RECHARGEABLE 3-D MICROBATTERIES FABRICATED WITH AN EXOTHERMIC NANOPOROUS CASTING PROCESS

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ABSTRACT

Microscale rechargeable batteries could enable new categories of miniature portable devices; however power traditionally provided by MEMS batteries is small. Thin-film MEMS batteries are susceptible to voltage breakdown, have short lifetimes, and frequently have limited rechargability [1]. This paper reports a microscale 3-D Pb/PbO_2 battery, which provides excellent rechargability, current densities and lifetimes.

KEYWORDS: Microbatteries, Exothermic Casting, Nanoporous, Rechargeable

INTRODUCTION

This paper reports on a new category of microbatteries that, insead of using thin-film electrodes, utilizes tall micro-cast porous alloys. Fabrication of the porous, and/or nano-composite micro-cast electrodes is enabled by a self-powered exothermic casting process reported at MEMS '05 [2]. Thin film batteries typically sport cathode current densities and battery lifetimes of around 10-20 mA/cm^2, and 2-20 seconds respectively [1]. The lead/lead oxide micro-cast battery presented here produces cathode current densities of 200 mA/cm^2, lasts 20 minutes, and recharges back to 2.3 volts over multiple cycles. The porous castings allow considerably higher surface area in contact with the electrolyte (Fig. 1). The battery microelectrodes are exothermically cast in deep, sandblasted glass cavities; this allows porous nano-composite metal castings to be fabricated on-chip (Fig. 2). These three dimensional nano-composite microstructures can be designed towards the batteries' surge current, lifetime, and operation stability requirements.

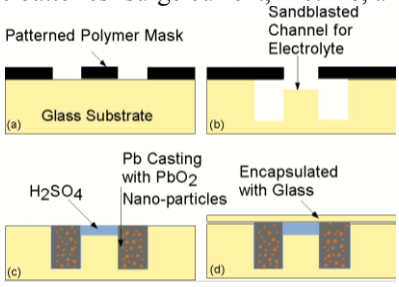

Fig. 1: (a) the patterned polymer mask allows for deep cavity sandblasting. (b) ~1mm deep channel sandblasted in 2 min. (c) Battery electrodes are cast into the device; channel filled with electrolyte. (d) Battery enclosed.

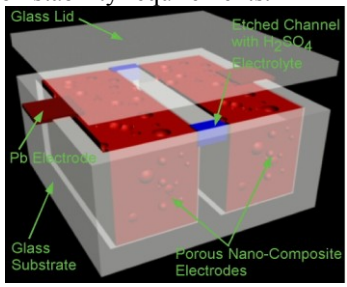

Fig. 2: Sandblasting provides a fast way to make deep cavities on glass. This supportive glass substrate, along with microcasting enables fabrication of the deep micro/nano porous electrodes needed for the battery.

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MICROBATTERY/POROUS CASTINGS

The casting process uses a graphite mold, where PbO_2, Al, and Ni nano/microparticles are ignited; the exothermic oxidization/reduction reaction forms molten metal without a furnace. This self-heated casting process forms molten metal in seconds, allowing non-equilibrium porous and nanocomposite structures (Fig. 3). In this device, castings are fabricated directly into two cavities micro-sandblasted into a 5-mm-thick glass substrate. Sandblasting allows mm deep cavities to be fabricated in minutes, and also provides connecting channels for the electrolyte. Microcast Pb, Pb/PbO_2 nanocomposites, and Pb/Ni porous alloys are used for electrodes (Fig. 4). Porous alloys allow dramatically larger surface areas, increasing current densities (Fig. 5). By adjusting the particle mix, porous castings can be fabricated, and PbO_2 nanoparticles can be imbedded in the lead (Fig. 6). This serves to increase the reaction surface area, and improves the oxidization reaction with the H_2SO_4.

