Nanoscale Power and Memory Unit Design for Nanoscale Sensor Systems

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Keywords: Nanotechnology, sensors, batteries, memory

ABSTRACT

Nanoscale sensor systems require the development of nanometer scale integrated circuits and components. Due to limits in device physics, new components must be developed to operate at the nanoscale level. As part of this effort, the authors have constructed nanoscale battery arrays that can implement power supply units for nanoscale sensor systems. In addition, the authors are currently developing a nanoscale crossbar system that will use the nanoscale battery cells as data bit storage units. The intended application is a nanoscale memory unit for sensor systems that can be used to store data collected from the sensors. Both the power supply and memory units will allow for the design of independent nanoscale sensor systems that can be embedded at various locations.

INTRODUCTION

Test, instrumentation, and control systems require reliable sensors to measure various environmental parameters, such as temperature, pressure, and radiation. For critical applications, such as military systems, these sensors must be small enough to be embedded in uniforms, weapons, and equipment [1]. Other applications, such as medicine, require sensors that can be used to monitor and assist patients [2]. Often, these sensors must be self-contained systems that include both the sensor and supporting electronic units. These typically include a power unit to supply power to the sensor system, and a memory unit to store data collected by the sensor [3].

Due to limits in device physics, microscale integrated circuits that previously have been used for sensor system designs will not operate properly at the nanoscale level [4]. Therefore, new nanotechnology components must be developed to implement the sensor, power, and memory unit functions. There has been previous research in nanoscale sensor design, such as optical biosensors [5], carbon nanotube thermal sensors [6], silicon nanowire chemical sensors [7], and $SrTiO_3$ oxygen

sensors [8]. However, further research is required in the development of nanoscale power and memory units for these systems. This paper discusses the design of components for both of these units.

NANOBATTERY DESIGN FOR SENSOR POWER UNITS

The expected applications of nanoscale sensors will require these systems to have an independent power source, such as a battery. Previous work has been performed by Teeters in the area of nanobattery development and characterization. This work has been concerned with the construction of individual nm scale battery arrays containing nanometer scale components, including nanoscale cathodes and anodes and their characterization [9 - 16]. Teeters' group has developed the methods to make arrays of these batteries using commercially available nanoporous alumina membranes (Synkera Technologies, Longmont, CO) having hexagonally ordered pores. These pores can range from several hundred nanometers to smaller than 10 nanometers in diameter. The thickness of the membranes is a maximum of 60 microns or less. The techniques for making nanobattery arrays have been developed by Teeters' group [9, 14-16] and will be summarized below.

Arrays of nanobatteries are made by sealing one side of the membrane with a polymer film and applying a coating of sol-gel electrolyte material such as V_2O_5 on the opposite side. Since the nanopores in the membrane are sealed on one side, the sol-gel can only partially penetrate into the pores. The sol-gel is then cured forming the electrodes for this side of the membrane. Excess sol-gel that is above the membrane pores has been found to simply slough off leaving individual nanoscale electrodes for the arrays of nanobatteries at the surface. The polymer seal is then removed from the other side of the membrane by use of a solvent opening the nanopores on this side. A molten poly(ethylene oxide) polymer/inorganic salt electrolyte is introduced into the open pores facilitated by capillary action under vacuum conditions. This side of the membrane is then placed on a continuous layer of electrode material. This is illustrated in Figure 1.

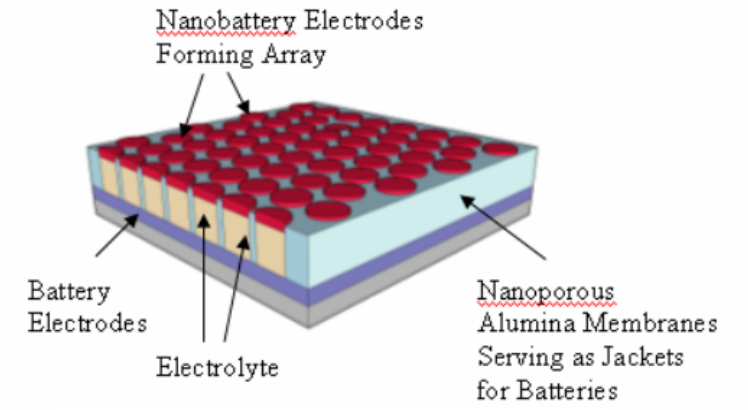

Figure 1. Nanoscale battery system.

