



Harvesting energy into lithium-ion batteries

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Modern portable micro-systems like biomedical implants and ad-hoc wireless transceiver micro-sensors continue to integrate more functions into smaller devices, which result in low energy levels and short operational lives. Researchers and industry alike are therefore considering harvesting energy from the surrounding environment as a means of offsetting this energy deficit. The fact is, even with power efficient designs, low duty-cycle operation, smart power-aware network architectures, and batteries with improved energy density, the stored energy in micro-scale systems is simply not sufficient to sustain extended lifetimes [1]. What is more, the ubiquity of sensor nodes within a network and their limited accessibility prohibit the use of external energy supplies and the maintenance of micro-scale rechargeable batteries, creating the need for *in situ* long-lasting and self-renewable chip-compatible energy harvesting sources, in other words, self-sustaining and self-powered micro-scale system-in-package (SiP) solutions.

Even if the harvester has low efficiency, tapping into the energy of the surrounding environment is attractive because it is, for all practical purposes, an infinite source. Ambient solar, kinetic (vibrations), and thermal energy can be harnessed on-chip with photovoltaic cells and micro-electromechanical systems (MEMS) generators [2-3]. The amounts of energy and power levels that can be achieved, however, depend on the conditions surrounding the application and the compatibility of the available technologies. Relatively low-frequency ambient vibrations from engines, flowing water, gusting winds, moving people, and others, however, are abundant, stable, and predictable [4].

A Self-Sustaining System

Energy from ambient mechanical vibrations can be harvested by means of a magnetic field, an electric field, or a strain on a piezoelectric material [3-4]. Electromagnetic and piezoelectric scavengers, however, are less CMOS-compatible and less scalable. Electrostatic harvesters, on the other hand, are fully compatible with MEMS technologies and capable of generating moderate power levels without the use of exotic materials or obscure process steps. The foregoing scheme therefore harvests energy from an electrostatic generator and stores it in a thin-film polymer lithium-ion (Li-Ion) battery, which in turn powers the system, as illustrated in Figure 1. The electrostatic harvester does not convert energy continuously so an intermittent battery charger is used. To ensure the system is fully operational and self-sustaining, power-intensive tasks such as data transmission and reception are constrained to low duty-cycle operation, in other words, operate only when there is sufficient energy in the system to do so. Sensing and other low power functions may have longer duty-cycles, but for the sake of energy, they are also limited, unless they perform indispensable functions in the system.

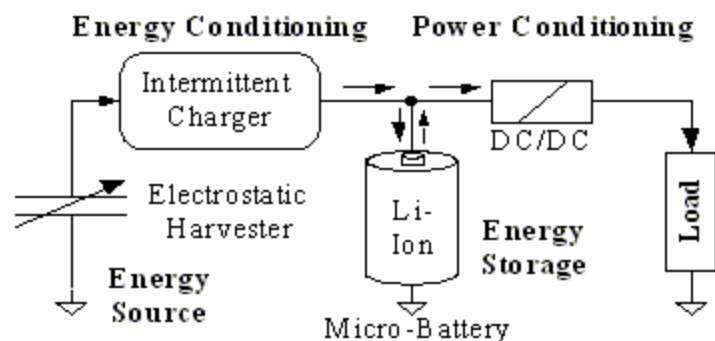


Figure 1. Self-sustaining micro-system

The Electrostatic generator

An electrostatic energy scavenger harnesses energy from the work done by vibrations against an electric field, the embodiment of which relies on the changing capacitance of a vibration-dependant MEMS variable plate capacitor, similar to the examples shown in Figure 2. Mechanical energy is converted into electrical energy as the plates of the charged capacitor separate, or their overlap area decreases, in response to externally applied vibrations, while either voltage or charge is constrained [5]. The capacitor must be pre-charged at its maximum capacitance point (that is, minimum plate separation or maximum overlap area) to initiate the harvesting cycle, much like the energy a lead-acid battery invests in igniting a car engine. This initial investment must of course constitute only a fraction of the net energy gained.

