Flexible Energy Supply for Distributed Electronics Powered by Organic Solar Cell and Printed Supercapacitor *

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Abstract— **In this work we report a flexible energy supply unit made by printing flexible disposable aqueous supercapacitor modules onto a light harvester. In order to demonstrate simpler and more scalable manufacturing processes, we printed the supercapacitors monolithically instead of laminating electrodes face-to-face and integrated the series connections into the fabrication process. The supercapacitor modules were printed onto the backside of the Organic Photovoltaic (OPV) modules to combine energy harvesting and storage module for harvesting light under normal indoor conditions, storing it in a supercapacitor module, and thus offering power for low power IoT devices.**

I. INTRODUCTION

The Internet of Things (IoT) continues to grow and will connect trillions of smart devices for healthcare, security, automation and wearable electronics.[1] Power management is one critical issue for IoT. Therefore, energy harvesting and energy storage have attracted the interest of scientists in last decades.[2] [3] Light is one of the most efficient and ubiquitous among the available energy harvesting sources, whether indoor or outdoor. Improvement of solar cells attracts significant interest from researchers[4]–[6] and quite good solar cells are available commercially nowadays. Typically, energy-scavenging systems require intermediate energy storage to provide energy when the primary energy source such as light is not available or when higher power is needed temporarily.

Using huge number of batteries is not a good option due to the toxic materials and recycling issue, as well as limited cycle life.[7] Aqueous supercapacitors are a suitable replacement for batteries in low power distributed electronics, as they can provide a good balance between cycle life and cost as well as between energy and power. They can be made using low cost, non-toxic materials using fabrication processes such printing.[8] On the other hand, the voltage of each cell is limited to just above 1 V due to the electrochemical window of water, so that for many applications series connected modules are needed. In this work, we report the monolithic fabrication, using printing, of non-toxic, disposable, flexible aqueous supercapacitor modules and their integration with a light energy harvester.

The supercapacitors are printed on the backside of Organic Photovoltaic (OPV) modules to form a monolithically integrated energy module. The system can harvest indoor light under normal office conditions and store the energy in a single or series connected printed supercapacitor.

The area of the OPV module was larger than would be desired for small, unobtrusive smart IoT objects that should fit seamlessly and mostly unnoticed into everyday environments. Nonetheless, we focused on optimization area usage in this work, as new materials, both organic and perovskite-based, can deliver significantly more PV power per unit area and the energy storage should be optimized to fit future form factors.

Printing the series connected supercapacitors monolithically on the back side of an OPV module is a fast, easy and cheap method to fabricate future energy modules for IoT.

II. EXPERIMENTAL

A. Methods and materials

The OPV modules were from an educational solar cell kit made by infinityPV. The advertised efficiency of the OPVs was 5%. The lamp was a 4000 K, 806 lm LED lamp from Airam Company. It was installed 41.5 cm above the OPV modules to simulate indoor lighting.

The current collector of the supercapacitors was graphite ink, Acheson PF407C and was cured at 95 ^{o}C for 30 minutes. The electrodes were fabricated from activated carbon (AC), Kuraray YP-80F made from coconut shells.[7] Chitosan (Sigma-Aldrich, Chitosan from shrimp shells, 50494) was used as a binder and the recipe of the AC ink has been reported

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previously.[9] The separators were made of 40 µm thick Dreamweaver Silver AR40 cellulose paper. The other separator used in some samples was made by combination of microfibrillated cellulose and chitosan called CM5050, it is described in [10].The electrolyte was NaCl (Fluka 38979) in deionized water in 1:5 mass ratio. Adhesive tape (468MP-200MP from 3M) was used for sealing. The graphite inks were applied by stencil printing (doctor blade applicator using mtv Messtechnik Film Applicator). Screen printing was used to apply AC ink on graphite films.[7], [11]–[13]

The capacitance, leakage current and ESR were determined according to the IEC 62391-1 standard [14] using a Maccor 4300 test system. The single cell supercapacitors were charged and discharged between 0 V and 1.2 V three times with constant current (1, 3 and 10 mA). Then the voltage was kept at 1.2 V for 30 min and capacitance was measured during the constant current discharge step between 0.96 V and 0.48 V potentials. The leakage current was measured by keeping the supercapacitor at constant voltage for 1 h. The ESR is calculated from the IR drop in the measurement with discharge current 10 mA. For series connected supercapacitors, the maximum voltage applied was 2.0 V.

