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DIPARTIMENTO
DI FISICA E GEOLOGIA

Micro and nano devices for computing and sensing

11/01/2022

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Luca Gammaitoni, Francesco Cottone, Alessandro Di Michele, M. Cristina Diamantini, Maurizio Mattarelli

Topics

- Physics of computing: zero power micro e nano devices

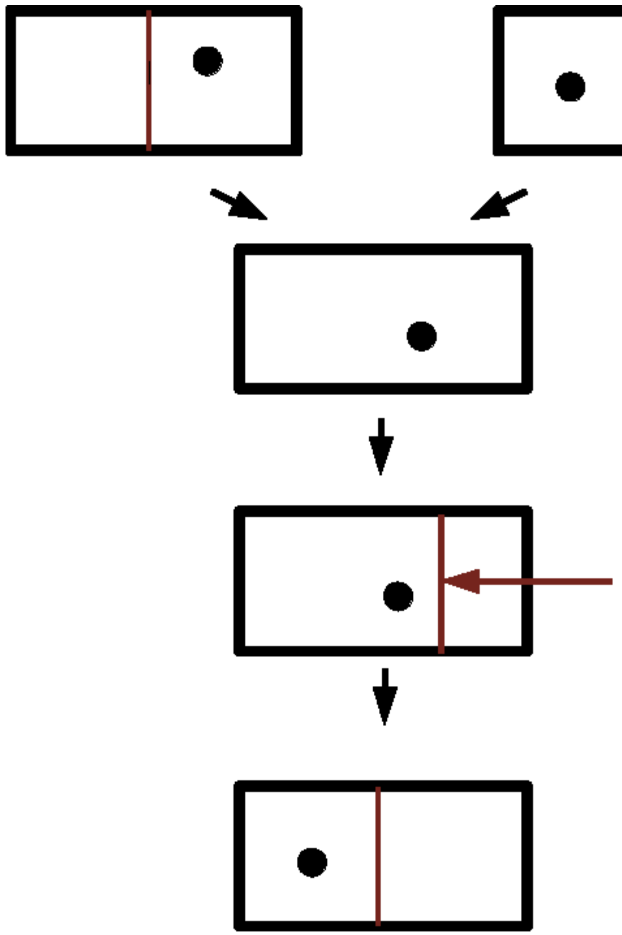
- 2D materials for computing and sensing

Information is physical

Landauer R. IBM Journal Of Research And Development, Vol. 5, no. 3, 1961

Landauer principle

- Minimum amount of energy required **greater than zero**
- Let assume the operation of **bit reset**
- # of initial states: 2
- # of final states: 1



Landauer principle

$$S = k_B \log W$$

$$Q \leq T\Delta S$$

Initial condition: two possible states

$$S_i = k_B \log 2$$

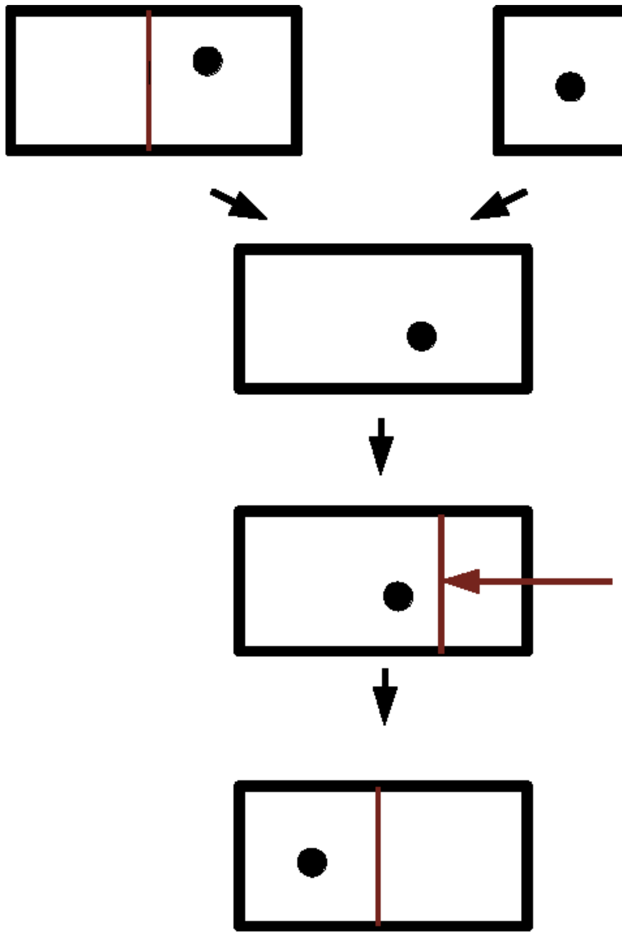
Final condition: one possible state

$$S_f = k_B \log 1$$

$$\Delta S = S_f - S_i = -k_B \log 2$$

Heat produced

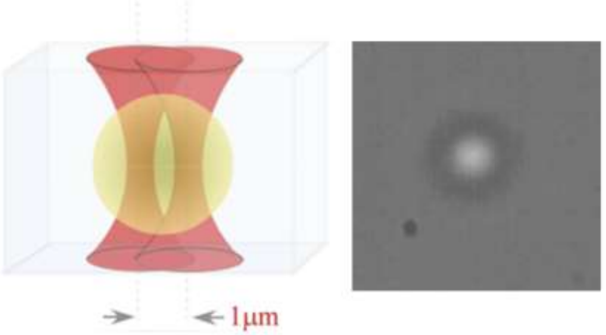
$$Q \leq T\Delta S = -k_B T \log 2$$

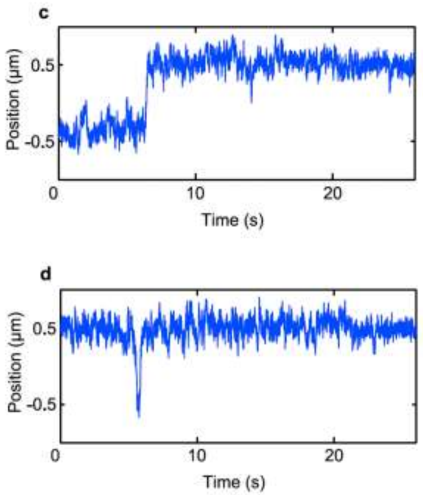


Landauer principle experimental verification

Brownian particle in a double-well potential

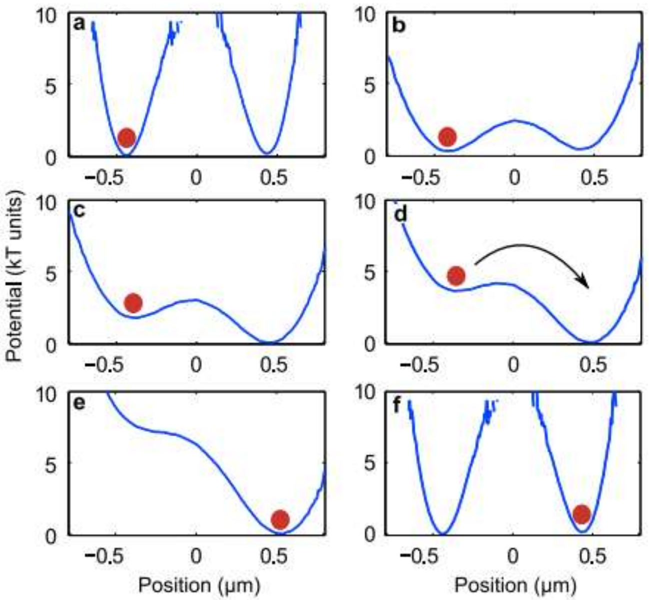
Berut et al. Nature 2012





Ciliberto ENS Lyon

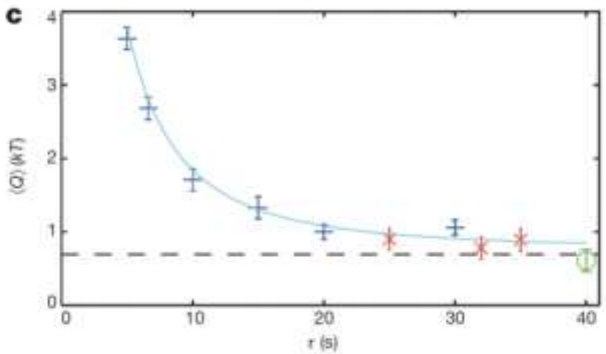
Measured erasure cycle:



Landauer's original thought experiment

Experimental results:

