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AN204360

Energy Calculation for Energy Harvesting

Associated Part Family: MB39C811/831

This Application Note describes the energy harvesting and the system design. The system performing low power operation should be designed since the amount of energy from harvester is very small. In such cases, the energy budget calculation is necessary.

Contents

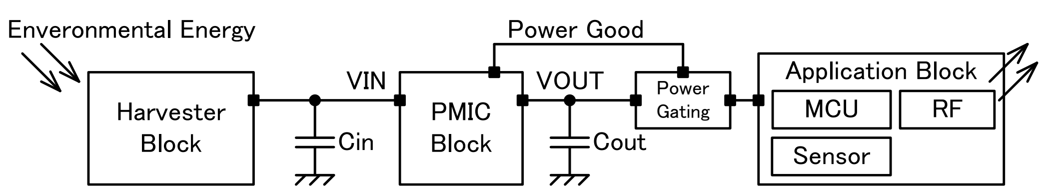
1 Introduction

For the energy harvesting, the system design is very important. The system performing low power operation should be designed since the amount of energy from harvester is very small. In such cases, the energy budget calculation is necessary

1.1 Energy Harvesting System

Figure 1 shows the popular energy harvesting system.

Figure 1. Popular Energy Harvesting System



Low power consumption devices are needed to design the energy harvesting system. Select low power PMIC and ICs for the application block because the energy from harvester is limited.

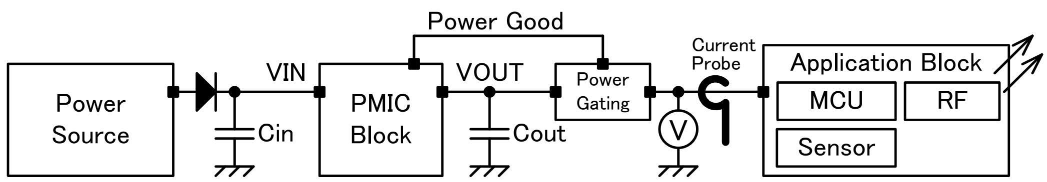
Also, energy from harvester should be stored on the Cin and Cout to operate the application block. If the size of these capacitors were too big, it would take too much time to charge energy into these capacitors, and the system cannot be operated frequently. On the other hand, if these capacitors were too small, enough energy cannot be stored on these capacitors for the application block. The sizing of the Cin and Cout is important, too

2 Energy Calculation

2.1 Energy Requirement in Application Block

Once the system is designed, make the prototype. The Figure 2 shows the measurement method of the energy requirement in application block.

Figure 2. Measurement of Energy Requirement

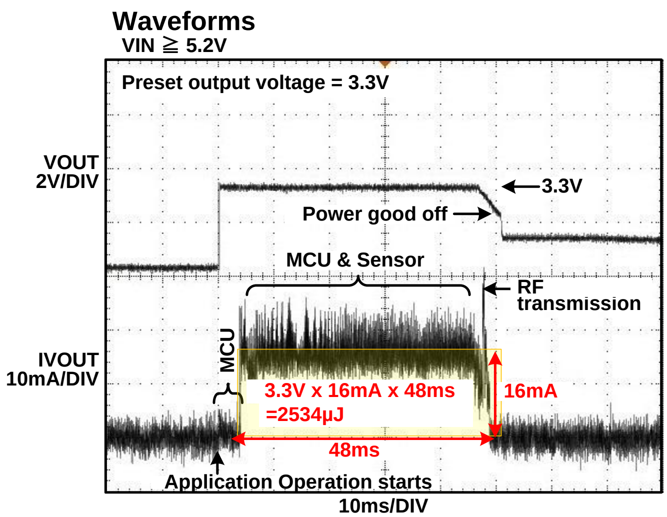


To calculate the necessary energy for the application, measure the voltage and current of VOUT. After the measurement, apply the following equation to calculate the energy requirement.

$E_{Appli.}[J] = V_{Appli.} \times I_{Appli.} \times t_{Appli.}$

The Figure 3 shows actual measurement waveform of the energy harvesting system. In this example, the energy requirement for the application block is roughly calculated at 2,534µJ.

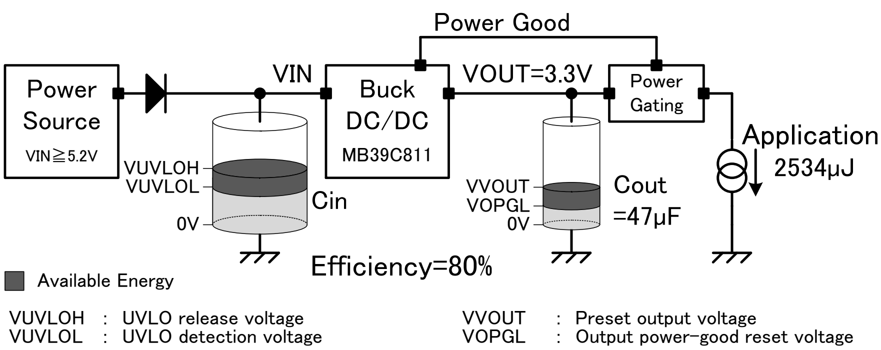
Figure 3. Waveform of VOUT and IVOUT



2.2 Sizing of Cin and Cout (for MB39C811)

The Cin and Cout should be sized. The Figure 4 shows the image of the capacitors with the buck DC/DC converter, MB39C811.

