Freescale Semiconductor
Application Note

A Miner's Lamp Using the MC9S08QG4

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1   Introduction

1.1   Old and New Miner's Lamps

A miner's lamp is one of the necessities of a miner. The traditional lamp uses a Pb-acid battery, an incandescent lamp with wires, and switches. The battery must be re-charged every few days, or even every day, by an offline charger. Among the disadvantages of such a lamp are:

- Limited life span of an incandescent lamp

- Risk of an incandescent lamp exploding

- High power consumption

- Short lifesaving of a Pb-acid battery

- A Pb-acid battery takes more time to be fully charged than a Li+ battery

- An offline charger is required, which is inconvenient

- The complete incandescent lamp assembly is bulky and heavy

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- Disposal of the Pb-acid battery is hazardous to the environment

The introduction of the high-illumination white LED has brought many benefits to the industry and now makes it possible to design a brand new solution for the miner's lamp. An LED-based miner's lamp is supplied by an Li+ battery gets rid of all the disadvantages associated with the traditional miner's lamp. This new solution consumes less power, works longer, is more stable, and is a safer lighting source. It also has a remarkably extended lifetime.

To implement an LED-based miner's lamp, the following function modules must be involved:

- A current source to drive the high-illumination LED
- A charger circuit to charge the battery online
- Power management and protection

This can be accomplished by using several analog ICs: a dedicated LED driver IC, a dedicated charger IC, and a DC-DC for power management. But, this is not the most cost-effective, most integrated, and smartest solution. With a small but powerful Freescale MCU, designers can do the job better.

1.2   Freescale's Low Power MCU: MC9S08QG4

MC9S08QG4CDTE is a 16-pin MCU with a rich built-in peripheral sets, this is a good fit for a miner's lamp design. Its key features are listed below.

- Power Supply
    — 1.8–3.6 V, 500 µA/MHz run supply current (I_{DD})
- Memory
    — 4–8 K flash, capable of EEPROM emulation
    — 512 bytes of RAM
- Internal Clock Source (ICS)
    — On-chip oscillator
    — 2% accuracy over full operating range
    — FLL for frequency multiplier
    — Up to 10 MHz bus
    — External crystal support (16-pin only) up to 10 MHz bus
- Serial Communication
    — IIC (synchronous), SPI (synchronous), and SCI (asynchronous)
- Timers
    — 2-channel timer/PWM module (TPM)
    — An 8-bit modulo timer module (MTIM) with an 8-bit prescaler
- Analog Modules
    — 8-channel, 10-bit ADC
    — Analog comparator

The resources needed for this miner's lamp application are:

- A PWM for a buck converter — drive sthe high-brightness LED
- A PWM for a buck converter — charges the battery
- An analog comparator — LED current feedback and for setting the current
- An ADC input channel — senses the battery current
- An ADC input channel — battery voltage detection

Comparing the resources needed for this application with this MCU's features, we can see that the MC9S08QG4 is a great match for this design.

1.3 Miner's Lamp Application Targets

To make the lamp reliable, easy to use, low-power, and safe, some performance criteria must be matched.

1.3.1 System Power Supply

The whole system is supplied by a 5,000 mAH Li+ battery. The voltage range where the system can work properly is approximately 3.6 V – 4.8 V. When the LED is turned on, the supply current to the whole system is around 300 mA. The MCU itself takes less than 1 mA current when running at 8 MHz bus frequency. The lamp can continuously work for more than eleven hours with a fully charged battery. The battery can be re-charged for more than 600 life cycles. Charging voltage for the battery is approximately 5.5 V – 12 V, and it takes eight hours to fully charge the battery.

1.3.2 LED Lighting

The LED is driven by a 300 mA constant current. Its luminous flux is 60 lm. When the battery is fully charged LEDs can keep the luminosity of 300 lux for more than eleven hours.

These parameters depend on the specifications of the selected battery.

1.4 System Block Diagram

Figure 1 shows a block diagram of this MCU-based miner's lamp. Figure 2 is the photo of a real application board.

