A Novel Battery Architecture Based on Superhydrophobic Nanostructured Materials

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ABSTRACT

The paper presents the details of a novel battery architecture based on the superhydrophobic nanostructured materials. In a proposed configuration both electrodes of a battery are formed on the nanostructured silicon surfaces that are subsequently treated to render them superhydrophobic, effectively separating liquid electrolyte from the active electrode material. When battery is activated to provide power, a phenomenon called electrowetting promotes electrolyte penetration into the electrode space to initiate electrochemical reaction. Such architecture provides for an extremely long shelf life, instantaneous ramp up to full power, and chemistry independent functionality.

Keywords: battery, nanostructured, superhydrophobic, electrowetting, shelf life.

1. INTRODUCTION

For decades semiconductor technologies enabling many portable electronic devices have been rapidly advancing at very high rates, at times doubling every twelve to eighteen months. In the meantime, battery technology has been advancing at only 3% to 5% per year and reserve battery capabilities at an even slower rate. Devices containing semiconductor components requiring primary battery or battery back up needs have rapidly proliferated throughout every major national and global economic sector imaginable: transportation, health, defense, security, energy, environmental, and many others. These devices take on forms ranging in physical size from large scale computing devices, personal computers, handheld devices, embedded devices, remote sensors, and even into newly emerging nano-sized devices. Furthermore, the applications of these proliferated devices have become more and more decision critical therefore there is a strong need for breakthrough technology to occur within battery technology.

mPhase Technologies along with its partner Lucent/Bell Labs, has been jointly conducting research over the past year that demonstrates control and manipulation of fluids on superhydrophobic surfaces to create power cells by controlling wetting behavior of electrolyte on nanostructured electrode surfaces [1]. The scientific research we have conducted this year has set the groundwork for continued exploration in the development of intelligent nanotechnology power cells (nano-batteries), and forms a path to commercialization of the technology for a broad range of market opportunities.

In this market environment, the proposed nanobattery would be considered a disruptive technology, a technology that provides a fundamental paradigm shift in battery and power technology. Size, weight and shelf life characteristics could be dramatically enhanced, and chemistries could be chosen to be appropriate for designs that that would be used for powering numerous portable electronic devices such as sensors and transmitters for sensor networks as just one example. Packaging could be more flexible with the potential of shaped or conformal batteries, but still could be designed to work within the requirements of the physical dimensions of existing electronic devices requiring power. Batteries would have intelligence with the potential of being able to activate cells as needed to the power output needed, thus extending the useful duty cycle of the battery. In a reserve configuration, power could always be available as a backup to the primary source because of the negligible capacity loss in such a battery in a reserved state due to its unique architecture. Shelf life would be increased dramatically because the electrolyte would not come in contact with the electrode until activation. Because of the very small distances of the nanostructures, response time to full activation power would be enhanced, creating a power source for high performance electronics needing these characteristics. For the Military, Homeland Security, and First Responders, this feature would be highly desirable because batteries could be stored, for decades, without fear of dissipation. Conventional batteries in storage dissipate as much as 10% per year before use, while the nanobattery is projected to last 15-20 years.

In advanced configurations the silicon based architecture of the battery that is currently being developed has the potential for integration of electronic components directly into the manufacturing process of the battery, to create new classes of tightly integrated devices such as integrated active RFID tags and lab-on-the-chip applications for both defense and commercial markets.

2 Principle of Operation

The proposed battery architecture places our battery into a so-called reserve battery class [2]. The main function of these batteries is to provide power when required while enduring prolonged storage periods (essentially, a battery may sit its entire life in reserve to be activated only for a brief period of time as a back-up power source).

In order to be able to provide such a long shelf life, a traditional reserve battery normally has a mechanical separator to keep electrolyte away from the active electrode materials. Clearly this leads to reduced power density because inert filler materials, actuation mechanism and separators occupy significant part of the battery volume.

