Ionic liquid gating of InAs nanowire-based FETs

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NW Thermoelectrics

Figure of merit: $$ZT = \frac{S^2\sigma}{k_l + k_e}T$$

NW Thermoelectrics

SUPPORTED NW devices: Seebeck & Power Factor

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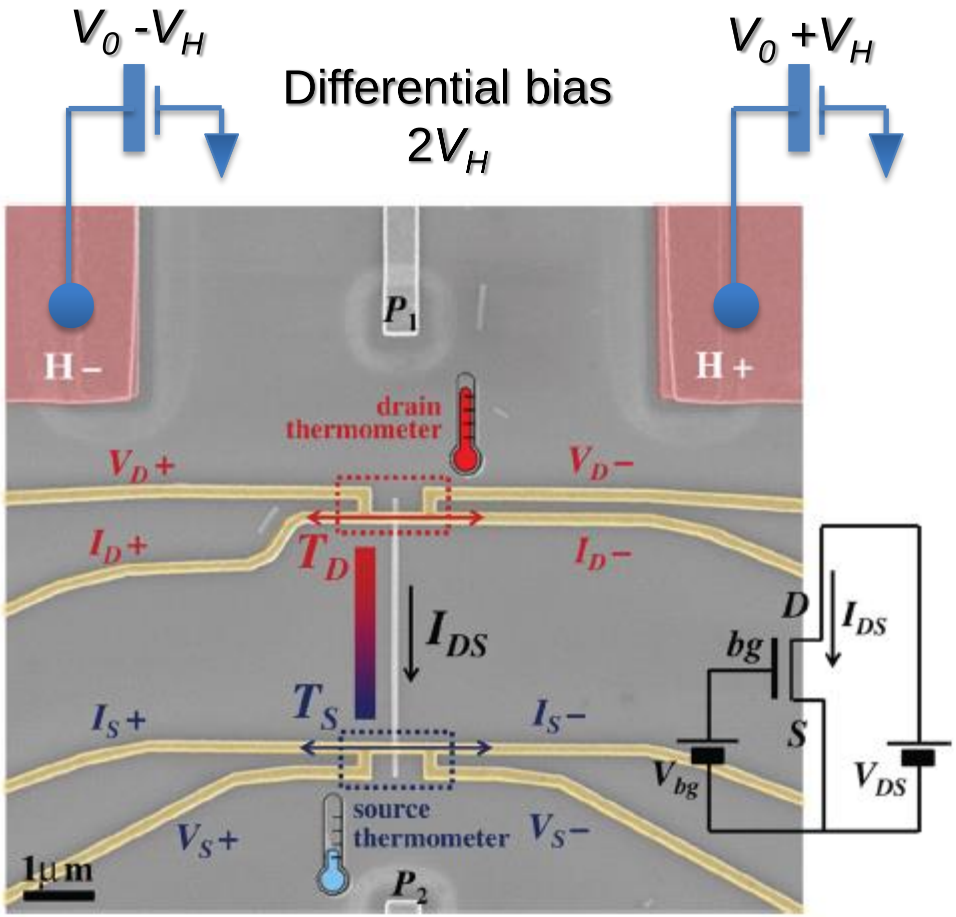

S.Roddaro, et al., Nano Research 2014

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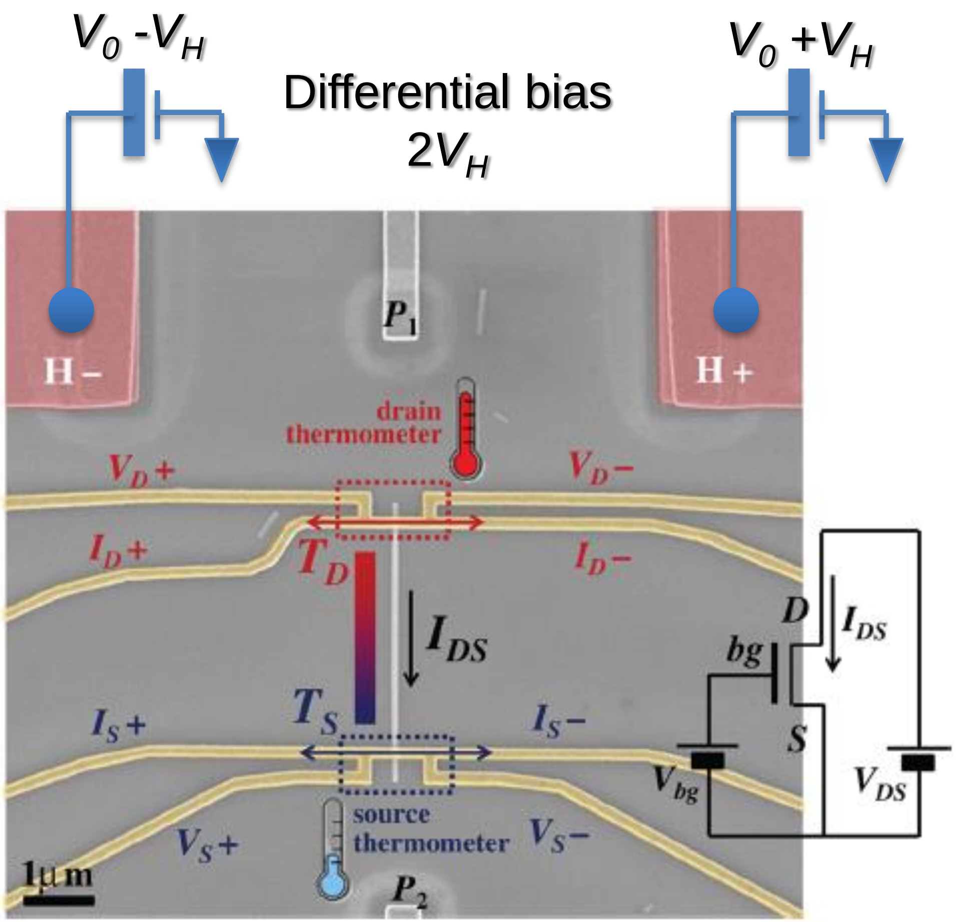

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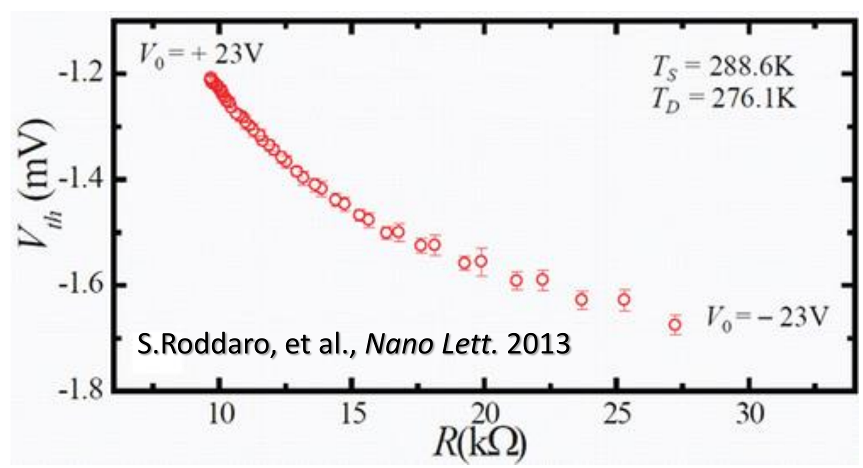

S.Roddaro, et al., *Nano Lett.* 2013

NW Thermoelectrics

SCUOLA NORMALE SUPERIORE PISA
CNR NANO PISA NEST

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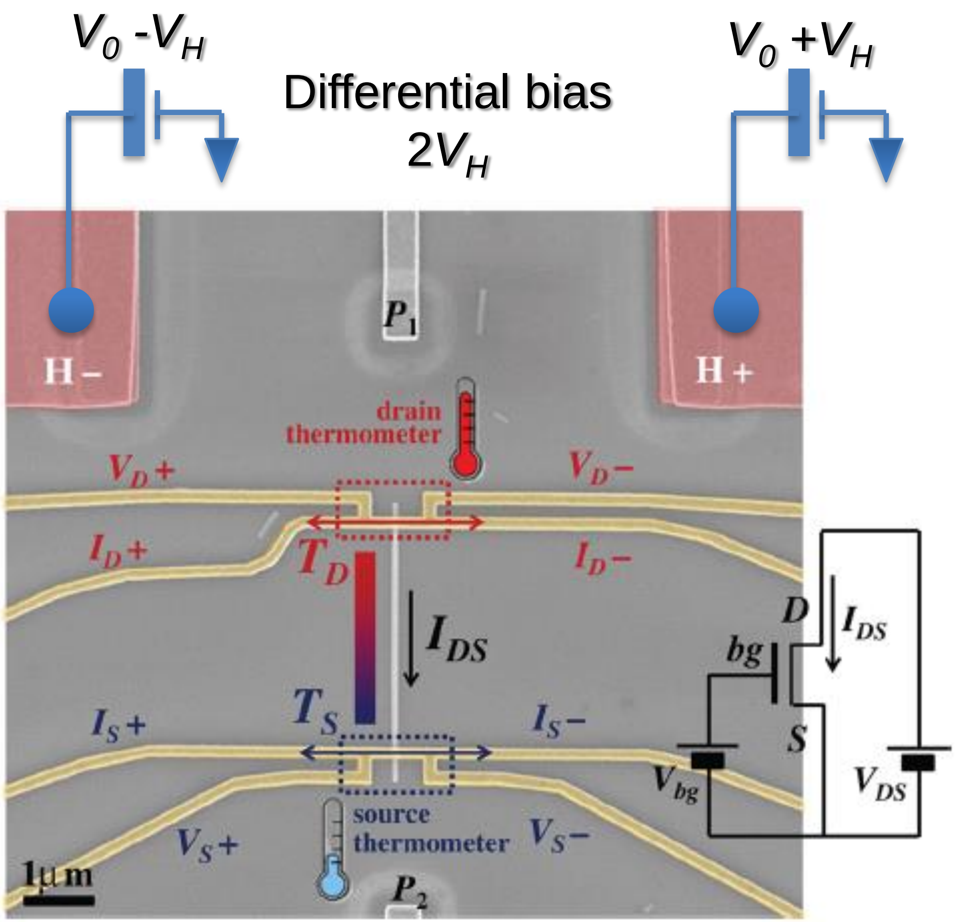
D.Prete et al, *in preparation* 2018
E. Tickonov, et al. *Sci. Rep.* 2016
E. Tickonov, et al. *SST* 2016