B. Manufacturing process development

Figure 1 shows the layout of the single device and the series connected two-supercapacitor module. Single supercapacitors (figure 1, top) were printed by applying the first 34 mm wide layer of the graphite ink as a current collector on the backside of the OPV (shown in red). The next layer is 31 mm wide activated carbon as electrode (black). The next layer is a 26 mm by 16 mm separator that can be of paper or made of a coatable composite of microfibrillated cellulose and chitosan [10] (blue). The upper layer of activated carbon is 22 mm wide, (black). The upper layer of graphite ink is 18 mm wide, shown (green).

The two series monolithic supercapacitors were printed using the same processes, materials and layer thicknesses as the single device. The layers are shown in figure 1 (bottom) with the same colours as in the case of the single device.

Graphite ink printed on the backside of the OPV modules needs to be cured at 95 °C for 30 minutes. The OPV modules were characterized after similar heat treatment to check if their properties are affected by the elevated temperature. Figure 2 shows the absorption spectra of the OPV before and after putting in the oven 95 °C for 30 minutes. Figure 3 shows IV characteristics of the OPV in dark and under irradiation, before and after the heat treatment. It is clear from the results that the heat treatment had very little effect on the absorption or performance of the OPV module.

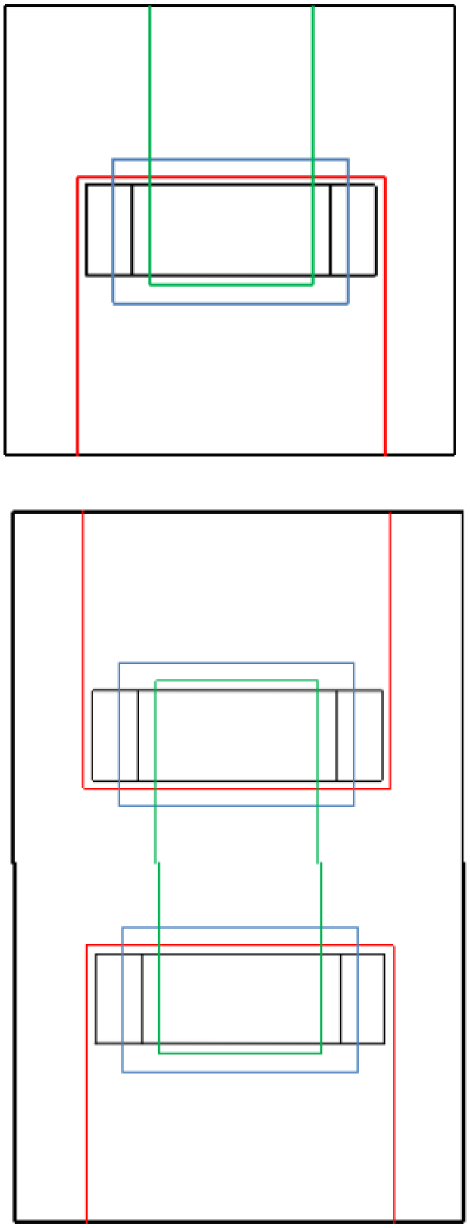


Figure 1 Layout pattern of the monolithic single supercapacitor (top) and two series capacitors (bottom).

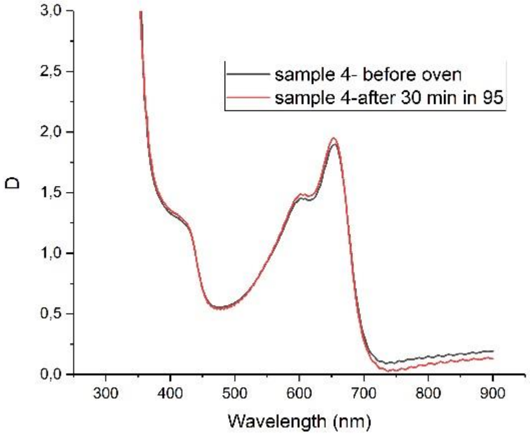


Figure 2 Absorption spectra of the OPV before and after heat treatment.

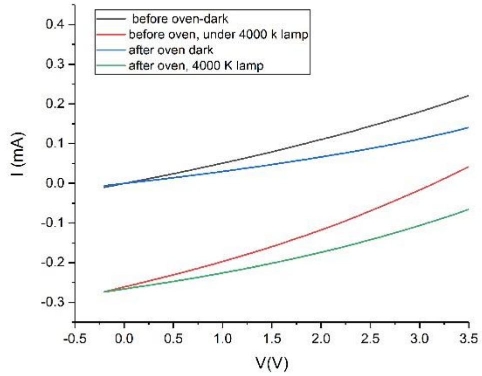


Figure 3 IV characterization of the OPV before and after heat treatment, in dark and under radiation of light.

