A 179-lux Energy-Autonomous Fully-Encapsulated 17-mm^3 Sensor Node with Initial Charge Delay Circuit for Battery Protection

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Abstract

We propose a fully encapsulated 17-mm^3 sensor node with perpetual operation enabled by light harvesting with as little as 179 lux. A battery charging and management circuit is self-starting and supports rapid charging of the battery with a custom GaAs stacked photovoltaic cell. It delays charging until the assembly process is complete to protect the battery from exposure to high temperatures while charged and premature discharge prior to operation.

Introduction

Millimeter-scale sensor nodes are an attractive solution for biomedical and IoT applications [1-2]. However, initial charging of the battery after encapsulation of the sensor node poses significant challenges that are not fully addressed. Specifically, the systems must be entirely encapsulated with epoxy for physical protection, which poses two difficulties. 1) The sensor must charge wirelessly since no external connection is feasible after encapsulation for such a small form-factor system. This requires an efficient "self-starting" harvester that does not rely on initial battery charge. 2) Accidental charging during the assembly process must be prevented since a charged lithium battery is damaged by the high temperature required during encapsulant curing. In addition, since battery voltage should not drop below a minimum level, premature charging of the battery introduces the risk of inadvertent discharge before deployment, which also degrades the battery capacity. Hence, the battery should only be charged (and preferably charged rapidly) right before deployment.

Proposed System

To address these issues, we present a battery charging and management (BCM) circuit that performs rapid, self-starting charging of the battery, but delays this until the assembly process has been fully completed and the device is ready for deployment. The BCM circuit is implemented in a complete 3.9 × 1.7 × 1.6 mm^3 sensor node system with a 1.1 × 1.3 mm^2 integrated GaAs photovoltaic (PV) cell and a 1.7 × 3.6 mm^2 lithium battery. The GaAs PV cell consists of 8 electrically stacked PV diodes and directly connects to the battery through a diode, thereby avoiding the switching loss of a switch-capacitor DC-DC converter. To prevent premature battery charging, the BCM uses a novel delay circuit, which is tolerant to 7 V, which can be generated by the PV cell when not loaded by the battery. After charging, it permanently connects the PV cell to the battery while continuing to monitor the battery voltage to prevent battery overcharging. With its delay, the BCM enables visual inspection and the use of strong light by pattern-recognition based assembly equipment without charging the battery. After the delay period, the BCM circuit can complete initial charging of the 16 μAh battery in under 2 hours at 43 klux while perpetually sustaining sensor node operation under as little as 179 lux.

Fig. 1 shows the proposed mm-scale sensor node assembly process. Without the BCM circuit, the battery would be partially charged during the assembly process and damaged during high temperature cure. Further, unless the sensor is constantly stored in a lit environment, which is impractical, the battery charge will leak away, resulting in further battery damage. Measurements show that even initial charging of the battery to 2.7% degrades battery capacity by 40% and resistance by 4.3×, illustrating the need for BCM.

The proposed BCM circuit disconnects the battery from the energy harvester (PV cell + diode) with a battery switch controlled by an ~1.0-minute delay circuit, which resets each time light is removed between assembly steps. In addition, while the delay circuit is exposed to light itself, it resets, providing further protection before black epoxy is applied. After the initial charging time of ~2 hours, the BCM circuit permanently closes the battery switch, avoiding any charging delay in the future. The BCM then switches to monitoring the battery voltage to prevent battery damage by overcharging.

The BCM circuit consists of a PV cell, delay circuit and power management layer (Fig. 2). The PV cells (PV8) charge the battery through a reverse-current-blocking diode and the BCM switch. To prevent battery overcharge, the power management layer (Fig. 3) monitors the battery voltage (VBAT) and disables energy harvesting by pulling down one of the middle node of the stacked PV cells (PV6). PV8 is not directly pulled down since its voltage is too high for the thick oxide devices during charging with strong light.

