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Article

A Self-Contained Startup Charging Circuit for Energy Harvesting Batteryless IoT Devices

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Abstract

This paper presents a self-contained startup charging circuit designed for energy harvesting batteryless IoT devices. The proposed circuit consists of a current biasing block, a current mirror, a reference voltage generator, and a comparator circuit. The current biasing circuit drives the current mirror, which supplies the charging current to the energy storage element. Simultaneously, the reference voltage generator—also biased by the current source produces a stable DC reference voltage. When the energy storage device (e.g., a supercapacitor) lacks sufficient charge, the comparator enables the charging path by activating the current biasing and mirror circuits. Once adequate energy is stored, the comparator disables these circuits to prevent overcharging. This self-contained solution is intended to autonomously initialize and manage the cold-start charging process in energy harvesting systems without relying on external controllers.

Keywords: startup charging circuit; self-contained charger; energy harvesting; batteryless IoT devices

Introduction

In batteryless Internet of Things (IoT) devices, energy harvesting systems rely heavily on supercapacitors as energy storage elements due to their high power density, rapid charging capability, and long cycle life [1–4]. However, efficiently charging supercapacitors, especially during cold-start conditions when the device has no pre-existing energy, remains a significant design challenge.

The charging circuit must operate reliably with low input power, avoid the need for external controllers, and ensure seamless startup across varying environmental conditions.

Moreover, the charging circuit plays a critical role in the entire system's operation it determines how quickly and efficiently the IoT node can become active, respond to sensed data, and maintain energy autonomy [5–8]. Any inefficiency or dependence on external control can compromise system performance, especially in intermittent or unpredictable energy environments. Therefore, developing a robust and efficient charging circuit that is self-starting and self-contained is essential to enabling practical and scalable deployment of batteryless IoT solutions.

In most existing designs, the charging circuit requires an external current source and reference voltage to operate effectively [9]. This paper presents a self-contained charging circuit with internal means for generating both the bias current and reference voltage. This design eliminates the need for external control elements, enabling autonomous startup and improving energy efficiency for batteryless IoT applications.

The paper [10–14] discloses a device with an external nano-watt bandgap voltage reference circuit with six-stage PTAT voltage generator where the stages, each equipped with a differential pair and current mirror, are cascaded in such a way that produces sufficient positive temperature coefficients. The disclosure also provides a separate nano- ampere current reference circuit that serves as the current source for the charging circuit. Crucially, such use of external current source and voltage reference circuit results in a complex circuit design that requires a substantial physical area when manufactured.

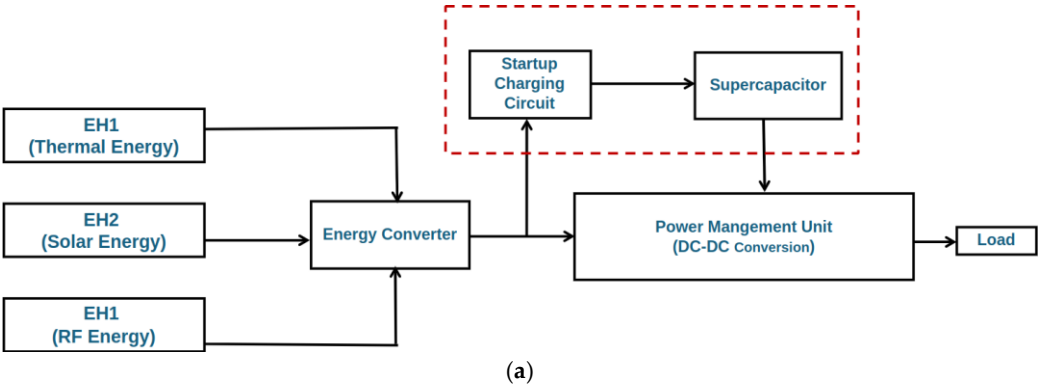
The works presented in [15,16] describe a startup circuit that (i) forces an arbitrary bias-generating circuit into a steady-current state during startup by conducting charging current from an external current source, and (ii) disconnects the external source afterward using switching means. When such an approach is adapted to charging circuits for energy storage devices, it inherits key design limitations—most notably, the dependence on an external current source.

