Supporting Information

Chemistry Letters

# Effect of Channel Geometry on Ionic Current Signal of a Bridge Circuit Based Microfluidic Channel

Hirotoshi Yasaki,*[1,2] Takao Yasui,[1,2,3] Takeshi Yanagida,[4,5] Noritada Kaji,[1,2,3] Masaki Kanai,[4] Kazuki Nagashima,[4] Tomoji Kawai,[5] and Yoshinobu Baba*[1,2,6]

[1]*Department of Biomolecular Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan*
[2]*ImPACT Research Center for Advanced Nanobiodevices, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan*
[3]*Japan Science and Technology Agency (JST), PRESTO, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan*
[4]*Laboratory of Integrated Nanostructure Materials Institute of Materials Chemistry and Engineering, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan*
[5]*Institute of Scientific and Industrial Research, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
[6]*Health Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Takamatsu, Kagawa 761-0395, Japan*

Received December 5, 2017; CL-171139; E-mail: yasaki.hirotoshi@e.mbox.nagoya-u.ac.jp (H. Yasaki), babaymtt@chembio.nagoya-u.ac.jp (Y. Baba)

Electronic Supporting Information for *Chemistry Letters*


**This file includes:**

Supplementary Figures S-1 to S-4, and Derivation of theoretical equation

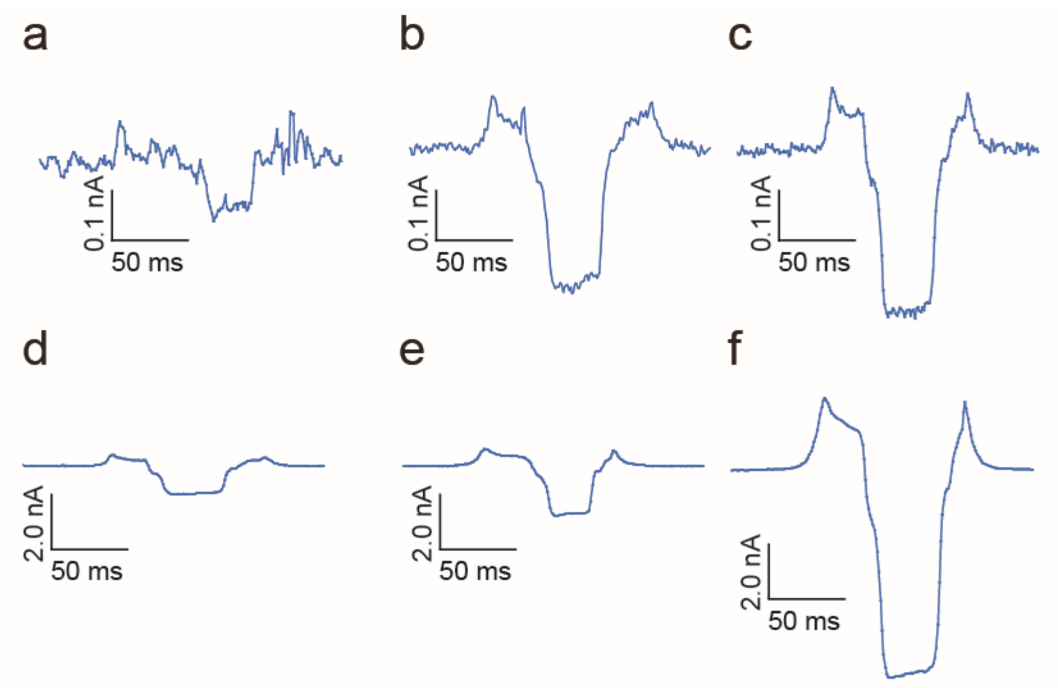


**Figure S-1. Current signals of various sized particles.** (a) 0.75-, (b) 1.00-, (c) 1.10-, (d) 1.75-, (e) 2.08-, and (f) 3.10-μm diameter polystyrene particles. Width, height, and length of the sensing area for this experiment were 4 μm, 7.5 μm, and 85 μm, respectively. Width of the sample flow channels was 4 μm.