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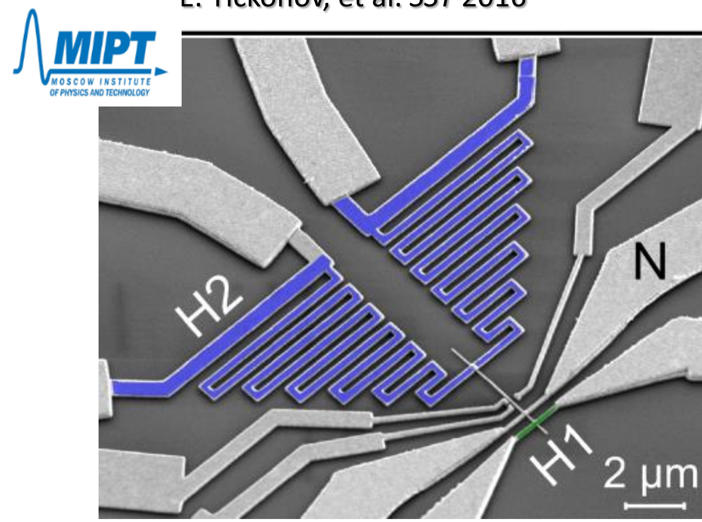

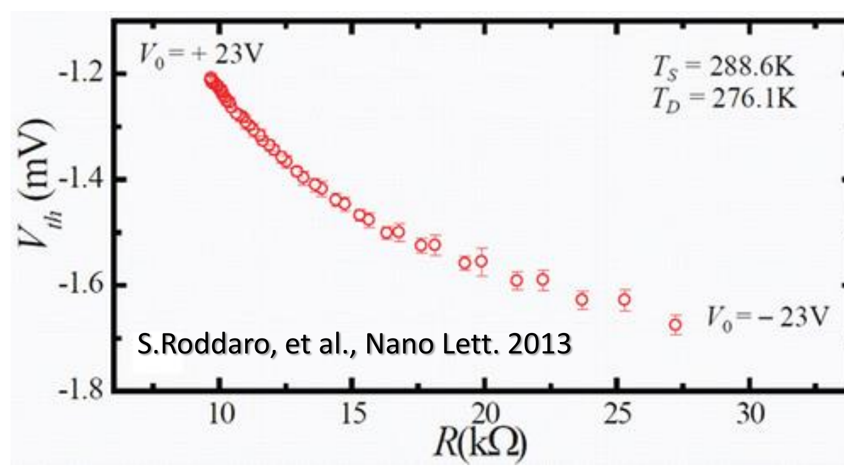

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NW Thermoelectrics

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SUSPENDED NW devices: thermal conductivity

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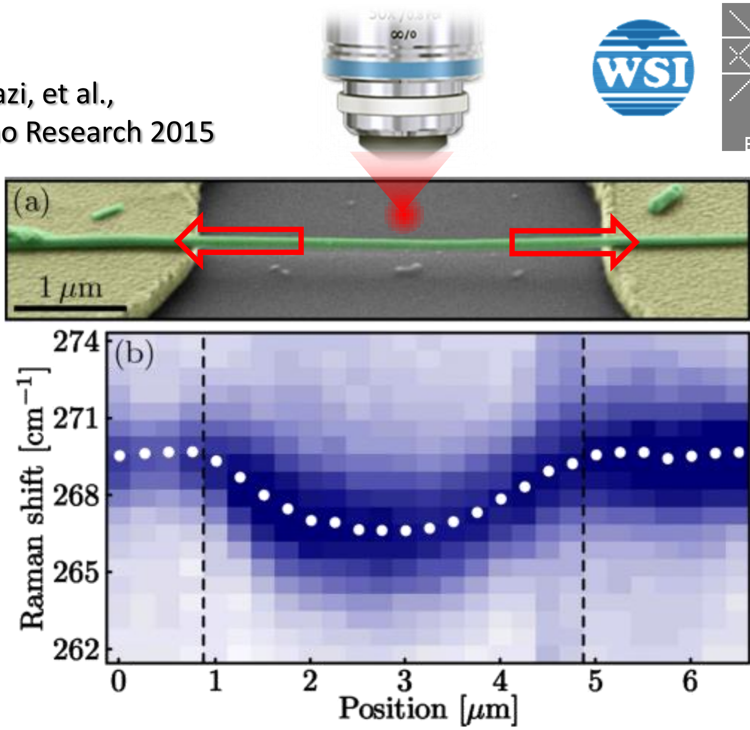
SUSPENDED NW devices: thermal conductivity

Optical approach

S. Yazi, et al.,
Nano Research 2015



NW Thermoelectrics

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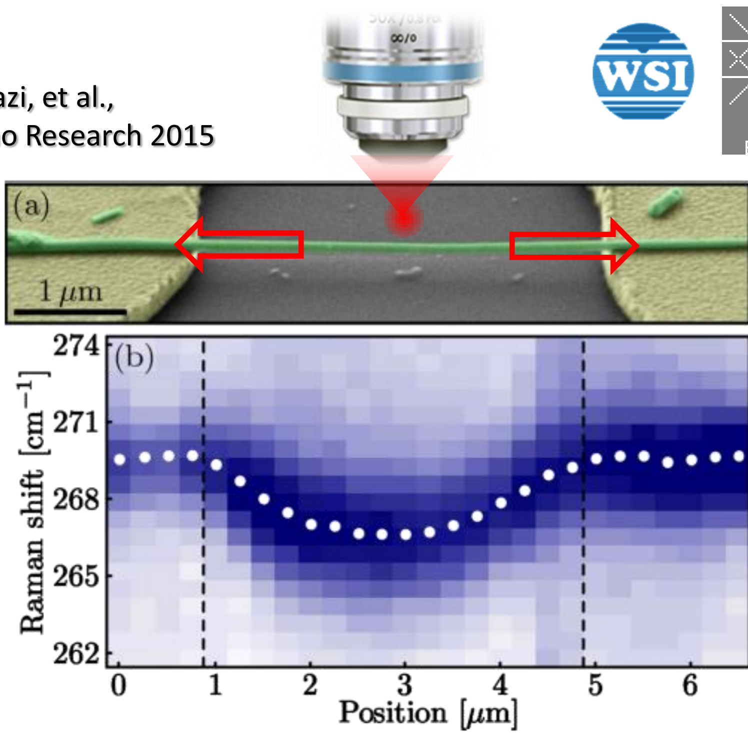
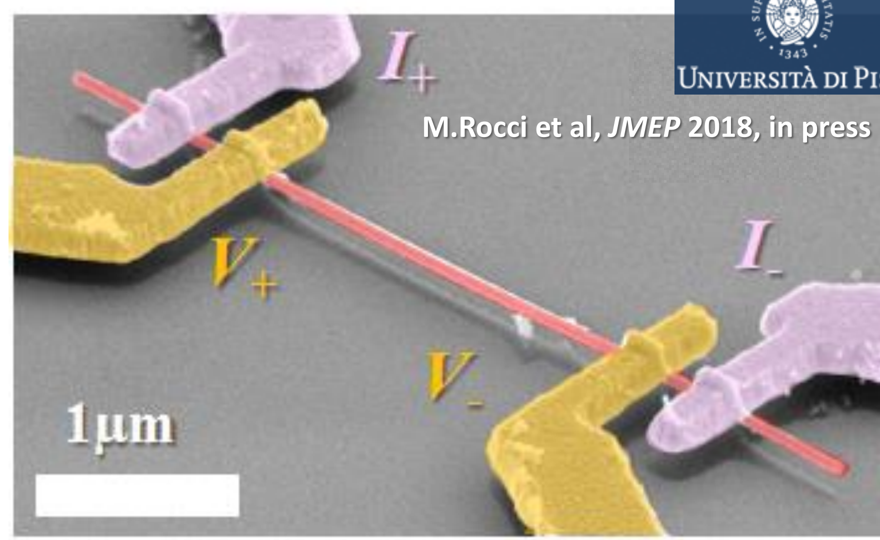


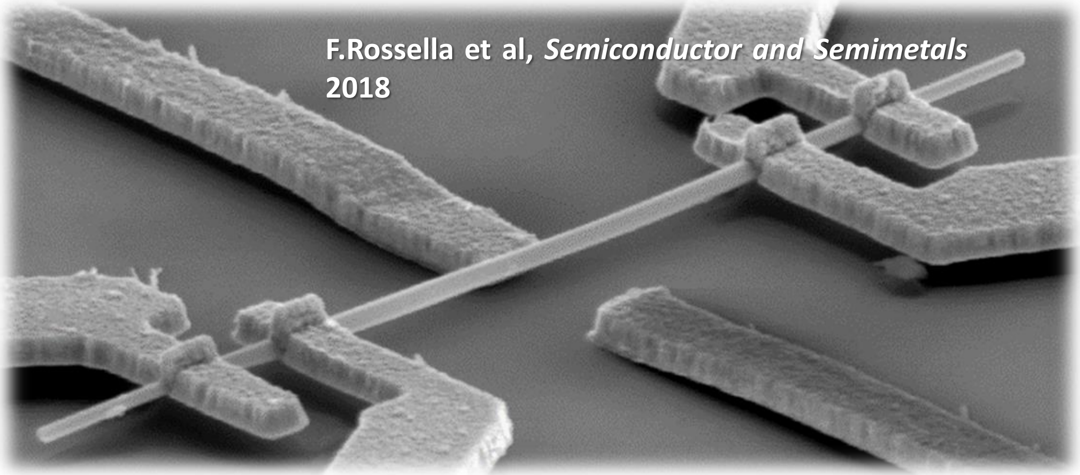
All-electrical method:
Current injection at freq ω
Voltage probing at freq 3ω



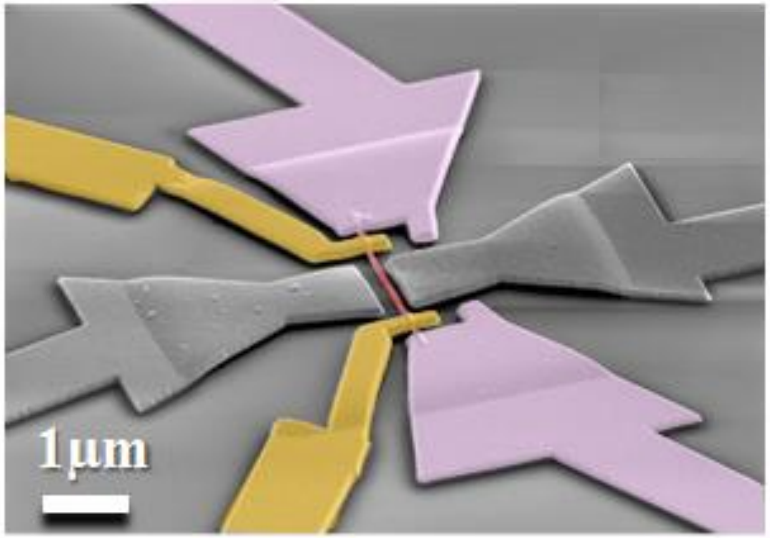
M.Rocci et al, *JMEP* 2018, in press

Suspended NW devices: strategies for gating?

