High-voltage Liquid-electrolyte Microbatteries using the Multiple Cells Isolated by Surface Tension Effect

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Abstract

We present high-voltage liquid-electrolyte microbatteries, where the electrolyte filled in a channel layer is isolated by the air purging with surface tension effects, thus forming serially connected multiple cell arrays. For high-voltage generation, we need to interconnect or stack the unit power cells of several volts in a serial format. The microbattery stacks, however, increase the interconnection loss between unit cells, thus hindering from high-voltage generation. In this paper, we propose integrated liquid-electrolyte single-chip microbatteries, composed of multiple unit cells for high-voltage generation. The experimental study shows that a maximum voltage of 12V, a maximum power density of 110μW/cm², and a maximum power capacity of 2.1µAh/cm² have been achieved by a 40-cell microbattery. Also, the present microbatteries can reduce the charging time compared to the liquid-electrolyte microbattery stacks which require individual cell charging process.

Keywords: Microbattery, high-voltage generation, liquid-electrolyte battery, multiple cell array, surface tension isolation

1 - INTRODUCTION

High-voltage microbatteries are demanded for high-power MEMS applications: such as MEMS actuators that require several tens of volts with the power of nW~mW [1]. For high-voltage generation, we need to interconnect or stack the unit power cells of several volts [2-4] in a serial format. The microbattery stacks, however, increase the interconnection loss between unit cells, thus hinder from high-voltage generation. In this paper, we propose an integrated liquid-electrolyte single-chip microbattery, composed of multiple unit cells for high-voltage generation (Fig.1). The present microbattery, isolating multiple cells on a single-chip using air purging process followed by electrolyte filling process, reduces the charging time compared to the liquid-electrolyte microbattery stacks [4] requiring individual cell charge process.

2 - WORKING PRINCIPLE

The present microbattery isolates multiple cells on a single-chip using air purging process (Fig.2b) followed by electrolyte filling process (Fig.2a). The high-voltage single-chip microbattery consists of a channel layer and an electrical layer. The channel layer (Fig.3a) includes electrolyte chambers, surface tension valves [5], inlet and outlet ports and interconnecting channels, while the electrode layer (Fig.3b) contains anode(gold)-cathode(zinc) electrode pairs [3], electrical lines and output pads.

Figure 1 – A high-voltage liquid-electrolyte microbattery.

Figure 2 – Liquid-electrolyte charging process for the multiple cell microbattery: (a) the liquid-electrolyte filled in the entire channel layer; (b) the liquid-electrolyte isolated by air for multi-cell formation.

Figure 3 – Microbattery layers: (a) the channel layer and (b) the electrode layer.

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Three kinds of surface tension valves (Fig.4), each having different threshold pressure, are designed on the channel layer in order to control the electrolyte and air flows during the electrolyte charging process (Fig.2). According to surface energy and their geometric structures, cell-front valve, cell-end valve, and outlet valve have their own threshold pressures [5] by Eq. (1), which mean absolute pressures required to overcome the surface tension from location 1 to location 2 of a microchannel.

$$\Delta p = \left( \frac{2}{w_2} + \frac{1}{h} \right) \cdot \gamma \cdot \cos \theta_2 + \frac{1}{h} \cdot \gamma \cdot \cos \theta_1$$  \hspace{1cm} (1)$$

where, $w$, $h$, $\theta$, and $\gamma$ denote channel width, height, interfacial contact angle, and surface energy.

If we design the threshold pressure of cell-front valve, outlet valve, cell-end valve in ascending order, when pressure of liquid-electrolyte in a microchannel increases, cell-front valves burst at its threshold pressure, but outlet valve still blocks liquid-electrolyte, unit cells are charged (Fig.2a). At the same way, air purging lead outlet valve to burst during cell-end valve keeping liquid-electrolyte.

Each pair of Zn-Au electrodes is integrated with the electrical lines and interconnected serially on the electrode layer (Fig.3b). As a result of liquid-electrolyte filling and air purging process, multiple cells are isolated and generates the electrochemical potential, which is summation of each a unit cell. In this study, we have varied the number of unit cells and have designed four different microbatteries (C1, C10, C20, and C40), respectively composed of single, ten, twenty and forty unit cells.

3 - FABRICATION PROCESS

Figure 5 illustrates the fabrication process for the high-voltage microbatteries. The channel layers are fabricated by single-mask PDMS molding process and the electrode layers are fabricated by 4-mask Au-Zn electrode process. The fabrication process is completed with the room-temperature bonding of the channel layers and the electrode layers. Figure 6 shows the fabricated high-voltage microbattery. Figure 7 presents the enlarged views of the electrode array, composed of gold anodes and the electroplated zinc cathodes.

