INTEGRAGION OF ULTRA-SENSITIVE ON-CHIP ELECTRIC CIRCUIT FOR NON-FARADAIC ELECTRIC CURRENT BASED FLOW SENSING

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ABSTRACT

We designed and developed an ultrasensitive and low-noise on-chip electrical measurement circuit, which was directly soldered on a microfluidic chip. The advantage of the on-chip format is not only in integration of electrical measurement unit to close to micro total analysis systems, but also suitable to minimize the electrical wiring to minimize external noise for ultrasensitive measurement. The performance of the on-chip circuit was experimentally demonstrated by sensing flow velocity of various liquids in microchannel. As a result, it was successfully obtained nearly liner relation between flow velocity of isopropyl alcohol, ethanol, and KCl solution.

KEYWORDS

microfluidics, flow sensing, on-chip circuit, integration, ultra-low current

INTRODUCTION

One of the most important issues on μTAS (Micro Total Analysis Systems) concept is addressed to the integration of all the required components into a single chip to realize fully portable system.[1-3] This issue however has been left unsolved behind the discovery of novel scientific phenomena or development of cutting-edge micro technology obtained in μTAS devices. However the integration of all required components are an important issue from the engineering aspect of μTAS. Thus, we developed an on-chip ultra-sensitive electric current (or resistance) measurement circuit, and experimentally demonstrated by sensing flow velocity of various liquids in microchannel. The important point on the on-chip electric circuit is not just a matter of instrumentation. On-chip circuit is possible to minimize electric wiring, which reflects in minimizing both internal and external noise. The low noise circuit means that it requires no additional filter and any additional inductor or capacitor to stabilize the circuit from instability caused by parasitic impedance. Such advantages lead to high signal-to-noise ratio, further miniaturization, and suppress power consumption, all of which them is preferable for μTAS concept.

From the point of electrochemistry, ultra-sensitive electrical measurement can realize the measurement of non-faradaic current without electrolysis of electrode in solution, because very low voltage of less than the standard electric potential (typically less than 1 V) will be enough to probe a solution by electric current. The absence of a faradaic current and subsequent non-faradaic behavior is advantageous since a multitude of other materials caused by faradaic reactions interferes electric responses. By using such advantages, we experimentally demonstrated the detection of electric current change caused by the change of flow velocity in microchannel. There has been reported many types of sensing methods based on heat transfer, drug force, differential pressure, electric resistance and capacitance, etc.[4-8] Our method will be categorized in electrical method, but it quite a small but will is different from conventional electrochemical measurementin term of non-faradaic current measurement. In the case of non-faradaic current measurement, the carrier of ions will be consumed within a short period if there is no flow condition. However the carrier ions will be continuously supplied if there is any flow. Therefore, the consumption of carrier ions per a certain period will be refracted as non-faradaic electrical current, which is quite small but would be detected by ultrasensitive measurement.

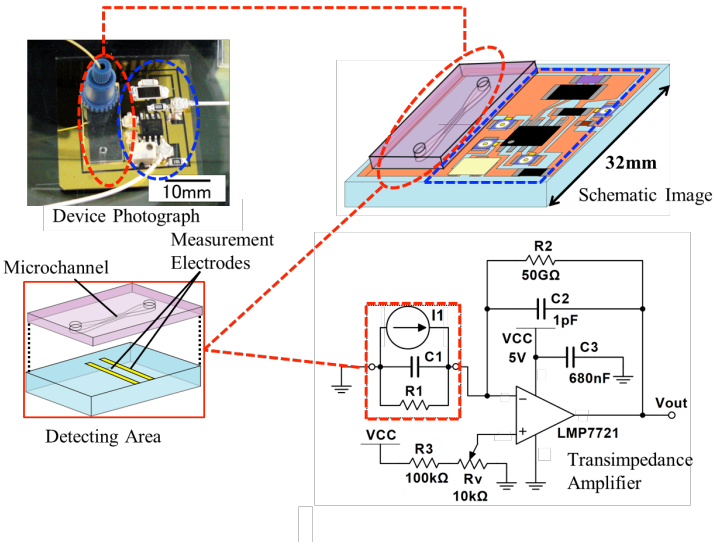

Figure 1. Schematic image and photo of microfluidic device embedded with the on-chip ultrasensitive electric current measurement circuit. The chip size is 32 ×32 mm engaged by 15 mm ×15 mm electric circuit area. The channel width and height are both 20μm, the electrodes width and the electrode gap are both 20μm.

