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Microbatteries for self-sustained hybrid micropower supplies

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Abstract

This paper describes the characteristics of microbatteries suitable for use in a hybrid micropower supply for powering autonomous MEMS and other microsystems. The hybrid power supply includes an energy conversion device, microscopic batteries for energy storage, and control/interface circuitry. Comparison of the hybrid approach with single power sources (either a battery or energy conversion device alone) shows that it offers several potential advantages including reduced size, increased flexibility, long lifetime and increased reliability. Such an approach is well suited to the expected duty cycles of remote microsensors. Realization of the advantages of a hybrid system depends on the availability of a battery with the required characteristics. Initial experimental results demonstrate the feasibility of fabricating microbatteries with the proper characteristics and the use of these batteries as part of a hybrid micropower supply. It is anticipated that hybrid micropower supplies with suitable microbatteries will play a critical role in the successful implementation of a wide variety of autonomous microsystems. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Micropower supply; Microbatteries; Hybrid micropower

1. Introduction

The development of microdevices has accelerated over the last few years, but the development of compatible power systems is required before the utility of many of these devices can be fully realized. Currently, the power systems for many microdevices are several times larger in size than the devices they power. In some applications (e.g. automobile airbag sensors and digital mirror displays) the power supply size is not an issue. However, micropower systems are a critical need for microdevices where a large power supply eliminates the advantages of the reduction in device size, or where it makes the application infeasible.

Two power options that have been considered are energy storage devices (i.e. batteries) and energy conversion devices (e.g. solar cells, piezoelectric generators, etc.). Both of the options have limitations in microsystems. Batteries are usually much larger than the device they are to power, particularly when the device is required to operate for long periods. Energy conversion devices provide an intermittent source of power (e.g. solar cells require light and a piezoelectric generator may require vibrations), and they require additional electronics to condition the fluctuating output. More recently, hybrid power systems that combine energy conversion and storage have been envisioned [1].

This paper focuses on the characteristics of microbatteries that are needed in a hybrid approach for powering autonomous microsystems. The microbatteries provide power when the energy conversion device is not operating or when pulses of peak power are needed. When it is operating, the energy conversion device powers the system and charges the microbatteries. A well-designed hybrid system has the potential to reduce the overall size of a power supply by allowing smaller batteries than would be required in a non-rechargeable system. Such a system should soon be feasible due to recent advances in rechargeable microbatteries [2,3], and is expected to be comparable to the size of the device it is powering.

Perhaps the most obvious application for a self-sustained micropower system is for use with microsensors. The increasing complexity of many engineering systems and the corresponding demands for greater degrees of automation and efficiency have led to an accelerated need for a variety of improved sensors. Despite improvements in sensor element technology, the demand for many sensor types remains unfulfilled, particularly for autonomous sensors that do not have a direct connection to a host for either power or

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communication. Of particular concern is the lack of a viable power supply [1].

This paper describes a representative duty cycle for autonomous sensors, and a hybrid power system suitable for use with such a cycle. A comparison of the hybrid approach to other methods is made, required battery characteristics are defined, and the results of proof-of-concept testing on a rudimentary hybrid system are provided.

2. Power requirements

The key elements of the duty cycle expected for typical autonomous microsensors are (1) a relatively long standby period of very low power for sensing, and (2) "high" power pulses of a few millisecond duration for R/F transmission and reception. The length of the standby period, as well as the low and high power requirements, are specific to the particular application. Different sensors have different power requirements. For example, some types of sensors require no outside power for actuation [4,5].

Mason et al. examined the architecture of a generic multielement microsystem for portable wireless applications [4]. Their system included capacitive sensors for measuring temperature, barometric pressure, relative humidity, and acceleration/vibration so that the sensor power requirements were limited to the power required for the analog readout circuits used. The components with the highest power dissipation were the microcontroller (<10 mW active, <20 mW standby) and the CMOS wireless communications system (10.5 mW active, 0 mW standby). Microcontrollers with even lower power requirements are now commercially available (see [6]). Consequently, it seems reasonable to assume a duty cycle with a peak power requirement of 5 mW and a standby power requirement of 10 μW. The duration of the peak power pulse depends on the specific application and includes readout time for transducers, data processing time and the time required to send and/or receive signals. A pulse width of approximately 10 ms should be sufficient to accomplish these tasks for a wide variety of sensor systems.