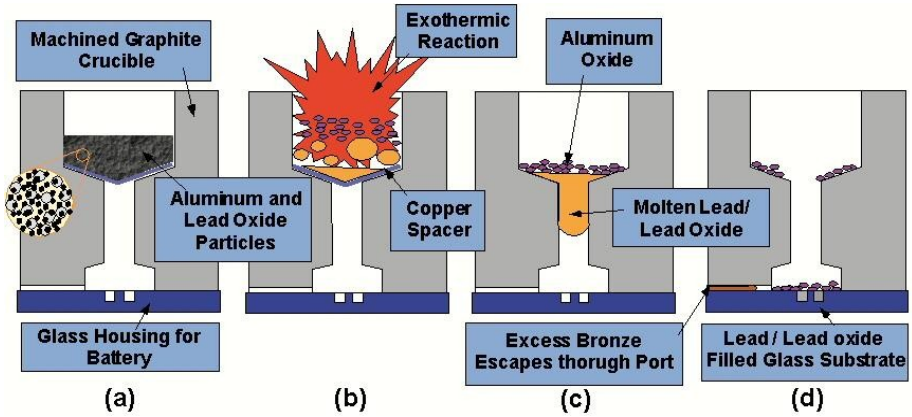

Fig. 3: How NExT AlChemy works: A graphite crucible, holding reactant particles is placed on a micromilled graphite mold (a). The mixture is ignited, reaches thousands of degrees, and produces molten Pb/PbO_2 (b). While an aluminum spacer melts, less dense Al_2O_3 floats to the top (c). Superheated, lower viscosity molten lead fills the glass electrode cavities, the excess material escapes via a side port (d). The graphite mold and crucible are re-usable.

EXPERIMENTAL RESULTS

With the lead/lead oxide microbattery, the maximum single-cell potential reached is 2.3 volts; several mA currents are produced, so the output voltage does not sag until the load impedance is less than 50 Ω (Fig. 7). The width and the length of the patterned glass sulfuric acid channel can be adjusted to change the batteries' voltage and current characteristics. Narrow channel devices produce over 49 mA at 2.3 V, which provides cathode current densities of >200 mA/cm^2. Thin film devices typically provide tens of mA/cm^2. Current densities are appreciably higher in this device because it is a bulk, porous microstructure. As the microbattery casing is glass, very high concentrations of H_2SO_4 can be used, producing higher voltages (Fig. 8). Microcast batteries have operation lifetimes which are appreciably longer

than thin film devices. Figure 9 shows a typical lifetime/charge cycle; the battery operates at reasonably stable voltages for around 20 minutes. Charging time varies, depending on charge voltage and the casting alloy.

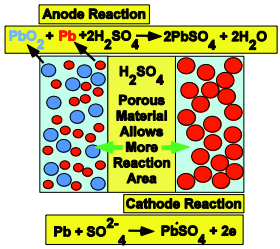

Fig. 4: Lead acid battery reaction: Lead and sulphate react at the cathode to form lead sulphate and 2 electrons. Lead oxide, lead, and sulphuric acid react at the anode to form lead sulphate and water.

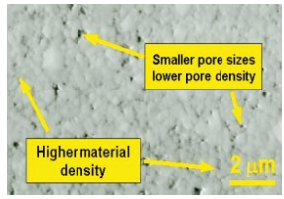

Fig. 5: SEM shot of porous Pb surface which had a higher material density and smaller pore size. These pores increase the surface area of the electrodes' surface allowing more of it to contact the separating electrolyte.

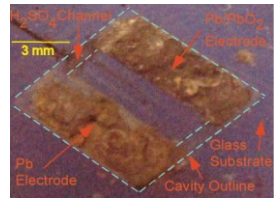

Fig. 6: Photo of battery showing cast electrodes with 2 mm channel widths. The anode is lead/lead oxide. Connecting electrodes are not shown.

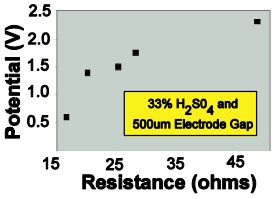

Fig. 7: Large currents produced! The microbattery is able to drive 50 Ω loads without voltage sag.

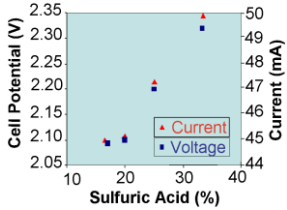

Fig. 8: Glass housing allows strong acid concentrations, nearing maximum theoretical voltages.

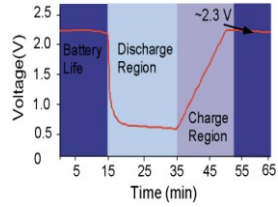

Fig. 9: The microbattery operates for 20 min. at reasonably constant voltages, over numerous cycles with approximately 20 min. required for recharge.

REFERENCES

[1] L.G. Salmon, et.al., Proc. Of the Solid-State Sensor and Actuator Workshop, Hilton Head, 1998, pp. 338-341.

[2] R. Jakka and C.G. Wilson, "NExt AlChemy: Nanoparticle Exothermic Alloying Chemistry for Producing Tall On-Chip Cast Microstructures", *Proc. IEEE Conference on MEMS*, Jan 2005.