We measure work W and deduce heat $Q = -\Delta U + W = W$

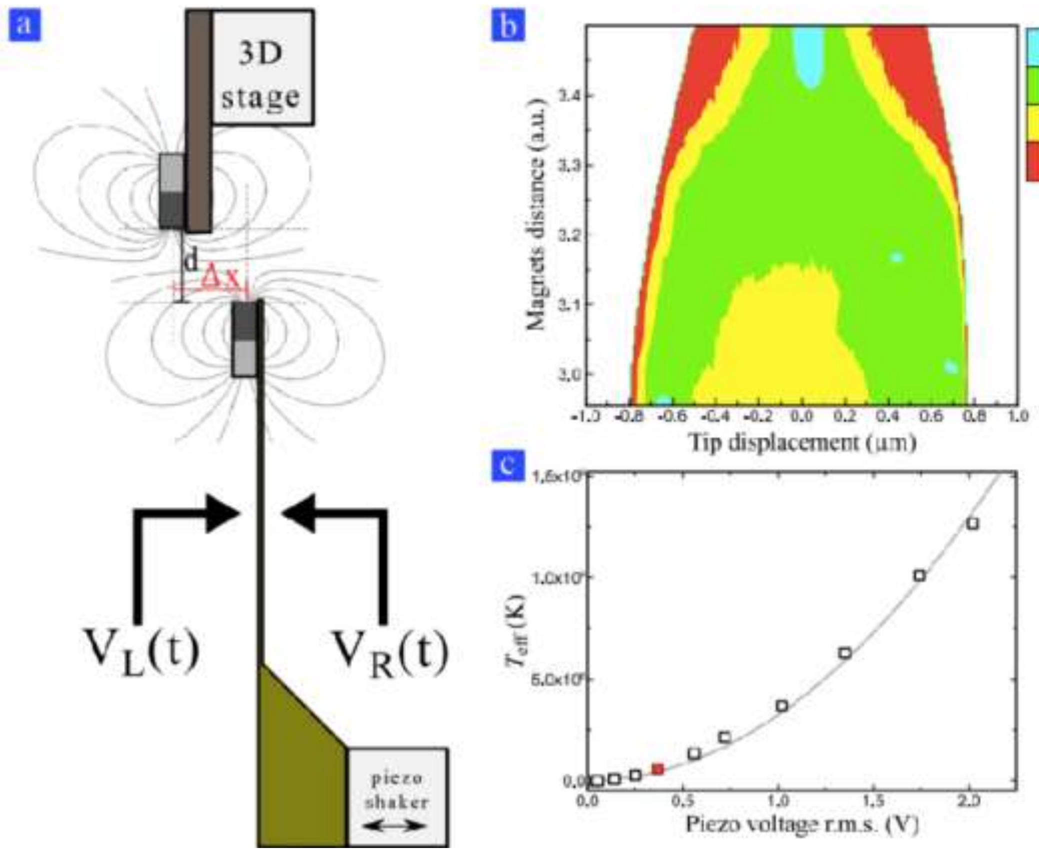


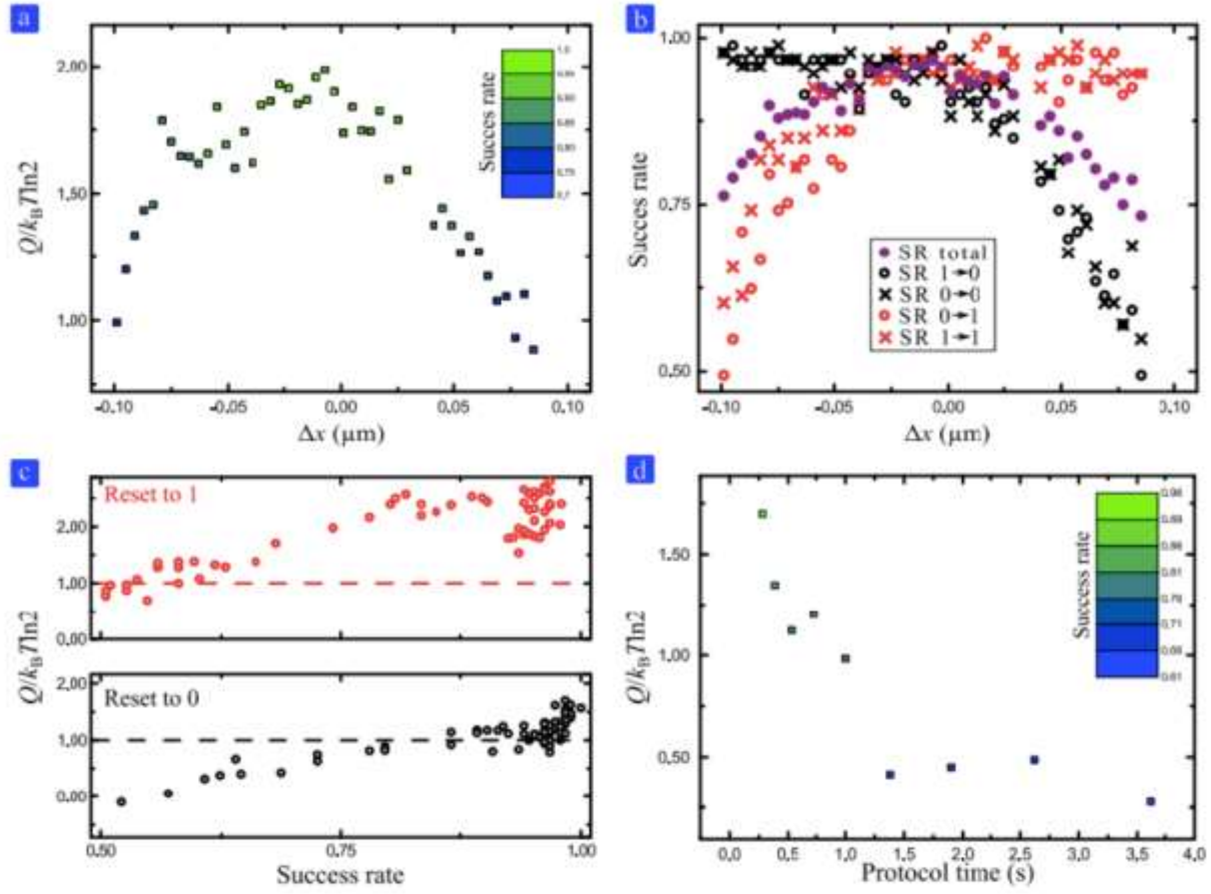
→ Landauer can be bound approached but not exceeded

Note: $kT \ln 2 \simeq 3 \times 10^{-21} J$ at room temperature

The physics of information: from Maxwell's demon to Landauer - Eric Lutz - University of Erlangen-Nürnberg

Landauer principle experimental verification





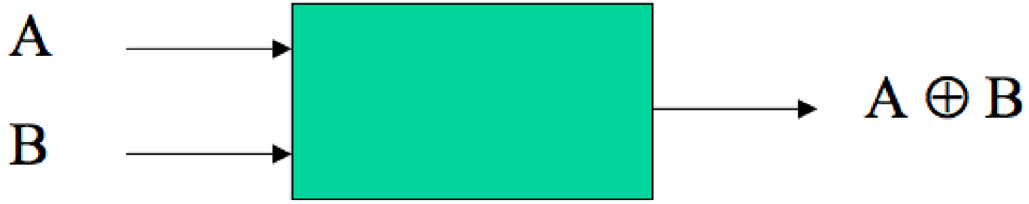
Neri, Igor, and Miquel López-Suárez. "Heat production and error probability relation in Landauer reset at effective temperature." *Scientific reports* 6.1 (2016): 1-7.

Logically irreversible devices

We shall call a device logically irreversible if the output of a device does not uniquely define the inputs. We believe that devices exhibiting logical irreversibility are essential to computing. Logical irreversibility, we believe, in turn implies physical irreversibility, and the latter is accompanied by dissipative effects.

Landauer R. IBM Journal Of Research And Development, Vol. 5, no. 3, 1961

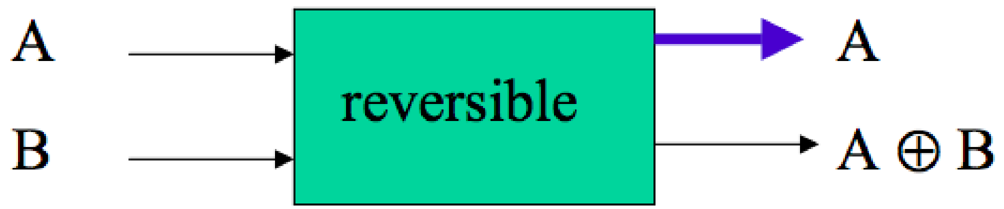
Information is Physical



Inputs		Output
A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

Rolf Landauer, 1961. Whenever we use a logically irreversible gate we dissipate energy into the environment.

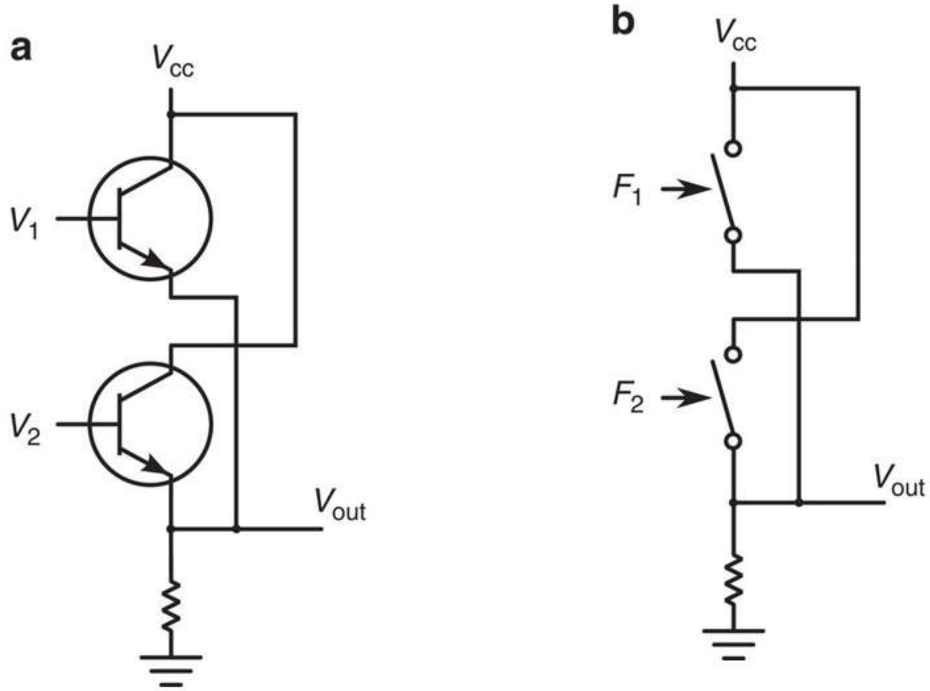
Solution = Reversibility

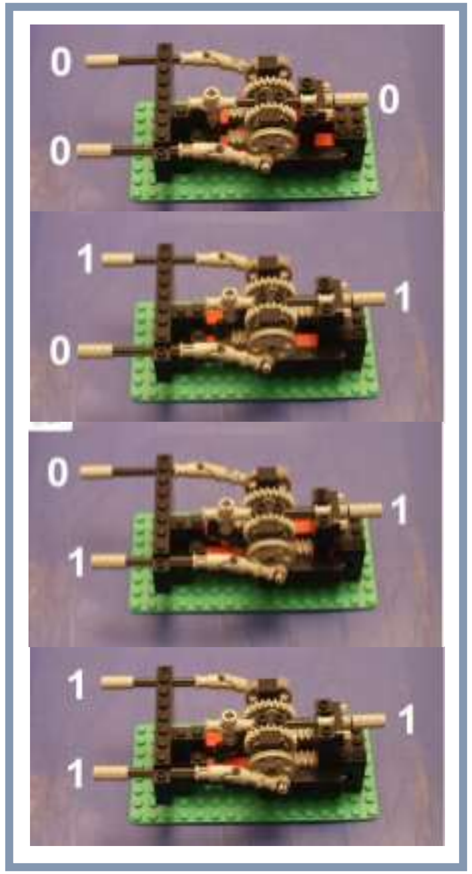


Inputs		Output
A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

- Charles Bennett, 1973: There are no unavoidable energy consumption requirements per step in a computer.
- Energy dissipation of reversible circuit, under ideal physical circumstances, is zero.