Fig. 4 shows the charging delay circuit and battery switch. As the PV cell raises VDD under light, DLY_GEN switches S0F from low to high after a certain delay, and then SW_CTRL turns on the battery switch MS1 & MS2 by switching SF0 and SH0 to 0V. A key issue is the high output voltage (>7 V) that the PV cell can produce under strong light when it is not loaded by the battery, stressing the oxide of the BCM transistors. Hence, two transistors (MS1 & MS2) are used as a battery switch where SF0 is VDD in the off-state, and SH0 is VDD/2, reducing the worst case oxide stress to VDD/2. The DLY_GEN consists of a voltage regulator and delay generator, where the delay generator consists of two thyristor-configured transistor pairs (MP4+MN1 and MP3+MN2) that are stacked to generate a long delay with small leakage current. Once the thyristors are enabled they maintain their state, permanently enabling the battery switch.

To achieve constant delay in different light conditions, it is necessary to regulate the supply voltage of the thyristor in DLY_GEN. However, we also need full swing on S0F to VDD since VDD becomes low once the battery switch is turned on (since battery is uncharged). To meet these two goals, we propose a native transistor chain MN0-MN9 to provide a regulated VDDR voltage for the delay circuit. The 10 stacked transistors cover up to 9 V VDD (simulated) without stressing MN9. In addition, it regulates VDDR at 1.34 V for VDD from 2 to 9 V (simulated), making the delay time independent of light level. The proposed circuit also provides SF0 with a full-swing transition: when MP3 turns on and shorts VDDM and VDDR, Vgs of MN0 becomes 0 V, which then sets Vds and Vgs to 0 V for all other transistors in the chain in a ripple effect, thus raising S0F to VDD. A Light-Reset Diode discharges Cdly when the chip is exposed to light for extra protection. Two stacked transistors (MP1+MP2, MP5+MP6) and their self-body connection help reduce GIDL leakage by 36× at 4.1 V (simulated) when they are off.

Measurement Results

Fabricated in 180-nm CMOS the BCM was tested at circuit and system level. The initial battery charging delay was measured across PV8 for three chips, showing only 11.5% variation (Fig. 5). The power consumption measured across VBAT/PV8 voltages in different switch scenarios was <163 pA, which is acceptable in nW sensors (Fig. 6). The measured harvesting efficiency is >70%, even at low light (400 – 800 lux), which is higher than previous best reported efficiency [3] for <300 nW capable fully-integrated harvesters (Fig. 7). The overcharging protection circuit shows tight trigger voltage variation (0.36% σ/μ, measured) across 10 chips despite its low 428 pW power consumption (simulated). A complete system was fabricated (Fig. 8) and shows that at 4.1 V VBAT (the worst case), the system consumes 6.2 nA and can be energy autonomous even at 179 lux (dim indoor light level) due to the efficient harvesting approach (Fig. 9). To fully charge, the 16 μAh battery requires 2 hours at 43 klux, which shows the wide dynamic range (>600×) of the harvester (Fig. 10). Fully functional in its final integrated and encapsulated form, the BMC circuit was able to protect the battery during assembly in multiple assembly test runs.

References

[1] M. H. Nazari, *et al.*, VLSI, 2014. [2] G. Kim, *et al.*, VLSI, 2014.
[3] W. Jung, *et al.*, ISSCC, 2014.