Figure 4. Stored Image of Capacitors (for MB39C811)



The energy stored on a capacitor is calculated by the following equation.

$$E_{capacitor}[J] = \frac{1}{2}CV^2$$

Because the energy in a capacitor is proportional to the square of the voltage, it is energetically advantageous for the buck DC/DC converter to make the Cin larger. On the other hand, for the boost DC/DC converter, it is energetically advantageous to make the Cout larger. In the example with MB39C811 of the Figure 4, adjust the Cin, and keep the Cout = 47μF (refer to the MB39C811 datasheet).

Calculate the available energy in Cout

The output power-good reset voltage (minimum voltage of the Cout) is 70 % of the preset output voltage (VOUT voltage), VOPGL is 2.31V (refer to the MB39C811 datasheet).

$$\text{Available energy in Cout }[\mu J] = \frac{1}{2} \times \text{Cout} \times (\text{VVOUT}^2 - \text{VOPGL}^2)$$

$$= \frac{1}{2} \times 47[\mu F] \times (3.3[V]^2 - 2.31[V]^2) = 131[\mu J]$$

In the Figure 3, the energy requirement for the application block was calculated at 2,534[μJ]. The available energy stored on the Cout was found 131μJ, so that the remaining energy requirement is

$$\text{Remaining energy requirement }[\mu J] = 2{,}534[\mu J] - 131[\mu J] = 2{,}403[\mu J]$$

The remaining energy requirement should be stored on the Cin.

Calculate the size of the Cin

For the Cin calculation, it is necessary to take the efficiency of PMIC into account. According to the datasheet, the efficiency is about 80% in the 16mA load current. (The "η" is the efficiency of PMIC.)

$$\text{Available energy in Cin }[\mu J] = \frac{1}{2} \times \eta \times \text{Cin} \times (\text{VUVLOH}^2 - \text{VUVLOL}^2)$$

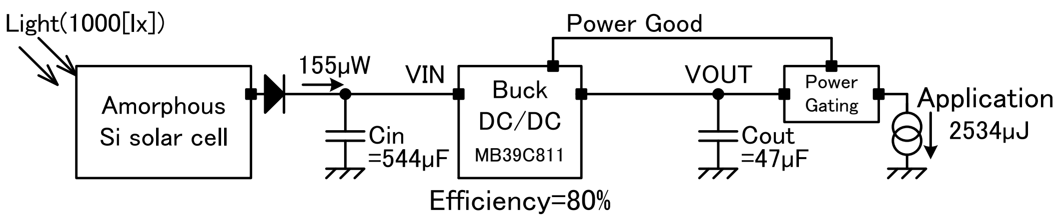
$$2403\ [\mu J] = \frac{1}{2} \times 80[\%] \times \text{Cin}[\mu F] \times (5.2[V]^2 - 4.0[V]^2)$$

$$\text{Cin }[\mu F] = 544[\mu J]$$

2.3 Charging Time of Cin and Cout (for MB39C811)

In order to calculate the charging time, the power generation capability is needed. (Refer to the Appendix, e.g. a solar cell has 155µW generation capability at the 1000[lx]). The Figure 5 shows the example of energy harvesting system focused on the charging time with a harvester.

Figure 5. Charging Time of Cin and Cout (for MB39C811)



Step1 for Initial charging time

Before calculating the initial charging time, calculate the total energy stored on both Cin and Cout.

$$\text{Total energy of Cin [µJ]} = \frac{1}{2} \times \text{Cin} \times (\text{VUVLOH}^2) = \frac{1}{2} \times 544[\text{µF}] \times 5.2[\text{V}]^2 = 7355[\text{µJ}]$$

$$\text{Total energy of Cout [µJ]} = \frac{1}{2} \times \text{Cout} \times (\text{VVOUT}^2) = \frac{1}{2} \times 47[\text{µF}] \times 3.3[\text{V}]^2 = 256[\text{µJ}]$$

Step2 for Initial charging time

$$\text{Initial charging time of Cin [s]} = \frac{\text{Total energy of Cin [µJ]}}{\text{Power of solar cell [µW]}} = \frac{7355\ [\text{µJ}]}{155\ [\text{µW}]} = 49.5[\text{sJ}]$$

$$\text{Initial charging time of Cout [s]} = \frac{\text{Total energy of Cout [µJ]}}{\text{Power of solar cell [µW]} \times 80[\%]} = \frac{256\ [\text{µJ}]}{155\ [\text{µW}] \times 0.8} = 2[\text{sJ}]$$

$$\text{Initial charging time [s]} = \text{Initial charging time of Cin [s]} + \text{Initial charging time in Cout [s]}$$

$$= 49.5\ [\text{s}] + 2\ [\text{s}] = 51.5\ [\text{s}]$$

Repeat charging time

$$\text{Repeat time for charging time of Cin [s]} = \frac{\text{Available energy in Cin [µJ]}}{\text{Power of solar cell [µW]}} = \frac{2403\ [\text{µJ}]}{155\ [\text{µW}]} = 15.5[\text{sJ}]$$

$$\text{Repeat charging time of Cout [s]} = \frac{\text{Available energy in Cout [µJ]}}{\text{Power of solar cell [µW]} \times 80[\%]} = \frac{131\ [\text{µJ}]}{155\ [\text{µW}] \times 0.8} = 1[\text{sJ}]$$

