DEVELOPMENT OF RECHARGEABLE MICROBATTERIES FOR AUTONOMOUS MEMS APPLICATIONS

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ABSTRACT

This paper outlines fabrication and evaluation of a thin-film, rechargeable microbattery that provides sufficient power for many autonomous MEMS applications. Initial prototype microbattery cells achieved current densities greater than 12mA/cm² and were recharged for more than 260 cycles at an operating voltage of ~1.5volts. Other prototype microbattery cells produced current densities greater than 18mA/cm² and successfully recharged more than 35 times. The microbattery reported here was fabricated using high-volume, thin-film processes that produce microbattery cells with thicknesses of less than 100µm (excluding the inert substrate) and a form factor consistent with high-volume electronic assembly methods.

MEMS REQUIREMENTS FOR MICROBATTERIES

MEMS devices have the potential to revolutionize the way computational capability connects with the world of our experience. The paradigm of fabrication for MEMS provides the promise of inexpensive, capable sensing/actuation systems that will permeate our lives in the future. MEMS promise to greatly enhance the gathering, evaluation, and communication of information in future applications.

The great strength of MEMS as a technology frequently depends on 1) the ability that MEMS provides to combine great functionality in a single, integrated system solution, 2) the low-cost, high-volume nature of MEMS fabrication, and 3) the overall reduction in size and mass of sensor/actuator systems. Most existing technology emphasizes development of the technology necessary to fabricate MEMS and electronic devices that meet these three goals. The overall goals of many applications will not be met, however, unless an appropriate power source solution is developed as well. For many applications a thin-film microbattery is such a power source solution.

Table 1 compares the characteristics of several power source options with respect to size, weight, energy supply capability, and difficulty of assembling the battery into a low-cost, high-volume system. The characteristics of each of these power sources determines the area of application for which they can be used. As can be seen from the table, the microbattery provides a small, rechargeable, easily integrable power solution that no other power option provides. Of particular interest is the capability of

microbatteries to be integrated into complete MEMS systems using automated assembly techniques developed for electronic systems. Use of these assembly techniques sharply decreases the cost and increases the obtainable complexity of integrated MEMS systems.

Power Source	Size	Weight	Energy Capability	Assembly Difficulty
From the Wall	Very Large	N/A	High	N/A
Battery Brick	Large	Heavy	Moderate	Very Difficult
Coin Type Battery	Small	Light	Low	Difficult
Micro-battery	Micro	Very Light	Low	Simple

Table 1 - Qualitative comparison of power source characteristics

Table 2 lists several potential high-volume applications for MEMS together with an indication of the power source requirements for the majority of applications in the given application area. As shown in the table, many of the application areas require an integrable microbattery power solution. In general, systems that require mobile, autonomous, extensively integrated sensors require a microbattery solution. A requirement for mobility excludes standard wired power sources. A requirement for autonomy excludes primary battery systems that cannot power integrated systems for extended periods. A requirement for small size, extensive integration, and large numbers of units excludes the use of coin or standard format batteries because of the difficulty of automated mounting such batteries into integrated system formats.

Microbatteries also have performance advantages that can be critical to specific system applications such as: multiple, definable voltage levels, high level of integrability, and better power distribution.

Applica- tion/ Require- ment	Remote Sensing Arrays	Integrated Fluidic Systems	Low- power Displays	Embedde d Sensors	Optical MEMS
Size	Micro	Small	Small/ Large	Micro/ Small	Micro/ Small
Weight	Very Light	Light/ Heavy	Light/ Heavy	Light/ Very Light	Light/ Very Light
Energy	Low	Moderate	Moderate	Low	Low/ Moderate
Assembly Difficulty	Simple	Moderate	Moderate	Simple	Simple/ Moderate
External Recharge	Required	Not Always Required	Required	Required	Not Always Required
Required Power Solution	μ Battery	Coin/ μ Battery	Brick/ μ Battery	μ Battery	Coin/ μ Battery

Table 2 - MEMS applications and associated power source requirements

BACKGROUND

Thin-film rechargeable batteries (batteries with active layers on the order of 1-10 μ m) have been a topic of research since at least the early 1980s. Thin-film microbatteries using a metallic lithium electrode layer have been reported.[1] These batteries have lateral dimensions greater than a centimeter and produced relatively low current densities.

Bates *et al.* built on this work and reported a thin-film, microbattery with electrodes of metallic lithium and LiMn_2O_4 and with a solid, Li_3PO_4 electrolyte. [1,2] The authors also reported development of a multi-layer coating that protected the highly reactive lithium electrode from reaction with the microbattery environment.