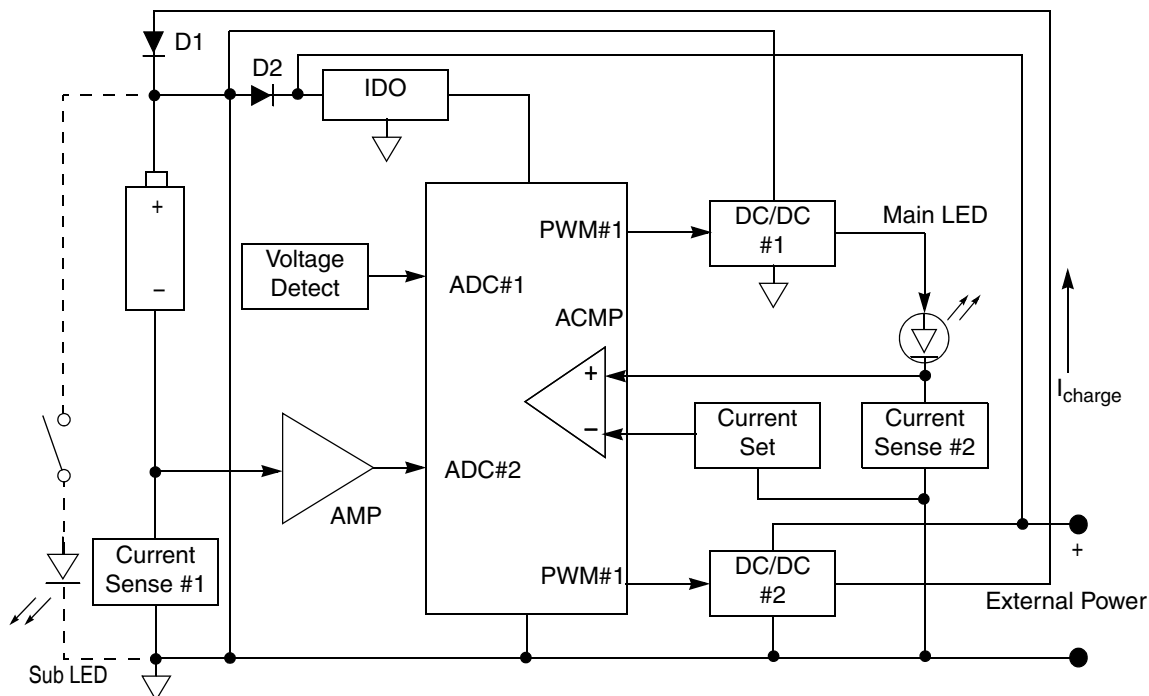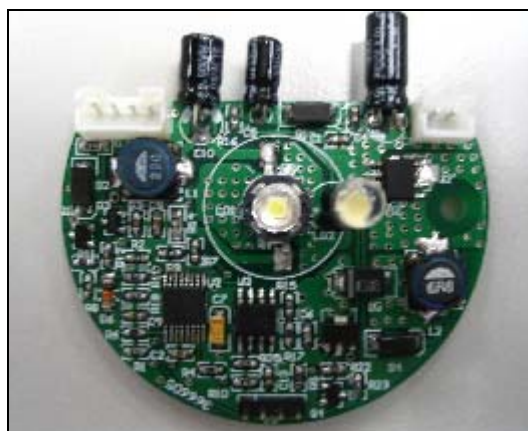**Figure 1. System Block Diagram**

Figure 2. Miner's Lamp Application Board

1.4.1 Brief Control Theory

The whole system includes three parts: system power supply, high-illumination LED driver, and a battery charger.

1.4.1.1 Power Supply for the MCU

In normal operating mode, the MCU is powered by the Li+ battery. Because the working voltage of the MC9S08QG4 ranges from 1.8 V to 3.6 V, an LDO is adopted to regulate battery voltage (typically 3.6 V) to 3.3 V.

If external DC power is supplied, the MCU is directly powered by this voltage instead of using the battery, and the same LDO regulates the external voltage to 3.3 V. The battery is also charged with this voltage input if necessary. Whether to charge the battery is decided by the MCU according to its current voltage. External power input ranges from 5.5 V to 12 V. Therefore diodes are used to switch and isolate the MCU from the external power supply and battery.