In contrast, the circuit proposed in this work is self- contained, integrating all essential functions—biasing, voltage reference generation, and switching control into a single autonomous block. This design simplifies system integration and enables reliable cold-start operation in batteryless IoT systems. The objective of this paper is to address and overcome the limitations of previous approaches by eliminating the need for external control elements.

The rest of this paper is organized as follows. Section 2 presents the design and architecture of the proposed self-contained charging circuit. Section 3 discusses the simulation results, including corner and Monte Carlo analyses, validating the circuit’s performance under various operating conditions. Section 4 details the post-simulation evaluation and actual chip measurement results. Finally, Section 5 concludes the paper by summarizing the key contributions and highlighting the advantages of the proposed design for energy harvesting applications.

Proposed Charging Circuit

Figure 1 illustrates the role and architecture of the proposed self-contained charging circuit within an energy harvesting system. Figure 1a shows a system-level diagram where multiple energy sources (thermal, solar, RF) are funneled through an energy converter to power a load. The proposed startup charging circuit is used to charge a supercapacitor, providing a reliable energy buffer for cold-start conditions [17].



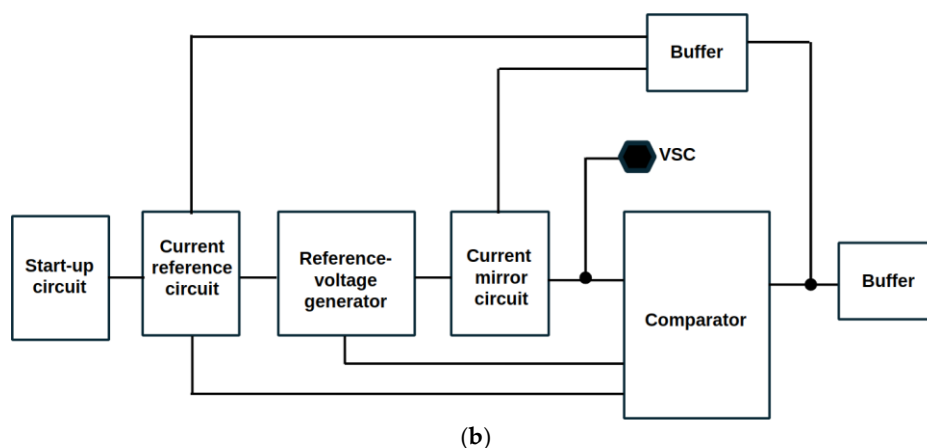


Figure 1. (a) System-level diagram of an energy harvesting application incorporating the proposed startup charging circuit to charge a supercapacitor [17]. (b) Block diagram of the proposed self-contained charging circuit, showing its main functional components including the startup circuit, internal biasing, reference generation, current mirror, comparator, and output buffer.

Figure 1b presents the internal block diagram of the proposed charging circuit. Unlike conventional designs, this implementation integrates all critical functions—startup circuit, current biasing, reference voltage generation, current mirror, comparator, and output buffer into a single autonomous module. This self-contained architecture enables reliable cold-start operation without the need for external biasing or reference inputs, thereby enhancing integration and suitability for batteryless IoT applications.

Previous startup charging circuits, such as those presented in [10], typically rely on external components such as a high-voltage pump (V_{pump}), a fixed reference voltage (V_{ref}), and external bias sources to enable operation. These dependencies pose critical limitations in energy harvesting applications particularly during cold-start conditions where no external energy sources are guaranteed at startup.

In contrast, the circuit proposed in this work is fully self-contained, integrating internal current biasing, voltage reference generation, and comparator control into a single autonomous block. This architecture eliminates the need for any external startup assistance, thereby enabling reliable cold-start operation and simplifying system integration in batteryless IoT devices. The self-contained design directly addresses the key challenges of energy-autonomous systems by ensuring that all essential charging functions are internally generated and managed.

