Hybrid Supplies for Wireless Micro-Systems

by Erick O. Torres, Lucas A. Milner, and Gabriel A. Rincón-Mora

Ultra-compact micro-electronic devices like wireless micro-sensors provide sensing and monitoring functions to a wide variety of applications in medicine, industry, and the military. Because of their diminutive micro-scale dimensions, these micro-systems are unobtrusive and can be deployed in numerous quantities as a network gathering information from typically inaccessible environments, such as inside the human body.[1-2] The problem is the inaccessibility and ubiquity of the constituent nodes render the upkeep of the on-board energy supply impractical, forcing the device to sustain itself from whatever energy it was able to store initially. This is a significant challenge because typical micro-scale energy sources do not feature the necessary energy densities to fully supply practical systems capable of sensing, storing, computing, and transmitting data for extended lifetimes.[3] As a result, micro-scale devices suffer from short operational lives, as determined by the amount of energy initially stored in their small volumes.[1,4]

An effective strategy for prolonging life is to decrease the average power consumed in the system by duty-cycling and offsetting power-intensive tasks. For instance, sensing and wireless communication functions need not engage continuously or simultaneously. Performing these functions periodically or asynchronously (on demand) and allowing the system to idle often, as shown in Fig. 1, reduce average power ($P_{Average}$) and therefore drain the energy source at a slower rate.[3-4] Fortunately, duty-cycling the load is compatible with many applications that only need to sample data at a low frequency because the sensed variable changes slowly with respect to time, as is often the case with temperature and air pressure,[5] just to cite two examples.

Duty-cycling, however, does little to attenuate peak power requirements. Wireless telecommunication, for instance, may demand micro- and even nano-Watts on average but draw milli-Watts of instantaneous power during transmission, as depicted by P_{Peak} in Fig. 1. This presents a challenge because energy-storage devices typically do not concurrently feature high energy and high power densities, as the Ragone plot in Fig. 2 shows.[3] Capacitors, for example, may source considerably higher power than similarly sized nuclear batteries but also suffer from substantially lower energy levels. The fact is micro-scale systems demand both high energy (to extend operational life) and high power (to perform important functions like wireless transmission).

Micro-Scale Sources

In applications where batteries cannot be recharged or replaced, the energy stored in the system determines its lifetime, which is why high energy density is so critical. Harvesters are most appealing in this respect because they extract virtually unbounded ambient energy in light, thermal gradients, magnetic fields, and/or vibrations, except their power levels are not only considerably low but also intermittent and often unpredictable.[6] Were it not for expense and safety concerns, betavoltaic (or atomic) batteries would attract more attention because they source slightly higher power levels continuously from a decomposing radioactive element whose half life is on the order of years.[7]

Alternatively, micro-scale fuel cells also offer relatively high energy densities (although not as high as nuclear batteries) and with safer byproducts, such as carbon dioxide (CO_2) and water in the case of direct-methanol (DM) proton-exchange membrane (PEM) fuel cells.[8] What is more, these fuel cells can be integrated on chip (alongside the microelectronics they