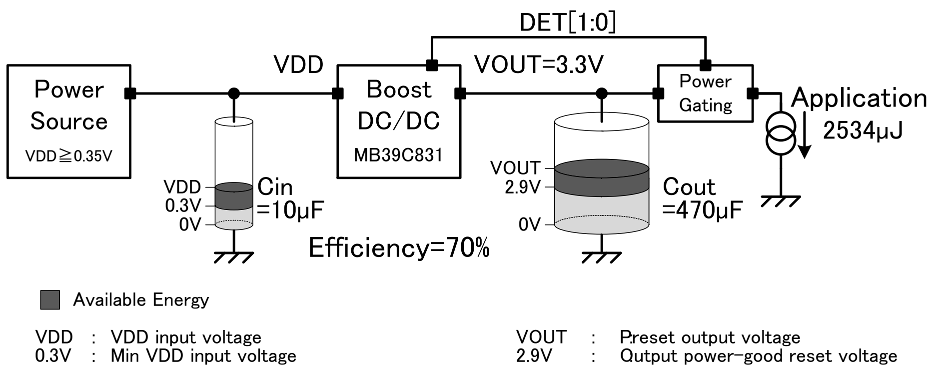
$$\text{Repeat charging time [s]} = \text{Repeat charging time of Cin [s]} + \text{Repeat charging time of Cout [s]}$$

$$= 15.5\ [\text{s}] + 1\ [\text{s}] = 16.5\ [\text{s}]$$

2.4 Sizing of Cin and Cout (for MB39C831)

The Figure 6 shows the image of the capacitors with the boost DC/DC converter, MB39C831.

Figure 6. Stored Image of Capacitors (for MB39C831)



Because the energy in a capacitor is proportional to the square of the voltage, it is energetically advantageous for the boost DC/DC converter to make the Cout larger. In the example with MB39C831 of the Figure 6, only adjust the Cout. Although the Cin = 10µF is used as the input capacitor, the Cin is excluded from the energy calculation because the stored energy on the Cin is very small.

In the Figure 3, the energy requirement for the application block was calculated at 2,534[µJ]. The energy requirement should be stored on the Cout.

Calculate the size of the Cout

The output power-good reset voltage (minimum voltage of the Cout) is set by 2.9V in MB39C831. (Refer to the MB39C831 datasheet).

$$\text{Available energy in Cout } [\mu\text{J}] = \frac{1}{2} \times \text{Cout} \times (\text{VOUT}^2 - 2.9[\text{V}]^2)$$

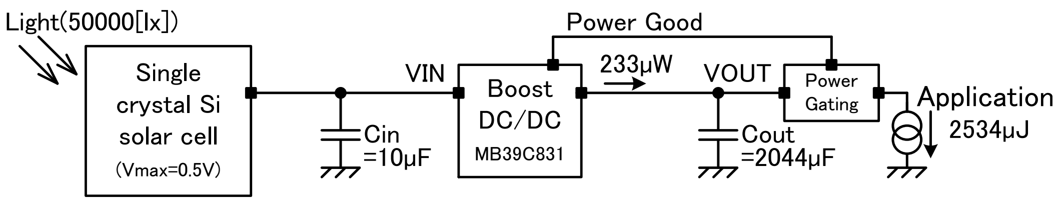
$$2534\ [\mu\text{J}] = \frac{1}{2} \times \text{Cout}[\mu\text{F}] \times (3.3[\text{V}]^2 - 2.9[\text{V}]^2)$$

$$\text{Cout}\ [\mu\text{F}] = 2044[\mu\text{F}]$$

2.5 Charging Time for Cin and Cout (for MB39C831)

In order to calculate the charging time, the power generation capability is needed. (Refer to the Appendix, e.g. the single crystal silicon solar cell (Vmax=0.5V) has 233µW generation capability including the MB39831's consumption at the 50000[lx]). The Figure 7 shows the example of energy harvesting system focused on the charging time with a harvester.

Figure 7. Charging Time of Cin and Cout (for MB39C831)



Step1 for Initial charging time

Before calculating the initial charging time, calculate the total energy stored on the Cout.(excluding the Cin because the stored energy on the Cin is very small.)

$$\text{Total energy of Cout }[\mu\text{J}] = \frac{1}{2} \times \text{Cout} \times (\text{VOUT}^2) = \frac{1}{2} \times 2044[\mu\text{F}] \times 3.3[\text{V}]^2 = 11127[\mu\text{J}]$$

Step2 for Initial charging time

$$\text{Initial charging time of Cout }[\text{s}] = \frac{\text{Total energy of Cout }[\mu\text{J}]}{\text{generation capability including IC}[\mu\text{W}]} = \frac{11127\ [\mu\text{J}]}{233\ [\mu\text{W}]} = 44.8[\text{s}]$$