III. RESULTS AND DISCUSSION

A. Electrical performance of the supercapacitors

Figure 4 shows the single supercapacitor printed on the backside of the OPV. The capacitance of the supercapacitor was 218 mF, equivalent series resistance (ESR) was 22 Ω and leakage current was 8.3 µA.

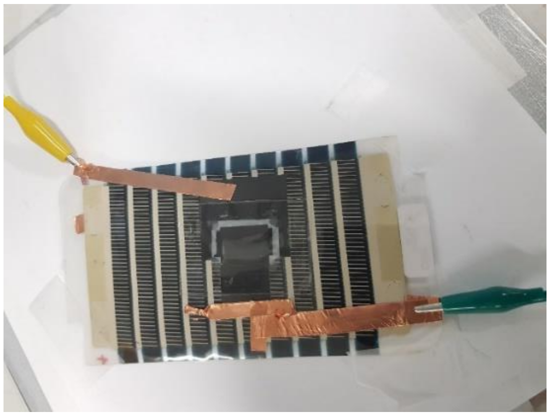
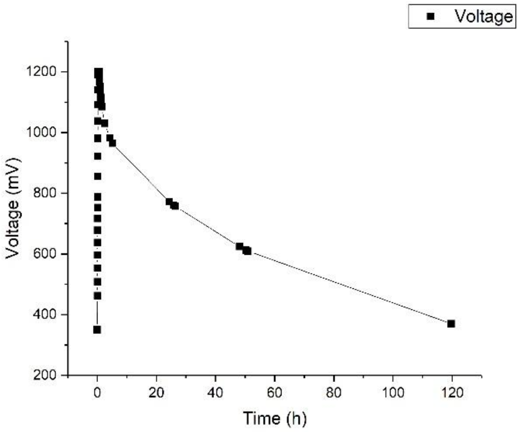


Figure 4 The single supercapacitor printed on the backside of the OPV.

The supercapacitor was charged using the OPV in indoor light condition. Figure 5 shows charge and self-discharge curves of the supercapacitor when it is charged using the OPV up to 1.2 V. The bottom figure in the figure 5 shows the beginning of the top one showing that the voltage was kept constant at 1.2 V before starting the self-discharge phase. The voltage of the OPV charged supercapacitor was measured for up to 5 days.



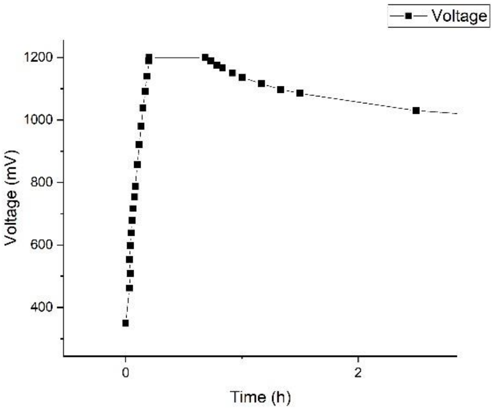


Figure 5 Charge and discharge curve of the single printed supercapacitor charged by OPV.

B. Electrical performance of the series supercapacitors

Figure 6 shows the series connected supercapacitors printed on the backside of the OPV. The performance of the module after charging to 2 V using the Maccor characterization interface shows capacitance of 93 mF, ESR of 22 Ω and leakage current of 47 µA. Figure 7 shows the charge and discharge curve of the series connected module when it is charged using the OPV up to 2 V and kept at 2 V for 1 h. The bottom figure in the figure 6 shows is expansion of the initial part of the top curve. Despite the unexpectedly large leakage current, a voltage of over 500 mV can be maintained for 90 hours.

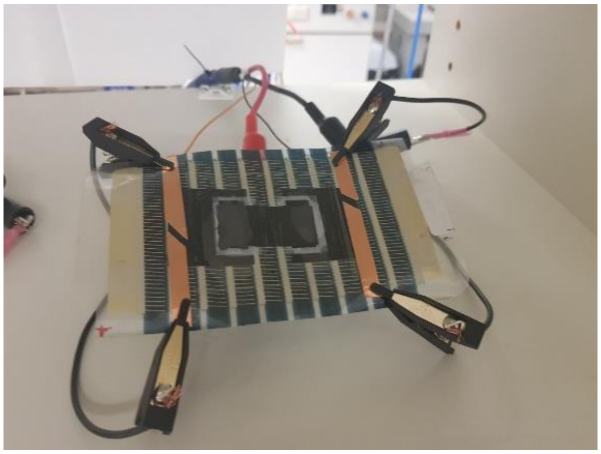


Figure 6 The series connected supercapacitors printed on the backside of the OPV.