The magnitudes of the peak power (5 mW), standby power (10 μW), and peak power pulse width (10 ms) are consistent with the demonstration of a low-power, remote, autonomous sensor by Puers and Wouters [7]. They reported a smart, integrated, accelerometer, intended to monitor the actions of wildlife. A capacitive accelerometer and two thermistors served as sensing elements. The microsystem included a microcontroller, A/D, and a miniature R/F transmitter and receiver. The device occupied a few square centimeter, and was powered by a single, 3 V, primary button cell. At standby, the power consumption was approximately 7 μW. A particularly interesting aspect of their work is the detailed documentation of power dissipation during the "active" period that included sensor monitoring, local data processing and communication. The highest current occurred during R/F transmission and reception, and the maximum total current (R/F + microprocesssor) was 1300 μA. The peak power at the maximum current was 3.9 mW and the duration of the peak power pulse was approximately 6 ms.

Since details of the power consumption during the "active" period vary substantially with application, and such details are not necessary to evaluate the feasibility of a self-sustained hybrid micropower system, a simple representative cycle for remote, autonomous sensors is assumed in this paper. As mentioned above, a peak power (P_p) of 5 mW occurring over pulses of $t_p = 10$ ms, and a standby power requirement (P_s) of 10 μW are assumed. The average length of the standby time (t_s) is left unspecified and is included as a variable in the analysis. The total energy consumed (E) over a period of time (t) is

$$E = \frac{t}{t_s + t_p}(P_s t_s + P_p t_p) \qquad (1)$$

Fig. 1 illustrates power and energy characteristics of this typical duty cycle as a function of the standby time (t_s). At a standby time equal to the pulse duration (0.01 s), the average power is very close to half of the peak power, and nearly all of the energy is dissipated during the high power pulses. However, at a standby time of 1 s, the average power is only about 1% of the peak power. Even so, nearly all of the energy is still dissipated at peak power. The average power requirement is essentially equivalent to the standby power requirement for standby times greater than 100 s. Also, the fraction of the energy dissipated at peak power is less than 1% for standby times greater than 1000 s.

These results illustrate the dual nature of the power requirement for systems that have the typical duty cycle with standby times of 1 s or more. The average power requirement is quite low (∼ 10 μW) for these systems

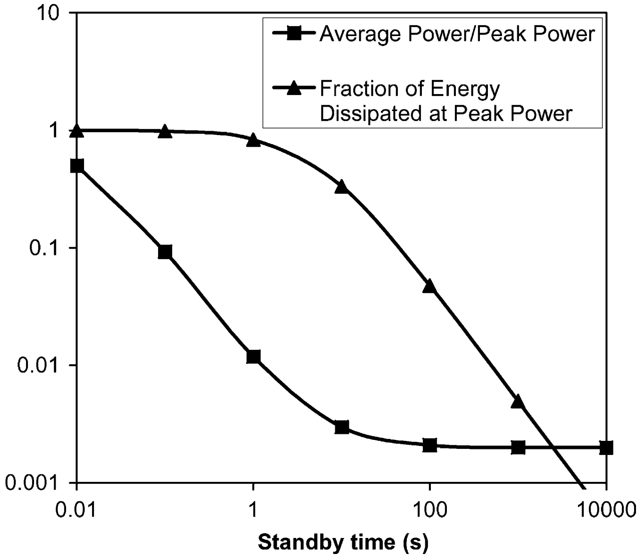

Fig. 1. Characteristics of the representative duty cycle as a function of standby time (t_s).

and represents the power that must be supplied continuously to operate the microsystem. In contrast, the peak power (5 mW) is several orders of magnitude higher and must also be supplied. This dual power requirement lends itself well to a hybrid power strategy as described in the next section.

3. Hybrid power supply for autonomous microsystems

The term "hybrid power supply" is used to denote a power supply that combines two or more different power sources, and is analogous to the use of the word hybrid in "hybrid electric vehicle". The type of energy usage described in Section 2 for a typical sensor duty cycle is well suited to a hybrid power system that combines a low power device to meet the average power requirement and a high power source to provide the peak power pulses. Use of an energy conversion device, such as a solar cell, to provide the average power for the system would obviate the need for an external power connection and make autonomous (self-sustained) operation possible. We propose the use of a microbattery to supply the peak power. Thus, in the proposed hybrid configuration, energy from the energy conversion device is used to meet standby needs and to recharge the microscopic battery(s) as needed. The battery is used to supply the peak power by storing energy from the energy conversion device (operating at a low rate) and delivering it at high rates.