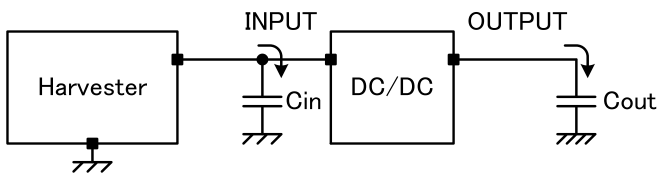
Repeat charging time

$$\text{Repeat charging time of Cout }[\text{s}] = \frac{\text{Available energy in Cout }[\mu\text{J}]}{\text{generation capability including IC}[\mu\text{W}]} = \frac{2534\ [\mu\text{J}]}{233\ [\mu\text{W}]} = 11[\text{s}]$$

A Appendix

A.1 Power Generation Capability

Figure 8. Power Generation Capability



To make it simple to calculate charging time at the section 2.3 and the section 2.5, the power generation capability is calculated based on the measured charging time of capacitors.

Table 1. Examples of Power Generation Capability (for MB39C811)

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	condition	Power generation capability [μW]
Solar	Amorphous Si	46×30	6.68 (6.4 + 0.28)	---	1000[lx]	155 [μW]
Solar	Amorphous Si	46×30 (2 series)	13.08 (12.8 + 0.28)	---	1000[lx]	193 [μW]
Piezo	Polymer	80×30	80(Vpp)	---	3Hz hand push	578 [μW]

The MB39C831 is designed for harvesters that have a high power generation capability, such as an outdoor solar cell. It is not possible to start up with a small indoor solar cell

Table 2. Examples of Power Generation Capability (for MB39C831)

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	condition	Power generation capability [μW]
Solar	Single crystal Si	50×50	0.5	500	50000[lx]	233 [μW] (*1)
Solar	Single crystal Si	82×68	1.5	500	50000[lx]	1706 [μW] (*1)
Peltier	---	10×10 (2 series)	0.704	117	ΔT=30℃	Larger than 44000 [μW] (*2)

1. The value including the MB39C831's consumption.
2. The value from a peltier's datasheet

A.2 Amorphous Silicon Solar Cell (for MB39C811)

Table 3. Characteristics of Amorphous Silicon Solar Cell

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	condition	Power generation capability [μW]
Solar	Amorphous Si	46×30	6.68	---	1000[lx]	155 [μW]

Figure 9. Block Diagram with Amorphous Silicon Solar Cell

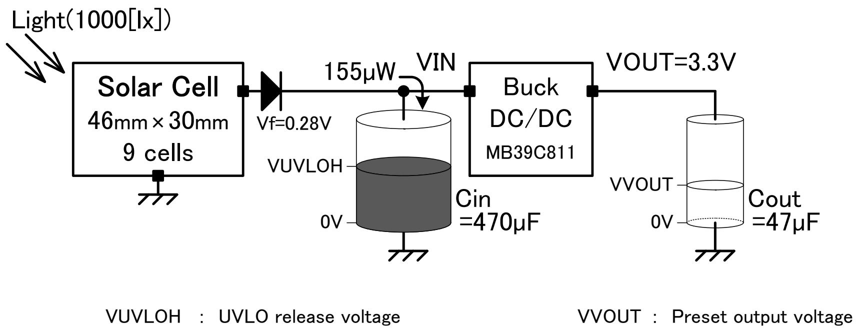
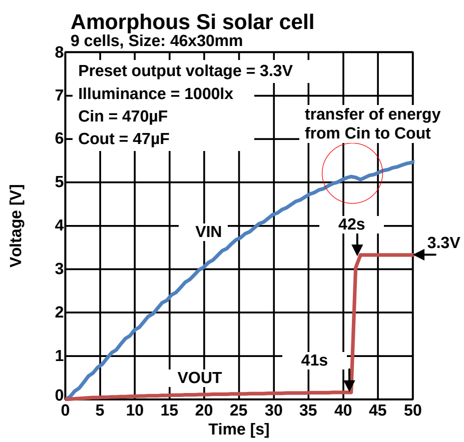


Figure 10. Charging time for Cin and Cout



1. Charging energy in Cin

$$\text{Charging energy}[\mu J] = \frac{1}{2} \times \text{Cin} \times (\text{VUVLOH}^2) = \frac{1}{2} \times 470[\mu F] \times 5.2[V]^2 = 6354[\mu J]$$

2. Charging time in Cin (measured value)

$$\text{Charging time}[s] = 41\ [s]$$

3. Power generation capability

$$\text{Power generation capability}[\mu W] = \text{Charging energy}[\mu J] \div \text{Charging time}[s]$$

$$= 6354\ [\mu J] \div 41\ [s] = 155\ [\mu W]$$

After the voltage of the Cout becomes the preset output voltage, more energy is charged into the Cin until the open circuit voltage of the solar cell. The power generation capability during the period is calculated.

