An Energy Autonomous Light Intensity Sensor for Monarch Butterfly Migration Tracking

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***Abstract*—This paper proposes a light intensity sensing circuit for a millimeter-scale system that tracks monarch butterfly migration. The system targets to be mounted on a butterfly and record light intensity during its 3-month migration. From the recorded data, light-based localization technique finds sunrise/sunset times and thus its longitude and latitude per day. The proposed circuit contributes to light measurement of the system by enabling battery recharging, averaging light level for 1-minute sleep mode, and suppressing temperature sensitivity. A prototype system achieves energy autonomy at >300lx. A prototype circuit obtains a 3σ inaccuracy of ±1.78% and σ/μ of 2.7% from 10lx to 100klx, a temperature sensitivity of 0.035%/°C from -20 to 85°C, and a supply sensitivity of 1.08%/V from 3.6 to 4.2V.**

Keywords—light intensity, animal tracking, low power, energy harvesting

I. Introduction

Animal migration provides important biological and ecological data since their long travel uniquely covers broad regions and seasonal time scales. Tracking technologies enables us to access the data and find how migration works and how environments changes [1]. However, the existing tracking solution supports to study majority of their migration only for large animals due to limitations in mounted system size or weight. Long migration period increases required device physical size and weight due to significant energy for localization, large data storage size to keep the recorded data, and large transceivers for long-distance wireless communication. Thus, it is challenging to access the migration data of small animals including insects that takes a large portion of the entire animal migrators [2].

A monarch butterfly is the most popular insect migrator. Each fall, millions of monarchs migrate up to 4,000 km from northern US and Canada to central Mexico. In spring, they mate and remigrate northwards over 2 – 4 generations. Each butterfly completes only part of the round trip so that amazingly they accomplish the long travel without learning from the prior generation. Without a proper tracking tool, the migration has been studied by attaching paper barcodes to the monarch butterflies in northern US and recollecting them from fallen dead ones in Mexico, localizing only starting and ending points [3].

Recently, a light-based localization technique is proposed to track their migration course daily, using machine learning algorithm [4]. Basically, it finds longitude and latitude of a butterfly based on sunrise and sunset times, instead of using power-hungry GPS technique. To realize this approach in hardware, a miniaturized sensor should be mounted on a butterfly and measure light levels over the entire migration time (3 months). Among many others, three critical challenges must be overcome in light level recording: 1) a small battery itself cannot support the light recording operation for 3 months; 2) repetitive instant light-level sampling consumes large power; 3) leakage current of a photodiode increases temperature sensitivity.

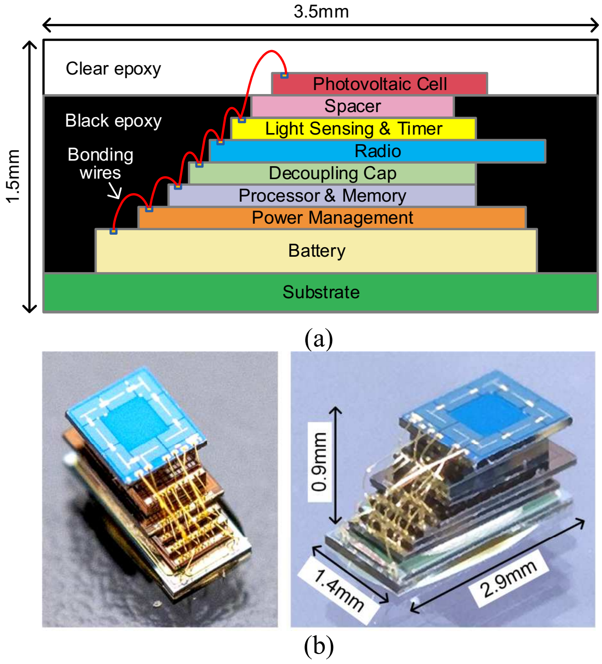

Fig. 1. Prototype of the proposed millimeter-scale light sensing system. (a) System diagram; (b) System photos before encapsulation.