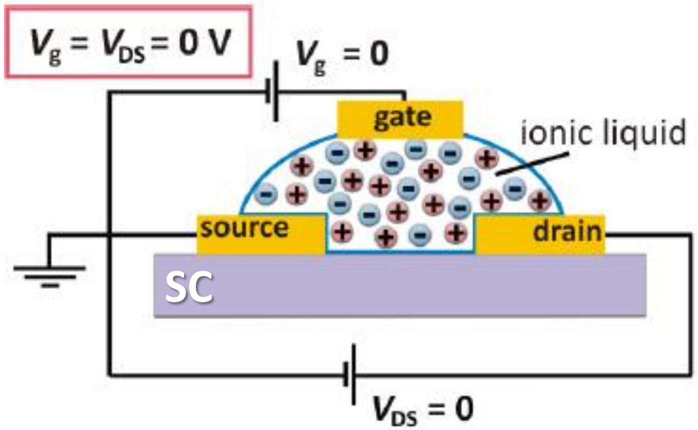
backgate, side gates ➡ poor modulation of σ at temperatures of interest



15% *R* modulation
within +/- 20V
(combining BG and SG)



Ionic liquid gating



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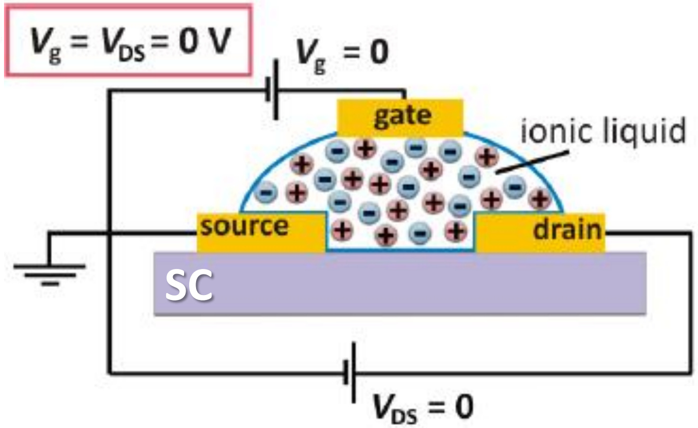

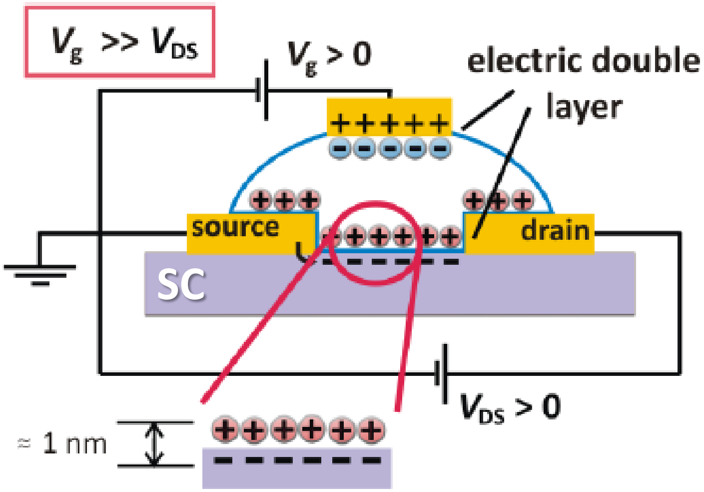

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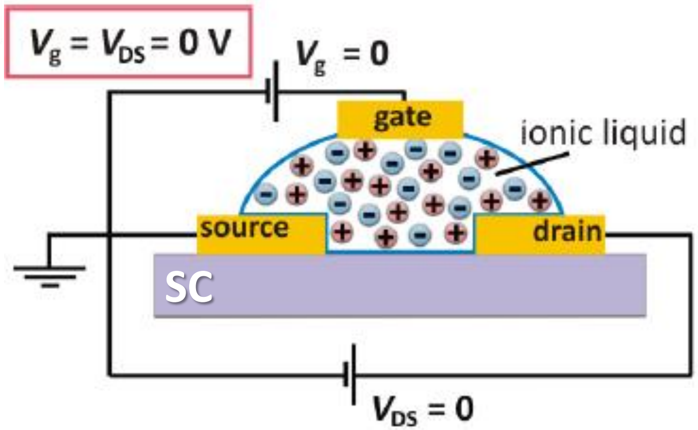
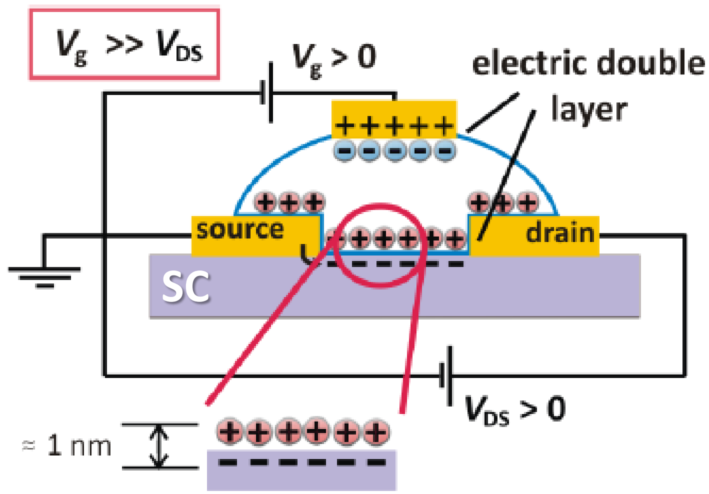
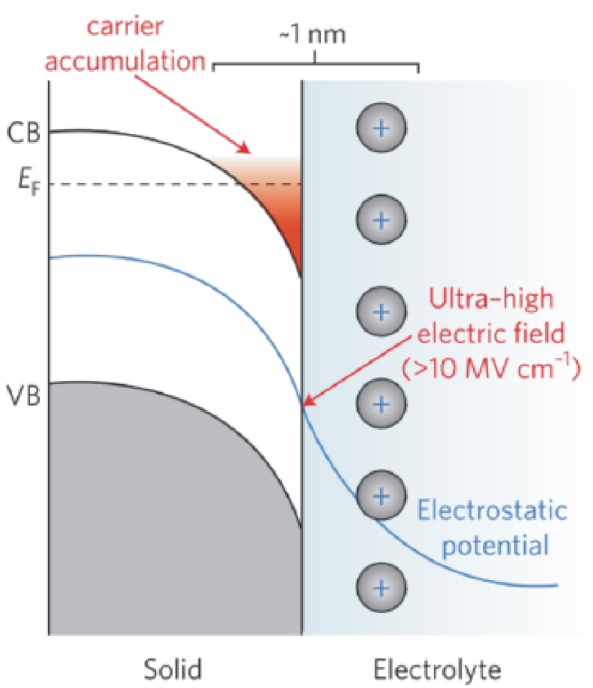
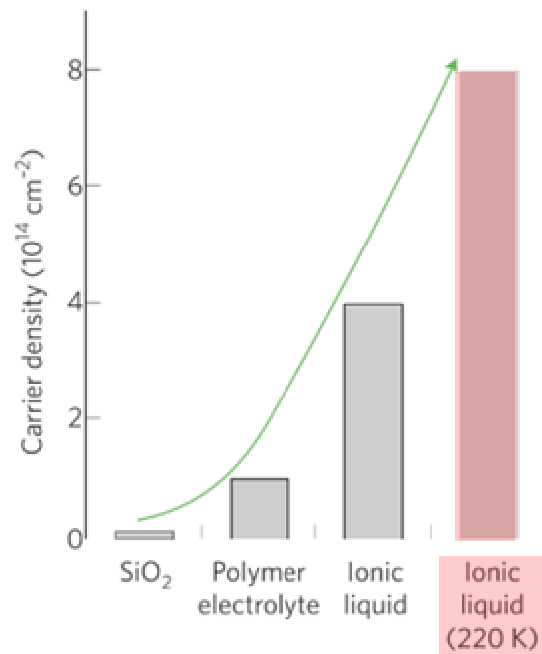