To date, nanoscale cathodes and anodes have been coupled with a polymeric electrolyte confined in pores in nanoporous alumina membranes, 200 nm and smaller, to make individual batteries having nm sized electrodes. These nanopower systems have superior electrochemical properties with respect to energy and power densities when compared to similar macroscale systems [14]. Such miniature battery systems are of interest since they have the potential to be integrated into nanoscale devices, such as sensor systems, where larger power sources simply would not fit. When nanoscale sensors collect information from their environment, they will require a memory unit to store the data. At present, the nanoscale electronic circuits that can be fabricated are limited in terms of available nanoscale circuit components and interconnection methods. Teeters' group developed the advanced techniques necessary to conduct tests on individual micro and nanobatteries, such as charge/discharge studies, a.c. impedance spectroscopy and other electrochemical tests [9-11, 13-16] by using the cantilever tip of an electrically conducting tip of an atomic force microscope (AFM) to make contact with the nanoelectrodes. If this tip conducts electrically, it can be touched to the small cathode or anode particle, making electrical contact so that the battery can be charged and tested. Figure 2 shows charge/discharge data collected by using the tip of an AFM cantilever to make electrical contact with the 200 nm in diameter anode of the nanobattery. A charge current of 60 picoamps of current was used while 5 picoamps was used as the discharge current. At this rate of charge at takes approximately 100 seconds to reach its full charge of 3.5 volts. At this discharge rate of 5 picoamps, approximately 10 minutes are required to totally discharge the individual nanobattery.

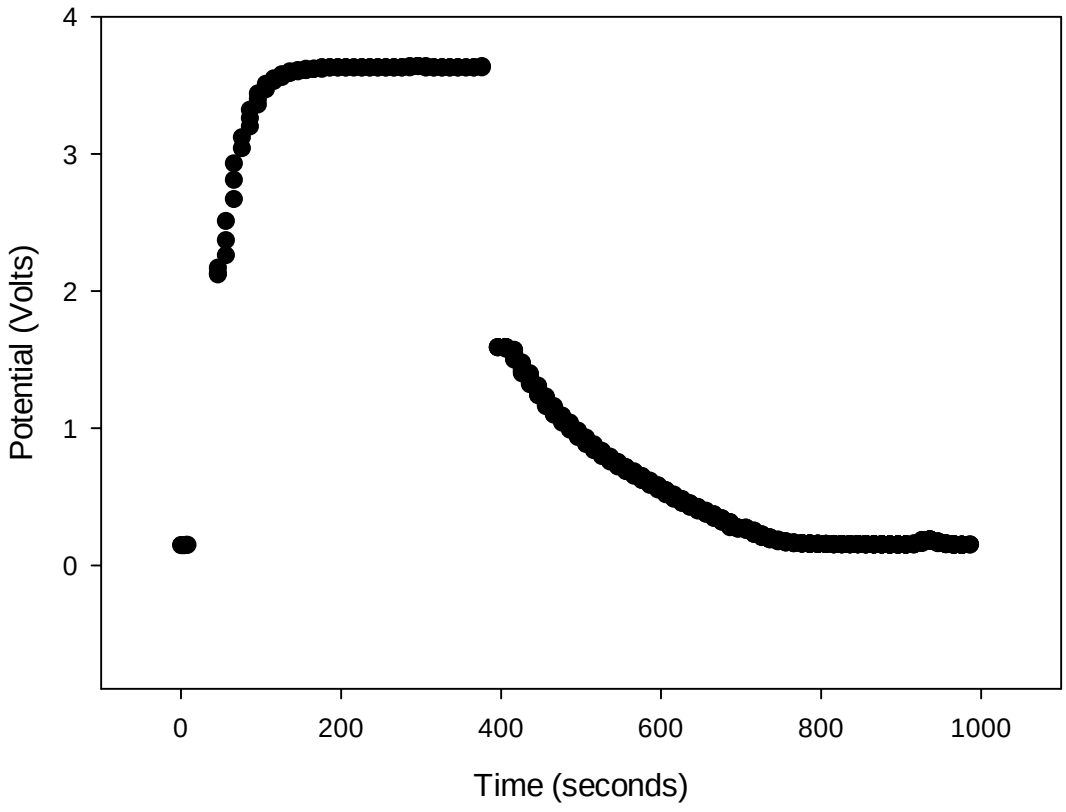

Figure 2: Charge/Discharge data for an individual Nanobattery

In the case of an array of these nanobatteries, the nanobatteries will be placed on a continuous electrically conducting substrate. If a nanobattery is later touched by a tip, seeking information, the tip will sense a voltage or current because the nanobattery has been charged (higher voltage or current). If this particular battery had not been charged, the tip will sense no voltage or current. In this manner, data can be "saved" and "read" from the nanobattery memory array. Because such small amounts of current would be used during the reading process, these batteries could in effect function as nonvolatile memory. Recording and retrieving data using the tip of an atomic force microscope would provide the necessary means to develop and characterize these nanobattery arrays. However, reading data at a rate fast enough for practical memory application would simply not be possible. A system under development by IBM called the Millipede system [17, 18] gives nanobattery arrays the potential to have technological utilization. IBM's system consists of arrays of AFM cantilevers. Thus far, they have used arrays of cantilevers that are 64 x 64. A nanobattery arrays could be accessed for their stored information in a similar manner. However, an array of cantilever AFM tips could be used to access the array of nanobatteries at an acceptable rate [17-19]. In this process, one tip would access numerous nanobattery memory elements. Because there are now many tips accessing the array of nanobatteries, the speed of data acquisition is greatly increased. A specific cantilever tip is accessed by the grid of electrical contacts on the cantilevers. This system still has its limitations. The construction of a functioning large array of cantilevers is difficult and its operation can be cumbersome. A better method is needed to facilitate the use of arrays of nanopower sources for memory elements in sensors

NANOCROSSBAR CIRCUITS FOR SENSOR MEMORY UNITS

A successful nanoelectronic structure that can access arrays of elements is the crossbar circuit (Figure 3), where the memory array is formed from sets of parallel nanowires crossing each other at right angles, with a memory storage cell at each intersection [20]. A demultiplexer (demux) is used to select the column and row of the desired memory cell location.