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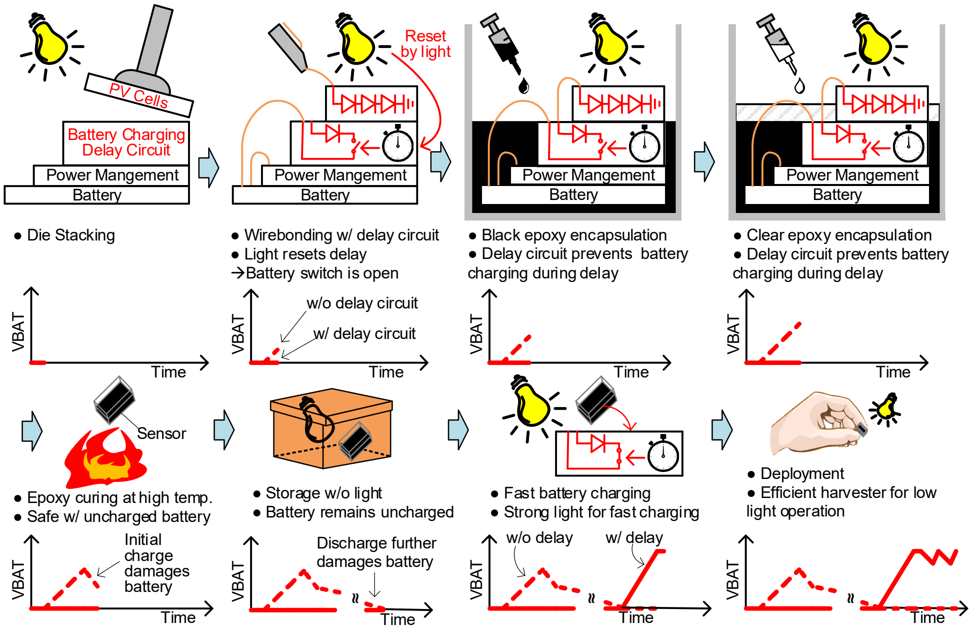


Figure 1. Millimeter-scale sensor node assembly process w/ or w/o the proposed circuit.

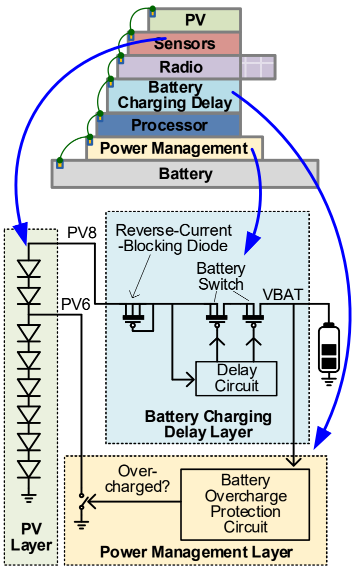


Figure 2. Proposed system diagram

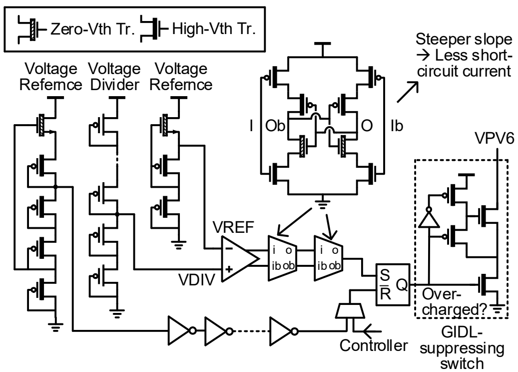


Figure 3. Battery Overcharge Protection Circuit.

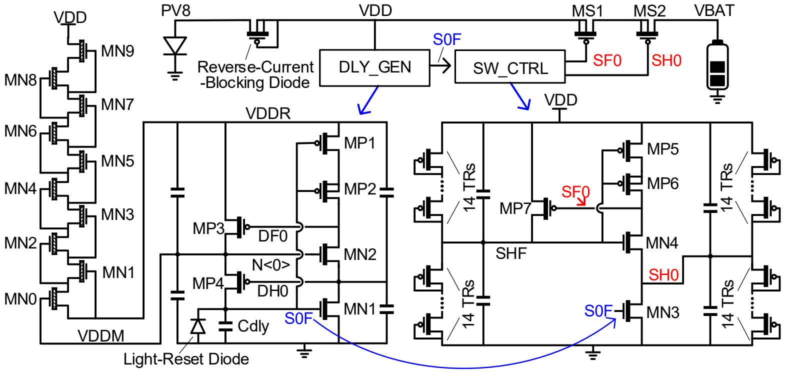


Figure 4. Battery Charging Delay Layer.