Figure 11. Block Diagram with Amorphous Silicon Solar Cell

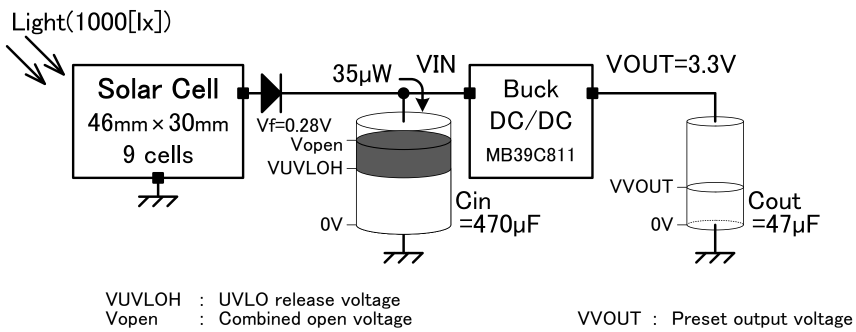
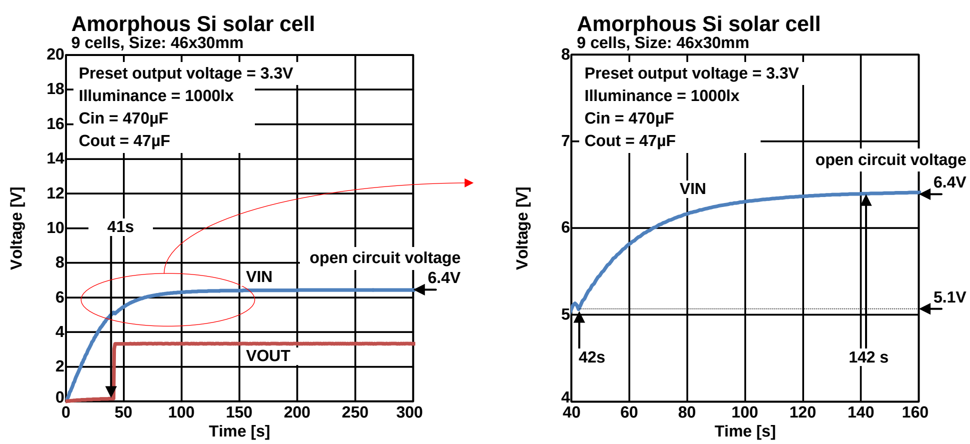


Figure 12. After the Charging time of Cin and Cout



1. Charging more energy in Cin

$$\text{Charging energy}[\mu\text{J}] = \frac{1}{2} \times 80[\%] \times 470[\mu\text{F}] \times (6.4[\text{V}]^2 - 5.1[\text{V}]^2) = 3513[\mu\text{J}]$$

2. Charging time in Cin (measured value)

$$\text{Charging time [s]} = 100\ [\text{s}]$$

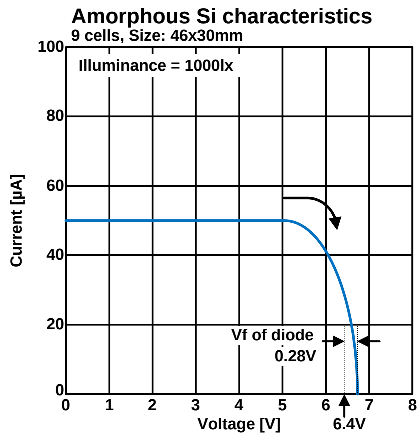
3. Power generation capability

$$\text{Power generation capability}[\mu\text{W}] = \text{Charging energy}[\mu\text{J}] \div \text{Charging time [s]}$$

$$= 3513[\mu\text{J}] \div 100\ [\text{s}] = 35[\mu\text{W}]$$

The power generation capability is much smaller than that until the Cin become the preset output voltage. That is because of the characteristics of the solar cell. This solar cell acts as a current source until around 5V (see Figure 13). However, the current supply suddenly decrease after the voltage goes over 5V.

Figure 13. Characteristic of Amorphous Silicon Solar Cell



A.3 Amorphous Silicon Solar Cell in Series (for MB39C811)

Table 4. Characteristics of 2 Series Amorphous Silicon Solar Cells

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	Condition	Power generation capability [μW]
Solar	Amorphous Si	46×30 (2 series)	13.8	---	1000[lx]	193 [μW]

Figure 14. Block Diagram with 2 Series Amorphous Silicon Solar Cells

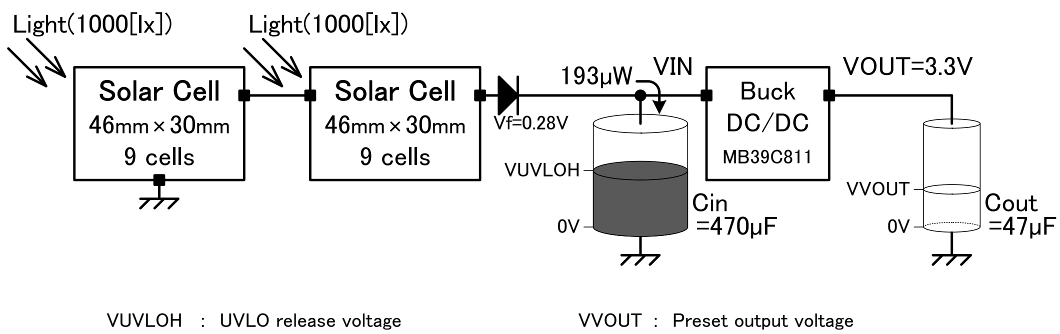
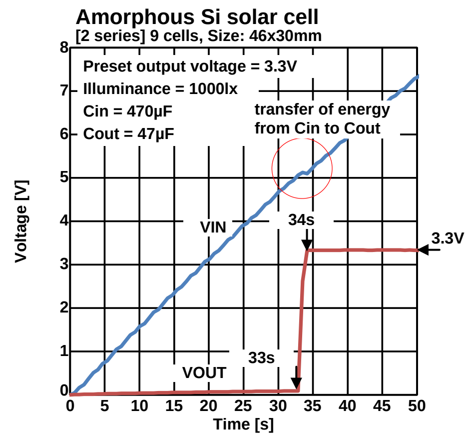


