Electrokinetic Transport in Fluidic Nanochannel

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Introduction

The transport of fluid, current and dissolved molecules in small fluidic nanochannels is affected by the close proximity of the wall surfaces. The transport is governed by electrokinetic phenomena, which depend on the electrostatic potential distribution in the channel. The double layer thickness can be of the same order as the width of the nanochannels, which has an impact on the transport by shaping the fluid velocity profile, local distributions of the electrolytes and charged analytes. Small channels may lead to qualitatively new effects like selective ionic transport based on charge numbers as well as different modes for molecular separation.

Theories

Poisson-Boltzmann equation of Electrostatic potential for Binary z_1:z_2 electrolyte

$$\nabla^2\tilde{\Psi} = -\frac{\kappa^2}{z_1+z_2}\left[\exp\left(-z_1\tilde{\Psi}\right)-\exp\left(z_2\tilde{\Psi}\right)\right], \quad \tilde{\Psi}=\frac{e\Psi}{kT}$$

Inverse of Debye double layer thickness

$$\kappa^2 = \frac{e^2\left(z_1^2 n_1 + z_2^2 n_2\right)}{\varepsilon\varepsilon_0 kT}$$

Boundary Condition: $\Psi = \zeta$ at the wall; $\nabla\Psi = 0$ in the center of the channel (symmetry).

Electroosmotic flow velocity

$$v_{eo}(x) = -\frac{\varepsilon\varepsilon_0 E}{\eta}\zeta\left[1-\frac{\Psi(x)}{\zeta}\right]$$

Average bulk velocity

$$U = -\frac{\varepsilon\varepsilon_0\zeta}{\eta}E$$

- *In the continuum regime*
- *P-B equation is not linearized*

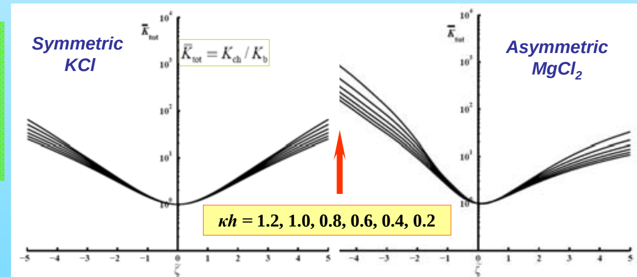
Conclusion

- Divalent counterions lead to greater current and fluid flow than monovalent electrolyte at same ionic strength
- Varying the channel wall ζ-potential in the presence of asymmetric electrolyte could be used to control the directionality of electric current and fluid transport
- Transport of fluid and current are different when KCl and $MgCl_2$ are both present in channel and encounter with polarity change (as shown in the schematic)
  - Apply AC field could lead to net ionic flux and fluid flow in one direction
  - This design could be developed into a fluid flow valve or current diode
- Simulation shows shorter channel decreases current leakage

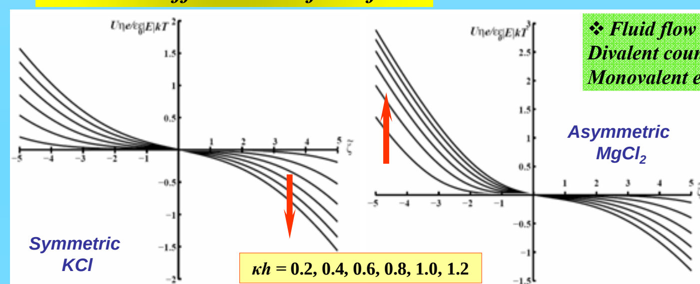
Computational Results

Relative conductivty in a slit-shaped nanochannel

- ***Conductivity symmetry broke in case of $MgCl_2$***
- ***Conductivity of $MgCl_2$ is more than an order of magnitude greater than that of KCl for kh =1***