OR logic gate

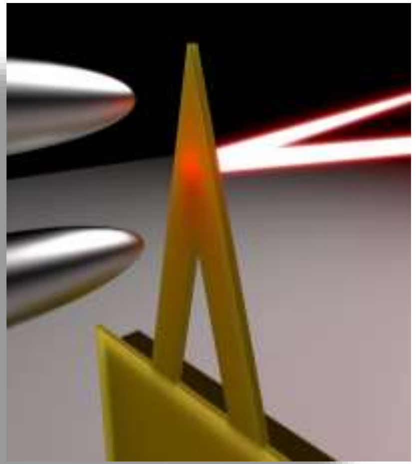


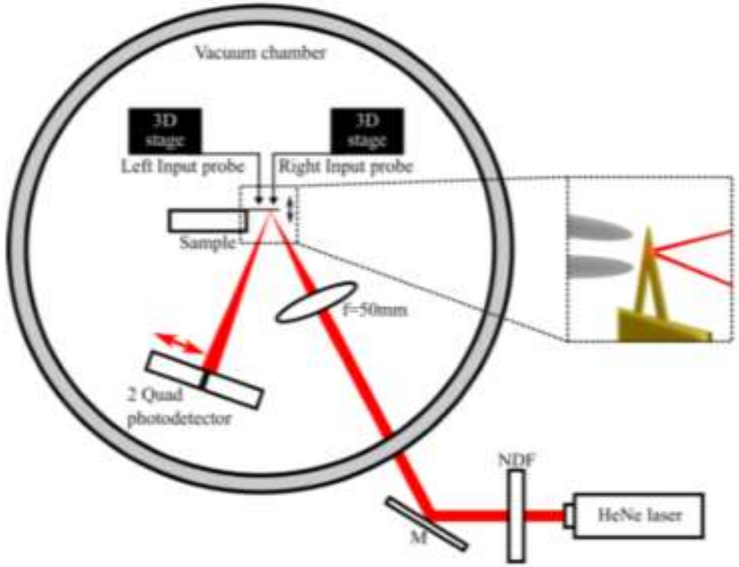


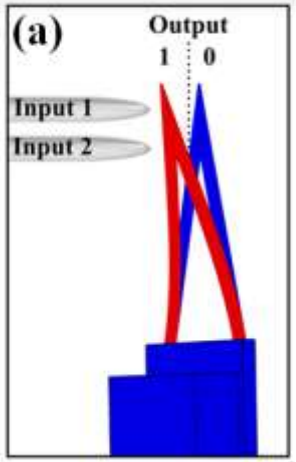
www.randomwraith.com

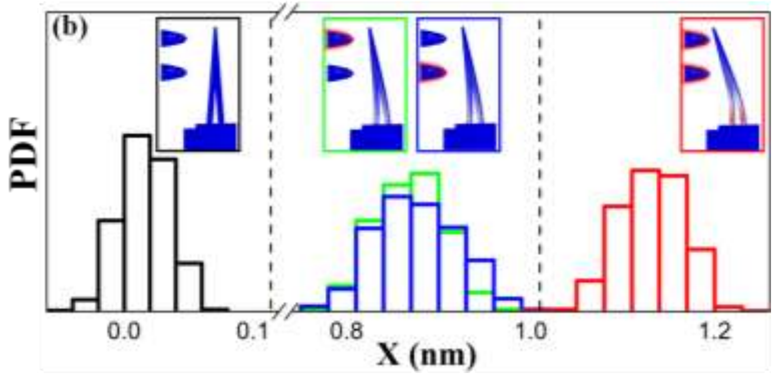
OR logic gate

nature COMMUNICATIONS









ARTICLE

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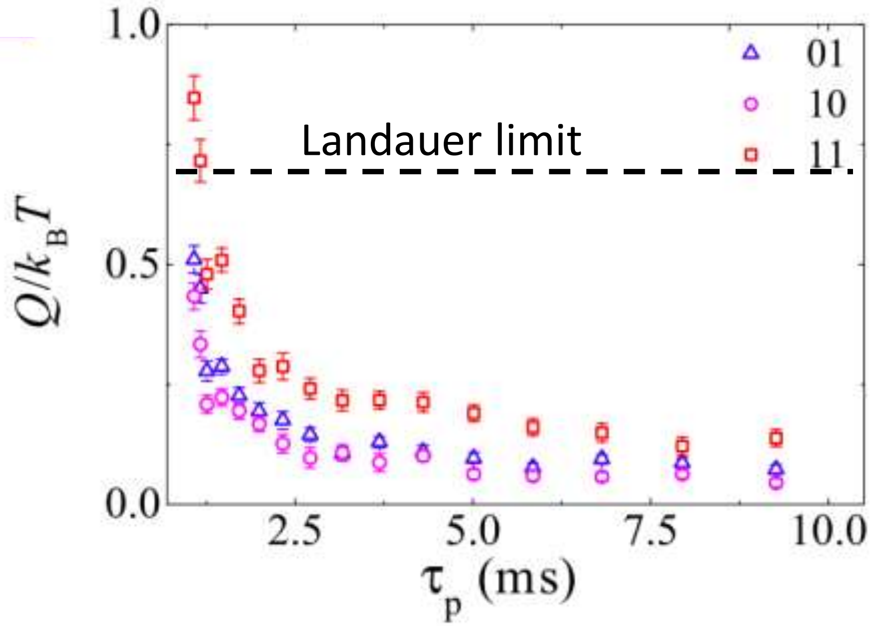
DOI: 10.1038/ncomms12068
OPEN

Sub-$k_B T$ micro-electromechanical irreversible logic gate

M. López-Suárez[1], I. Neri[1,2] & L. Gammaitoni[1]



PHYSICAL REVIEW A **97**, 052108 (2018)

Cost of remembering a bit of information

D. Chiuchiù,[1,*] M. López-Suárez,[1] I. Neri,[1,2,†] M. C. Diamantini,[1,2] and L. Gammaitoni[1]
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[2]*INFN, Sezione di Perugia, 06123 Perugia, Italy*

(Received 8 May 2017; rev

In 1961, Landauer [R. Landauer, IB
memory requires a minimum energy of
content if no action is taken. To avoid m
a theoretical model and an experiment
required to preserve one bit of informa
energetic cost to preserve information fo
reduced if the refresh procedure is perfo
upper bound on the memory lifetime.

DOI: 10.1103/PhysRevA.97.052108

ERS **109**, 133505 (2016)

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Landauer Bound for Analog Computing Systems

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Carlo A. Trugenberger‡
SwissScientific, chemin Diodati 10, CH-1223 Cologny, Switzerland

(Dated: July 7, 2016)

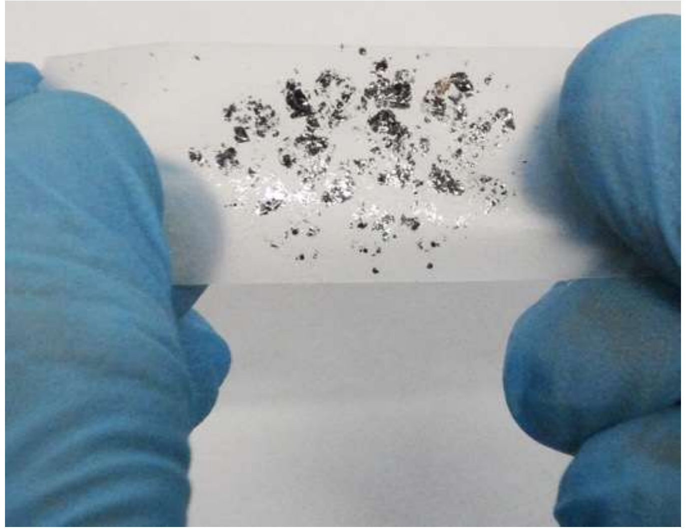
By establishing a relation between information erasure and continuous phase transitions we generalise the Landauer bound to analog computing systems. The entropy production per degree of freedom during erasure of an analog variable (reset to standard value) is given by the logarithm of the configurational volume measured in units of its minimal quantum. As a consequence every computation has to be carried on with a finite number of bits and infinite precision is forbidden by the fundamental laws of physics, since it would require an infinite amount of energy.

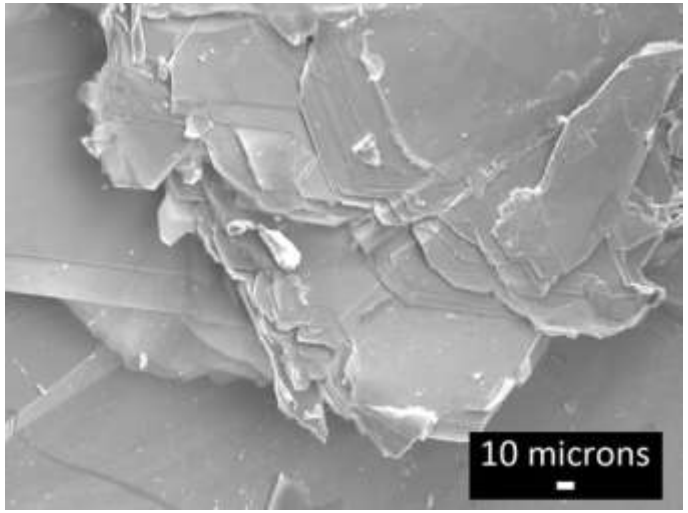
published online 22 July 2015

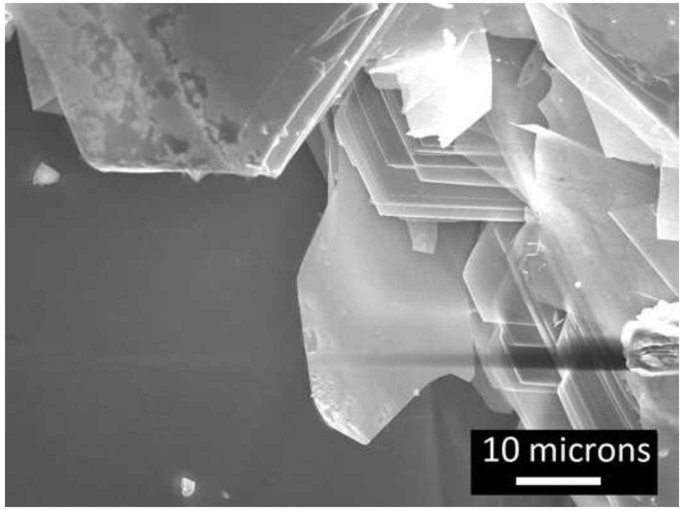
PACS 05.70.Ln – Nonequilibrium and irr
PACS 81.07.Oj – Nanoelectromechanical
PACS 02.70.Ns – Molecular dynamics an

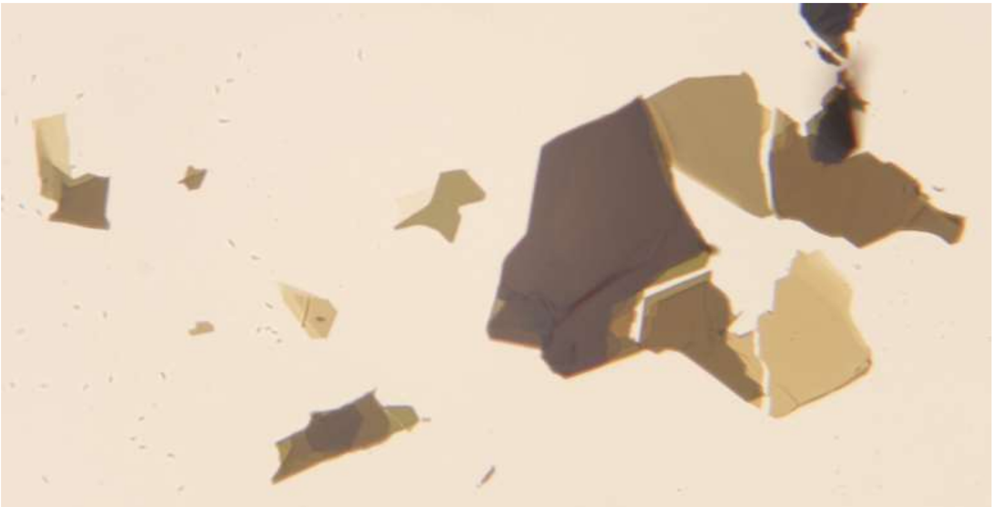
Abstract – Heat produced during a re
known as Landauer limit, while simple sy
produced heat equal to zero. However, in
far beyond these theoretical limits. In thi
simulations, where reset and switch protocols are applied on a graphene buckled ribbon, employed
here as a nano electromechanical switch working at the thermodynamic limit.

