Study of Paper Batteries & Performance Analysis of Its Types

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Abstract-With the reduced size paper batteries are flexible and eco-friendly. Battery plays a vital role in almost all the electronic machines and a necessary component in all the devices. It is helpful to the people to work in the absence of electricity. Commonly used batteries may leak sometimes releasing chemical components. The toxic metal pollution takes place with the large use of batteries. This paper gives the information about construction, working principle and applications, performance analysis of different types of paper batteries.

Keywords*:Microbial fuel cells, paper-based biobatteries, origami techniques, bacterial respiration, paper-based biosensors*

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I. INTRODUCTION

A paper battery is an electric battery engineered to use a spacer formed largely of cellulose. It incorporates nanoscale structures to act as high surface-area electrodes to improve conductivity. Their functioning is similar to conventional chemical batteries with the important difference that they are non-corrosive and do not require extensive housing. A paper battery is a flexible, ultra-thin energy storage device made of cellulose (paper) and Carbon nano tubes. A paper battery can act as a super capacitor and also as a high – energy battery.

Electronic devices and gadgets require a power supply (either AC or DC), this power supply can be taken directly from the mains power supply or from the electrical batteries. The battery can be defined as an electronic device comprised of (one or more) electrochemical cells. The chemical energy of the electrochemical cells can be converted into electrical energy. Based on different criteria batteries are classified into various types such thatbased on rechargeable condition they are classified as rechargeable batteries and non-rechargeable batteries.

II. PAPER BATTERY CONSTRUCTION

The major components used for the construction of paper battery include:

a) Carbon Nanotube (CNT) used for cathode terminal
b) Lithium metal (Li+) used for anode terminal
c) Different types of electrolytes that include blood, urine, and sweat (which are termed as bio-electrolytes)
d) Paper (Cellulose-Separator)

Construction of a paper battery mainly includes the following steps:

Step 1: Black carbon ink is applied on a cellulose-based paper.

Step2: Black carbon ink is being spread on a paper spread on the paper.

Step3: A thin lithium film is laminated over the exposed cellulose surface.

Step4: The cellulosepaper is heated at 800C for 5 minutes.

Step5: Next, the film is peeled off from the substrate

Step6: The film acts as electrodes of the paper battery. One film is connected to the electrolyte LTO (Li4Ti5012) and another film is pasted to the electrolyteLCO(LiCo02).

Step7: Next, Connect a LED on both the ends of the battery and check its functionality.

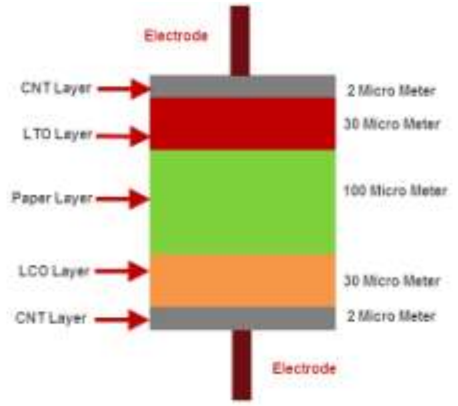

Fig1: Construction of paper battery

Paper Battery Working:

The conventional rechargeable batteries which we use in our day-to-day life consist of various separating components which are used for producing electrons with the chemical reaction of a metal and electrolyte. Once the paper of the battery is dipped in ion-based liquid, itstarts working.The electricity is generated by the movement of electrons from cathode terminal to anode terminal. This is due to the chemical reaction between the electrodes of paper battery and liquid. Due to the quick flow of the ions within a few seconds (10sec) energy will be stored in the paper-electrode during the recharging. By stacking various paper-batteries up on each other, the output of the paper battery can be increased.

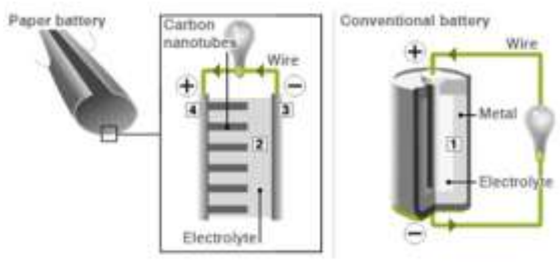

Fig 2: Working of paper battery

As the paper batteries are connected each other very closely for increasing their output, there is chance of occurring short betweenthe anode terminal and cathode terminal. If once the anode terminal contacts with cathode terminal, then there will be no flow of current in the external circuit. Thus, to avoid the short circuit between anode and cathode a barrier or separator is needed, which can be fulfilled by the paper separator.