Our approach is to employ novel nanostructured superhydrophobic materials coupled with electrowetting phenomenon to create an architecture that allows to keep electrolyte and electrode separate from each other and yet to provide significant reduction in a dead volume in the battery. In the following discussion each component will be individually addressed.

2.1 Nanostructured superhydrophobic surfaces.

Our development capitalizes on the fundamental work performed at Lucent Bell Labs on the dynamic tuning and control of fluids on nanostructured surfaces [1]. The battery utilizes surfaces with the regularly spaced nanostructures etched by a suitable semiconductor fabrication method. The surface represents an array of cylindrical posts, 1 to 5 microns apart, 5-10 microns tall, 100 to 300 nanometers in diameter. When treated with an appropriate fluorocarbon polymer such a surface demonstrates superhydrophobic behavior that distinguishes itself from a regular surface by substantially higher contact angle of a liquid on such a surface (e.g. 120 degrees vs. <90 degrees). A droplet of electrolyte when placed on this surface does not stick to it but rather remains highly mobile as a consequence of small solid-liquid interface. In essence, the droplet is only supported by the very tips of the nanoposts and does not penetrate into the space between them.

Electrowetting gives one the ability to change the contact angle of the solid-liquid interface by applying voltage to the liquid. It has been successfully applied to create a variety of optical devices such as lenses, diffraction gratings and is now combines with nanostructures to create novel batteries and battery architecture with unique characteristics [3-6].

In a situation when a pool of electrolyte sits on top of the nanoposts of a nanostructured surface, it can be triggered to penetrate the nanoposts space and initiate the electrochemical reaction with active electrode material deposited on the bottom.

To fully characterize operation principle, characteristics and proof of concept of our novel concept we decided to start with a well known and well documented battery chemistry to make quick assessment and comparison possible. Therefore, Zn/MnO_2 electrode pair in $ZnCl_2/NH_4Cl$ electrolyte has been chosen to be the first proof of concept system. The next section deals with the advantages that such a battery will have as well as technical challenges that need to be overcome for successful commercialization.

Figure 1 gives a schematic depiction of such a battery showing two electrodes and details of the nanostructure.

3 Nanobattery Advantages

The advantages to using this nanostructured approach gives the battery the following characteristics:

- Improved power densities compared to other reserve battery technologies for its size, due to better utilization of internal surface area of the batteries design that does not require the ancillary structures to create physical separators between the electrolyte and electrodes (Our energy and power density calculations are early extrapolations based on our initial proof of concept feasibility prototype of reserved nano cell based on Zn/MnO_2 chemistries, and we expect similar improvements with other chemistries).
- Flexible architecture allows for wide range of aqueous and non-aqueous chemistries adapted to fit the design.
- Long shelf life, predicted to last over 15-20 years.
- Unique architecture design that allows for individual addressability of nano cells to be selectively activated as required.
- Applicability for primary and reserve battery applications.
- Readily scalable, easy to miniaturize battery.
- Fast ramp up to full power ~ 1 ms.
- Compatible with semiconductor processing and inexpensive to mass produce using microelectronic manufacturing techniques.
- Can be integrated into package with devices it is powering.

4 Technical challenges and demonstration.

The manipulation and control of the electrolytic solution on the electrodes of our battery is the result of our undertaking into the study of organic coatings on the nanostructures such that a superhydrophobic state is maintained on the portions of the nanostructures to repel the aqueous electrolyte, while other potions of the nano structures are kept in hydrophilic state. This superhydrophobic/hydrophilic transition provides the underlying physics of our design that allow the contact angle of the electrolyte solution to change, from having no physical contact with the electrode, in an inactive state, to an active state, where the electrolyte comes into contact with the electrodes, thus producing voltage in the battery.

In Figure 2 we show a typical image of the Zn electrode deposited in the nanopost space using a modified electroplating process. It gives reliable and controllable way of producing metal deposits on a highly conjugated superhydrophobic surface.