Going nano: 2D material

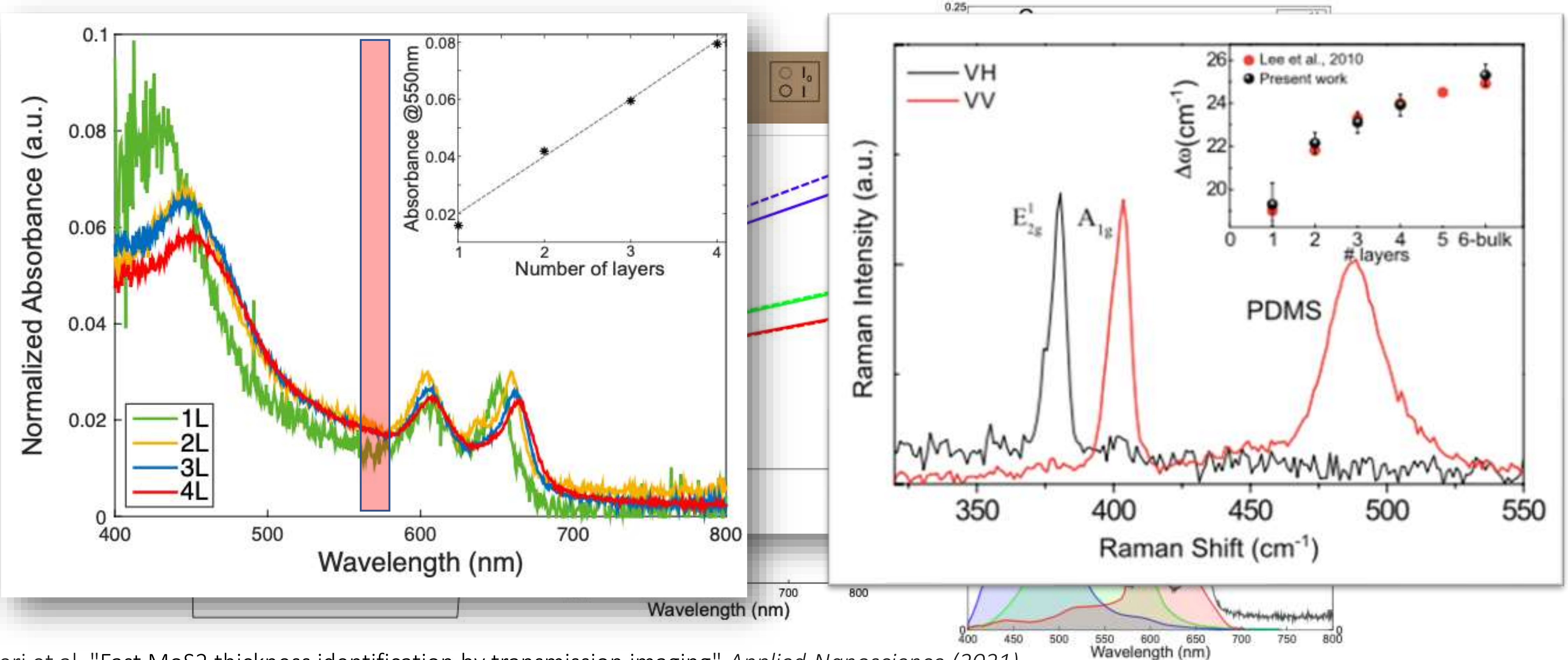






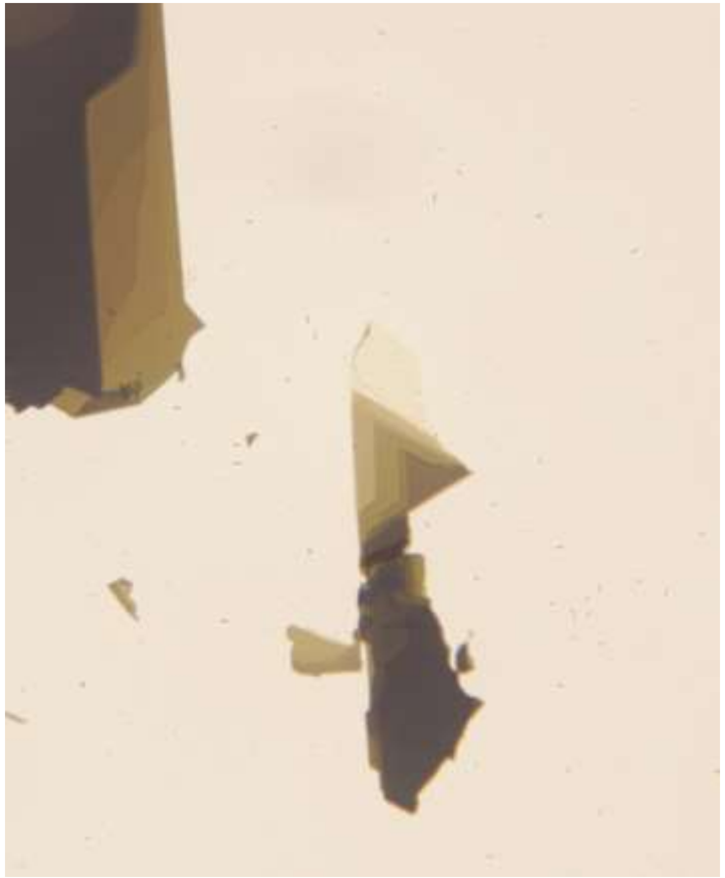


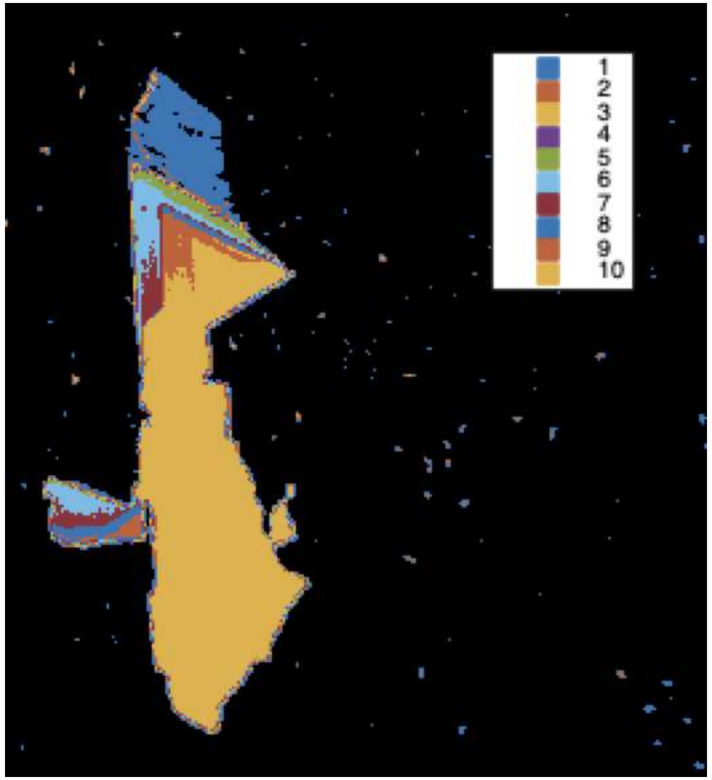
Fast MoS2 thickness identification by transmission imaging



I. Neri et al. "Fast MoS2 thickness identification by transmission imaging" *Applied Nanoscience (2021)*.

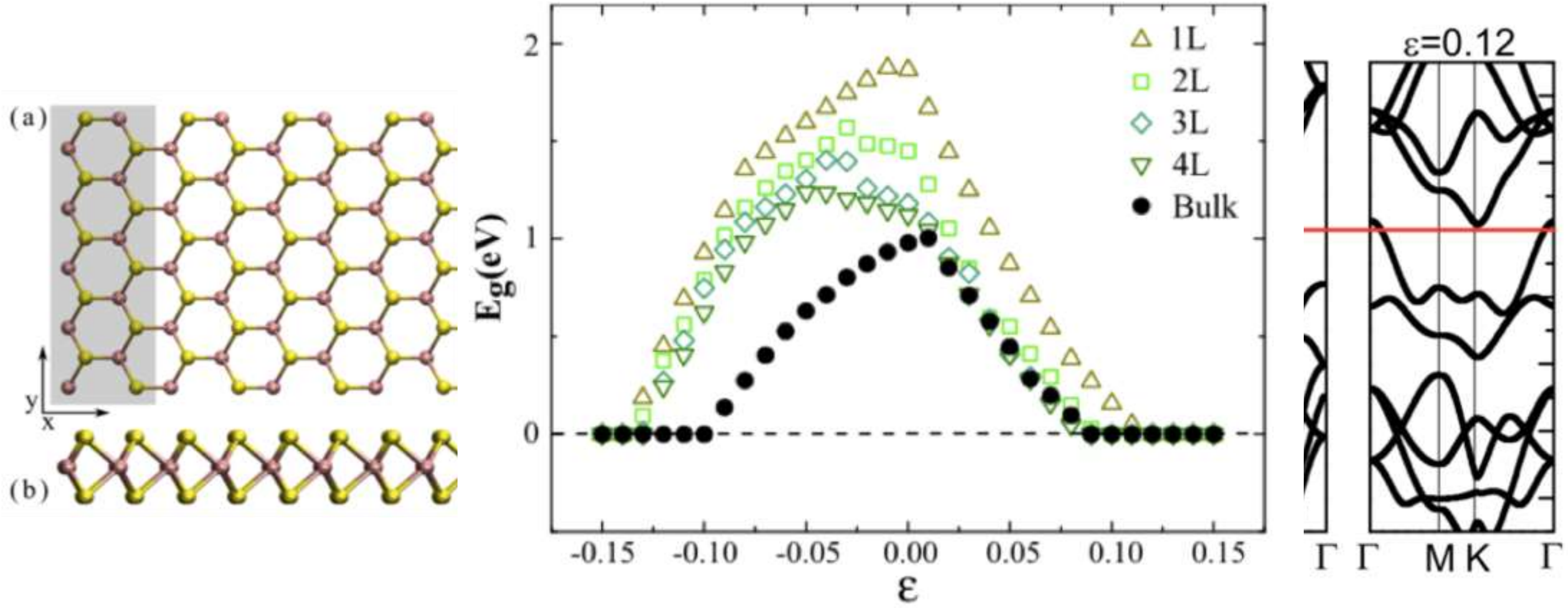
Fast MoS2 thickness identification by transmission imaging





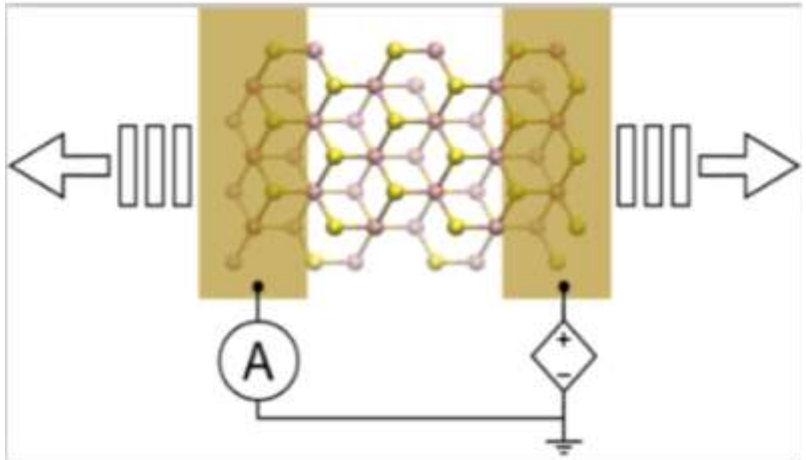
I. Neri et al. "Fast MoS2 thickness identification by transmission imaging" *Applied Nanoscience (2021)*.

