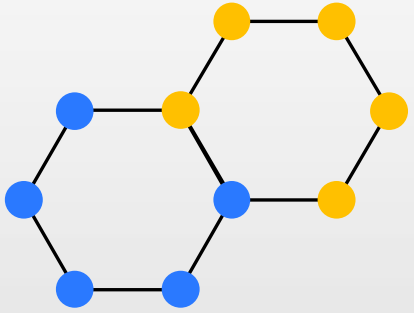
Single-layer MoS2 nanopores as nanopower generators

Aleksandra Radenovic

EPFL – Ecole Polytechnique Federale de Lausanne

Bioengineering Institute Laboratory of Nanoscale Biology



Barcelona, **Graphene 2017.** March 29th 2017.

Nature inspired nanoengineering

Nature creates nano-stuctures

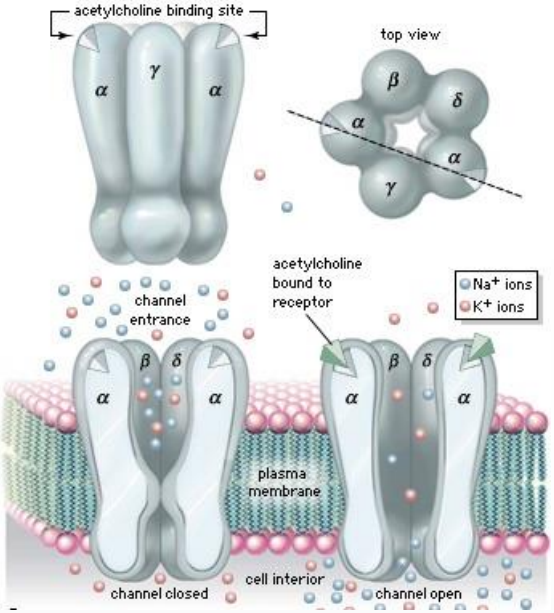
Biological systems are an existing proof of molecular nanotechnology.

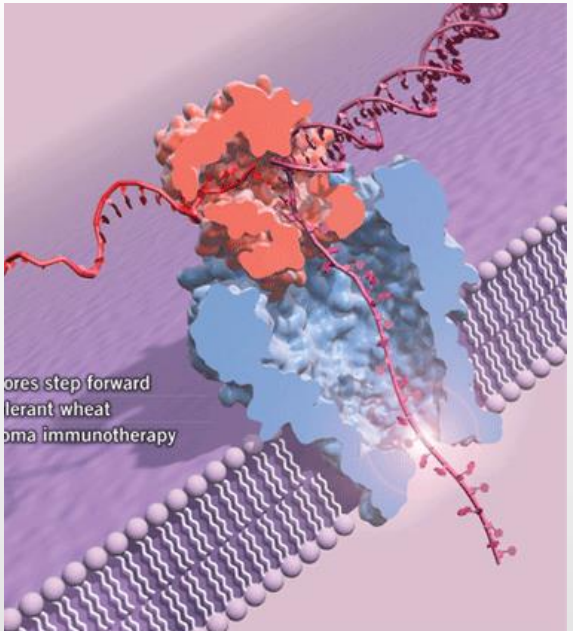
The Biology is an ingenious form of nanotechnology

Cell compartmentalization

Pores –ion channels

Biopolymer translocations

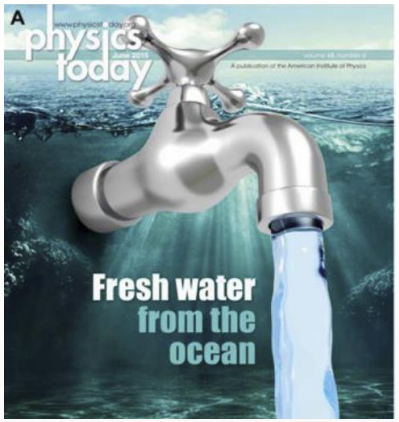


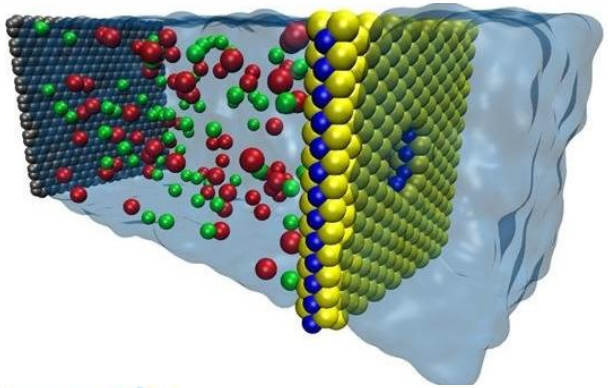


Engineered nanopores

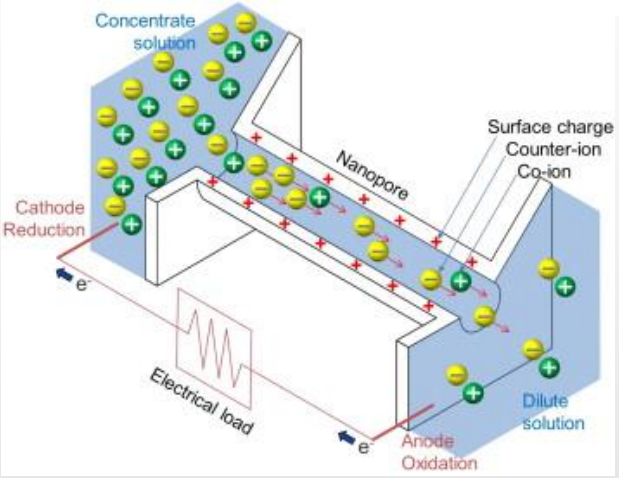
Nanopores- as sensors

Nanopores – in filtration

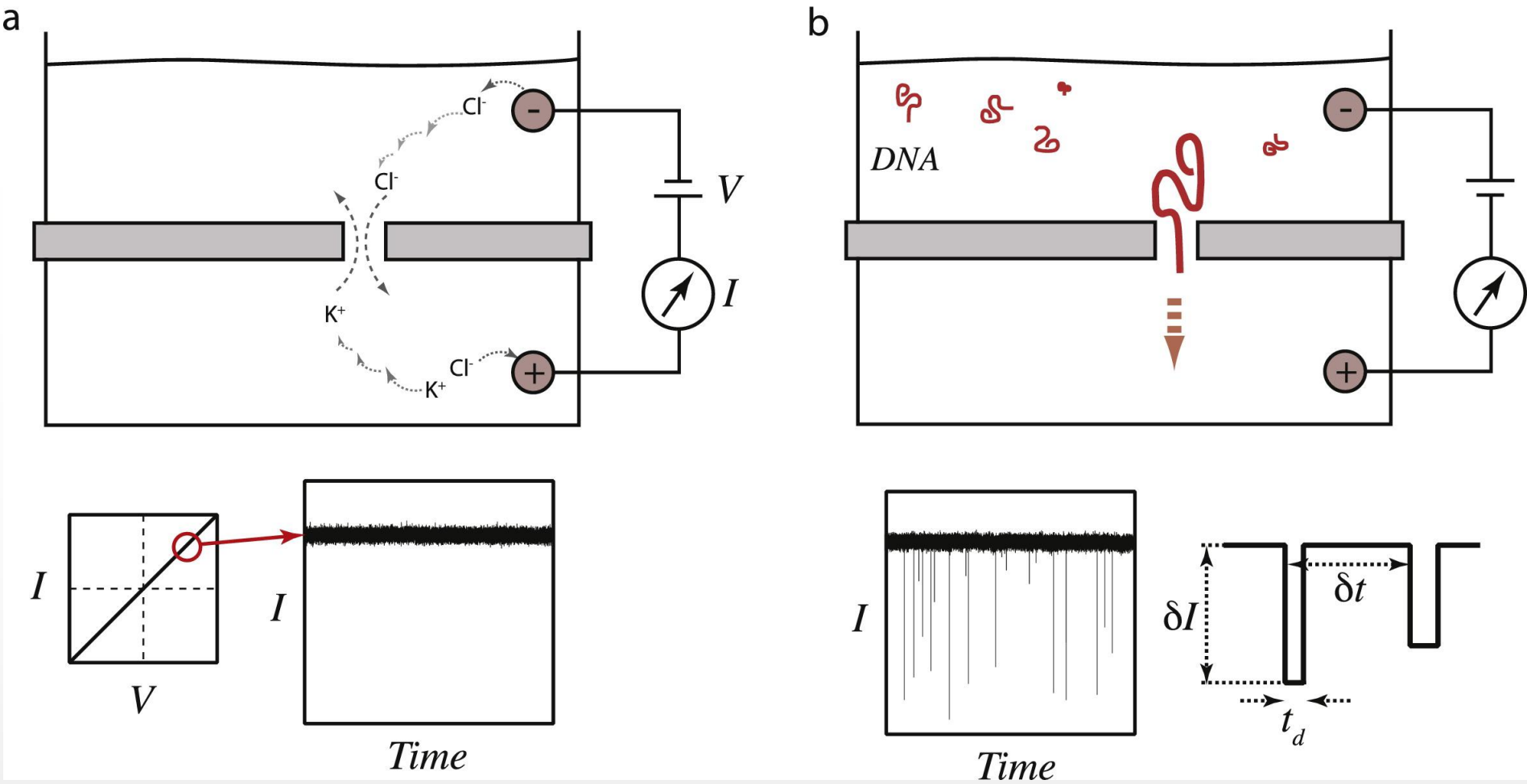




Nanopores – as powergenerators



Nanopores



Wanunu, M. (2012). Nanopores: A journey towards DNA sequencing. Physics of Life Reviews, 9(2), 125–158.

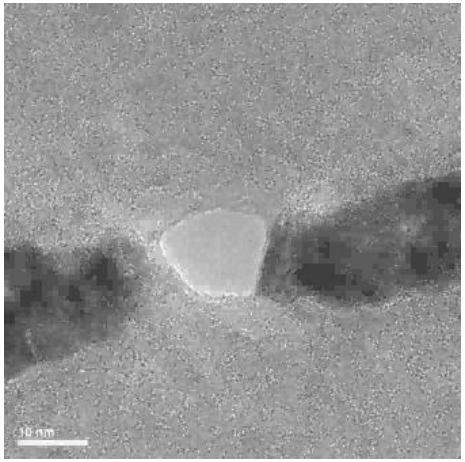
Nanopores - materials

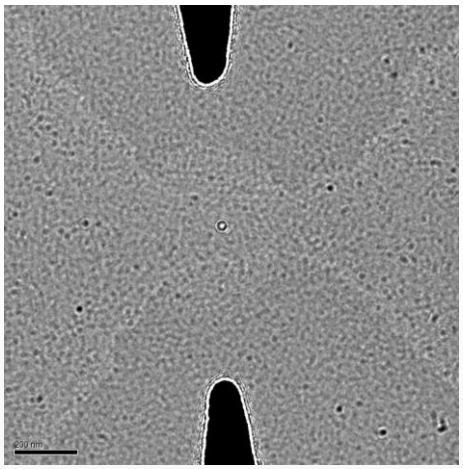
Nanopore material – dictates application

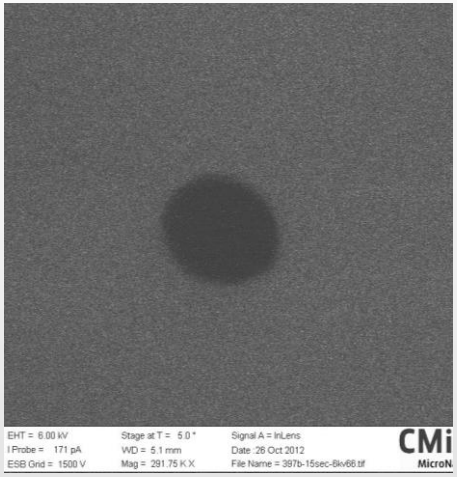
Silicon nitride nanopores – gold standard for solid state nanopores **5-20 nm thick**

2D material nanopores: graphene, hexagonal boron nitride (hBN) and molybdenum disulfide (MoS_2)-**0.3-0-7 nm thick**

