Application Circuit of Low Power Consumption Op-Amp TC75S102F

Design guide

RD229-DGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

This Design Guide describes the design of the Application Circuit of Low Power Consumption Op-Amp TC75S102F (hereafter referred to as this Reference Design).

This reference design uses low-power op amp(s) TC75S102F to achieve various functions. Schottky barrier diodes 1SS389 are used to prevent reverse current flow to the power supply terminal, a Zener diode CEZ5V6 is used to protect from overvoltage, a MOSFET SSM3K15AFU is used for driving LED, and a low dropout regulator (LDO) TCR3UF20A is used as a power supply IC.

2. Components Used

2.1. Operational Amplifier TC75S102F

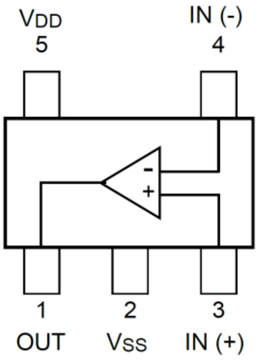
This reference design uses the op-amp TC75S102F manufactured by Toshiba Corporation. This op-amp is used for implementing various circuits in this reference design. TC75S102F is an CMOS op-amp featuring ultra-low current consumption. It is ideal for devices requiring long battery life, for example IoT devices.

The features of TC75S102F are as follows.

Features

- I/O full range (I/O Rail to Rail)
- Ultra-Low current consumption 0.27 μA (Typ.) @V_{DD} = 1.5 V
- Low input offset voltage 1.3 mV (Max.) @V_{DD} = 1.5 V
- Can be used with low power supply voltage V_{opr} = 1.5 V to 5.5 V

External View and Pinout (Top View)



2.2. Low Dropout Regulator (LDO) TCR3UF20A

This reference design uses a low dropout regulator (LDO) TCR3UF20A in the power supply circuit. TCR3UF20A LDO features low current consumption. Thus, it is ideal for driving of IoT and mobile devices for long duration.

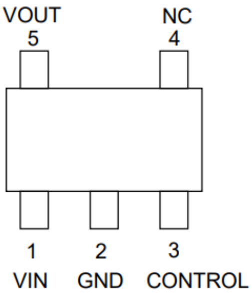
The features of TCR3UF20A are as follows.

Features

- Ultra low current consumption 0.34 μA (Typ.) @I_{OUT} = 0 mA
- Fast load transient response -51/+36 mV @0.8 V output, I_{OUT} = 1 mA ⇔ 50 mA
- High ripple rejection ratio = 70 dB (Typ.) @0.8 V Power
- Overcurrent protection, thermal shutdown, auto-discharge, and inrush current reduction circuit

External View and Pinout (Top View)

SMV(SOT-25)(SC-74A)



2.3. Schottky Barrier Diode 1SS389

This reference design uses a Schottky barrier diode 1SS389 in the power supply circuit. It features low V_F (forward voltage). The features of 1SS389 are as follows.

Features

- Compact two pin package (ESC, SOD-523:1.6 x 0.8 x 0.6 mm)
- Low forward voltage V_F = 0.23 V (Typ.) @I_F = 5 mA

2.4. Zener Diode CEZ5V6

This reference design uses a Zener diode CEZ5V6 in the power supply circuit. Suitable for overvoltage protection. The features of CEZ5V6 are as follows.

Features

- Compact two pin package (ESC, SOD-523:1.6 x 0.8 x 0.6 mm)
- Zener voltage V_Z = 5.6 V (Typ.) @I_Z = 5 mA

2.5. N-ch MOSFET SSM3K15AFU

This reference design uses a N-ch MOSFET SSM3K15AFU in LED drive circuit. Ideal for load switch applications. The features of SSM3K15AFU are as follows.

Features

- Compact package (USM, SOT-323:2.0 x 2.1 x 0.9 mm)
- Low on-resistance $R_{DS(ON)}$ = 3.6 Ω (Max.) @V_{GS} = 4 V
- $R_{DS(ON)}$ = 6.0 Ω (Max.) @V_{GS} = 2.5 V

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3. Specifications and Block Diagram

3.1. Specifications

Table 3.1 lists the main specifications of various circuit designs in this reference design, and Fig. 3.1 shows a block diagram.

Table 3.1 Specifications of various Circuit Designs

Design Name	Onboard Sensor	Charging Method	Op-Amp 1 (OP1) Function	Op-Amp 2 (OP2) Function	Operation
A1	Light sensor (photodiode)	USB Type-C®	I-V converter	(not used)	LED turns on after sensor detection
A2				Astable multivibrator circuit	LED blinking interval changes according to the sensor value
A3		USB Type-C® Solar cell			
B1	Pressure sensor (Polymer thick film)	USB Type-C®	Voltage follower circuit	(not used)	LED turns on after sensor detection
B2				Astable multivibrator circuit	LED blinking interval changes according to the sensor value
B3		USB Type-C® Solar cell			
C1	Sound sensor (MEMS microphone)	USB Type-C®	Amplifier circuit	(not used)	LED turns on after sensor detection
C2				DC servo circuit (Offset cancel)	LED turns on after sensor detection (equipped with Op-Amp offset cancelling DC servo function)
C3		USB Type-C® Solar cell			