Paper Battery= Paper (Cellulose) + Carbon Nanotubes

The paper battery can be used for various applications as it facilitates advantages such as folding, twisting, molding, crumpling, shaping, and cutting without affecting on its efficiency. As the paper batteries are the combination of cellulose paper and carbon nanotubes, which facilitates advantages of long term usage, steady power, and bursts of energy. These types of paper batteries are estimated touse for powering the next generation vehicles and medical devices.Paper-based supercapacitors developed so far are made from paper-like composites of cellulose which constitutes a major obstacle in their integration with paper-based electronic devices. This leaves us with biofuel cells and more specifically microbial fuel cells (MFCs) as the most promising candidate for powering low-power single-use paper-based analytical and diagnostic devices especially for low-resource regions of the world.

MFCs generate electricity through bacterial metabolism; the fuel used can be any type of biodegradable organic substrate including wastewater and urine, or even soiled water in a puddle. They typically have a simple structure of two chambers; an anode and a cathode separated by a proton exchange membrane (PEM). Moreover, affordable materials and fabrication processes are used to build such device, which renders them more cost effective than other paper-based power sources. This type of batteries is environmentally friendly as it can be disposed of by incineration.

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III. TYPES OF PAPER BATTERIES

1) Paper-Based Bacteria-Powered Battery high power generation
2) An Origami Paper-Based Bacteria-Powered Battery with an Air-Cathode

1) Paper-Based Bacteria-Powered Battery high power generation

A.Working Principle

MFCs are typically comprised of anodic and cathodic chambers separated by a proton exchange membrane (PEM) so that only H^+ or other cations can pass from the anode to the cathode. A conductive load connects the two electrodes to complete the external circuit. Microorganisms oxidize organic matter in the anodic chamber, completing respiration by transferring electrons to the anode. During this process, chemical energy is captured throughout the electron transport chain. Nicotinamide adenine dinucleotide (NAD^+) and nicotinamide adenine dinucleotide dehydrogenase (NADH) function as coenzymes for the reactions, repeatedly oxidizing and reducing to synthesize adenosine triphosphate (ATP), the biological energy unit. MFC technology uses microorganisms that can transfer electrons produced via metabolism across the cell membrane to an external electrode; the process is called extracellular electron transfer (EET), and it plays a key role in harvesting electrons.

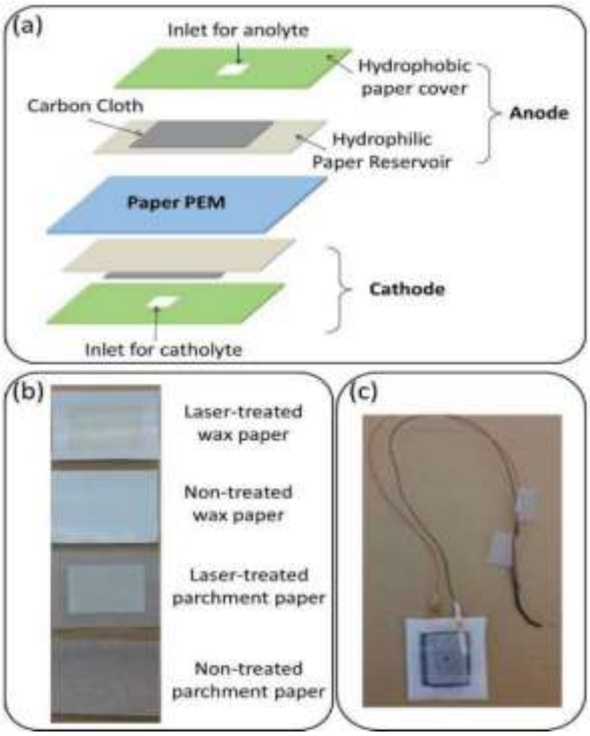

Fig3: a) Schematic of paper based bacteria powered battery b) four different paper based PEMs c) Assembled battery

B. Device Fabrication

The paper-based battery was created by sandwiching four major components: carbon cloth-based anode/cathode layers, paper anode/cathode reservoirs, a paper-based PEM, and hydrophobic paper covers with windows for sample inputs. Copper tape (3M^{TM} copper conductive tape) was used to provide electrical contact to the anode and the cathode. Since carbon cloth is hydrophobic, it needed to be exposed to oxygen plasma for hyrophilization for 1 min. Four different paper-based PEMs were examined: (1) laser-treated wax paper, (2) non-treated wax paper, (3) laser-treated parchment