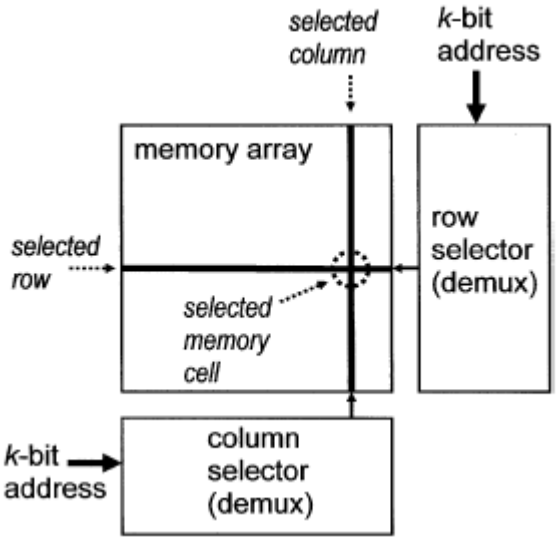

Figure 3. Nanoscale memory array using crossbar structure [20].

There are several advantages to using the crossbar circuit structure for nanoscale memory units. First, wire dimensions can be scaled down to molecular sizes, while the number of wires in the memory array can be scaled up to accommodate additional memory storage cells. Next, only 2k address wires are required to individually address 2^{2k} memory cells using the demultiplexers; this feature also helps to accommodate additional memory storage. Finally, the crossbar structure has been shown to be feasible and potentially inexpensive to fabricate at the nanoscale level [21].

Each memory cell in the crossbar array must be able to store a logic “1” or “0”, and allow this value to change as directed by the crossbar selection wires. Existing crossbar circuits connect the horizontal and vertical wires with either ohmic (resistive) contact switches or semiconductor (diode) switches to represent the memory cells. The "on" or "off" state of the switch represents a logic "1" or "0", respectively [22].

While switching can represent a logic state, it also is important for a memory cell to be able to store the value of the logic state for extended periods of time. Therefore, the authors are investigating the use of nanoelectrochemical cells for this purpose, where a charged cell represents a logic “1” and a discharged cell represents a logic “0”. The wires on each side would be at angles to each other such that a nanobattery would be between the crossing nanowires thus forming the crossbar system. This is illustrated in Figure 4 where the alumina membrane has been removed from the figure so the nanobattery crossbar system can be better seen. Not only will this system work for the basic design of nanosensor storage units, but ordered arrays of battery electrodes of this size would result in memory systems of expanded capacity. Based upon calculations completed by IBM researchers, information stored with this density would be able to exceed the limit predicted for magnetic data storage systems [17-19].

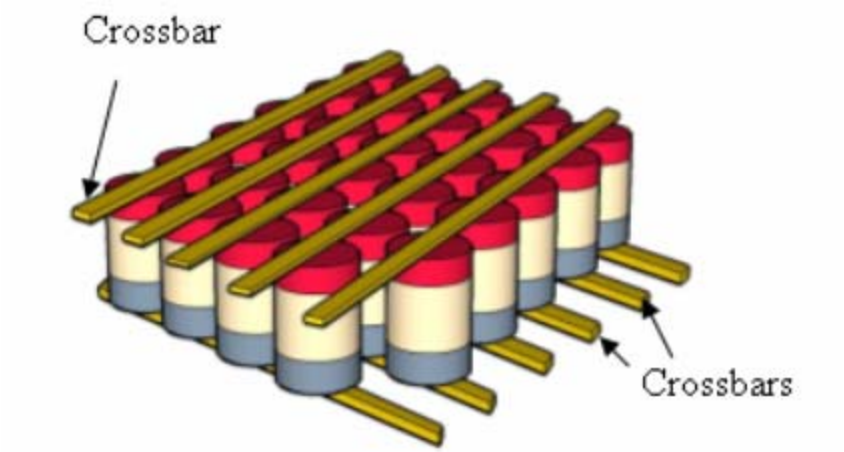

Figure 4. Nanosensor memory unit design using nanobatteries with crossbar arrays.

SUMMARY

Nanoscale sensor systems require the development of nanoscale devices to implement the various system units. The authors have developed a nanoscale battery system that can be used as a power supply unit in a nanoscale sensor system, and are currently developing crossbar memory systems that can be used for nanoscale sensor system memory units. It is anticipated that these units will be combined with current nanoscale sensors for applications such as military and medical measurement and monitoring systems.

ACKNOWLEDGEMENTS

The authors would like to thank the NSF EPSCoR program through grant EPS-0447262, the NASA EPSCoR program through grant NCC5-586 and the Oklahoma State Board of Regents for grants AA-5-89565 and 2002-30, for funding a portion of this work.

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