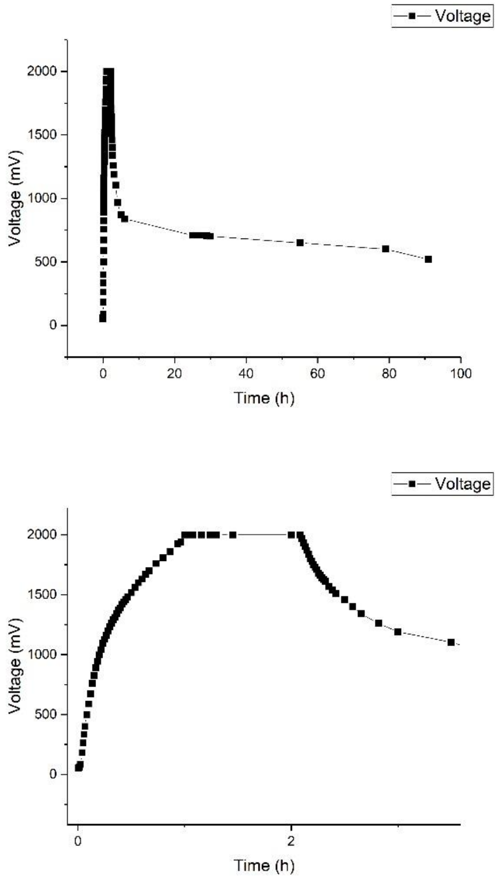


Figure 7 Charge and discharge curve of the series printed supercapacitor with paper separator charged by OPV.

The other series connected supercapacitor module connected to OPV was fabricated using a printable separator as reported previously[10]. As with the other samples, the device was first characterized with the Maccor interface, yielding capacitance of 125 mF, ESR of 56 Ω and leakage current of 7.4 µA. These results are comparable with the results on single devices published previously [10]. Figure 8 shows charge and discharge curve when the module is charged using the OPV up to 2 V and kept at 2 V for 1 h. The bottom figure in the figure 6 shows an expansion of the beginning of the top one.

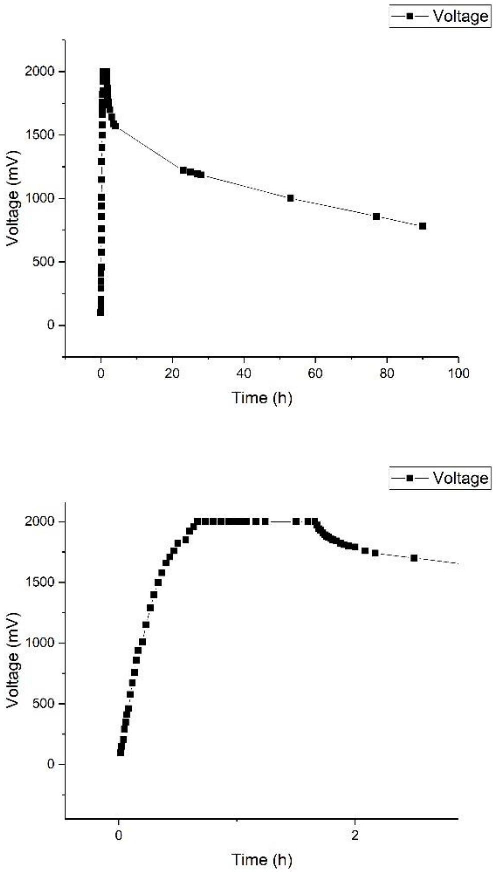


Figure 8 Charge and discharge curve of the series printed supercapacitor with CM5050 separator charged by OPV.

The voltage of the series connected supercapacitor module was measured for up to 90 h. After 90 hours, the voltage was still close to 1000 mV. With encapsulation having enhanced barrier properties or by keeping the voltage at constant level for longer time slower self-discharge could be expected.[9]

IV. CONCLUSION

We have demonstrated an architecture and a scalable fabrication process for integration of monolithic supercapacitor modules and flexible OPV modules onto a single substrate to provide an energy module for energy autonomous devices. In addition, we have shown that the energy module can provide sufficient energy from indoor light to charge the energy storage, which can maintain a large fraction of the energy for several days.

The printed energy module can provide an environmentally and economically sustainable source of energy to autonomous wireless sensor nodes for the IoT.

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