

ELECTRO OSMOTIC SHEAR FLOW IN MICROCHANNELS

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ABSTRACT

We study electro osmotic shear flow in micro channels by chemically and electrically modifying the surface charge of the channel walls. For chemical modification one of the channel walls was treated with cationic polymer. For electric modification, we patterned gate electrodes on one of the channel walls. The applied shear stress is controlled either by the electro osmotic flow (EOF) driving field or by the gate voltage. Such a system can work as an in situ micro-rheometer for lab on a chip devices.

KEYWORDS: electro osmotic flow, shear flow, gate electrodes

INTRODUCTION

Microfluidic devices are used for analysis of chemical or biological fluids. Studying the rheological properties of these fluids is very important in medical diagnostics or in many other industrial applications. Shear flow can be used for characterizing soft materials such as biological proteins and aggregates or colloids.

By modifying the surface charge of one of the channel walls, the plug flow of EOF [1] can be changed to a shear flow. We modify the surface charge of the channel walls by chemical modification [2] and electric modification by using gate electrodes [3] on the channel walls. The native negative surface charge of channel walls can be decreased or even modified to positive by coating them with a cationic polymer. The electric modification of surface charge is accomplished by applying voltage on the gate electrodes patterned on the channel walls.

Here we present measurements of the electro osmotic shear flow (EOSF) and discuss the practical shear rates that can be achieved by changing the surface charge of the channel wall by both methods described above.

THEORY

The EOF velocity is given by $-\epsilon\zeta E/\eta$, where ϵ is the permittivity of the liquid, ζ the zeta potential, E the applied electric field and η the viscosity of the liquid. When the surface charge of the walls is different in magnitude or sign, the plug flow of EOF becomes a shear flow. The EOSF profile in a channel along its height h , for a Newtonian liquid can be derived as

$$u(y) = \frac{-\epsilon E}{2\eta} \left[\Delta\psi \frac{2y}{h} + \langle\psi\rangle \right] - \frac{h^2}{8\eta} \frac{dp}{dz} \left(1 - \frac{4y^2}{h^2} \right) \quad (1)$$

where $\Delta\psi$ and $\langle\psi\rangle$ are the difference and the sum of the zeta potentials of the upper and lower channel walls. The pressure gradients (dp/dz) can be set to zero and a linear shear flow is obtained in the channel.

EXPERIMENTS

The channel with chemical modification of surface charge is made of two flat borosilicate glass slides (Menzel–Glaser) separated by a para film from which a rectangle $L \times w=14 \text{ mm} \times 0.5 \text{ mm}$ was cut out (channel 1). The height was $30 \mu\text{m}$. The bottom glass slide was dip coated with solutions of 10% w/v Polybrene (PB), 3% w/v dextran sulfate (DS), and again 10% w/v PB and washed with DI water.

For electrically modifying the surface charge, we constructed channel (channel 2) with Cr/W gate electrodes by lift off technique on borofloat glass. Each of the five electrodes is $600 \mu\text{m}$ in width and are separated by $60 \mu\text{m}$. This substrate with electrodes is coated with $\text{SiO}_2/\text{Si}_3\text{N}_4/\text{SiO}_2$ trilayer (ONO layer) with total thickness of $750 \pm 50 \text{ nm}$ to form the insulation layer. The substrate is then annealed at $400 \text{ }^\circ\text{C}$ for 24 hours. A micro channel of height $20 \mu\text{m}$, width $200 \mu\text{m}$ and length 6 mm is made of PDMS using soft lithography.

We diluted pH 3 buffer (Fluka, cat no. 82565) with DI water to form pH 3.6 electrolyte solution with 1.7 mM concentration. And green fluorescent polystyrene tracer particles of diameter $0.43 \mu\text{m}$ were put in the electrolyte. The flow at different height from the bottom wall of the channel was recorded using a fast camera (Photron fastcam Ultima 512). In the same manner, in channel 2, the flow was recorded applying the gate voltage, V_G ranging from 0 to 500 V and at various driving electric field. V_G is applied through a resistive network such that a constant potential difference exists between every gate electrodes and the bulk of the fluid.