To overcome the challenges, this paper proposes a light intensity sensing circuit that enables battery recharging, averages light level in low power, and cancels leakage current of a photodiode. Based on an light energy harvester and adaptive light sensing scheme, it achieves negative battery power consumption at >300lx and the average power consumption of -449nW from a 1-week lab test next to a window. The sensor continuously averages light measurement by integrating photocurrent without turning on other circuits in the system, saving 481× power (32.8μW vs. 68.2nW) at the maximum. Also, a replica photodiode, covered by metal, improves temperature sensitivity by 23% (0.035%/°C) from -20 to 85°C that a monarch butterfly experiences.

II. Proposed System Design

Fig. 1 shows the proposed millimeter-scale light sensing system. To minimize the system form factor, we employ the die-stacked platform [5] by stacking 8 small die to obtain a compact design, thinning each die to 100 μm thickness to reduce stack height, and using a custom designed chip-scale rechargeable battery that integrates in the same chip stack. The system includes photovoltaic (PV) cell layer, spacer layer, light sensing & timer layer, radio layer, decoupling capacitor layer, processor & memory layer, power management layer, and battery layer. They are connected by bonding wires for power delivery and communication. The top PV cell layer is covered by clear epoxy to expose the PV cells to light. The bottom layers are encapsulated with black epoxy to block light from reaching the sensitive electronics. The system is 3.5×1.5×2.0mm and 16mg, including epoxy for encapsulation.

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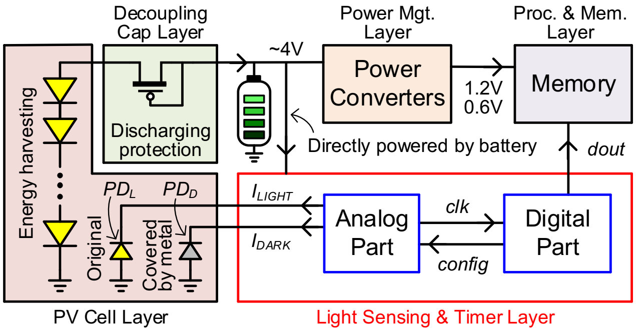


Fig. 2. Proposed light intensity sensing circuit.

The thin-film lithium battery powers the entire system by providing ~4V voltage to the power management unit, which efficiently converts the high voltage to 0.6V and 1.2V to protect standard CMOS circuits and perform given computation efficiently. The ultra-low-power processor (ARM Cortex-M0) executes the program stored in the ultra-low-leakage memory and controls the proposed light sensing circuit as programed, with a help of a ultra-low-power timer. The PV cell layer extends the system lifetime by connecting multiple PV cells in series and recharging the batteries using light while providing small cells for light level sensing. The layers communicate using a custom low-power bus protocol. The memory size (8kB) and radio communication range (<10cm) are severely limited to accomplish the goal of monarch butterfly migration tracking, but we focus on the light intensity recording in this paper.

III. Proposed Circuit Design

A conventional light level sensor measures light intensity by digitizing a photocurrent using a power hungry amplifier and an ADC. It typically consumes µW regardless of light level and obtains fast sampling speed (e.g., 2.6µW for 25ms [6]). However, this approach cannot be accepted since the target application requires to record light intensity continuously, and the significant power consumption discharges a small battery (e.g., 6µAh) in a few hours. Instead, we integrate photocurrent by averaging light intensity for a minute, which is found to be acceptable for the light-based localization algorithm [4]. The 1-minute averaging time enables the system to go to a microwatt active mode only for 150ms every minute, to transfer the output data to memory in a different layer, saving 353× power. Thus, the proposed light sensing circuit mainly operates in the nanowatt sleep mode. Also, it is designed to be directly powered by a battery since the power management unit cannot efficiently cover instantly varying photocurrent.

Fig. 2 shows the proposed light sensing circuit, located in the light sensing & timer layer (Fig. 1(a)), consisting of analog and digital parts. The analog part converts photocurrent (I_{LIGHT}) drawn by a photodiode (PD_L) of the PV cell layer to a pulse stream (*clk*), and then the digital circuit generates a digital code (*dout*) by counting it for constant time. For power saving, the digital block provides feedback signal (*config*) back to the analog circuit. *dout* is stored in memory of the processor & memory layer.