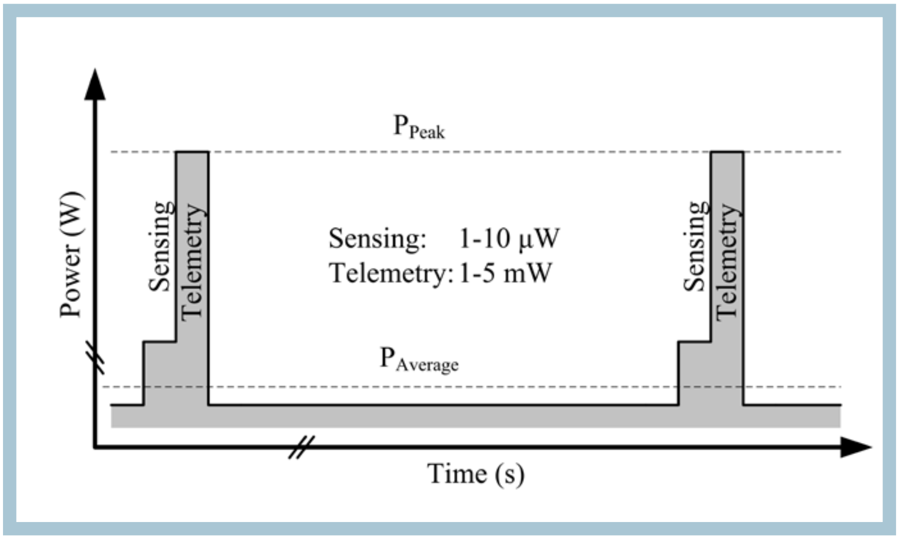

Fig. 1. *Load profile of a duty-cycled wireless micro-sensor.*

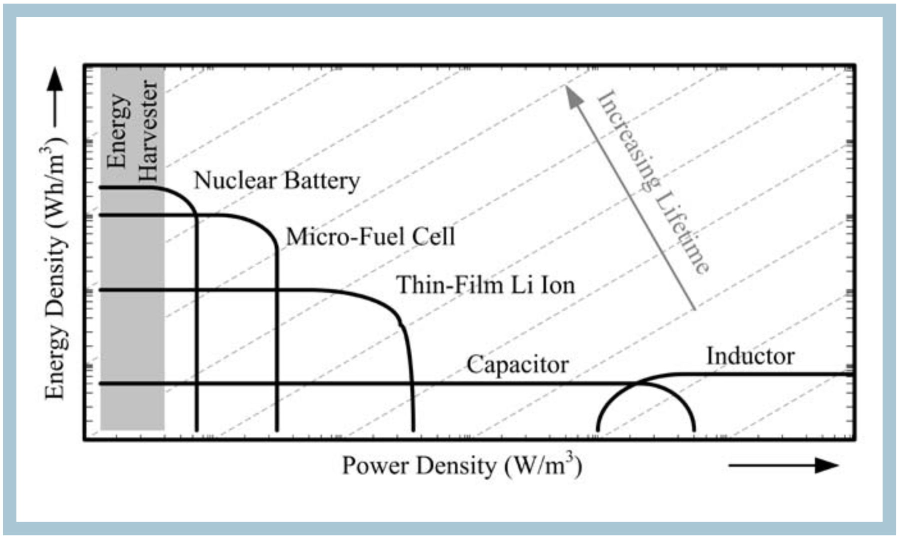

Fig. 2. *Ragone plot of state-of-the-art energy sources.*

(continued from previous page)

support) with micro-electromechanical systems (MEMS) technologies. Fuel cells, however, in addition to low power levels, also suffer from slow kinetics (or reaction times) and fuel loss (*i.e.*, energy loss) through the membrane and corresponding vents. Ultimately, even when discounting the relevant drawbacks, constrained volume space in nuclear batteries and fuel cells continues to place severe limits on how much fuel and reactive material can be stored, which means, unlike energy harvesters, on-board energy is finite and easily exhausted.

As discussed earlier, high power density is also important, so capacitors and inductors thrive in this arena. The problem is the energy they store when constrained to micro-scale dimensions is considerably low, which means they deplete quickly. Lithium-ion (Li-ion) batteries, on the other hand, are popular energy-storage devices because they embody a balanced compromise in energy, power, and speed while losing little-to-no energy to self discharge, maintaining capacity over numerous re-charge cycles (*i.e.*, long cycle life)[9] and even featuring on-chip integration with thin-film technologies.[10-11] Compromising energy and power for the sake of a single source, however, is not acceptable in micro-scale applications, especially when incorporating wireless telemetry and targeting operational lives on the order of years.