1.4.1.2   LED Driver

A buck DC/DC converter circuit driven by the MCU's PWM output functions as the current source to drive the high-illumination LED. Details of this part are discussed in Section 2, "LED Driver." The power supply for this circuit comes directly from the battery.

1.4.1.3   Battery Charger

Another buck DC/DC converter circuit with the same architecture as the LED driver is adopted to charge the battery. See Section 3, "Battery Charger," for details. This part is powered directly by the external power supply.

Both the LED driver and the battery charger are buck-switching-mode power supply circuits. See Section 1.4.2, "Buck Converter," for details.

1.4.2   Buck Converter

Figure 3 shows the topology of a typical buck mode (forward mode) DC/DC converter. Figure 4 shows the diode voltage and inductor current of Figure 3 in the time domain.

When the power switch SW is turned on, diode D is reverse-biased, and the input voltage is directly supplied to the LC filter composed of L and C_{out}. The inductor current begins a linear ramp from I_{min} to I_{max}. R_{Load} is energized by this inductor current.

When the power switch SW is turned off, the L still contains energy stored in the on-period to supply the load. D is forward biased, the stored energy then flows to the R_{Load} through D and L. The inductor current decreases from I_{max} to I_{min} until the SW is turned on again.

To implement the buck-switching-mode power supply, an inductor, a current-forwarding diode, an output filtering capacitor, a power switch, and a controller for the power switch are necessary. One channel of the MC9S08QG4's TPM module can be configured as a PWM to control a power MOSFET by switching it on and off. By changing the duty cycle of this PWM, time periods of on and off can be easily modulated; in turn, the output current on R_{Load} is controlled.
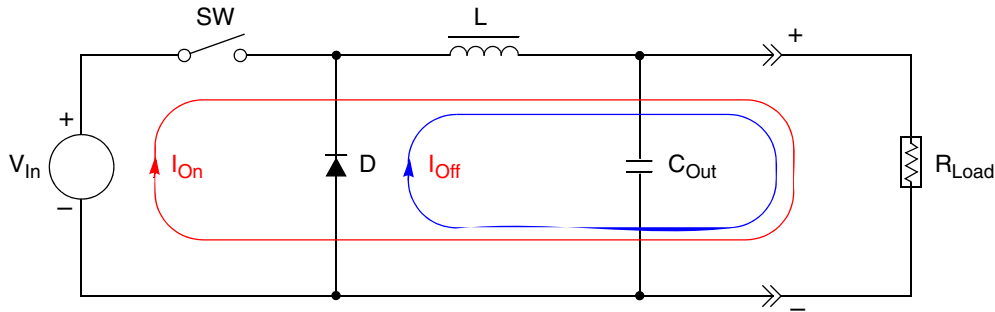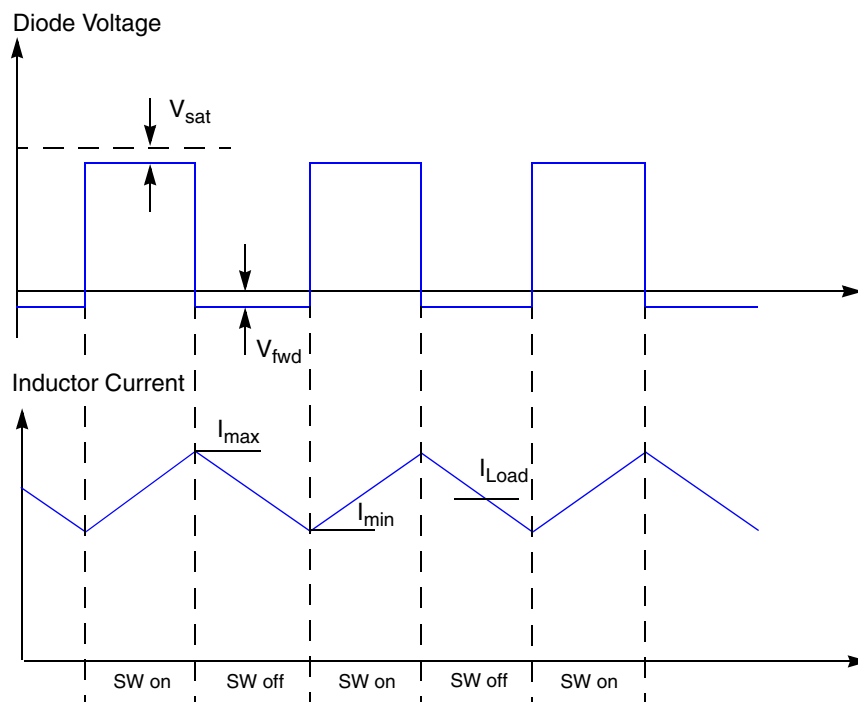
Figure 3. Forward Mode Converter (Buck)

