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Energy-harvesting chips and the quest for everlasting life

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Modern electronics continue to push past boundaries of integration and functional density, towards the elusive completely autonomous self-powered microchip. As systems continue to shrink, however, less energy is available on-board, leading to short device lifetime (runtime or battery life). Research continues to develop higher energy-density batteries but the amount of energy available is not only finite but also low, limiting the system's lifespan, which is paramount in portable electronics. Extended life is also particularly advantageous in systems with limited accessibility, such as biomedical implants and structure-embedded micro-sensors. The ultimate long-lasting solution should therefore be independent of the limited energy available during start-up, which is where a self-renewing energy source comes in, continually replenishing the energy consumed by the micro-system.

State-of-the-art micro-electromechanical system (MEMS) generators and transducers can be such self-renewing sources, extracting energy from vibrations, thermal gradients, and light [1]. The energy extracted from these sources is stored in chip-compatible, rechargeable batteries such as thin-film lithium ion, which powers the loading application (e.g., sensor, etc.) via a regulator circuit [2]. Since harvested energy manifests itself in irregular, random, low energy "bursts," a power-efficient, discontinuous, intermittent charger is required to transfer the energy from the sourcing devices to the battery. Energy that is typically lost or dissipated in the environment is therefore recovered and used to power the system, significantly extending the operational lifetime of the device.

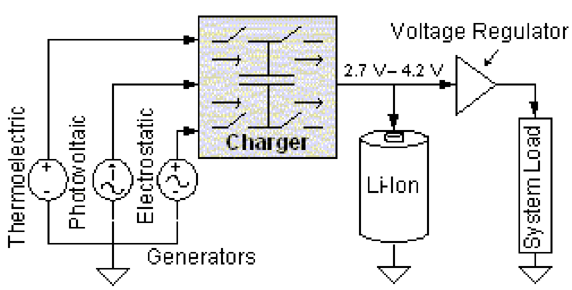

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Figure 1. Electrical diagram of the energy-harvesting system.

Harvesting Energy

Energy harvesting is defined as the conversion of ambient energy into usable electrical energy. When compared with the energy stored in common storage elements, like batteries and the like, the environment represents a relatively inexhaustible source of energy. Consequently, energy harvesting (i.e., scavenging) methods must be characterized by their power density, rather than energy density. Table 1 compares the estimated power and challenges of various ambient energy sources. Light, for instance, can be a significant source of energy, but it is highly dependant on the application and the exposure to which the device is subjected. Thermal energy, on the other hand, is limited because the temperature differentials across a chip are typically low. Vibration energy is a moderate source, but again dependent on the particular application.

Energy Source	Challenge	Estimated Power (in 1 cm3 or 1 cm2)
Light	Conform to small surface area	10 µW - 15 mW (Outdoors: 0.15 - 15 mW) (Indoors: <10 µW)
Vibrations	Variability of vibration	1 - 200 µW (Piezoelectric: ~ 200 µW) (Electrostatic: 50 - 100 µW) (Electromagnetic: < 1µW)
Thermal	Small thermal gradients	15 µW (10°C gradient)

Table 1. Comparison between different ambient energy sources

Vibration Energy: Energy extraction from vibrations is based on the movement of a "spring-mounted" mass relative to its support frame [3]. Mechanical acceleration is produced by vibrations that in turn cause the mass component to move and oscillate (kinetic energy). This relative displacement causes opposing frictional and damping forces to be exerted against the mass, thereby reducing and eventually extinguishing the oscillations. The damping forces literally absorb the kinetic energy of the initial vibration. This energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material. These energy-conversion schemes amount to harvesting energy from vibrations.