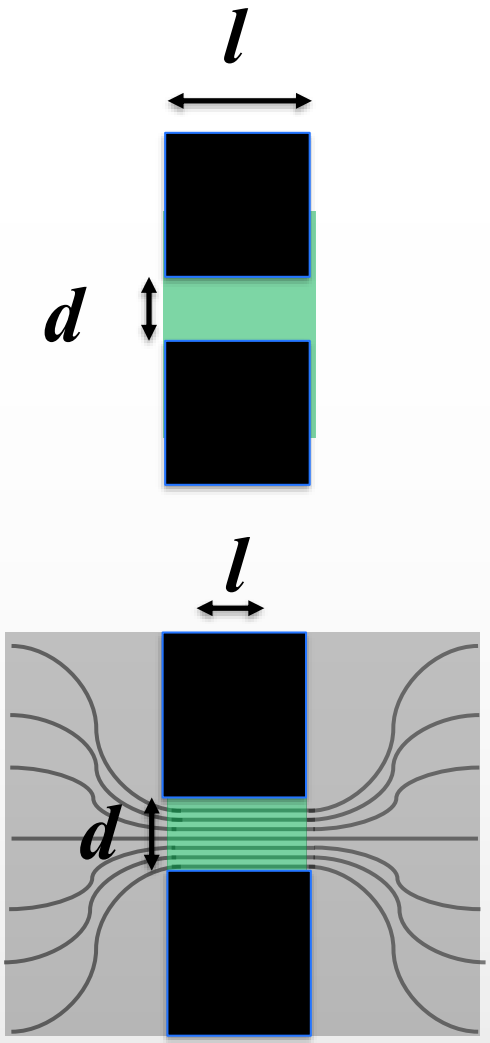
Glass/Quartz nanocapillaries

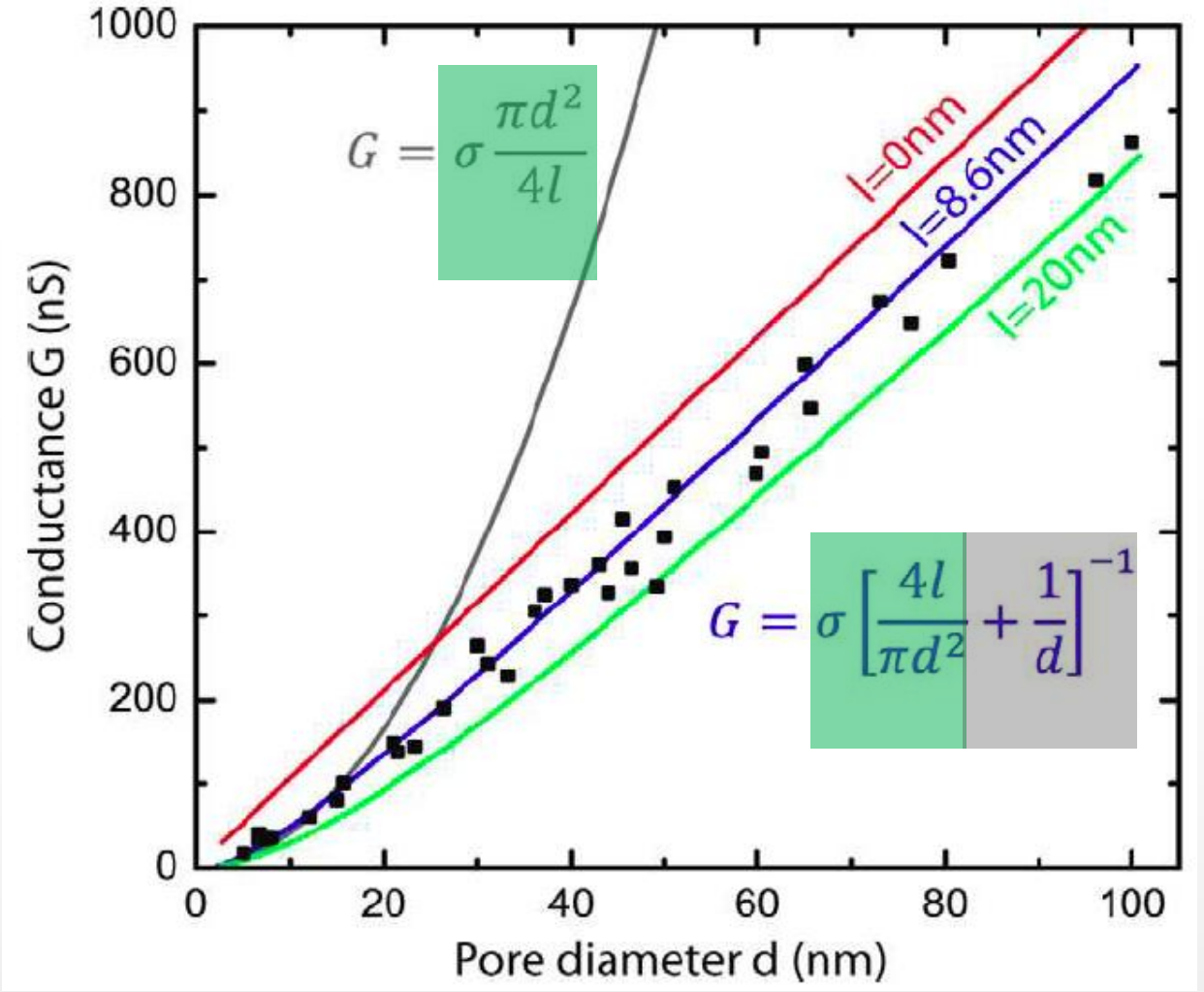






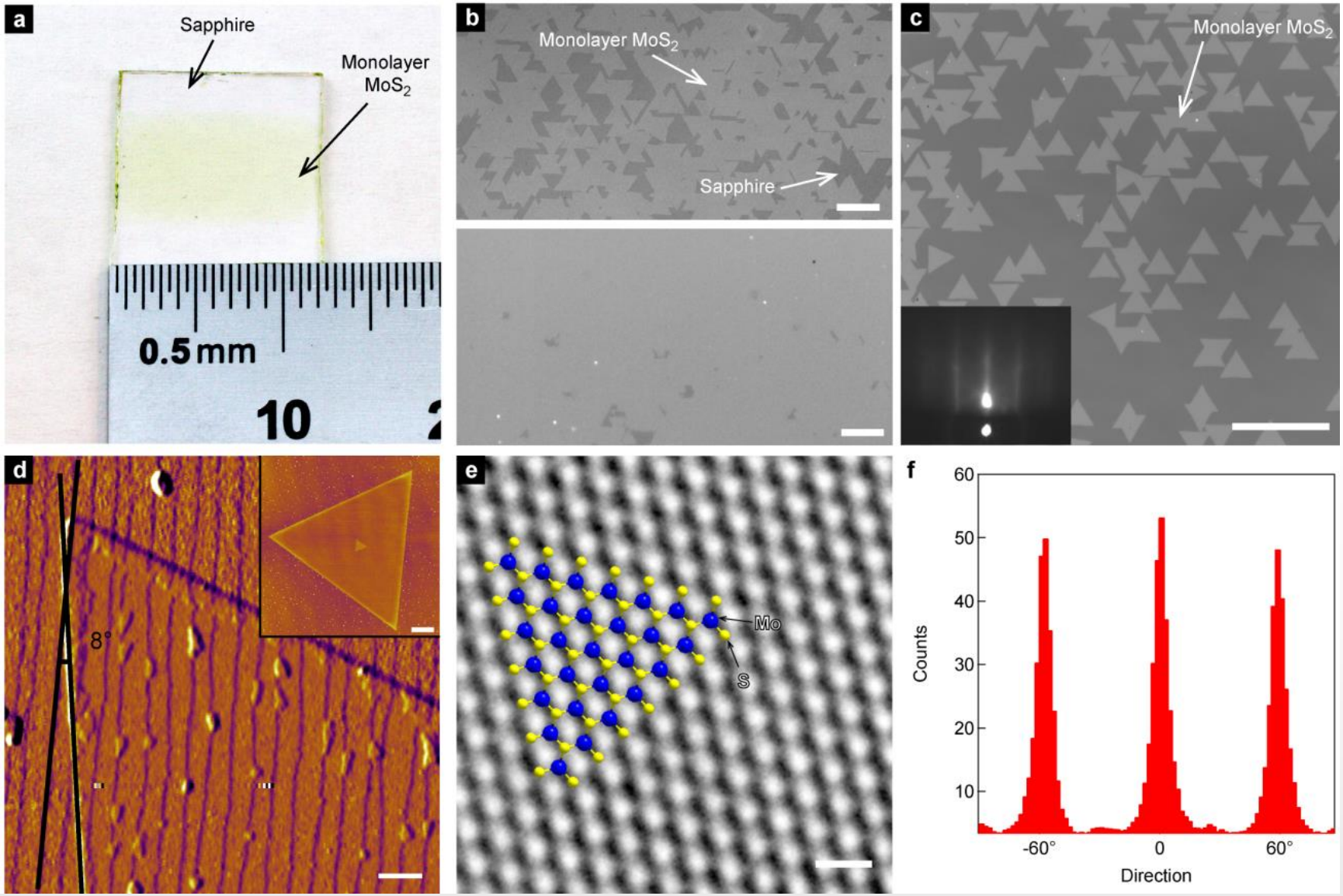
Nanopore sensitivity - geometry





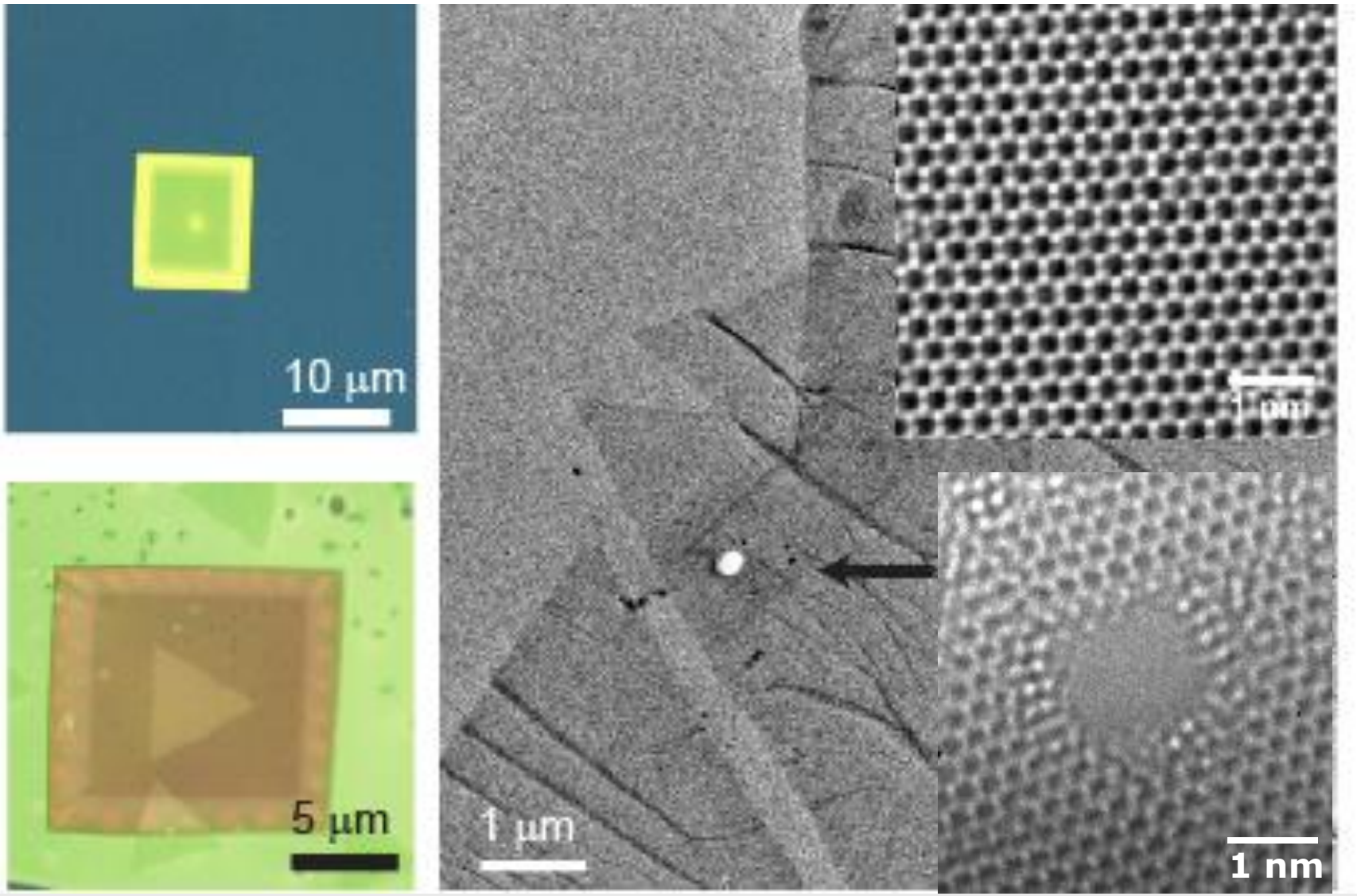
Kowalczyk et al. Nanotechnology **2011.**

CVD grown MoS_2



Dumenco et al. ACS Nano **2015.**

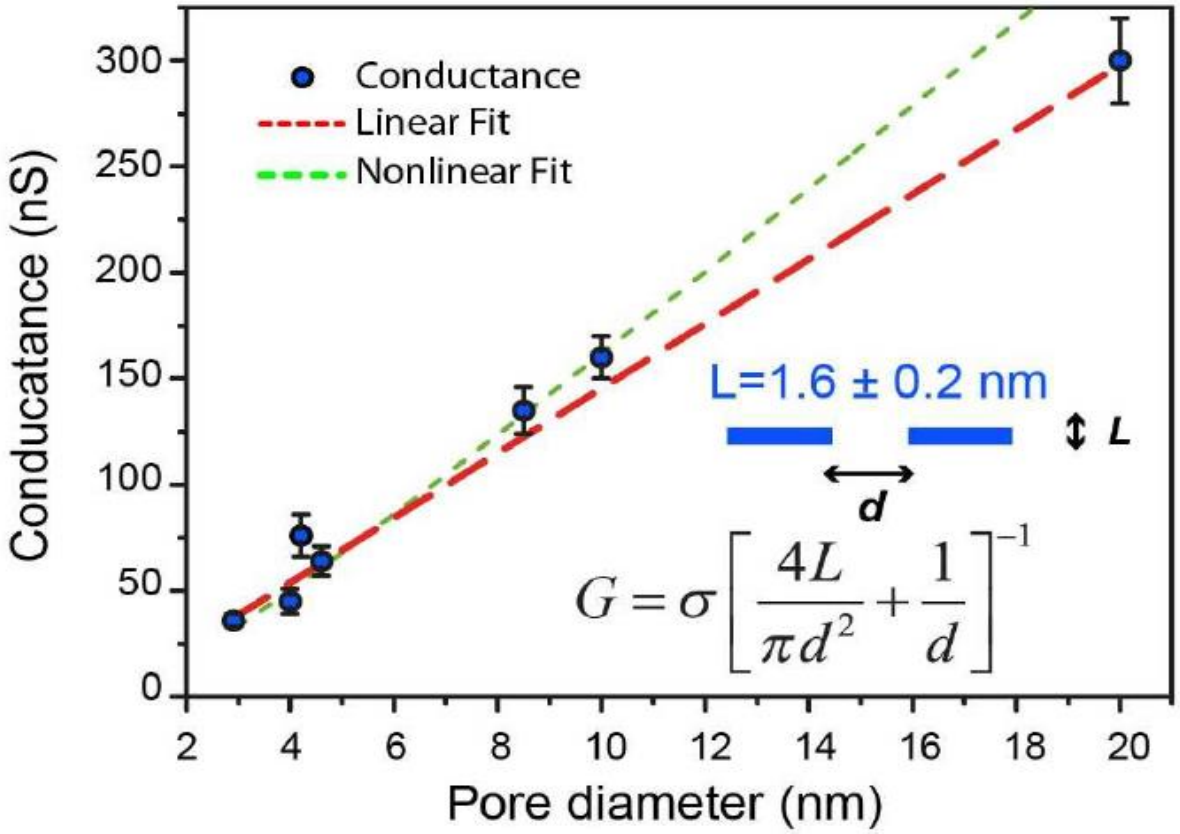
Nanopores from CVD grown MoS_2

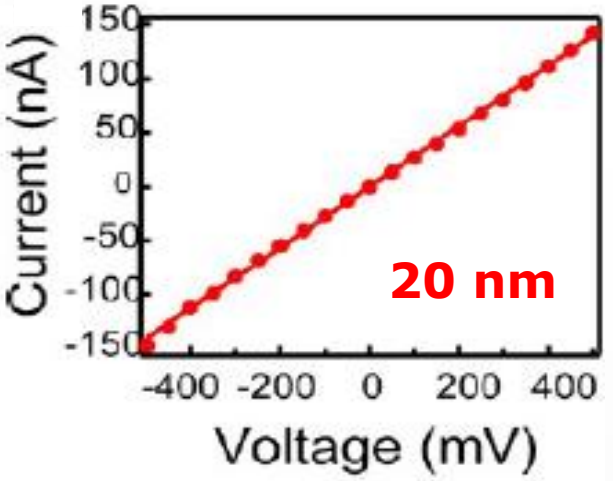


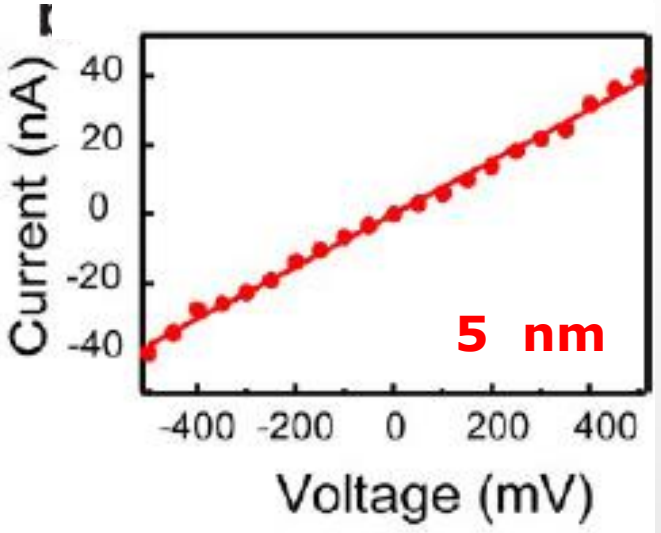
Feng et al. **Nano Lett.** 15 (5), **2015.**