Figure 4 – Surface tension valves in the boxes 1, 2, and 3 of Fig. 3(a): (a) cell-front valve; (b) cell-end valve; (c) outlet valve, respectively.

Figure 5 – Fabrication process for the high-voltage microbattery.

Figure 6 – Fabricated high-voltage microbattery.

Figure 7 – Fabricated electrode layer: (a) cathode(Zn)-anode(Au) array; (b) an enlarged view of cathode(Zn) in (a).
EXPERIMENTAL RESULTS AND DISCUSSION

Using the fabricated devices, we have performed two experiments whose scope and conditions are listed in Table 1. In the threshold pressure measurement (Table 1), we have used the DI water instead of the liquid-electrolyte (H$_2$SO$_4$[1.5M]:H$_2$O$_2$[18M]=1:10, volume ratio), since the measured contact angle of DI water (110±0.32°) is similar to that (110±0.38°) of the electrolyte on the PDMS surface.

Figure 9 shows the results of threshold pressure measurement, where we have monitored the pressures required to pass over the surface tension valves for the flow rates varying in the range of 5~500 [μl/min]. The average values of threshold pressures in the three valves (Fig.4) are measured as 460±47Pa, 2,800±170Pa, and 1,000±53Pa, respectively.

In the battery performance measurement (Table 1), we have monitored the voltage and the current of four different microbatteries (C1, C10, C20, and C40) after the liquid-electrolyte filling and air purging process.

Table 1 - Experiments and conditions.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Experimental conditions</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold pressure of surface tension valves</td>
<td>Varying DI water flow rate in the range of 5~500 [μl/min]</td>
<td>Absolute pressure required to overcome the surface tension</td>
</tr>
<tr>
<td>Battery voltage, current, power, and capacity</td>
<td>LE* flow rate=100 [μl/min] Air flow rate=200 [μl/min] Load resistor: 1MΩ</td>
<td>Time-dependent voltage and current</td>
</tr>
</tbody>
</table>

*LE: The liquid-electrolyte of H$_2$SO$_4$[1.5M]:H$_2$O$_2$[18M]=1:10, volume ratio

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Table 2 - Performance of the fabricated high-voltage microbatteries.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>C1</th>
<th>C10</th>
<th>C20</th>
<th>C40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum voltage [V]</td>
<td>1.0</td>
<td>7.6</td>
<td>9.1</td>
<td>12</td>
</tr>
<tr>
<td>Maximum current [μA]</td>
<td>1.1</td>
<td>6.7</td>
<td>9.0</td>
<td>10</td>
</tr>
<tr>
<td>Maximum power density [μW/cm²]</td>
<td>40</td>
<td>160</td>
<td>150</td>
<td>110</td>
</tr>
<tr>
<td>Power capacity [μAh/cm²]</td>
<td>6.1</td>
<td>2.5</td>
<td>1.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 2 summarizes and compares the voltage, current, power density, and power capacity measured from C1, C10, C20, and C40. A 1MΩ of load resistor is selected, because MEMS actuators [1] have reasonably the value of resistance. Figure 10 presents the time-dependent voltage and the maximum voltage characteristics measured from the four different microbatteries, respectively.

Figure 8 – Liquid-electrolyte chambers isolated by the cell-front valve (Fig.4a) when the air is supplied to the channel layer filled with liquid-electrolyte.

Figure 9 – Threshold pressures measured from three different surface tension valves for varying DI water flow rates.

Figure 10 – Voltage-time characteristics measured from: (a) the single cell battery (C1); (b) the multi-cell batteries (C10, C20, and C40).
Figure 10b indicates the dramatic decrease in time-dependent voltage performance for C10, C20, and C40, caused by bubble electrode shielding. Figure 11 indicates that the maximum voltage measured from the multiple cell microbattery is proportional to the number of activated cells. Bubble generation in each unit cell is proportional to the number of activated cells; therefore, we remain a bubble reducing or removing issue for lower interconnection loss with higher power capacity in this work.

Figure 11 – Maximum voltage depending on the number of activated cells (C1, C10, C20, and C40).

5 - CONCLUSIONS
We have designed, fabricated and characterized the high-voltage liquid-electrolyte microbatteries, composed of the multiple cells isolated by surface tension effect. We have verified the feasibility of high-voltage generation and multiple cells isolation using liquid-electrolyte filling and air purging process. The experimentally study shows that the maximum voltages, maximum power density, power capacity, and charging time of the fabricated batteries are measured as 12V, 110μW/cm², 2.1μAh/cm², and 26.8±4.9sec, respectively from a 40-cell battery.

Therefore, the present microbatteries have potential use in high-power applications such as MEMS actuators; however, we remain the future work for bubble reducing or removing methods for lower interconnection loss with higher power capacity.

ACKNOWLEDGMENTS
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