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Ion channel-based flexible temperature sensor with humidity insensitivity

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ABSTRACT

We report an energy-efficient and mechanically durable temperature sensor with high selectivity and sensitivity. This sensor structure is inspired by ion channels in the cell membranes of living organisms that enable them to respond to temperature changes. For this purpose, a pore membrane and ionic solution are used for measuring the temperature based on the electrophoretic transport of ions. As the results indicate, we achieve a low consumption of power (8 μW/mm^2), high linearity ($R > 0.99$), and a high temperature coefficient of resistance (0.022 $^\circ$C^{-1}) over the specified temperature range (20–70 $^\circ$C). Our sensor intrinsically exhibits high selectivity to the humidity change and high signal stability to mechanical deformation. In addition, we also fabricate a flexible 3×3 matrix ion-channel-based temperature sensor, and demonstrate that it is capable of highly selective, sensitive, and flexible measurement (or area mapping) of the temperature over a specified area.

1. Introduction

Flexible temperature sensors have attracted much attention in recent years. Applications include electronic skin, soft devices, and robotic sensors [1–10]. In the early days, flexible temperature sensors were developed by miniaturization of classical temperature sensor e.g., inserting a thermosensitive transistor or thermistor into a flexible pad [2]. Nowadays, new thermosensitive materials or structures are applied to perform better flexing functions [4]. Mahadeva et al. demonstrated a biodegradable and flexible temperature sensor using composite nanomaterials combined with cellulose and polypyrrole [5]. Yang et al. developed a flexible temperature sensor based on graphene nanowalls [6]. These temperature sensors used flexible thermosensitive materials and provided additional advantages such as biocompatibilities or high efficiencies. These sensors were dependent on the inherent properties of utilized materials; however, the development of a unique temperature sensor insensitive to other variables such as humidity, pressure, or bending remained an ongoing challenge.

Ion channels are a component of the biosensor systems in living organisms and play key roles in the transport of ions. When a specific stimulus is applied, ions are transported through the ion channels and a biological signal is generated due to the potential difference between across the cell membrane (inside and outside of the cell). In general, while there are many different types of ion channels, these structures produce signals only for the specific stimuli [11–17]. Ion channels are very efficient biological sensing systems that precisely exclude the effects of other physical stimuli.

Herein, we demonstrate a flexible temperature sensor using an ion channel that has linear temperature dependency under humidity change or mechanical bending. A polycarbonate track-etched (PCTE) membrane is used as an ion channel. The operating power is relatively small in this ion-channel cell and the linear temperature dependence can be secured in a similar manner as is the case of a mechanism of electrophoresis. Also, the PCTE membrane increased the resistance to ion current changes caused by external stimuli e.g., bending. The undesirable flow of ions or fluid caused by flexing was suppressed during ion transfer through ion channels. Therefore, this sensor maintained a stable ion current in a deformable environment. In addition, this system filled with an aqueous electrolyte made the sensor biocompatible and insensitive to humidity.

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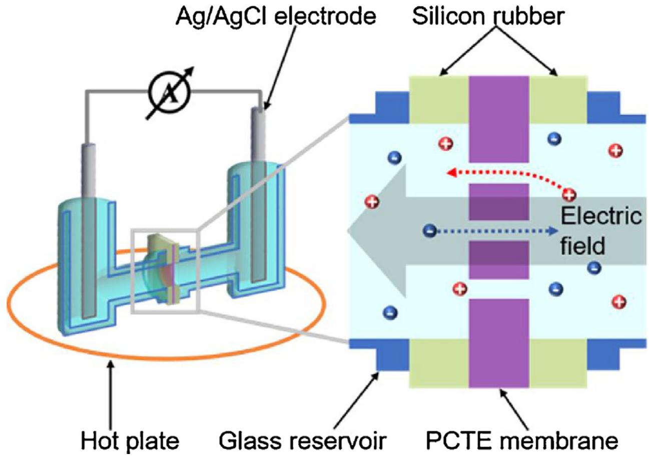

Fig. 1. Schematic of ion channel cell. Ions pass through PCTE membrane as a function of the applied electric field. The current change is measured by potentiometer according to the applying voltage.

2. Experimental

2.1. Ion channel cell

PCTE membranes were purchased from Sterlitech. The ion channel cell resembled a typical electrophoresis system as shown in Fig. 1. The electrolyte was KCl, which was purchased from Sigma-Aldrich. Two 2-mL-glass reservoirs were fixed with a steel holder. Two 1-mm-thick silicon rubbers were placed between the reservoirs to ensure a seal and so that a PCTE membrane could be inserted between two silicon rubbers. Two reservoirs were filled with the same concentration of 1 M aqueous KCl solution and Ag/AgCl electrodes settled in the center of each reservoir. Ag/AgCl electrodes were connected to a potentiometer (Princeton Applied Research, VersaSTAT 3) to measure the current change between two reservoirs.