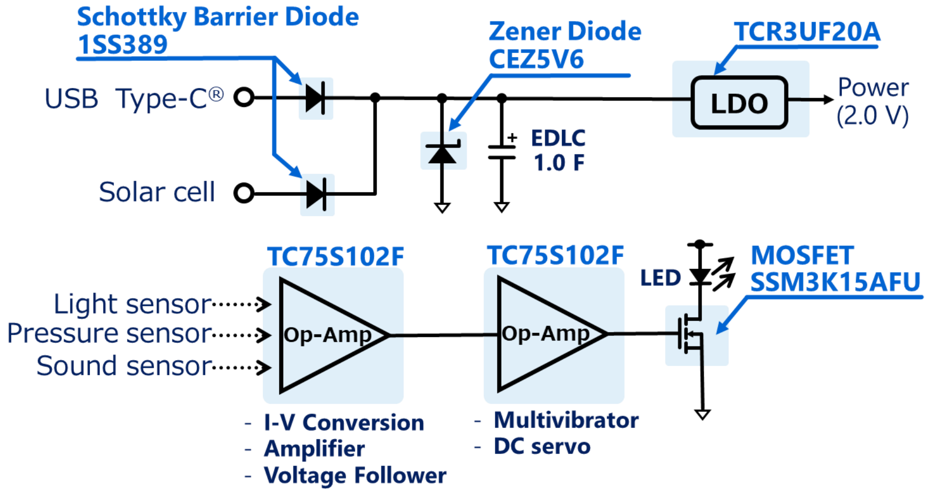

Fig. 3.1 Block Diagram of Low Power Op-Amp TC75S102F Application Circuit

4. Circuit Design

4.1. Light Sensor Circuit (Design A1, A2, A3)

Fig. 4.1 shows the light sensor circuit.