Figure 2b shows the simplified schematic of the proposed charging circuit. The start-up circuit transistors are labelled by SU1, SU2 and SU3 which provides initial bias to the current biasing circuit through the gate of SU2 and the drain of SU3. The current biasing circuit generates the current reference for the entire block. The fixed DC reference voltage generated at the reference voltage is fed to the comparator circuit.

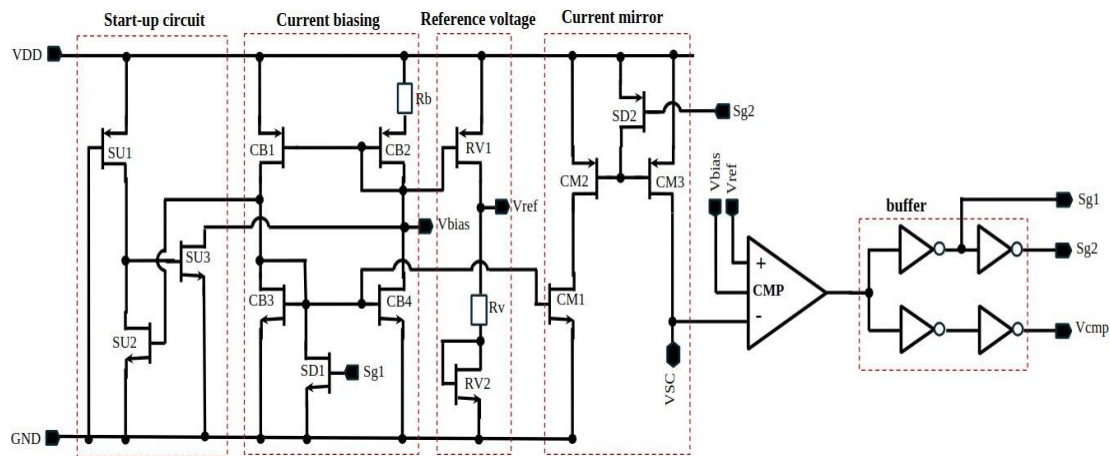


Figure 2. The proposed self-contained charging circuit for energy-harvesting batteryless IoT devices.

Resistor R_v and transistor $RV2$ are configured to serve as PTAT and CTAT generators, respectively, such that the voltage V_{ref} is temperature-insensitive. R_v and $RV2$ are scaled in size and parameters so that their linear temperature coefficients are equal in magnitude and opposite in sign. Such configuration of the reference voltage generator enables the charging circuit of this paper to forego other components (such as six-stage PTAT voltage generator, as in the prior art) and consequently minimize the layout area.

The current mirror circuit receives current from the current biasing circuit through $CM1$, mirroring to $CM3$ and generates charging current at the V_{sc} terminal.

Under normal operation, the current biasing circuit generates a constant current which translates to a bias voltage at V_{bias} . Transistor $CM1$ then mirrors the drain current at $CB3$ through V_{bias} . Similarly, the drain current at $CM1$ is mirrored to $CM2$ and $CM3$.

When charging the energy storage device, the drain voltage at $CM3$ or the voltage V_{sc} of the energy storage device ramps up from zero (i.e., at zero charge) to the reference voltage V_{ref} (i.e., at sufficiently high or full charge). When the energy storage is fully charged that its voltage V_{sc} surpasses the reference voltage V_{ref} , the comparator circuit outputs a signal that activates the shutdown transistors ($SD1$ and $SD2$) and pulls the gates of $CM3$ and $CM2$, this disabling the entire charging circuit into a standby state. The charging circuit is now uncoupled from the energy storage device and will stop the charging current. The charging circuit remains disabled until the voltage V_{sc} of the energy storage device is less than the reference voltage V_{ref} .