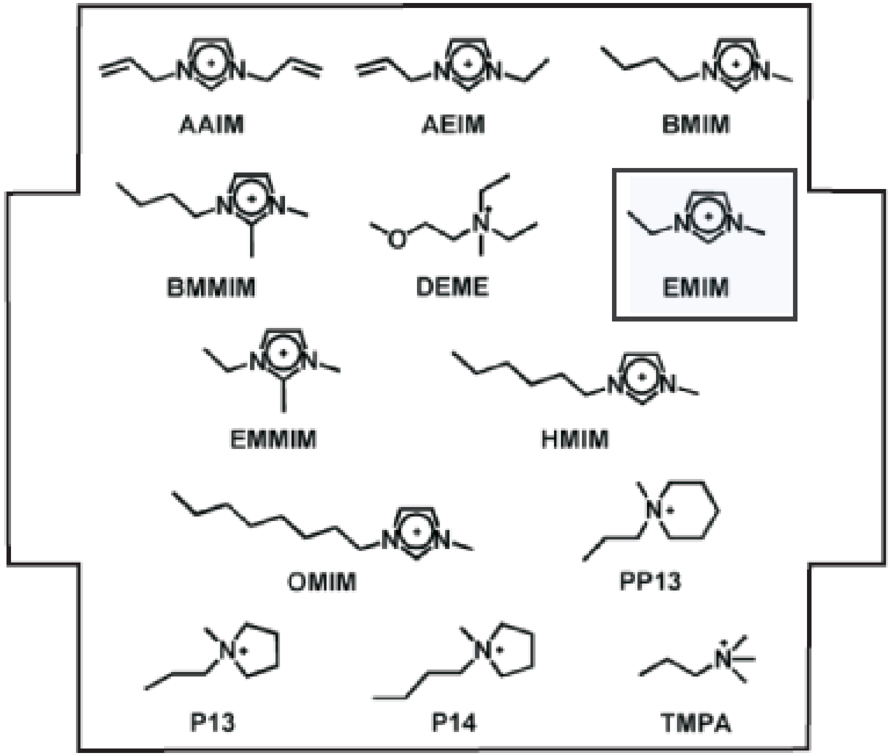




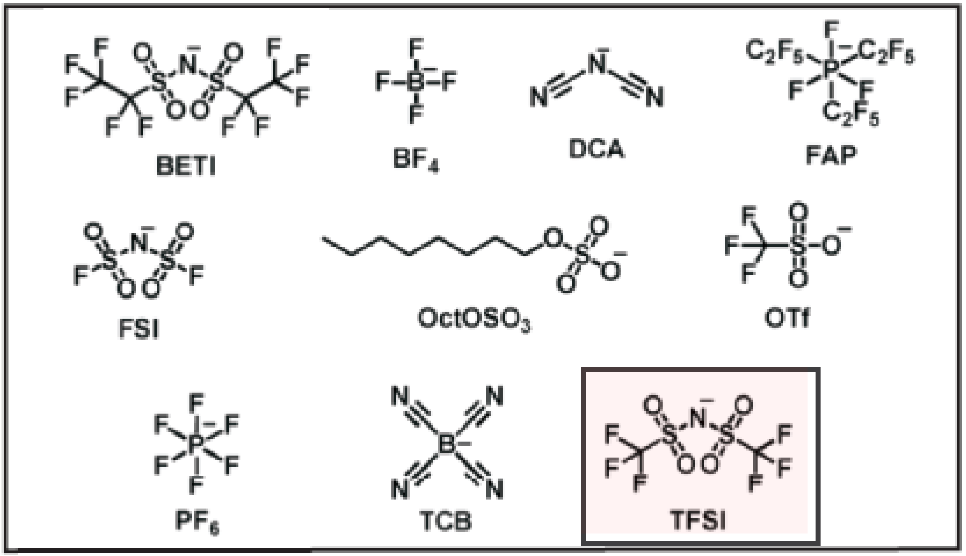


Zoology of ionic liquids

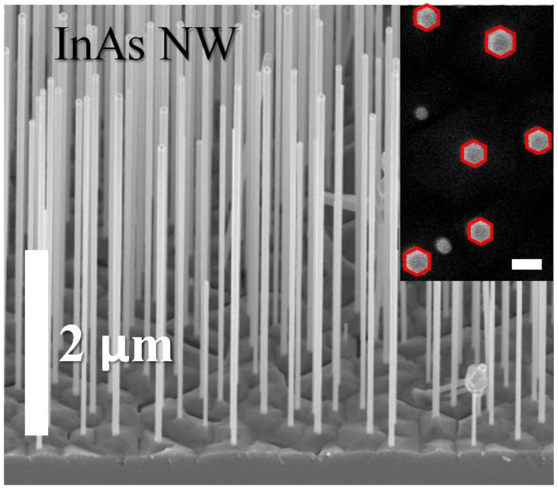
CATIONS



ANIONS



Ionic liquid gated InAs NW FET: realization



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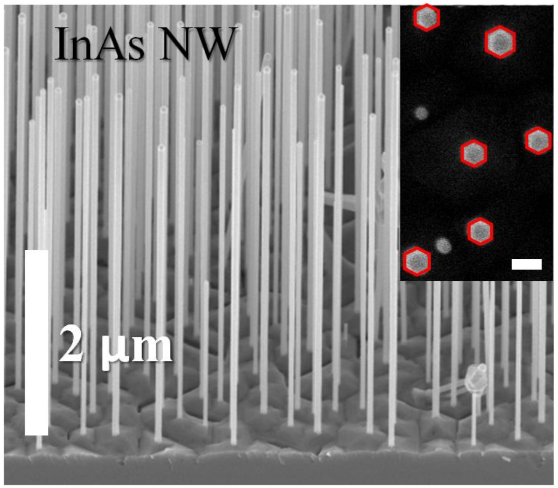

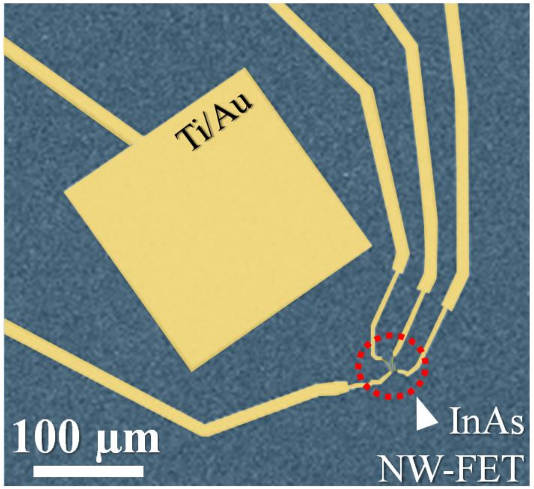

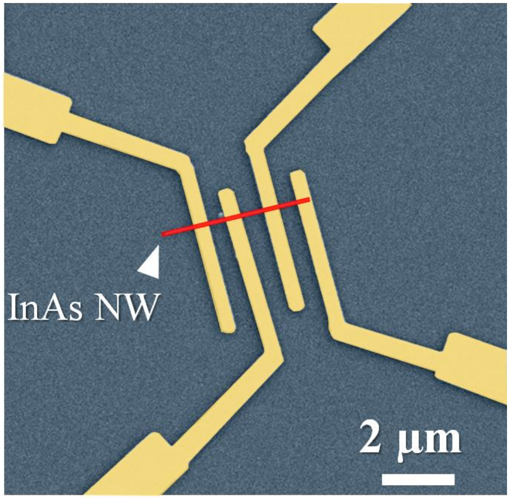

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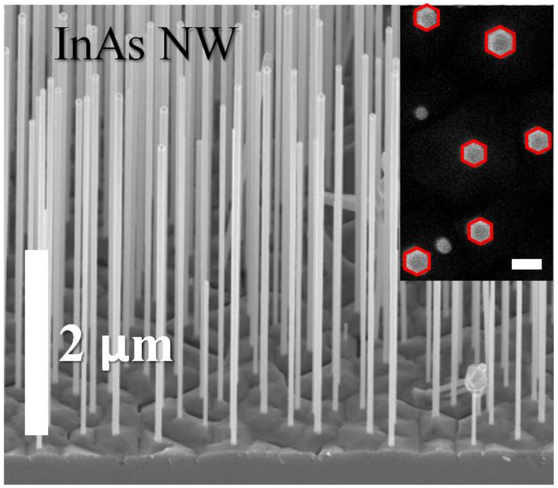

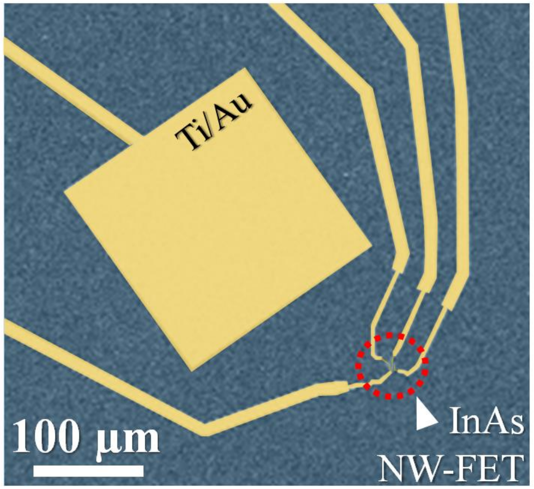

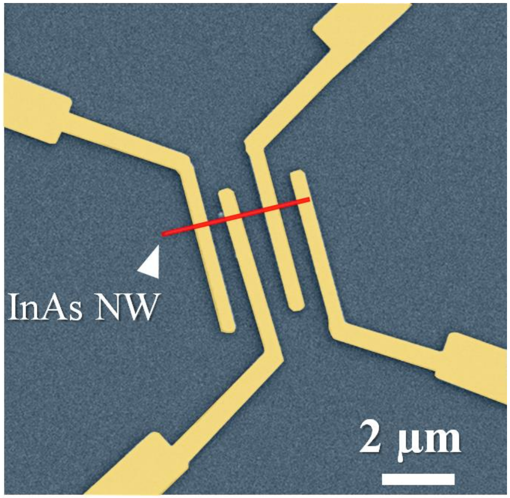

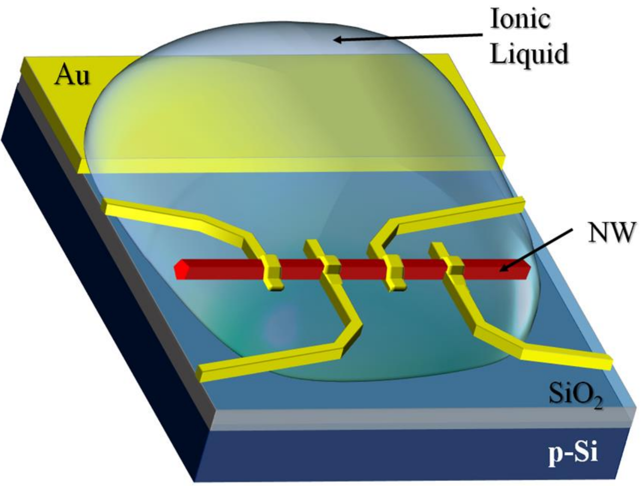

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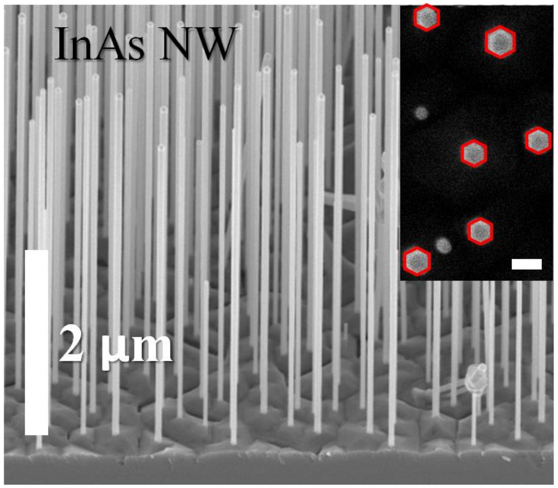