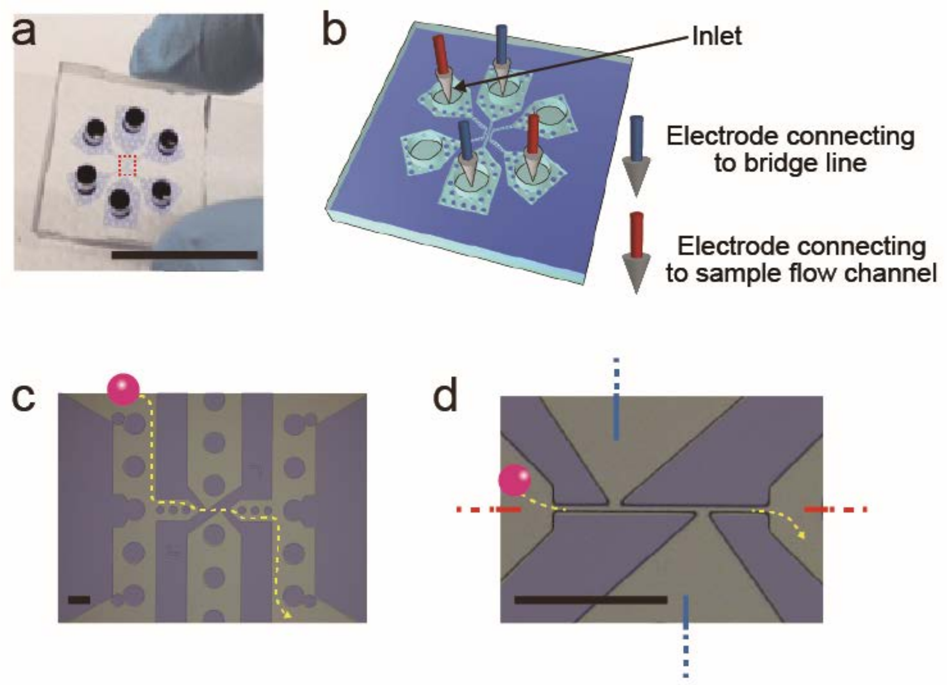


**Figure S-2. Experimental set up and photo images.** All figures are adapted with slight modification from reference 14. (a) A photo of the fabricated PDMS chip; scale bar, 2 cm. (b) A schematic illustration for a microfluidic channel with electrodes. (c, d) Sample injection schemes ; scale bars, 100 µm. Width, height, and length of the sensing area for this experiment were 4 µm, 7.5 µm, and 85 µm, respectively.