MoS2 straintronic

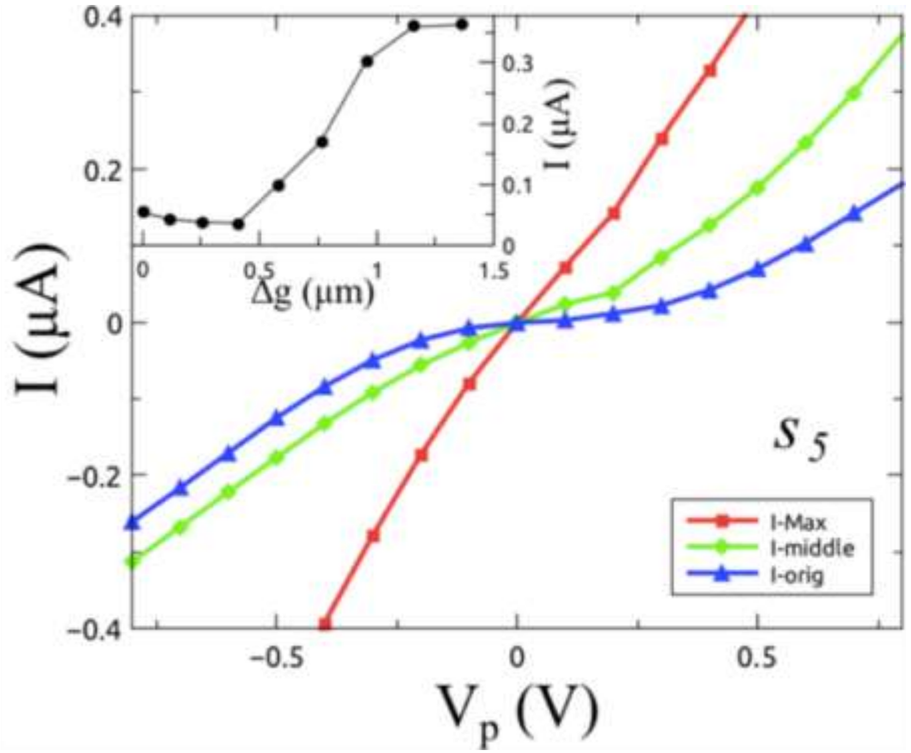


Electronic transport modulation on suspended few-layer MoS2 under strain, I Neri, M López-Suárez, Physical Review B 97 (24), 241408, 2018

MoS2 straintronic



Sample	l (μm)	w (μm)	n	A_L (μm^2)	A_R (μm^2)	Clamped
s_1	4.96	6.7	3	23.9	165.6	No
s_2	7.14	11.7	8	385.8	674.8	No
s_3	3.07	9.43	7	321.2	245.6	No
s_4	6.16	7.28	6			Yes
s_5	9.2	2.92	7-bulk			Yes



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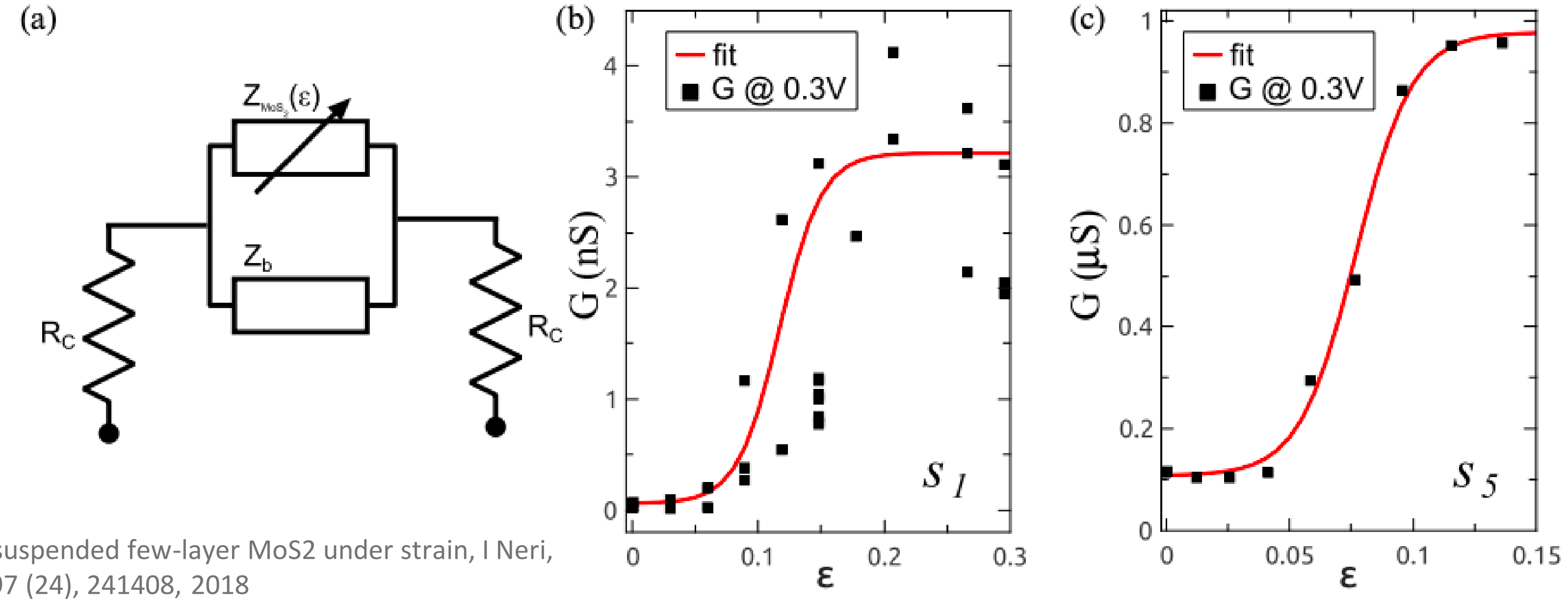
MoS2 straintronic

$$G_{\mathrm{MoS_2}}(\varepsilon) = G_0 \exp\left[-\frac{\varepsilon}{2k_B T}\frac{\partial E_g}{\partial \varepsilon}\right]$$

Parameter	s_1	s_5
R_C	$310.7 \times 10^6\ \Omega$	$1.02 \times 10^6\ \Omega$
Z_b	$1.67 \times 10^{10}\ \Omega$	$8.24 \times 10^6\ \Omega$
G_0	2.94×10^{-12} S	13.05×10^{-10} S
$\partial E_g/\partial\varepsilon$	−31 meV/% strain	−45 meV/% strain