Figure 15. Measured Graph Using Amorphous Silicon Solar Cells in Series



1. Charging energy in Cin

$$\text{Charging energy}[\mu\text{J}] = \frac{1}{2} \times \text{Cin} \times (\text{VUVLOH}^2) = \frac{1}{2} \times 470[\mu\text{F}] \times 5.2[\text{V}]^2 = 6354[\mu\text{J}]$$

2. Charging time in Cin (measured value)

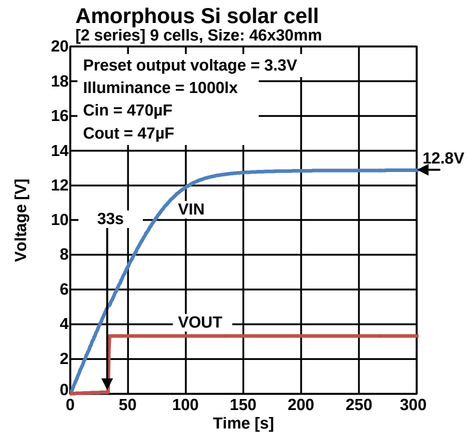
$$\text{Charging time } [\text{s}] = 33\ [\text{s}]$$

3. Power generation capability

$$\text{Power generation capability}[\mu\text{W}] = \text{Charging energy}[\mu\text{J}] \div \text{Charging time}[\text{s}]$$

$$= 6354\ [\mu\text{J}] \div 33\ [\text{s}] = 193\ [\mu\text{W}]$$

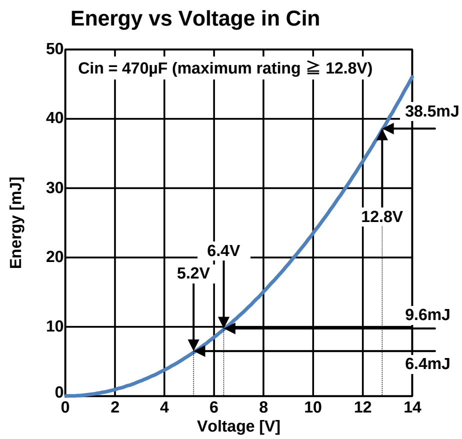
Figure 16. Measured Graph Using Amorphous Silicon Solar Cell in Series



The more energy from a harvester can be stored on a capacitor because the energy in a capacitor is proportional to the square of the voltage.

$$\text{Energy}[\mu\text{J}] = \frac{1}{2} \times 470[\mu\text{F}] \times \text{Voltage}^2$$

Figure 17. Energy vs Input Voltage in Capacitor



A.4 Piezo (for MB39C811)

Table 5. Characteristics of Piezo

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	Condition	Power generation capability [µW]
Piezo	Polymer	80×30	80(Vpp)	---	3Hz, hand push	578 [µW]

Figure 18. Testing Method Using Piezo

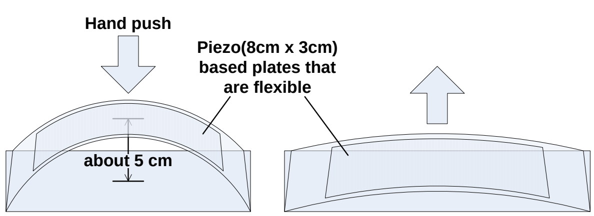
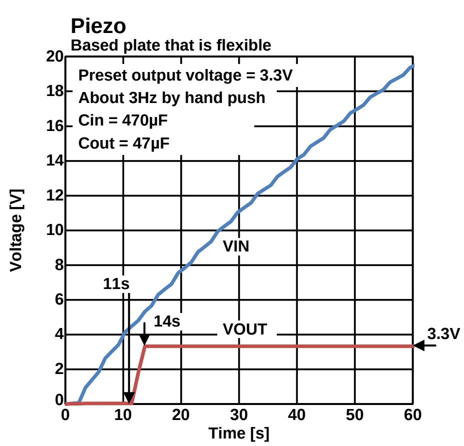


Figure 19. Measured Graph Using Piezo



1. Charging energy in Cin

$$\text{Energy for charging}[\mu J] = \frac{1}{2} \times \text{Cin} \times (\text{VUVLOH}^2) = \frac{1}{2} \times 470[\mu F] \times 5.2[V]^2 = 6354[\mu J]$$