Hybrid Supplies

Extending operational life in ubiquitous high-performance micro-scale applications to practical and unprecedented levels leaves little room for sacrifice. In this light, under similar micro-scale volumes, capacitors and inductors should only supply instantaneous peak power because they are quick and capable of sourcing the highest power. Li-ions should supply burst power because they are fast enough to do so and able to source more energy in the process. Fuel cells and nuclear batteries, on the other hand, should only supply low average power because, in addition to their slow response times, they source more energy in this state. Harvesters alone may not be able to supply any load but they can replenish an otherwise exhaustible reservoir of energy and extend system life. Mixing the power from these sources to charge intermediate stages and supply the load, however, also requires energy and power.

Using a Li-ion as momentary power cache to supply burst power and complementing it with a fuel cell, for instance, for energy (*i.e.*, extended operational life) to match the various loading requirements of a micro-scale system demands a smart and power-efficient mixer–charger–supply integrated circuit (IC), as illustrated in Fig. 3.[12] During stand-by mode, the IC channels 0.4-0.6 V fuel-cell energy and power to concurrently supply the 1-2 V load and recharge the 2.7-4.2 V Li-ion. Similarly, during high-power events, the IC draws energy and power from both the 0.6 V fuel cell and 2.7-4.2 V Li-ion to supply the 1-2 V load. While an inductor is important to transfer energy and circumvent the energy and power otherwise lost in switches, several inductors are prohibitive in micro-scale applications. Finally, output and fuel-cell capacitors C_{OUT} and C_{FB} supply the instantaneous load and power the Li-ion and fuel cell are unable to source during load dumps and the various switching phases of the IC. In other words, the IC ensures the load draws low and high currents with the highest possible energy at all times.

Harvesters can boost the lifetimes of these hybrid systems by harnessing, converting, and transferring additional energy into the Li-ion reservoir, decoupling the initial energy stored in the system (*e.g.*, fuel) from the resulting operational life. This is possible because ambient energy is abundant, and in the case of mechanical vibrations, also stable and often predictable. Although harvesting energy from strain exerted on piezoelectric materials, magnetic fields, and electric fields are all possible, electrostatic harvesters enjoy the benefits of on-chip integration because they are fully compatible with MEMS process technologies (*e.g.*, accelerometers) and do not require exotic materials or additional processing steps.

Deriving energy from these variable electrostatic capacitors (*i.e.*, varactors), however, requires an initial energy investment in the form of initial charge to initiate the harvesting process. This necessity arises because variable

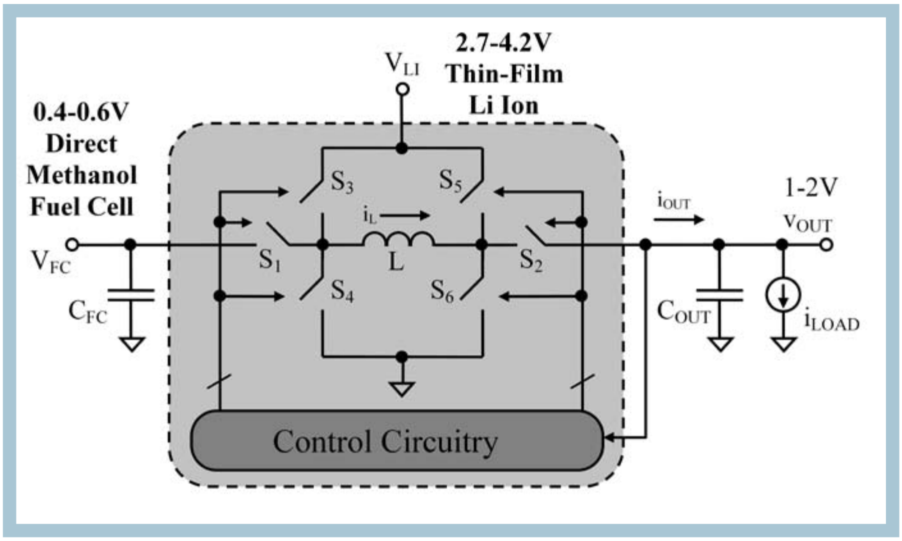

Fig. 3. *Fuel cell–Li ion hybrid source with its supporting mixer–charger–supply circuit.*