2.2. Measurement of temperature dependency from the ion channel cells

Distilled water was added to the large beaker to a level higher than the KCl aqueous solution in the cell but lower than the height of cell to prevent water from entering the cell. The beaker with the ion channel cell was placed on a thermo-stirrer and the magnetic bar was placed close to the ion channel cell in order to ensure uniform distribution of the water temperature. A digital thermometer was used to indirectly determine the temperature of the ion channel cell by measuring the temperature of the water. The current was measured by determining the potential difference from −0.5 to 0.5 V applied by the potentiometer (which simultaneously provided the potential).

2.3. Fabrication of flexible ion channel temperature sensor

Two sheets of 1-mm thick silicon rubbers with 1 cm × 1 cm square holes were prepared for use as electrolyte trays. The PCTE membrane was located between two sheets of silicon rubbers. The electrolyte consisted of agarose gel containing 0.1 M KCl as follows. The solution was prepared by adding 1 g agarose powder and 745 mg KCl to 100 mL distilled water. This solution was heated on the thermo-stirrer for a few minutes with stirring until the agarose was completely dissolved. It was left to cool down with stirring to keep the concentration uniform. The KCl agarose solution was inserted into the silicon rubber tray and permeated into the ion channel of the PCTE membrane located at the bottom of the tray. This inserted gel was left at room temperature for 30 min to complete solidification and permeation in the PCTE membrane. The opposite silicon rubber tray which shared the same membrane as the underside was equally filled with gel in the same way. Ag/AgCl electrodes were inserted in each tray to apply a potential and measure the current. Then the silicon rubber tray was capped using non-hold, 0.5 mm thick silicon rubber. When measuring the surface temperature difference, the sensors were arranged in a passive matrix.

2.4. Measurement of surface temperature from flexible temperature sensor

The round glass bottle stored in 70 °C oven was prepared to form a surface with a temperature difference. A glass bottle was half-filled with 50 mL ice water and the flexible temperature sensor with 3 × 3 passive-matrix design was perfectly attached to the round surface of a glass bottle. Since the ice water was half filled, the boundary of the ice water was in the middle of the sensor. The abrupt temperature change occurred in the early stage because the glass bottle stored in the oven was filled with ice water. Therefore, it was left for 5 min to measure in a smooth condition which was likely a quasi-static process. The temperature of each matrix cells was determined by a digital thermometer. The on current was measured as a cyclic potential difference from −0.2 to 0.2 V (applied by the potentiometer). The cyclic potential difference circulated 10 times at a rate of 0.2 V/s, and the current-voltage (I–V) curve converged to a specific value during circulation. Finally, a maximum ion current converged in the last cycle and was measured at 0.2 V.

3. Results and discussion

3.1. Performance of PCTE ion channel cell

Fig. 2(a) shows an I–V curve of typical electrophoresis which is an ion channel cell without PCTE membrane. The 0.1 M KCl aqueous solution was used as the electrolyte and a voltage from −0.5 to 0.5 V was applied to measure the ion current in various temperature. Experiments were performed from 25 to 50 °C and the gradient of the I–V curve linearly increased with increasing temperature. It is well known that the temperature dependency of the ion current is due to the increase of the ion mobility with temperature. A very similar performance was observed in the PCTE (pore diameter: 100 nm) ion channel system as shown in Fig. 2(b). It should be noted that 100 nm pore-sized PCTE membrane has only 3% open area resulting in a large resistance and a drastic decrease in ion current but little change (Supplementary data, Table S1). As shown in Fig. 2(c), the ion current is halved in the ion channel system with 10 nm pore-sized PCTE membrane. However, considering that the open area is 0.3%, this decrease is very small. Here, we can consider that the highly monodisperse distribution property of the PCTE membrane counteracts ion current decrease. In addition, the correlation coefficient R^2 in Fig. 2(c) shows the relationship between the pore size and the resolution of ion current with temperature. The typical electrophoresis without PCTE membrane shows temperature dependency at $R^2 = 0.972$, but the ion channel cell shows temperature dependency with high resolution with $R^2 > 0.99$. Furthermore, as the pore size of ion channel decreased, higher R^2 is obtained as shown in the confirmation of $R^2 = 0.998$ at 10 nm pore-sized PCTE membrane. By applying the ion channel, we realize that the only low current loss is tolerated and temperature dependency with high resolution can be achieved. It shows that electrophoresis has linear temperature dependency from 25–50 °C. Theoretically, under the same conditions, the change of current characteristic showed a similar value without significant deviation and a linear