Chapter 56
A Micro-Scale Solar Energy Harvesting Circuit with MPPT Control for Self-Powered Systems

Eun Jung Yoon and Chong Gun Yu

Abstract In this paper a micro-scale solar energy harvesting system with Maximum Power Point Tracking (MPPT) control using a miniature photovoltaic cell of which the output is less than 0.5 V is proposed. The MPPT control is implemented using linear relationship between the open-circuit voltage of a main solar cell and its Maximum Power Point (MPP) voltage such that a pilot solar cell can track the MPP of the main solar cell in real time. The proposed circuit is designed in 0.18 μm CMOS process. The designed chip area is 1370 × 900 μm including a load charge pump and pads. Measured results show that the designed system can track the MPP voltage changes with variations of light intensity. The designed circuit with MPPT control provides load with MPP voltages even though the load is heavy such that it can supply more energy when the MPPT control is applied.

Keywords Energy harvesting · Solar energy · PV cell · MPPT · ISC · USN

56.1 Introduction

Recently, there is an increasing interest in using free available environmental energy sources for powering small electronic systems, a process known as energy harvesting [1–3]. Among the energy harvesting sources such as solar, vibration, thermal energy, and RF energy, solar energy is the most popular because of its ubiquitousness and its relatively high power density. Due to the form-factor constraint, micro-scale solar energy harvesting systems require the use of miniature photovoltaic (PV) cells or even monolithic integrated solar cells (ISC), which

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output very low voltage less than 0.5 V. As a result, they cannot be used to directly power electronic systems. The amount of solar energy available usually varies with the environment. There is a maximum power point (MPP) for each PV cell and the point changes with varying light intensity. To harvest the maximum power, the energy harvesting system should be able to track the MPP such that the PV cell always operates at its MPP. The MPP tracking (MPPT) becomes even more important in micro-scale energy harvesting because the output power of a miniature PV cell is extremely small, often only a few tens of uW. Therefore, it is crucial to extract as much power as possible from the PV cell while the power overhead introduced by the MPPT scheme should be minimized.

Among various techniques for MPPT, the hill-climbing method and the fractional open-circuit (FOC) method have been commonly used for micro-scale solar energy harvesting systems [4]. In the conventional hill-climbing [9–11], the instantaneous output power is usually computed using a microcontroller, making this approach be unsuitable for micro-scale energy harvesting. To implement the hill-climbing method without a microcontroller, the use of dedicated hardware (current sensor, VCO, control logic, etc.) has been proposed in [8]. To reduce the power/hardware overhead further, the use of a negative-feedback control loop has been proposed in [7], where the MPPT control is implemented using a polynomial VCO without any sensor or extra control circuits. However, the methods proposed in [7, 8] require a precharged rechargeable battery to start up, making them unsuitable for batteryless self-powered systems.

The FOC method is based on the empirical observation that the MPP voltage of a PV cell is an almost-constant fraction of its open circuit voltage. In this method, the MPP voltage is computed by sensing its open circuit voltage. To implement the FOC method with low hardware/power overhead, the Linear Reoriented Coordinate Method has been proposed in [6], where sub-threshold and floating-gate design techniques have been adopted to achieve low-power operation. In this method, an ISC (CMOS photodiodes) was used as a solar energy transducer, and an auxiliary photodiode array was used to power up the MPPT control circuitry. However, the use of auxiliary photodiodes in series for powering up the internal circuitry may cause problems because of the current consumption in the parasitic diodes. Also, this scheme has not been verified through silicon implementation.

In this paper, a micro-scale solar energy harvesting circuit for batteryless miniaturized self-powered systems is proposed. To minimize the system, our targeted solar energy transducer is a miniature PV cell (0.14 cm^2) or monolithic ISC. The MPPT control is implemented using the FOC method. However, the open-circuit voltage of a smaller pilot cell (0.07 cm^2) is monitored instead of the main PV cell, thus avoiding frequent interruption to the normal energy harvesting process. The MPPT controller is powered from the main PV cell through a small boosting circuit such that the proposed energy harvesting circuit does not require a precharged battery. Therefore it is well suited for batteryless miniaturized systems. The design and implementation of the proposed system is presented and experimental results are also presented.

