Printed Electrochemical Capacitors for Energy Scavenging Sensor Networks

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Abstract—**The application of energy scavenging technology significantly improves wireless sensor network nodes long-term operation and ensures minimal user attendance. For most of the scavenging technologies, ambient energy is available only under particular environmental conditions. For this reason, wireless sensor nodes have to keep the scavenged energy in storage elements. In this paper we present a kind of electrochemical capacitors manufactured using the *direct write* technology. This technology allows the supercapacitors to be printed directly on board of the sensor nodes. The experimental results on scavenging outdoor solar radiation and indoor light, stored on the printed capacitors, demonstrate high potential in terms of supplying the sensor nodes.**

Keywords- ***energy harvesting; wireless sensor networks; electrochemical devices***

I. INTRODUCTION

A Wireless Sensor Network (WSN) [24] is a collection of sensor nodes with limited on-board energy resources. The application of energy scavenging technology [25] to WSNs may significantly improve the lifetime of the sensor nodes. The first popular sensor node platforms, like TelosB, MicaZ and Mica2, were powered by a pair of AA batteries. However, the energy stored in the batteries was not sufficient for a number of deployments in difficult-to-access areas like volcanos, islands, icebergs. That is why developers and researchers began to customize the available sensor nodes by adopting energy scavenging technologies, to take advantage of the available ambient energy. For example, Prometheus [5], Trio [10], and Heliomote [7] are energy scavenging platforms based on the TelosB or Mica2 sensor platforms and are capable of harvesting solar energy. At the same time, a number of energy scavenging sensor platforms with predefined harvesting technology have appeared in the research community. The VIBES [11] and Perpetuum [13] sensor platforms are supplied by ambient vibrations and have only primary (supercapacitors) energy buffer. The Everlast [6] platform scavenges solar radiation and supports only one primary buffer as well. Ambimax [12] harvests wind, vibrations, solar radiation, and thermal energy and stores the energy in both a primary and a secondary (rechargeable battery) energy buffer.

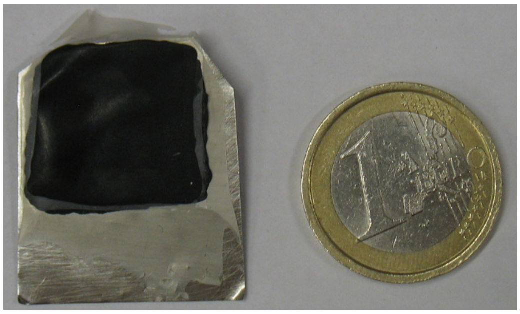

Figure 1. Printed capacitor sample (200 uF, 1.4 V, 1.5x1.5 cm).

Nowadays, in contrast to the TelosB and Mica platforms, there are sensor platforms by Libelium [8] and Cymbet [1] which provide users with the flexibility of connecting different harvesting component to the sensor nodes and replenish an energy buffer. Besides scavenging, storing the scavenged energy, however, is another problem of vital importance. Rechargeable batteries, in fact, have a significant disadvantage in their application in enegy harvesting sensor systems: the charge-discharge cycle is limited to up to 300-500 cycles [5]. Super capacitors, on the other hand, have high leakage current and can not store as much energy as batteries can. The problem of high leakage current can be partially solved by wiring the supercapacitors in series [5] and/or using a passive balancing approach [9].

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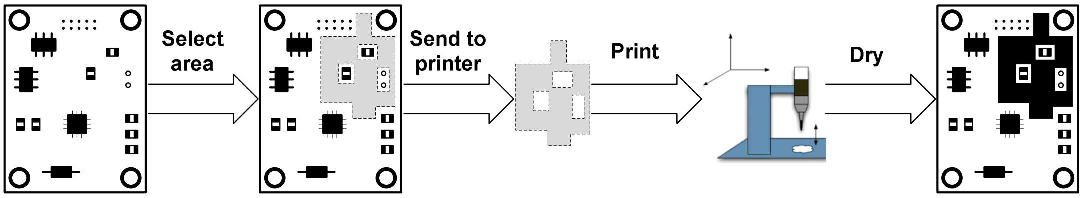

Figure 2. Our goal: print anywhere.

In this work we describe a kind of electrochemical supercapacitors manufactured using the direct write technology and evaluate their operation during the deployment of a sensor node. The capacitors store the energy scavenged from the ambient light (outdoor and indoor) and supply the sensor node.