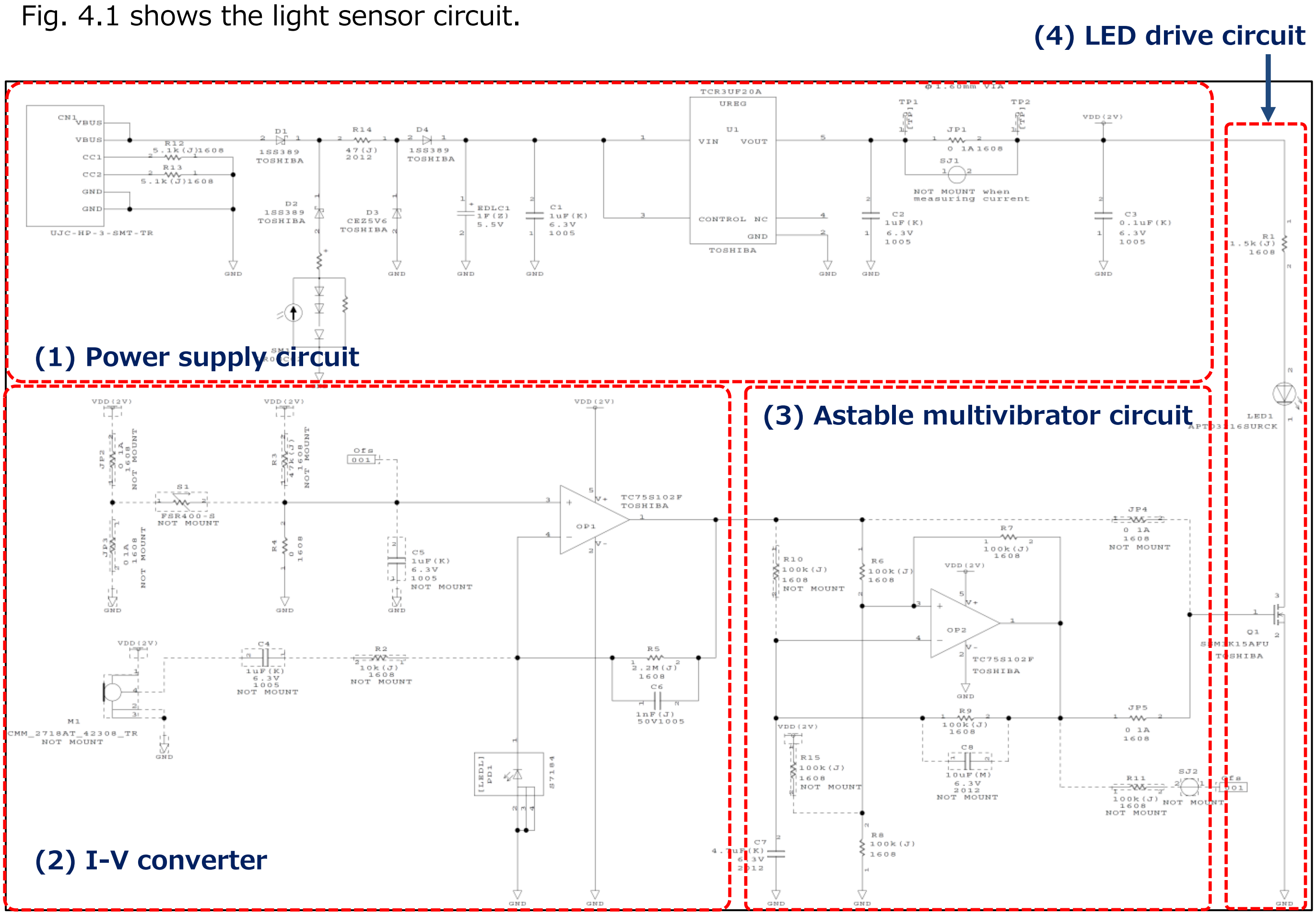

Fig. 4.1 Light Sensor Circuit (for Design A3)

4.1.1. Power Supply Circuit

The electric double layer capacitor (EDLC1) can be charged by either connecting the USB charger to USB Type-C® connector (CN1), or by irradiating the solar cell (SM1) with sunlight. The USB charger can be disconnected after the electric double layer capacitor is charged and now the board can be used standalone. The LDO, TCR3UF20A (U1) takes input from the electric double layer capacitor and produces a stable 2.0V output which is used as power supply on this board. Solar cell module is mounted on A3, B3 and C3 designs.

In order to supply 5.0 V power from the USB Type-C® connector (CN1), the CC1 and CC2 pins of CN1 detect the receptacle on the voltage sink side when an external plug is inserted based on the USB Type-C® configuration, thus these pins are pulled down with 5.1 kΩ. This board can be charged from either the solar cell (SM1) or USB Type-C® connector (CN1), so it is equipped with Schottky barrier diodes 1SS389 (D1, D2) to configure ORing circuit to prevent reverse current flow. Resistor 47 Ω (R14), Zener Diode CEZ5V6 (D3), and Schottky Barrier Diode 1SS389 (D4) are used to limit the inrush current caused by pre-charging when EDLC1 charge is zero. They also prevent the application of voltage more than the rated voltage of 5.5 V to the electric double layer capacitor (EDLC1).

The voltage is limited by the zener diode D3 which is present after ORing circuit consisting of D1 and D2. The forward voltage drop of the Schottky barrier diode 1SS389 (D4) is approximately 0.3 V, thus the electric double layer capacitor is protected from overvoltage.
Resistor 47 Ω (R14) limits the current going to the electric double layer capacitor. When the charge voltage is 5.0 V and the charge of the electric double layer capacitor is zero, approximately 0.3 V voltage drops at 1SS389 (D1) and approximately 0.3 V voltage drops at 1SS389 (D4), so that approximately 4.4 V is applied to the electric double layer capacitor (EDLC1). At this time, the inrush current caused by pre-charging is limited to approximately 4.4 V/47 Ω ≈ 94 mA or less.

4.1.2. I-V Converter

This unit is equipped with a light-sensor (photodiode, PD1). The light-sensor output current I_L is converted to the voltage by I-V (current-voltage) converter consisting of an op-amp OP1, a resistor of 2.2 MΩ (R5), and a capacitor of 1 nF (C6). Output voltage V_{OUT} of OP1 is as follows:

$$V_{OUT} = -I_L \times 2.2 \times 10^6 (\mathrm{V})$$

A low-pass filter (LPF) with a cutoff frequency f_Z is also used to prevent oscillation and eliminate unwanted high-frequency components. The cutoff frequency fz is as follows:

$$f_Z = \frac{1}{2 \times \pi \times C6 \times R5} = \frac{1}{2 \times \pi \times 1 \times 10^{-9} \times 2.2 \times 10^6} \approx 72 (Hz)$$

In design A1, the output voltage V_{OUT} (0 V to 2.0 V) of I-V converter OP1 is used to control the gate-pin of the subsequent MOSFET (Q1) to turn on the LED. Designs A2 and A3 consist of another op-amp OP2 which is used as an astable multivibrator for changing the LED blinking interval.

4.1.3. Astable Multivibrator Circuit

Designs A2, A3, B2 and B3 are equipped with an astable multivibrator circuit.

The astable multivibrator circuit consists of a hysteresis comparator circuit configured using R6, R7 and R8. When the reference voltage of the non-inverting input pin of the op-amp OP2 is V+ and the voltage of the inverting input pin is V-, then immediately after power-on if V+>V- the output voltage V_{Output} of the op-amp becomes High. At this time, the capacitor C7 of 4.7 μF is charged by V_{Output} voltage via the feedback resistor R9. When C7 is charged and V->V+, OP2's output voltage V_{Output} becomes Low and C7 starts discharging. Therefore, this astable multivibrator circuit repeatedly charges and discharges the capacitor C7.