MoS_2 nanopores conductivity

- Linear current voltage characteristics

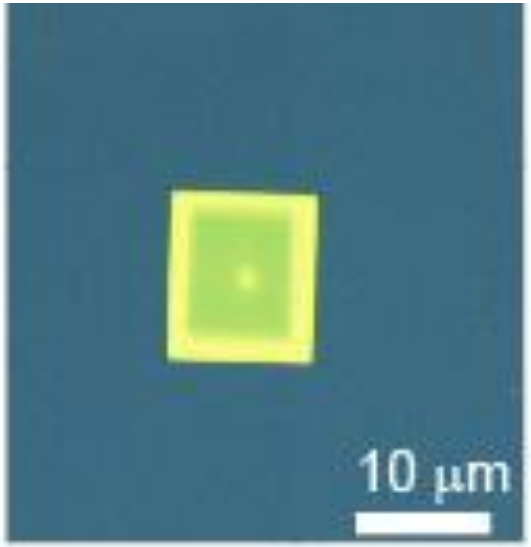


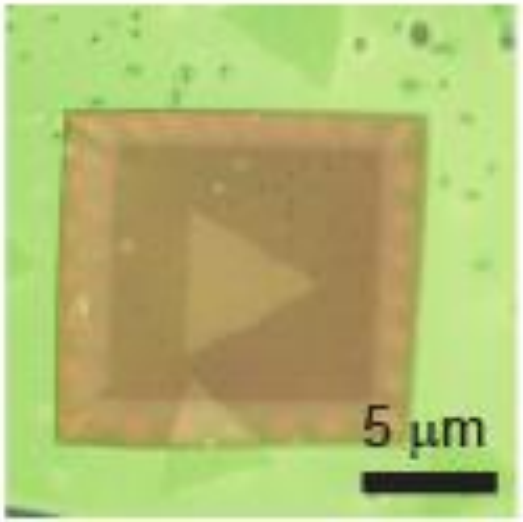


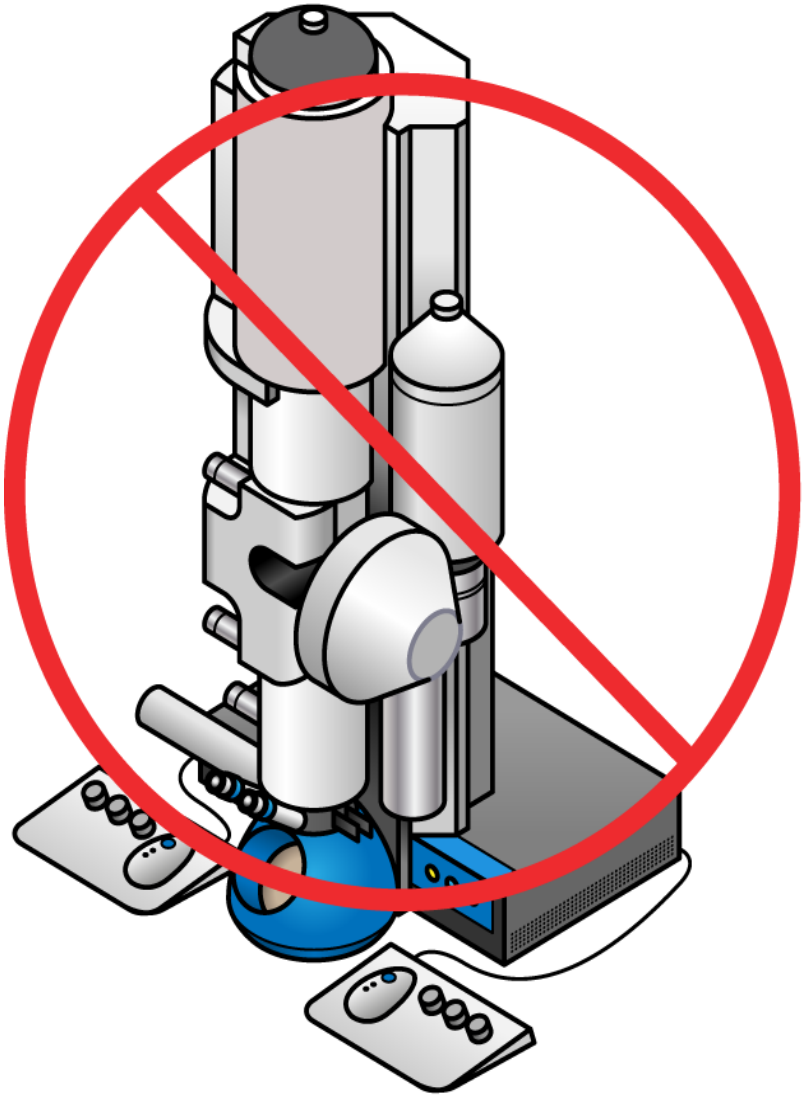


Liu et al. ACS Nano **2014.**

Nanopores from CVD grown MoS_2

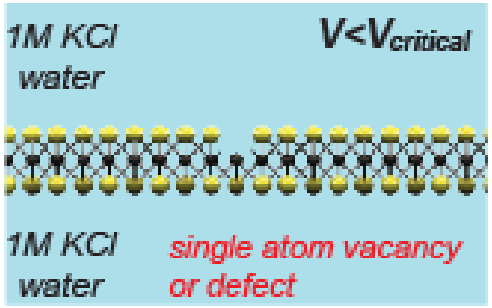


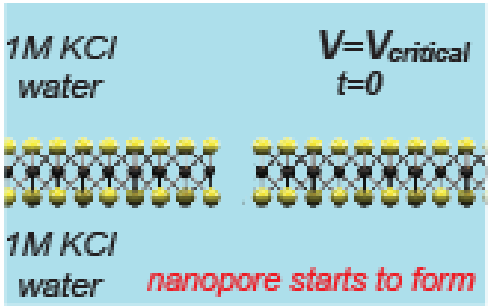


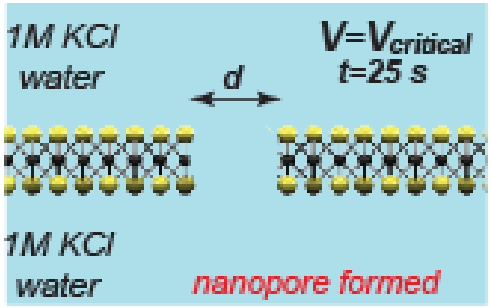


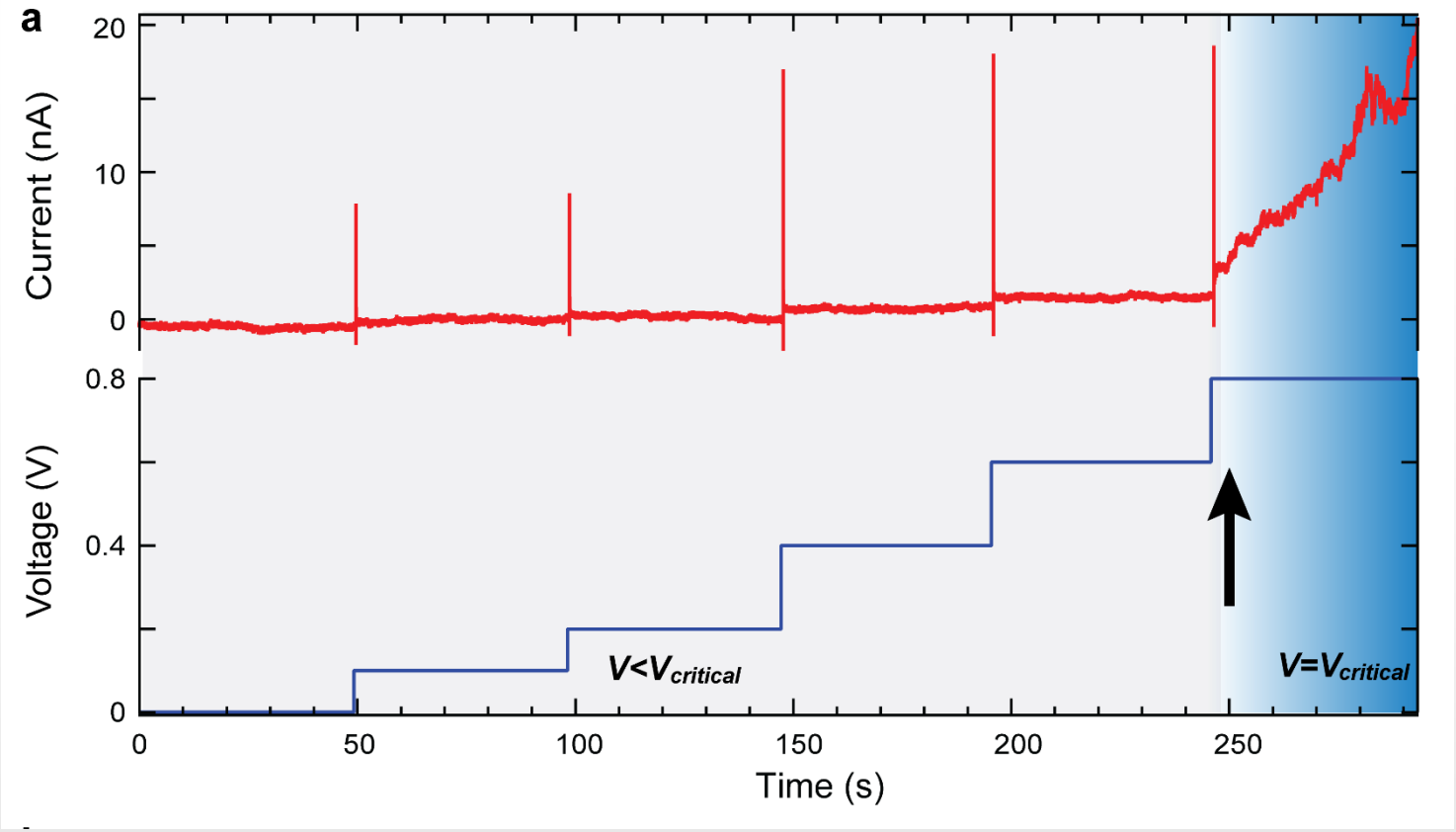
Feng et al. **Nano Lett.** 15 (5), **2015.**

Electrochemical etching of monolayer MoS_2









Feng, et al. Nano Lett. 15 (5), **2015.**

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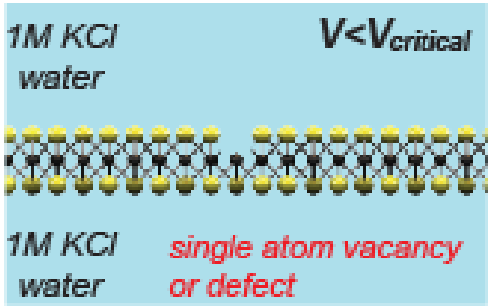
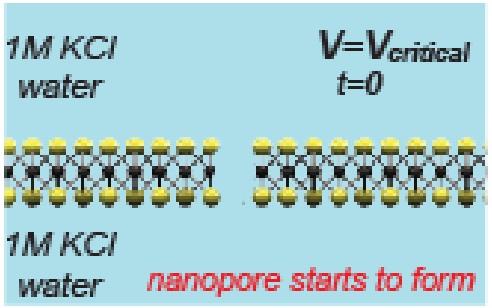
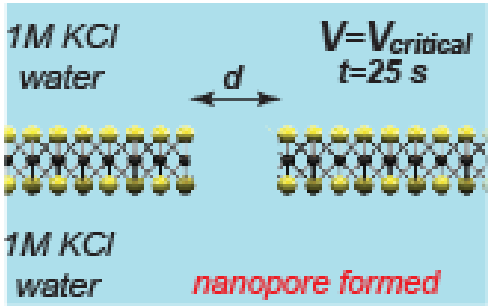
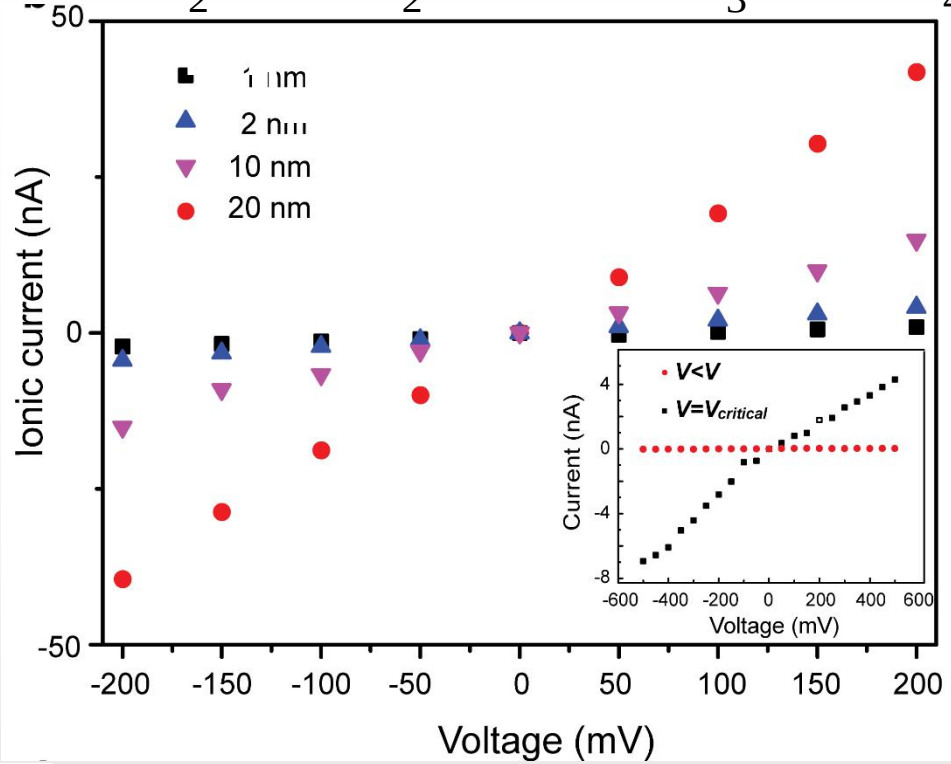
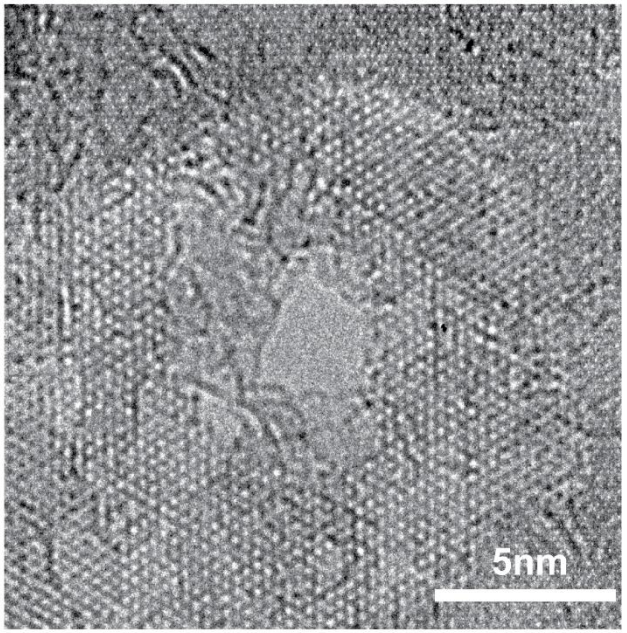