Figure 4. Waveforms of Forward Mode Converter

2 LED Driver

To drive a high-illumination LED to provide sufficient brightness for a miner's lamp, a buck converter driven by the PWM works in current source mode. The circuit contains current-setting components and a buck converter that supplies constant current to keep constant luminance. Meanwhile, the voltage and current of the battery are monitored to protect against too high a current and to detect a low battery condition.

Additionally, a backup LED is necessary to ensure safety, in case the main LED or its driver is down. This backup LED is directly driven by battery voltage and can be turned on and off manually.

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2.1 LED Driver

In the schematic in Appendix A, "Schematics," PWM channel 1 on the MC9S08QG4 is used to drive a switching MOSFET through a transistor. The duty cycle of this PWM channel is modulated to supply a constant 300 mA load current to drive one watt of white LED power.

2.2 Setting the Current of the LED

The internal analog comparator of MC9S08QG4 and some external components are adopted to set the current for the LED. A Zener diode connected between V_{DD} and ground offers a reference voltage for the current-setting circuit. This reference voltage is divided by a resistor ladder and then fed to the positive input of the analog comparator. The negative input of the analog comparator is connected to the current-sensing circuit. The analog comparator compares the divided reference voltage with the voltage on the current-sensing resistor. MC9S08QG4 adjusts the PWM duty cycle according to the output of the analog comparator.

By adjusting the divisor of the reference voltage, in other words the current-setting resistor, the LED current can be changed.

$$V_{Set} = R_{Set} \times V_{Zener} / (R + R_{Set}) \qquad \textit{Eqn. 1}$$

2.3 Sensing the Current of the LED

A 0.1 Ω resistor is put into the LED current loop serially for sensing the current. Voltage on this current-sensing resistor is fed to the reverse input of the analog comparator on MC9S08QG4. If the LED driving current is 300 mA, voltage on this current-sensing resistor is around 30 mV.

$$V_{Sense} = I_{LED} \times R_{Sense} \qquad \textit{Eqn. 2}$$

If $V_{Sense} > V_{Set}$, the comparator output is low; if $V_{Sense} < V_{Set}$, the comparator output is high. The average current is determined by this formula:

$$I_{set} = [R_{Set} \times V_{Zener} / (R + R_{Set})] \div R_{Sense} \qquad \textit{Eqn. 3}$$

This circuit also contributes to LED over-current protection. If LED current is larger than 300 mA, the comparator output is low; the MCU temporarily stops PWM output to turn off the MOSFET, to protect the system.

2.4 Battery Voltage Detection

Voltage that is being discharged on the battery must be monitored to test for low battery status. Battery voltage is divided by a resistor ladder and is then fed to one of the ADC channels on the MC9S08QG4.

If the battery voltage is lower than 3.6 V, the LED turns off automatically. If the battery voltage is lower than 2.7 V, the battery protection circuit is triggered to shut down the battery.

2.5 Backup LED

A backup LED is used in case the main LED or its driver circuit is broken. It is a high brightness LED that is connected directly between the battery voltage and ground with a necessary current limit resistor, controlled by an on/off switch. Although it is not shown in the block diagram, the on/off switch is actually a SPDT. When it is switched to the backup LED side, only the backup LED is driven on by the battery through a resistor. If it is switched to the other side, the whole circuit except the backup LED is powered. The MC9S08QG4 starts to work and the main LED is turned on. If external power is plugged in, the battery is charged.