The threshold voltage of the inverting input pin (V-) of OP2 constituting the hysteresis comparator circuit can be expressed as shown below.

$$a = \frac{1}{\frac{1}{R6} + \frac{1}{R7} + \frac{1}{R8}}$$

$$V_{thH} = \frac{a}{R6} \times V_{Input} + \frac{a}{R7} \times V_{OH}$$

$$V_{thL} = \frac{a}{R6} \times V_{Input} + \frac{a}{R7} \times V_{OL}$$

Where V_{thH} is the threshold for High level, V_{thL} is the threshold for Low level, V_{OH} is the output voltage for High level, and V_{OL} is the output voltage for Low level of the op-amp OP2. If TC75S102F is powered by 2.0 V, V_{OH}=1.9 V (Min.), V_{OL} = 0.1 V (Max.).

When the V_{Input} line is used as the input of astable multivibrator,
・When V_{Input} is 2.0 V

$$a = \frac{1}{\frac{1}{100 \times 10^3} + \frac{1}{100 \times 10^3} + \frac{1}{100 \times 10^3}} \approx 33.3 \times 10^3 (\Omega)$$

$$V_{thH} = \frac{33.3 \times 10^3}{100 \times 10^3} \times 2 + \frac{33.3 \times 10^3}{100 \times 10^3} \times 1.9 \approx 1.3(V)$$

$$V_{thL} = \frac{33.3 \times 10^3}{100 \times 10^3} \times 2 + \frac{33.3 \times 10^3}{100 \times 10^3} \times 0.1 \approx 0.7(V)$$

As a result, the capacitor C7 connected to V-pin is repeatedly charged and discharged between 1.3 V and 0.7 V.
Since the power supply voltage of the op-amp OP2 is 2.0 V, and if the discharge starting time is t1, and the discharge ending time is t2, then

$$V_{thH} = 1.3 = 2.0 \times e^{\frac{-t1}{C7 \times R9}}$$

$$V_{thL} = 0.7 = 2.0 \times e^{\frac{-t2}{C7 \times R9}}$$

And the discharge time,

$$t2 - t1 = -C7 \times R9 \times (ln\frac{0.7}{2.0} - ln\frac{1.3}{2.0})$$

$$= -4.7 \times 10^{-6} \times 100 \times 10^3 \times (ln\frac{0.7}{2.0} - ln\frac{1.3}{2.0})$$

$$\approx 0.29(s)$$

Since the charge time is same as the discharge time, so when V_{Input}=2.0 V, the period T and the frequency f are as follows.

$$T = 0.29 \times 2 \approx 0.58(s)$$

$$f = \frac{1}{T} \approx 1.72(Hz)$$

・When V_{Input} is 0 V

$$V_{thH} = \frac{33.3 \times 10^3}{100 \times 10^3} \times 0 + \frac{33.3 \times 10^3}{100 \times 10^3} \times 1.9 \approx 0.633(V)$$

$$V_{thL} = \frac{33.3 \times 10^3}{100 \times 10^3} \times 0 + \frac{33.3 \times 10^3}{100 \times 10^3} \times 0.1 \approx 0.033(V)$$

As a result, the capacitor C7 connected to V-pin is repeatedly charged and discharged between 0.63 V and 0.03 V.

Since the power supply of the op-amp OP2 is 2.0 V, and if the discharge starting time is t1, and the discharge ending time is t2,

$$V_{thH} = 0.633 = 2.0 \times e^{\frac{-t1}{C7 \times R9}}$$

$$V_{thL} = 0.033 = 2.0 \times e^{\frac{-t2}{C7 \times R9}}$$

And the discharge time,

$$t2 - t1 = -C7 \times R9 \times (ln\frac{0.033}{2.0} - ln\frac{0.633}{2.0})$$

$$= -4.7 \times 10^{-6} \times 100 \times 10^3 (ln\frac{0.033}{2.0} - ln\frac{0.633}{2.0})$$

$$\approx 1.39(s)$$

Since the charge time is same as the discharge time the period T and the frequency f during V_{Input} = 0 V are as follows.

$$T = 1.39 \times 2 \approx 2.78(s)$$

$$f = \frac{1}{T} \approx 0.36(Hz)$$

Therefore, in the circuit consisting of OP1, OP2, the photocurrent I_L of the photodiode PD1 is converted from current to voltage by the op-amp OP1, and then this output voltage (0 V to 2.0 V) is used by OP2 to change the blinking frequency of LED (LED1) within the range of approximately 0.36 Hz to 1.72 Hz . The actual blinking period may not match with the calculated value due to variations in the characteristics of components, etc.

4.1.4. LED Drive Circuit

LED drive circuit consists of a LED (LED1), a current limiting resistor R1, and a low-side switch MOSFET (Q1) to control the circuit. This LED drive circuit is used in all designs in this reference design. The output voltage of LDO (U1) is 2.0 V, the forward voltage V_F of LED is 1.85 V, the drain-source on resistance ($R_{DS(ON)}$) of MOSFET when V_{GS} = 2.0 V is 6 Ω, so in order to keep LED forward current I_F = 100 μA, the value of current limiting resistor R1 is selected to be 1.5 kΩ. Thus I_F can be calculated as shown below.

$$I_F = \frac{(2.0 - 1.85)}{(1.5 \times 10^3 + 6)} \approx 100(\mu A)$$

LED is turned on and driven by applying a High voltage to the gate pin of MOSFET (Q1).