In this paper, the reference voltage achieves a value of 700mV with minimal swing under varying process parameters, supply voltage, and operating temperature. It is designed to operate at a supply voltage ranging from 900mV to 1.9V and an operating temperature ranging from -40°C to 85°C . The charging current reaches 31.21mA considering the worst case slow-slow corner simulation. The proposed charging circuit is implemented using the 22nm fully depleted silicon-on-insulator (FDSOI) technology and is integrated into a working energy storage harvesting system.

Simulation Results and Discussion

Circuit simulation was performed to verify the performance of the design while considering the target specification shown in Table 1. As part of the requirements, the design should operate in AV_{DD} minimum voltage of 0.9V and up to the maximum supply voltage of 1.8V. The charging current across Supercapacitor (SC) is expected to be from 1mA to 50mA including worst case conditions. Supercapacitor voltage (V_{sc}) full charge should be from 700mV to 900mV.

Table 1. Target specification of proposed charging circuit.

Parameters	Symbol	Minimum	Typical	Maximum	Unit
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Supply Voltage	AVDD	0.9	—	1.8	V
SC Charge Current	iCharge	1	20	50	mA
Reference Voltage	V _{ref}	0.7	0.75	0.8	V
Supercapacitor Voltage	V _{SC}	0.6	0.7	0.8	V

Corner Simulation Results

Using block simulation setup, behavior of charging circuit is tested. At typical simulation, transient analysis ran from 0s to 5000s, 25°C and nominal model. Figure 3 shows the typical simulation waveform plot of V_{sc}, V_{comp}, and the charging current showing meeting the target specifications.

As shown in Figure 3, the full battery voltage is measured at the stable state of V_{sc} pin, which is also connected to the supercapacitor, after the ramp up or the charging time. The V_{comp} signal is “high” at the beginning of the ramp and toggles to “low” after it detects the battery full in the V_{sc} pin, where the V_{sc} voltage surpasses the V_{ref} voltage at the comparator.

The block is also tested for maximum VDD of 1.8V and typical conditions for temperature and process parameters. Figure 4 shows the resulting graph for these conditions.

Further verification through corner simulation was performed to confirm the functionality of the proposed charger block. Table 2 presents the tabular data summarizing the 136 results of corner simulation.

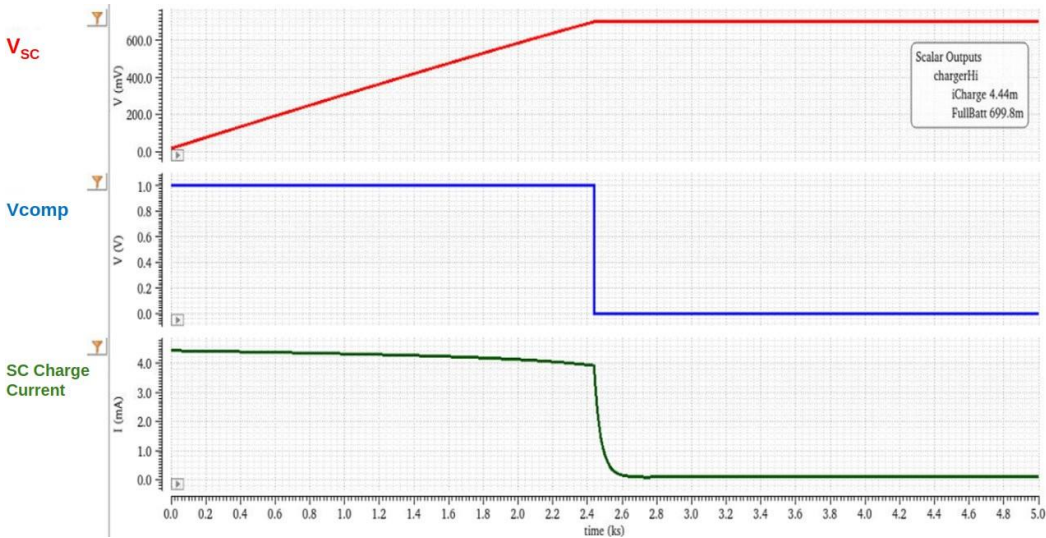


Figure 3. Typical simulation results for VDD=1.0V.

