FUZZY LOGIC-BASED SOLAR CHARGE CONTROLLER FOR MICROBATTERIES

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ABSTRACT

A severe limitation on the functional capability of remote, autonomous, microelectromechanical (MEMS)-based sensors is the lack of a suitable micropower supply to power these devices. Such sensors often have low power requirements that may be provided by the combination of an energy scavenger (e.g., a solar cell) and a rechargeable microbattery ("µbattery") made using integrated circuit fabrication methods. While rechargeable µbatteries and solar cells have been previously demonstrated, the development of a micro-charge/discharge controller has not. In this paper we present a novel, fuzzy logic-based solar charge controller that allows control of the charge/discharge of µbatteries. A breadboard implementation of the controller and its integration with a solar cell and µbattery will be presented.

The circuit topology of the µbattery controller is based on a buck converter design. During charging, the solar cell's operating point is adjusted by modulating the duty cycle of the buck converter's switching MOSFET using a fuzzy logic control algorithm to optimally charge the µbattery. Discharge data on the µbatteries and current-voltage characteristics of the solar cell will be presented and the fuzzy logic model development for the charge control will also be presented.

INTRODUCTION

There are many applications for MEMS (Microelectromechanical systems) devices for remote sensor applications. Presently, there exists growing interest in the development, fabrication, and volume manufacture of µbatteries as elements of power supplies that can be integrated with micro sensor and actuator systems in MEMS [1]. While primary µbatteries are capable of providing energy to a MEMS sensor, the available energy is very limited because of the small size of the µbatteries. Secondary batteries offer the prospect of powering MEMS devices for much longer periods of time but require a recharging power source and charge controller. For MEMS devices used in remote locations, it is important to select a recharging source that is available from the environment surrounding the µbatteries.

One such source is solar power and efficient silicon solar cells can be made using conventional silicon wafer microfabrication techniques [2]. Bipolar Technologies Corp. ("BTC") has also been developing a novel microfabrication method for manufacturing secondary µbatteries of both Ni-Zn and Li-ion chemistries using silicon wafer processing methods [3]. The final element that is required for a complete micro-power supply for MEMS applications is a charge controller that can control the charging of the µbatteries. In this paper we present recent results obtained in a DARPA Phase I SBIR program, where we have fabricated µbatteries by BTC's unique process, and have designed and implemented a fuzzy logic-based charge controller for charging µbatteries using small solar cells.

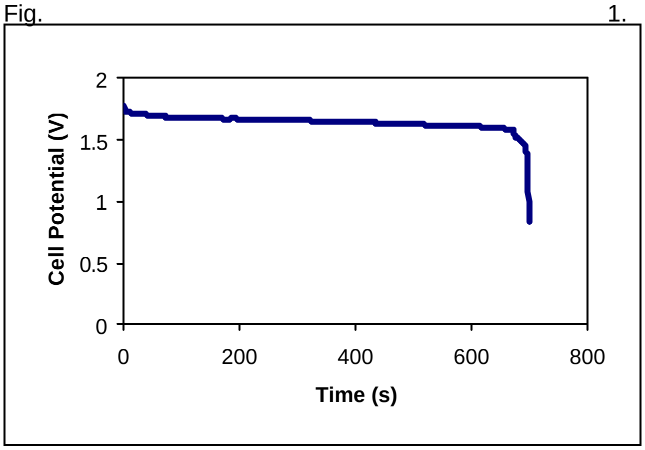
MICROBATTERIES

Microbattery development programs have been reported at NASA's JPL [4] and DOE's Sandia [5] and Oak Ridge [6] facilities. Typically, electrode fabrication is based upon in situ methods, such as (i) manual pasting or (ii) electron beam deposition followed by annealing (700 ^{o}C), processes which are not fully integrable with IC-industry standard microelectronic fabrication techniques, such as are used to make transistors and other IC components. In distinction, ex situ manufacture of the battery active materials with subsequent fabrication of μbattery components, using IC-industry standard unit operations (patterning, masking, etching, and deposition) on a wafer in a clean room environment would enable high volume low-cost manufacture of fully integrable μbatteries.

devices [3]. Typically, these devices are characterized by low power, but are capable of producing short bursts of high current and have long cycle life (~10,000 cycles). Although “macroscopic” cylindrical Li-Ion cells are well known to provide significant specific energy (Wh/kg) advantages in comparison to Ni-MH (and Ni-Zn) batteries, μbatteries cannot take advantage of these gravimetric effects, since their weight is negligible with respect to the device. In fact, from the standpoint of commercial products, the energy densities (Wh/l) of the lithium and alkaline systems are similar.