3 Battery Charger

3.1 Battery Charger Circuit

3.1.1 Buck Converter for Charger

The battery charger uses the same buck converter as the LED driver. PWM channel 2 on MC9S08QG4 is used to drive a MOSFET. By controlling the PWM output, the charger circuit can work as a current source or a voltage source, to generate a good charging curve.

This charging curve described in this chapter is software-controlled. It can be easily changed to work with different batteries.

3.1.2 Charge Voltage Detection

The same circuit is used to monitor the charge voltage and the discharge voltage.

3.1.3 Charge Current Sensing

The same circuit is used to sense the charge current and the discharge current.

3.2 Charge Procedure

3.2.1 Pre-Charge

If the battery voltage is lower than 2.5 V, the MCU begins its pre-charge period. The charge current in the pre-charge period is 400 mA. Pre-charge ends after the battery voltage ramps to 3 V, where constant charge begins. If the battery voltage does not ramp to 3 V in three hours, the MCU forces charging to end because the battery may be damaged.

If the battery voltage is lower than 1 V, the battery may be already damaged. The MCU forces charging to end.

3.2.2 Constant Current Charge

If the battery voltage is not lower than 2.5 V, constant current charge begins. This implies that the battery is not over-discharged, or has been pre-charged already. In constant charge period, charge current is driven to 800 mA for rapid charging. When the battery voltage ramps to 4.2 V, constant current charge ends.

3.2.3 Constant Voltage Charge

After the constant current charge period, constant voltage charge begins. The charge voltage stays at 4.2 V until the charge current is lower than 400 mA. If the charge current has not decreased to lower than 400 mA in eight hours, the MCU forces an end to charging because the battery may be damaged.

3.2.4 End of Charge

In the constant voltage period, if the charge current decreases to 400 mA or less, the battery is fully charged, and the charge procedure ends. Otherwise, if the charging time is longer than eight hours but the normal end-of-charge condition does not occur, the battery may be damaged and cannot be charged properly. The MCU forces an end to the charging procedure.

3.3 Charge Curve

The charge curve of this MCU-controlled Li+ battery charger is shown in Figure 5.
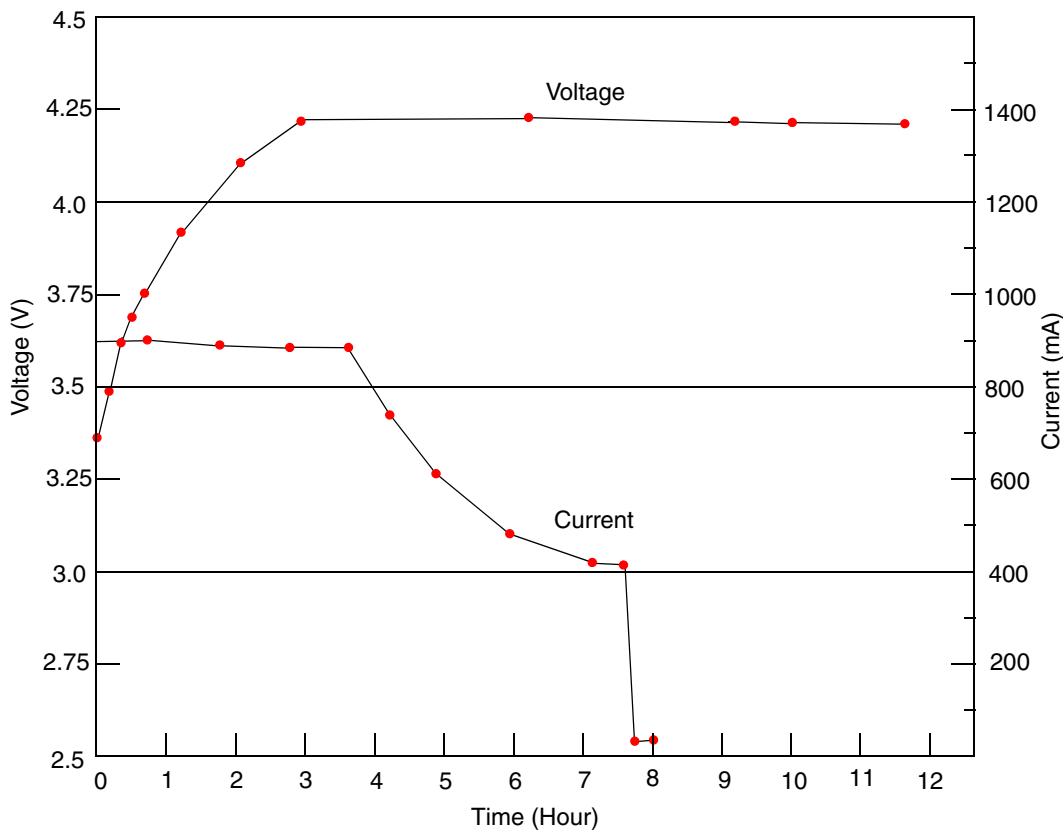
Figure 5. Charge Curve