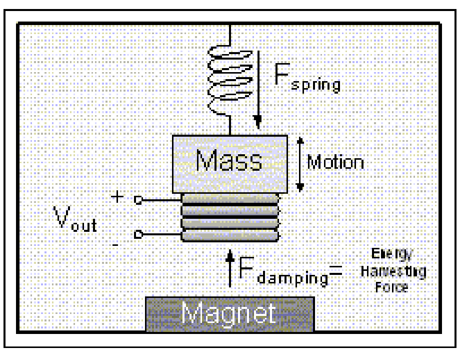

Figure 2. Electromagnetic vibration energy harvester

Electromagnetic energy harvesting uses a magnetic field to convert mechanical energy to electrical [4-5]. A coil attached to the oscillating mass traverses through a magnetic field that is established by a stationary magnet. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and must therefore be increased to viably source energy. Methods to increase the induced voltage include using a transformer, increasing the number of turns of the coil, and/or increasing the permanent magnetic field. However, each is limited by the size constraints of a microchip.

Piezoelectric energy harvesting converts mechanical energy to electrical by straining a piezoelectric material [3, 6-7]. Strain, or deformation, in a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, since it provides higher strain for a given input force [3, 6] - see Figure 3a. The voltage produced varies with time and strain, effectively producing an

irregular ac signal. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system.

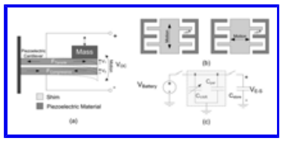

Figure 3. (a) Piezoelectric energy harvesting beam and (b) MEMS varactors (c) in an energy-harvesting circuit

Electrostatic (capacitive) energy harvesting relies on the changing capacitance of vibration-dependant varactors [3, 8-9]. A varactor, or variable capacitor, is initially charged and, as its plates separate because of vibrations, mechanical energy is transformed into electrical energy (Figures 3b and 3c). The most attractive feature of this method is its IC-compatible nature, given that MEMS variable capacitors are fabricated through relatively mature silicon micro-machining techniques. This scheme produces higher and more practical output voltage levels than the electromagnetic method, with moderate power density.

Thermal Energy: Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect (10-11). Temperature differentials between opposite segments of a conducting material result in heat flow and consequently charge flow, since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low temperature end, establishing in the process a voltage difference across the base electrodes (Figure 4a). The generated voltage and power is proportional to the temperature differential and the Seebeck coefficient of the thermoelectric materials. Large thermal gradients are essential to produce practical voltage and power levels. Nevertheless, temperature differences greater than 10°C are rare in a micro-system, consequently producing low voltage and power levels [1].

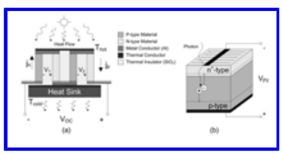

Figure 4. (a) Thermoelectric energy converter and (b) a photovoltaic cell

Light Energy: Photovoltaic cells convert incident light into electrical energy [12-13]. Each cell consists of a reverse biased pn+-junction, where light interfaces with the heavily doped and narrow n+-region. Photons are absorbed within the depletion region, generating electron-hole pairs. The built-in electric field of the junction immediately separates each pair, accumulating electrons and holes in the n+- and p-regions, respectively, and establishing in the process an open circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the p-side, generating a photocurrent that is directly proportional to light intensity and independent of cell voltage. Research demonstrates that photovoltaic cells can generate sufficient power to sustain a micro-system, although at lower power efficiencies than their macro-scale counterparts [13], since the power required to harvest the energy is a significant portion of all the energy extracted (area is small in micro-scale systems). A three-dimensional diode structure constructed on porous silicon helps increase efficiency by significantly increasing the exposed internal surface area of the device [14]. Overall, photovoltaic energy conversion is a mature IC-compatible technology that offers higher power output levels, when compared with the other energy-harvesting mechanisms. Nevertheless, its power output is strongly dependent on environmental conditions, in other words, varying light intensity.