Two different lithium-ion cell geometries are in development. The first is a “coplanar” cell, where flat electrodes are placed next to one another (i.e. in the same plane). This type of cell is easily fabricated but suffers from reduced power output, due to ohmic losses through the long electrolyte path between electrodes. The second cell geometry is a “stacked” arrangement, where the anode, separator, and cathode layers are placed upon one another. This geometry has, obviously, lower cell impedance and makes more efficient use of available space on a wafer substrate. Initial efforts to fabricate such cells with photolithography have been disappointing, but improved processes have recently been successfully used, and this cell concept is rapidly maturing.

Additionally, BTC has recently manufactured sealed Ni-Zn μbatteries. These are also made in a coplanar arrangement and have exhibited long cycle life and good low-temperature operation. Discharge characteristics on a recently manufactured sealed Ni-Zn cell is shown in Fig. 1.



Pioneering work in this area has been conducted by BTC in which both Ni-Zn and Li-Ion μbatteries have been fabricated on Si wafers and are fully integrable into MEMS

Fig. 1. 50 μA Discharge characteristics of a 1.9 x1.3 mm sealed Ni-ZN μBattery

SOLAR CELL CHARACTERISTICS

Calculator-size, amorphous silicon-based solar modules were acquired and characterized to determine their suitability for the present application. The current-voltage characteristics of these devices were measured using a 100 W incandescent light source held 40 cm from the solar cell. The solar cell selected for developing the μbattery charge controller was one obtained from Sinonar (Model No. SS-5816). This solar module comprised sixteen series connected cells of 0.52 cm^2 area each. This module was selected because it was the only one that offered an open-circuit voltage higher than the open circuit voltage of the Li-ion cell (3.75-4.25V). The output characteristics of this module are shown in Fig. 2.

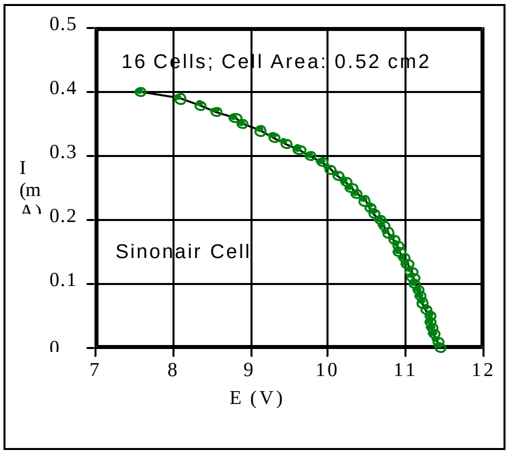


Fig. 2 Current-Voltage Characteristics of the Sinonar Model SS-5816 Amorphous Silicon Solar Module (measured under 100W incandescent illumination at a distance of 40 cm. from the module)

FUZZY LOGIC-BASED MICROBATTERY CHARGE CONTROLLER

The power output of a solar cell varies according to the load across the device. In order to provide maximum power transfer from the solar cell to the load, the voltage across the load must correspond to the peak power point of the solar cell. To reduce the current flow from the solar cell to the load, the operating point of the solar cell can be shifted to be close to the open-circuit voltage of the cell. Thus current output control may be achieved by controlling the effective impedance seen by the solar cell.

A suitable charge controller topology to achieve the control described above is a dc-to-dc controller with pulse width modulation control. A buck type converter, which steps down a solar cell voltage to a lower value is shown in Fig. 3.

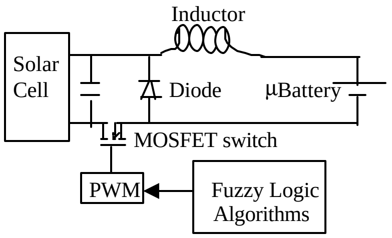


Fig. 3. Fuzzy Logic-Based Solar Charge Controller Circuit Topology

A pulse width modulator ("PWM") is used to supply a pulse train to the switching MOSFET. The MOSFET is biased into a conducting state when the pulse voltage is high and into a non-conducting state when the pulse voltage is low. The duty cycle of the pulse determines the effective impedance seen by the solar cell. Thus by simply adjusting the duty cycle of the switch, the current flow to the battery may be controlled.