4 Conclusion and Customization

The solution introduced in this document; a miner's lamp based on a high-illumination LED and Li+ battery controlled by an MCU, results in a device that is an implementation of basic MC9S08QG4 functions. It offers a replacement to the traditional miner's lamp that is more energy efficient, has higher reliability and a longer life cycle, is more environmentally friendly, and is safer. A Freescale 8-bit MCU, the MC9S08QG4, is used in this solution.

The design details of this solution are available in source files. This solution can be easily customized to work with any high-illumination LED and battery. Some additional functions can also be easily added. It is smarter and scalable thanks to the small but powerful MC9S08QG4.

Appendix A Schematics
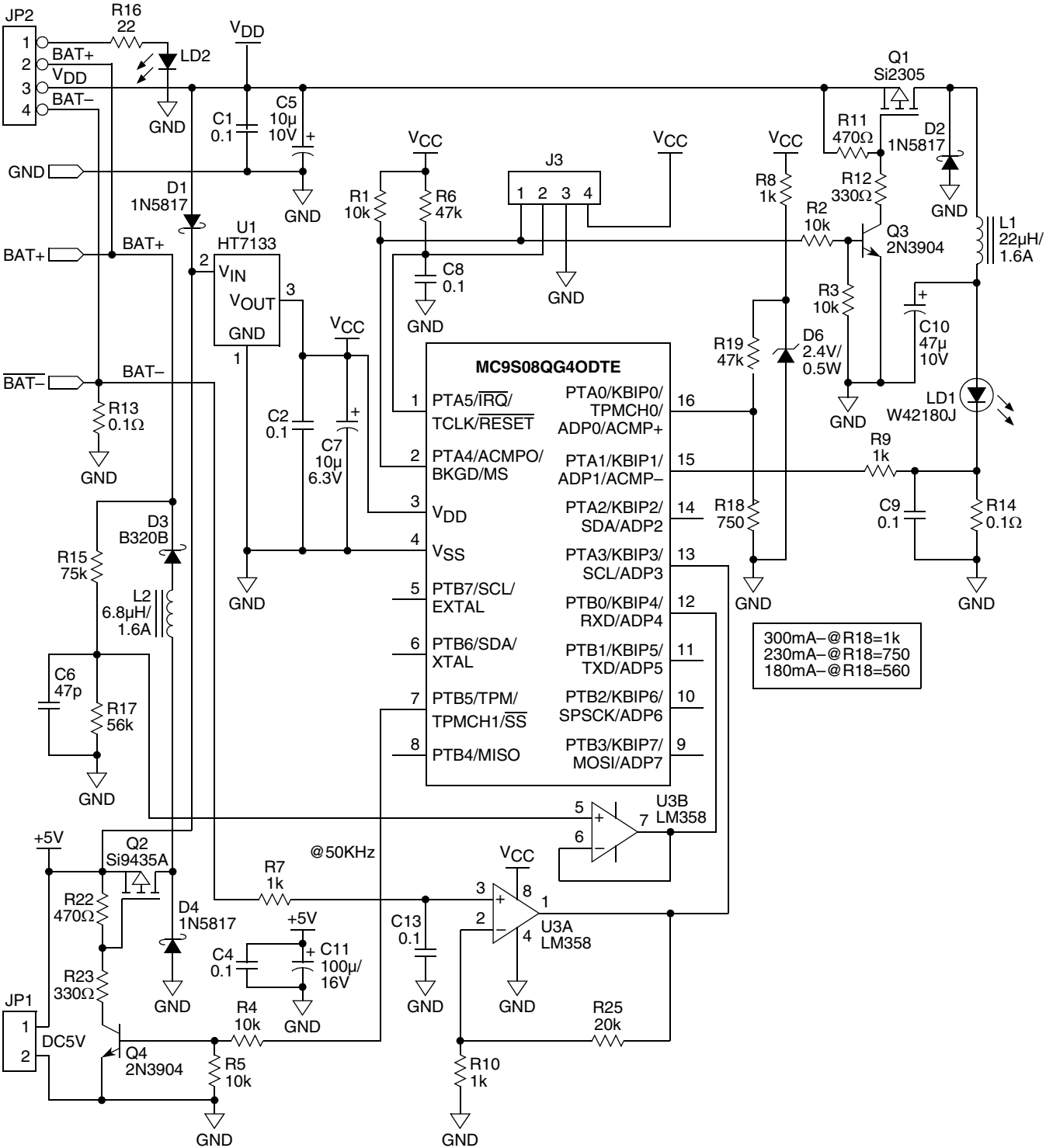
Appendix B Bill of Material