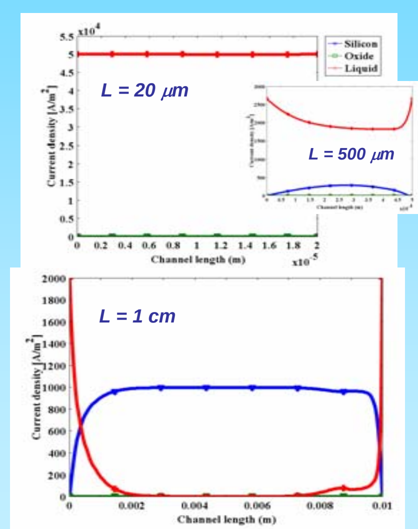


Countion effect on the fluid flow



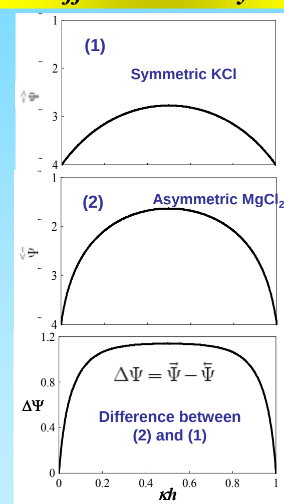
- ***Fluid flow velocity is greater for Divalent counterions ($MgCl_2$) than Monovalent electrolyte (KCl)***

Channel Length vs Leakage Current



- *No current leaks to silicon layer in 20-μm channel*
- *Most current goes into silicon layer in 1-cm channel*
- *Measuring currents in long channel should be carefully monitored*

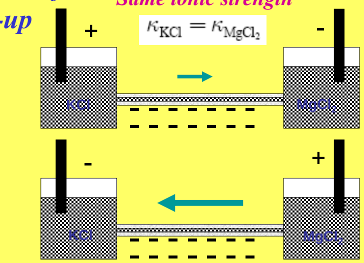
Potential Distribution for Different Electrolytes



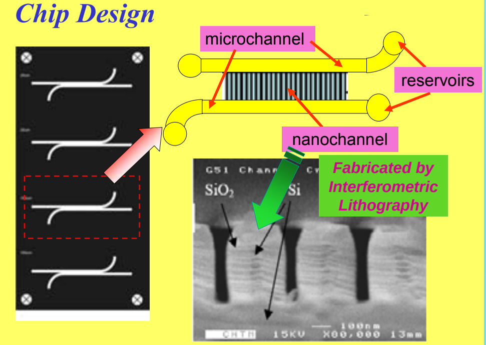
- *Step-wise change in the field with time*
- *Fluid and dissolved ions response immediately*
- *A net flow of current and fluid electroosmotic flow in one direction can be expected*

Experiment & Design

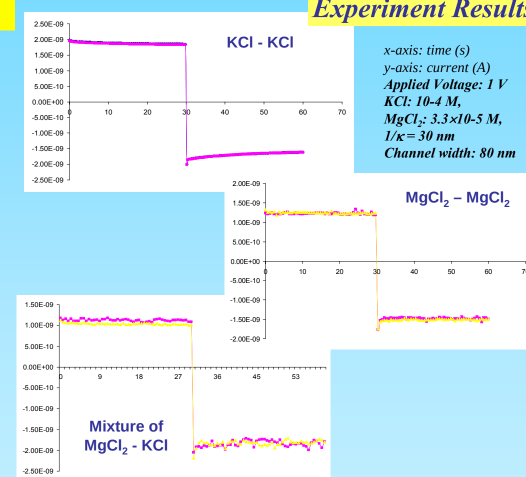
Schematic of the Set-up



Chip Design



Experiment Results



x-axis: time (s)
y-axis: current (A)
Applied Voltage: 1 V
KCl: 10-4 M,
$MgCl_2$: 3.3x10-5 M,
1/κ = 30 nm
Channel width: 80 nm

- ***Symmetric current at both directions when reservoirs are filled with same electrolyte***
- ***Difference presented when comparing two electrolytes (KCl-KCl, $MgCl_2$-$MgCl_2$)***
- ***Currents increase when external field direction switches between two reservoirs***

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