Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp259-260

CMOS-based Optical Energy Harvesting Circuit for Implantable and IoT Devices

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Abstract

This work presents a novel CMOS-based optical energy harvesting technology for implantable and IoT (Internet of Things) devices. In the proposed system, a CMOS energy harvesting circuit accumulates in an external capacitor a small amount of photoelectrically converted energy and intermittently supplies the power to a target device. Two types of optical energy harvesting circuits were implemented and evaluated. We also developed a photoelectrically powered optical ID circuit suitable for IoT technology applications.

1. Introduction

There is a continuously increasing demand within the energy conversion/harvesting technologies field for various types of small-sized electronic circuits, including medical and IoT devices. Light, including solar energy, is one of the most common sources for the miniaturized energy conversion/harvesting technology. Light can be directly converted into electric energy by the photovoltaic effect. Since the typical voltage generated by a Si solar cell is approximately 0.4 V, it is a reasonable option to use serially connected, small solar cells, as a power receiver providing "sufficient voltage and limited current."

In this work, we propose and demonstrate an optical energy harvesting circuit that accumulates small amounts of energy from a serially connected, ultra-small solar cells string, and delivers the power intermittently to a target circuit. The circuit can also provide a clock signal to support clock-driven devices. Figure 1 is a conceptual illustration showing a target application for IoT technology.

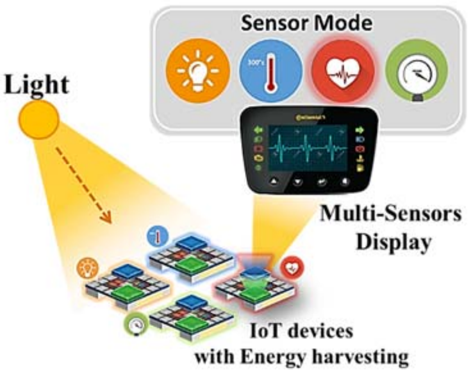
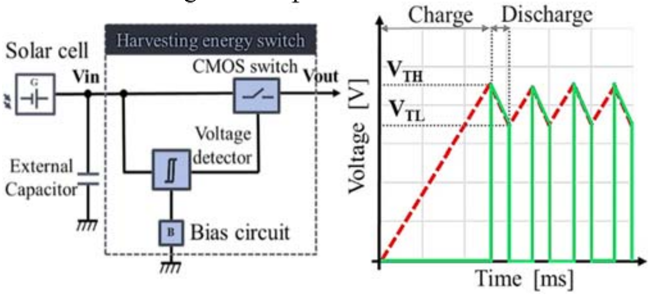


Fig. 1 Target application of the optical energy harvesting device.

2. Single-Stage Energy Harvesting Circuit Design

The core of the proposed optical energy harvesting technology comprises a single-stage energy harvesting circuit, designed for energy accumulation and intermittent load operation. Figure 2(a) shows the block diagram of the single-stage energy harvesting circuit. The circuit consists of an external capacitor, a CMOS voltage detector, a bias circuit, and a CMOS switch. Figure 2(b) shows the typical waveforms during circuit operation.



(a) (b)

Fig. 2 (a) Block diagram and (b) simulated waveforms of the single-stage energy harvesting circuit. In Fig. 2(b), dashed red and solid green lines represent V_{in} (capacitor voltage) and V_{out} (target circuit voltage source), respectively.

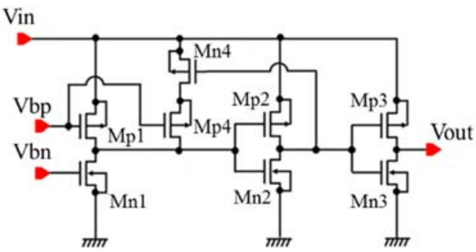


Fig. 3 MOS-level schematic of voltage detector circuit

The single-stage circuit operation begins by charging the external capacitor with the current generated by the solar cells. When the capacitor voltage reaches V_{TH}, the voltage detector turns on a CMOS switch and supplies power to the target circuit. After a discharge phase, when the capacitor voltage drops to V_{TL}, the voltage detector turns off the CMOS switch and stops supplying power, as shown in Fig. 2(b). While no load is present, the capacitor is recharged. V_{TH} and V_{TL} levels depend on V_{bn} and V_{bp} voltages from the bias circuit. Figure 3 shows the schematic of the voltage detector that receives V_{bp} as the gate voltage of the first PMOS (Mp1) and V_{bn} as the gate voltage of the first NMOS (Mn1). Therefore, the on-off period of the energy harvesting switch is adjustable by changing V_{bn} and V_{bp}. The on-off digital signal resulting from the circuit's operation can be used as an optional clock signal for the target circuit.

We designed and fabricated a prototype circuit for evaluation using a 0.35 µm 2-poly, 4-metals standard CMOS process.

3. Single-Stage Circuit Experiment & Result

To evaluate the voltage detector circuit, a 4 Vp-p ramp voltage was applied to the circuit input, Vin. The relationship between the threshold voltages (V_{TH} and V_{TL}) and bias voltages (V_{bn} and V_{bp}) in Fig. 4 is assessed by applying a matrix of bias voltages and measuring the corresponding threshold voltages.