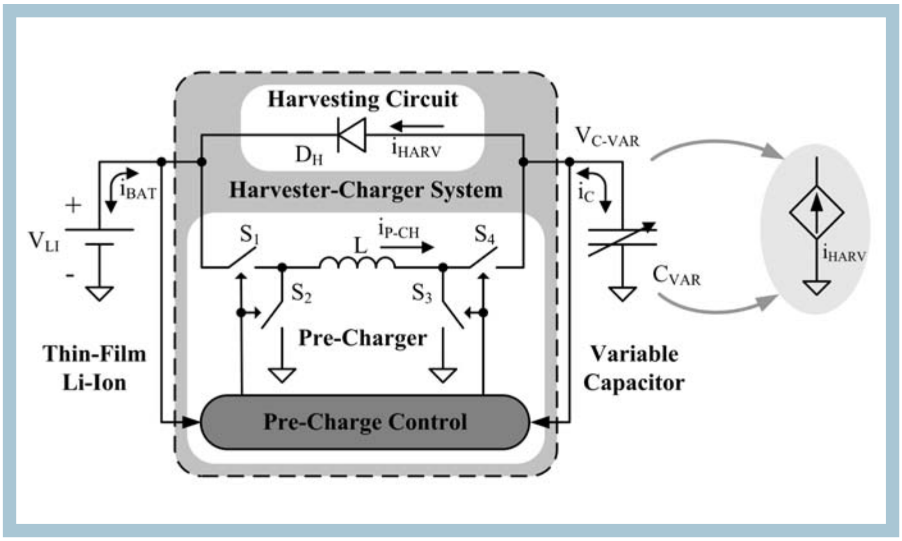

Fig. 4. *Electrostatic-based harvester-charger circuit and system.*

capacitor C_{VAR} must be pre-charged to Li-ion voltage V_{LI} before a decreasing capacitance can induce a harvesting charge current i_{HARV} into the Li-ion:

$$i_{HARV}=\frac{dq_{VAR}}{dt}=\frac{d\left(C_{VAR}V_{VAR}\right)}{dt}=V_{LI}\frac{dC_{VAR}}{dt} \tag{1}$$

As a result, the harvester-charger IC shown in Fig. 4, for example, charges C_{VAR} to V_{LI} quickly while C_{VAR} is at its maximum value and channels i_{HARV} back to the Li-ion through diode D_{HARV} when C_{VAR} decreases.[13] The main challenge here is to guarantee a net energy gain; that is to say, the energy harvested must exceed the initial investment and whatever losses the IC incurs, which is why an inductor is again used, to reduce transfer losses. Note the control block and all switches in the system also dissipate power.

Low-Power Operation

Even with the unlimited supply of energy that harvesters can provide, the power available still limits the quality (*e.g.*, resolution) and quantity (*e.g.*, transmission rate) of data the system can process. The circuits required to collect, discern, and transmit information accurately, for example, can easily exhaust all the energy accumulated over the span of minutes or days. Transmitting too much data and/or across wide distances similarly strains the system. Circuits that consume low energy and low power and maintain high performance are therefore as important as the sources that supply them.

In design, energy per transmission or conversion and absolute power are the most important metrics. Low power, as before, implies a source with higher energy density can supply it, which results in longer operational life. If the incremental changes in power do not justify changing sources, however, energy per transmission or conversion supersedes power in importance because higher short-burst power requires the same energy as low power over extended periods. Normally, the power associated with wireless transmission overwhelms most other components in the system, including converting sensed data into digital format (*i.e.*, analog-digital converters). Reducing peak wireless power consequently takes precedence over energy per transmission, if it means a higher energy source device can be used. Otherwise, as is often the case in sensing, energy per transmission and conversion are more important.