Fig. 3 shows the analog part. It charges a 101pF MIM capacitor (C_S) with capacitor charging current (I_{CAP}), proportional to the photocurrent (I_{LIGHT}). The ratio between I_{CAP} and I_{LIGHT} is set by a reconfigurable current mirror. I_{LIGHT} is sensitive to temperature since leakage current of a

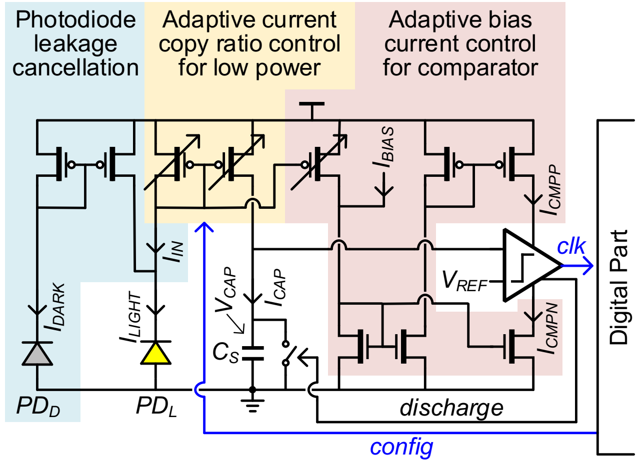


Fig. 3. Circuit diagram of the analog part.

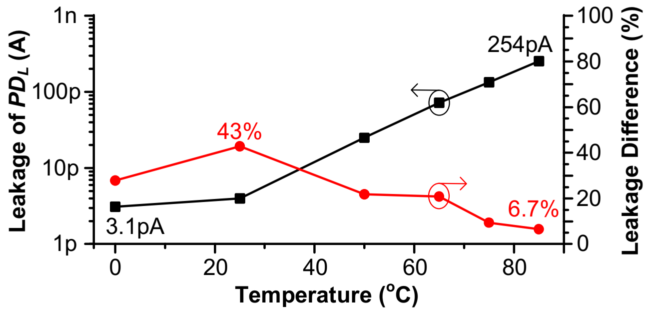
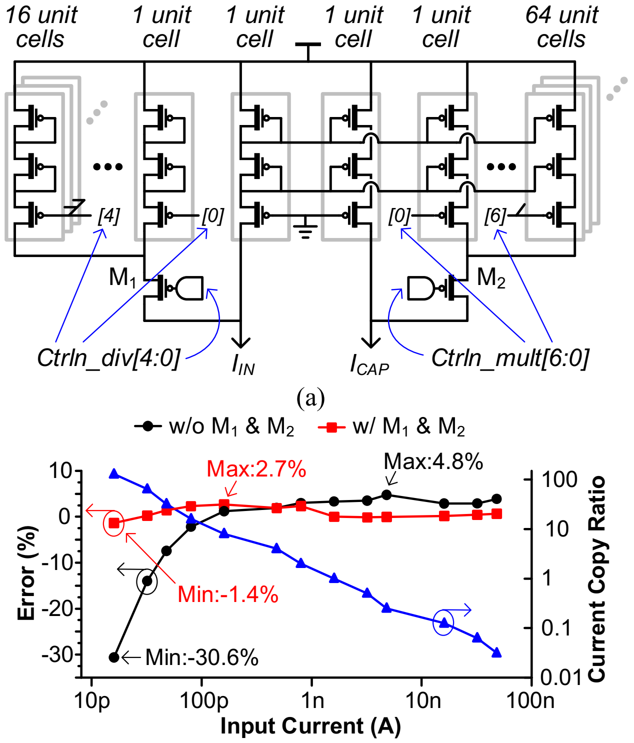


Fig. 4. Measured leakage current of the photodiodes (PD_L & PD_D) and their difference.

photodiode exponentially increases at higher temperature (Fig. 4). To improve the temperature sensitivity, we employ another photodiode (PD_D) on the same chip which has the same design with PD_L but covered by metal. PD_D draws the sum (I_{DARK}) of photocurrent lower than I_{LIGHT} (e.g., 10%) and similar leakage current. The proposed circuit subtracts I_{DARK} from I_{LIGHT} and cancels the leakage current. Fig. 4 shows an example where the proposed method can cancel the leakage of PD_L by 57 – 94%.