The paper is organized as follows: we introduce the method of electrochemical materials deposition in Section II. After the description of the implementation of printed capacitors in Section III we demonstrate the test bed and obtained experimental results in Section IV. We discuss related work in Section V and, finally, provide the conclusions and discuss our future work in Section VI.

II. METHOD OF ELECTROCHEMICAL MATERIALS DEPOSITION

In this section we describe a printing method for fabricating electrochemical capacitors directly onto a substrate.

Recent research improvements in carbon electrode and electrolyte material have resulted in a growing interest in carbon electrochemical capacitors as suitable devices for both solitary and load leveling energy buffer configurations [15]. Electrochemical capacitors store energy via electrostatic arrangements at the interface between carbon electrode particles and electrolyte ions. The combination of high surface area carbon electrode materials along with electrolytes stable under large electrochemical potentials results in substantial energy storage capabilities within a small device volume [16].

The utilization of organic solvents [17], and more recently novel ionic liquids [18] as supercapacitor electrolytes has enabled greater electrochemical stability over larger potential ranges than aqueous electrolytes, which are only stable up to Δ1 V. As a result, energy density, being a function of the square of the potential difference achievable in a capacitor, increases significantly. Ionic liquids especially are interesting because they effectively remain liquid at room temperature with negligible vapor pressure, and therefore are not volatile [19]. Besides being safe and requiring less hermetic packaging, these novel liquids provide an interesting opportunity when incorporated with polymer gels to form solid-like films that maintain liquid-like properties. We have developed a gel electrolyte with high mechanical strength and good ionic conductivity by incorporating 1-butyl-3-methylimidazolium tetrafluoroborate ($BMIM^+BF_4^-$) ionic liquid with polyvinlydene fluoride (PVDF) polymer [20]. Using this gel electrolyte, solid-state electrochemical capacitors can be deposited utilizing direct write solutions processing.

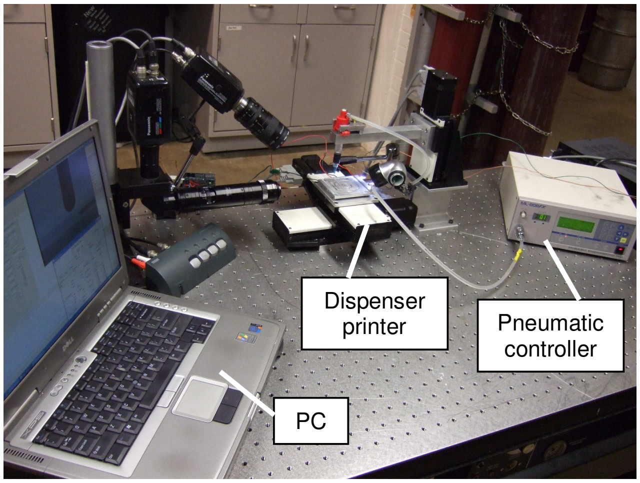

Figure 3. Dispenser printer.

Direct write solutions processes are typically simple methods for depositing materials additively onto a substrate in ambient environments and in room temperature conditions. They provide a suitable alternative to standard thin film microfabrication techniques for devices that benefit from thick films or non-planar geometries such as electrochemical capacitors. We have developed a pneumatic dispenser printing tool which extrudes slurries and solutions onto a substrate mounted on a 3-axis stage with 5 micron accuracy (Figure 3). Because the deposition of solutions is gentle, films of different compositions can be deposited in a subsequent manner, and devices can be built (see Figure 2).

Several direct write processes have been used to deposit similar structures [21], [22], but our printer provides the added benefits of reducing energy inputs and waste generated, as well as being able to deposit material around existing components, effectively utilizing any open space on a substrate. Earlier results have shown this method to be both cost effective and scalable for the mass production [23].

III. PRINTED CAPACITORS IMPLEMENTATION

Electrode slurries are composed of 50 wt.% activated carbon with 24 wt.% PVDF polymer binder, 2 wt.% conductive carbon black additives, and 24 wt.% $BMIM^+BF_4^-$ ionic liquid. Electrolyte gels are a 1:1 composite of PVDF and $BMIM^+BF_4^-$. Current collector slurries of conductive particles (such as nickel or carbon) in PVDF are also being developed. The viscosities of the slurries are tailored by adding a volatile solvent such as n-methyl-2-pyrollidone (NMP). The pneumatic dispenser printer extrudes a rapid succession of drops through a syringe tip onto the substrate. The drops eventually coalesce to form a film as NMP is removed via drying. To fabricate a capacitor, a five-layer planar and symmetric sandwich of current collector, carbon electrode, and electrolyte ink are printed as shown in Figure 4. Figure 5 displays a micrograph showing the material morphology of the electrode and electrolyte.