The second purpose for the battery is to provide power for the system when the energy conversion device is off-line. This is necessary because it is unlikely that the energy conversion device operates at a constant rate. For example, a solar cell does not produce power unless a light source is available, and the battery would need to supply both standby and peak power during periods of darkness if continuous system operation is to be maintained. Control circuitry is also needed to provide energy management in order to insure that battery lifetime is extended through use of appropriate charge and discharge strategies.

3.1. Advantages

A hybrid power system offers several advantages. Because the hybrid system extracts energy from the environment, its useful life is not limited by the amount of energy that is stored initially. In theory, the system should be able to continue functioning indefinitely. In practice, however, the lifetime will be limited by the cycle life of the batteries. The cycle life is expected to be high for batteries undergoing high rate discharge at low depth-of-discharge (DOD). Another advantage is that a hybrid system provides flexibility not possible with a single power source such as a coin cell battery. For example, a large number of very small batteries may be connected in series to provide the high voltage needed for some applications. The use of multiple microscopic cells also makes it possible to build redundancy into the system, so that system functionality is not dependent on the reliability of a single battery. Additional advantages associated with a hybrid system include the potential for increased levels of integration and automated assembly due to the use of small microfabricated components (see Section 3.3).

3.2. Disadvantages

Disadvantages associated with the use of a hybrid power system include the increased complexity and the need to interface the multiple components that make up the system. In particular, use of rechargeable microbatteries requires careful energy management in order to charge and discharge the batteries in a way that maximizes battery life.

3.3. Size

Perhaps the principal question with respect to a hybrid power system is whether or not the system can be made sufficiently small to be useful for autonomous MEMS (microelectromechanical systems) applications. An evaluation of the potential size and the factors that constrain the size is provided in the paragraphs that follow for the two different power sources that constitute the major components of the hybrid power system.

3.3.1. Energy conversion device

A number of energy conversion strategies are possible, including piezoelectric, thermoelectric, and direct mechanical energy conversion. For the purpose of illustration, this paper focuses on photovoltaic energy conversion.

Typically, in daylight one would expect a solar irradiance of nearly 1 kW/m^2. This means a square solar cell 1 mm on a side would receive 1 mW of solar power. The fraction of this power that can be put to use is determined by the efficiency of the solar cells, how closely spaced they can be fabricated, and how much electrical loss is associated with the charging and system circuitry.

Assuming a solar cell efficiency of 12%, minimal electrical losses, and a standard macro-scale packing fraction of 0.77, over 90 μW would be available from a 1 mm^2 solar cell [8]. This is considerably more than the 10 μW required for the typical cycle. In the ideal case, the energy conversion element, the power conditioning circuitry, sensors, and transmitters would all be created on the same substrate. This type of integration is possible because simple solar cells can be fabricated to achieve almost any desired power level by merely changing the area of the cell. Arranging several separate cells in series allows for a wide range of voltages and currents. The solar cell area required for the typical duty cycle would be significantly less than 1 mm^2.

3.3.2. Battery

The battery size may be limited by either the power requirement or the storage requirement. The battery size required to meet the peak power requirements will first be considered. Battery thickness is typically limited by materials and fabrication constraints, and cannot be changed arbitrarily to adjust the volume and mass of the battery. Consequently, the critical dimension relevant to use of the batteries in a microsystem is the area or footprint of the battery. The objective is to minimize the footprint of the battery while meeting both the power and capacity requirements. A footprint less than or equal to 0.1 cm^2 is chosen as a target value and is assumed to be suitable for integrated microsystems. Therefore, a power density, based on the footprint area, of 50 $\mathrm{mW/cm}^2$ would be needed to meet the 5 mW power requirement of the typical duty cycle with a battery area of 0.1 cm^2. This power requirement is well above that available from a typical thin-film lithium battery which has a power density of about 0.5 $\mathrm{mW/cm}^2$. Neudecker et al. [3] recently reported thin-film rechargeable lithium cells with a much higher power density of about 30 $\mathrm{mW/cm}^2$—close to the required value. The only microbatteries that we are aware of that have exceeded the required power density are those fabricated in the Integrated Microelectronics Laboratory (IML), Brigham Young University, which have been demonstrated to have a power density of 70 $\mathrm{mW/cm}^2$ [2].