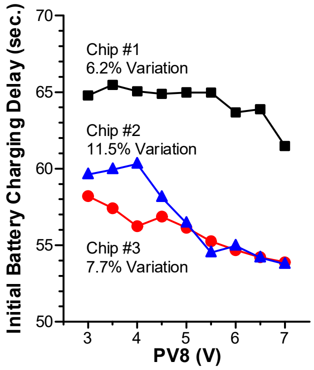


Figure 5. Measured battery charging delay.

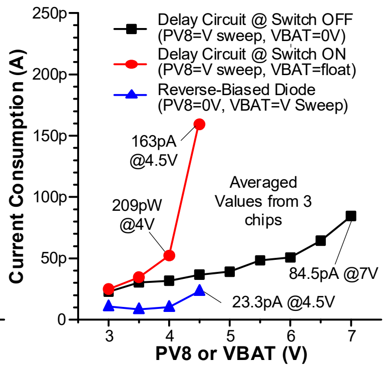


Figure 6. Measured current of battery charging delay layer.

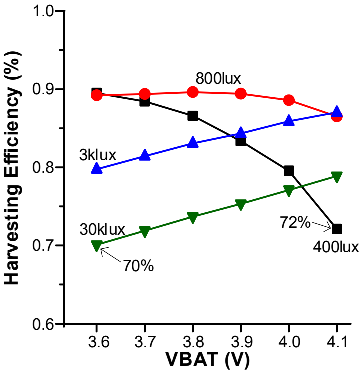


Figure 7. Measured harvesting efficiency

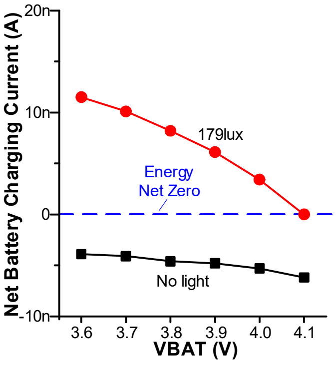


Figure 9. Measured battery charging current w/o light and w/ 179lux.

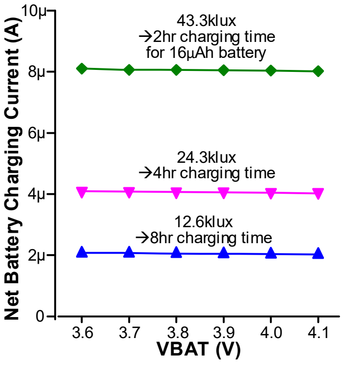
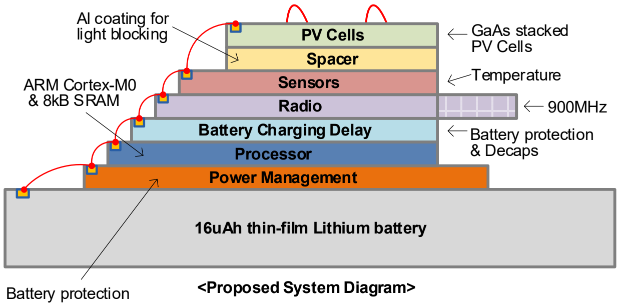


Figure 10. Measured battery charging current w/ >12klux light



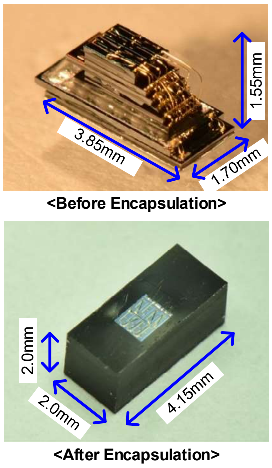


Figure 8. System diagram & photographs