IC not detecting the charge termination current I(TERM). When a 0.2 Ohm resistor was placed the charge was successful terminated. Therefore, I will be using a 0.2 Ohm resistor for the first series of charging modules, just to go safe. The main issue was in the R(SNS) used which was too small. Another thing that I observed is that the voltage at VCC does not influence the charge process as long as VCC is greater than VO(REG) which in the case of the BQ2057W is 8.4V. Also, as I measured, the voltage that triggered my BQ2057W into detecting I(TERM) was **-14 mV** at SNS with respect to VCC which falls into the typical behavior of the device.

2. This characteristic is similar to that of I(TERM) detection. Just that it does not seem to be a threshold. In fact, I think this voltage is never checked by the IC. The BQ2057W decides to put the battery in pre-charge by comparing V(BAT) and V(min). This I will cover next while interpreting the operation flowchart.

3. V(RCH) is compared to the voltage of the battery in order to declare a fully charged battery in a permanent basis. In the case the bq2057W **V(RCH) = V(REG) - 0.2V typically**. This is important because V(REG) = 8.4 V however, the value being compared to the battery is 8.4-0.2 = **8.2 V** typically.

1.3 Analysis of the operation flowchart and charge profile

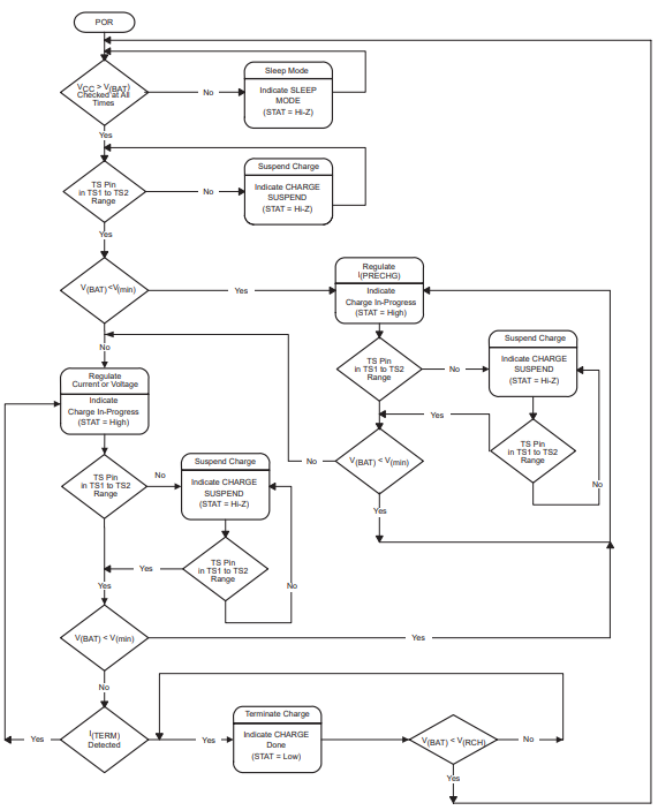


Figure 2. Operation Flowchart

This operation flowchart indicates how the device operates, which factors it considers and compares and what actions it takes based on such considerations. The first thing the device checks is whether VCC < V(BAT), if such is true it falls into sleep mode to save power. Otherwise it checks the temperature, using a thermostat, any time the battery is too hot charge is suspended and STAT is set to low. Next, as previously mentioned if V(BAT) < V(min) pre-charge phase kicks in and STAT pin is set to high. Otherwise, regular current or voltage regulation kicks in and battery charges at full current. Again if temperature is not right charge is suspended. If the battery voltage falls below V(min) pre-charge phase kicks in. Otherwise, I(TERM) is checked to detect if the battery is done charging. If not, current or voltage keeps being regulated and the battery continues to charge. If I(TERM) is detected then STAT is set to low and if V(BAT) < V(RCH) the whole process of charge is restarted. Otherwise, the IC falls into a loop with STAT in low to indicate the charge is done. As it could be seen I(PRECHG) is not part of any conditional statement (diamond box), therefore it doesn't appear to be part of any decision making logic in the IC.