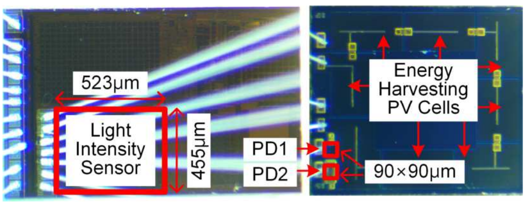
The copy ratio of the current mirror is reconfigured among 13 different values from 1/32 to 128 with 2× increase, generating I_{CAP} near 1.6nA for light from 1lx to 3klx. As the voltage of C_S (V_{CAP}) reaches a reference voltage (V_{REF}, [7]), a comparator discharges C_S to ground, repeatedly generating pulses. The output frequency is proportional to I_{CAP}. By suppressing the range of I_{CAP} and thus the output pulse frequency, current consumption is saved at strong light levels (e.g., 50% power reduction at >3klx). The comparator (in Fig. 3) is also adaptively powered by current (I_{CMPP} & I_{CMPN}) proportional to I_{CAP} in addition to default I_{BIAS} of 100pA since it requires faster response time for faster charging speed of C_S.

Fig. 5(a) shows the detailed current mirror based on unit cells for better matching. The unit cell includes two stacked PFETs as a current mirror for the high battery voltage and a switch to control the current copy ratio. It employs additional switches at the bottom (M_1 and M_2) to suppress leakage current. In a weak light condition, only one default unit cell on the left is turned on while the others are turned off by the switches in the unit cells. However, the leakage current through each unit cell (e.g., 160fA) is not negligible, compared with the low input current (e.g., 16pA). The additional switch (M_1) further suppresses the leakage current (e.g., 20.3× reduction to 7.9fA). M_2 plays the same role for the



(b)

Fig. 5. Reconfigurable current mirror for adaptive low-power operation. (a) Circuit diagram; (b) Simulated current copy error at FF and 85°C.



(a) (b)

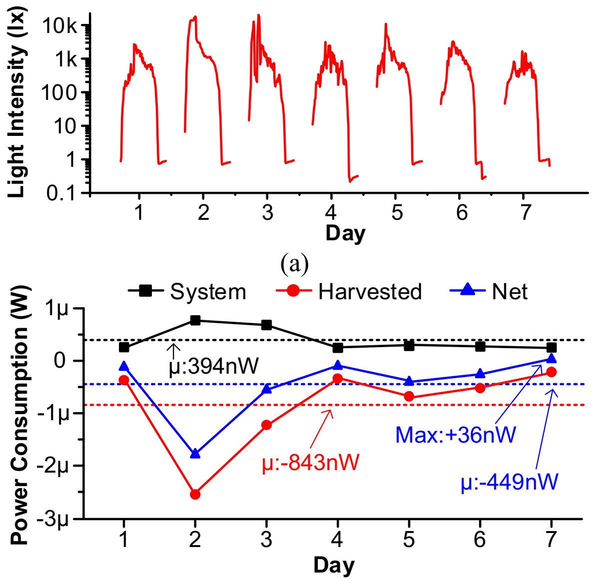
Fig. 6. Chip photograph. (a) Light sensing & timer layer; (b) PV cell layer.

strong light condition. Fig. 5(b) shows simulation results at the worst-case (FF & 85°C). As the input current increases by 3,000×, the current copy ratio is reconfigured from 128 to 1/32. The design without M_1 and M_2 suffers from large current copy error, especially at low input current level (-30.6% at 16pA). The proposed circuit with M_1 and M_2 reduces the error by 8.6× from 35.4% to 4.1% (Max – Min).

The reconfigurable current copy ratio saves power but makes the frequency of *clk* not proportional to I_{LIGHT}. The digital circuit (Fig. 2) compensates the mismatches by shifting the accumulation point and current copy ratio simultaneously when converting *clk* to *dout* [8].

