

Field-effect control of electro-osmotic flow in microfluidic networks

E.J. van der Wouden, T. Heuser, D.C. Hermes, R.E. Oosterbroek,
J.G.E. Gardeniers*, A. van den Berg

*BIOS Lab-on-a-Chip Group, MESA+ Research Institute for Nanotechnology, University of Twente,
P.O. Box 217, 7500 AE Enschede, The Netherlands*

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Abstract

This paper describes microfluidic networks based on glass microchannels with integrated insulated gate electrodes that are used to modify the zeta-potential at specific locations on the wall surface of the microchannels. This modification is used to control direction and size of the electro-osmotic flow (EOF) in the microchannels. A new microfabrication process was developed that compared to earlier work in our institute [R.B.M. Schasfoort, S. Schlautmann, J. Hendrikse, A. van den Berg, *Science* 286 (1999) 942] leads to mechanically more robust structures and better flow visualization in the gate region. In the new process sequence, the microfluidic chips were fabricated using deposition on a Pyrex glass substrate of a thin-film metal electrode, which was covered with a thin insulating film of silicon dioxide, followed by chemical mechanical polishing prior to bonding to a second glass plate to form closed microchannels. Electrical breakdown of the metal–insulator structures was measured and occurred at 9.6 ± 0.3 MV/cm. Experiments using fluorescent beads to visualize the flow patterns in the microchannel showed that the EOF is linearly dependent on the applied gate voltage. The average EOF could be stopped completely for longitudinal fields of 150 V/cm by applying a gate field of 1.7 MV/cm.

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1. Introduction

Integrated microfluidic devices containing micromachined channels are currently being studied for automated and high-throughput synthesis and analysis of chemical compounds or for the study of biological processes in (single) cell cultures [1–4]. In these microchannel networks, pumping and valving is an important issue. Although traditionally these functions have been performed by mechanical means [5], during recent years, other ways of liquid transport and control have been introduced, e.g. using capillary forces to drive and hydrophobic patches to stop the flow at specific locations [6]. In a large number of microfluidic circuits, especially those that use electrophoretic separations, liquid is driven and directed by electrokinetic principles (see, e.g. [7]), which offer some advantages over pressure-driven methods, like ease of fabrication, absence of moving parts and low dis-

persion of sample plugs due to the almost uniform velocity profile across the microchannel width. Electrokinetic pumps are usually controlled by manipulating voltages applied to the ends of microchannels. In this paper, we will discuss the control of electrokinetic flow by applying a principle that resembles the field-effect that is well-known in electronic transistor circuits and which for the fluidic case was named “flow-FET” (FET for field-effect transistor) [8] or field-effect flow control (FEFC) [9] in previous publications. The paper will describe the design, fabrication, modeling and testing of a new microfluidic device, that has integrated electrodes covered with an insulating layer, of which the zeta-potential will be modified by a voltage applied to the electrodes. Compared to previous work at our institute [8], in which very thin and therefore fragile micromachined silicon nitride tube structures, locally covered with thick silicon gate electrodes were used, which obstructed flow visualization in the gate region, in the present study, a microfabrication process is used that leads to robust structures and allows flow analysis in the gate region.

* Corresponding author. Tel.: +31 53 4894356; fax: +31 53 4893595.
E-mail address: j.g.e.gardeniers@utwente.nl (J.G.E. Gardeniers).

2. Theoretical background and FEFC simulations

2.1. Principle of field-effect flow control

It is well-known that, especially in aqueous systems, an electrical double layer (EDL) forms spontaneously at the phase boundary of the liquid with a solid, due to preferential adsorption or desorption of certain ions [10]. For example, when fused silica is immersed in an aqueous solution with a pH above the pK_a value of silica, 2.8, it will acquire a negative surface charge due to deprotonation of surface silanol groups. Because of the resulting surface charge, co-ions from the solution will be repelled and counter-ions will be attracted in order to screen the surface charge, creating a charged region close to the surface forming the EDL. Due to strong electrostatic interaction, the layer of counter-ions closest to the surface will be immobilized, a region referred to as the Stern layer. Further away from the surface, the counter-ions will have more freedom to move, this layer is called the diffuse layer. The potential at the interface of these two layers is the so-called zeta-potential, ζ .