It should be noted that the volumetric power and/or energy density of a battery should be used with caution when estimating battery size. For example, a very thin battery may have a very high volumetric power/energy density. However, the maximum thickness of the battery may be very small (e.g. $\sim$ 15 μm) owing to fabrication/materials constraints. As a result, the required battery area (footprint) will be much larger than would have been necessary if the thickness had not been constrained to such small values.

The battery size required to meet the energy storage needs depends on the availability of the energy conversion device. If energy conversion is continuously active, the capacity requirement is minimal and the battery must only store sufficient energy to supply that consumed in the peak discharge. For example, a 5 mW pulse of 10 ms duration would require a total energy of 50 μJ or 0.5 $\mathrm{mJ/cm}^2$ for a 0.1 cm^2 cell. The present capacity of microbatteries fabricated in the IML at Brigham Young University is considerably higher than this at about 2.3 $\mathrm{J/cm}^2$. Consequently, the size of a battery in a microsystem with an energy conversion device that is continuously active is likely to be limited by power and not capacity.

As mentioned previously, there are situations where operation of the energy conversion device is intermittent rather than continuous, such as an outdoor application that utilizes solar cells for energy conversion. For simplification purposes, it is assumed that the conversion device is either on or off. The microbattery must store sufficient energy to power the system when the energy conversion device is not operating. To illustrate, consider the example shown in Table 1 where a solar cell is assumed to be on for 12 h and off for the same amount of time. The energy requirement for 12 h operation under the specified conditions is 0.435 J, which corresponds to a battery area of 0.174 cm^2. Note that this assumes full DOD. Typically, the battery would be sized somewhat larger to reduce the DOD in order to extend its life. In this case, the battery size is limited by the required capacity since the power requirement can be met with a smaller 0.1 cm^2 battery.

Table 1
Example conditions to illustrate hybrid system with solar energy conversion

Peak power requirement (mW)	5
Width of peak power pulse (ms)	10
Standby power requirement (μW)	10
Duration of standby time (min)	10
Operation of solar cell (h on per 24 h period)	12
Reserve storage requirement (h)	12
Specific energy of battery ($\mathrm{J/cm}^2$)	2.5
Specific power of battery ($\mathrm{mW/cm}^2$)	50

The battery size may be limited by either power or capacity, depending on the characteristics of the energy conversion device, but a relatively high power density (power per area) is required in all the cases in order to meet the needs of MEMS duty cycles with a small footprint battery.

Fig. 2 illustrates the battery size needed to meet the typical power and energy requirements for a range of battery capabilities. The horizontal lines indicate the size (area) required to satisfy the power requirement (5 mW) for different power densities. As noted previously, a high power density of $\sim$ 50 $\mathrm{mW/cm}^2$ is needed in order to reduce the battery footprint to the desired level (<0.1 cm^2). The slanted lines show the size required to meet the energy demands of the system as a function of the reserve energy storage requirement. The battery size needed to meet the system requirements is the maximum of the size required to satisfy the power requirement and that required to meet the capacity needs. When little or no reserve capacity is needed, the battery size is clearly limited by the power requirement. Capacity limitations become important as the reserve storage time increases. It is assumed in all of these applications that the battery voltage was above that needed to operate the system. Voltage requirements are steadily decreasing and are moving toward a standard of 1 V.

3.3.3. Comparison

A comparison of a hybrid power supply with a power supply consisting of only a battery or only a solar cell will now be made. The situation where a battery alone is used as the power supply is considered first. In this case, the battery must supply all of the energy for the lifetime of the device as no energy is harvested from the environment. The total energy requirement for the duty cycle shown in Table 1, as calculated by Eq. (1), is 318 J. This amount of energy is equivalent to approximately 60 mAh for a 1.5 V battery, or 30 mAh for a 3 V battery. If a "microfabricated" battery with a specific energy of 2.5 $\mathrm{J/cm}^2$ (Table 1) were used, a very large battery area of about 127 cm^2 (12.7 cm diameter)