RESULTS AND DISCUSSION

The recorded video of the flow is analysed using particle tracking algorithm [4] with imageJ. The trajectory data is then analysed with home made matlab code to extract the flow profile. From the measured flow profile, the EOF mobility is calculated subtracting the mobility of the particles. The profiles were fitted linear and the EOF mobility near the PB

coated glass and the bare glass are calculated as $+0.036 \times 10^{-6} \text{ m}^2/\text{Vs}$ and $+0.058 \times 10^{-6} \text{ m}^2/\text{Vs}$ respectively. The corresponding surface charges are $-4.9 \pm 0.1 \text{ mC}/\text{m}^2$ and $-7.9 \pm 0.2 \text{ mC}/\text{m}^2$. The PB coated glass actually carries not positive but less negative surface charge compared to the bare glass. This is because the PB coated glass slides were rinsed in DI water such that most of the PB washes away. When bare silica capillaries are fully coated with PB, by successive flushing with PB and DS solutions, the wall surface charge was measured as $+18.0 \pm 2 \text{ mC}/\text{m}^2$ by current monitoring method [5]. The surface charge of the PB coated capillaries is independent of the pH [6]. The shear rates are shown in figure 1.B. The shear rate per field is $0.75 \text{ s}^{-1}/\text{Vm}^{-1}$

The surface charge modulation with chemical coating has some drawbacks. The cationic polymer dissolves in the working liquid and adsorbs onto the other walls destroying the shear flow. And the surface charge cannot be controlled. By modulating the surface charge by gate voltage, enables to control the shear rate not only by changing the driving voltage but also by the gate voltage. And also larger shear rates can be achieved without involving chemicals in the channel.

The flow profiles were measured in channel 2, at different electric fields ranging from 2.5 to 12.5 V/mm keeping the gate voltage at 500 V. The EOF mobility with and without gate voltage is shown in figure 2.A. Near the PDMS wall at the bottom of the channel, EOF mobility is $+0.058 \pm 0.007 \times 10^{-6} \text{ m}^2/\text{Vs}$. The corresponding surface charge and zeta potential are $-8 \pm 1 \text{ mC}/\text{m}^2$ and $-82 \pm 10 \text{ mV}$. Near the upper wall of ONO layer, the mobility is $+0.039 \pm 0.005 \times 10^{-6} \text{ m}^2/\text{Vs}$. The corresponding surface charge and zeta potential are $-5 \pm 0.5 \text{ mC}/\text{m}^2$ and $-55 \pm 7 \text{ mV}$. Due to the low surface charge of PECVD deposited SiO_2 layer, compared to that of PDMS, a linear shear flow exists in the channel. The shear rates are shown in figure 2.B.

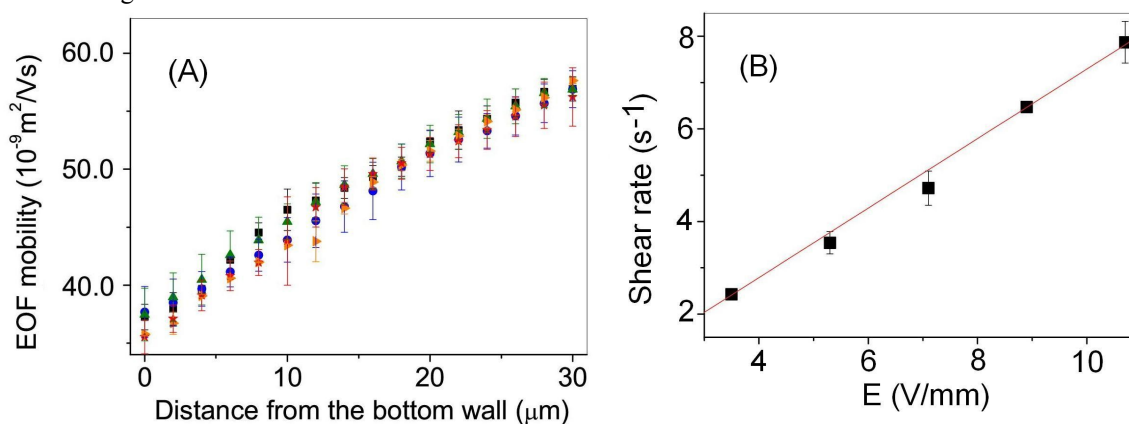


Figure 1: (A) The EOF mobility by chemical modification of the surface charge measured at different EOF driving field, E . (B) The shear rate as a function of E .