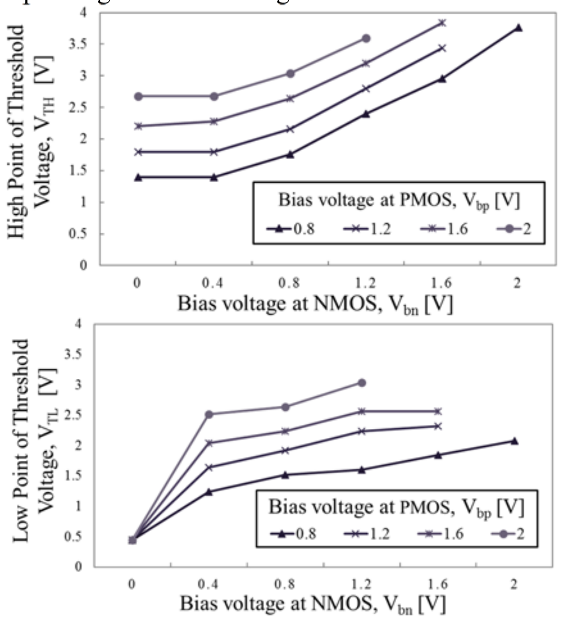


Fig. 4 Relationship between threshold voltages and bias voltages

For the appropriate settings of V_{bn} and V_{bp}, the optical energy harvesting circuit works as in the simulation shown in Fig. 2(b).

4. Dual-Stage Energy Harvesting Circuit Design

In order to continuously supply a small amount of power for sequential operation of the target circuit, a dual-stage energy harvesting circuit (Fig. 5) was developed. Two single-stage energy harvesting circuits with different V_{bn} and V_{bp} values were serially connected. The first circuit generates powering pulses for a load such as an LED, also providing a clock signal informing the target circuit that C1 is providing current. On the other hand, the second energy harvesting circuit is operating as an active rectifier to provide a small amount of power from C_2 to the control section of the target circuit. This architecture allows implementing a sequential operation on the target circuit.

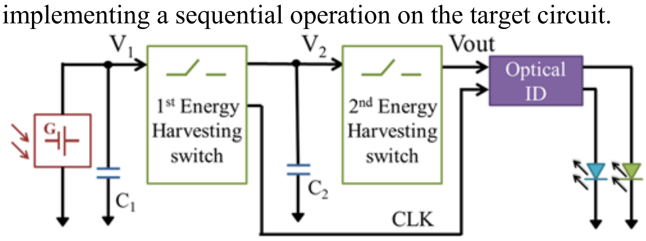


Fig. 5 Two-stage optical energy harvesting circuit block diagram

The dual-stage energy harvesting circuit, including an optically powered ID circuit to support IoT applications, was designed and evaluated. When powered, the circuit automatically transmits two-color optical ID signals. We used the same 0.35 µm process technology as for the prototype chip presented in the previous section. The chip size is approximately 700 µm × 700 µm.

5. Dual-Stage Circuit Experiment & Result

The fabricated dual-stage energy harvesting chip was integrated at board level with ten serially connected discrete photodiodes operating as the small-current solar cells to obtain sufficient voltage (approximately 4 V) and five serially connected photodiodes as the bias circuit. We also connected two discrete 4.7 µF capacitors as C1 and C2. Fig. 6 shows V1, V2, and the two LED waveforms acquired during the optically powered circuit operation. Figure 7 shows the images of an integrated prototype device. Figure 6 demonstrates that the circuits work as expected, the optical energy harvesting chip charging the two capacitors and supplying continuous voltage to power the control section of the optical ID circuit. The LEDs were successfully operated in the designed sequence, synchronously with the pulses generated by the first energy harvesting switch (drop of V1).

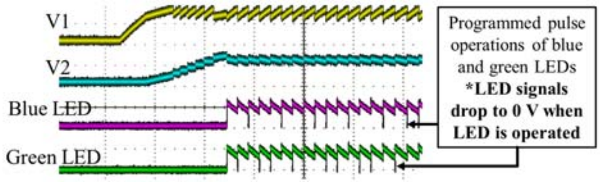


Fig. 6 Traces during the device operation.

Fig. 7 Top/bottom view of the device (2 cm × 2 cm)

6. Conclusions

In order to comply with various application requirements including those for IoT devices, a CMOS-based optical energy harvesting technology was proposed and demonstrated. Single-stage and dual-stage energy harvesting circuits were designed and evaluated. We obtained successful results for both circuits. A battery-less, photoelectrically powered, optical ID device was developed by integrating our chip with external discrete photodiodes and capacitors.

We are currently designing a smaller-size device (less than 1 cm) with photodiodes and LEDs on the same board side. We are also developing CMOS integrated photodiodes as the power harvesting solar cells.

Acknowledgements

This work was supported in part by JST, PRESTO (JPMJPR1689), Japan, and JSPS KAKENHI (JP15KK0209), Japan. The CMOS chips were designed with the support of the VLSI Design and Education Centre (VDEC), University of Tokyo, in collaboration with the Cadence Corporation and the Mentor Graphics Corporation.