The algorithms used to provide the charge control are based on a fuzzy logic approach. There are four parameters that are monitored inputs to the fuzzy model: 1) the solar cell voltage, 2) the current flowing through the battery, 3) the battery voltage, and 4) the analog control voltage that controls the duty cycle of the PWM chip. The output of the fuzzy model is a bipolar voltage signal that is summed with the control signal to decrease, increase, or leave unchanged the control voltage input to the PWM chip. The input and output parameters were fuzzified into three subsets each – low, medium and high, and triangular/trapezoidal membership functions used for each variable. A large number (81) of control rules were established to control the system of the form, e.g., *"if solar cell voltage is high and current flowing is high and battery voltage is low and control voltage is high, output is constant"*. When the solar cell is in the dark, the battery is disconnected from the load to prevent the battery from discharging through the solar cell. If the battery is fully charged, the solar cell is again detached from the battery to prevent overcharging. The fuzzy logic approach allows a smooth control surface to be established with a fast development time. The current model is not optimized but provides a good initial model for the charge control.

EXPERIMENTAL RESULTS

The dc-to-dc converter has been implemented on a breadboard using discrete components including an ultrafast switching diode (Motorola MUR190), a low loss MOSFET (Motorola MTP7N20) and an inductor of 122 mH. The inductor size was calculated based on a switching frequency of 20 kHz and a capacitance value for the μbattery of 1 nF. A high speed MOSFET driver chip with totem pole output (Motorola MC34151) is being used to rapidly switch the MOSFET to minimize switching losses, and a precision switchmode pulse width modulator control circuit (Motorola MC34060A) has been set up to provide the switching control for the MOSFET.

A Motorola MC68HC11EVB evaluation board containing a Motorola 68HC11 microcontroller, a parallel communication port for downloading the development software from a PC to the microcontroller, and additional peripherals were used to implement the controller for controlling the charging of the battery. The sensed input variables were signal conditioned to lie in a 0-5V range to fully utilize the input resolution of the A/D converters on the microcontroller, and the fuzzy algorithms were coded into the microcontroller. Additional control software was written to control the microcontroller data processing. A software summing of the previous control voltage to the fuzzy computed control voltage error signal was coded into the microcontroller. The resulting digital form of the modified control voltage was then fed to a D/A converter from which it was output to the PWM chip.

The circuit has performed as expected, disconnecting the battery when the solar cell is in the dark or if the battery is close to fully charged and offering good current control to the battery at different μbattery states of charge. Two sample test condition results are presented below:

1) Vbattery = 0.86 V , Vsolar cell = 4.18 V , Current = 0.38 mA and Vcontrol = 1V

   The new control voltage = 1.8 V

2) Vbattery = 1.55 V , Vsolar cell = 4.22 V , Current = 0.36 mA and Vcontrol = 3.3V

   The new control voltage = 0.18 V

In the first case, the μbattery is in a low state of charge and the solar cell current and voltage are relatively high. This results in an increase in the control voltage to supply more current from the solar cell to the μbattery. In the second case, the μbattery is in a high state of charge and the solar cell current and voltage are relatively high.

This results in a reduction of the control voltage to disconnect the solar cell from the battery.

A limitation with the present algorithm is that the slight overcharging required for Ni-Zn cells has not been effectively included in the fuzzy algorithm. This will be incorporated into the next generation device.

CONCLUSIONS

The goal of this project is to demonstrate a micropower supply design for MEMS devices which has the potential to be fully integrable on a silicon wafer with the MEMS device. We have presented recent developments on µbatteries that are manufactured using IC microfabrication techniques. We have also designed, built, and tested a fuzzy logic-based solar controller to provide charge control to a µbattery. The design of the controller is based on a step-down dc-to-dc converter topology with the operating point of the solar cell being controlled by a fuzzy logic algorithm implemented on a Motorola 68HC11 microcontroller.

The next step in this project is to design and fabricate a multi-chip module MEMS micro-power supply comprising a high efficiency Si solar cell, an ASIC charge controller, and the µbatteries fabricated using microelectronic fabrication techniques.

ACKNOWLEDGMENTS

This work was supported by a DARPA SBIR Phase I Award (Contract No. USZA22-98-C-0005). The authors gratefully acknowledge Paul Humble at Brigham Young University (Provo, UT) for assisting in the fabrication of the µbatteries.

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