# THREE-DIMENSIONAL MICROBATTERIES FOR MEMS/NEMS TECHNOLOGY

Bruce Dunn[1], Chang-Jin Kim[2] and Sarah Tolbert[3]
[1]Department of Materials Science and Engineering, [2]Mechanical and Aerospace Engineering Department, [3]Department of Chemistry and Biochemistry
University of California, Los Angeles (UCLA) U.S.A.

## ABSTRACT

We recently developed a new approach for battery design based on three-dimensional architectures which offer potential solutions for powering autonomous devices and maintaining small footprint areas. This paper provides a brief review of our work which applies micromachining methods to fabricate electrode arrays which serve as the central design element for these architectures. The results with the zinc-air primary batteries demonstrate that 3D configurations can achieve both high power and energy densities within a small footprint area. The development of lithium-ion batteries has not been as rapid although reversible electrochemical behavior has been demonstrated with 3D electrode array structures.

## INTRODUCTION

The continued emergence of microelectromechanical systems (MEMS) for an ever-widening range of electrical, mechanical and optical products is already enabling small autonomous devices to be created which exhibit such functions as sensing and actuation, communication, and rapid chemical/biological analysis. In order to operate independently, these devices must have on-board power from power sources on millimeter or smaller scales that deliver milliwatt levels of power for tens of hours. Wireless sensor networks represent an especially appealing opportunity because of the potential use of this technology across a broad range of environments including urban infrastructure, buildings, and automobiles [1]. One vision for future wireless sensor networks is to combine energy harvesting from ambient sources (solar, thermal, vibrational) with a rechargeable battery to create a completely self-sustaining power source.

The miniaturization of batteries has not kept pace with the size scaling achieved with CMOS electronics. The smaller area available on the various microdevices requires that batteries reduce their areal footprint. This creates a problem for traditional battery designs with two-dimensional (2D) electrode geometries because the total amount of stored energy for 2D batteries decreases and the corresponding increase in current density often leads to poor battery performance.

In this paper, we present an overview of the emerging area of three-dimensional batteries. These architectures represent a new approach for miniaturized power sources that are purposely designed to maintain small footprint areas and yet provide sufficient power and energy density to operate the autonomous devices described above. Although relatively few results have been reported on functional and practical 3D batteries, the active research efforts on designs, fabrication methods, and materials portend a promising future for this field.

## 3-D BATTERY DESIGNS

A brief comparison (Fig. 1) between the conventional 2-D parallel-plate design (left) and the 3-D array cell (right) illustrates the advantages of the 3-D architecture [2]. The 3-D configuration is based on using the out-of-plane dimension in contrast to traditional battery electrodes which use only the in-

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plane surface. The use of the "vertical" dimension with 3-D architectures provides a design option which enables the battery to have a small areal "footprint". The interdigitated 3-D battery design has a lower energy capacity per total cell volume than that of the 2-D battery. However, the energy density of the 3-D design can be increased by increasing *L*, the length of the electrode rods. In this way, neither the small areal footprint nor high power density are compromised. The length is restricted because of the ohmic resistance of the electrodes, thus limiting the advantages of increased areal capacity. The optimized value of *L* will be determined by a combination of parameters including the electronic and ionic conductivity of the electrodes materials, the ionic conductivity of the electrolyte, and the specific electrode geometry.

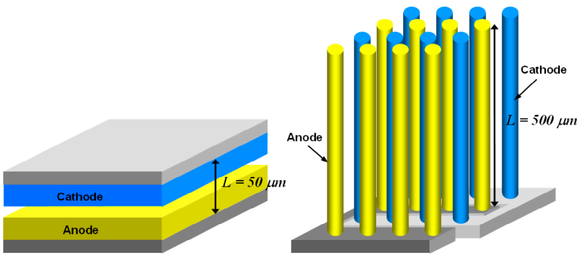



Fig. 1. Schematic of 2-D parallel-plate and 3-D interdigitated-array batteries.

We recently reviewed the various 3-D battery designs which have been either fabricated or proposed [3]. In the interdigitated design (Fig. 1), the anode and the anode and cathode consist of arrays of rods separated by a continuous electrolyte phase (Fig. 2a). The short transport distances between anode and cathode lead to a much lower interelectrode ohmic resistance as compared to traditional planar battery configurations. Another 3-D design is based on a concentric arrangement in which the 3-D electrode array composed of one of the electrochemically active materials is coated by an electrolyte layer (Fig. 2). The other electrode material fills the remaining free volume and serves as the continuous phase. This design also involves short transport distances between electrodes, leading to low ohmic resistance. Another type of 3-D architecture is based on amplifying the area of a thin film battery. This approach is based on anisotropic etching of a silicon substrate and consists of a thin film Si anode, a solid-state electrolyte and a thin film cathode [4]. The prospect of integrating silicon-compatible energy storage with silicon-based devices is very attractive, especially in light of the high energy density for silicon [5].