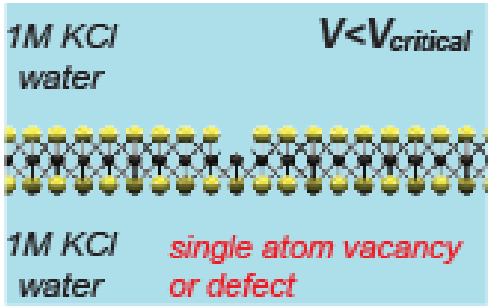
$$MoS_2 + 11H_2O \rightarrow MoO_3 + 2SO_4^{2-} + 22H^+ + 18e^-$$

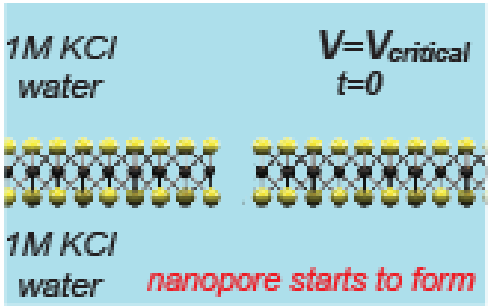


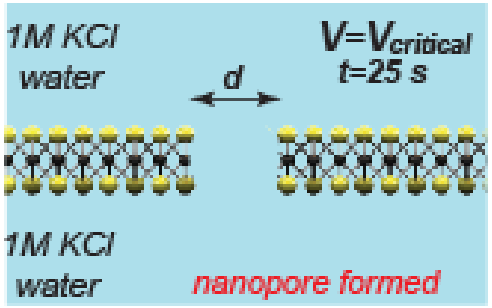


Feng, et al. **Nano Lett.** 15 (5), **2015.**

Electrochemical etching of monolayer MoS_2







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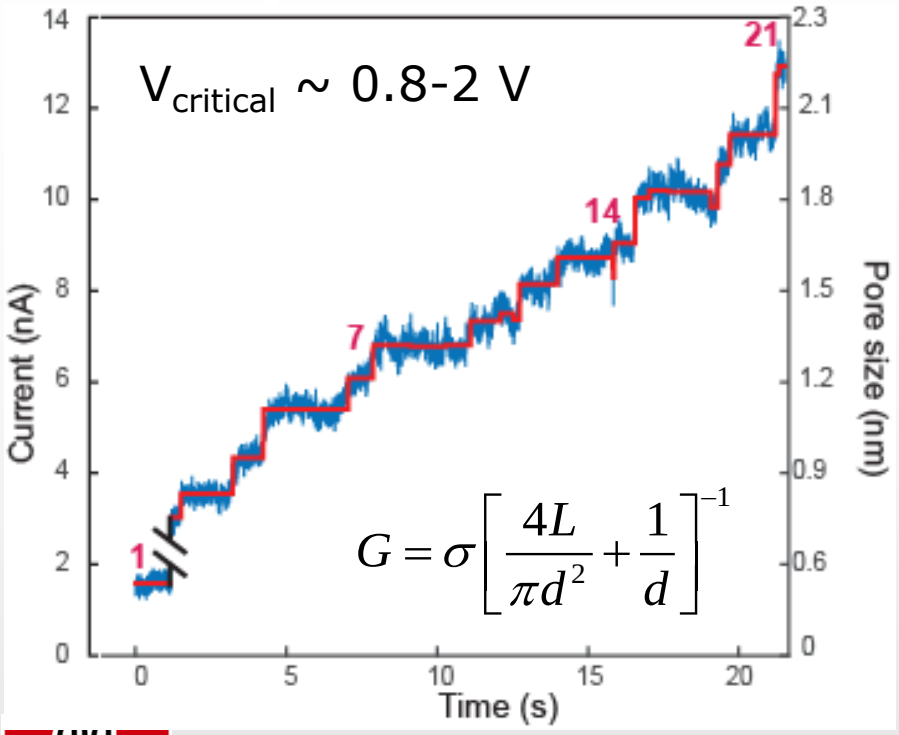
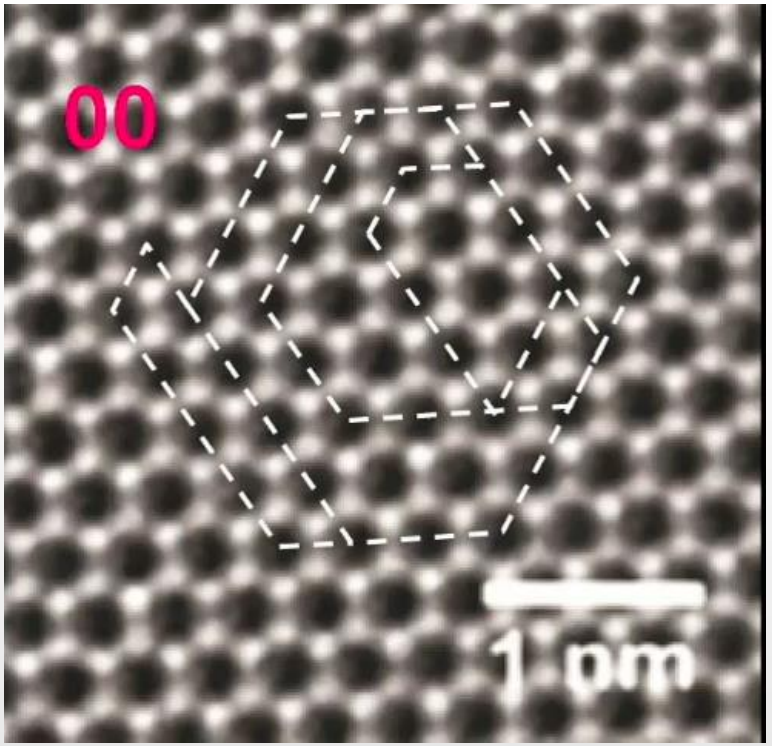
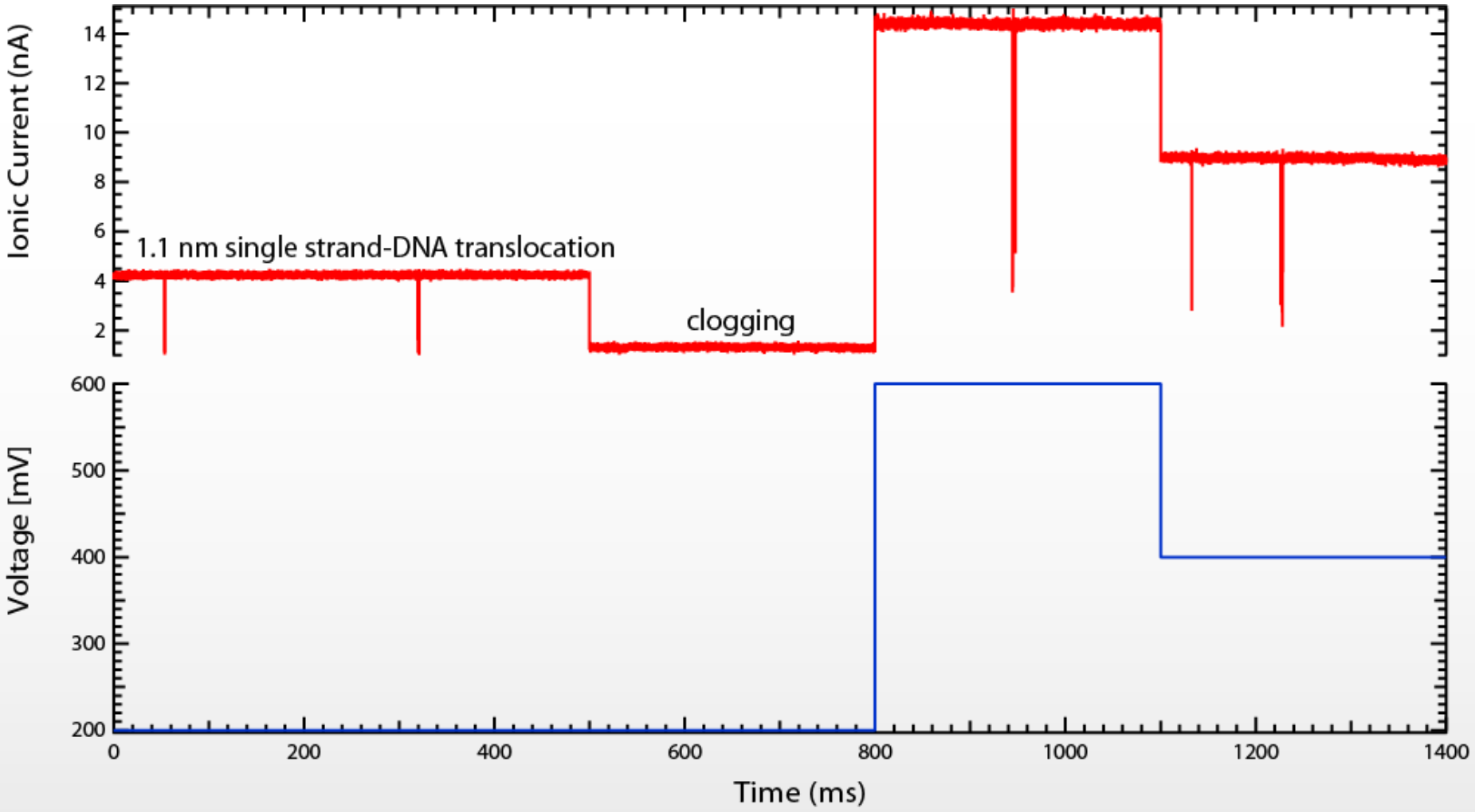




Feng, et al. Nano Lett. 15 (5), **2015.**

Using dsDNA and ssDNA translocations to verify the size of nanopores



Enabling technology

nature materials

LETTERS

PUBLISHED ONLINE: 28 MARCH 2016 | DOI: 10.1038/NMAT4607

Observation of ionic Coulomb blockade in nanopores

Jiandong Feng[1]*, Ke Liu[1], Michael Graf[1], Dumitru Dumcenco[2], Andras Kis[2], Massimiliano Di Ventra[3] and Aleksandra Radenovic[1]*

ARTICLES

PUBLISHED ONLINE: 21 SEPTEMBER 2015 | DOI: 10.1038/NNANO.2015.219

nature nanotechnology

Identification of single nucleotides in MoS_2 nanopores

Jiandong Feng[1†], Ke Liu[1†], Roman D. Bulushev[1], Sergey Khlybov[1], Dumitru Dumcenco[2], Andras Kis[2] and Aleksandra Radenovic[1]*