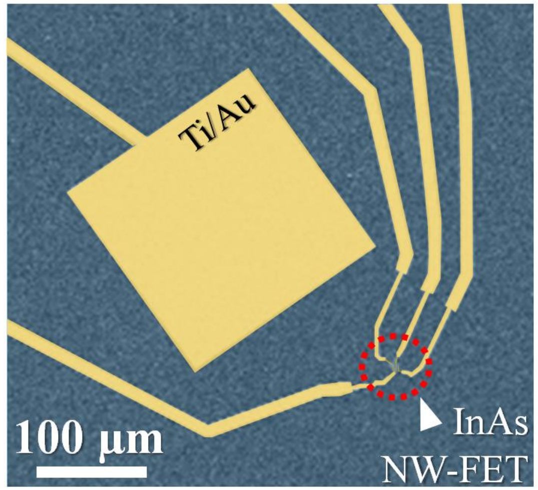

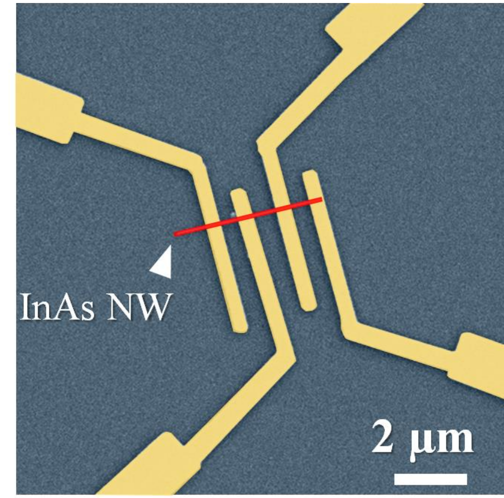

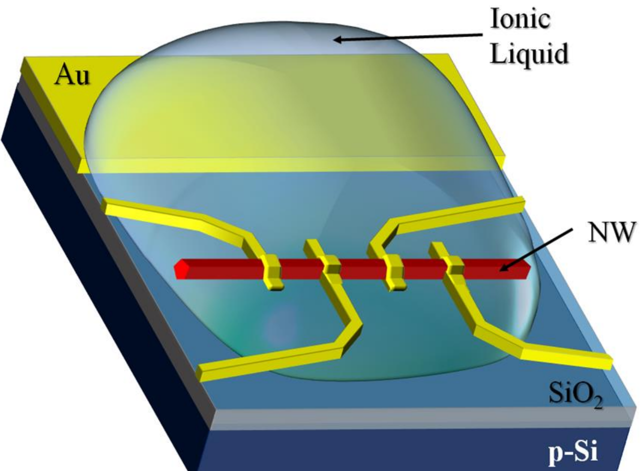

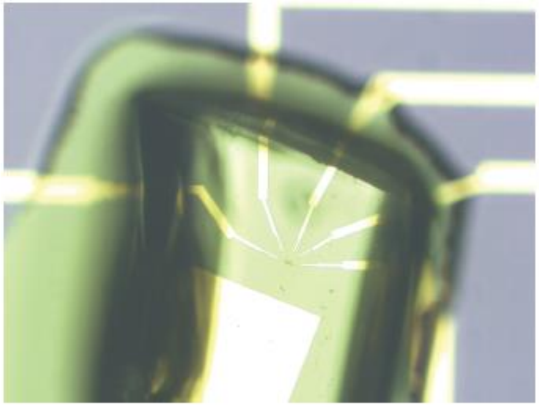

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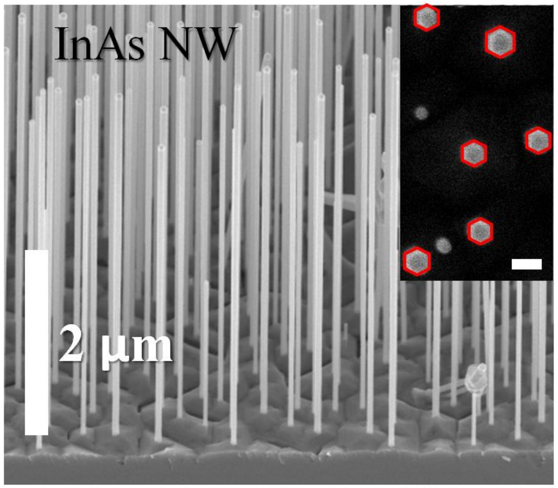
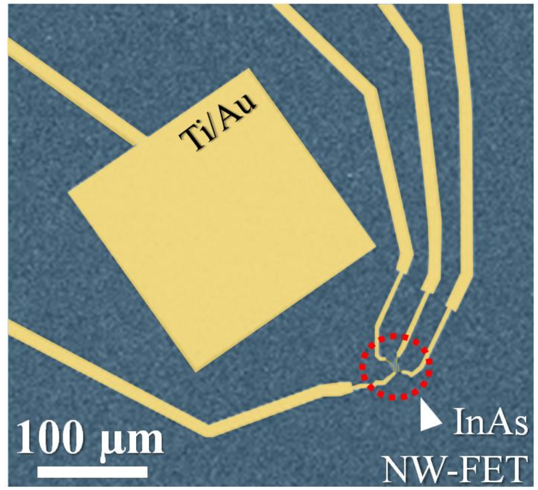
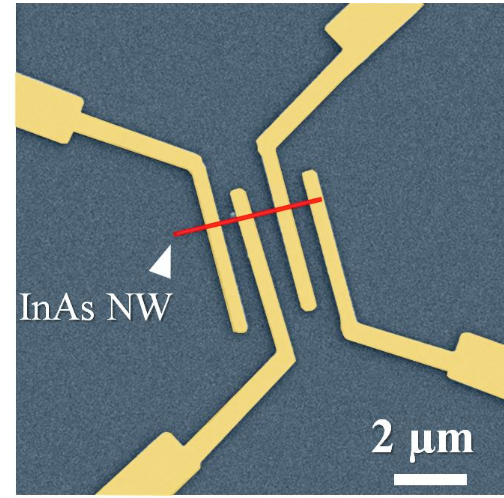
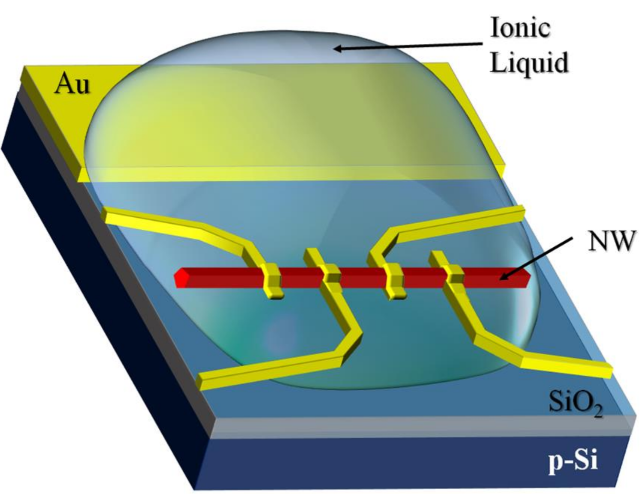
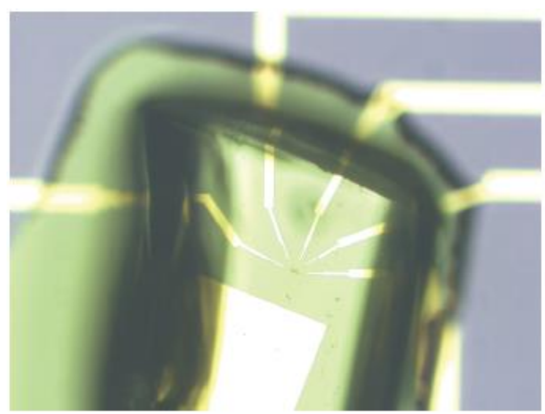
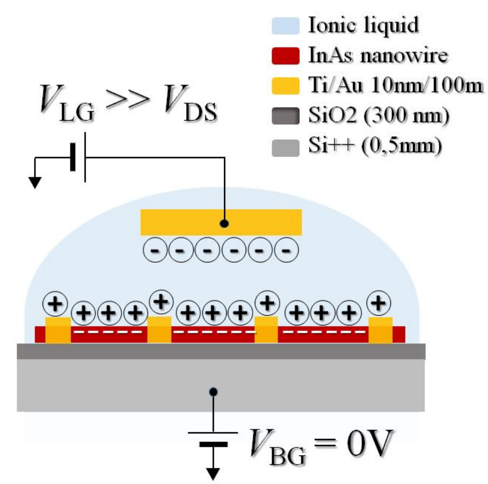




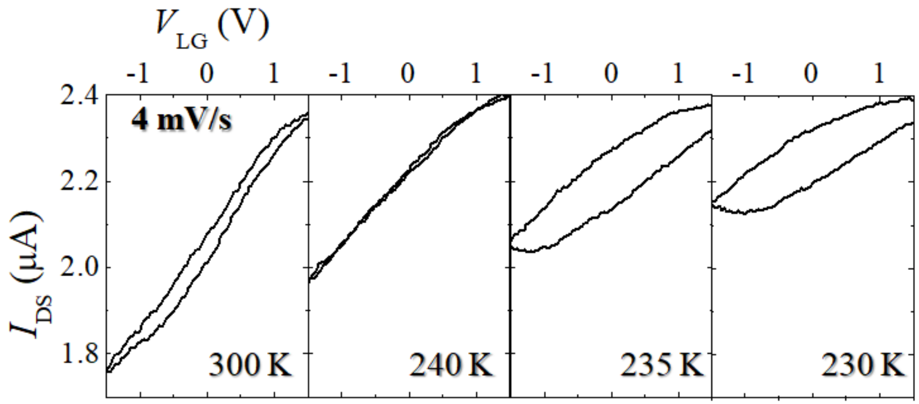








Hysteresis (getting rid of)



Parameter space:

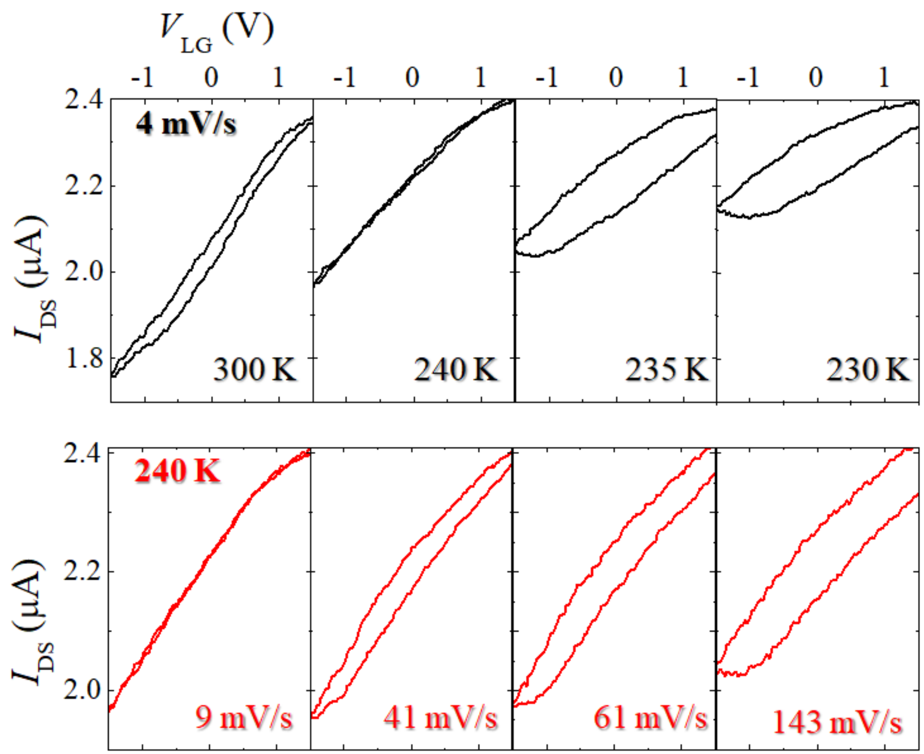
- Temperature

Hysteresis (getting rid of)

Parameter space:

- Temperature
- dV_{LG}/dt

(liquid gate voltage
Sweep rate)