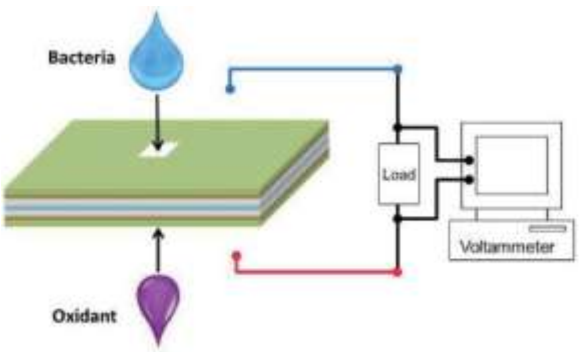

Fig. 4: Schematic of the test setup for monitoring the paper-based bacteria-powered battery.

paper, and (4) non-treated parchment paper. Selective surface modification of the hydrophobic papers was done using computer-controlled CO2 laser cutting and engraving system (Universal Laser System, VLS 3.5). This treatment converted hydrophobic areas to hydrophilic ones for better proton exchange rates and minimal transfer of the anolyte and the catholyte. Fig. 3 shows a schematic diagram of the different layers of the paper-battery, and photo images of the different types of paper PEMs to be tested and the fully assembled device.

Wild-type Shewanella Oneidensiswas grown in L-broth medium as the anolyte, while a phosphate-buffered ferricyanide (50mM, pH 7.0) was used as the catholyte. L-broth media contained 10.0 g tryptone, 5.0 g yeast extract and 5.0 g NaCl per liter. Inoculum (anolyte) and catholyte were introduced onto the paper by pipettes containing 1mL of each and the MFCs were operated at 30 ºC. The solutions wicked through the carbon cloth and remained in the paper reservoirs.

C. Measurement Setup

The potential between the anode and the cathode was measured by a data acquisition system (NI, USB-6212) and recorded the results every 1 min via a customized LabVIEW interface (Fig. 4). An external resistor (1.5 kΩ) was used to close the circuit by connecting the anode and cathode. The current through the load was calculated via Ohm's law and the output power was calculated via P=V×I. Current and power densities were normalized to the electrode area.

LED illumination:

To illuminate an LED, the four identical paper-based batteries were connected in series. Each of the four batteries generated an OCV of ~500 mV which is a typical value for bacteria-powered batteries. The OCV of the battery stack was 2 V, which is equal to the sum of the individual battery voltages. Once this voltage was applied to the terminals of a red LED, it illuminated instantly, and was able to power the LED for more than 30 minutes, Fig.5 shows a photo image of the four-battery stack and the illuminated LED.

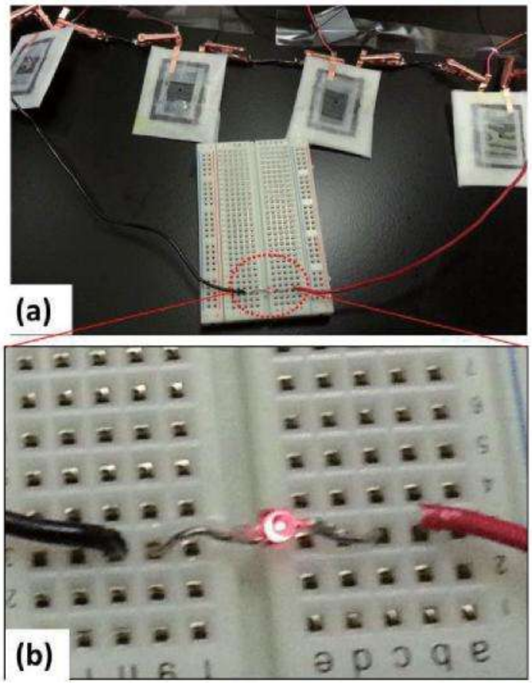

Fig. 5: Lighting a red LED with the four batteries connected in series (battery stack).

While the LED was being illuminated by the battery stack, the voltage across the individual batteries and the series array for the whole duration of the operation were recorded.

2) An Origami Paper-Based Bacteria-Powered Battery with an Air-Cathode

It is high performance paper-based bacteria-powered battery with a stackable and integrative 3-D configuration. This 3-D biobattery will enable the development of new types of powered, paper-based biosensing easy-to-use packages.