**Derivation of theoretical equation**

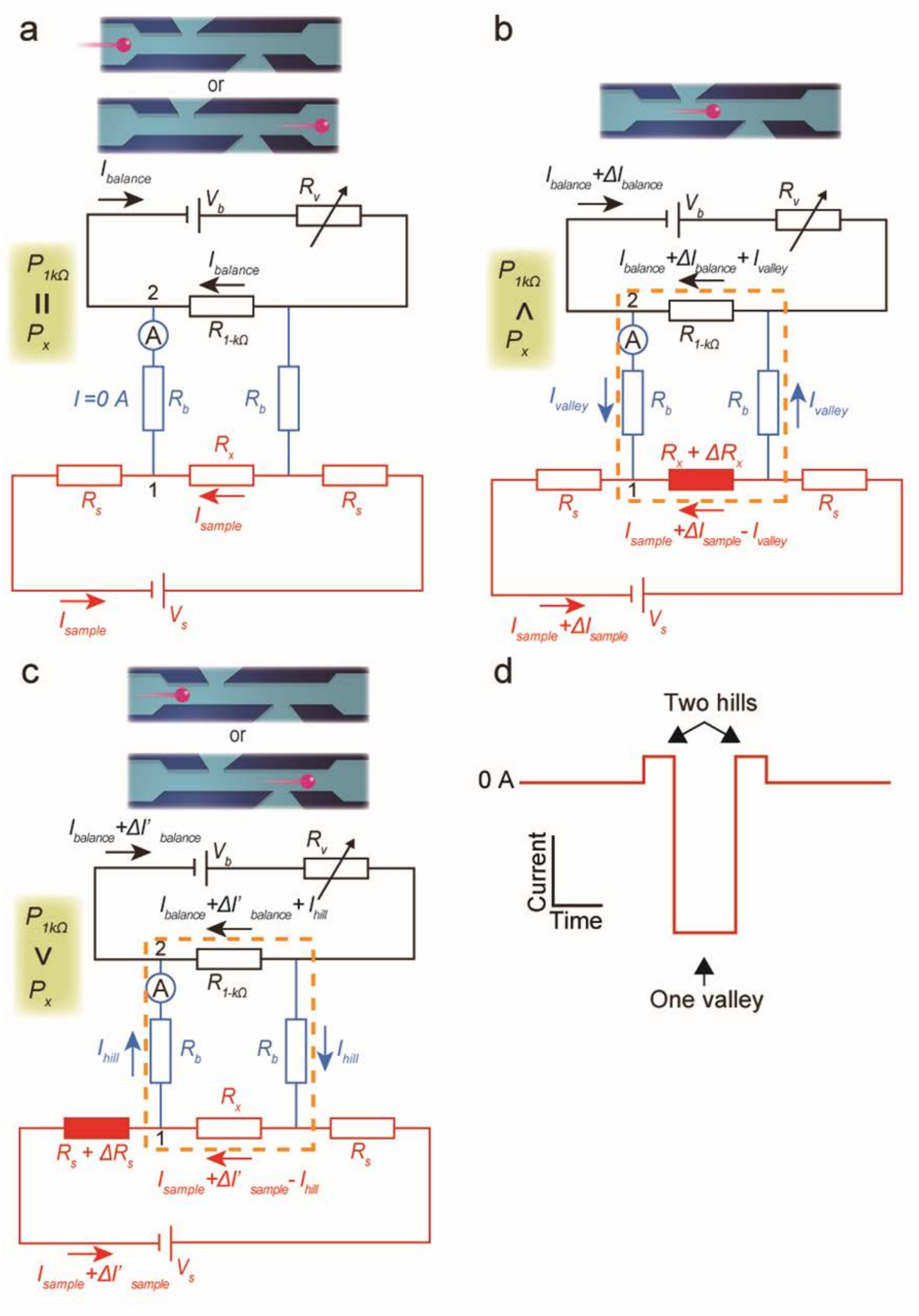


**Figure S-3.** **Schematic illustrations of sample particle translocation, electric circuit diagrams, and schematic current signal shape in the microfluidic bridge circuit for**

**derivation of theoretical equation.** (a) The situation before and after passage of a sample particle in sample flow channels. Red lines are for the sample circuit, blue lines are for the bridge lines, and black lines are for the balance circuit. The sample circuit has a voltage source ($V_s$) and resistors for the sensing area ($R_x$) and sample flow channels ($R_s$). The bridge lines have resistors ($R_b$) and an Ampere meter (A). The balance circuit has a voltage source ($V_b$), a variable resistor ($R_v$), and a 1-kΩ resistor ($R_{1\text{-}k\Omega}$). Red and black arrows show flow directions of current in the sample circuit and the balance circuit, respectively. The numbers “1” and “2” are the electrical potential of the sensing area entrance and the electrical potential of the cathode of the voltage source in the balance circuit, respectively. $P_{1k\Omega}$ and $P_x$ are the potential differences of both ends for the 1-kΩ resistor and the sensing area, respectively. (b) The situation at the time the sample particle passed through the sensing area. Red filled squares show increased resistance by sample introduction. Blue arrows show provisional flow directions of current by deviation of potential differences between the sample and balance circuits. (c) The situation at the time the sample particle passed through the sample flow channels. (d) Schematic illustration of current signal shape by translocation of the sample particle in the sample flow channels and the sensing area. Amplitude of hills in the current signal by translocation of sample in the sample flow channels is higher than 0 A. Amplitude of the valley in the current signal by translocation of sample in the sensing area is lower than 0 A.

Our method uses two electrical circuits: a sample circuit and a balance circuit. We derived a theoretical equation to calculate signal amplitudes, which are detected in this method, based on Ohm's law and Kirchhoff's law. In the balanced state, no current flows in the bridge channels (Figure S3a), and the following equations are formulated for each "isolated" circuit:

$$I_{sample} = \frac{V_s}{2R_s + R_x} \qquad (S1)$$

$$I_{balance} = \frac{V_b}{R_{1-k\Omega} + R_v} \qquad (S2)$$

where $R_s$, $R_x$, $R_{1\text{-}k\Omega}$, and $R_v$ are the electrical resistances of the sample flow channels, the sensing structure, the 1-kΩ resistor, and the variable resistor, respectively. $V_s$ and $V_b$ are the applied voltages for the sample and balance circuits, respectively. $I_{sample}$ and $I_{balance}$ are currents in the sample and balance circuits, respectively. Since potential differences between both ends of the sensing structure ($R_x$) and the 1-kΩ resistor ($R_{1\text{-}k\Omega}$) are the same in the balanced state, Eqs (S1) and (S2) are transformed as:

$$R_x \times I_{sample} = R_{1-k\Omega} \times I_{balance}. \qquad (S3)$$

When a sample is passing through a sample flow channel, the current in the sample circuit changes from $I_s$ to $I_{sample}+\Delta I'_{sample}$ (Figure S3c):

$$I_{sample} + \Delta I'_{sample} = \frac{V_s}{2R_s + \Delta R_s + R_x} \qquad (S4)$$