System Integration

The integration of the constituent components of the micro-system, as illustrated in Fig. 5a, also deserve consideration because they must ultimately conform to a single miniaturized, light-weight, non-invasive, self-contained, and self-sustained system-in-package (SiP) platform. The fuel reservoir (or tank), for example, probably requires the largest volume so dueling it as a chassis, as shown in Fig. 5b, increases space efficiency. A MEMS DM PEM fuel-cell membrane[8] could constitute the top face of the tank, the side immediately underneath the IC. The thin-film Li-Ion micro-battery can be integrated on chip (above the microelectronic circuits[10-11]), on a separate substrate and wire-bonded to the IC,[14] or on a flexible medium so that it may wrap around the tank and exploit the three-dimensional features of the SiP device.

The IC, wire bonds, and related passives comprise the space above the PEM membrane. Note that on-chip vibration-sensitive MEMS varactors[15] used in an electrostatic harvester can also double as motion sensors. While on-chip inductors and capacitors for the mixer–charger–supply IC would be ideal, their inductances (*e.g.*, 20-100 nH) and capacitances (*e.g.*, 20-100 pF) are orders of magnitude below practical levels (*e.g.*, 1-10 μH and 0.1-1 μF), and their equivalent series resistances (ESRs) are similarly prohibitively high (*e.g.*, 0.5-1 Ω). As a result, the system must resort to 1-5 mm^3 off-chip capacitors and inductors.[16] Keeping the number of off-chip capacitors and inductors in the mixer–charger–supply low to keep overhead low, however, requires innovation, especially when targeting high-power efficiency and high-accuracy performance.

In addition to the mixer–charger–supply, the IC must also include sensors, data converters, processors, oscillators, mixers, power amplifiers, and other supporting microelectronics. Such a diverse system usually demands a plethora of supply voltages (derived from the same IC) for optimum efficiency and operation. Inductor-based dc-dc converters are versatile and efficient, but dedicating one for each sub-system is unacceptable because the real estate above the tank is a precious commodity—off-chip components subtract volume from the tank and battery and therefore reduce operational life and peak-power performance. Supplying a myriad of supply voltages from several non-ideal sources must therefore rest on a single off-chip 1-5 mm^3 inductor and its driving IC controller. The IC must be sufficiently efficient and smart enough to channel energy from the best available source