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4.2. Pressure Sensor Circuit (Design B1, B2, B3)

Fig. 4.2 shows the pressure sensor circuit.

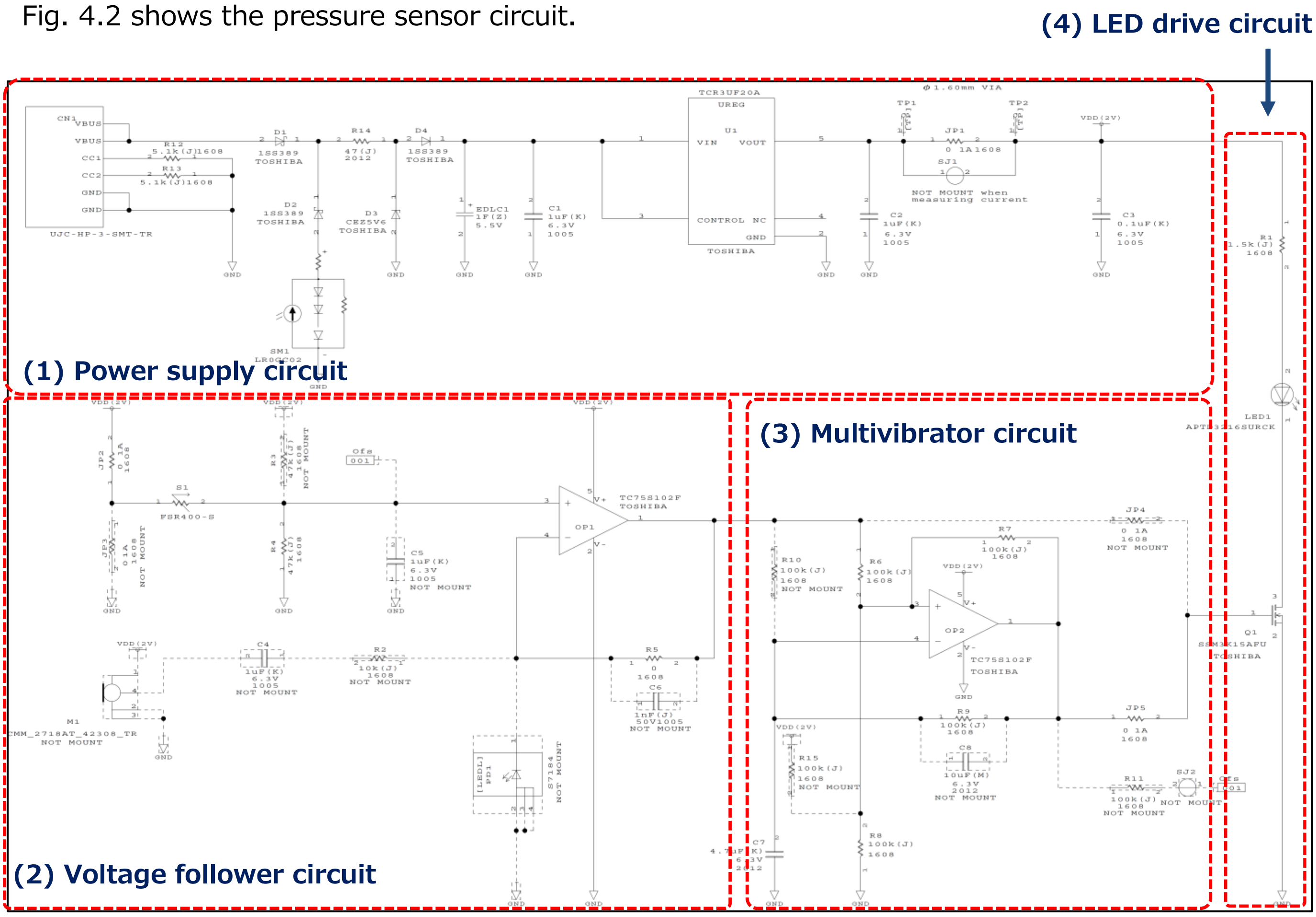

Fig. 4.2 Pressure Sensor Circuit (for Design B3)

4.2.1. Voltage Follower Circuit

The pressure sensor circuit uses FSR400-S (Interlink Electronics) as a pressure sensor. When no pressure is applied this sensor has high resistance (more than 100 kΩ), however when the pressure of more than 20 g is applied, it’s resistance decreases gradually as the applied pressure increases (Fig. 4.3).