2. Charging time in Cin (measured value)

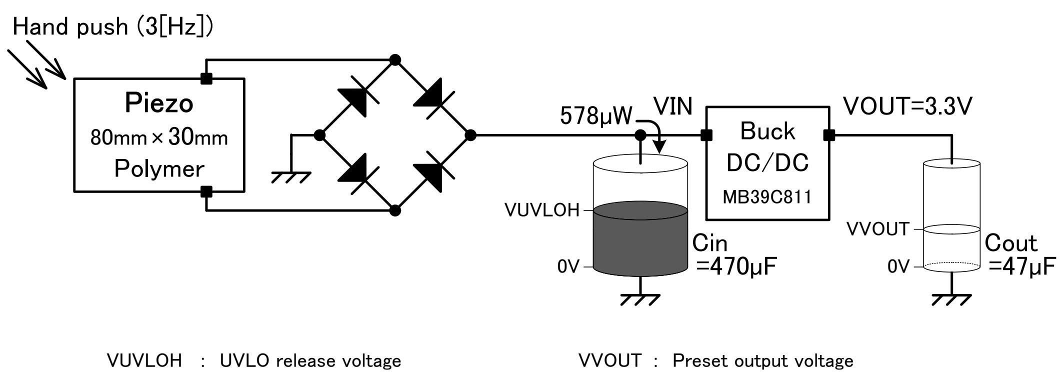
$$\text{Charging time}[s] = 11\ [s]$$

3. Power generation capability

$$\text{Power generation capability}[\mu W] = \text{Charging energy}[\mu J] \div \text{Charging time}[s]$$

$$= 6354[\mu J] \div 11\ [s] = 578\ [\mu W]$$

Figure 20. Block Diagram with Single Crystal Silicone Solar Cell -1



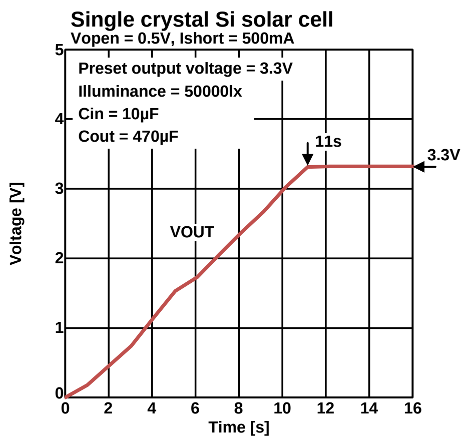
A.5 Single Crystal Silicon Solar Cell -1 (for MB39C831)

Table 6. Characteristics of Single Crystal Silicone Solar Cell -1

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	condition	Power generation capability [μW]
Solar	Single crystal Si	50×50	0.5	500	50000[lx]	233 [μW] (*1)

1. The value including the MB39C831's consumption

Figure 21. Measured Graph Using Single Crystal Silicone Solar Cell -1



The Cin is excluded from the energy calculation because the input voltage (VDD) is not stable in the start-up and the stored energy is very small.

1. Charging energy in Cout

$$\text{Chargeing energy}[\mu J] = \frac{1}{2} \times \text{Cout} \times (\text{VOUT}^2) = \frac{1}{2} \times 470[\mu F] \times 3.3[V]^2 = 2559[\mu J]$$

2. Charging time in Cout (measured value)

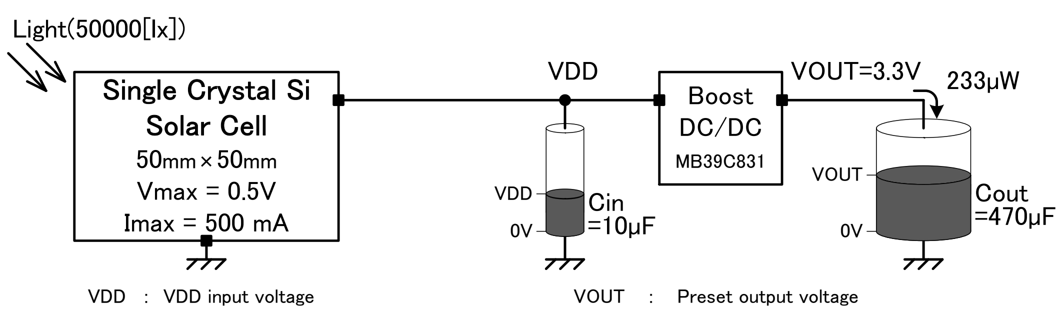
$$\text{Time for charging}[s] = 11\ [s]$$

3. Power generation capability

$$\text{Power generation capability}[\mu W] = \text{Charging energy}[\mu J]\ \div \text{Charging time}\ [s]$$

$$= 2559\ [\mu J] \div 11\ [s] = 233\ [\mu W]$$

Figure 22. Block Diagram with Single Crystal Silicone Solar Cell -1



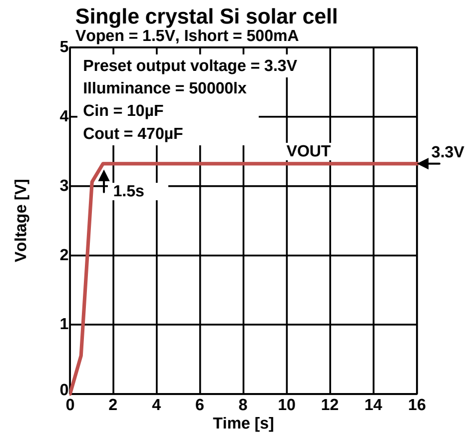
A.6 Single Crystal Silicon Solar Cell -2 (for MB39C831)