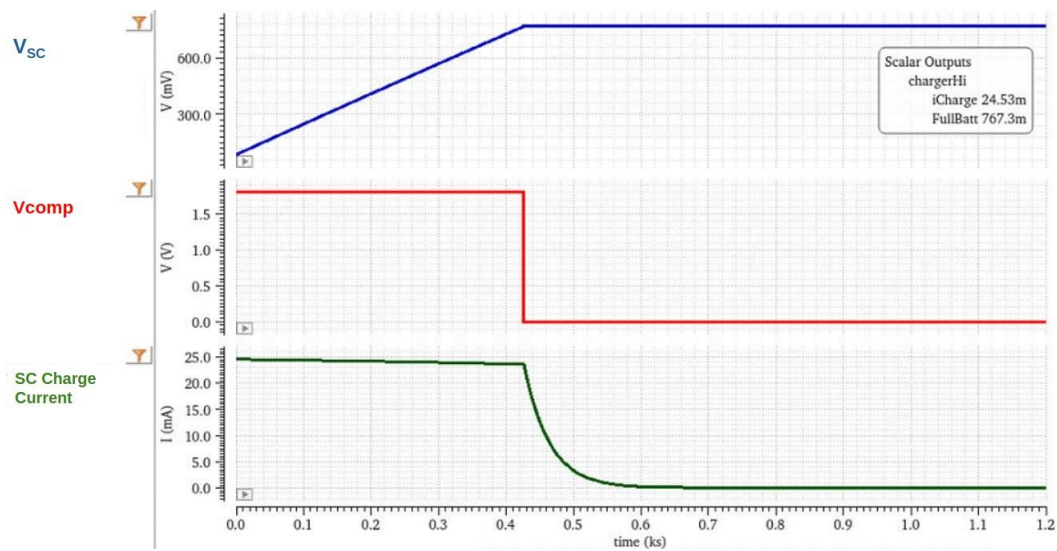


Figure 4. Typical simulation results for VDD=1.8V.

Table 2. Corner Simulation Results.

Parameters	For $V_{DD} = 1.0\text{ V}$			For $V_{DD} = 1.8\text{ V}$			Unit
	Min	Typ	Max	Min	Typ	Max	
SC Charge Current	3.16	3.98	4.78	18.75	23.21	27.81	mA
SC Voltage	0.576	0.700	0.809	0.639	0.765	0.890	V

Corner simulations were tested using three temperature variations (−40°C, 25°C and 85°C), different model variations (slow, typical, fast) and two levels of VDD (1.0V and 1.8V). All results are passed and within the target specifications, no abnormal response was observed.

Monte Carlo Simulation Results

To validate the robustness of the proposed charging circuit design, Monte Carlo simulation was executed. The simulation was done under minimum and maximum condition of temperature (−40°C and 85°C), two VDD values (1.0V and 1.8V), sampling of 200 runs, and using mismatch variation option. Table 3 summarizes the Monte Carlo simulation results separated by the VDD value. All results are within the target specifications.

Table 3. Statistical summary of Monte Carlo Simulation Results under under different VDD conditions.

Parameters	Min	Max	Mean	Median	Std Dev	Unit
For $V_{DD} = 1.0\text{V}$						
SC Charge Current	3.79	4.04	3.91	3.90	0.65	mA
SC Voltage	0.571	0.717	0.642	0.638	0.57	V
For $V_{DD} = 1.8\text{V}$						
SC Charge Current	23.02	25.70	24.35	24.34	1.15	mA
SC Voltage	0.751	0.889	0.822	0.821	0.057	V

