

Nano current charging algorithms for thin film lithium microbatteries

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Abstract

Integrated microbatteries are currently being developed to help provide localized current capacities or embedded power supplies at the chip level, for space exploration.

This paper presents a design approach for charging and discharging such microbatteries. The microbatteries are charged using these complementary algorithms based on constant current, constant voltage and pulsed current. A unique experimental setup is developed to implement the above mentioned algorithms. Lab results are shown as part of this paper. The microbatteries used are rated at 50nAH capacity and are solid state lithium electrolyte based.

Index Terms – Micropower, Microbattery, Pulse Charging and Battery Chargers.

1. Introduction.

Over the years, there has been an increased growth in wireless electronics and distributed electronic architectures. This has pushed the need for developing miniaturized power sources. Recent work has focused on the integration of the power generation, storage and distribution into a single, highly compact package. This module can be integrated with the microdevices to be powered – a “micropower” source. Micro power sources also find a wide range of terrestrial applications, particularly where battery lifetime and environmental limitations play a role.



Figure 1 Microbatteries fabricated on a Si substrate

TABLE I

LITHIUM BATTERY	CHARACTERISTICS
Capacity	1- 200nAH
Voltage Rating	
Rated Voltage	4.25V
Maximum Overcharge Voltage	4.3 - 4.4V
Electrical Breakdown	5.5V
Operating Range	4.25V – 3V
Deep Discharge to	0V
Charge / Discharge Rating	
Rate of Charge	0.1C to 10 C
Efficient Rate	0.1C to 0.15 C
Normal Rate	1.0 C

Towards achieving this goal, Jet Propulsion Laboratory (JPL) has recently reported the development of microscale batteries, fabricated on silicon wafers (Figure 1), with footprints on the order of $(50-100\mu\text{m})^2$ [1]. The capacities of these cells are primarily limited by the thickness and area of the cathode film. These microbatteries, unlike the traditional polymer batteries, are composed of a sputtered cathode (a lithium-transition metal oxide) and anode (typically tin oxide). Cathode films are composed of lithium cobalt oxide and the anode is either sputtered tin oxide or evaporated lithium metal. At the heart of the microbattery is the solid-state electrolyte, composed of a glassy lithium ion conductor, usually a compound containing lithium, phosphorous and nitrogen. This electrolyte imparts a long calendar life to the cells (with respect to traditional liquid electrolytes)[2].

These microscale batteries are fabricated in the discharged state and thus must be charged before use [3]. Charging these microbatteries is a challenging task since they exhibit capacities in the range of nano-ampere-hours. This paper describes the several charging algorithms, which can be used to charge the microbatteries. The microscale batteries are charged using methods based on constant current, constant voltage, and pulsed current [3]. A unique laboratory setup is developed which helps in charging/discharging the microbatteries efficiently.

2. Microbattery characteristics.

The microbatteries used for the project have been designed, fabricated and tested at JPL, California Institute of technology [2]. The characteristics of the microbatteries are listed in TABLE I. These microbatteries are prepared using a special microfabrication process [2]. Microbatteries prepared using this process have specific capacities, with acceptable rate capabilities and discharge voltage profiles. These microbatteries can be cycled hundred of times with minimal capacity loss (Figure 2) [2].

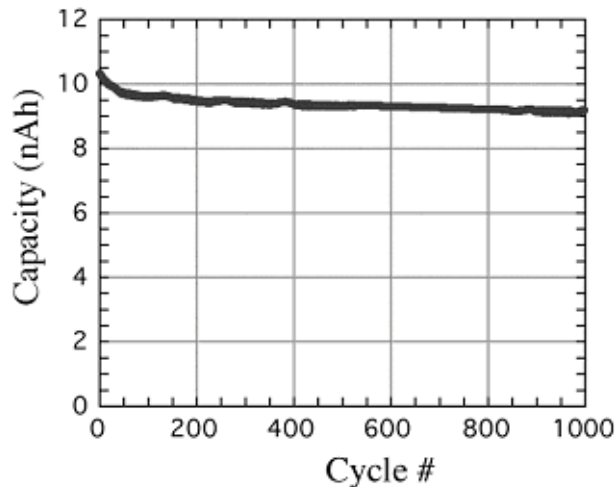


Figure 2 Microbattery capacity as a function of cycles

The basic electrochemistry of the cell involves only the transfer of lithium ions between the two electrodes as seen in Figure 2. Due to the high cell voltages of 4.25V, the specific energy of this battery system is very favorable in comparison to the other known and commercialized secondary battery systems. They use a non-aqueous electrolyte, which is composed of organic liquids and salts of lithium to provide ionic conductivity [5]. This system has much higher cell voltages than the aqueous electrolyte systems.