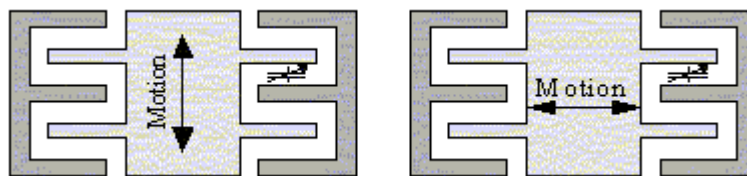


Figure 2. MEMS variable plate capacitors

If the capacitor is open-circuited, charge is held constant, and as the capacitor plates separate in response to vibrations, capacitance falls and causes the voltage ($Q_{\text{Constant}} = C_{\text{MEMS}} V$) and therefore energy stored in the capacitor ($E = 1/2 CV^2$) to necessarily increase. The main drawback here is that the magnitude of the increasing voltage surpasses the breakdown limits of most modern CMOS technologies. Specialized silicon-on-insulator (SOI) process technologies can sustain these voltages [6], but they are costly and not compatible with standard CMOS process nodes.

By constraining the capacitor voltage through the harvesting phase, on the other hand, when the parallel-plate distance increases and capacitance decreases, charge is driven out of the capacitor ($Q = C_{\text{MEMS}} V_{\text{Constant}}$). The mechanical energy required to move the plates and charges is therefore harvested and stored in another capacitor, or better yet, a rechargeable battery, as shown in Figure 1. In essence, the variable capacitor behaves like a current source because the change in capacitance causes variations in charge ($I = dQ/dt$), in spite of no changes in voltage.

The Harvester circuit

The proposed energy harvester operates in three separate phases: pre-charge, harvesting, and recovery. The variable capacitor is first pre-charged to the battery voltage via a quasi-lossless inductor, as shown in Figure 3. The pre-charge phase is therefore decomposed into a sequence of two steps. First, energy is transferred from the Li-Ion battery into the inductor by superimposing the battery voltage across the inductor with switches S_1 and S_3 . The inductor current then increases linearly, and when sufficient

energy is stored, S_1 and S_3 open. The second step is to drive the stored energy into the variable MEMS capacitor by connecting the inductor to the capacitor with S_2 and S_4 . The inductor current ultimately charges the variable capacitor until its voltage reaches that of the battery, at which point S_2 and S_4 open.

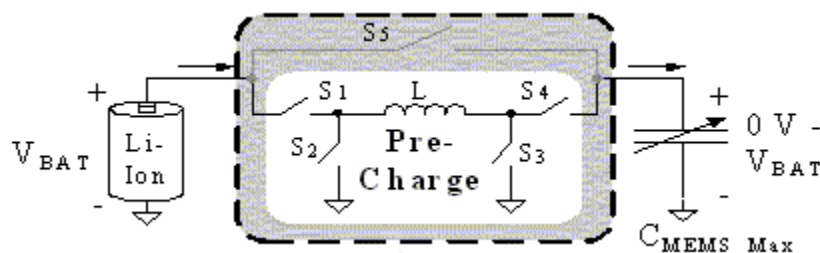


Figure 3. Pre-charge phase

During the harvesting phase, the MEMS capacitor is connected to the rechargeable battery with S_5 so that charge can be driven into the battery (Figure 4). Since the battery is a low impedance source, the voltage across the battery is practically constant and the decreasing capacitance therefore produces a harvesting current ($I = C \, dV/dt + V \, dC/dt \approx V \, dC/dt$). Although this current charges the battery, the resulting increase in voltage is minimal because the magnitude of the current is low, which is why the capacitor voltage is still constrained.