Evaluation Results and Post Simulation

Performance Comparison

Table 4 presents a comparative analysis of the proposed self-contained charging circuit against the state-of-the-art energy harvesting solutions. Unlike traditional designs that rely heavily on charge pumps or complex multi-stage rectification, this work demonstrates a self-contained charging topology capable of delivering a significantly higher output current of 25mA, with a modest output voltage of 0.7V–0.8V, making it well-suited for low-voltage supercapacitor charging in batteryless IoT systems. Prior works, such as those in [6,10], and [11], exhibit lower current outputs ranging from 10μA to 395μA, primarily due to limitations imposed by their charge pump-based or rectifier-based architectures. Moreover, while earlier studies used older CMOS technologies (down to 0.18μm), this work achieves its performance on a 22nm FDSOI process, emphasizing its scalability and integration potential. The results validate the effectiveness of a fully self-contained circuit in delivering 160 high current without relying on auxiliary power stages or external control logic.

Table 4. Comparison of the Proposed Circuit with Published Works.

Work	Input Voltage	Output Voltage	Output Current	Power Conversion Topology	Technology
[6]	0.18V	0.74V	10uA	Charge-pump with boost converter	65 nm CMOS
[10]	0.55V	1.26V	310uA	DTCMOS Differential-drive two-stage charge pump	0.18 μm CMOS
[11]	0.5V	1.3V	395uA	Differential-drive multistage rectifier	0.18 μm CMOS
[16]	5V	4.2V	700mA	Dual-mode integrated charge-pump charger	0.18 μm CMOS
This work	1V - 1.8V	0.7 - 0.8V	25mA	Self-Contained Charging Topology	22 nm FDSOI

Post Simulation Results

The functionality of the charging circuit was evaluated under different temperature variations, VDD, and using 5 samples. Since the proposed design is a stand-alone block, the setup is simplified and tested activating the charging circuit only by supplying VDD. Figure 5 shows the evaluation results or actual chip testing of chips 6 to 10, labelled C6 to C10 in the graph, and post simulation at 25°C. As shown in the figure, there is no significant difference observed comparing post simulation and the measurement of the 5 samples tested.

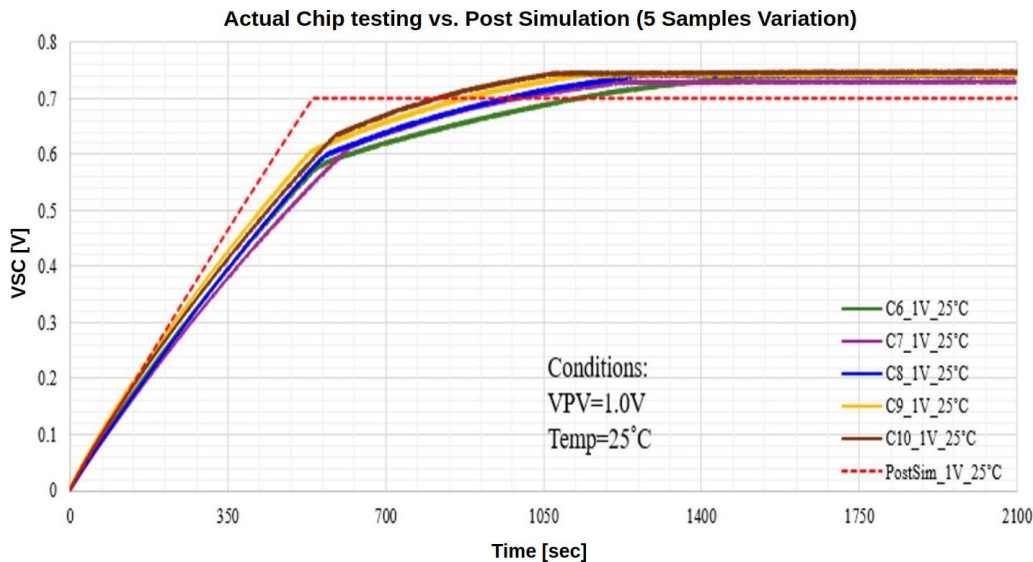


Figure 5. Supercapacitor voltage (VSC) measurement. Actual chip testing of 5 samples comparing with post simulation at 25°C.