56.2 Proposed Micro-Scale Solar Energy Harvesting Circuit

Figure 56.1 shows the block diagram of the proposed micro-scale solar energy harvesting circuit with MPPT control. It consists of four blocks: the main PV cell, the voltage booster (VB), the solar energy MPPT control (SEMC) and the load charge pump. The PV cell used in this design outputs very low voltages less than 0.5 V. The VB thus steps up the PV cell's output voltage to a higher value that is enough for powering the SEMC. The SEMC controls the switch connected between the PV cell and the load charge pump such that the PV cell always operates at its MPP.

To minimize the self-powered system size, our targeted solar energy transducer is a miniature PV cell or monolithic ISC. The used PV cell is the device of SCPD [12] of which the output voltage is less than 0.5 V and the size is 0.14 cm^2, so it has similar features and size with an ISC implemented in CMOS process. To model the PV cell using the equivalent circuit shown in Fig. 56.1, its open circuit voltage and short-circuit current have been measured at 10 klux. The measured results are $V_{OC} = 350$ mV and $I_{SC} = 147$ uA. The operation voltage of the PV cell (V_{OP}) can be expressed as Eq. (56.1).

$$V_{OP} \cong K_{OP} \cdot V_{OC} \tag{56.1}$$

At the MPP, the V_{OP} and K_{OP} can be denoted as V_{MPP} and K_{MPP}, respectively as in Eq. (56.2).

$$V_{MPP} \cong K_{MPP} \cdot V_{OC} \tag{56.2}$$

The K_{MPP} is usually constant ranging from 0.6 to 0.8 [4–6], in our case 0.75.

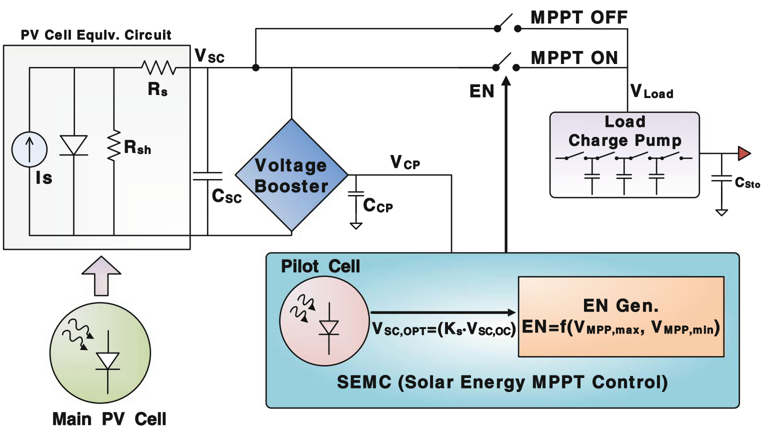

Fig. 56.1 Proposed micro-scale solar energy harvesting circuit

The VB boosts the PV cell's output voltage (<0.5 V) to a higher value ($\sim$1 V) powering up the SEMC. It consists of a ring oscillator and a charge pump. The ring oscillator has three inverter stages. The used charge pump is a simple Dickson charge pump with eight stages and stage capacitance of 10pF where native MOSFETs are used to increase the pumping capability.

Figure 56.2 shows the block diagram of the SEMC. The SEMC consists of a pilot PV cell, two comparators and a latch. The pilot PV cell with a resistor divider supplies the comparators with the reference MPP voltages ($V_{MPP,max}$, $V_{MPP,min}$). The upper comparator detects whether the output voltage of the main PV cell (V_{SC}) reaches $V_{MPP,max}$, while the lower one detects whether it reaches $V_{MPP,min}$. The signals generated by the comparators are used by the latch to generate the 'EN' signal (V_{EN}) determining on/off states of the pMOS power switch (see Fig. 56.1).