where $\Delta R_S$ and $\Delta I'_{sample}$ are resistance change of that sample flow channel and current change in the sample circuit by sample introduction, respectively. This situation will also occur when the sample is passing through a later sample flow channel. At this time, the potential difference between both ends of the sensing area ($P_x$) is decreased by the decreasing current, and the signal ($I_{hill}$) flows to an Ampere meter to compensate for the potential difference between points 1and 2. At the same time, the balanced state is lost. The following equation is the sum of the voltages of the circuit surrounded by the orange dotted line:

$$\left(I_{sample} + \Delta I'_{sample} + I_{hill}\right)(R_x) = \\ -I_{hill}(2R_b + R_{1-k\Omega}) + (I_{balance} + \Delta I'_{balance})R_{1-k\Omega} \qquad (S5)$$

where $\Delta I'_{balance}$ is current change in the balance circuit by sample introduction to one sample flow channel. The following equation is the expansion equation of Eq (S5).

$$\left(I_{sample} + \Delta I'_{sample}\right)R_x - (I_{balance} + \Delta I'_{balance})R_{1-k\Omega} \\ = -I_{hill}(2R_b + R_{1-k\Omega} + R_x) \qquad (S6)$$

Eq (S6) can be transformed by Eq (S3) as follows.

$$\Delta I'_{sample}R_x - \Delta I'_{balance}R_{1-k\Omega} = -I_{hill}(2R_b + R_{1-k\Omega} + R_x) \qquad (S7)$$

The following equation is the sum of the voltages of the balance circuit.

$$V_b = R_v(I_{balance} + \Delta I'_{balance}) + R_{1-k\Omega}(I_{balance} + \Delta I'_{balance} - I_{hill}) \quad \text{(S8)}$$

Eq (S8) can be transformed by Eq (S2) as follows.

$$\Delta I'_{balance} = \frac{R_{1-k\Omega}}{R_v + R_{1-k\Omega}} \cdot I_{hill} \quad \text{(S9)}$$

Eq (S7) can be transformed by Eqs (S1), (S4), and (S9) as follows.

$$\frac{-V_s \cdot \Delta R_s}{(2R_s + \Delta R_s + R_x)(2R_s + R_x)} \cdot R_x - \frac{(R_{1-k\Omega})^2}{R_v + R_{1-k\Omega}} \cdot I_{hill}$$
$$= -I_{hill}(2R_b + R_{1-k\Omega} + R_x) \quad (S10)$$

Eq (S10) can be transformed as follows.

$$I_{hill} = \frac{V_s \times R_x \times \Delta R_s}{(2R_b + R_{1-k\Omega} + R_x - \frac{R_{1-k\Omega}{}^2}{R_v + R_{1-k\Omega}}) \times (2R_s + \Delta R_s + R_x) \times (2R_s + R_x)} \quad (S11)$$

When $R_v$ and $R_{1\text{-}k\Omega}$ are small enough compared with $R_x$ and $R_b$, Eq (S24) can be transformed as follows.

$$I_{hill} = \frac{V_s \times R_x \times \Delta R_s}{(2R_b + R_x) \times (2R_s + \Delta R_s + R_x) \times (2R_s + R_x)} \quad (S12)$$

When $\Delta R_s$ is small enough compared with $R_x$ and $R_s$, Eq (S12) can be transformed as follows (this is Eq 2 of the main text).

$$I_{hill} = \frac{V_s \times R_x \times \Delta R_s}{(2R_b + R_x) \times (2R_s + R_x)^2} \quad (S13)$$

Based on Eq (S13), value of $I_{hill}$ is positive.

Therefore, the same as for the provisional direction, current flows from points 1 to 2 in this situation.

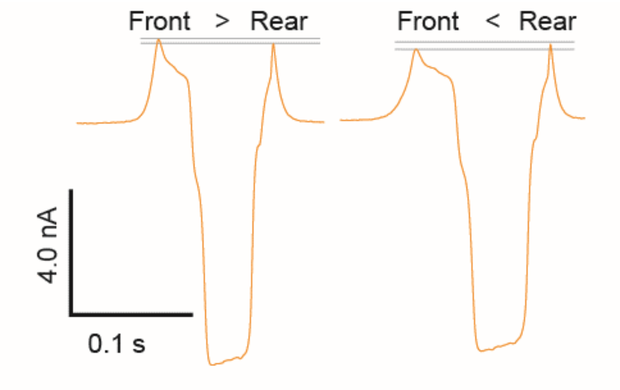


**Figure S-4. Comparison of amplitudes of front and rear hills.** In the same microfluidic sensing chip, regularity was not observed in the relationship of amplitudes of front and rear hills. Therefore, there was no systematic error in the amplitude difference of front and rear hills.