Figure 6 shows the comparison between actual chip testing and post simulation results across -35°C, 25°C, and 100°C. As observed, the simulated output slightly overestimates the measured V_{sc} , but the temperature trend is consistent, confirming reliable behavior under varying thermal conditions.

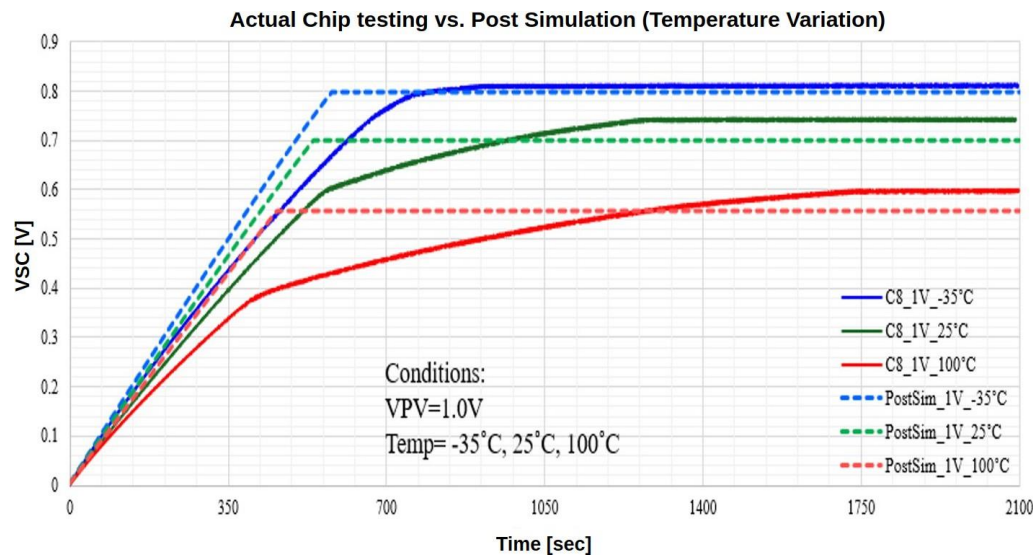


Figure 6. Supercapacitor voltage (VSC) measurement. Actual chip testing of Chip8 compared with post simulation in three temperatures.

Chip Layout and Implementation

Figure 7a shows the layout of the charging core, designed and implemented in 22nm FDSOI technology. It highlights the transistor-level design of key components such as power switches, capacitors, and control circuitry, all optimized for efficient energy transfer. Figure 7b presents the full-chip layout, with the entire energy harvesting system—including the charging circuit occupying a total area of 1000um x 400um. The design is intended for packaging in a QFN40 (5mm x 5mm) package. This layout illustrates the system-level integration of the proposed charging circuit, including its connections to power management, energy storage, and control blocks, with routing carefully optimized to minimize parasitic losses. Figure 7c shows the chip die micrograph, illustrating the fabricated silicon layout of the charging circuit with visible pad placements and key functional blocks. Finally, Figure 7d Testing set-up with DC Power Analyzer and Thermal Chamber for performance validation and measurement.