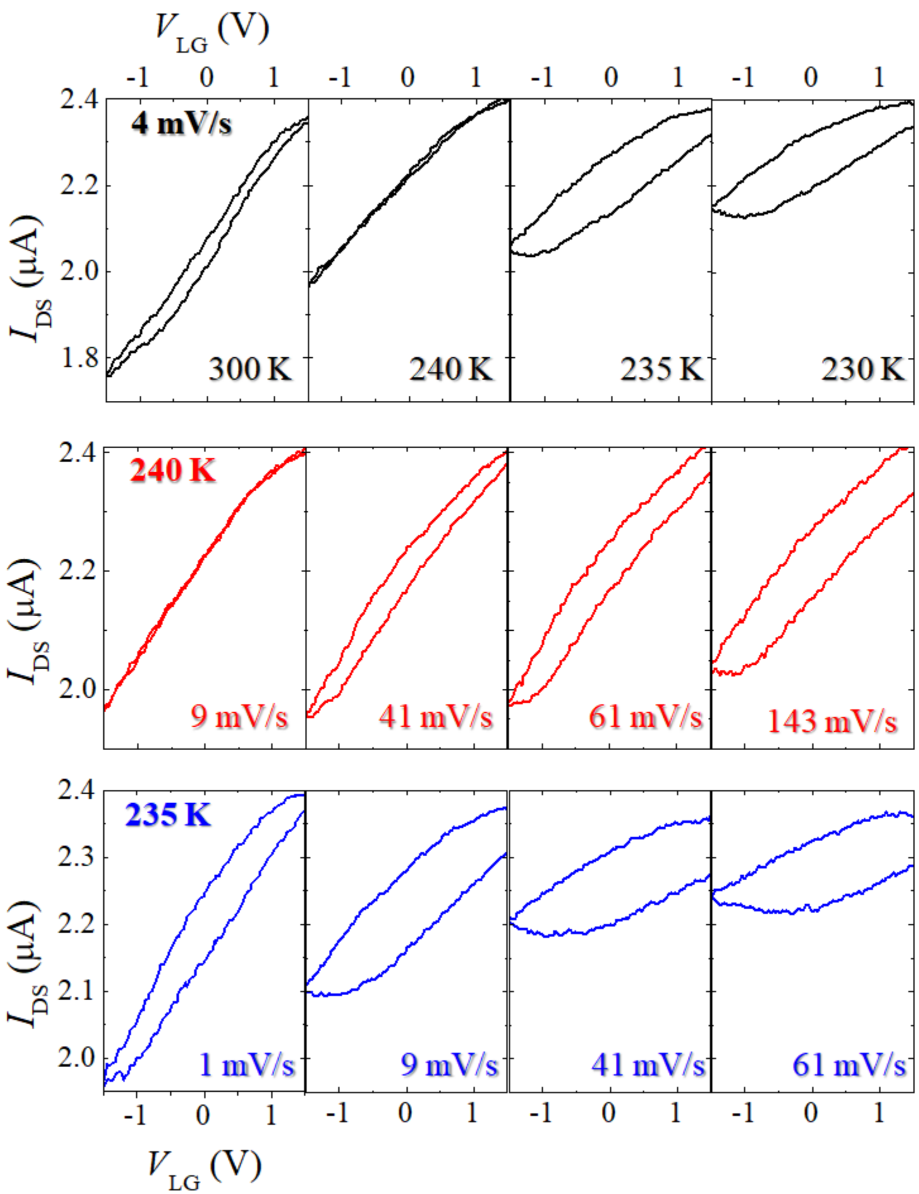
Hysteresis (getting rid of)

Parameter space:

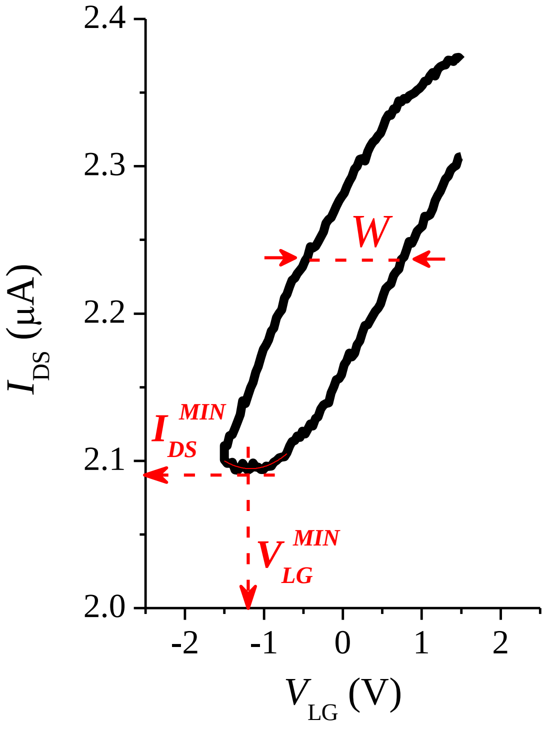
- Temperature
- dV_{LG}/dt

(liquid gate voltage Sweep rate)

T = 240 K
$dV_{LG}/dt < 10$ mV/s



Hysteresis (analysis)



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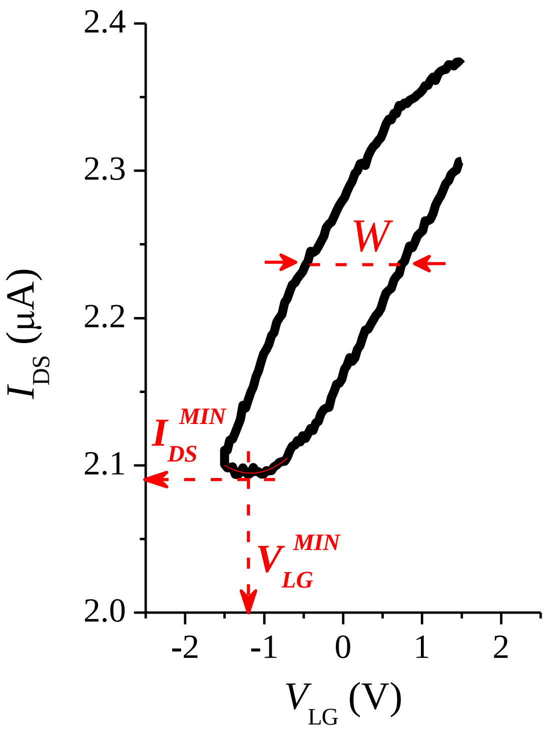

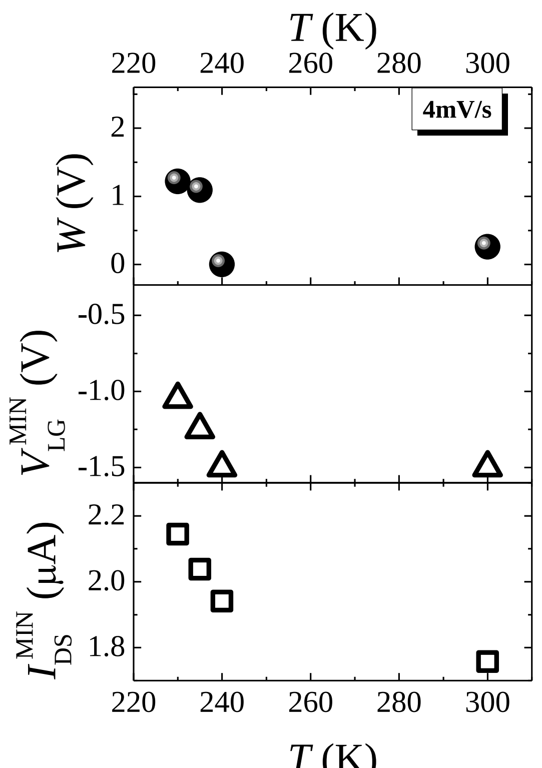

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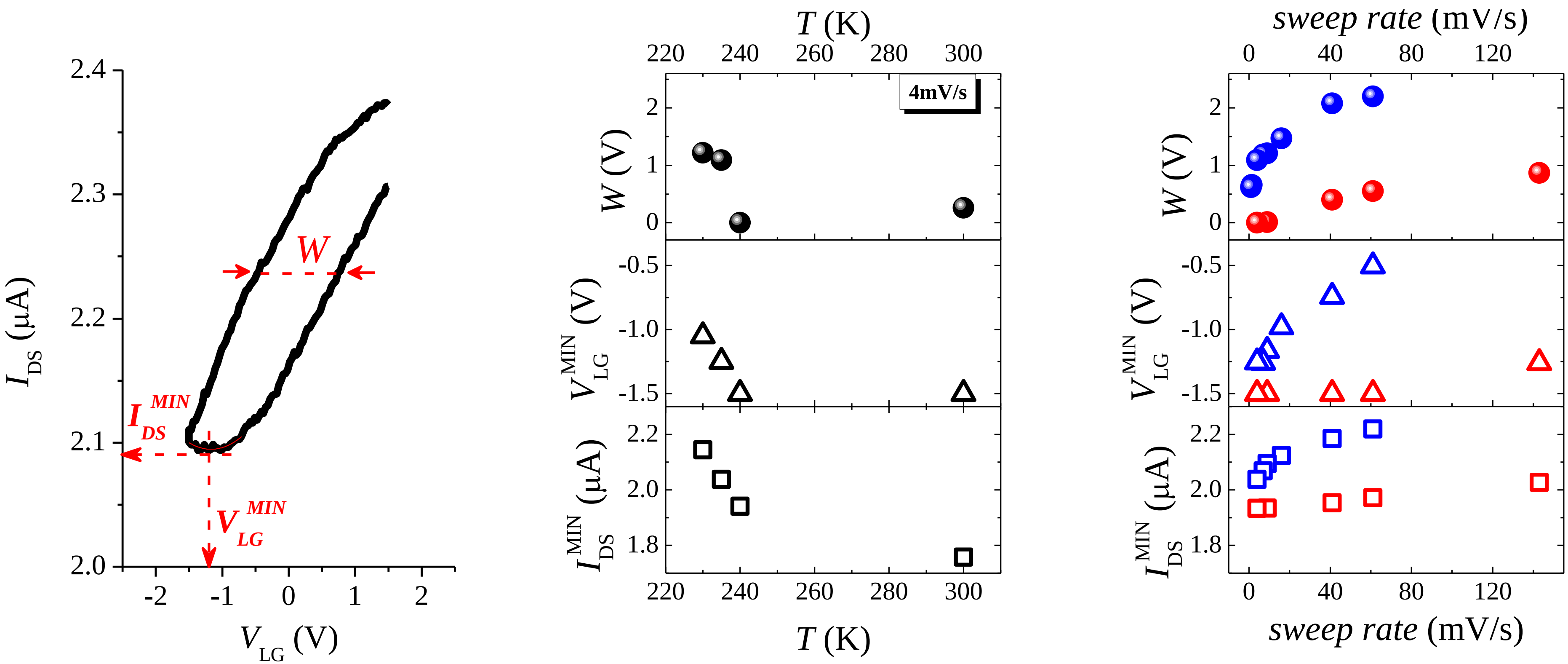
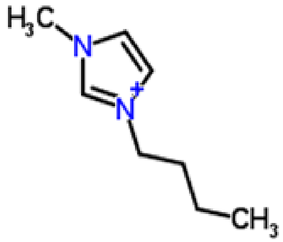
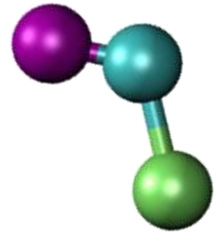
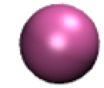
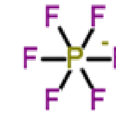