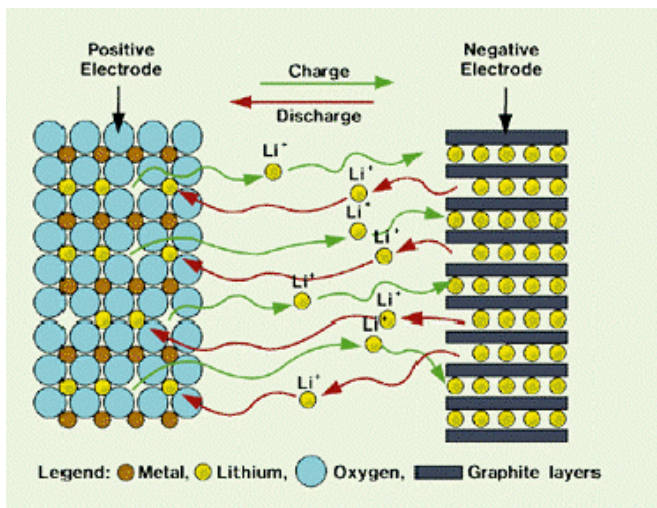


Figure 3 Lithium microbattery behavior [8]

Overcharging or deep discharge for thin film microbatteries is not advisable. This is because overcharging leads to capacity loss with a significant increase in microbattery resistance due to cathode degradation. Also due to overcharge, lithium metal gets deposited on the anode and thereby hydrogen gas is released.

Deep discharge also should not be practiced because, it leads to uneven deposition of lithium on the cathode material. This leads to the formation of dendrites or other surface defects. If deep discharge is continued to be practiced, then these dendrites get more into the electrolyte and the overall system fails short. Another failure mechanism is the formation of regions of material that do not exchange ions as well. The system eventually fails open in the latter case.

3. Charging algorithms.

Lithium microbatteries commonly employ a constant current constant voltage (CCCV) charging algorithm as seen in Figure 4. In other words, a lithium microbattery is charged at a set current level (normally equal to 1C (capacity) rating of the microbattery) until it reaches its final voltage. At this point, the charger circuitry switches over to constant voltage mode, and provides the current necessary to hold the microbattery at this final voltage (4.25V per cell). During the constant voltage phase, current drops exponentially to a zero value. Thus, the charger should be capable of providing stable control loops for maintaining either current or voltage at a constant value, depending on the state of the microbattery [3].

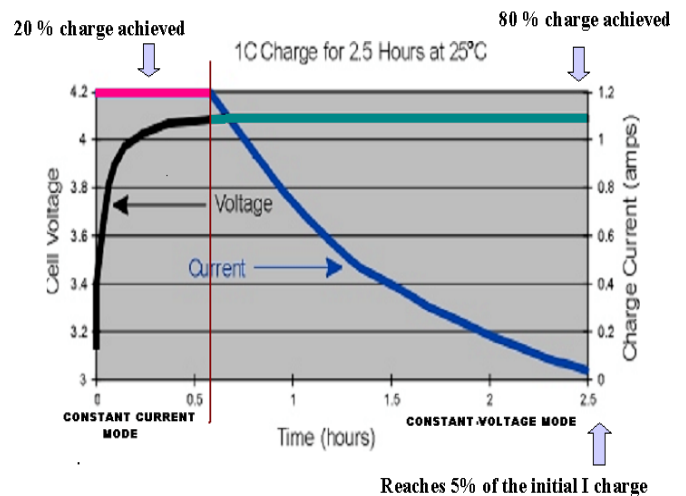


Figure 4 Constant current constant voltage(CCCV) behavior

The constant voltage regime is terminated when the charge current tapers down to a preset value (Normally set to 5% of the constant current value). At this point, it is observed that the microbatteries are charged to their rated values. In the constant current mode, about 20% of the charge is deposited. During the constant voltage mode, the rest of the charge is deposited. The percentage numbers vary depending on the thin film microbattery manufacturer.

TABLE I indicates that the capacity of the microbatteries is in the nano-ampere-hour range. As such, it is difficult to generate a finely accurate nanoampere current source using

discrete components. To overcome this difficulty, pulse charging is considered. It is our experience that the microbatteries can tolerate pulse charging without any apparent deleterious effects. Experimental results have proved that pulse-charging increases the cycle life of the microbatteries due to improved replating of lithium [3]. The basic concept is to charge thin film microbatteries with large values of current, but with a small duty cycle at high frequencies. This produces a finely accurate net lower average current.