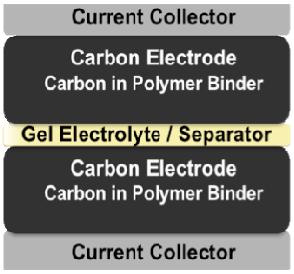

Figure 4. Schematic of a carbon electrochemical capacitor.

To deposit supercapacitors on a substrate already populated with other components, automated alignment software and image processing are used to determine any open spaces available for printing. An image is taken of the substrate and any open spaces are translated into a bitmap image. The printer then deposits material in the pattern of the bitmap, and the alignment software maintains accurate orientation in between the printing of films even with the adjustment of syringe tips, substrate rotation, or other printing parameters. In this study, capacitor modules were tested rather than integrated cells, and each module was clamped to maintain the interfaces adjacent to each printed layer.

TABLE I. TECHNICAL SPECIFICATION OF THE PRINTED CAPACITORS

Parameter	Value
Capacity, mF/cm^2	40-60
Power density, uW/ cm^2	575
Maximum voltage, V	2.5
Maximum charge/discharge current, mA	4.5
Life cycles	>120,000
Footprint, cm	5 x 7.5

Table I summarizes the technical specifications of the printed capacitors used in this work. Besides, we outline their features as follows:

- High temperature can damage the printed storage.
- Storage needs can be customized for each level of a device (see Figure 2).
- The elctrode thickness can be easily tailored by the dispenser printer for required energy and power performance.
- Storage can be printed at room temperature in ambient conditions.
- If the printing surface is slicky the polymers are peeling off.

IV. EXPERIMENTAL RESULTS

In this section we assess the potential of printed capacitors to operate as a primary energy buffer for energy scavenging sensor networks.

A. *Test-bed description*

During the experimentation we used a BP SX305M solar panel as the harvesting component, an energy scavenging module presented in our previous work [9] to convert the ambient energy into electrical energy, and two digital multimeters to monitor the charging current for the capacitors (Multimeter #1) and to log the potential of the capacitors (Multimeter #2). The experimental setup is shown in Figure 5.

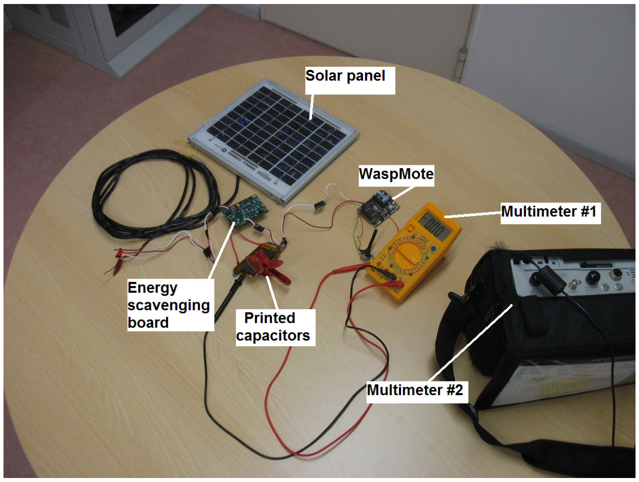

Figure 5. Experimental setup.

The technical details of the experimental setup are shown in Figure 6.

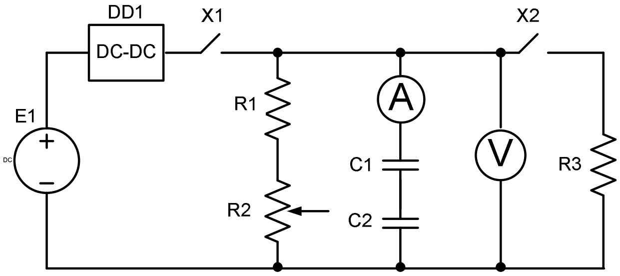

Figure 6. Equivalent testing circuit showing the technical details of the experimental setup: (*E1*) – solar panel, (*DD1*) – DC-DC on the energy scavenging board to support the printed capacitors with a stable charging voltage, (*X1, X2*) – switches to charge and dischsrge printed capacitors, (*R1*) – resistor to limit charging current, (*R2*) – potentiometer, (*C1, C2*) – printed capacitors wired in series, (*R3*) – WaspMote, (*A*) – ampermeter (multimeter #1), and (*V*) – voltmeter (multimeter #2).