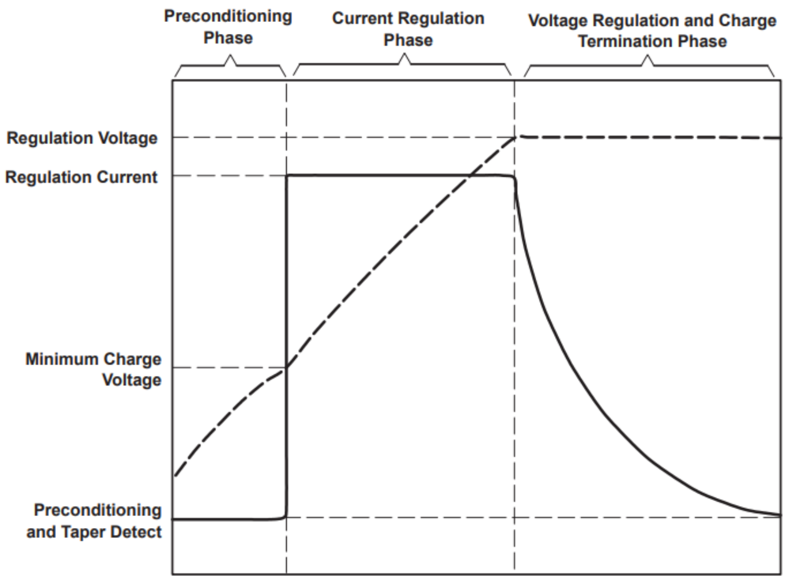


Figure 3. Typical Charge Profile

As seen in the graph above, for a battery that has V(BAT) < V(min) a typical charge profile should look like the solid line as for the current flowing into the battery and like the dashed line for the voltage across the battery. First there exists a preconditioning phase which charges the battery to V(min). Second, above V(min) full current is let into the battery during the current regulation phase until finally the battery gets close to the regulation voltage.

1.4 Circuit

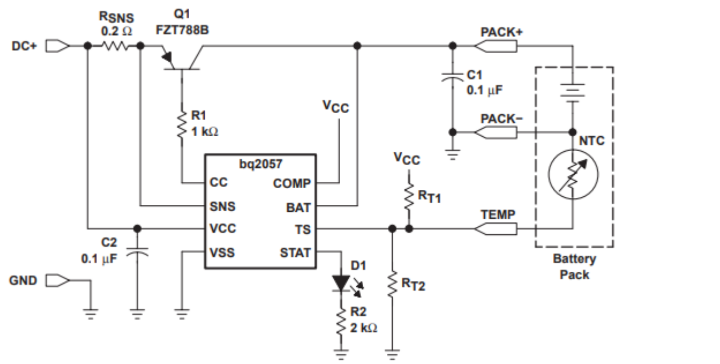


Figure 1. Low Dropout Single- or Two-Cell Li-Ion/Li-Pol Charger

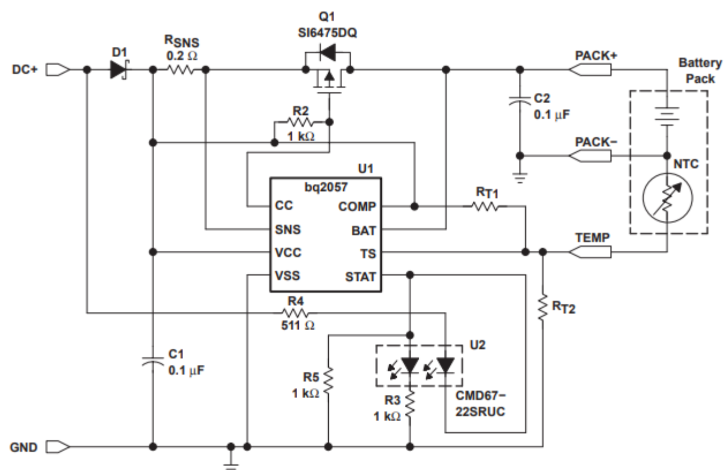
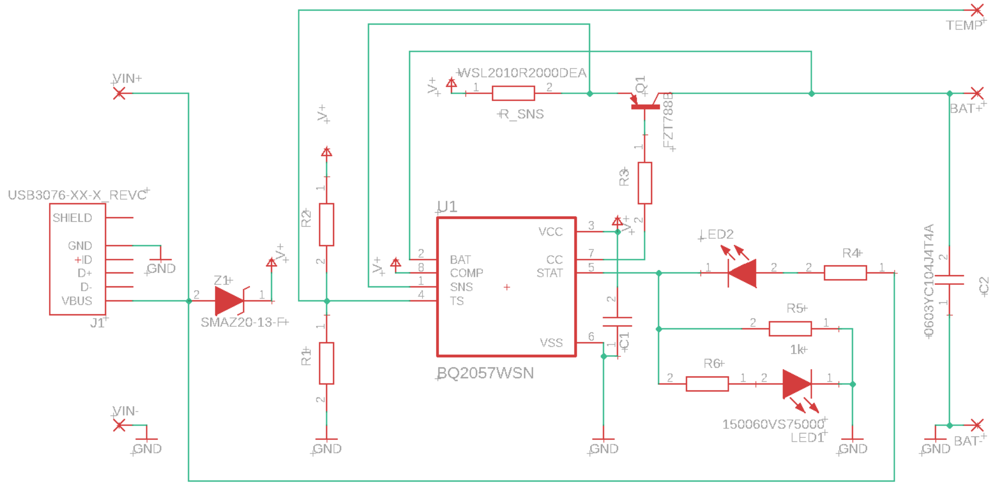