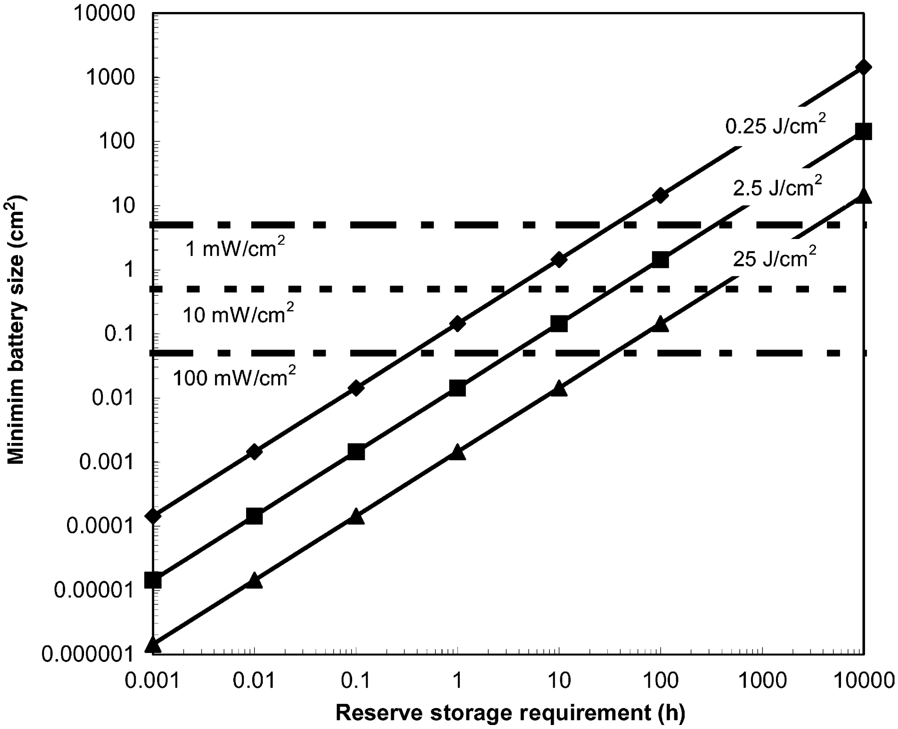

Fig. 2. Battery size as a function of reserve storage requirement and the specific power and energy of the battery for the conditions shown in Table 1.

would be required. This unacceptably large area is due to the limited layer thickness that is possible with microfabrication techniques. A commercial coin cell may actually be more suitable for the battery-only situation. Puers and Wouters [7] used a 3 V primary coin cell battery to power a smart, autonomous sensor designed to monitor the temperature and activity of wildlife. The battery they used had a relatively high capacity (500 mAh), and was by far the largest component of the system (diameter ~ 30 mm, footprint ~ 7 cm^2). Smaller cells are available. For example, Panasonic makes a primary coin cell (diameter = 12.5 mm, thickness = 2.5 mm, footprint = 1.2 cm^2) with a nominal capacity of 48 mAh (3 V nominal, 2 V capacity cutoff) that appears to meet the energy and power requirements for the duty cycle of interest here. Even this small coin cell has a volume and mass much larger than those of a microbattery used in a hybrid system.

The size of a power system consisting of a solar cell alone would be limited by the peak power requirement since the average power requirement can easily be met by a solar cell with an area less than 1 mm^2 as discussed earlier. It is estimated that at least four cells in a series would be required to provide 1.5 V at a current of 3.3 mA (i.e. 5 mW). Each of these cells would require an area of approximately 0.54 cm^2 at full solar intensity. This area should at least be doubled to account for times when the available solar intensity is diminished, yielding a total area of approximately 4.3 cm^2 for the four cells.

The battery size for the hybrid power supply is limited by the capacity required to satisfy the 12 h reserve requirement. This was determined earlier to be 0.174 cm^2 at full depth of discharge. Oversizing of the battery so that the maximum DOD is 50% yields a battery area of approximately 0.35 cm^2. The additional area for the solar cells and circuitry is minimal (<1 mm^2), yielding a total area for the hybrid system of approximately 0.36 cm^2. This area is a small fraction of that required for solar cells alone. Also, the hybrid supply would be operational during nighttime hours when power from the solar cells is not available. The footprint of the hybrid supply is less than one-third the footprint of the small coin cell, while its volume is only about 1% of the coin cell volume. In addition, the hybrid system should not be limited to a 1 year lifetime since energy is continually harvested from the environment. Also, the microfabrication techniques used to build the hybrid power supply facilitate integration with other microsystem components.