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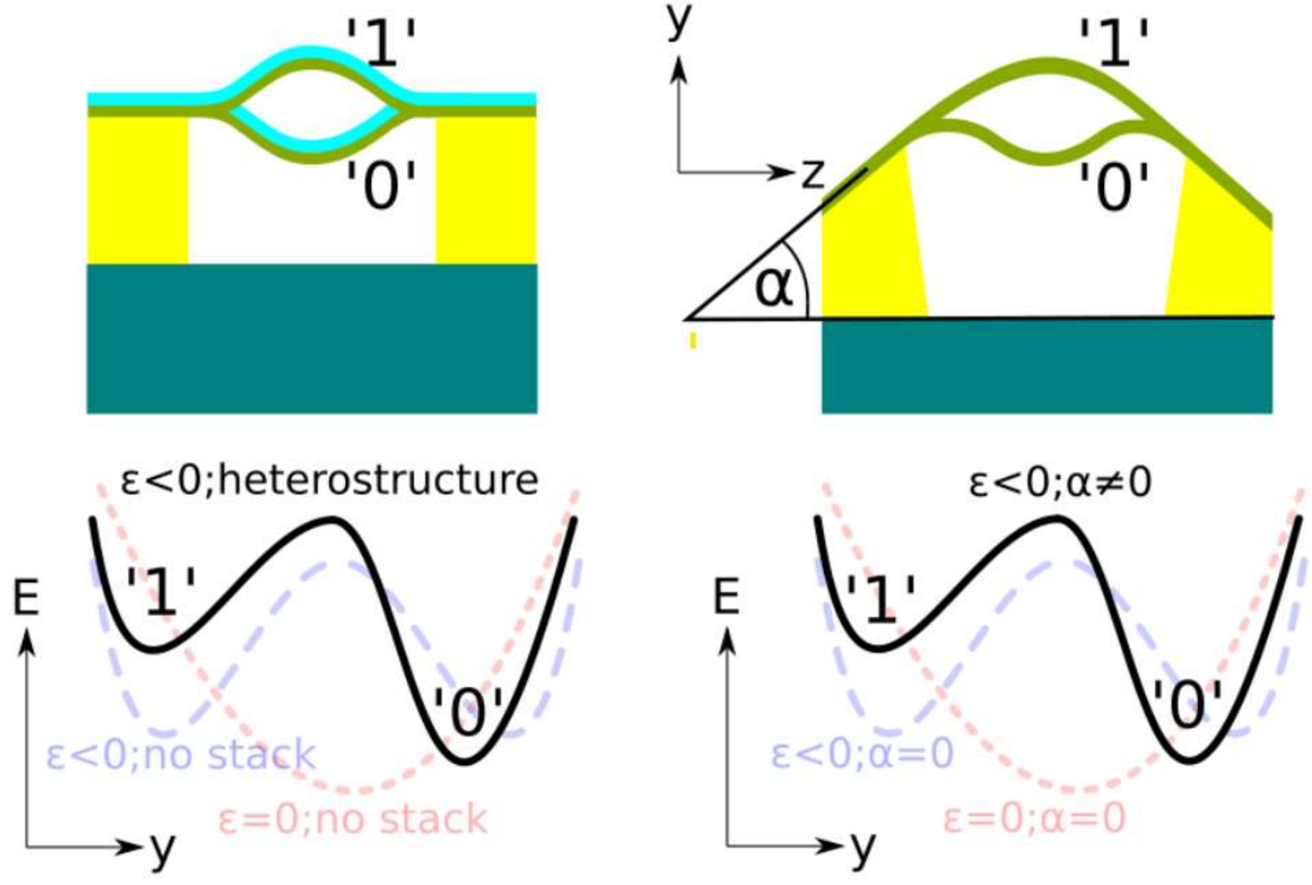
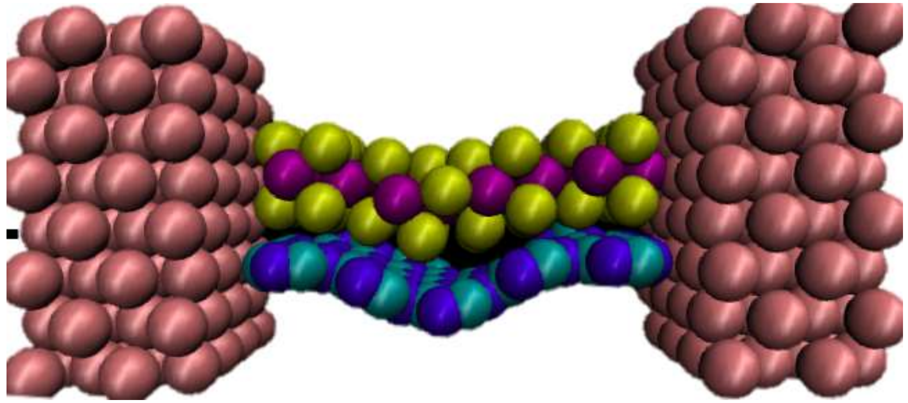
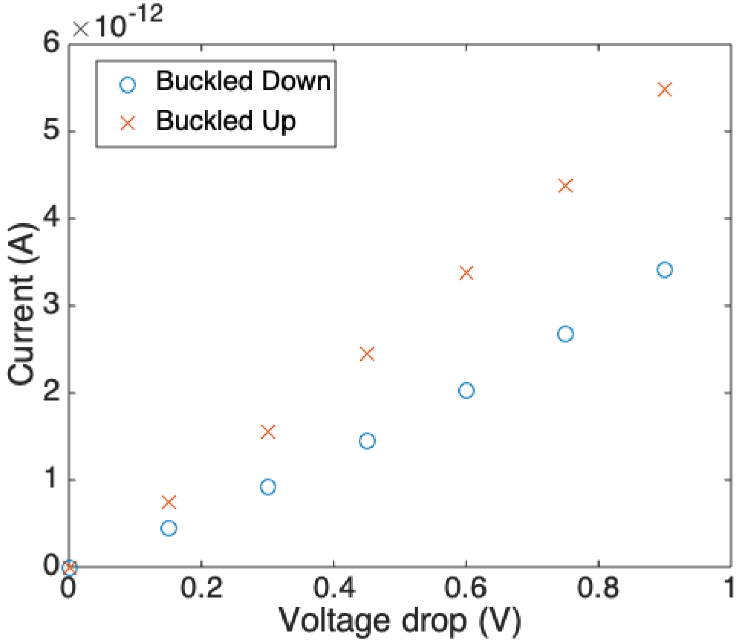
Memory unit

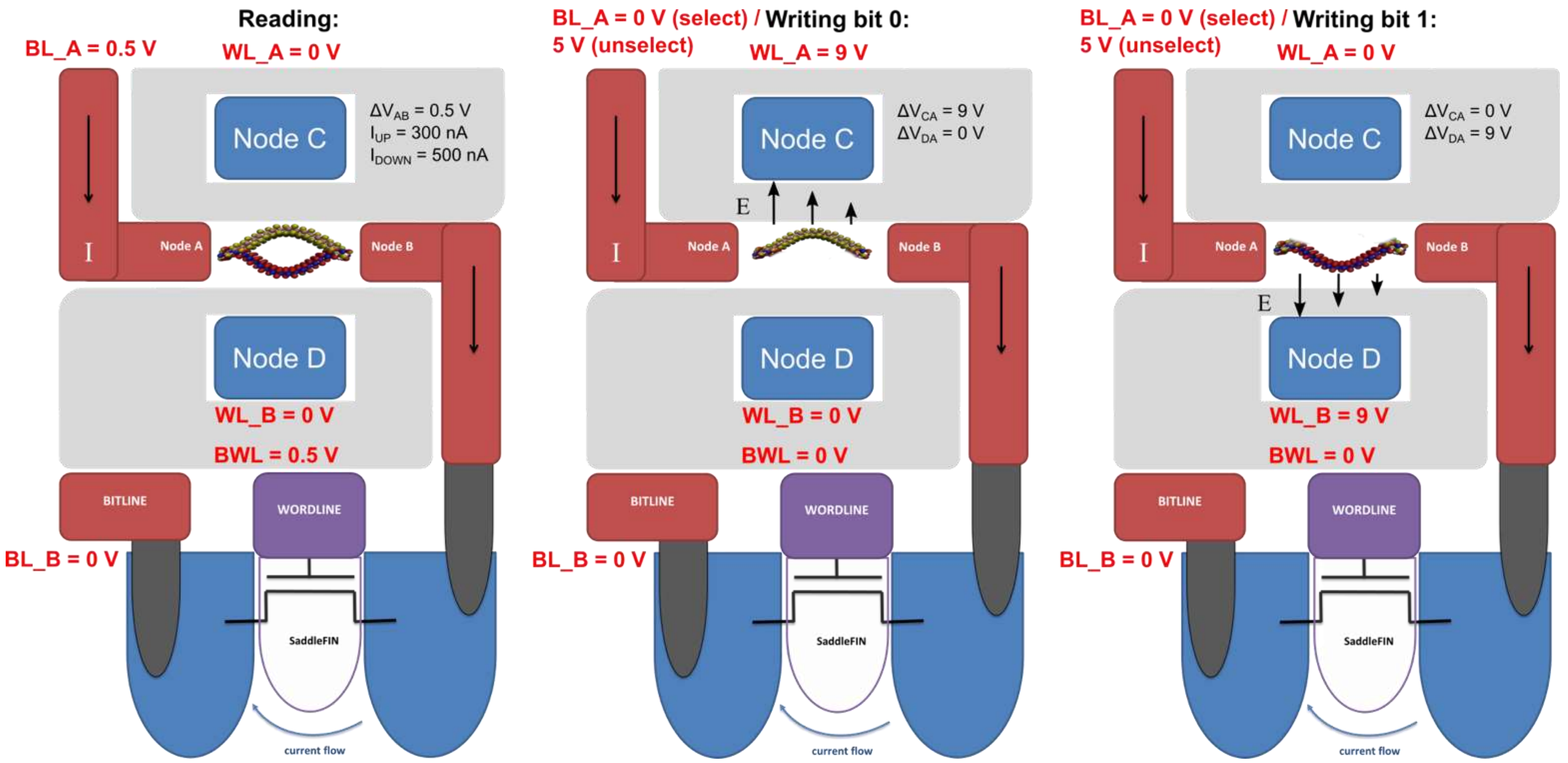






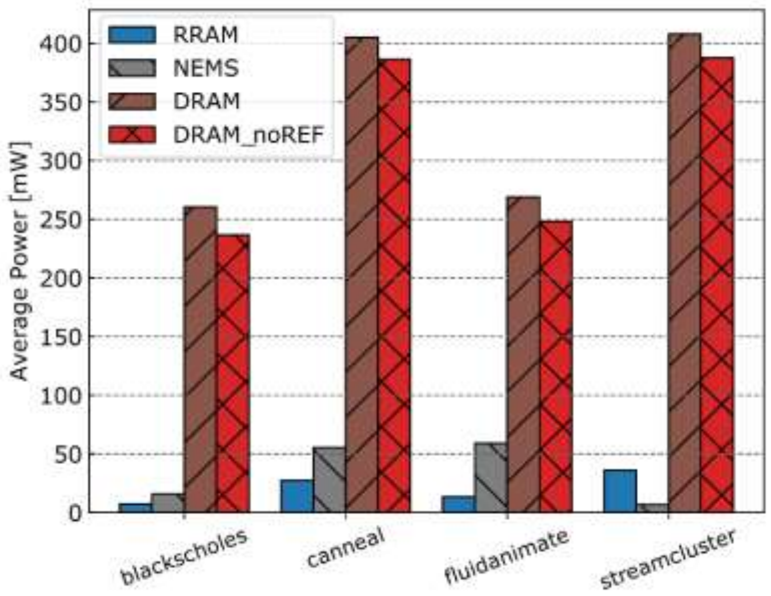
- Low energy consumption
  - Readout current ~100nA
  - Writing energy ~7eV

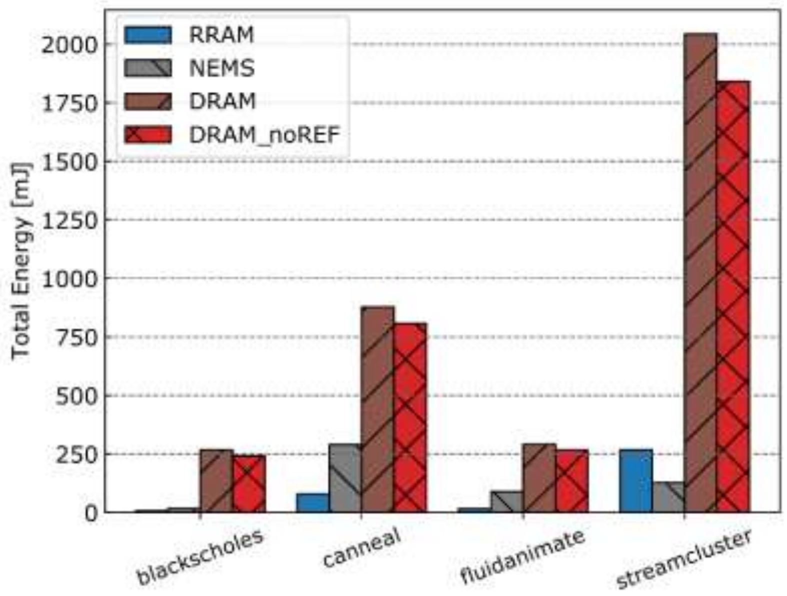
Piezoresistive memories based on two-dimensional nano-scale electromechanical systems [in preparation]