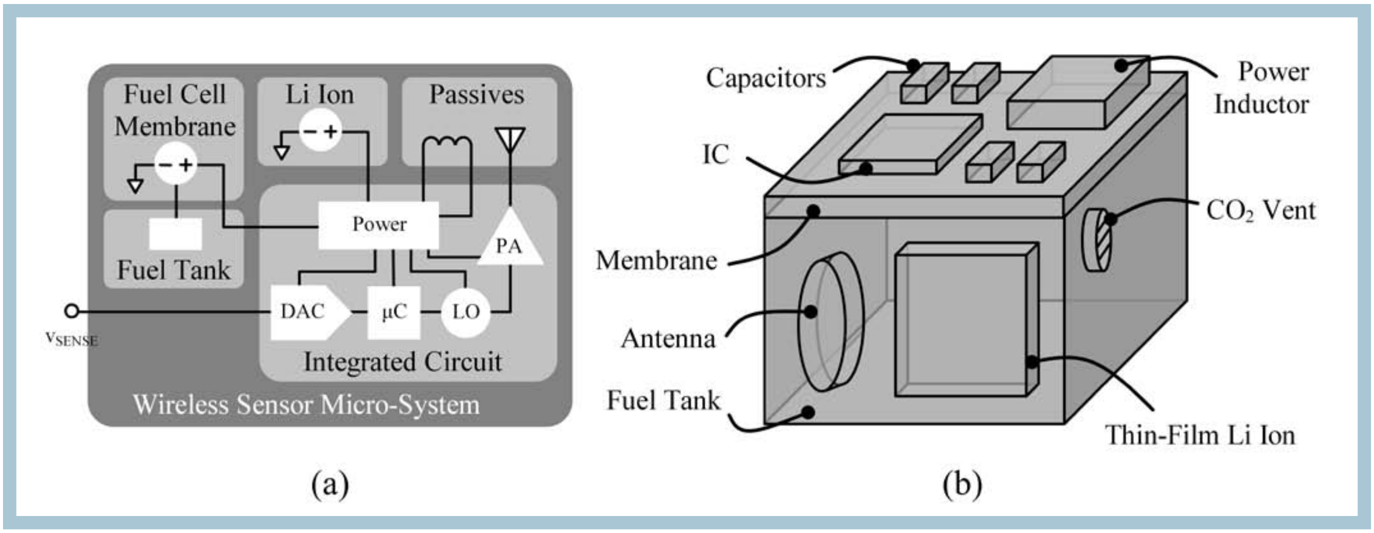

Fig. 5. *(a) Electrical architecture and (b) a possible system-in-package (SiP) embodiment of a wireless micro-sensor.*

Torres, *et al.*
(continued from previous page)

while accommodating for their non-idealities, such as limited response times, internal resistances, etc.

The antenna is another challenge. Generally, a higher carrier frequency needs a smaller antenna, which is (thankfully) more easily integrated—efficient radiation for a 1 cm^3 micro-system, for instance, requires frequencies greater than 30 GHz.[5] The problem with high frequency is that the oscillator and power amplifier consume considerably higher power. Unfortunately, reducing the carrier frequency without increasing the size of the antenna is not an easy option because the power losses in the antenna itself increase substantially as a result. In summary, as with energy and power, transmission performance is almost entirely dependent on the space available, just as lifetime depends on the size of the fuel-cell tank, the Li-ion's series resistance on area, and inductance and inductor's power rating on the size of the core. Regardless, using the outer surface of the tank to adhere a stacked, two-dimensional antenna is an option for the foregoing micro-system.

Conclusion

Generally, storage capacity, power rating, lifetime, system performance, and antenna efficiency decrease with decreasing dimensions. Li-ions are moderate and balanced in almost all respects, so much so, in fact, that confining them to micro-scale dimensions necessarily sacrifices the energy and power wireless sensor systems cannot afford to lose. Complementing the high-energy characteristics of harvesters, fuel cells, and nuclear batteries with the moderate- and high-power levels available in Li-ions, capacitors, and inductors is an appealing prospect, even if the driving and loading microelectronics must now include additional intelligence, require less space, and consume less power. The fact is that over-sizing the Li-ion to accommodate the energy demands of the system or similarly over-sizing the fuel cell or harvester to fully supply the load power requires more volume than a hybrid source, which is why research continues not only in developing the constituent technologies of the system discussed here but also in integrating them. ■

About the Authors

Erick O. Torres received a BS degree from the University of Central Florida and an MSEE degree from Georgia Institute of Technology in 2003 and 2006, respectively, both in electrical engineering. Currently, he is working toward a PhD degree in electrical engineering at Georgia Tech, where he is a research assistant with the Georgia Tech Power, Analog, and Energy IC Design Lab. He has been awarded several fellowships, including the Goizueta Foundation Fellowship, the Georgia Tech President's Fellowship, and the Texas Instruments Analog Fellowship. Additionally, during a six-month co-op assignment in 2006, he worked as a circuit design engineer with the Texas Instruments Mixed-Signal Automotive group designing several analog circuit blocks for various power management IC projects. His research interests include energy-harvesting for micro-devices and low-power analog and power IC design. He may be reached at ertorres@ece.gatech.edu.