D. Prete et al., *AIP Proceeding* 2019
L. Bellucci, D. Prete et al., in preparation (2018)





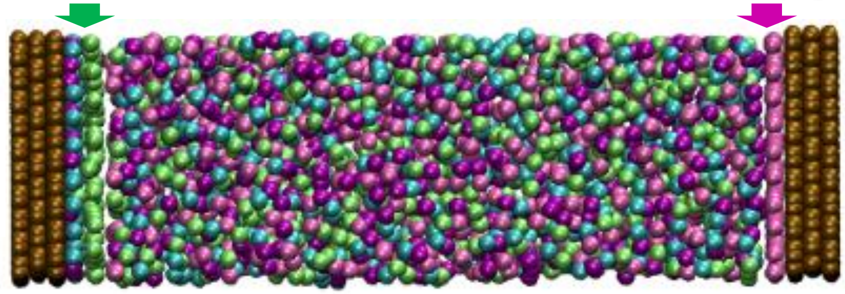




BMI+

PF6-

InAs



InAs

-q

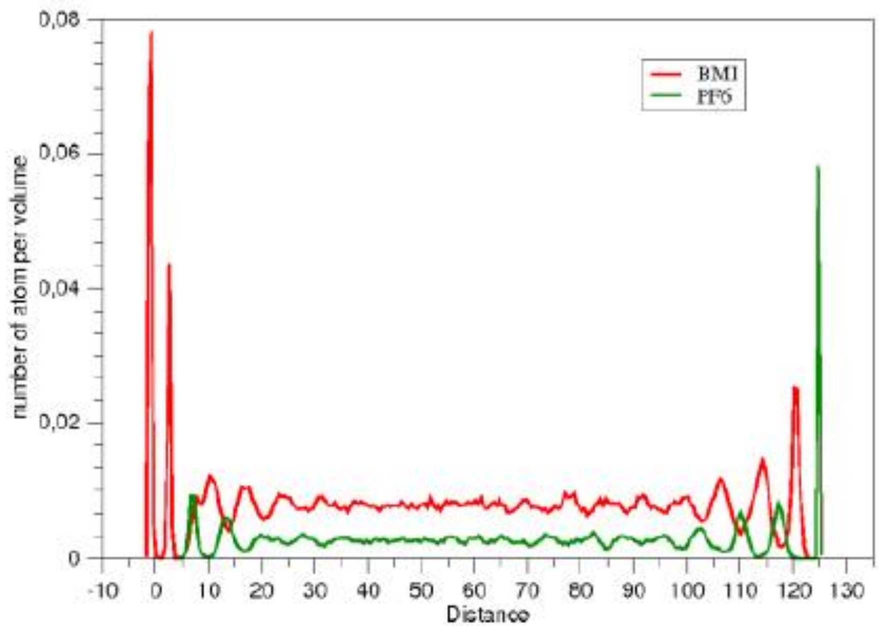
q

DFT

Hexafluorophosphate
(coarse grain)
+ layered electrodes
+ porosity

Molecular dynamics

diffusion coefficients



(Angstrom)

V. Tozzini

L. Bellucci

Many additional problems in simulations!

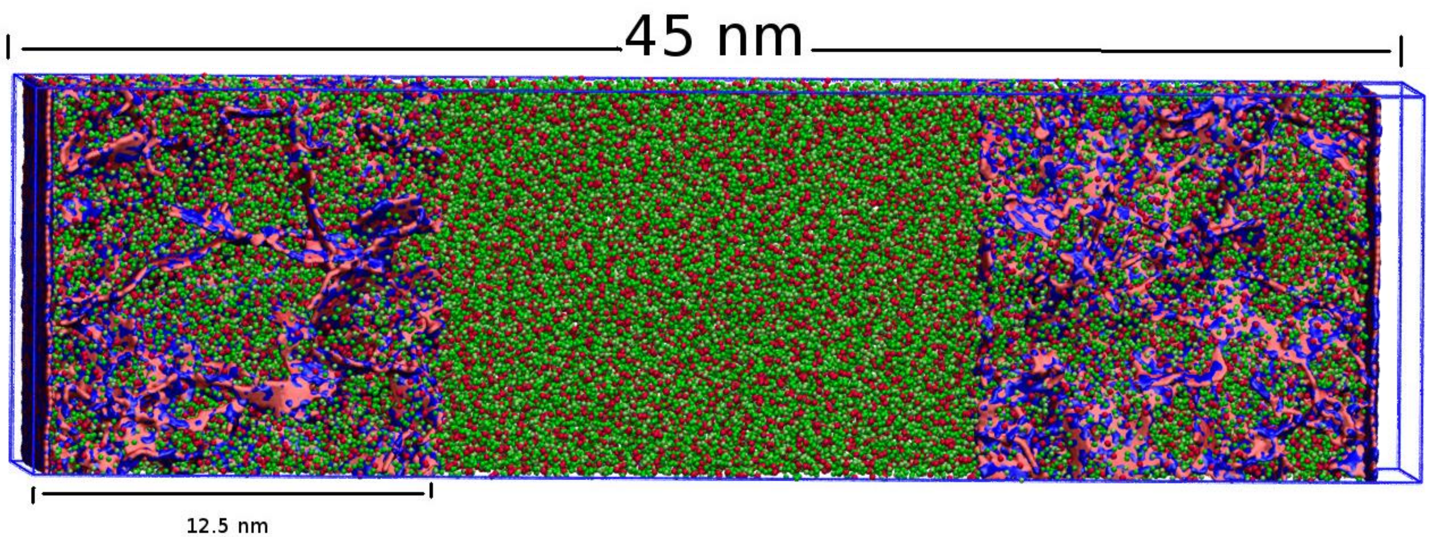
- ✓ realistic structure of the porosity (→ sponge builder)
- ✓ Size of the system
- ✓ The model of electrode must be polarizable

Tests to

- ✓ validate the model
- ✓ optimize the simulation parameters

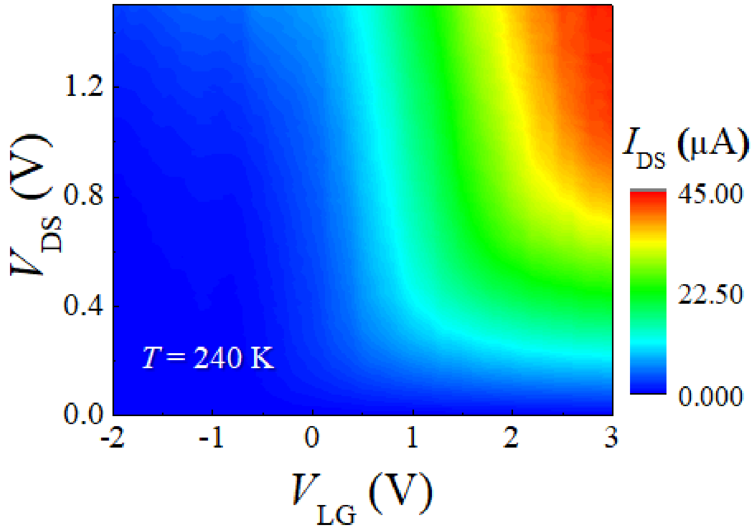
Test with mechanically induced diffusion: anion has a larger diffusivity than the cation

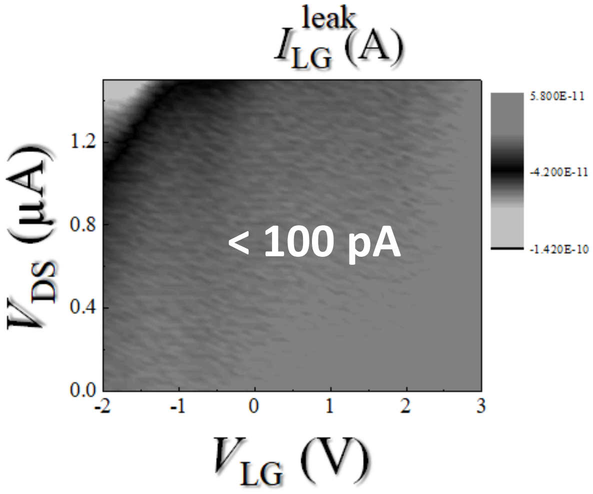
Test with nanoporous charged polarizable electrodes



Ionic liquid gated InAs NW FET: operation

Full pinch-off





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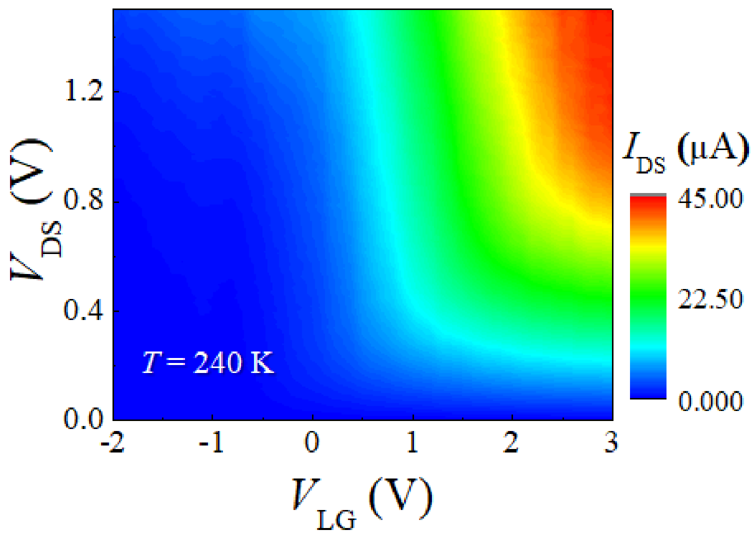
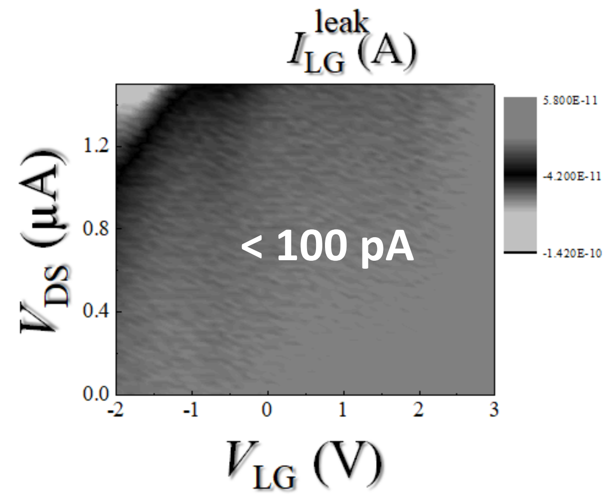
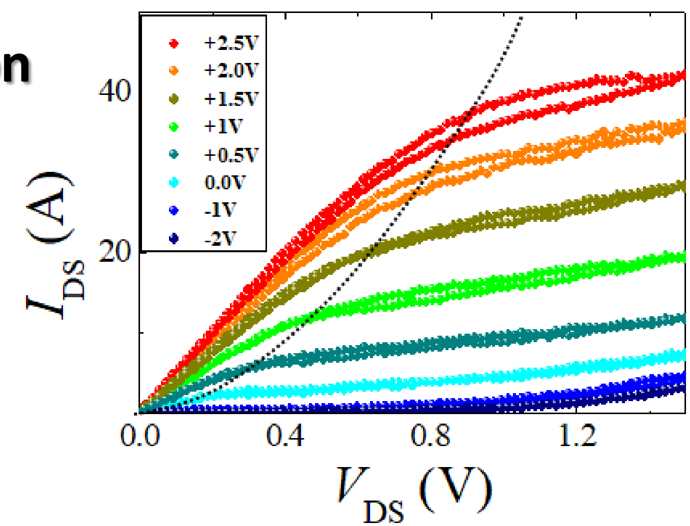
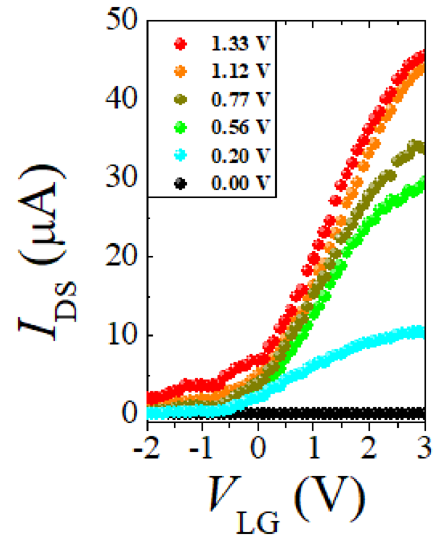