Reading:
BL_A = 0.5 V
WL_A = 0 V
ΔV_AB = 0.5 V
I_UP = 300 nA
I_DOWN = 500 nA
Node C
I
Node A
Node B
Node D
WL_B = 0 V
BWL = 0.5 V
BITLINE
WORDLINE
BL_B = 0 V
SaddleFIN
current flow
BL_A = 0 V (select) / Writing bit 0:
5 V (unselect)
WL_A = 9 V
ΔV_CA = 9 V
ΔV_DA = 0 V
Node C
E
I
Node A
Node B
Node D
WL_B = 0 V
BWL = 0 V
BITLINE
WORDLINE
BL_B = 0 V
SaddleFIN
current flow
BL_A = 0 V (select) / Writing bit 1:
5 V (unselect)
WL_A = 0 V
ΔV_CA = 0 V
ΔV_DA = 9 V
Node C
I
Node A
Node B
E
Node D
WL_B = 9 V
BWL = 0 V
BITLINE
WORDLINE
BL_B = 0 V
SaddleFIN
current flow

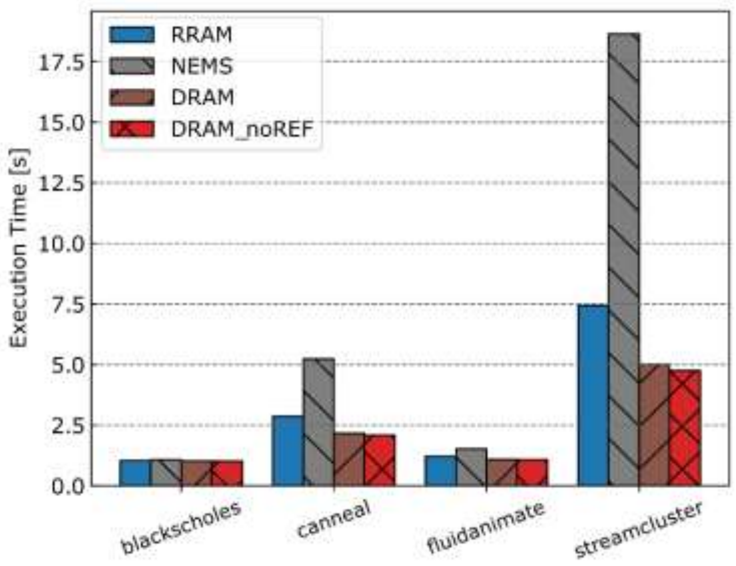
Simulation with ReRAM simulator

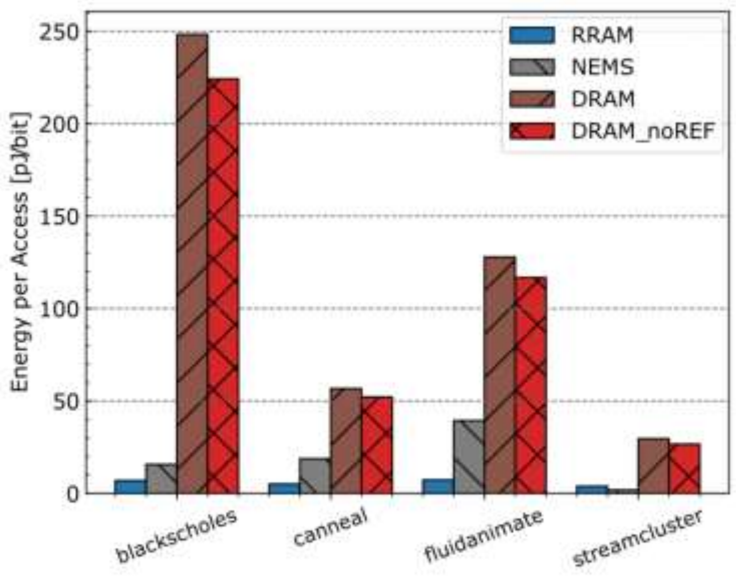
System Architecture	Specification
NEMS only system (NEMS)	1GB NEMS
ReRAM only system (RRAM)	2GB ReRAM
DRAM only system (DRAM)	2GB DDR4 DRAM (Four 4Gb x8 DRAM devices)
DRAM only system with refresh disabled (DRAM_noREF)	2GB DDR4 DRAM (Four 4Gb x8 DRAM devices)





Simulation with ReRAM simulator

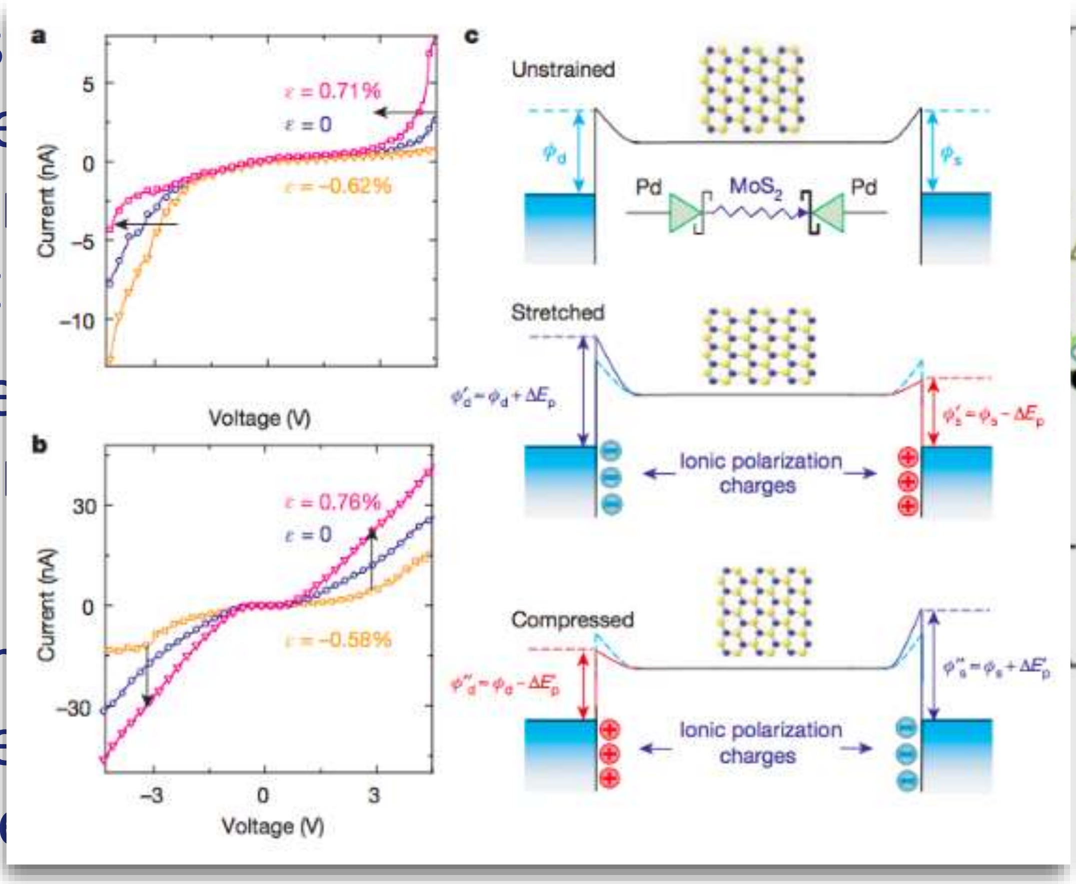


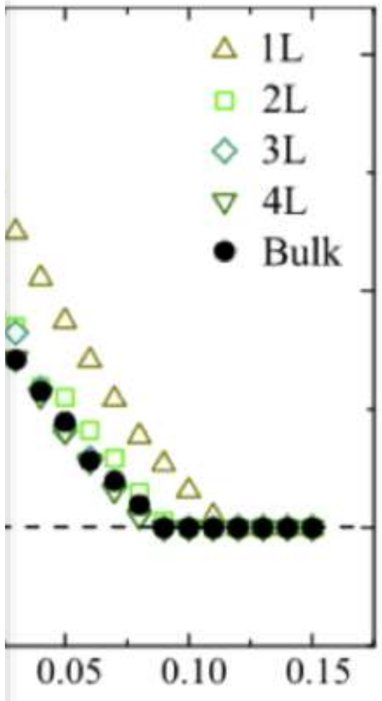


Memory Type	Energy per Access (pJ/bit) for streamcluster
RRAM	3.87
NEMS	1.84
DRAM	29.6
DRAM without Refresh	26.6

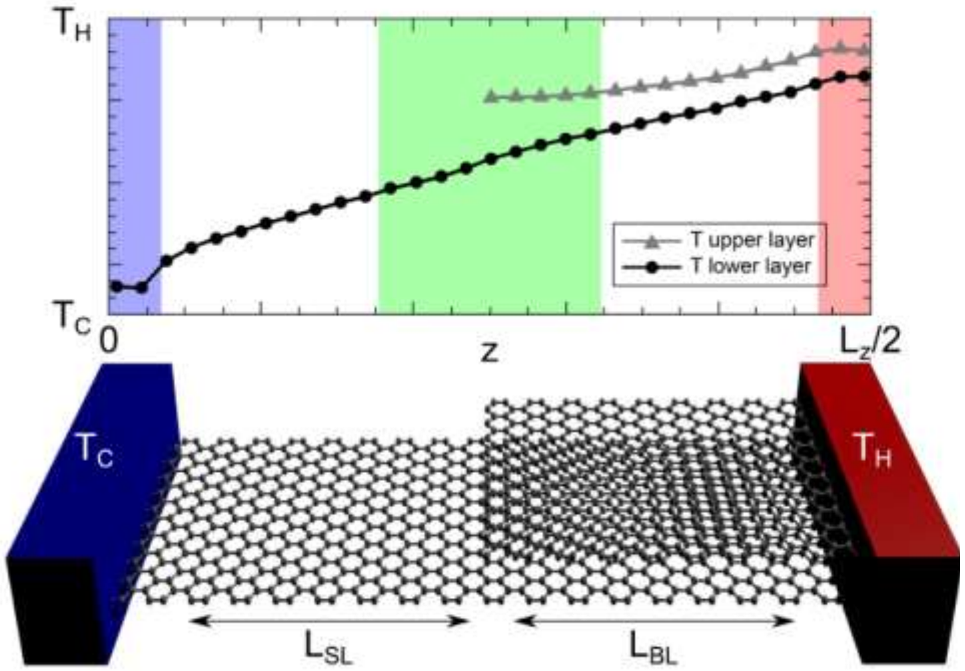
Tunable MoS2 strain sensor

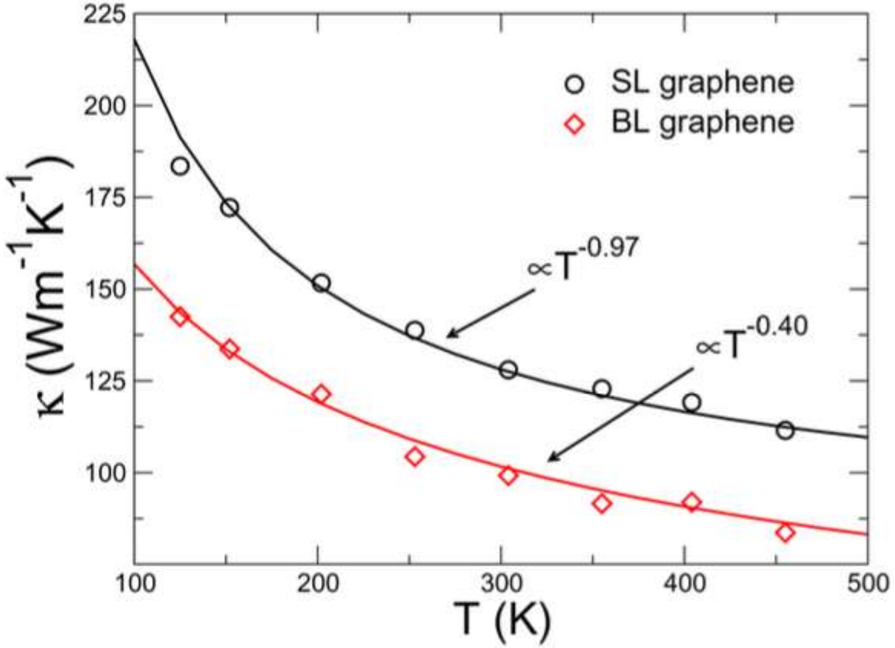
- Sensors
  direct re
  betwee
  propert
- Not dire
  betwee
  strain
- Solutio
  piezoele
  odd-lay