One of the several pulse charge algorithms that can be implemented is as shown in Figure 5. In this method, a positive pulse equal to the 10C rating of the microbattery is applied. The initial current pulse is approximately set to 200ms. The duty cycle of the applied pulse is slowly increased. This slowly raises the charge potential of the microbattery. As the microbattery potential nears the 4.25V value, the amplitude of the current pulses is slowly decreased. At this time, the current pulse is reduced to 0.1C rate for one hour. At the end of one hour, the microbatteries are charged as defined by the 5% trickle current. The OFF periods allow the ions a chance to diffuse and distribute more evenly throughout the microbattery.

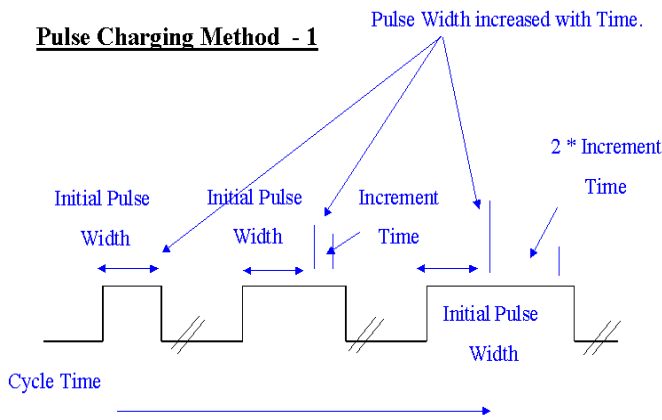


Figure 5 Pulse charge algorithm - A

Another pulse charge algorithm that can be implemented is as shown in Figure 6. The amplitude of the charging current pulse is determined by taking into account the charging circuit design capabilities. Parameters include the current and voltage capability of the charging system and the recharge time.

The amplitude of the charging current is set near the 7C rating of the microbattery. On the charge step, the LiCoO_2 cathode is oxidized rapidly due to the increased flow of carriers [6]. The Li^+ ions also simultaneously migrate at a faster rate to the anode where they are reduced to form the Li metal.

When a high positive current pulse is applied, an island of charge carriers gets eventually stagnated at the positive electrode. This takes some time to disperse. The total charging time can be lowered if the electrodes are given time to equalize their internal charge polarization gradients. This is achieved by applying a negative pulse, which is typically set at about the same amplitude as the charging current limit. After the recovery period, the charge current, which had

dropped to low values, will start and continue at higher values. This is carried on till the polarization gradients reach the previous high value. For the microbatteries in hand, discharge pulse is approximately set to 5ms for every 1.1 second. This complete pulse pattern repeats for every 1.1 second. The pattern is repeated till the microbatteries reach their rated capacities. The discharge pulse also reduces the voltage-induced stress in the microbattery due to the high positive pulse.

Pulse Charging Method - 2

Pulse Amplitude determined by Charging Environment.

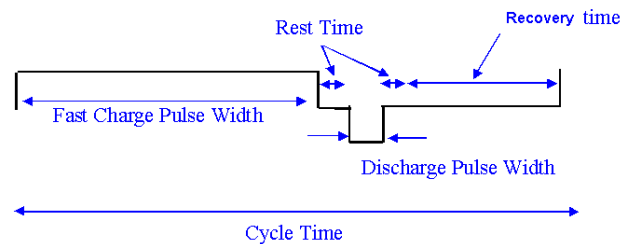


Figure 6 Pulse charge algorithm - B

4. Lab based battery characterization setup.

A special laboratory based setup is implemented to charge these microscale batteries. As seen in Figure 7, a HP 4145B Semiconductor Analyzer acts as a voltage/current source. Both the CCCV and the pulse charge algorithm can be practiced. The charged cell can also be discharged by reversing the polarity of the current.

The HP 4145B Semiconductor Analyzer supplies the desired constant current to the microbattery. This slowly raises the microbattery voltage. At the same time, the multimeter records the voltage reading for every ten-second interval. When the microbattery reaches its rated voltage value, the current source is replaced by a voltage source.

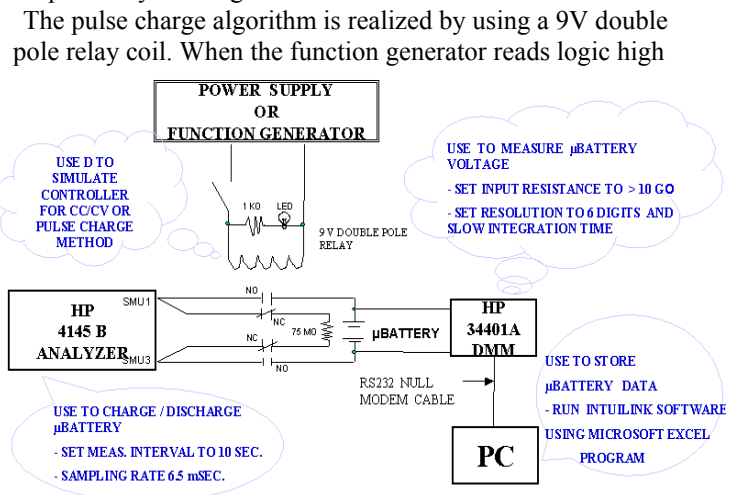


Figure 7 Microbattery characterization setup

value, an electrical contact is established between the microbattery and current/voltage source. In this condition, there is a charge flow into the microbattery. Otherwise, the relay is open and the current flows through a 85Mohms resistor. This makes sure that the source always sees an equivalent load and doesn't change mode of operation erroneously.