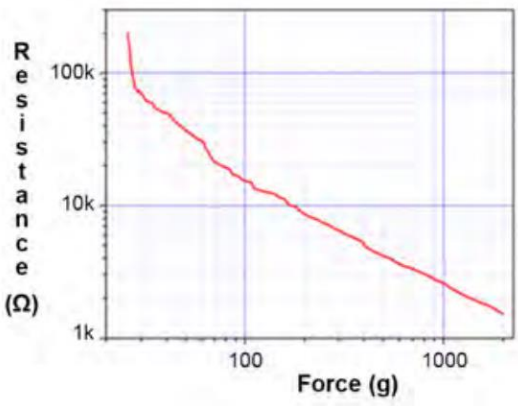

Fig. 4.3 FSR400 Resistance-Pressure Characteristic (quoted from Interlink's FSR400 datasheet)

A voltage follower circuit is configured using op-amp OP1 and a 0 Ω resistor (R5). A voltage obtained by dividing the power supply voltage 2.0 V by FSR400 and 47 kΩ (R4) is applied to the non-inverting input pin. This causes the output voltage of OP1 to be same as the voltage generated by applying pressure on the sensor.

4.3. Sound Sensor Circuit (Design C1, C2, C3)

Fig. 4.4 shows the sound sensor circuit.

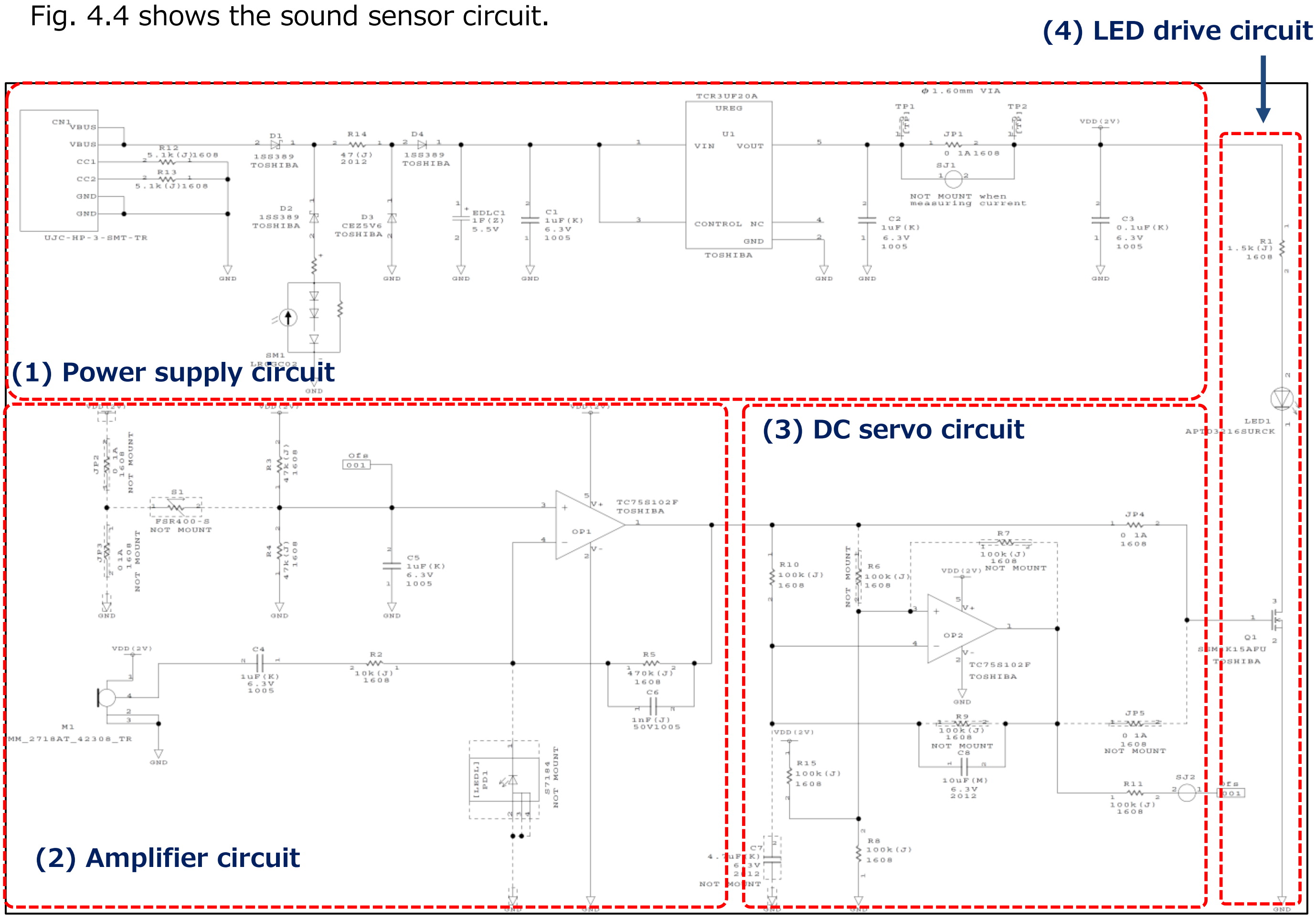

Fig. 4.4 Sound Sensor Circuit (for Design C3)