B. *First Sample Testing*

As a proof of concept, we manufactured a small sample of a printed capacitor, as depicted in Figure 1. This capacitor is of 200 uF capacity and operates at 1.4 V. The experimental curve shown in Figure 7 demonstrates the sample's charging with solar light (charging current is approximately 1.2 mA) and its self discharge.

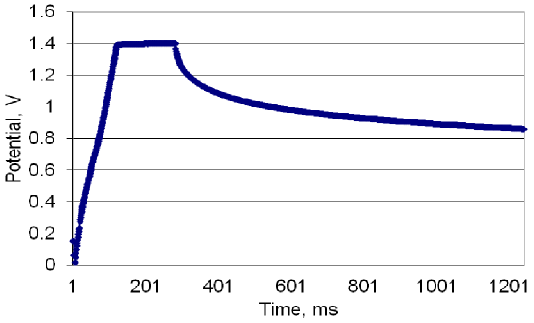

Figure 7. Printed capacitor (C=200 uF, U=1.4 V) charging with ambient solar light and its self-discharge.

Figure 8 shows the degradation of capacity of printed storage with respect to the number of charge-discharge cycles. Initially the capacitance decreases significantly, but in approximately 1000 cycles reaches a steady state.

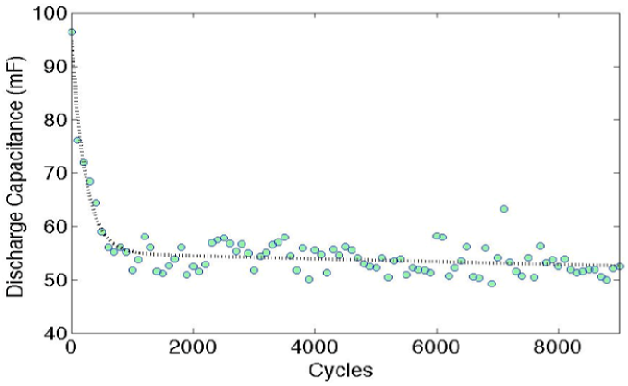

Figure 8. Discharge capacitance with respect to cycle number.

C. *Testing Printed Capacitors with the WaspMote*

To supply a sensor node we need capacitors with improved capacitance and higher operational voltage. For this reason, we printed several samples of printed capacitors of bigger size (5 x 7.5 cm, C=300 mF, U=2.5V). We connected two capacitors in series to ensure higher operational voltage and decrease the leakage current.

First, we charged the capacitors with scavenged ambient solar light (see Figure 9). To charge the capacitors we use an energy scavenging board in conjunction with the solar panel. Besides, to limit the current up to 2 mA we used a potentiometer and a limiting resistor (see Figure 6). Then we started to discharge them using a sensor node as a load. For our experiments, we have chosen the *WaspMote* sensor platform by Libelium [8]. The WaspMote was programmed to measure the environmental temperature each 3 s, save the data, and go to sleep mode. We would like to note that during the experimentation we did not use the radio which consumes more than 5 mA, which is the amount over which the energy storage devices may be damaged. Thus, the node can be made fully functional only by using a secondary buffer in addition to the printed capacitors. The experimental curve shows that it takes around 3.5 minutes to charge the capacitors. At the same time the sensor node discharges the capacitors after 3 minutes of operation. Obviously, the printed capacitors operate properly outdoor using scavenged solar radiation during the day time. At the same time the printed capacitors are quickly exhausted if no harvester is available.

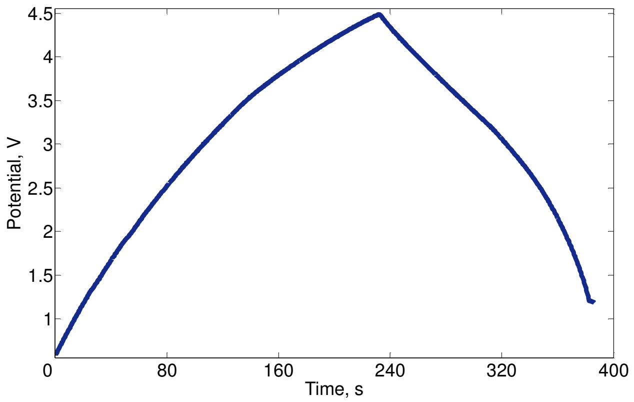

Figure 9. Printed capacitor charging with solar light and discharging using 'WaspMote' sensor node.

Next, we charged the primary buffer and started the experiment indoor during the day time, but without artificial light. Figure 10 shows that the printed capacitors can support the operation of the sensor node for 19 minutes.