The $\text{Li}/\text{LiMn}_2\text{O}_4$ electrochemical system produced an output voltage between 3.8 and 4.5 volts and were able to be cycled from charge to discharge more than 600 times. The microbattery cells described in these papers were fully solid state and were processed using evaporation and sputtering deposition techniques. The microbattery cells reported in reference 1 exhibited an energy capacity of 34.2mC/cm² (9.50 μ A-hr/cm²) at a current density of 8.3 μ A/cm² and an output voltage of ~4.1volts.

Due to diffusion limits in the LiMn_2O_4 cathode, current densities for the reported $\text{Li}/\text{LiMn}_2\text{O}_4$ cells were limited to less than 1mA/cm² and battery output current densities above 0.2mA/cm² resulted in reduced energy capacity. For example, the microbattery reported in reference 1 produced a maximum current density of 0.83mA/cm² but with an energy capacity of 20.8mC/cm² at an output voltage of ~3.9volts.

The low current density and energy capacity of the microbatteries reported by Bates *et al.* limits their use in many MEMS applications, even those with low-power requirements. The reactivity of metallic lithium also limits the integration of the microbattery process with integrated circuit and MEMS processes.

The goal of the work reported in this paper is to produce a microbattery that can produce current densities greater than 10mA/cm², with an associate energy capacity of greater than 250mC/cm². Battery output voltage must also be greater than 1.0volt. Higher system voltages can be easily obtained using these 1.0volt cells due to the ease with which the microbattery cells can be placed in series to produce higher output voltages.

The Ni/Zn system using a KOH electrolyte was selected because it met these requirements. The open circuit voltage of this electrochemical system is 1.73 volts and high current densities are possible. The promise of this system was born out by the measured results reported here for microbattery cells fabricated using the NiO-OH/KOH/Zn system. Fabricated prototype microbattery cells produced current densities as high as 12mA/cm² with an associated energy capacity of 290mC/cm² at an output voltage of ~1.5volts.

FABRICATION

The microbatteries developed in this work are based on a Ni/Zn electrochemical couple and an aqueous KOH electrolyte. The processes used to fabricate the microbatteries are all traditional integrated circuit processes and were fabricated in the class-10 cleanroom facility of the Integrated Microelectronics Laboratory at Brigham Young University. The completed microbattery structure has a thickness of less than 100 μ m, excluding the thickness of the base silicon substrate. Figure 1 illustrates the process flow using schematic profiles of the process during fabrication.

The process begins with growth of a global, thermal SiO_2 layer on the silicon substrate. The purpose of the SiO_2 layer is to electrically isolate the first battery electrode from the substrate and from other microbattery cells. The only function of the silicon wafer is to act as a substrate for subsequent fabrication and it does not participate electrically in the function of the microbattery.

Following SiO_2 growth, a 0.7 μ m Ti/Ni plating base is deposited by e-beam evaporation and the first electrode is globally electro-deposited. The electro-deposited material is 5 μ m of NiO-OH that reacts with Zn and H_2O to form $\text{Ni}(\text{OH})_2$ during discharge of the microbattery cell. At this point of the process, no patterning of the wafer has occurred and figure 1-a) represents the wafer profile.

A photosensitive layer is then spin-deposited on the wafer and the first electrode material is patterned using an aqueous etch of the NiO-OH and Ni layers. The patterned etch is required in order to separate individual microbattery cells as shown in figure 1-b).

Following the deposition and patterning of the first electrode, a 10 μ m layer of Dupont Pyralin 2611D polyimide is spin-deposited on the wafer and cured at 210C. Following cure of the polyimide, a 1 μ m layer of Zn is thermally evaporated onto the wafer to form the top electrode of the microbattery. A photoresist layer is then deposited and a pattern is developed. The Zn layer is then etched with HCl using the resist as a mask. The structure profile at this point of the process is illustrated in figure 1-c).

The patterned Zn then serves as a mask for subsequent O_2 etching of the well for the electrolyte in the polyimide. The etching is performed using a plasma etcher that provides an isotropic etch of the polyimide. The polyimide is thus etched underneath the Zn

mask and the resulting structure profile is shown in figure 1-d). The amount of underetch is critical to proper operation of the microbattery since the cavity volume determines the current output of the cell. During the development phase of the process, test wafers were fabricated that replaced the Zn layer with an evaporated layer of SiO_x . The SiO_x layer is transparent and when test wafers and microbattery wafers were etched in the same etch run, the test wafer could be used to visually evaluate the cavity volume.