Heat rectifier





For bulk

$$\gamma_{max} \simeq \frac{(n_1 - n_2)}{4}\frac{\Delta T}{T_0}$$

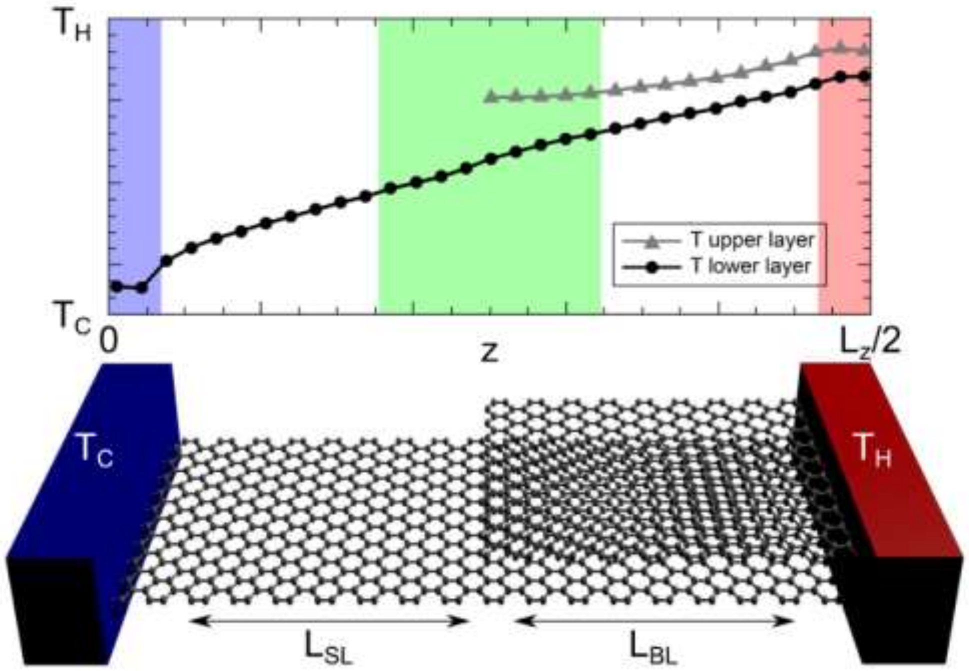
negative

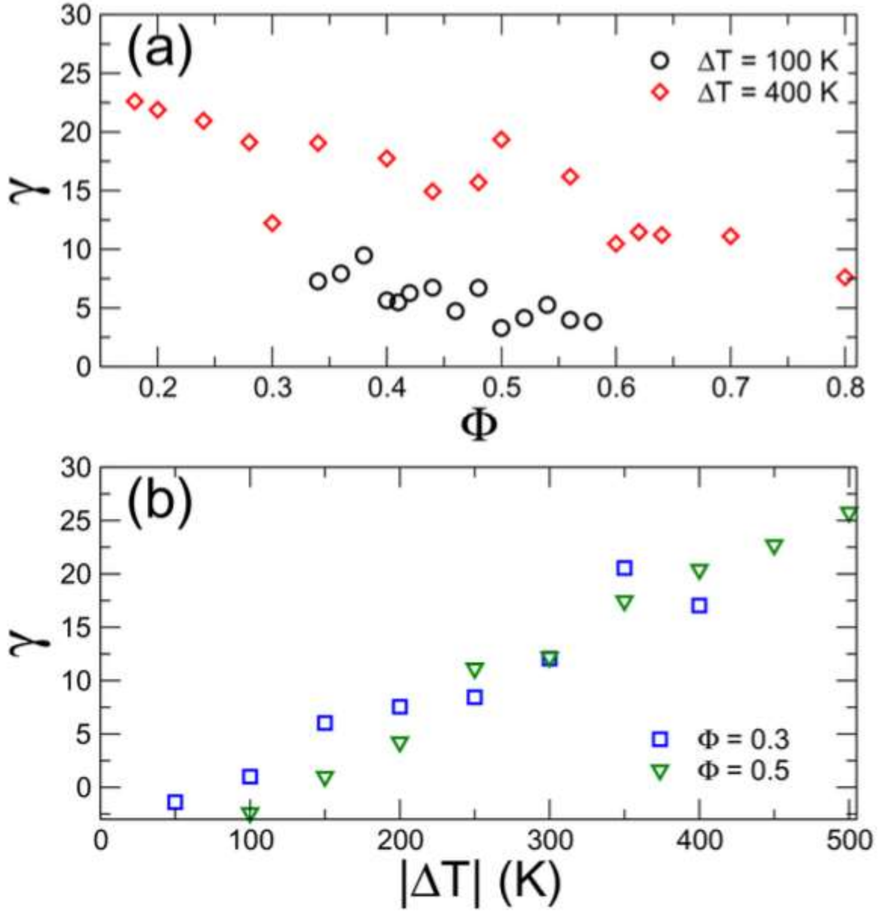
Expected γ_{max} ~5% for T=300 K and ΔT = 100K

γ_{max} ~20% for T=300 K and ΔT = 400K

Interface driven thermal rectification in a graphene–bilayer graphene junction from nonequilibrium molecular dynamics, M López-Suárez, I Neri, R Rurali, Journal of Applied Physics 124 (22), 224301 (2018)

Heat rectifier

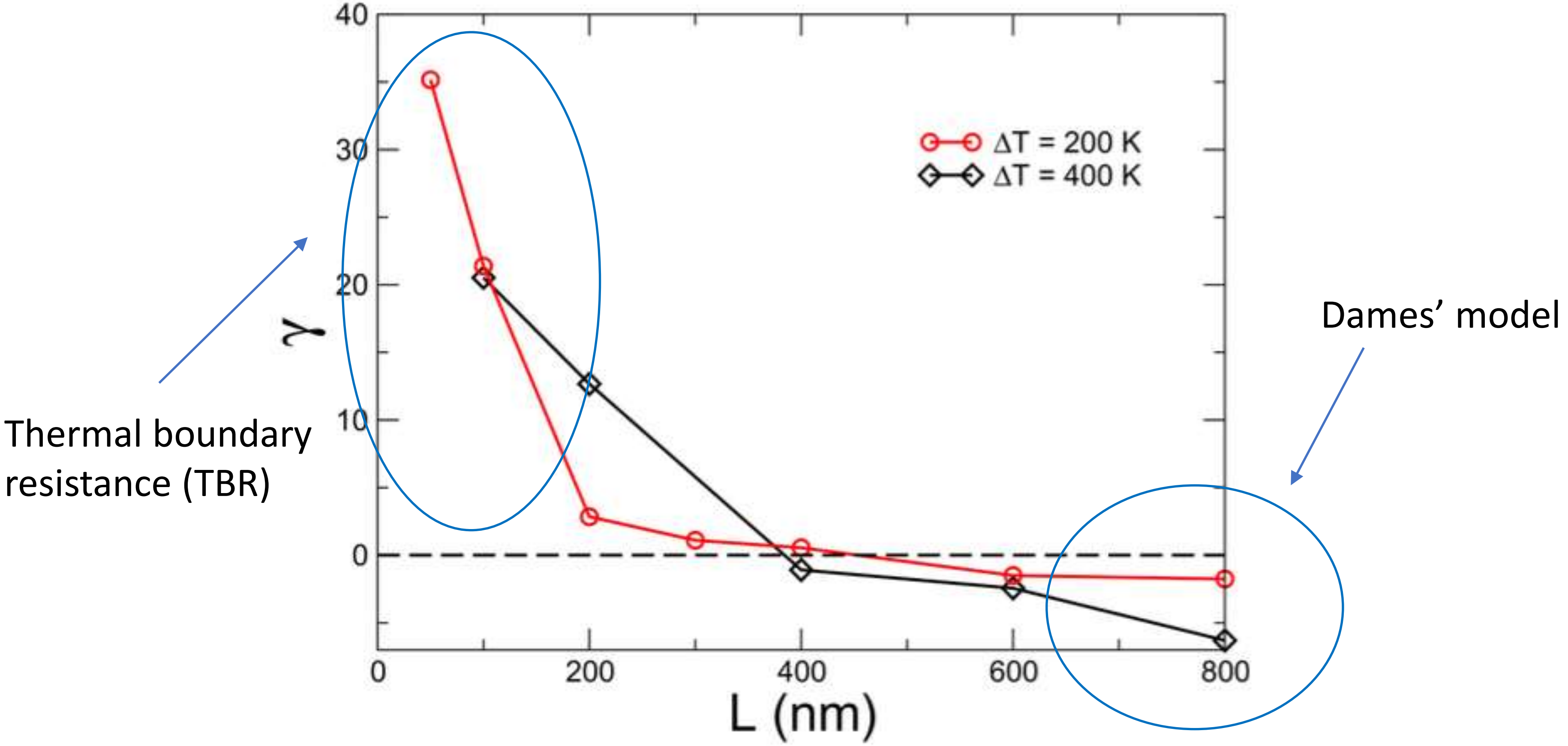




positive

Interface driven thermal rectification in a graphene–bilayer graphene junction from nonequilibrium molecular dynamics, M López-Suárez, I Neri, R Rurali, Journal of Applied Physics 124 (22), 224301 (2018)

Heat rectifier



Interface driven thermal rectification in a graphene–bilayer graphene junction from nonequilibrium molecular dynamics, M López-Suárez, I Neri, R Rurali, Journal of Applied Physics 124 (22), 224301 (2018)

Conclusions and Foresights

- Ambito/i del PTSR interessato/i: Ambito 5: **Nanoscienze**, Ambito 6: **Energy harvesting e ICT**

- Azioni collaborative di Ateneo coinvolte: Azione 4 (Digitale. Industria e Spazio), WP 4.2: Nanoscienze e nanotecnologie

Thank you for your attention