A variety of coatings have been evaluated to render surfaces hydrophobic. The material of choice so far remains a coating of conformal low-surface energy fluorocarbon polymer conveniently deposited in a commercial system.

A counter electrode made out of MnO_2 can be created on similar nanostructured surfaces or planar substrate as well. The following Figure 3 presents an actual voltage trace taken from the battery in its inactive state, followed by the triggering pulse with voltage being generated. One can clearly see all the features of the proposed system: dormant state of zero voltage, trigger by a voltage pulse, and voltage generated in accordance with thermodynamic predictions.

In conclusion, we have demonstrated a working reserve battery prototype based on superhydrophobic nanostructured surfaces. It has three distinct features: first, inactive state in which electrolyte is completely separated from the electrodes by the nanostructure; second, battery actuation by a voltage pulse, and third, stable voltage generation. We are now in the stage to refine and fully characterize battery parameters to compare them with the conventional battery structures. The architecture proposed is a disruptive technology, a technology that provides a fundamental paradigm shift in battery and power technology.

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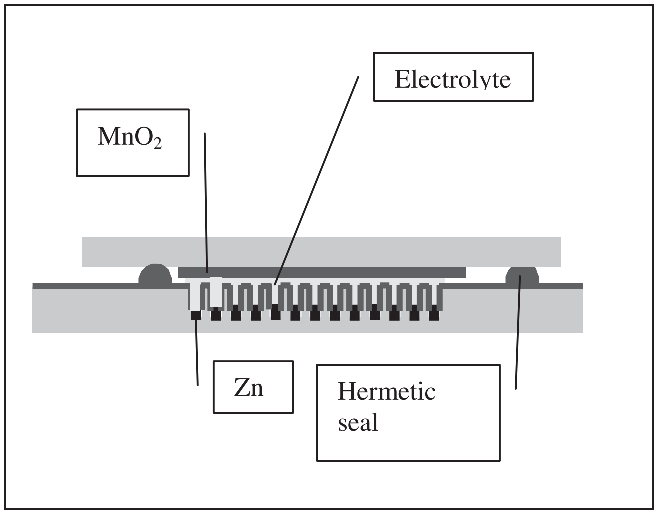

Figure 1. Cross-section of nanobattery in active state. Only essential parts are shown, such as nanoposts, electrolyte penetrating the nanopost space, Zn plated into the nanostructure and MnO_2 deposited onto a planar substrate.

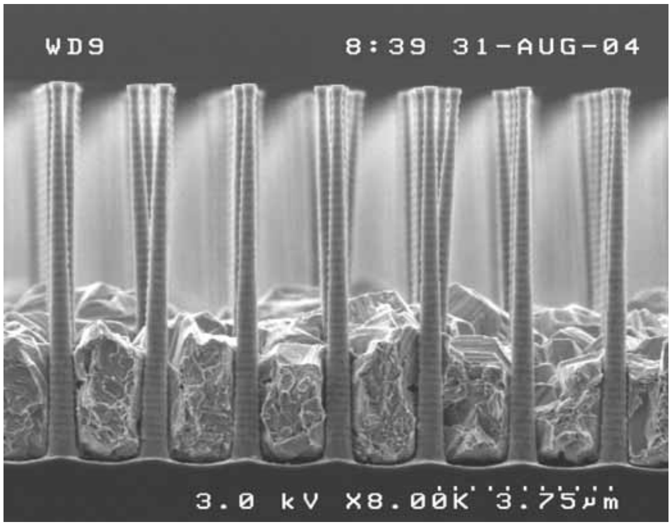

Figure 2. SEM image of Zn deposit on nanostuctructure.

