MEMS–PMU Co-Simulation of an Electrostatic Energy Harvesting Interface for Battery-Free IoT Devices

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***Abstract*—Battery-free Internet-of-Things (IoT) nodes are essential for long-term sensing where battery replacement is impractical. This work presents a fully autonomous IoT platform monolithically integrated in 180nm CMOS/MEMS processes. The system features an in-plane electrostatic MEMS vibration harvester utilizing a photodiode charging system for initial startup. An interface circuit, based on a Bennet's doubler and consisting of MOSFET-based active diodes, efficiently transfers harvested energy, demonstrating up to a 183% efficiency improvement over passive alternatives. The energy is then processed by a power management unit (PMU) featuring two-dimensional maximum power point tracking (2D-MPPT) and a serial-stacked single-inductor multi-input multi-output (SS-SIMIMO) power stage. The PMU maintains stable 0.8V and 1.2V supply rails with a peak power conversion efficiency (PCE) of 88.8% and a tracking accuracy of 98%. System-level co-simulations validate the feasibility of the integrated architecture for self-sustainable sensing applications.**

***Keywords*—Battery-free, IoT, Electrostatic Energy Harvesting**

I. Introduction

The deployment of distributed Internet-of-Things (IoT) sensing nodes in applications like environmental and structural monitoring often makes battery replacement costly and impractical. Energy harvesting offers a maintenance-free alternative. Among the available technologies, vibration-based electrostatic MEMS harvesters are highly advantageous due to their amenability to miniaturization and their ability to be monolithically integrated using CMOS-compatible processes. However, the energy generated is extremely small and highly variable, posing significant challenges for energy extraction and steady system operation.

II. System Architecture

To address these challenges, this work presents a fully autonomous, battery-free IoT platform fabricated using the UMC 0.18-μm CMOS/MEMS process. The platform consists of three primary components: an electrostatic MEMS energy harvester, a Bennet's doubler-based energy interface, and a highly specialized Power Management Unit (PMU). To compensate for the unpredictable nature of ambient vibrations, the system incorporates a dual-source topology, utilizing an RF energy harvester as a secondary backup source.

III. MEMS Harvester and Interface Circuit

The energy transducer is an in-plane comb-drive MEMS harvester designed to mitigate failure risks like the pull-in effect and minimize air damping. A major challenge in standard CMOS/MEMS integration is the lack of support for conventional electret layers used for initial electrical biasing. To overcome this, the design introduces a novel on-chip photodiode charging system that generates a photocurrent upon illumination to provide the necessary initial bias charge. To efficiently rectify and boost the harvested charge, the interface circuit utilizes a Bennet's doubler equipped with MOSFET-based active diodes. This active diode configuration demonstrates an efficiency improvement of up to 183% over traditional passive alternatives.

IV. Power Management Circuit

The PMU acts as the central hub, utilizing a 3-input (MEMS, RF, and recycled energy from a storage capacitor C_{STO}) and 3-output architecture (V_{OUT1}, V_{OUT2}, and C_{STO} charging). It features a serial-stacked single-inductor multi-input multi-output (SS-SIMIMO) buck-boost power stage, which allows simultaneous power extraction from multiple sources within a single charging cycle, ensuring the unused source does not deviate from its maximum power point. Adaptive impedance matching is achieved via a two-dimensional maximum power point tracking (2D-MPPT) mechanism based on fractional open-circuit voltage (FOCV) sampling. For fully autonomous cold-start and steady-state operation, the PMU integrates ultra-low-power support blocks including a charge-pump startup circuit with under-voltage lockout (UVLO), a low-voltage-supportable bandgap reference (LVS-BGR), and an oscillator.

V. MEMS–PMU Co-Simulation

To verify the dynamic interaction between the highly pulsed mechanical-electrical energy profile and the PMU, a joint co-simulation framework was established. An array of 100,000 stacked MEMS transducers was modeled to emulate an approximately 5 μW input power source. The simulation validates the system's ability to successfully execute cold-start operations, transition between sleep and active modes, and regulate stable 0.8V and 1.2V supply rails. Overall, the PMU achieves a peak power conversion efficiency (PCE) of 88.8% and a tracking accuracy of approximately 98%, proving the viability of this integrated architecture for self-sustainable sensing applications.