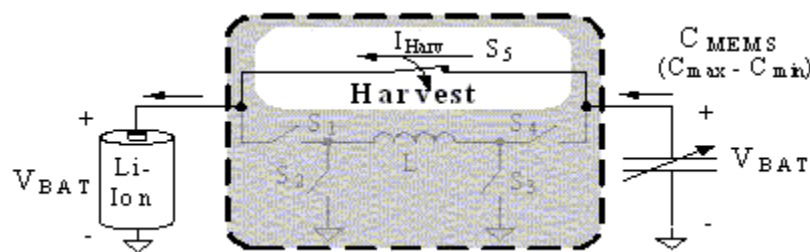


Figure 4. Harvesting phase

To complete the cycle, after the minimum capacitance is reached and harvesting ends, the energy remaining in the capacitor is recovered with the same inductor used in the pre-charge phase (Figure 5). In essence, the pre-charge sequence is reversed: the residual energy is transferred into the inductor with S_2 and S_4 and later delivered to the battery with S_1 and S_3 . After the capacitor is fully discharged, its electric field no longer exists and its plates are free to move and return to their minimum separation state without requiring any electrical energy.

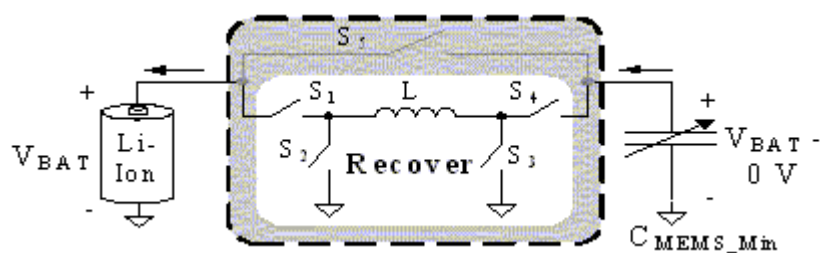


Figure 5. Recovery phase

Energy gain

A net energy gain is possible only if the system starts with some initial energy and parasitic losses are

negligibly small. The battery must therefore have enough energy to pre-charge the variable capacitor and establish the electric field against which vibrations will work. Assuming this is the case and all power losses are negligible, the maximum energy that can be harvested in any given cycle is

$$\Delta E_{Gain_Max} = -\Delta E_{Invested} + \Delta E_{Harvested} + \Delta E_{Recovered} = \frac{1}{2} \Delta C V_{Bat}^2$$

[Click for equation](#)

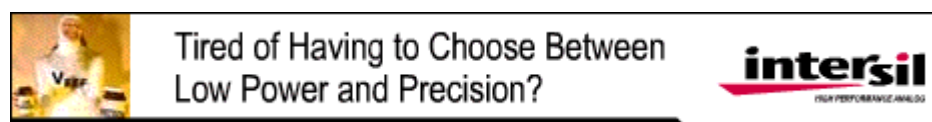
However, keeping the resistive and switching power losses of the pre-charge, recovery, control, and power-conditioning circuits low is not trivial, to say the least. Even a voltage difference between the pre-charged capacitor and the battery at the onset of the harvesting phase incurs additional resistive power losses through the switch ($P = V^2/R_{Switch}$). Its penalty is of course mitigated when the capacitor is only slightly overcharged or undercharged.

Simulations with CMOS transistors and their relevant parasitic body diodes in place of the switches have thus far shown promising results with a net energy gain of 560 pJ per 100-1 pF cycle and an average harvesting current of 40 μ A for vibrations with a period of 15 μ s. After fully comprehending and addressing the parasitic losses with careful design techniques, a proof-of-concept and lithium-ion-compatible printed-circuit board (PCB) prototype is planned. Synchronizing the electronics to an engine or a system of the ilk is next. The ultimate objective of this research is to develop a harvesting and self-sustaining system-in-package (SiP) solution that harnesses energy from an on-chip variable parallel-plate MEMS capacitor, stores it in an in-package thin-film Li-Ion battery, and conditions it for a practical loading application like a sensor node.

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech Analog and Power IC Design Laboratory, at gtap@ece.gatech.edu. More information about our research can be found at <http://www.rincon-mora.com/research>.

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