Storing Energy

The energy-harvesting system requires a charger capable of capturing and transferring intermittent low energy bursts to a rechargeable battery, thin-film lithium-ion batteries, in the case of chip-compatible solutions. Maximum battery life, capacity, and energy content of a lithium-ion battery is achieved by adopting a constant-current/constant-voltage charging scheme (Figure 5). Initially, a low preconditioning charging current is applied to the battery to ensure that the cell voltage is at least 2.7 V. Afterwards, the constant-current phase follows with the application of a full charging current, until the battery voltage nears the end-of-charge voltage, typically between 4.1 and 4.2 V. Subsequently, a voltage-controlled loop sources whatever little current is necessary to slowly pull the battery voltage to the end-of-charge voltage. The cell voltage increases quickly during the constant-current phase, before allowing the system to reach full capacity [15]. Therefore, fast-charging the cell by merely applying a constant charge current achieves only between 40% and 70% of its maximum possible capacity. As a result, both charging steps are required to charge the battery completely.

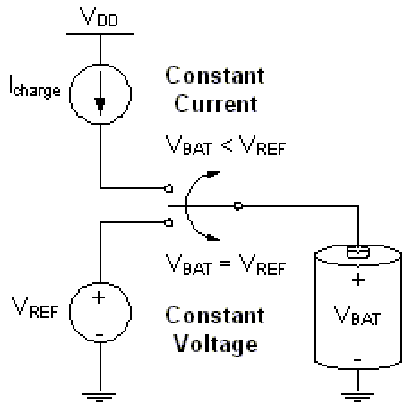

Figure 5. Constant-current/constant-voltage battery charging model

The charging circuit depends on the nature of the input energy that is to be stored in the battery [16]. Mainly, the charging current applied to the battery can be either continuous or discontinuous. Continuous charging techniques may utilize linear and switching regulators. A linear regulator linearly controls the conductance of a series pass device via a feedback loop to regulate the output against variations in load current and supply voltage, continuously supplying current. Linear regulators are analogous to resistive voltage dividers in that they can only source voltages below the input supply.

Switching regulators, on the other hand, can boost (step-up) or buck (step-down) the input voltage. In this latter scheme, fully on or off switching devices alternately store and deliver energy to the load via a combination of inductors and capacitors. Viewed from a different perspective, the LC components filter the inherent switching waveforms of the circuit and the duty cycle of these waveforms are in turn normally regulated via a pulse-width modulated (PWM) controller, or by another switching scheme. The supplementary filter and switching controller not only increase the complexity of the charger but also inject high frequency noise to the output. However, the switching nature of these regulators inherently achieves high power efficiency because the switches incur negligible voltage drops, even at high current levels, thereby dissipating little power, when compared to the series pass device of the linear regulator. Although the circuit switches, the output is regulated and can continuously supply a charge current, albeit with a noisy ac ripple.

Discontinuous charging refers to the application of alternating and discrete charge current pulses to the battery. The duty cycle of the pulsating current waveform gradually decreases as full charge conditions are approached. Efficiency is improved because periodically interrupting the charge current allows ions to diffuse and redistribute more evenly, thereby reaching higher capacity levels [17]. Adding a brief discharge pulse after each charging pulse further accelerates this diffusion process. It is noted that each charging scheme depends on a continuous, steady source of energy and is therefore incompatible with intermittent and irregular sources (e.g., electrostatic energy harvesters and other vibration-based generators).

The energy-harvesting sources supply energy in irregular, random "bursts," unfortunately. Since none of the previously discussed charging circuits is compatible with intermittent low energy bursts, a new alternative is therefore required, which is what we are working on. The intermittent charger must wait until sufficient energy is accumulated in a specially designed transitional capacitor before attempting to transfer it to the storage device, lithium-ion battery, in this case. Moreover, since energy and power are invariably small in a micro-scale system, the system must partition its functions into time slices (time-division multiplex), ensuring enough energy is harvested and stored in the battery before engaging in power-sensitive tasks. The system would continually self-replenish its energy consumption, resulting in extended and maybe ever-lasting operational life.

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

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