Table 7. Characteristics of Single Crystal Silicone Solar Cell -2

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	Condition	Power generation capability [μW]
Solar	Single crystal Si	80×70	1.5	500	50000[lx]	1706 [μW] (*1)

1. The value including the MB39C831's consumption

Figure 23. Measured Graph Using Single Crystal Silicone Solar Cell -2



The Cin is excluded from the energy calculation because the input voltage (VDD) is not stable in the start-up and the stored energy is very small.

1. Charging energy in Cout

$$\text{Charging energy}[\mu\text{J}] = \frac{1}{2} \times \text{Cout} \times (\text{VOUT}^2) = \frac{1}{2} \times 470[\mu\text{F}] \times 3.3[\text{V}]^2 = 2559[\mu\text{J}]$$

2. Charging time in Cout (measured value)

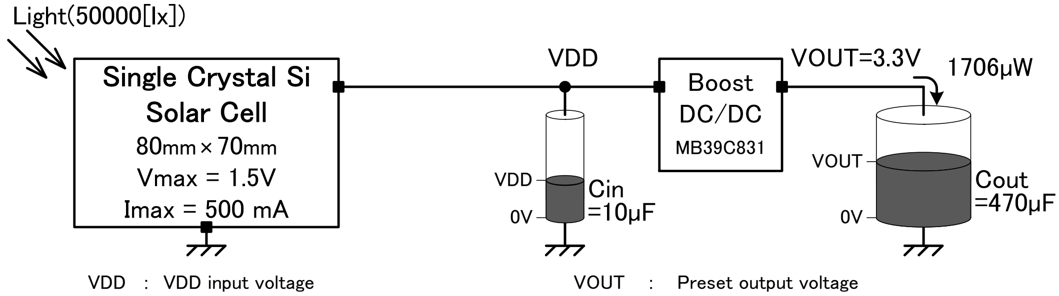
$$\text{Time for charging}[\text{s}] = 1.5\ [\text{s}]$$

3. Power generation capability

$$\text{Power generation capability}[\mu\text{W}] = \text{Charging energy}[\mu\text{J}] \div \text{Charging time}\ [\text{s}]$$

$$= 2559\ [\mu\text{J}] \div 1.5\ [\text{s}] = 1706\ [\mu\text{W}]$$

Figure 24. Block Diagram with Single Crystal Silicone Solar Cell -2



A.7 Peltier (for MB39C831)

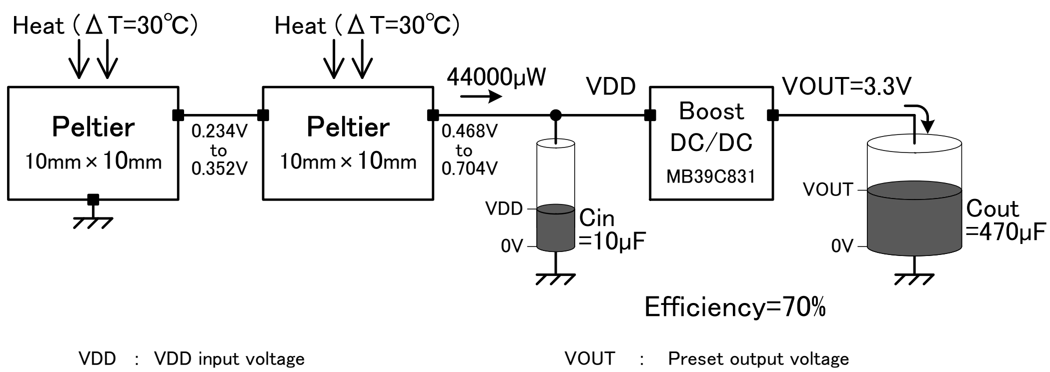
Peltier elements provide relatively large amount energy upon being given temperature difference. However, they do not supply high voltage. The peltier element shown in Table 8 supplies up to 0.352V. To meet the minimum start-up input voltage of MB39C831, use the peltier elements connected in series.

Table 8. Characteristics of Peltier

Generator	Type	Size [mm]	Vmax [V]	Imax [mA]	Condition	Power generation capability [μW]
Peltier	---	10×10	0.234 - 0.352	0.077 - 0.117	ΔT=30℃	Larger than 22000 [μW] (*1)
Peltier	---	10×10 (2 series)	0.468 - 0.704	0.077 - 0.117	ΔT=30℃	Larger than 44000 [μW] (*1)

1. The value from a peltier's datasheet

Figure 25. Block diagram with Peltier



3 Document History

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Revision	ECN	Orig. of Change	Submission Date	Description of Change
**	-	TAOA	01/18/2014	Initial Release
*A	5037823	TAOA	12/07/2015	Migrated Spansion Application Note from AN405-00001-1v0-E to Cypress format
*B	5790555	AESATMP8	06/29/2017	Updated logo and Copyright.

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