When an electric field is applied along the surface as described above, ions in the EDL will move due to the forces exerted on them by the electric field. Due to viscous coupling between the ions in the EDL and the bulk liquid, electro-osmotic flow (EOF) will develop. EOF has been used to pump liquids in microfluidic networks and has been well-studied in the field of capillary electrophoresis [11–14]. The linear velocity v_{EOF} corresponding to the EOF is given by:

$$v_{EOF} = \frac{\varepsilon_0 \varepsilon_r \zeta}{\eta} E \quad (1)$$

with ε_0 and ε_r the dielectric constant of vacuum and liquid, respectively, E the electric field and η is the viscosity of the liquid.

Eq. (1) shows that the EOF in a specific liquid can be controlled by both the electric field and the zeta-potential. It was demonstrated that in a microchannel network, liquid flows can be switched between different branches by changing the electric fields along the different channels via switching of the voltages at electrodes at the outlets of the microchannels [14]. A drawback of this method is that in more complex

networks, with many crossing microchannels, independent control of the flow in the different branches becomes difficult, due to the fact that the electrical voltages in the channels are all resistively linked. Thus, switching the voltage at one outlet of the network changes the voltages and therewith the EOF throughout the network. Local control of the voltages by introducing electrodes inside the channels is generally not feasible due to the generation of gas bubbles by electrolysis at these electrodes, which may disrupt the electrical network or block the channels.

A more subtle control over liquid flow can be obtained by introducing local changes in the ζ -potential, keeping the main electric fields along the channels constant. This can be done, e.g. by applying a transverse electric field over the thickness of a thin insulator that is integrated in the walls of a microfluidic channel.

The principle was demonstrated already in the beginning of the 1990s [15–20]. In these early studies, fused silica capillaries were used, with electrodes on the outside wall of the capillary to change the ζ -potential on the inside wall. The purpose of that work was the enhancement of electrophoretic separation efficiency, rather than flow control. Because of the thickness of the capillary walls, relatively high voltages (several kilovolts) were required to establish a significant effect on ζ . Since modern microfabrication and thin-film deposition techniques allow the fabrication of channels with extremely thin walls, the required radial electrical fields can now be achieved with more acceptable voltages, like a few tens of volts, as was demonstrated in recent work [8,21]. We will refer to this principle as “field-effect flow control” [9].

The change in ζ that can be achieved in FEFC depends on the potential distribution across the different capacitors that can be identified in an electrical circuit description of the channel wall–electrolyte system, as shown in Fig. 1. The EDL can be modeled as a series of two capacitances [22], i.e. that corresponding to the Stern layer, C_{Stern} , and that of the diffuse layer, C_d . For dilute aqueous solutions at 25 °C, the diffuse layer capacitance per unit surface area in $\mu\text{F}/\text{cm}^2$ has the value [23]:

$$C_d = 228z\sqrt{c} \cosh(19.5z\zeta) \quad (2)$$

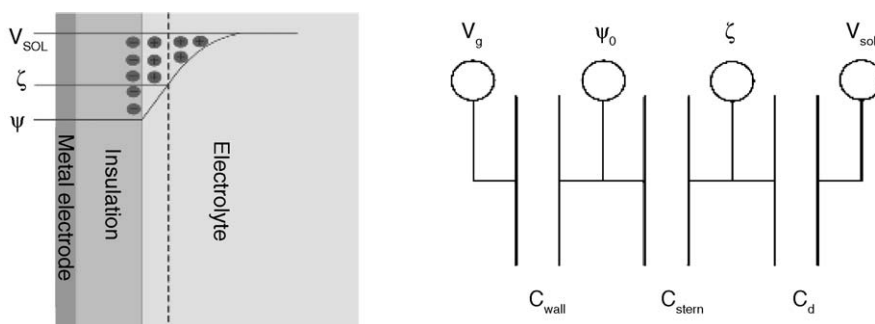


Fig. 1. Left: simplified drawing of the electric double layer close to an insulator-covered electrode; right: three-capacitor model for the solid/liquid interface, where V_g is the gate potential applied on the electrode and ψ_0 the surface potential.

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