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EXPERIMENT

The microfluidic chip consists of two functional sub-chips as shown in Figure 1. The one is a glass-made circuit chip, on which a couple of measurement electrodes and a current measurement circuit are fabricated. The circuit pattern was fabricated by typical photolithography and consists of 100 nm Au and 3nm Ti adhesion layers. All electric parts were soldered by hand. The other one is a PDMS-made microchannel chip having a microchannel inside.[9]

The design of measurement circuit is based on a transimpedance amplifier. Because the on-chip circuit is intrinsically low noise and LMP7721 operational amplifier (National Semiconductor) wastes only a few femto ampere as input bias current, we successfully obtained ultra-sensitivity of 20 fA with good linearity from tens fA to tens pA without any additional circuit and an enclosed shield box. We used a syringe pump (KDS210, KD Scientific) to control the flow rate precisely. We tested two types of liquids. One is water solutions of deionized water and KCl solution with various concentrations. The other is organic solvent of isopropyl alcohol (IPA), ethanol, and fluorinert (FC-43, 3M).

RESULTS

Figure 2 shows the typical electric current response with respect to the stepwise velocity changes of isopropyl alcohol. As shown in the figure, the response time of electric current against flow rate is about a few seconds. The periodical noise is due to the stability of the pump system. This graph apparently shows that the electric current is well correspond to the velocity of liquid flow.

Figure 3 shows the relation between flow velocity of various liquids and the measured electric current. The non-conductive liquid of fluorinert induces almost no current change, because it is probably due to no carrier of cation and anion in the liquid. On the other hand, ionic solution and organic solvent show electric current change as shown in the figure. KCl solution shows nearly linear electric current change on flow velocity in the measured flow velocity range. The KCl concentration dependency on electric current is not apparent from 0 M (pure water) to 1 μM. Table 1 summarizes the result of the sensitivity of flow velocity in tested liquids. The sensitivity is better with the conductivity is lower in KCl solution. It means that the electric current is inversely proportional to the carrier density. We have no answer to explain this trend at the moment. There is a possibility that the streaming current and potential caused by the presence of electric double layer on the surface might affect the measured electric current. Ion density change induces the change in the thickness electric double layer, so that the amount of counter ion may be changed, which affects to the measured electric current. We are now investigating the mechanism behind the electric current measurement on flow velocity change in our experimental system. In contrast, organic solvents of IPA and ethanol shows higher current than ionic solution of KCl. It might reflect lower ion density leads higher current. The other possible reasons can be caused by the impurity of IPA and ethanol. Both of them used in the experiment were the high purity analytical grade, however it is hard to remove water or other impurity from such a polar solvents completely. Other reason may be caused by generation of peroxide, aldehyde, ketone, etc. It is known that IPA generates peroxide by the reaction with atmospheric oxygen, so that peroxide ions may be a possible candidate as a carrier. By a recent study, a couple of Pt / Au catalytic reaction can effectively generate aldehyde and ketone from alcohols [10]. The presence of Pt in the PDMS chip as a catalyst of PDMS and Au electrode might induce the same catalytic reaction by applying electric field for measurement. As described above, there are several possibility why the organic solvents showed relatively high electric current rather than KCl solution.

Even though the mechanism still remains unclear, it was succeed to measure the flow velocity of water solution and organic solvent from 0 mm/s to 125 mm/s except for fluorinert.