Figure 4. 0.5-A Charger Using P-Channel MOSFET

These are the two circuits shown in the data-sheet, very helpful indeed. I am reproducing for my charger module by mainly using the circuit in Figure 1. However, I added the two LED feature from the circuit in Figure 4 to make the module more user interactive. Also, I don't have any thermostat and is not necessary in order to charge the battery using the IC. The temperature check feature could be bypassed by choosing RT1 and RT2 to be of the same resistance. This keeps the voltage at TS to be close to VCC/2 which is what the IC checks. If the voltage at pin TS is in the approximate exclusive range of 31.9 % - 61.8% of VCC then the IC will consider temperature is good for charge to be performed. Therefore by using a voltage divider the voltage at TS is just about VCC/2 which is in the range and the temperature check is bypassed. Nevertheless, when I am charging the battery at high currents 1A or above I will definitely be using a thermostat to avoid any possible overheating problem. In the circuit of Figure 4 there is a z-diode, which serves so that the battery doesn't power the indicator LEDs. I didn't use the SI6475DQ transistor for my demo circuit but the FZT788B one instead. I noticed that the FZT788B enters saturation mode at around (6.0 ? V) allowing current from the battery into the circuit thus discharging the battery. I believe this inefficiency could be fixed by placing a low Vf diode capable of handling 1A between the transistor and the battery.

1.5 Building and implementing the circuit

In this sub-subsection I used the circuits discussed below to design a similar circuit schematic as shown below.