One characteristic which seems to best define 3-D batteries is that transport between electrodes remains one-dimensional at the microscopic level, while the electrodes are configured in nonplanar geometries in order to increase the energy density of the cell within the areal footprint. Moreover, since 3-D batteries are designed for incorporation into autonomous devices with limited available area for the power source, the operational characteristics of 3-D designs are area normalized rather than traditional gravimetric or volumetric normalization as occurs with 2-D batteries. Thus, the parameters of concern are $mW/mm^2$ and $J/mm^2$ for areal power and energy densities, respectively. The importance of using the areal capacity metric is illustrated by the example of MEMS-based sensing, where the required areal capacity for a lithium-ion battery is estimated to be 5 to 10 $mAh/cm^2$ (0.05–0.10 $mAh/mm^2$) in order for the device to operate continuously for one day [2]. The fact that thin-film lithium-ion batteries provide substantially less than 1 $mAh/cm^2$ underscores the need for 3-D batteries.

## OPERATION OF 3-D BATTERIES

Both lithium-ion secondary and zinc-air primary batteries have been fabricated and operated. Moderately successful results were obtained with a lithium-ion battery based on using an amplified thin film design.

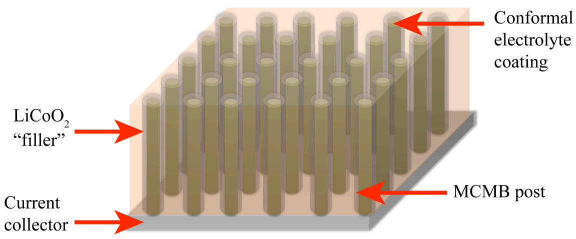
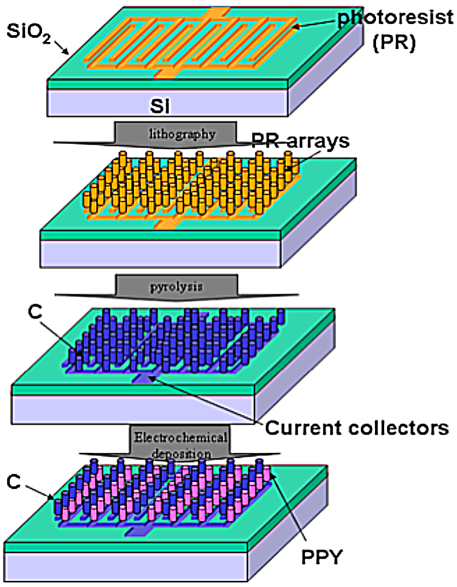



Fig. 2. Schematic of the concentric tube 3-D battery. The key component is a conformal electrolyte film deposited on the carbon array electrode.

The battery could be cycled some 200 times and the areal capacity at low power was ~ 2 mAh/cm$^2$, which agreed well with calculations. Recently, we fabricated a lithium ion secondary battery based on using carbon and polypyrrole as the negative and positive electrodes, respectively [6]. The battery was fabricated by the C-MEMS (carbon-microelectromechanical systems) process. In the C-MEMS approach, photoresist is patterned by photolithography and subsequently pyrolyzed at elevated temperature in an oxygen-free atmosphere. To construct the interdigitated battery (Fig. 3) two separate electrode arrays were fabricated by patterning a two-level SU-8 structure. After pyrolysis, polypyrrole was electrodeposited on one of the carbon arrays. The procedure for fabricating the carbon/polypyrrole battery and the resulting interdigitated structure are shown in Fig. 3. The battery could be charged and discharged, however, its operation was limited because of an electrical short. Nonetheless, this result is an important one for 3-D battery technology as it identified certain shortcomings associated with the interdigitated design.

A much more successful result has been achieved with the zinc-air battery [7]. The anode in this battery consists of an array of high aspect-ratio zinc rods (10-µm diameter) while the separator and air cathode are similar to that found in commercial zinc-air batteries. The operating characteristics of the battery show that high specific capacity is retained even at a discharge rate of 3C. During discharge, oxidation occurs at the outer surface of the rod while each zinc metal core serves as a current collector. The low resistivity of the metal ensures that ohmic losses are minimized and enables high-aspect ratio rods to be used. In this way we have been able to retain high energy and power densities, > 40 mWh/cm$^2$ and > 50 mW/cm$^2$, respectively, with a footprint area of < 0.3 cm$^2$.