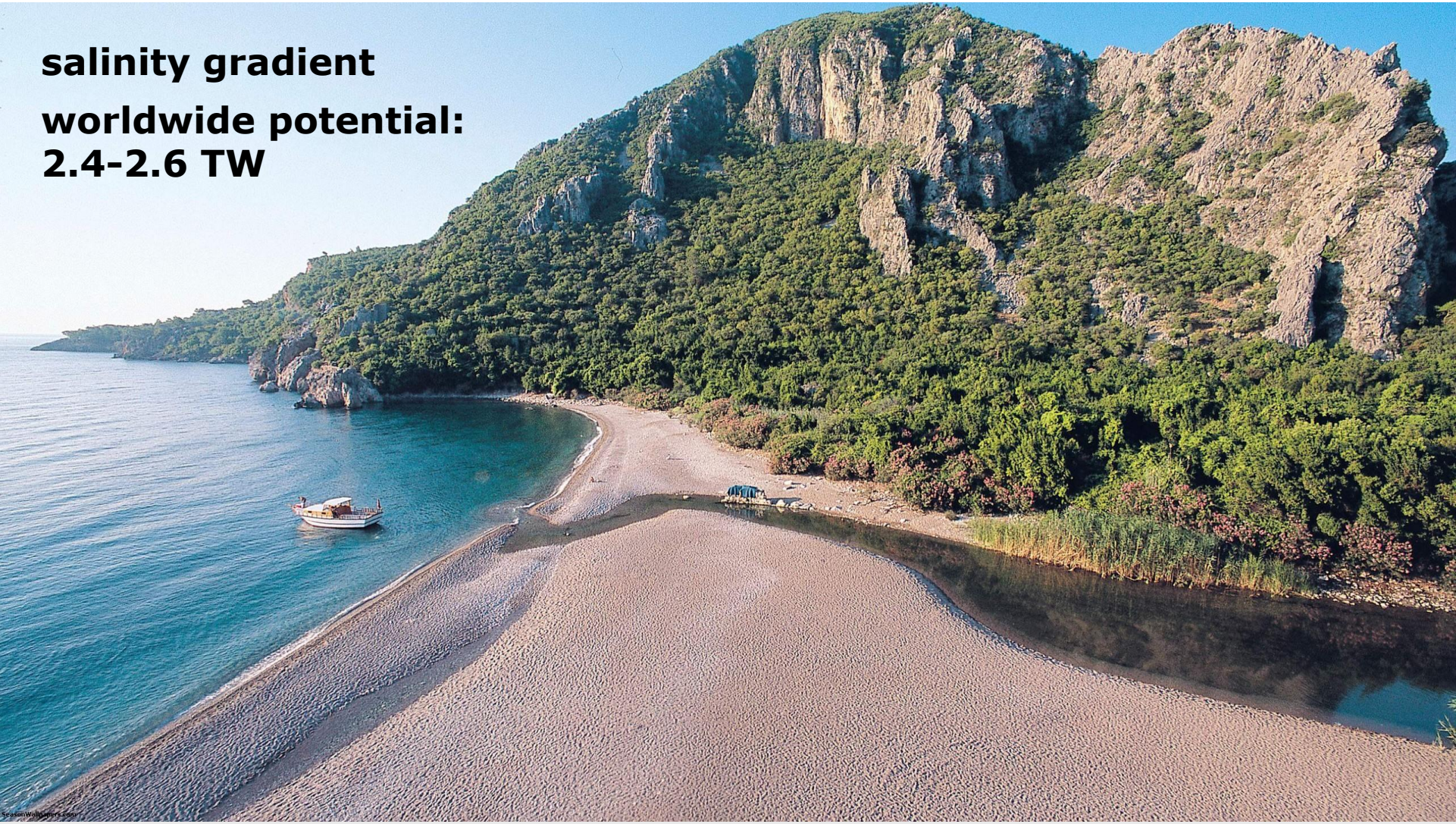
LETTER

doi:10.1038/nature18593

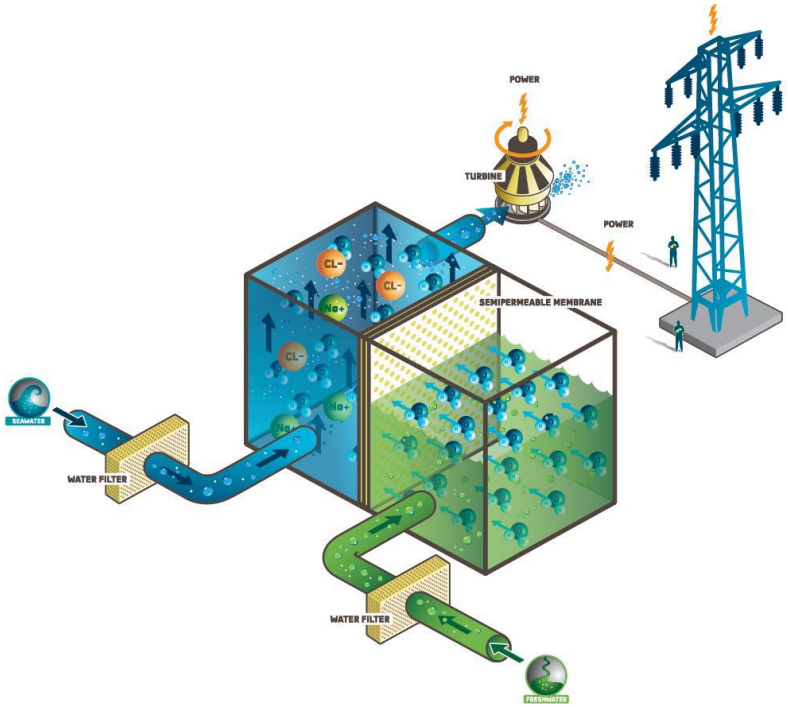
Single-layer MoS_2 nanopores as nanopower generators

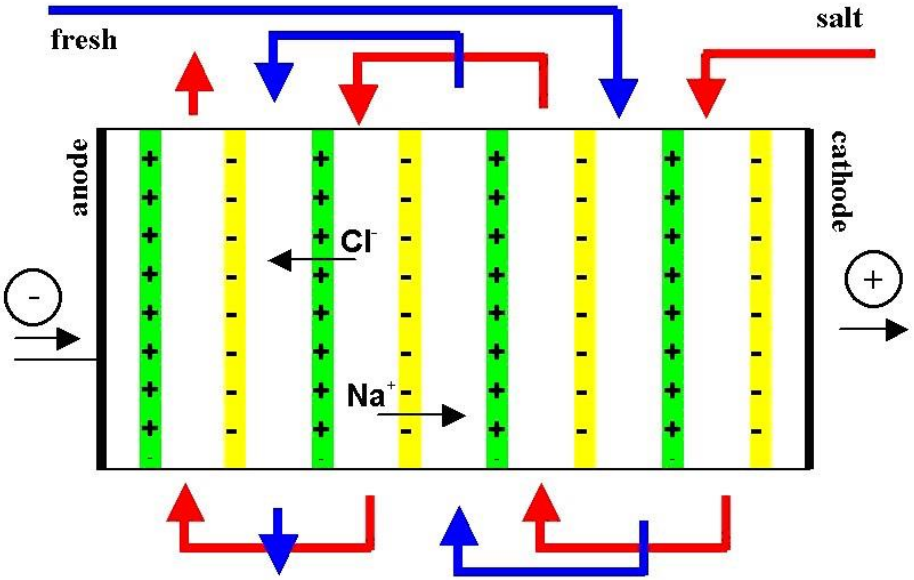
Jiandong Feng[1], Michael Graf[1], Ke Liu[1], Dmitry Ovchinnikov[2], Dumitru Dumcenco[2], Mohammad Heiranian[3], Vishal Nandigana[3], Narayana R. Aluru[3], Andras Kis[2] & Aleksandra Radenovic[1]

Blue energy



Technologies in use





Pressure Retarded Osmosis (PRO)
Water selective membrane
Stratkraft SF, Tofte, Norway
MegaTon -Japan

RED (reverse electrodialysis)
Ion selective membrane
RedStack, Afsluitdijk, the Netherlands

https://en.wikipedia.org/wiki/Osmotic_power

Common membranes

Low efficiency- a few Watts per meter squared of membranes for sea/river combination

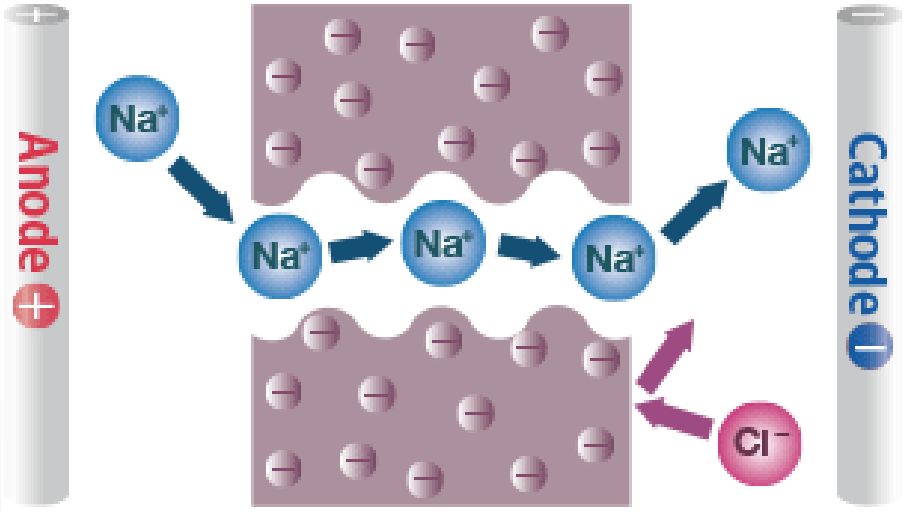


Figure 1-1 Selective permeability of CEM

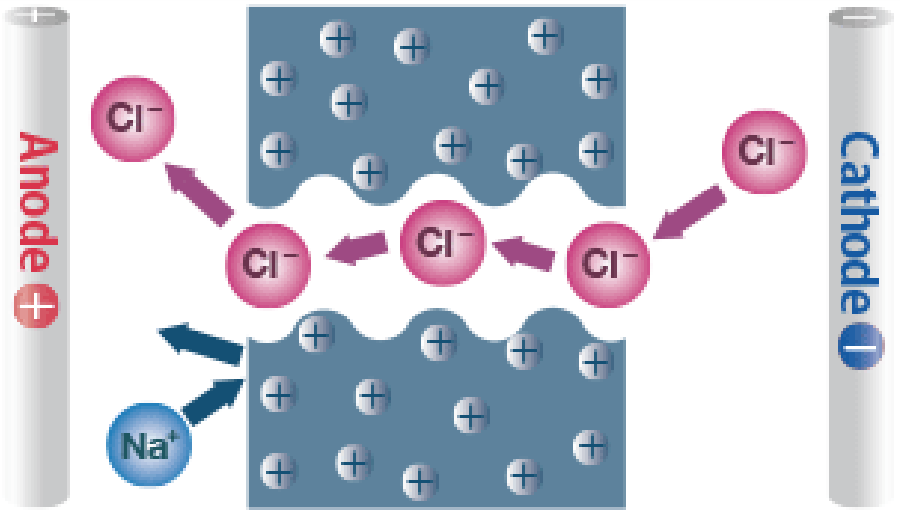
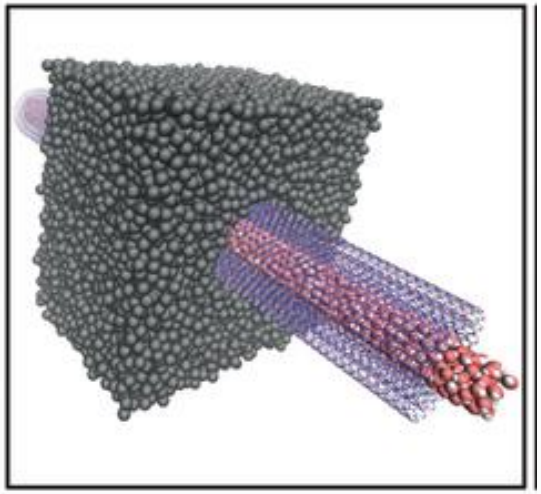


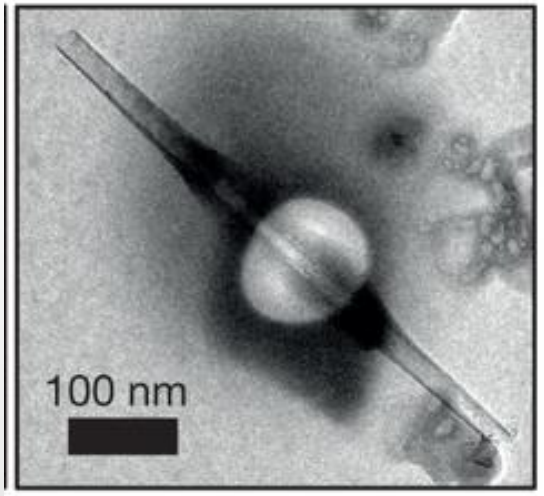
Figure 1-2 Selective permeability of AEM

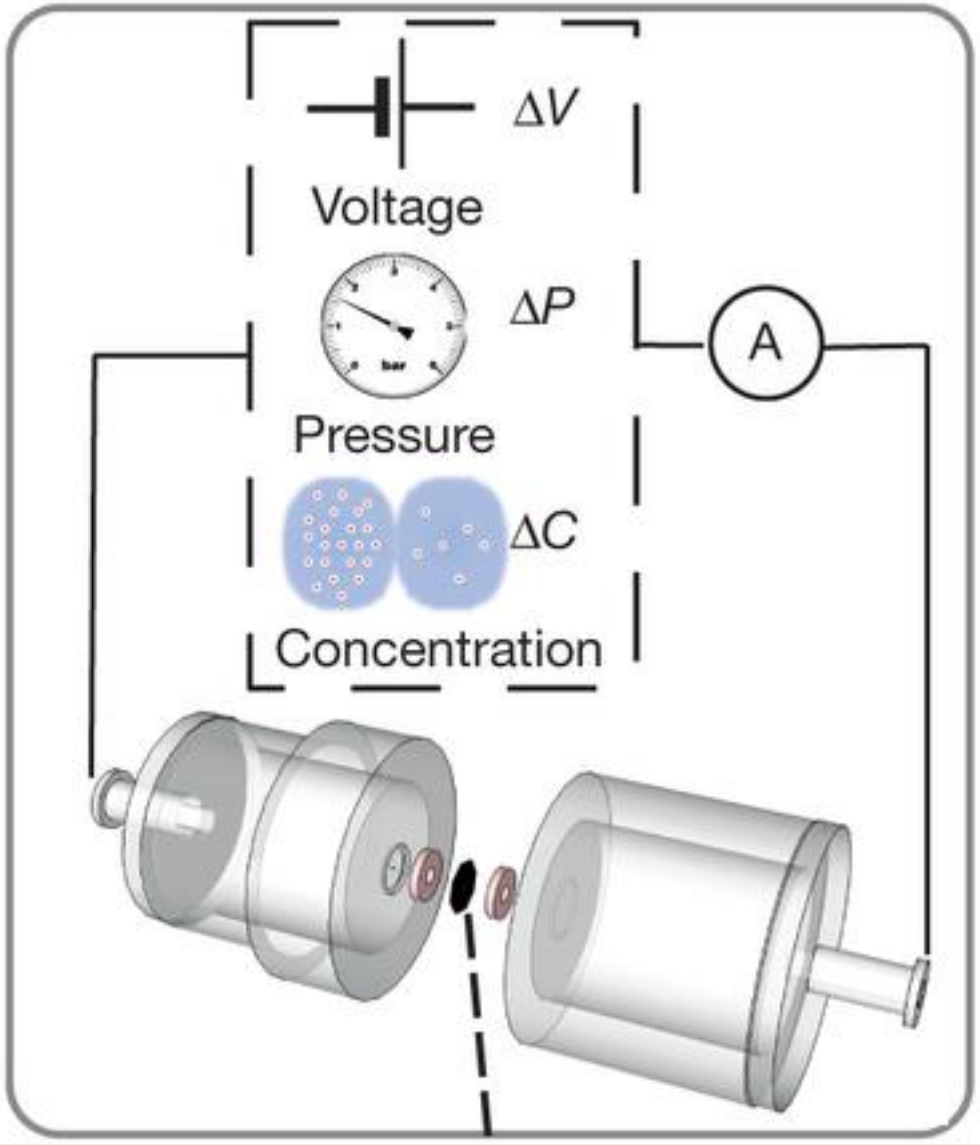
https://en.wikipedia.org/wiki/Osmotic_power

Boron Nitride Nanotube based powergenerators

Siria, A., et al. & Bocquet, L. (**2013**) Nature, 494(7438), 455–458.