IV. Measurement Results

The proposed light intensity sensing circuit is fabricated in a 180nm CMOS process and tested with the custom PV cells (Fig. 6). As a layer of the complete system, the sensor circuit is integrated with a custom bus controller and a low-power timer. The PV cell layer consists of 8 PV large cells connected in series for energy harvesting [8] and 2 small PV cells for light sensing. The prototype millimeter-scale system (Fig. 1) is manufactured, including the proposed light level sensing chip, and several access points are added to observe power consumption. The system is placed next to a window and



(b)

Fig. 7. Measured light intensity recording system for 1 week next to a window. (a) Light intensity; (b) Average power per day.

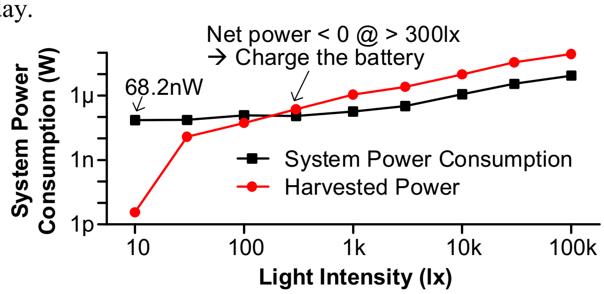
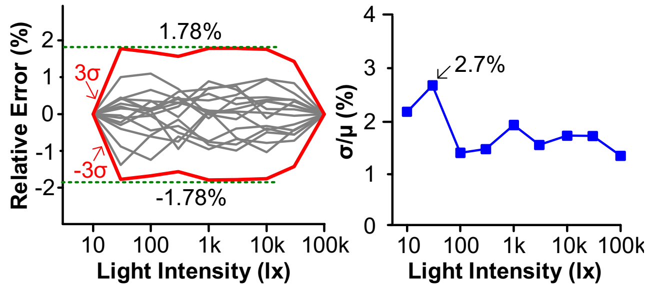


Fig. 8. Measured system power across light intensities.

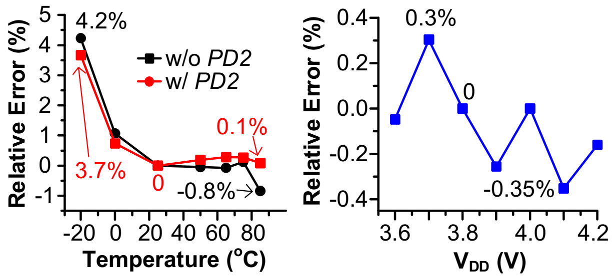


(a) (b)

Fig. 9. Measured accuracy with 5s measurement time. (a) Relative error across light intensities after 2-point & batch calibration across from 15 samples; (b) σ/μ.

records natural light intensity every minute for a week. It is programmed to not go to the active mode from 10pm to 4am for power saving since natural light level during the time is not useful for localization. Fig. 7(a) shows the 1-week-long light profile after calibration, and Fig. 7(b) shows its energy autonomous operation with the average negative battery power consumption of -449nW. The average daily battery power consumption is positive on the 7th day (very cloudy), but the loss (227nAh) discharges the target battery (6μAh) only by 3.8%. Fig. 8 depicts that the system can be energy autonomous at light levels stronger than 300lx, which is weaker than a typical outdoor daylight level (1klx – 25klx).

15 samples of the proposed circuit are tested. Fig. 9 shows the 3σ inaccuracy of ±1.78% and σ/μ of 2.7% for a wide range of light levels from 10lx to 100klx. The measurement time is reduced to 5s to accelerate the testing and also to be fairly



(a) (b)

Fig. 10. Measured sensitivity. (a) Temperature; (b) V_{DD}.