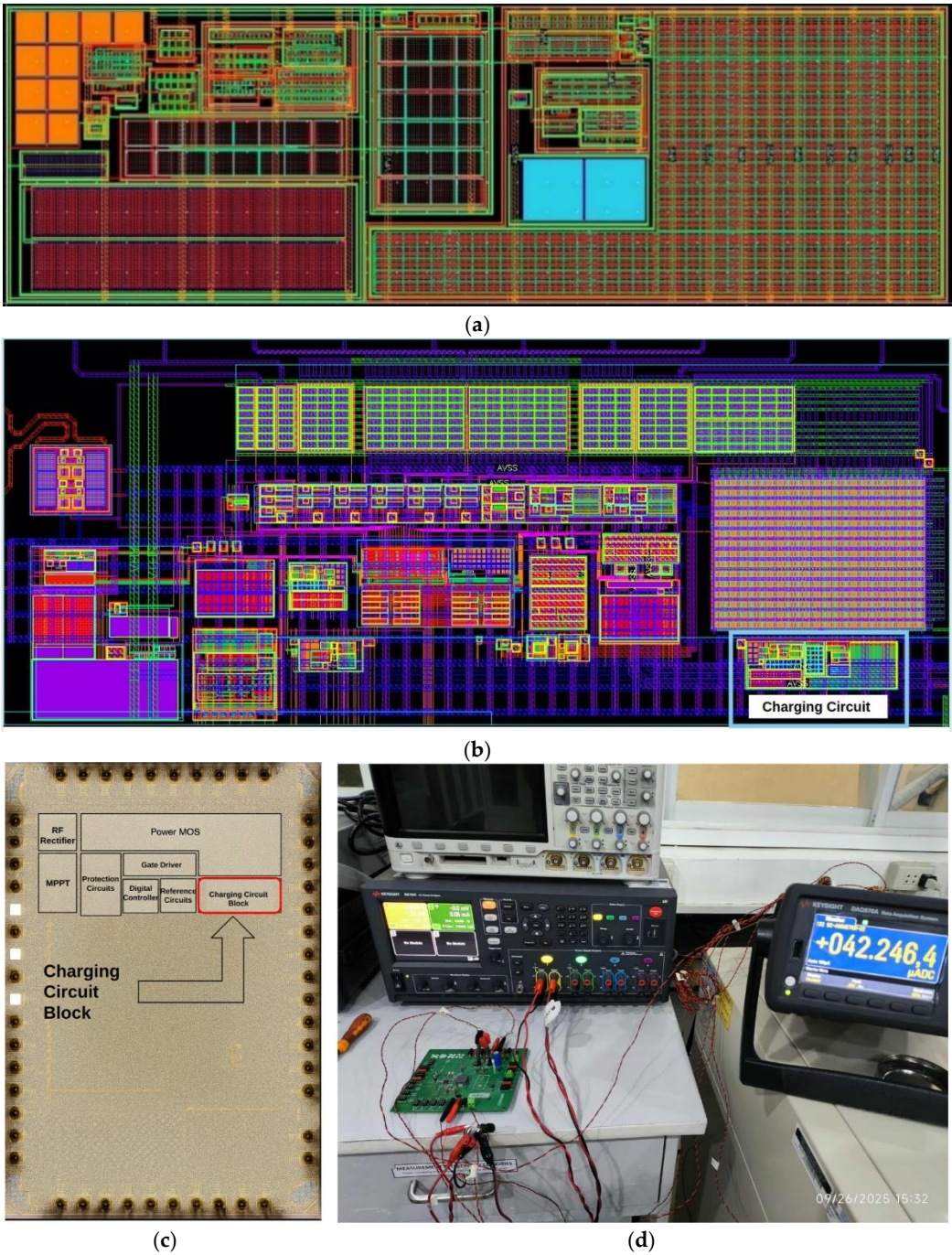


Figure 7. Chip layout and implementation: (a) Charging core layout (b) Full-chip layout of the energy harvesting system with integrated charging circuit (c) Chip Die Micrograph (d) Testing set-up with DC Power Analyzer and Thermal Chamber.

Conclusions

This paper presented a self-contained charging circuit designed for energy harvesting systems. The proposed design eliminates the need for external current and voltage references by integrating a current biasing circuit and a temperature-insensitive reference voltage generator. A simplified yet effective control mechanism using a comparator circuit enables autonomous switching between active charging and standby states, optimizing energy usage.

Simulation results, including typical, corner, and Monte Carlo analyses, confirm the circuit's robustness across a wide range of process, voltage, and temperature variations. The charging current meets the target specifications, and the reference voltage remains stable across operating conditions. Furthermore, post-layout and actual chip testing show strong agreement with simulation results, validating the design's functionality and reliability in a fabricated silicon implementation.

Overall, the proposed charging circuit demonstrates high efficiency, compactness, and suitability for integration into low-power energy harvesting applications, such as systems utilizing supercapacitors for energy storage.

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