Luke Milner received his BS and MS in electrical engineering from Georgia Tech in 2004 and 2006. He is currently working on his PhD at Georgia Tech under the supervision of Gabriel Rincon-Mora. Their work together focuses on fully integrated dc-dc converters. In addition to his experience as a graduate research assistant, Luke has worked for National Semiconductor in Santa Clara, California as a circuit design intern. He may be reached at lucas.milner@ece.gatech.edu.

Gabriel A. Rincón-Mora (BS, MS, & PhD in electrocical engineering) has been a professor at Georgia Tech since 2001. He was an adjunct professor for Georgia Tech in (1999-2001), and a Design Team Leader for Texas Instruments (1994-2003). His scholarly work includes five books and one book chapter, 26 patents, over 100 scientific publications, and 26 commercial power management chip designs. Among his many awards, he received the National Hispanic in Technology Award from the Society of Professional Hispanic Engineers, and the Charles E. Perry Visionary Award from Florida International University. He was inducted into the Council of Outstanding Young Engineering Alumni by Georgia Tech and featured on the cover of Hispanic Business Magazine as one of "The 100 Most Influential Hispanics." He is (was/has been) an Associate Editor for IEEE's *Transactions on Circuits and Systems II* since 2007 His research is on designing and developing energy and power efficient, high performance, totally integrated, system-on-chip (SoC) and system-in-package (SiP) power- and energy-conscious integrated circuit solutions for mobile and portable applications. He may be reached at rincon-mora@ece.gatech.edu.

References

1. D. Puccinelli and M. Haenggi, *IEEE Circuits and Systems Magazine*, **3**(3), 19 (2005).
2. P. Dario, M. C. Carrozza, A. Benvenuto, and A. Menciassi, *J. Micromechanics and Micro-engineering*, **10**, 235 (2000).
3. M. Chen, J. P. Vogt, and G. A. Rincón-Mora, *Proc. IEEE International Midwest Symposium on Circuits and Systems (MWSCAS)*, Aug. 2007.
4. J. N. Harb, R. M. LaFollette, R. H. Selfridge, and L. L. Howell, *J. Power Sources*, **104**, 46 (2002).
5. J. P. Vogt and G. A. Rincón-Mora, "SiP Wireless Micro-Power Sensors," presented at *Government Microcircuit Applications and Critical Technology Conference*, Lake Buena Vista, FL, March 2007.
6. E. O. Torres and G. A. Rincón-Mora, *ASCE Journal of Energy Engineering*, (in press).
7. H. Guo and A. Lal, *Proc. 12th International Conference on Solid State Sensors, Actuators, and Microsystems*, **1**, 36 (2003).
8. W. Mustain, S. Prakash, H. Kim, P. Kohl, and G. A. Rincón-Mora, Abstract 606, The Electrochemical Society Meeting Abstracts, Vol. 2007-02, Washington, DC, Oct. 7-12, 2007.
9 D. Linden and T. B. Reddy, *Handbook of Batteries*, 3rd ed., McGraw-Hill, New York, NY (2002).
10. J. B. Bates, N. J. Dudney, B. Neudecker, A. Ueda, and C. D. Evans, *Solid State Ionics*, **135**, 33 (2000).
11. H. Lhermet, C. Condemine, M. Plissonnier, R. Salot, P. Audebert, and M. Rosset, *IEEE Journal of Solid-State Circuits*, **43**, 246 (2008).
12. M. Chen and G. A. Rincón-Mora, *Proc. International Symposium on Low Power Electronics and Design (ISLPED)*, Aug. 2007.
13. E. O. Torres and G. A. Rincón-Mora, *Proc. IEEE Midwest Symposium on Circuits and Systems (MWSCAS)*, p. 65, Aug. 2006.
14. Cymbet Corporation, www.cymbet.com.
15. M. Rabaey, *Energy Scavenging for Wireless Sensor Networks with Special Focus on Vibrations*, 1st ed., Kluwer Academic Publishers, Massachusetts (2004).
16. Coilcraft Inc., www.coilcraft.com.