Part Type	Designator	Footprint	Description	Manufacturer
0.1 μF	C1	0603	Capacitor	
0.1 μF	C2	0603	Capacitor	
0.1 μF	C4	0603	Capacitor	
10 μF/10 V	C5	RB.05 / 0.1	Capacitor	
47 pF	C6	0603	Capacitor	
10 μF/6.3 V	C7	3216	Capacitor	
0.1 μF	C8	0603	Capacitor	
0.1 μF	C9	0603	Capacitor	
47 μF/10 V	C10	RB.1 / 0.2	Capacitor	
100 μF/16 V	C11	RB.1 / 0.2	Capacitor	
0.1 μF	C13	0603	Capacitor	
1N5817	D1	1808	Schottky Diode	
1N5817	D2	1808	Schottky Diode	
B320B	D3	SOD-2010	Schottky Diode	
1N5817	D4	1808	Schottky Diode	
2.4 V / 0.5 W	D6	LL34	Zener Diode	
CON4	J3	SSIP4	Connector	
CON2	JP1	CNT2MM2	Connector	
22 μH / 1.6 A	L1	SLF7045	Inductor	
6.8 μH / 1.6 A	L2	SLF7045	Inductor	
W42180J	LD1	LD-1W	LED	SEOUL SEMICONDUCTOR
LED	LD2	LD-0.5	LED	
Si2305	Q1	SOT-23	MOSFET-P Channel	Vishay
Si9435A	Q2	SO-8	MOSFET-P Channel	Vishay
2N3904	Q3	SOT-23	NPN Transistor	
2N3904	Q4	SOT-23	NPN Transistor	
10 kΩ	R1	0603	Resistor	
1 kΩ	R10	0603	Resistor	
470 Ω	R11	0603	Resistor	
330 Ω	R12	0603	Resistor	
0.1 Ω	R13	0805	Resistor	
0.1 Ω	R14	0805	Resistor	
75 kΩ	R15	0603	Resistor	

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Part Type	Designator	Footprint	Description	Manufacturer
22 kΩ	R16	0603	Resistor	
56 kΩ	R17	0603	Resistor	
750 Ω	R18	0603	Resistor	
47 kΩ	R19	0603	Resistor	
10 kΩ	R2	0603	Resistor	
470 Ω	R22	0603	Resistor	
330 Ω	R23	0603	Resistor	
20 kΩ	R25	0603	Resistor	
10 kΩ	R3	0603	Resistor	
10 kΩ	R4	0603	Resistor	
10 kΩ	R5	0603	Resistor	
4.7 kΩ	R6	0603	Resistor	
1 kΩ	R7	0603	Resistor	
1 kΩ	R8	0603	Resistor	
1 kΩ	R9	0603	Resistor	
HT7133	U1	SOT-89	Voltage Regulator	Holtek
MC9S08QG4CDTE	U2	TSSOP16	MCU	Freescale
LM358	U3	SO-8	Dual Op Amp	National Semiconductor
PL175667			Li+ Battery	TIRICH ENERGY

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