4.3.1. Amplifier Circuit

It is equipped with a MEMS microphone CMM-2718AT-42308-TR (CUI DEVICES) as a sound sensor. The op-amp OP1 with resistors 10 kΩ (R2) and 470 Ω (R5) acts as an inverting amplifier with an gain of -47 (gain A_V = -R5/R2 = -470k/10k = 33 dB). A 1.0 V bias obtained by dividing the supply voltage 2.0 V by the resistors of 47 kΩ (R3) and 47 kΩ (R4) is applied to the non-inverting input pin of the op-amp. Therefore, output of the op-amp is the voltage obtained by amplifying the output of MEMS microphone by 33 dB around 1.0 V bias.

4.3.2. DC Servo Circuit

In the designs C2 and C3, after OP1, an op-amp OP2 is also connected. Op-amp OP2 is configured as a DC servo circuit that inverts only DC offset component of the output and then feeds back to the non-inverting input pin of OP1. And because this circuit cancels DC input offset voltage of the op-amp OP1, it becomes a highly accurate amplifier circuit.

Calculation of 3 dB cutoff frequency f_{CL} of the DC servo circuit is as follows.

$$f_{CL} = \frac{1}{(2 \times \pi \times C8 \times R10)} \times \frac{R4}{R4 + R11} \times \frac{R2 + R5}{R2}$$

$$= \frac{1}{2 \times \pi \times 10 \times 10^{-6} \times 100 \times 10^3} \times \frac{47 \times 10^3}{47 \times 10^3 + 100 \times 10^3} \times \frac{4.7 \times 10^3 + 470 \times 10^3}{4.7 \times 10^3}$$

$$= 5.14(Hz)$$

This circuit feeds back frequencies below f_{CL} to the inverting amplifier circuit.

In addition, OP1 and OP2 are operated with a single power supply of 2.0 V, so the AC signal output of the MEMS microphone is biased with 1.0 V at OP1 as described above. In the DC servo circuit, the power supply voltage is divided by R8 and R15 at the non-inverting input pin of OP2, creating a 1.0 V bias, and then the DC component of OP2 output is fed back into OP1.

4.4. Estimation of Operation Time Duration (Design A1)

The operation time duration of this circuit is estimated by referring to the design A1. Let's assume that the electric double layer capacitor voltage is 5.0 V, the capacitance value is 1.0 F, and the output LED turns on for a total of 5 seconds in every 1 hour according to the sensor input.

The current consumption of the main elements of the circuit,

Current draw of op-amp TC75S102F (OP1) approx. 0.27 μA
Current draw of LDO TCR3UF20A (U1) approx. 0.4 μA
Current draw of LED (LED1) approx. 100 μA (when turned on 100 %)

Since LED has a forward current of 100 μA and it turns on for a total of 5 seconds in every 1 hour, the average consumption current of LED is 0.139 μA, so the average consumption current I of the main elements of the Circuit becomes:

$$I = 0.27 + 0.4 + 0.139 \approx 0.809(\mu A)$$

When the operation starting voltage of the electric double layer capacitor is 5.0 V and the operation ending voltage is 2.0 V,

$$Q = C \times V = \int Idt = I \times t$$

Thus,

$$Q = 1.0 \times (5.0 - 2.0) = 0.809(\mu A) \times t$$

$$t = \frac{1.0 \times 3.0}{0.809 \times 10^{-6}} \approx 3.71 \times 10^6(s) \approx 42.9(days)$$

Therefore, according to the calculation this circuit can operate for about 42.9 days using the electric charge stored in the electric double layer capacitor.

5. PCB Design

5.1. Component Layout Example

Fig. 5.1 and Fig. 5.2 show examples of component arrangement.