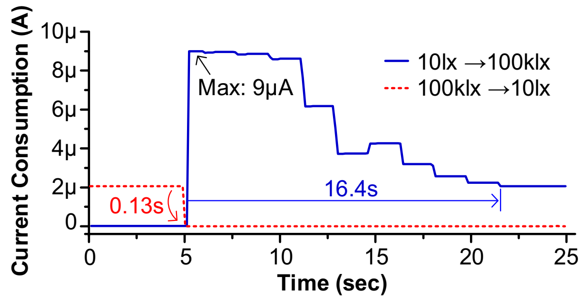
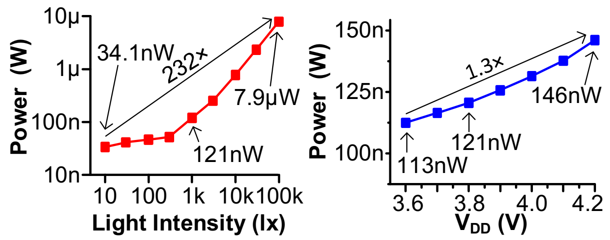


Fig. 11. Measured adaptive reconfiguration for low power.



(a) (b)

Fig. 12. Measured power consumption of the light level sensing circuit. (a) Across light intensities; (b) Across V_{DD}.

compared with [8]. Longer measurement time improves σ/µ. The maximum light intensity of 100klx well covers the maximum light intensity that a monarch butterfly experiences. Fig. 10 shows that the proposed photodiode leakage cancellation improves the temperature sensitivity by 1.4× (0.047 to 0.036%/°C) from -20 to 85°C, with a supply sensitivity of 1.08%/V from 3.6 to 4.2V. The temperature range sufficiently covers the target application, while the supply voltage range is the typical operating voltage of the target thin-film Lithium battery. Fig. 11 depicts how the adaptive control on the current copy ratio reduces the power consumption over time. Fig. 12 shows the power consumption across light intensities and supply voltages. The photocurrent changes by 10^4× as light intensity changes from 10lx to 100klx, but the adaptive current mirror limits the power increase only to 232× (43× lower increase).

Table I compares the proposed system/circuit with the state-of-the-art light intensity sensors consuming power less than 5µW. This work shows the minimum 3σ in accuracy (2.1× lower than [8]) and competitive σ/µ, covering natural light range for the target application. It becomes energy autonomous supported by the light energy harvester that compensates the increased circuit power consumption under strong light, requiring 40% weaker light intensity than [8] for zero net power. This work achieves the best stability against temperature and supply voltage variation, with significantly simpler design than [8] that uses complex feedbacks with amplifiers. [6] and [10] reports the fastest measurement time and lowest σ/µ, respectively, but they consumes µW regardless of light level, which can discharge a small battery in several hours (e.g., 6 hours for the target 6µAh battery) at weak light condition.

Table I. Performance summary and comparison with the state-of-the-art light level sensors consuming power <5µW.

	This Work	[6] ISSCC'19	[8] VLSI'19	[9] ISSCC'17	[10] JSSC'14
Process (nm)	180	180	N/A	180	180
3σ Inaccuracy (%)	3.6 @10 – 100klx	N/A	7.6 @10 – 300klx	N/A	N/A
σ/µ @ T_{MEAS}	2.7% @ 5s	N/A @ 25ms	2.4% @ 5s	2.8% @ 7.5s	0.45% @ N/A
Min. Light Level for P_{SYSTEM} < 0	300lx	N/A	500lx	N/A	N/A
Circuit Power (W)	34.1n – 7.9µ	2.63µ	35.3n – 339n	550p	4µ
Temp. Sen. (%/°C)	0.035 @1klx	N/A	0.036 @1klx	0.065 @ 500lx*	N/A
Supply Sen. (%/V)	1.08	N/A	1.15	N/A	N/A
System Size	3.7	N/A	10.1	N/A	N/A

* w/o PV cell. ** w/o epoxy.

V. Conclusion

This paper proposes a light intensity sensing circuit for a miniaturized system that tracks monarch butterfly migration. It contributes to light measurement of the system by enabling battery recharging, averaging light level for 1-minute sleep mode, and suppressing temperature sensitivity. A prototype becomes energy autonomous at >300lx. It achieves a 3σ inaccuracy of 3.6% and σ/µ of 2.7% from 10lx to 100klx, a temperature sensitivity of 0.035%/°C from -20 to 85°C, and a supply sensitivity of 1.08%/V from 3.6 to 4.2V.

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