The operational principles of the SEMC are as follows:

- Firstly, when the system receives light, the output voltage of the main PV cell, V_{SC}, increases by charging the capacitor C_{SC}. (Charging phase).
- When the V_{SC} reaches the predefined upper MPP limit ($V_{MPP,max}$) at $t = t_1$, the SEMC generates 'EN' signal to switch on the power pMOS transistor, supplying the harvested power to the load.
- During the power switch is on, the V_{SC} decreases because the power available from the PV cell is usually less than the power required from the load. (Discharging phase).
- When the V_{SC} decreases down to the predefined lower MPP limit ($V_{MPP,min}$) at $t = t_2$, the power transistor is switched off, and then the V_{SC} increases again.
- This charging and discharging phases are repeated, and the main PV cell always operates around the MPP.

The pilot PV cell is used to monitor in real time the V_{MPP} of the main PV cell. Since the main and pilot PV cells are the same model made by [12], it can be assumed that their MPP voltages are matched under the same environment and light intensity. Small errors at most 5 % in the V_{MPP} evaluation have been demonstrated experimentally in [1] if K_{MPP} is considered as a constant under changing irradiance conditions. Therefore, a constant value of 0.75 is used for K_{MPP} in our design which has been determined from the measured data ($V_{OC} = 350$ mV, $V_{MPP} = 266$ mV @10 klux). The resistances of the resistor divider are chosen

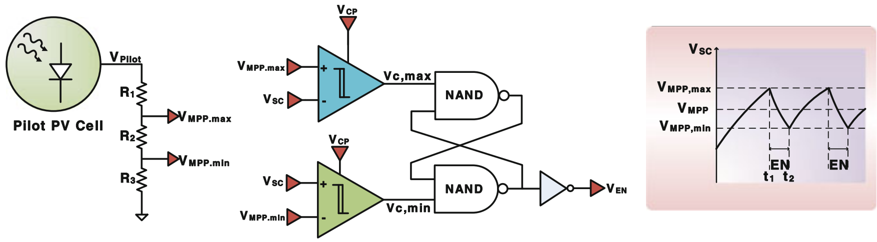

Fig. 56.2 Block diagram of SEMC and its operational principles

such that the $V_{MPP,max}$ and $V_{MPP,min}$ track the V_{MPP} within ±10 %. The sum of their resistances is 2 MΩ, so the output voltage of the pilot PV cell is almost equal to its open-circuit voltage. Thus, the $V_{MPP,max}$ and $V_{MPP,min}$ are the fractions of the PV cell's open-circuit voltage.

56.3 Experimental Results

The designed micro-scale solar energy harvesting circuit has been fabricated in a 0.18 μm CMOS process. The layout and chip photograph are shown in Fig. 56.3. The chip size including pads is 1370 × 900 μm. Figure 56.4a shows the experimental responses at 10 klux when the load terminal (V_{Load}) is connected to a resistor (650 Ω) instead of the load charge pump. It can be seen that $V_{MPP,max}$ is 292 mV and $V_{MPP,min}$ is 236 mV, and the Vsc is thus tracking the MPP voltage of 266 mV within ±11 %. The waveform of V_{Load} shows that the harvested power is supplied to the load resistor during the discharging phase. Figure 56.4b shows the measured waveforms when the load terminal is connected to the load charge pump. The ring oscillator of the load charge pump operates in discharging phase only. The starting clock frequency is 1.37 MHz.

Figure 56.5 shows the waveforms of the V_{SC} and V_{Load} at different load resistances. The duty cycles at 440 Ω and 2.1 kΩ are 13.7 and 79.3 %, respectively. As the load resistance increases, the power consumed by the load resistor decreases and the duty cycle increases. Figure 56.6 shows the measured V_{SC} waveform when the light intensity is varied from 6.7 to 4.2 klux. As the light intensity decreases, the V_{OC} and thus V_{MPP} of the PV cell are also decreased. It can be seen from the figure that the designed system can track the MPP voltage changes with variations of light intensity.