Starting from almost full discharge of the capacitors we turned on the office light. The capacitors started steadily to charge. In 90 minutes the printed capacitors were fully charged. In fact, the charging time depends on office conditions: quality of illumination, model/size and deployment area of the solar panel, passing personnel who in our case could shadow the light from time to time.

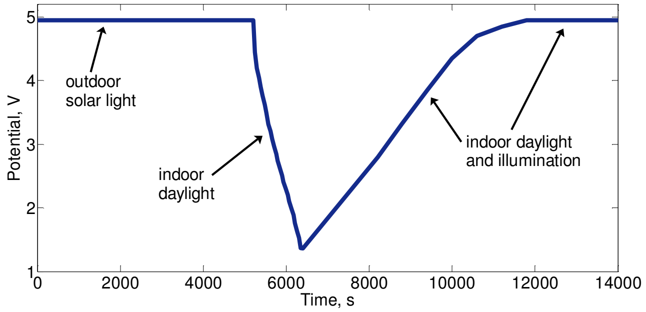

Figure 10. Testing the printed capacitors (charging/discharging) with different types of light.

The aim of this deployment is to assess the operation of the system in office conditions. The experiment shows that the system operates for 19 minute during the day time if the lights are turned off. With the lights turned on the system can operate ‘perpetually’.

V. RELATED WORK

Nowadays, there are three typically used combinations of energy storage devices for sensor networks supporting the energy scavenging technology: supercapacitor only [6], rechargeable battery only [7], or a combination of the tow to supplement each other [5].

In our recent work [14], we have tested the separate printed capacitors during a 24-hour period for a TelosB sensor node which performed sensing of temperature and humidity each 5 s and sent the measured values to a gateway node. The deployment included two 12-hour tests of scavenging of solar radiation and ambient vibrations (generated in laboratory). The experiment has demonstrated successful operation of the sensor node supplied by solar radiation. In the ‘vibrations’ case, the sensor node could successfully operate on printed capacitors for almost 8 hours. It should be noted, however, that the radio chip was supplied by an extra Li-ion rechargeable battery in order not to damage the printed capacitors with the high current consumption of the radio (23 mA). In contrast to that work, in this one we have tested the supercapacitors in the indoor conditions as well as carried out some single tests as it is shown in Figure 8 and Figure 9.

To the best of our knowledge, printed devices for ambient energy buffering have been implemented and integrated *only* in a commercial platform by Cymbet. CBC-EVAL-08 node [1] is a demonstration kit designed by Cymbet Corporation. This node has a small solar panel on board and it supports AC-based ambient signal harvesting. An external AC-based harvester can be connected to the node through the connector on the board. To store the harvested energy, the module has two 50 uAh EnerChip batteries manufactured with thin film technology [2]. In order to save as much energy as possible, the module supports SimpliciTI [3], the energy aware wireless network protocol. The power management block prevents deep battery discharge and the monitoring of high current operation. In spite of the low battery capacity and in case of proper device use, the CBC-EVAL-08 developers claim that the module can operate for up to 10 years.

The PicoCube [4] is a 1 cm^3 sensor node which consists of five stacked printed boards: a radio, a switch, a sensor, the MCU, and the storage. The harvested energy is stored in a NiMH battery. In the future, the authors plan to exchange the packed battery with a battery manufactured by using the direct write printing method.

VI. CONCLUSIONS AND FUTURE WORK

In this work we tested the printed supercapacitors fabricated using the ‘direct write’ technology as an energy buffer to improve the lifetime of the WaspMote sensor platform. The experiments show that the ‘direct write’ technology has the potential to efficiently use the free available space of the board and manufacture the capacitors with the required parameters.

The experiments show that the printed capacitors operate well using scavenged solar radiation and indoor light. During the day time, in the CREATE-NET office conditions without the lights turned on, the sensor node could operate for 19 minutes. Indoor lights are sufficient to guarantee perpetual operation. It should be noted that for achieving the best capacity and low leakage currents, the plates of the printed storage must be stressed properly.

Our future work includes printing the supercapacitors directly on board of a sensor node, since in our experience we discovered some issues with cracking on a board surface: it is very slick and many of the polymers are peeling off. To address this problem in the future we may have to chemically etch the surface of the board in order to create some sort of roughness, at which point the polymer may stick better.

Besides, we plan to resolve the problem with low charge-discharge current of the storage, so that the printed capacitors could also supply the communication part of a sensor node. Implementation and testing of printed energy storage devices is underway.

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