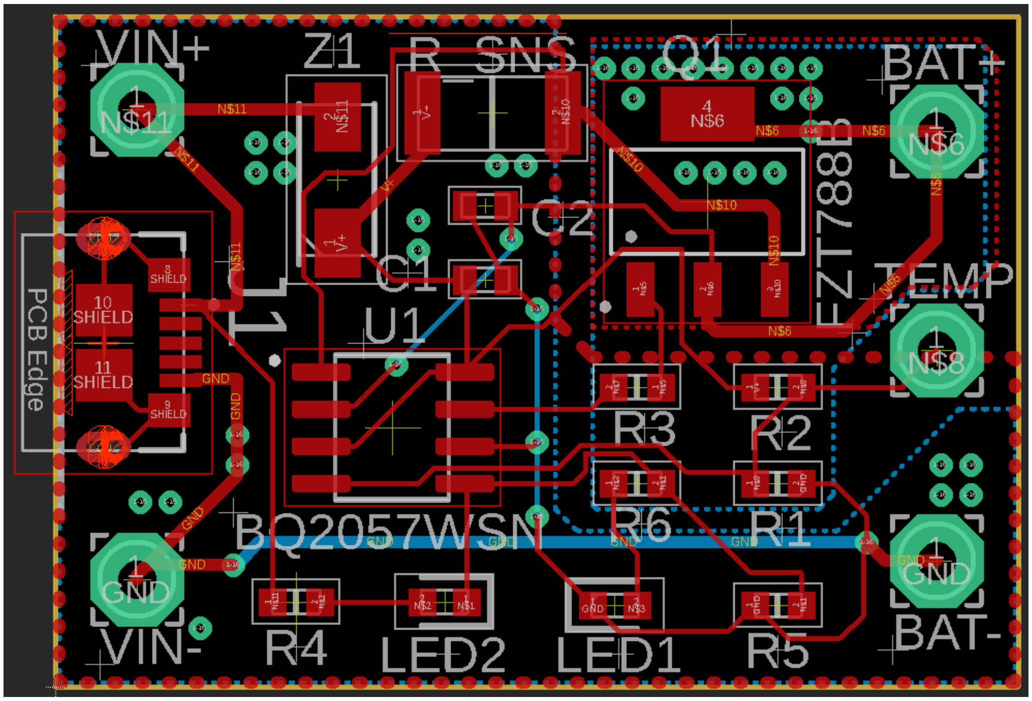


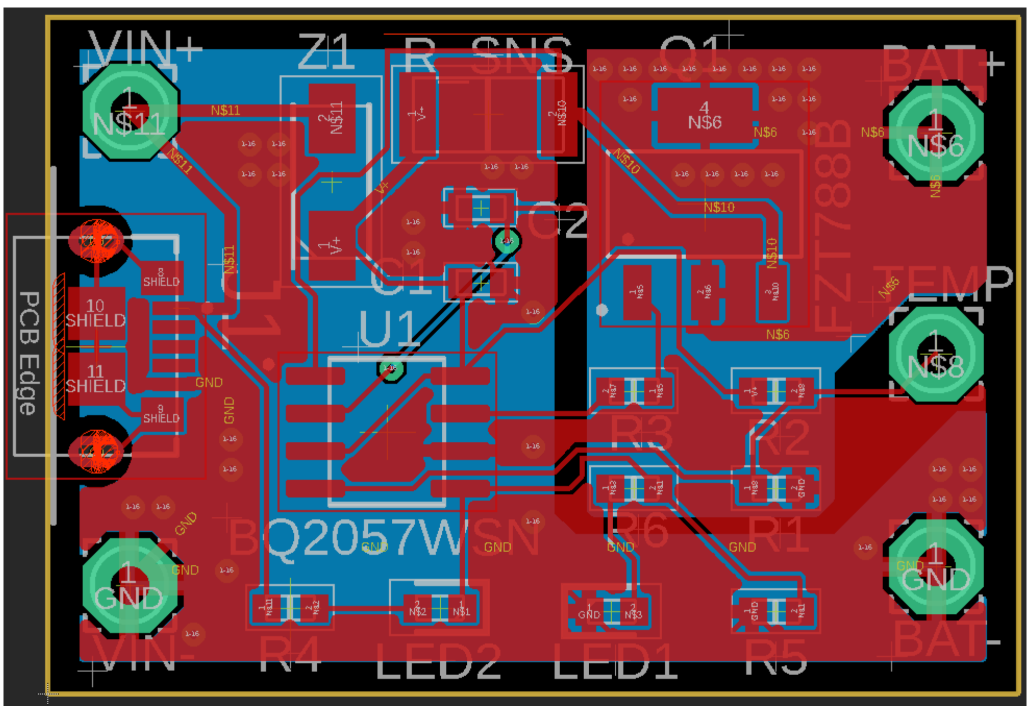
As it could be seen, this circuit is a bit of a mixture between the circuits shown in the data sheet. In the case that a z-diode is not available, I believe a regular diode could be used. It should be considered however the power rating of such device. It should be noted that since a diode was placed there will be a drop at VCC with respect to the VIN. The diode that was added could have a of about 1.2 V across it, depending on the current trough it. Please refer to the diode's data sheet for this device for more details. The drop across the diode is important because VCC = VIN - Vf(diode), then if VIN is 5V and Vf is 1V then VCC is 4V which means that V(RCH) = ~3.8V. Therefore, the battery will charge up to around 3.8 V before the IC enters sleep mode due to the condition VCC > V(BAT), at least this is what I expect. For the sense resistor I used a Vishay current sense 0.2 Ohm resistor, other values like 0.15, 0.125, 0.1 could be used to increase charging current. Further improvements to this circuit include a diode between the transistor and the node connected to the BAT pin. This diode should be able to dissipate the charging current. Furthermore, placing the diode in such position will reduce the charge current significantly, which is really not desired. Further testing will be done to determine the position of the diode.

TESTING:

Demonstrate charging current with corresponding calculations, find best position for diode

Below is a picture of the circuit above implemented on a PCB. A considerably big double layer cooling pad was added to cool down the transistor. Further improvements could include individual cooling pads for other components like the z-diode and the sense resistor. I placed components a bit separate since I am learning how to solder small SMD components, but this module board could be made smaller.


VIN+
Z1
R_SNS
Q1
BAT+
C2
C1
U1
PCB Edge
FZT788B
TEMP
R3
R2
R6
R1
BQ2057WSN
VIN-
R4
LED2
LED1
R5
BAT-


VIN+
Z1
R_SNS
Q1
BAT+
C2
C1
U1
PCB Edge
FZT788B
TEMP
R3
R2
R6
R1
BQ2057WSN
VIN-
R4
LED2
LED1
R5
BAT-