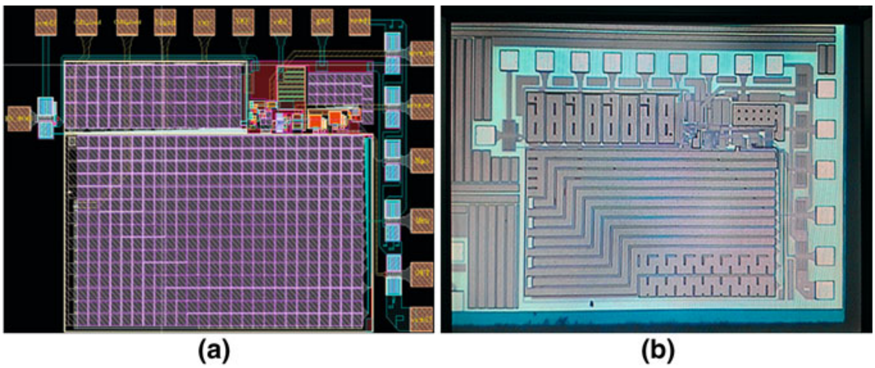

Fig. 56.3 Designed micro-scale solar energy harvesting circuit. **a** Layout **b** Photograph

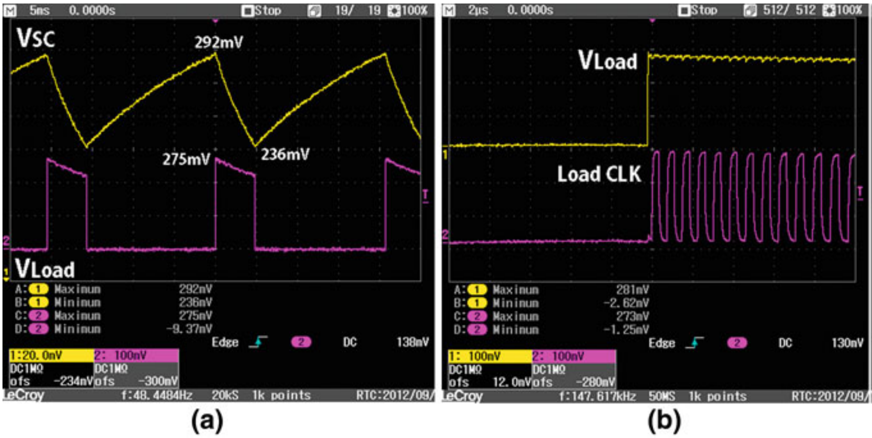

Fig. 56.4 Experimental responses **a** V_{SC} and V_{Load}, **b** V_{Load} and load charge pump clock

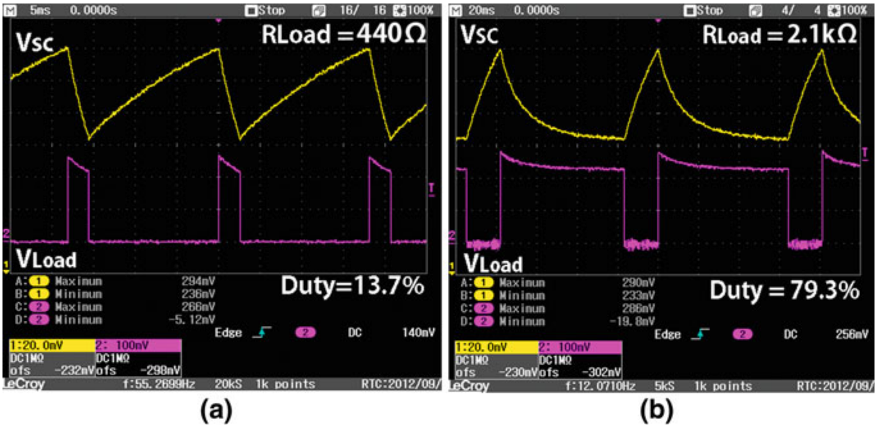

Fig. 56.5 Measured duty cycles at different load resistances **a** R_{Load} = 440 Ω, **b** R_{Load} = 2.1 Ω