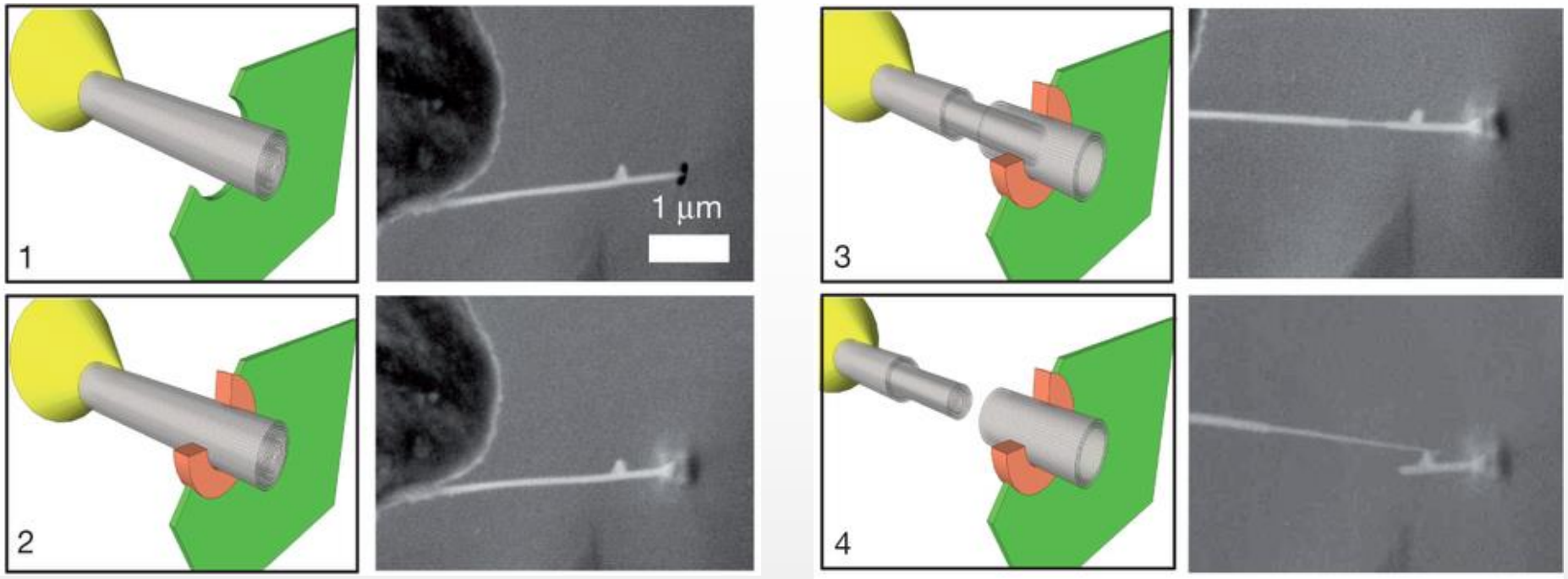






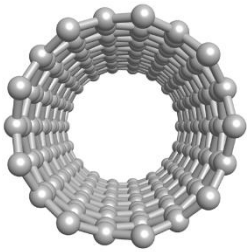
Boron Nitride Nanotube

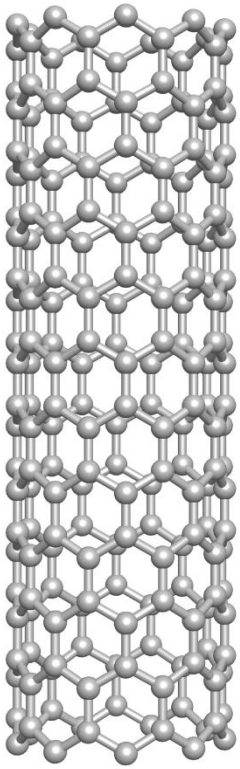
2013 –improved efficiency



Siria, A., et al. & Bocquet, L. (**2013**) **Nature**, 494(7438), 455–458.

Our approach



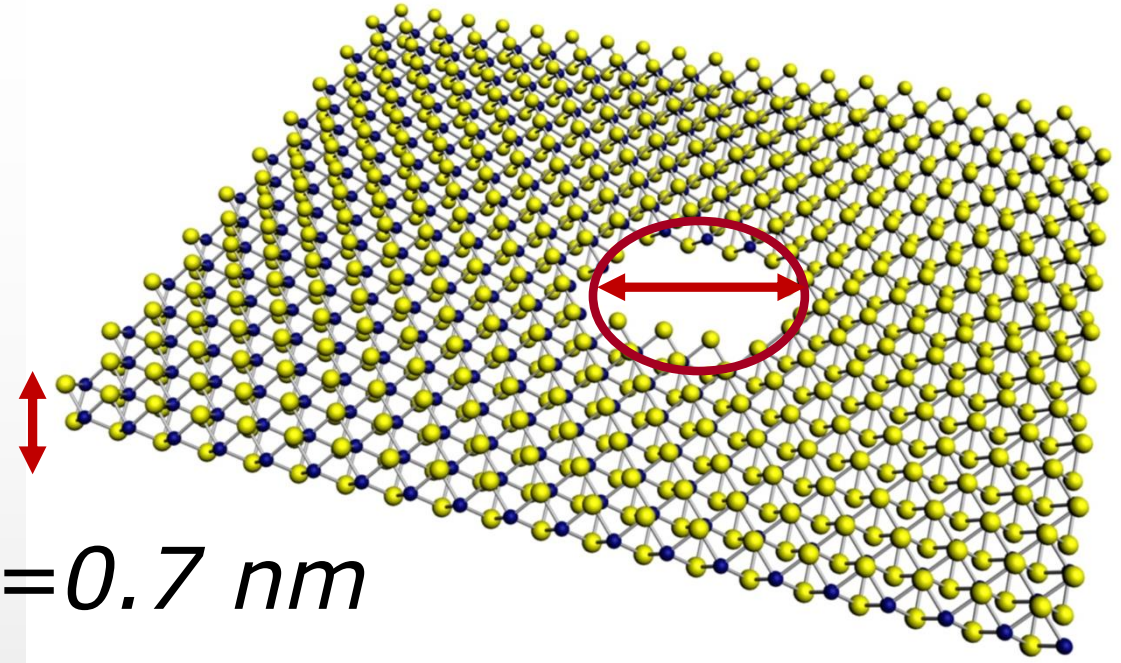


Boron nitride nanotube

L

d

MoS_2 membrane with a single nanopore



L=0.7 nm

Tunable d

Overview of osmotic power generator

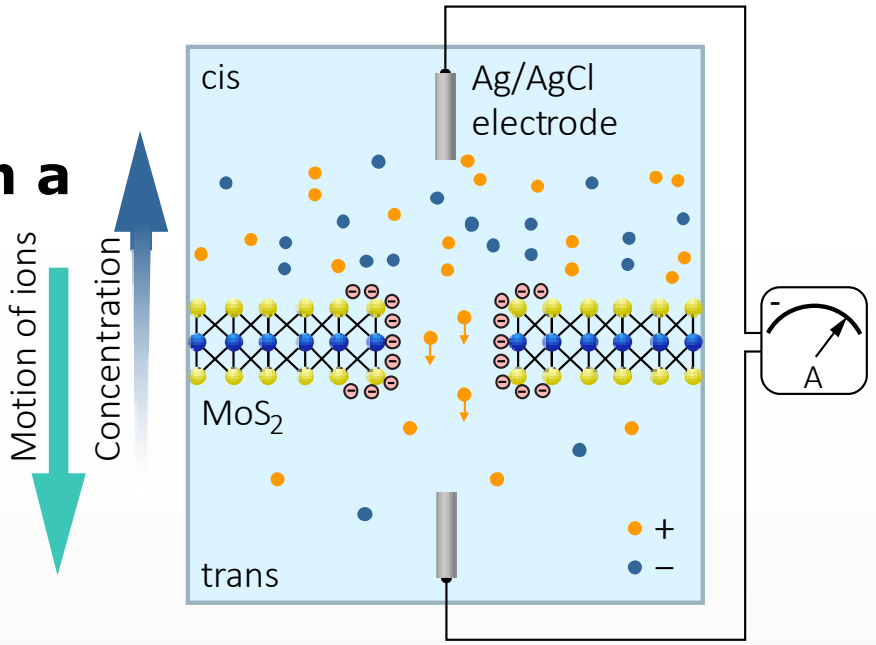
Exploiting osmotic potential from a salt concentration gradient