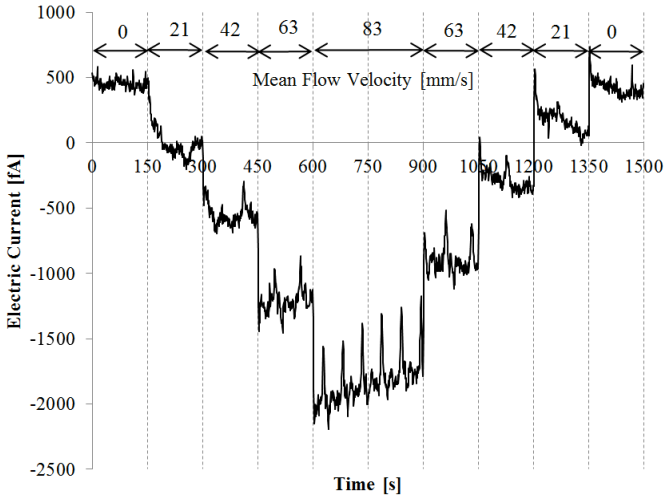
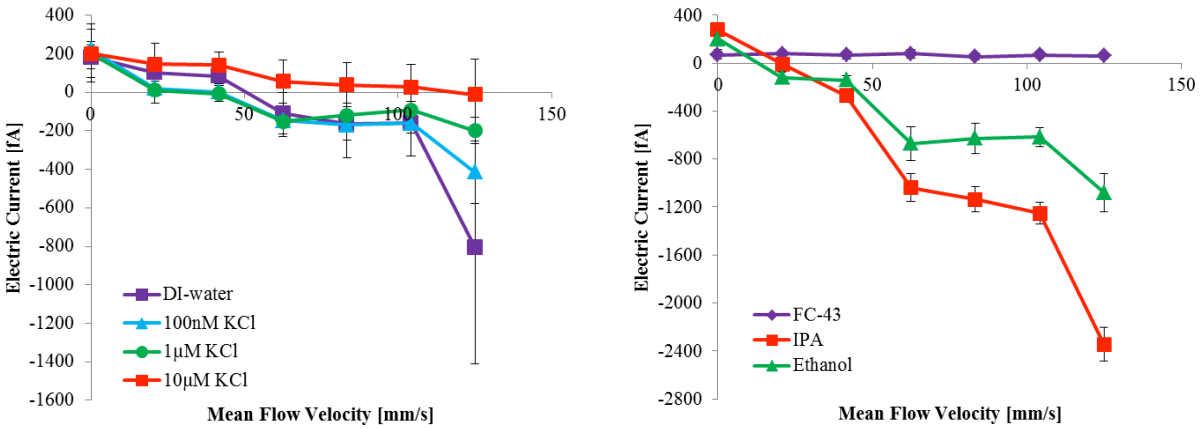


Figure 2. Time response of electric current with respect to flow velocity in the microfluidic device.



(a) Water solutions (b) Organic solutions

Figure 3. The relation between electric current and flow velocity of liquids.

Table.1 Electric Current – Mean Flow Velocity Slope (fA·s/mm) calculated by least-squares method

FC-43	IPA	Ethanol	DI-water	100nM KCl	1μM KCl	10μM KCl
-0.0934	-17.3	-9.11	-4.99	-4.18	-2.62	-1.68

CONCLUSION

We have successfully developed a simple but ultra-sensitive on-chip electric current measurement circuit, which was directly embedded on a microfluidic chip. The performance of the on-chip circuit was experimentally demonstrated by sensing flow velocity of various liquids in microchannel. There remains the mechanism of the relation between electric current and flow velocity, however we have found that flow velocity dependent electrical current change was occurred in fA regime at the concentration from 0 M (ultra-pure water) to 10 μM KCl solution and organic solvant. We will investigate higher concentration regime, which may help to reveal the detailed mechanism of the relation of flow velocity and electric current. Our on-chip circuit will be universally used for not only an electric current sensing, but also many possible applications in high sensitive photo sensing, pH sensing, electrochemical sensing, etc.

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