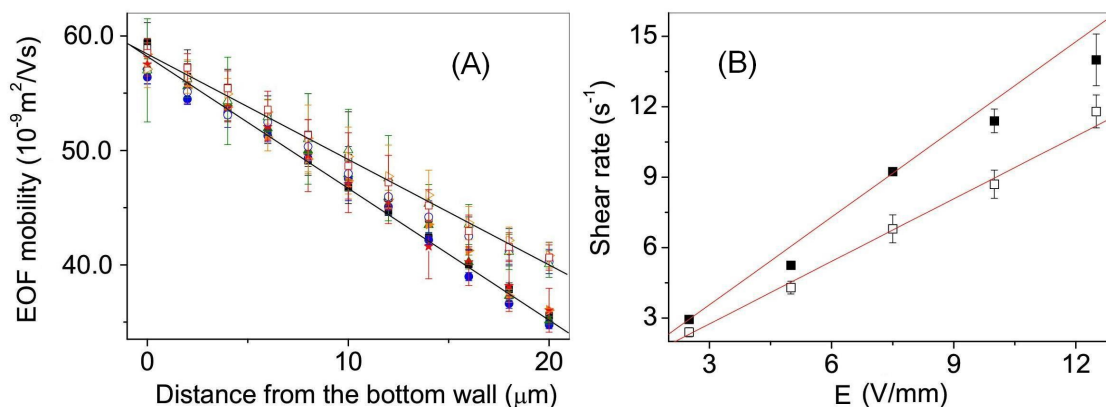


Figure 2: (A) The EOF mobility by electric modification of the surface charge. The open symbols are for $V_G = 0 \text{ V}$ and filled symbols are for $V_G = 500 \text{ V}$. In each case measurements are done at different EOF driving fields. (B) The shear rates obtained versus the applied EOF driving field.

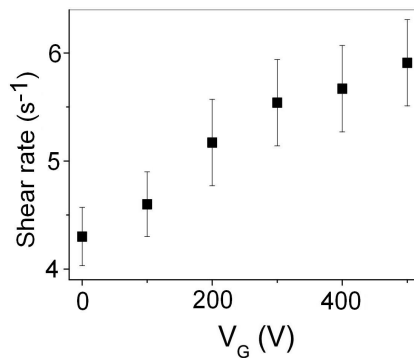


Figure 3: Shear rate as a function of the gate voltage. The EOF driving field was set constant at 5 V/mm.

When gate electrode is kept at 500 V, the mobility measured near the upper wall is $+0.035 \pm 0.004 \times 10^{-6} \text{ m}^2/\text{Vs}$. This is due to the average surface charge of the wall. The actual surface charge (zeta potential) can be calculated as $-4 \pm 0.5 \text{ mC/m}^2$ ($-43 \pm 5 \text{ mV}$). Thus the gate voltage made a change in surface charge (zeta potential) by $1 \pm 1 \text{ mC/m}^2$ ($13 \pm 12 \text{ mV}$). The shear rates are shown in figure 2.b. The shear rates are increased by about 42 % when gate voltage is applied. The maximum applied gate voltage is limited by the dielectric breakdown voltage of the insulation layer. At very large gate voltage, the change in surface charge will saturate (hence the shear rate) due to the large influence of the double layer capacitance. Shear rate as a function of the gate voltage is shown in figure 3.

CONCLUSIONS

We have shown that linear EOF shear flow can be created by chemical and electrical modification of the surface charge. The adsorption of chemicals by the opposite bare wall can destroy the shear flow. Therefore this technique is limited by the amount of chemical coating that can present on the channel wall. When one of the walls is deposited with ONO layer, due to its very low native surface charge, shear flow can be produced. By modulating the surface charge of this layer with voltage, shear rate is increased by 42 %. The shear rates produced in this study is comparable to those used to study soft matter under shear flow [7,8,9]. Increasing the efficiency of the gate voltage, by using other kind of insulation materials such as Al_2O_3 , even higher shear rates can be achieved.

REFERENCES

- [1] Kirby, B. J., Hasselbrink, E. F., Electrophoresis, **25**, 187-202, (2004)
- [2] Hiroyuki Katayama, Yasushi Ishihama, and Naoki Asakawa Anal. Chem., **70** (24), pp 5272-5277, (1998)
- [3] Richard B. M. Schasfoort, Stefan Schlautmann, Jan Hendrikse, Albert van den Berg Science **286**, 942 (1999)
- [4] F.Sbalzarini and P. Koumoutsakos. Feature Point Tracking and Trajectory Analysis for Video Imaging in Cell Biology; Journal of Structural Biology, **151**(2):182-195, (2005)
- [5] Dileep Mampallil, Dirk van den Ende, Frieder Mugele, Electrophoresis, **31**, 563–569, (2010)
- [6] Rob Haselberg Gerhardus J. de Jong Govert W. Somsen, J. Sep. Sci., **32**, pp. 2408-2415, (2009)
- [7] L. E. Silbert and J. R. Melrose, J. Rheol. **43**(3), (1999)
- [8] Itai Cohen, Thomas G. Mason, and David A. Weitz, Phys. Rev. Lett. **93**(4), (2004)
- [9] Justice M. Thwala, Jim W. Goodwin, and Paul D. Mills, Langmuir, **25**(22), 12926–12936, (2009)

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