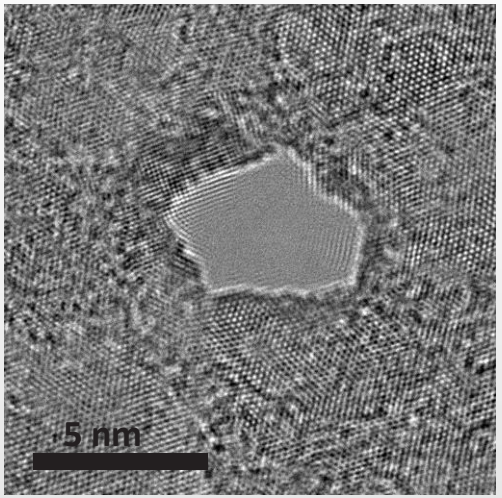
Pores drilled using TEM or ECR

Varied ΔC

Varied Surface Charge by adjusting pH

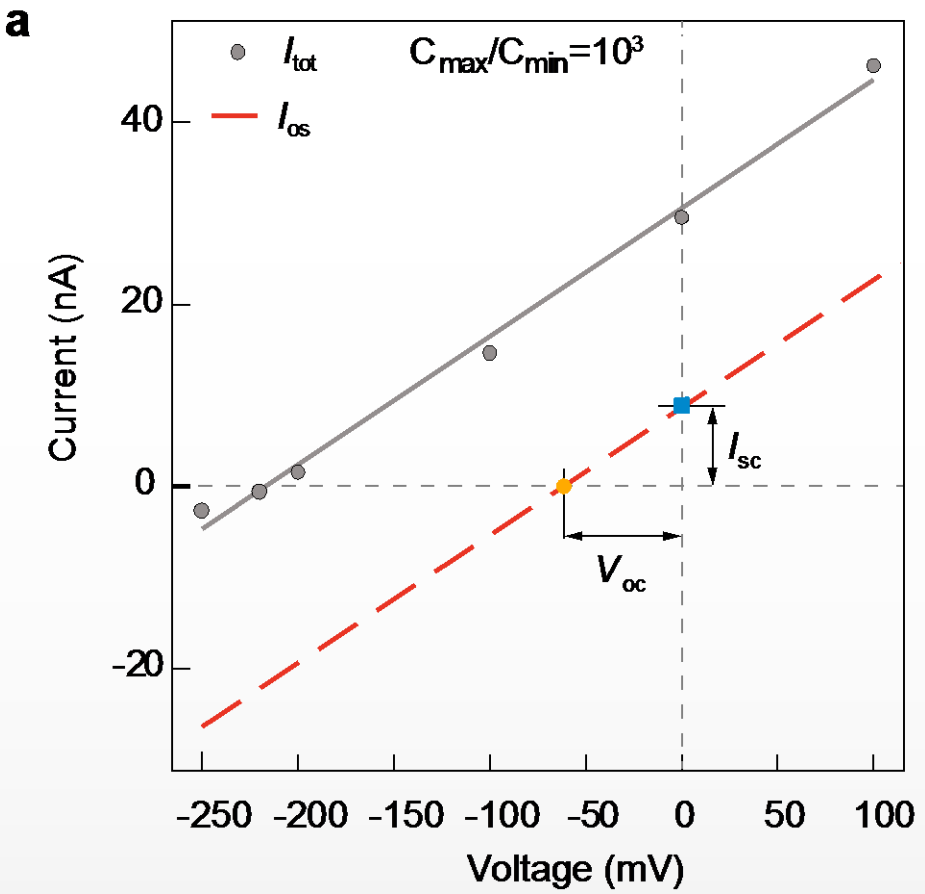
MD- Simulations to confirm results

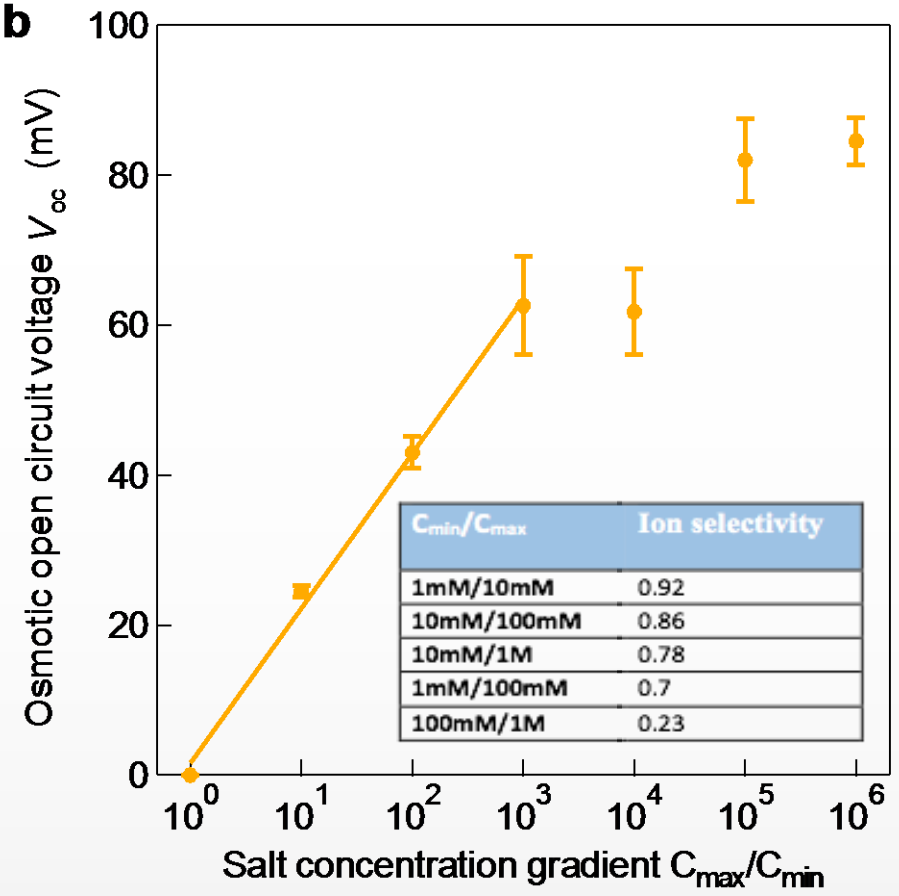




Siria, A., **Bocquet, L**. et. al. **Nature 2013**
Feng et al. **Nature 2016**

Osmotic power generation



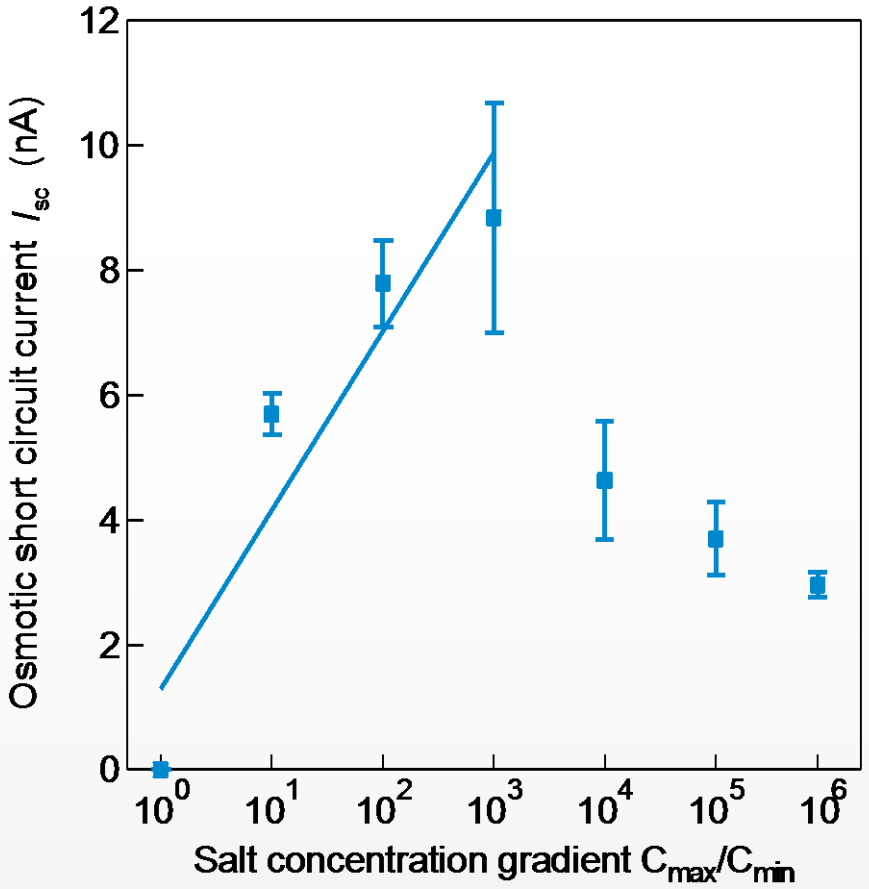


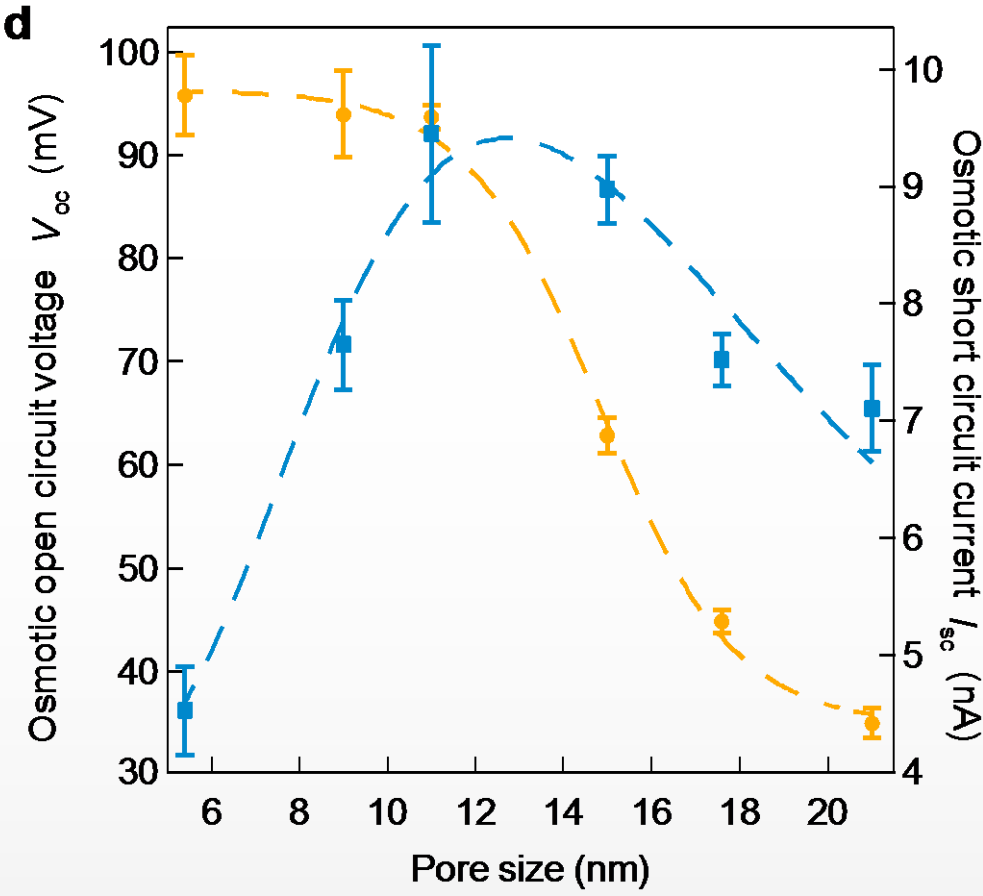
$$I_{os} \propto \frac{2\pi r f(\Sigma)}{L} \frac{k_B T}{\eta \lambda_B} \ln\left[\frac{a_{KCl}^{cis}}{a_{KCl}^{trans}}\right]$$

$$V_{os} = f(\Sigma)_{is} \frac{RT}{F} \ln\left[\frac{a_{KCl}^{cis}}{a_{KCl}^{trans}}\right]$$

Feng et al. **Nature 2016**

Osmotic power generation





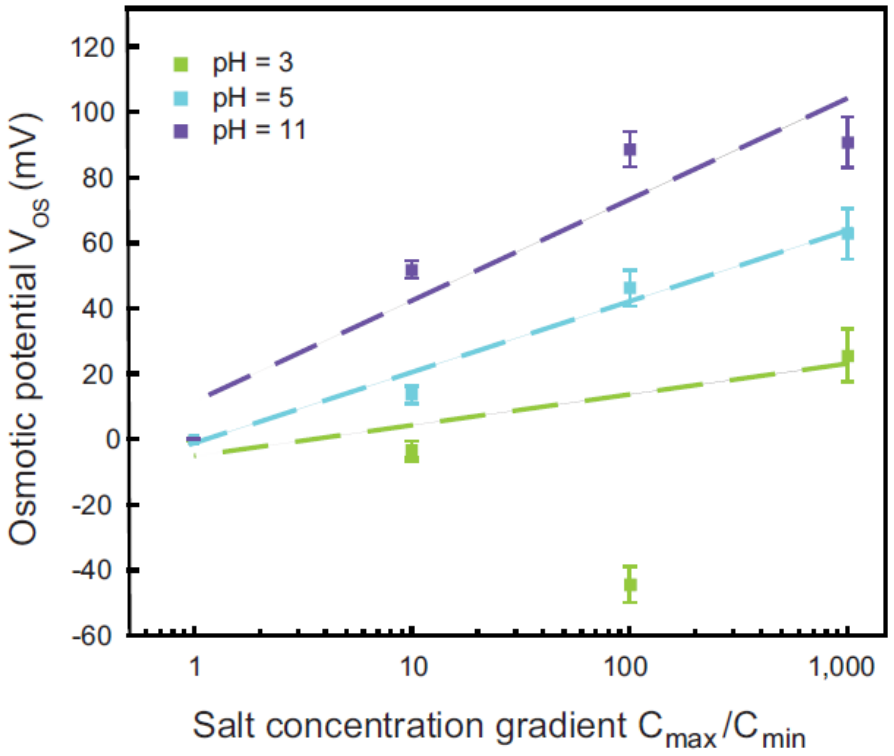
$$I_{os} \propto \frac{2\pi r f(\Sigma)}{L} \frac{k_B T}{\eta \lambda_B} \ln\left[\frac{a_{KCl}^{cis}}{a_{KCl}^{trans}}\right]$$

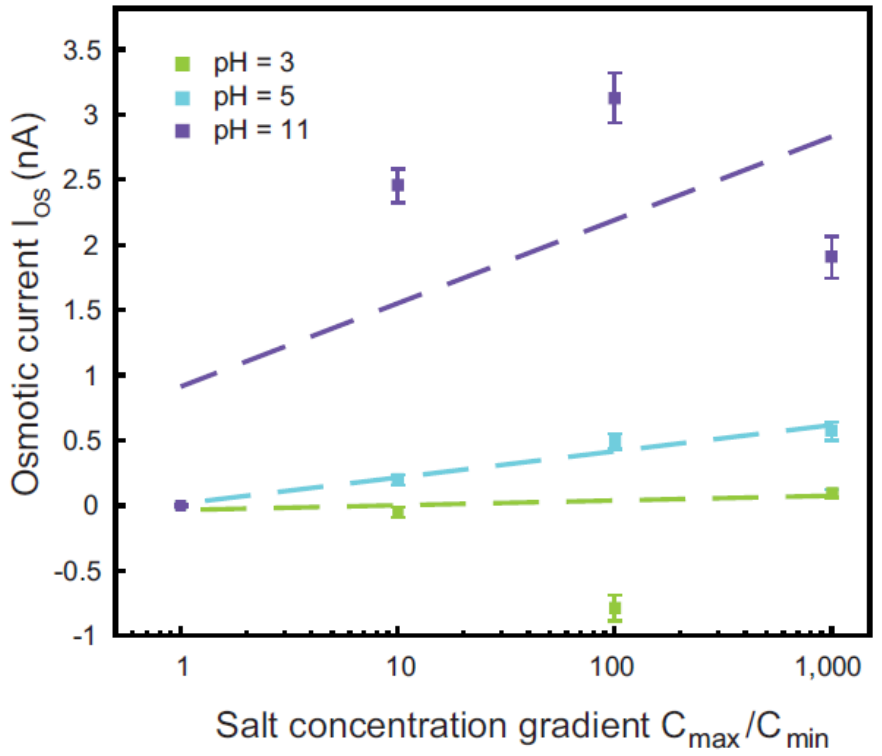
$$V_{os} = f(\Sigma)_{is} \frac{RT}{F} \ln\left[\frac{a_{KCl}^{cis}}{a_{KCl}^{trans}}\right]$$

Feng et al. **Nature 2016**

Osmotic power generation

The role of pH (3-11)





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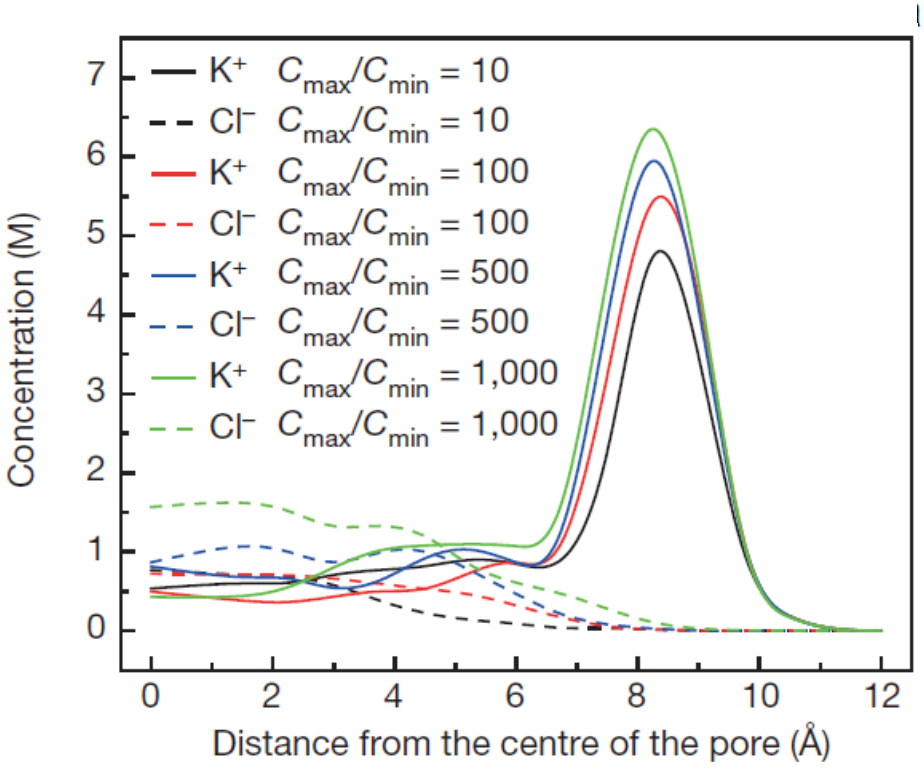
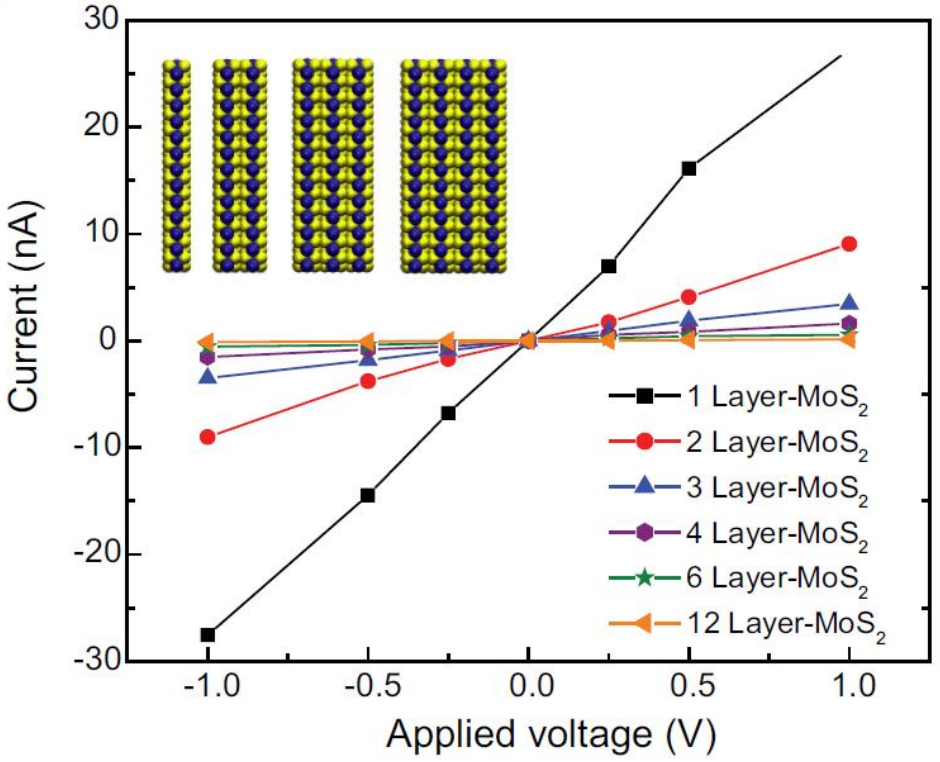
Molecular-dynamics-simulation