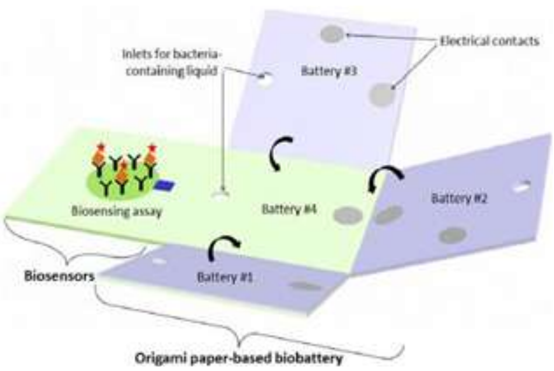

Fig 6:An Origami-based biobattery for potentially powering on-chip biosensors

A.Working Principle

A bacteria-powered battery, or a microbial fuel cell (MFC) is an electrochemical device that converts chemical energy to electricity through bacterial metabolism . Electrons produced by the bacteria from the organic chemicals are transferred to the anodic surface and flow to the cathode connected by an external resistor. The electrons can be extracellularly transferred to the anode by direct cell membrane, electron mediators, or nanowires produced by the bacteria. Typically, the MFCs have anodic and cathodic chambers separated by a proton exchange membrane (PEM). The electrons that reach the cathode combine with protons that diffuse from the anode through the PEM to maintain electroneutrality.

MFCs are normally made of solid substrates such as polymers, glasses, quartz, or silicon wafers to form the chambers or to support device components. Recently, our group created MFCs on paper substrates which were used as a chamber for holding the bacterial media and catholyte, orforming a microfluidic channel for transporting the solutions . The paper-based MFCs showed a short start-up time relative to rigid material-based MFCs, since the paper allowed for rapid adsorption of the liquid and promoted bacterial cell attachment to the anode, where the electrons transfer is made. Therefore, we proposed the paper-based MFCs as a simple and easy-to-use power source for disposable diagnostic biosensors in resource-limited settings because sewage or soiled water in a puddle can become an excellent source for extracting bioelectricity through bacterial metabolism. However, battery stacking in series and/or in parallels is essential to producing higher power output and operating voltages. Simple electrical connections between single MFC units are not suitable for compact and easily-operable paper systems because the MFC array requires a large footprint and each MFC unit needs a drop of liquid. Furthermore, our previous paper-based MFCs required catholyte as an electron acceptor such as potassium ferricyanide, which is not suitable for actual application in resource-limited regions because it is both toxic and expensive.

A three-dimensionally folded paper battery containing air cathodes was generated. This battery could lead to a very practical application by allowing the use of freely-available oxygen in the air as the electron acceptor. This platform not only provided an easily operable concept with just one drop of bacteria-containing liquid, it also had a small footprint in the paper-based system. Using origami, compact, stackable 3-D battery structures were created from 2-D sheets through high folding degrees along pre-defined creases. Moreover, 3-D microfluidic paths through paper layers showed great advantages for liquid-based fuel cell batteries, since one drop of liquid can be enough to power all stacked devices.

B.Device Fabrication

The paper-based origami bacterial battery was manually assembled with adhesive spray by sandwiching two functional layers: (i) paper reservoir layer, and (ii) front/back paper electrodes (carbon anode/air-cathode) (Fig. 7). The hydrophilic zone with hydrophobic wax boundaries was made by using a commercially-available solid-wax printer. The paper air-cathodes were fabricated from Whatman #1 filter paper with the mixture of activated carbon, isopropanol, DI water, and 5wt% Nafion on the sprayed Nickel electrode. Each electrode was connected in series by spraying a layer of Nickel (Fig. 8).

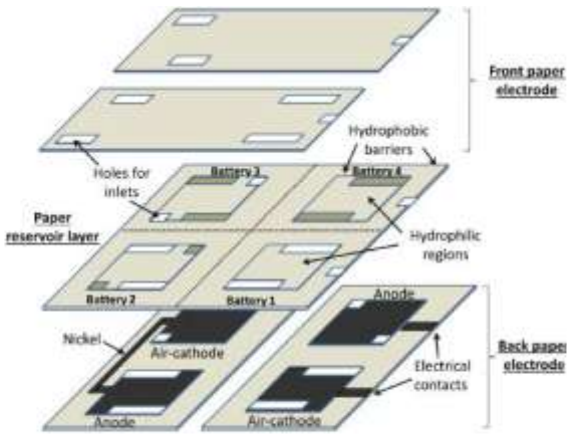

Fig 7: Schematic representations of the 3D origami-based bacterial battery showing individual layers

Bacterial inoculums:
The cultures of Shewanella oneidensiswas grown in L-broth medium under the consistent temperature at 30 °C.
L-broth medium contained 10.0g triptone, 5.0g yeast extract and 5.0g NaCl per 1 L of distilled water.