Figure 56.7 shows the K_{OP} plots at different light intensity. The measured K_{OP} range with MPPT control is 0.7–0.8 which lies in the MPP range (K_{MPP} = 0.75 in our case), and thus the power at the MPP is delivered to the load. However, the measured K_{OP} without MPPT control has values of 0.5–0.75 of which the large portion is out of the MPP range, especially in the low light intensity. Figure 56.8 shows the operation voltages of the main PV cell at different load resistance. The measured V_{OP} with MPPT control is almost constant (240–260 mV) while the measured V_{OP} without MPPT control varies between 0 V and 250 mV. The V_{OP} without MPPT control gets out of the MPP range and is very low, especially in the low load resistances corresponding to heavy loads.

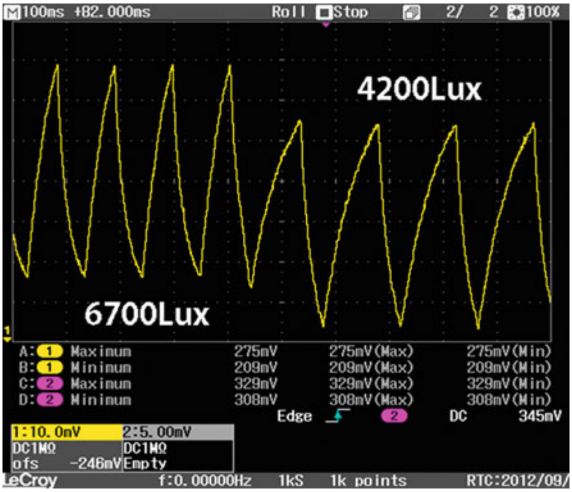

Fig. 56.6 MPP tracking process with the variation of light intensity

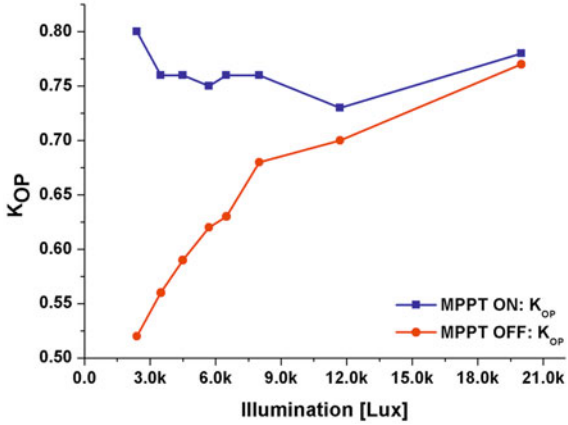

Fig. 56.7 K_{OP} versus illumination

The load power graph at different load resistance is shown in Fig. 56.9. When the MPPT control is on, the more power from the PV cell is delivered to the load, especially in the low load resistances. Thus, using the MPPT control is more efficient when the load is heavy. The measured maximum load power is 25.7 uW at the load resistance of 2.1 kΩ. Figure 56.10 shows the power efficiency defined as the ratio between the power delivered to the load resistor and the maximum available power of the main PV cell. The measured maximum power efficiency is 78 % at the load of 2.1 kΩ.

Table 56.1 compares recent MPPT approaches in micro-scale solar energy harvesting systems. The methods proposed in [7, 8] require a precharged battery to start up, making them unsuitable for batteryless self-powered systems. In [6], the FOC method with low hardware/power overhead has been implemented using ISC’s, but the use of auxiliary photodiodes in series for powering up the internal

