Nanofluidics and 2D Materials Based Nanosensors

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Outline

• What are nanosensors and why do we need them?
• Learning from Nature is the key!
• Microfluidics vs Nanofludics
• Examples of Nanosensors based on nanofluidics
• Fluidic electronics
• Graphene based membranes for sensing
• Future outlook
Oak Ridge National Laboratory

ORNL major expertise:
- Engineering
- Material Science
- Supercomputing

~18 petaFLOPS
Memory: 710 TB
Storage: 10 PB
Power: 8 MW

40 km²
4400 staff
Sensors vs Nanosensors

• Sensors are used virtually in every device: from smartphones to cars and biotechnology

• We can “sense” different phenomena and objects of various scales

• From Earthquakes, Supernovas and Relic Radiation to Higgs Boson.
Sensors vs Nanosensors

Nanosensors allow for INTEGRATION of many sensing elements in small volume

Connection between nano and macro world:
- Neural interface: connection between living species and electronics
- Artificial cells.
- Bionics
Lessons from Nature: Perfect Sensors Arrangement

Wall of a cell is an impermeable lipid (fat) membrane i.e. BARRIER

Pores in the membrane are “smart holes”

Sensitive to
- Light
- Voltage
- Chemicals
- Temperature
A potassium selective channel is a very important player in the nerve signaling.

Potassium selective channel with four K$^+$ in the selectivity filter (right panel).


What the Nanofluidics is?

In a macro channel ions can not interact with the channel wall significantly.

If the size of the channel is small, ions can interact with the surface!!

- Size of the channel
- Surface energy
- Surface Charge
- Chemical modification
- Electrostatic forces
Volume exclusion – DNA sensor and purification

Vlassiouk et al. Langmuir, 20, 9913; Vlassiouk et al, 21, 4776
Light sensitive channels

Nature example - Channelrhodopsin

We employ hydrophobic interactions!

Resistance drops after UV irradiation

Vlassiouk et al, Nanolett, 2006, 1013-1017
Old technique for new applications: preparation of ion channel

1. Irradiation with e.g. Xe, Au, U

2. Chemical etching

1 ion → 1 latent track → 1 pore!

Fabrication of nanopores array in SiN

Vlassiok et al, PNAS, 2009, 106, 21039
Electrostatics – paramount for nanofluidics based nanosensors.

Microchannels – concentrations of positive and negative ions are equal.

Nanochannels – small volume but large surface: concentration of counter ions is higher!

\[ \Delta C = \frac{2\sigma}{er} \]
How to Make an Ionic diode?

Depletion zone


OPEN State of Ionic Diode.

BIPOLAR DEVICE – current carried by both
Ionic Bipolar Diodes

\[
\frac{I(+5V)}{I(-5V)} \approx 200
\]

\[
\frac{I(-5V)}{I(+5V)} = 61
\]

5 nm pore

I. Vlassiouk, Z.S. Siwy, *Nano Lett.* 7, 553 (2007);
1D Analytical solution

\[ l_{n,p} \approx \sqrt{ \left( \frac{N_n}{N_p} \right) \varepsilon_0 \Delta V } \]

\[ l_{dep} \approx \sqrt{ \frac{\Delta V a \varepsilon_0}{\sigma} } \]

- \( a \) – pore radius
- \( \sigma \) - surface charge density

\[ I_{open} = \left( I_{h}^{gen} + I_{e}^{gen} \right) \left( e^{\frac{eV}{k_B T}} - 1 \right) \]

\[ I_{BP}^{open} \approx \left( \frac{ea}{2k_B T} \right)^2 \frac{e \pi D \Delta C}{L} \left( V + V_o \right)^2 \]

\[ I_{closed} = \left( I_{h}^{gen} + I_{e}^{gen} \right) \]

\[ I_{BP}^{closed} = 2e^2 \pi D \frac{a^3 C_{bulk}^2}{\sigma L} \]


Biosensing with Nanofluidic Diodes.

Avidin is positive!

Tip modified with biotin

Avidin on top

Vlassiouk et al, JACS, 2009, 131, 8211
Biosensing with Nanofluidic Diodes. Streptavidin. pH meter.

Vlassiouk et al, JACS, 2009, 131, 8211
Graphene – atomically thin layer of carbon

- Transparent
- Flexible
- High Electrical conductivity
- High Thermal Conductivity
- Exceptional Mechanical Strength

Unique properties define wide range of applications:

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Graphene: Perfect membrane?

Perfect for
- Desalination
- Separation

Graphene suspended structure fabrication:

Aquaporin:
Good quality, Large Quantity

1 mm crystals

40” continues film

Future outlook

- Personalized medicine
- Bionics / mimicking the Nature
- Neural interface