Figure 1 - Outline of the microbattery process

After etching of the cavity, the cavity is filled with the liquid, 5 Molar KOH electrolyte. During the development of this technology the microbattery cavities were filled individually using a teflon coated syringe needle that was manipulated into position using a probe station and an adapted probe manipulator. Eventually filling will be performed using a batch process. After completion of cell formation, the cells can be sealed using a laminated polymer film. Contact to the Zn and NiO-OH layers is then made through contact holes etched in the polymeric overlayer. The final microbattery profile is shown in Figure 1-e).

Figure 2 is a micrograph of a completed microbattery prototype that was $(200\mu\text{m})^2$. The rough surface of the lower microbattery electrode is critical to the high-capacity of the cell. Also note the etch/fill hole in the top Zn electrode layer. This hole is the opening in the electrolyte cavity. During prototype fabrication, a teflon coated needle was used to introduce the small volumes of KOH required for operation of the cell. This opening

can be sealed using an inert polymeric laminate after filling of the electrolyte cavity.

Microbattery cells were fabricated in the Integrated Microelectronics Laboratory at Brigham Young University using the process discussed above. Microbattery cells were fabricated with various geometries from a minimum size of $(100\mu\text{m})^2$ to a maximum size of $(1000\mu\text{m})^2$. All of the cells had a thickness of less than $100\mu\text{m}$, excluding the thickness of the substrate. A variety of microbattery geometries were fabricated and the current density results were found to scale with area except for the minimum size microbatteries, $(100\mu\text{m})^2$, where processing limitations significantly degraded microbattery performance.

Figure 2 - SEM micrograph of microbattery cell

MEASUREMENT RESULTS

Initial prototype microbatteries fabricated using this process provided capacities of $200\text{-}300\text{mC}/\text{cm}^2$ at current densities of 10 to $20\text{mA}/\text{cm}^2$. Given an operating voltage of approximately 1.5 volts, these cells produced power densities from $15\text{mW}/\text{cm}^2$ to $30\text{mW}/\text{cm}^2$. The results from this work are much higher than current density results reported by Bates *et al.* for $\text{Li}/\text{LiMn}_2\text{O}_4$ microbatteries and were within the original design targets for the Ni/Zn microbattery cell.

Figure 3 shows discharge data for a set of six microscopic Ni/Zn , $(300\mu\text{m})^2$ cells connected in parallel. These cells produced an average current density of $12.2\text{mA}/\text{cm}^2$ and showed an adequate cycle life of 265 cycles. It is believed that the cycle life of these cells was limited by loss of electrolyte from the cells and will be improved by sealing the cells prior to testing. Greater detail of the measurement of these cells is provided in the paper by LaFollette *et al.*[4]

Although the current densities reported for these cells is high enough for many MEMS devices, the energy capacity is lower than needed for many autonomous applications. As part of this work, the

authors have developed an improved procedure for plating of the NiO-OH electrode that has resulted in energy capacities of greater than $2\text{C}/\text{cm}^2$ in patterned microscopic electrodes. Work is continuing whose goal is to incorporate this high capacity electrode material in a complete microbattery cell. If this improved electrode material is successfully implemented into the microbattery structure described in this paper, a microbattery system consisting of a set of $(200\mu\text{m})^2$ microbattery cells with a total area of 2cm^2 will provide for the period of an hour between recharging: a peak current of 20mA , an average current output of 1mA , and an output voltage of 1.5volts . Applications requiring longer time between charges can be accommodated in a straightforward manner by decreasing average power consumption, increasing the microbattery area, or by stacking the microbattery cells to decrease the system area required to obtain the required energy density.

Figure 3 - Performance of a set of parallel microbattery cells

CONCLUSIONS

This work reports fabrication and testing of a thin-film, microscopic Ni/Zn battery that can provide the power requirements for a number of MEMS applications. The fabricated microbattery cells were measured and provided current densities as high as $12\text{mA}/\text{cm}^2$ at an output voltage of $\sim 1.5\text{volts}$ and were cycled through the charge/discharge cycle more than 260 times. The energy capacity of these same cells was $290\text{mC}/\text{cm}^2$. A new electrode deposition process tested using macroscopic thin-film batteries was measured to have an energy capacity of $2\text{C}/\text{cm}^2$. Future work incorporating this electrode material into a thin-film microbattery promises to produce microbattery cells that provide current densities as high as $10\text{mA}/\text{cm}^2$ for extended periods.

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