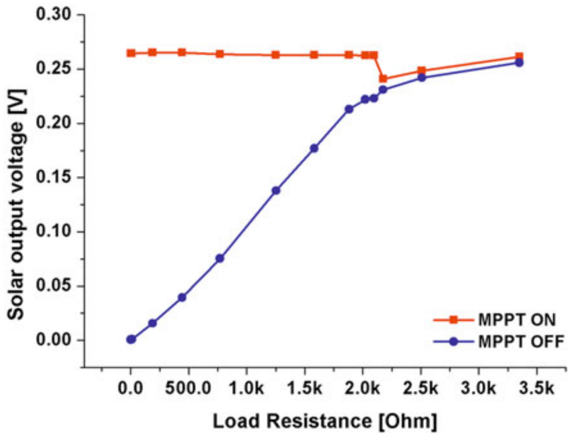

Fig. 56.8 V_{OP} versus load resistance

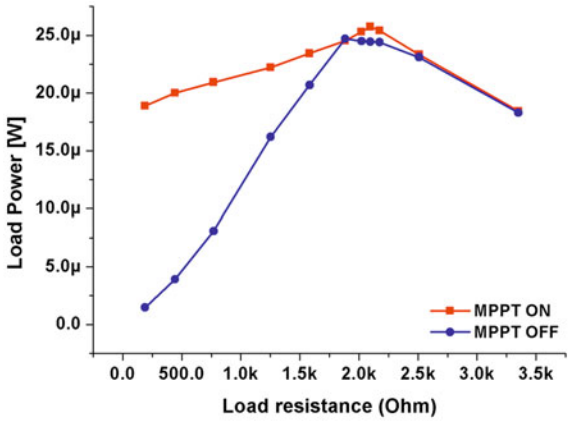

Fig. 56.9 Load power versus load resistance

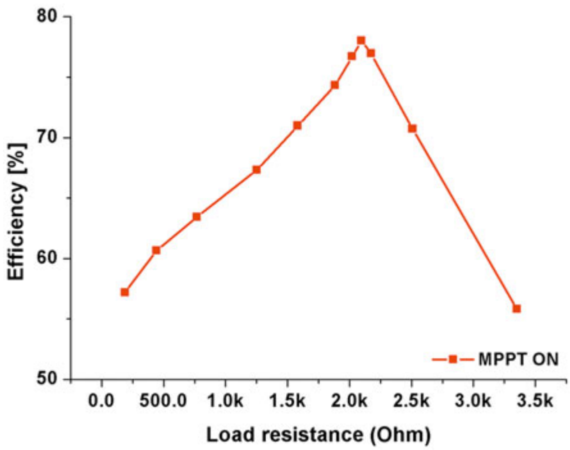

Fig. 56.10 Power efficiency when MPPT is on

Table 56.1 Comparison of micro-scale solar energy harvesting circuits

	[6]	[7]	[8]	This work
PV cell type (Size)	ISC (N/A)	Single cell (0.64 cm^2)	two single cells in series (20.2 cm^2)	Single cell (0.14 cm^2)
PV cell open voltage Voc (V)	<0.5	<0.5	<1.1	<0.5
MPPT Scheme	FOC	Negative-feedback automatic tracking	Hill climbing	FOC & pilot cell(0.07 cm^2)
Controller power source	Auxiliary 4 diodes in series (1.6 V)	Rechargeable battery (0.9 V)	Rechargeable battery (1 V)	Main PV cell (<0.5 V)
Max. Efficiency (%)	N/A	39.5	90	78 (w/o load charge pump)
Verification	Simulation	Simulation	Simulation	Measurement
Process (nm)	500	45	65	180
Year	2010	2012	2012	2013

circuitry may cause problems. These approaches have not been verified through silicon implementation.

In this paper, a micro-scale solar energy harvesting circuit for batteryless miniaturized systems has been proposed, designed and experimentally verified. It does not require any precharged battery resulting in more suitability for miniaturized self-powered systems compared to the existing works.

56.4 Conclusion

This paper presented a micro-scale solar energy harvesting circuit for miniaturized self-powered systems such as sensor nodes. The MPPT control is implemented using the FOC method, where the MPP voltages are monitored from the open-circuit voltage of a pilot cell instead of the main PV cell. The MPPT controller is powered from the main PV cell through a small boosting circuit so that the proposed circuit does not require a precharged battery. The proposed circuit is designed in 0.18 μm CMOS process. The designed chip area is 1370 × 900 μm including a load charge pump and pads. Measured results show that the designed system can track the MPP voltage changes with variations of light intensity.

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