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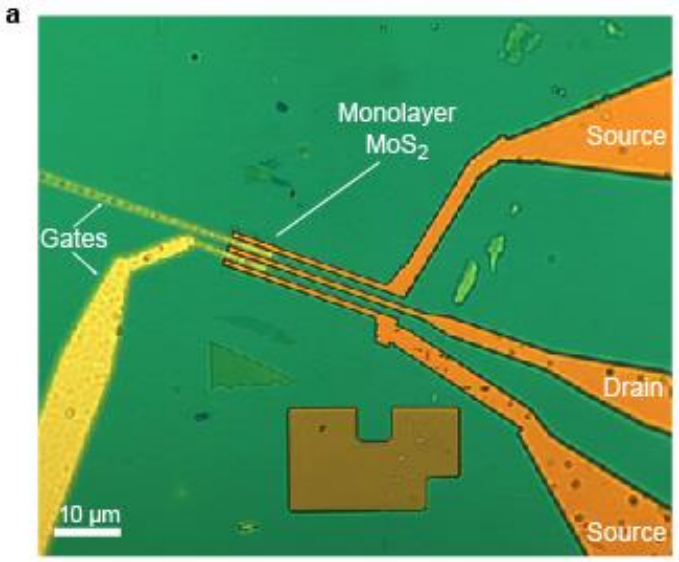
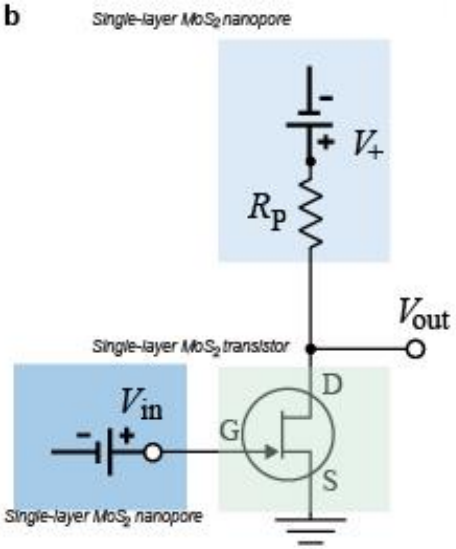
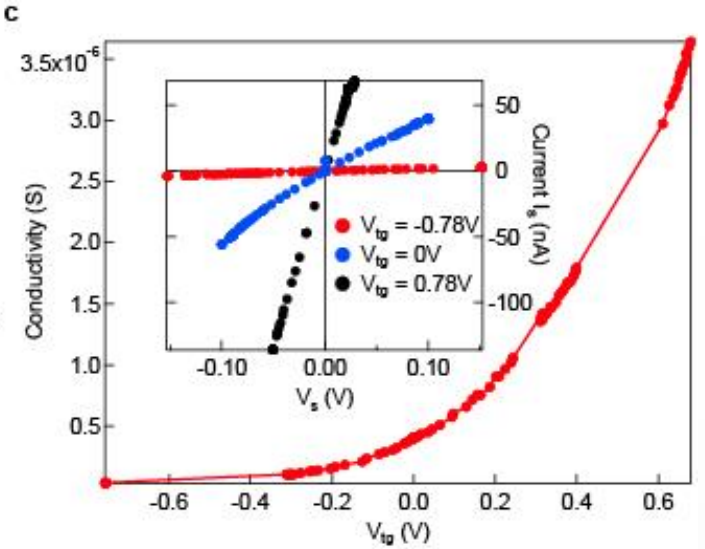
Osmotic power generation

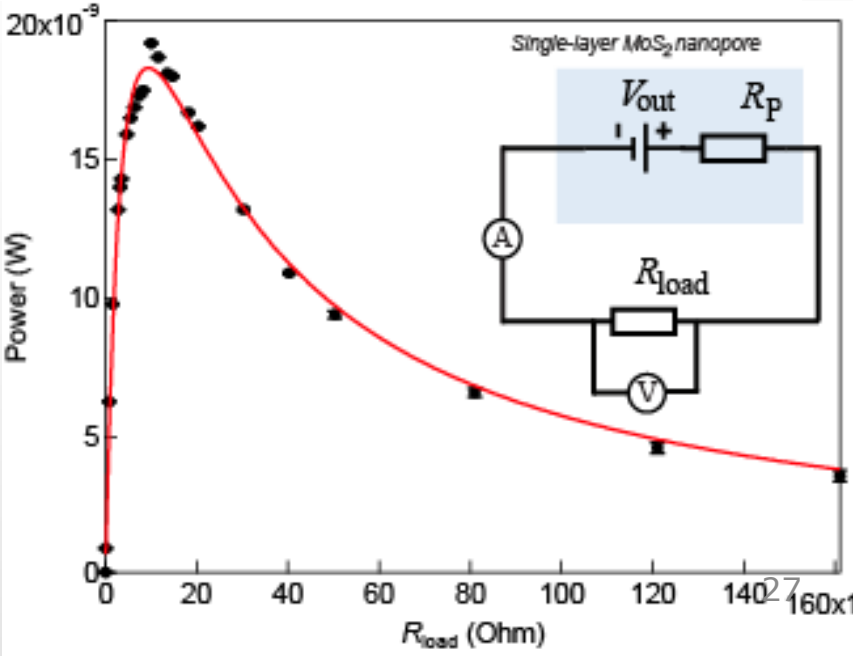






Self-powered system

$$Power = \frac{V_{out}R_{load}}{(R_P + R_{load})^2}$$



Feng et al. **Nature 2016**

Conclusion

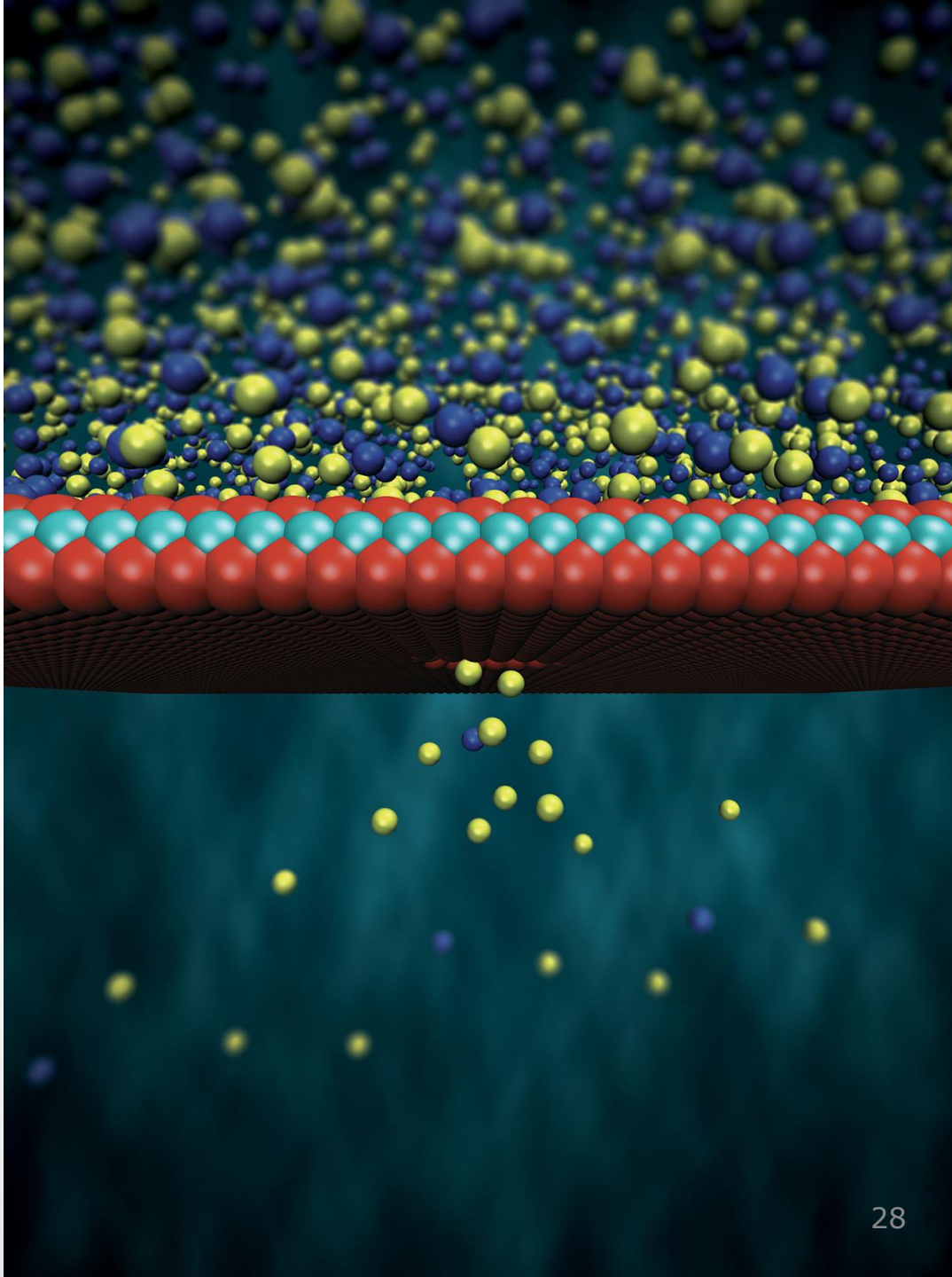
2D material membranes

ideal size of the pore:

10nm

single pore power:

1-10 nW



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Starting **PorABEL**
Consolidator **Bionic**

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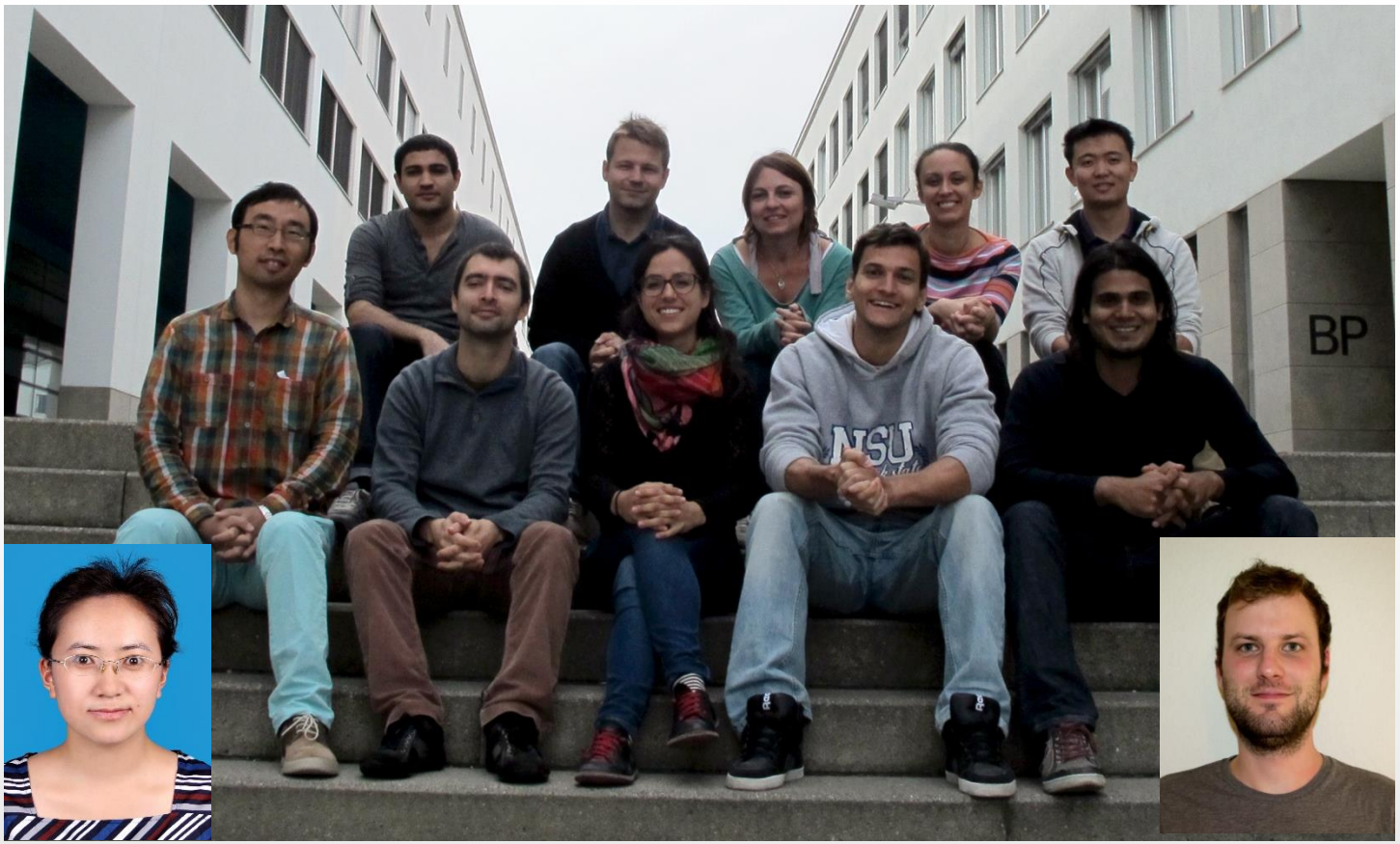
SEVENTH FRAMEWORK PROGRAMME

Swiss National Science Foundation



Prof. N.R. Aluru

Prof. Andras Kis