3.3.4. Proof of concept

The principal obstacle to the realization of a hybrid micropower supply is the development of a battery with the required performance characteristics. Batteries with the required energy and power density have recently been developed [2]. These batteries were tested under a simulated MEMS duty cycle in order to assess their feasibility for use in a hybrid power supply such as that described above. Note that the cells tested were quite small at 0.02 cm^2, and that, for simplicity, tests were performed by controlling the current rather than the power. Tests utilized standard commercial solar cells that were connected to the microbattery

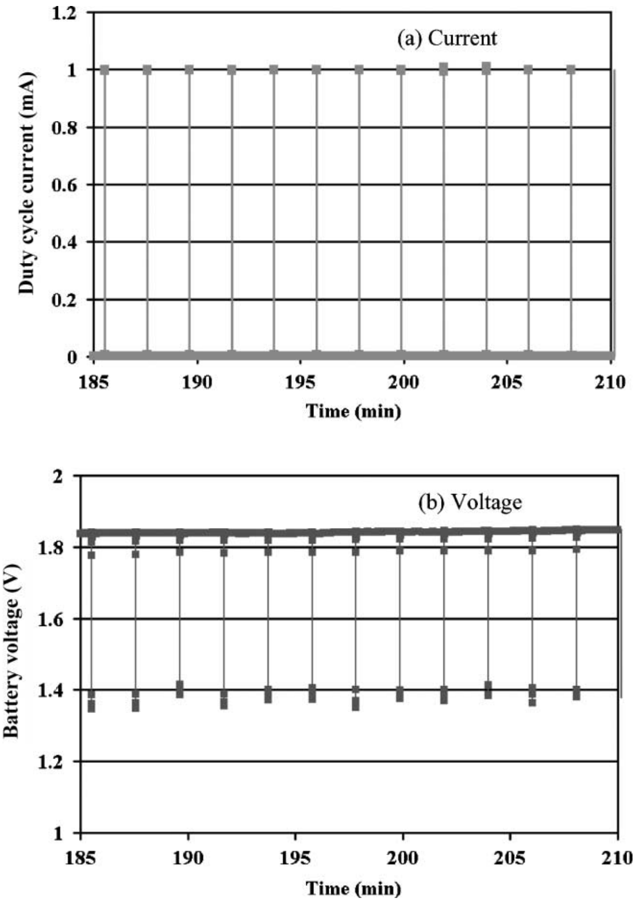

Fig. 3. Experimental results illustrating hybrid operation of a microbattery and solar cell (see Table 2 for experimental conditions).

Table 2
Experimental conditions for microbattery feasibility experiments

Peak current (mA)	1
Width of peak current pulse (ms)	30
Standby current (μA)	3
Duration of standby time (min)	2
Battery size (cm^2)	0.02
Reserve storage requirement	None

through a low power voltage regulating circuit developed specifically for this application. The interface circuitry used in these initial experiments was assembled with discrete components rather than fabricated onto a single substrate. Fig. 3 shows the current and voltage behavior for the specific test conditions provided in Table 2. The peak power was 1.35–1.4 mW from this small cell. The battery performed extremely well and no degradation of performance was observed for the duration of the test. Tests have been performed for over 2300 charge/discharge cycles with no discernable degradation in battery performance. Longer cycling experiments have not yet been attempted, but are expected to yield similar results. These tests clearly demonstrate the feasibility of using these microbatteries as part of a hybrid micropower system.

4. Conclusions

A hybrid micropower supply for use with autonomous microsystems provides several advantages over use of a single power source. These advantages include reduced size, increased flexibility, long lifetime, and increased reliability. A small self-sustained power supply is critically needed for microdevices where a large power supply eliminates the advantages of the reduction in device size, or where it makes the application infeasible. A hybrid micropower supply has the potential to meet this need, especially for remote microsensors.

Realization of the advantages of a hybrid power supply is dependent upon the development of a battery with the required characteristics. This paper defines the necessary battery characteristics based on a duty cycle representative of that required for remote microsensors. Batteries with these characteristics have been fabricated, and initial experimental results demonstrate the feasibility of using these batteries as part of a hybrid micropower supply. It is anticipated that hybrid micropower supplies will play a critical role in the successful implementation of a wide variety of autonomous microsystems.

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