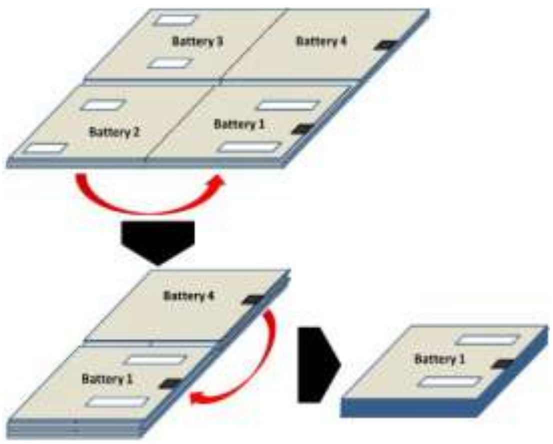

Fig 8: Schematic representations of the origami paper-based bacterial battery stack showing the folding steps

C. Measurement Setup

When the bacterial culture was added onto the common inlets of the folded battery stack, it was transported horizontally and then vertically, first filling the reservoir of each battery, and then reaching the different batteries. After the inoculum introduction, the folded stack was unfolded to expose all the air-cathodes to be air to maximize cathodic reactions . An output voltage generated from the origami biobattery was shown in Fig. 9. The gradual increase in the open circuit voltage (OCV) was observed and reached the saturated value of ~0.9V. Then, we connected resistors between the anode and cathode to monitor the current generation. Output voltages were monitored under two resistors; 470 kΩ and 100 kΩ. With 470 kΩ, the voltage was about 0.12V while it dropped to 0.03V at 100 kΩ (Fig. 9a).

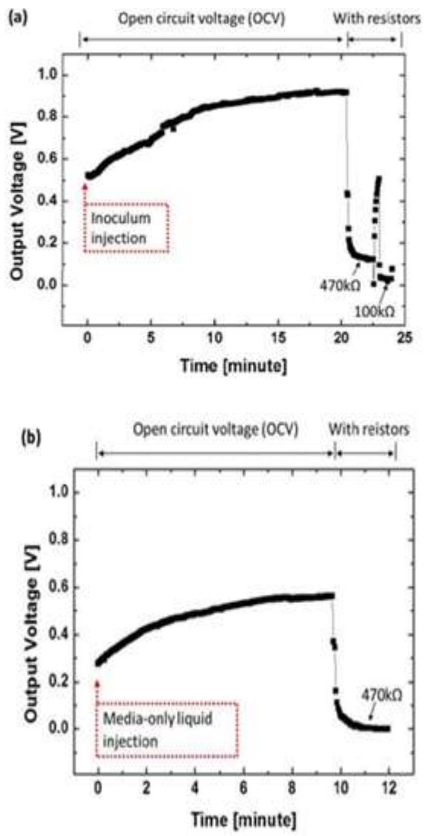

Fig.9: Output voltage measured from origami bacterial battery a) with bacteria b) without

As shown in Fig. 9b, the OCV with media-only liquid was slightly lower compared to that of bacteria. The current was not generated from the liquid without bacteria (Fig.9b), which indicates that thecurrent generation in Fig. 9a was attributed to bacterial metabolism. The electron transfer mechanisms of the bacterial cells through paper-based biobatteries are likely based on direct electron transfer, where the cells attach physically to the anode surface and transfer electrons to the anode.

IV.CONCLUSION

Energy crisis is one of the major problems in the world. Every nation needs energy and everyone needs power. A paper battery provides solution for the same. These batteries are made up of biodegradable, light-weight, non-toxic and flexible paper and have ability to power electronics, medical devices etc. Here we have discussed about a series-connected array of four microfabricated paper-based bacteria-powered battery batteries generated enough power to operate a practical electronic device for more than 30 minutes. The paper-based battery offers the advantages of simple fabrication process, and low production cost since used cheap commercial parchment paper for the PEM. This device is suitable for use as a power source for paper-based analytical and diagnostic platforms in resource-limited regions of the world.

Also a stackable, 3-D, paper-based, bacteria-powered, biobattery was capable of generating power from microbial metabolism, delivering, with one drop of bacteria-containing liquid, on-board energy to the next generation of paper-based systems. The advantages over other paper-based batteries in resource-limited and remote regions because water in every environment generally hosts various microorganisms that can operate such a battery.

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