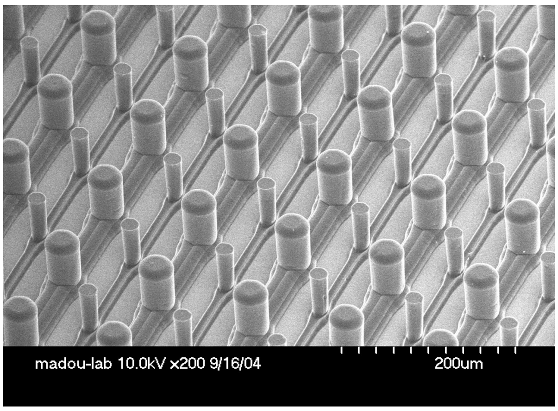




Fig. 3. Process flow for fabricating the carbon/polypyrrole interdigitated battery. The larger diameter rods are the polypyrrole array.

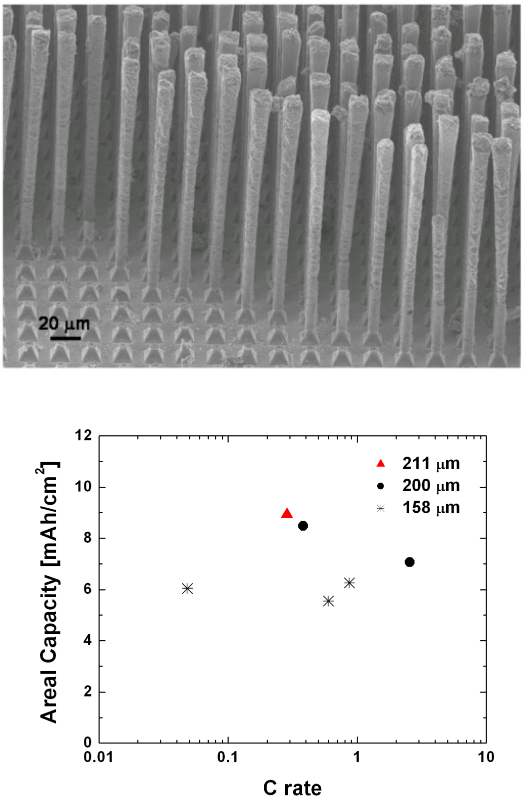



Fig. 4. (Top) Array of zinc rods, 10 µm diameter with a length of 200 µm. (Bottom) Areal capacity as a function of discharge rate for rods of different lengths.

## CONCLUSION

Miniaturized, integrated microsystems such as MEMS and on-chip devices will never reach their undeniable potential until the power source that drives these systems matches their dimensional scale and delivers the energy/power densities required for operation. 3-D battery architectures offer a new approach to the problem of small portable power sources and, as demonstrated with the zinc-air battery, provide a strategy for having both high-rate discharge capability and high energy density within a small footprint area. The 3-D battery field is just beginning to attract attention and the first steps towards realizing miniature power sources are just emerging. It is apparent that with the wide range of architecture designs and materials, the 3-D battery area will continue to be an active area of interest in the future.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] S. Roundy, D. Steingart, L. Frechette, P. Wright and J. Rabaey, "Power Sources for Wireless Sensor Networks", Proceedings Wireless Sensor Networks, 2920, 1-17, 2004

[2] J.W. Long, B. Dunn, D. Rolison and H.S. White, "Three-Dimensional Battery Architectures", Chemical Reviews, 104, 4463-4492, 2004.

[3] B. Dunn, J.W. Long and D. Rolison, "Rethinking Multifunction in Three Dimensions for Miniaturizing Electrical Energy Storage", Interface, 17, 49-53, 2008.

[4] P.H.L. Notten, F.Roozeboom, R.A. Niessen, L. Baggetto, L. "Integrated All Solid-State Rechargeable Batteries", Advanced Materials 19, 4564 (2007).

[5] J-M. Tarascon, M. Armand, "Issues and Challenges Facing Rechargeable Lithium Batteries" Nature 414, 359-367, 2001

[6] H-S. Min, B. Park, L. Taherabadi, C. Wang, Y. Yeh, R. Zaouk, M.J. Madou and B. Dunn, "Fabrication and Properties of a Carbon/Polypyrrole Three-Dimensional Microbattery", J. Power Sources 178, 795-800, 2008.

[7] F. Chamran, H.-S. Min, B. Dunn, C-J. Kim, "Zinc-air Microbattery with Electrode Arrays for Zinc Microposts," in *IEEE Int. Conf. MicroElectromechanical Systems (MEMS '07)* Kobe, Japan, 2007, p 871-874.