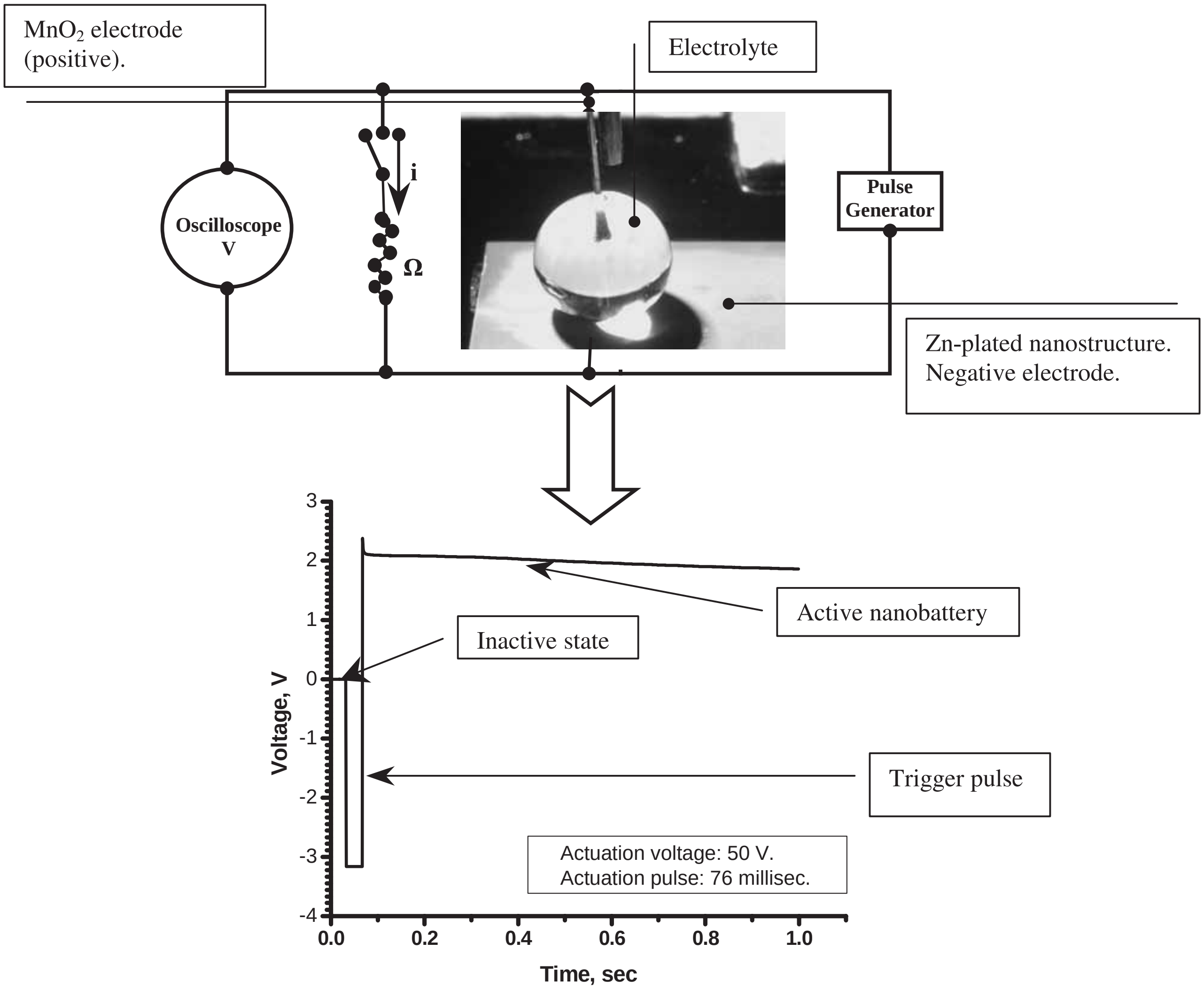

Figure 3. Schematic of battery triggering test and the actual graph of the battery output, showing 3 regions: 1) inactive battery, 2) actuation pulse, and 3) active power generation.