As mentioned earlier, a HP34401A multimeter is connected in parallel to the microbattery for data recording. The internal resistance of the meter is set to a very high value ($>10\text{Gohms}$). This is done to minimize leakage currents. Since nano ampere measurements are made, it is important to gain additional noise rejection. This is done by changing the resolution value to six digits with slow integration time. The recorded data (voltage and current) can be plotted in a graph as a function of time as shown in Figures 8 and 9. This is achieved by using a personal computer running a software program called the Intulink Software.

5. Characterization results.

Several thin film microbatteries were charged using the experimental setup shown in Figure 7. Figure 8 shows the charge profile of the microbattery using the CCCV algorithm. The microbatteries showed a behavioral response consistent with a nice RC model during the constant current phase. When the microbatteries reach the rated voltage value, a transition to constant voltage regime occurs. The microbattery is maintained under constant voltage mode for a period of one hour. By the end of one hour, the microbattery is fully charged as defined by the 5% trickle current.

From experimental data gathered over many charge cycles, an interesting observation is made. It is seen that the amount of time required to reach the voltage peak is an inverse function of the cycles. In other words, older microbatteries spent less charge cycle time under constant current mode.

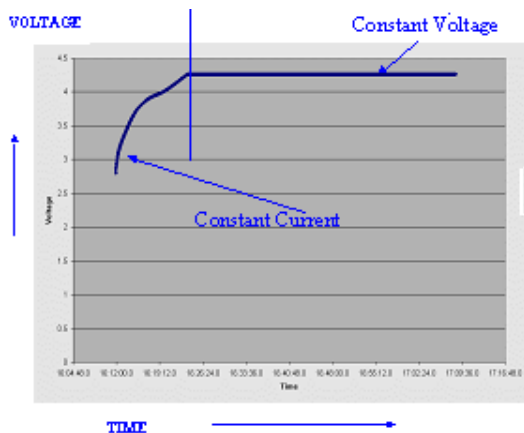


Figure 8 Microbattery charge profile

The microbattery is discharged by reversing the polarity of the current as seen in Figure 8. The discharge current is maintained close to 1C rating of the microbattery. The microbattery exhibits a nice flat discharge profile before it reaches its lower region of operation. For applications such as

on-chip voltage reference, it is important that the microbattery have a flat discharge curve.

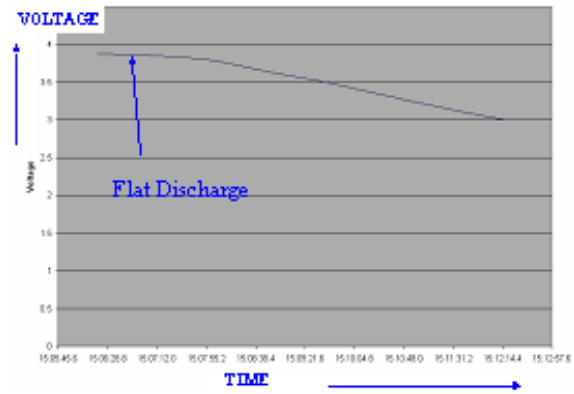


Figure 9 Microbattery discharge profile

From experimental data, again an interesting observation is made:

Microbatteries more closely approximate ideal microbattery response, as the number of discharge cycle increases. (Ideal microbattery has a constant voltage throughout a discharge, which drops instantaneously to its lower acceptable range, when the microbattery is fully discharged).

The microbatteries have yet to be tested using the pulse charge algorithm. Experimental data will be presented in the conference.

The charging algorithms have also been implemented at the chip level. Maximum flexibility in terms of voltages and currents are also obtained through the use of a switching matrix. The designs are built using Microwave Silicon-on-Insulator Process [7].

6. Conclusions.

The operating characteristics of the microbatteries are presented. Charging algorithms for the microbatteries using constant current, constant voltage and pulse current are proposed. A unique experimental setup to implement the nano current charging algorithms is developed. This is appropriate for any microbattery charge of the stated size (50nAH microbattery). A desired discharge profile of the microbatteries is successfully achieved by using negative current pulses. Microbattery discharge response is directly proportional to the cycles of usage.

7. Acknowledgements.

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