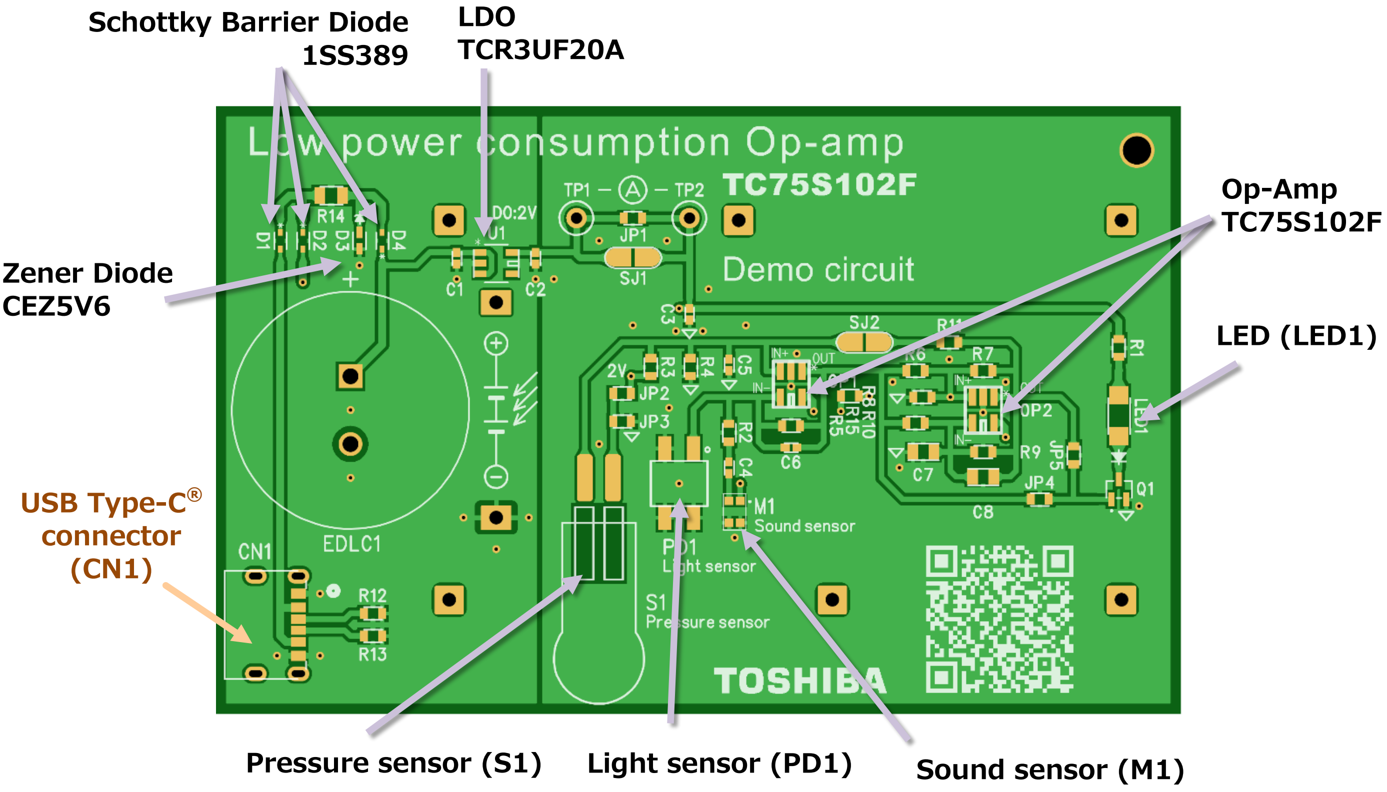

Fig. 5.1 PCB Component Layout (Front Side)

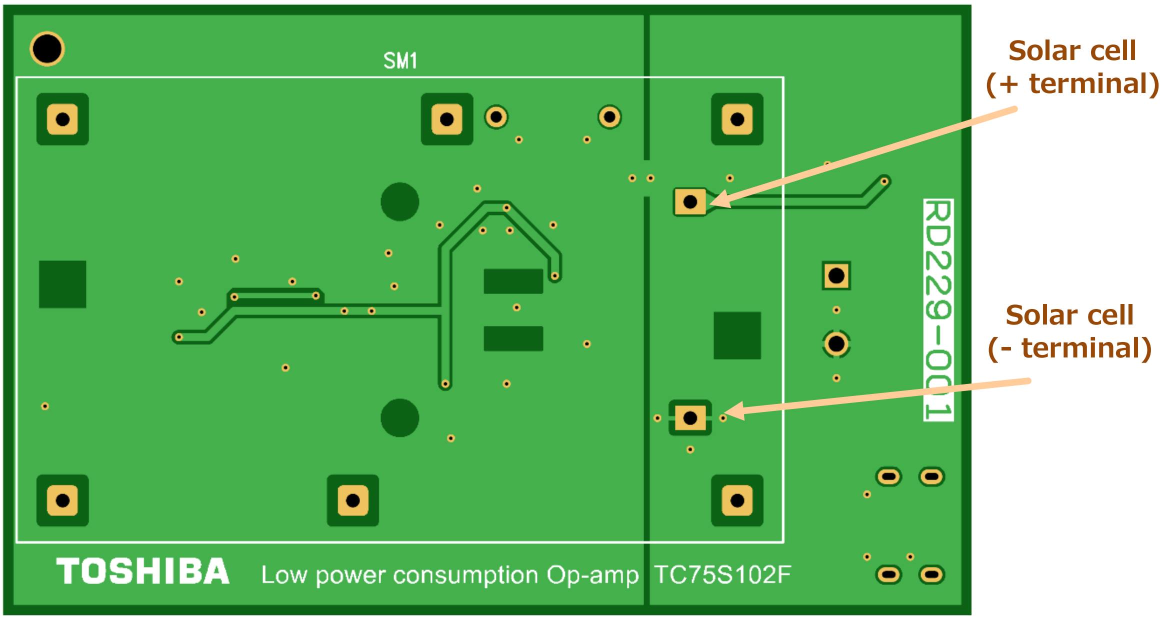

Fig. 5.2 PCB Component Layout (Back Side)

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