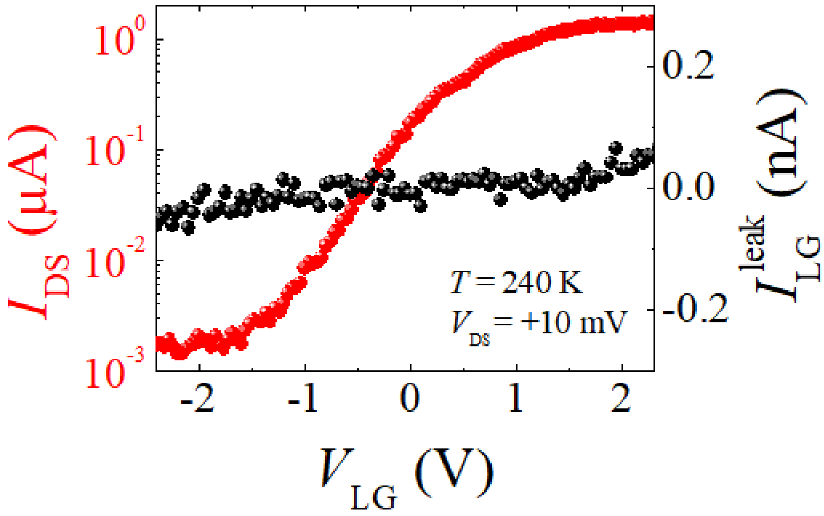
Linear
& saturation
regions





Ionic Liquid Gate *vs* back gate

LIQUID GATE



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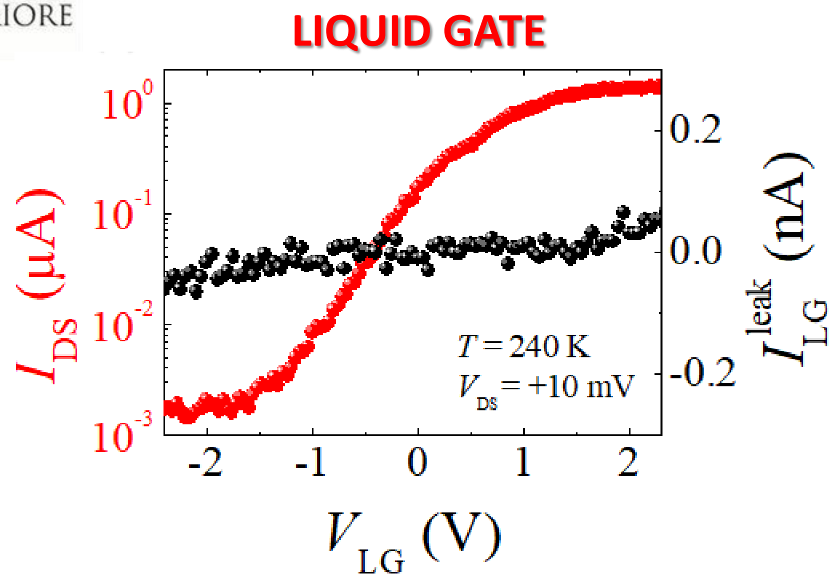
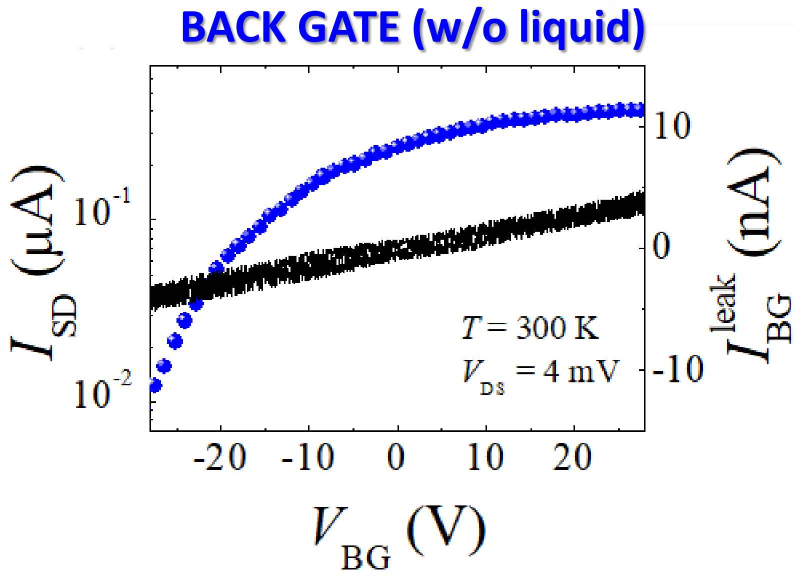
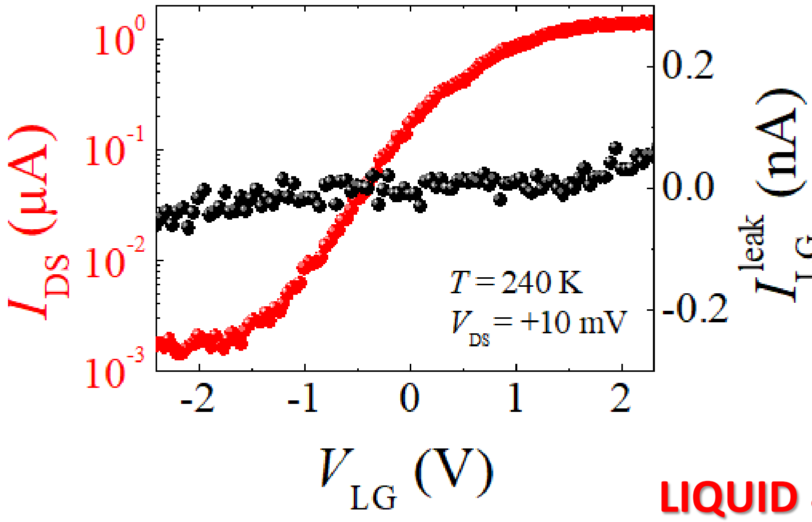




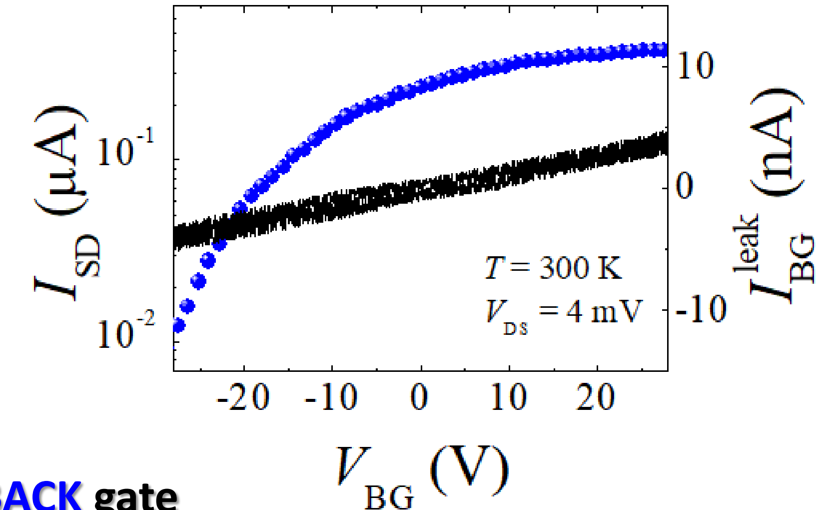
n ≈ $5*10^{17}$ cm^{-3}
μ ≈ 200 cm^2/Vs
C_{BG} ≈ 60 aF

Ionic Liquid Gate *vs* back gate

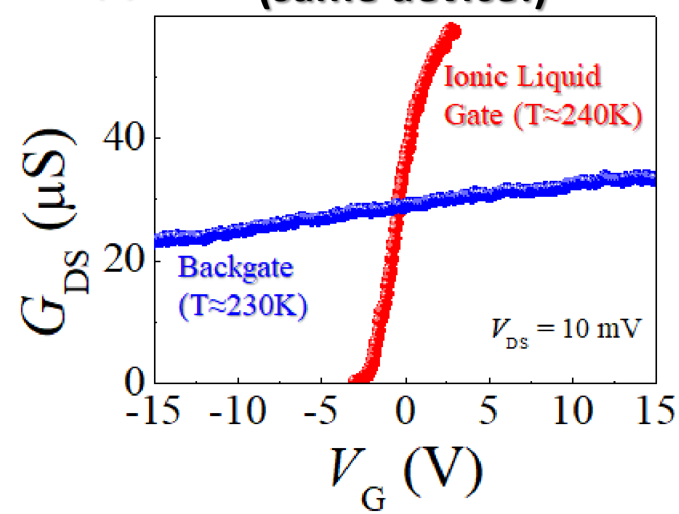
LIQUID GATE



BACK GATE (w/o liquid)



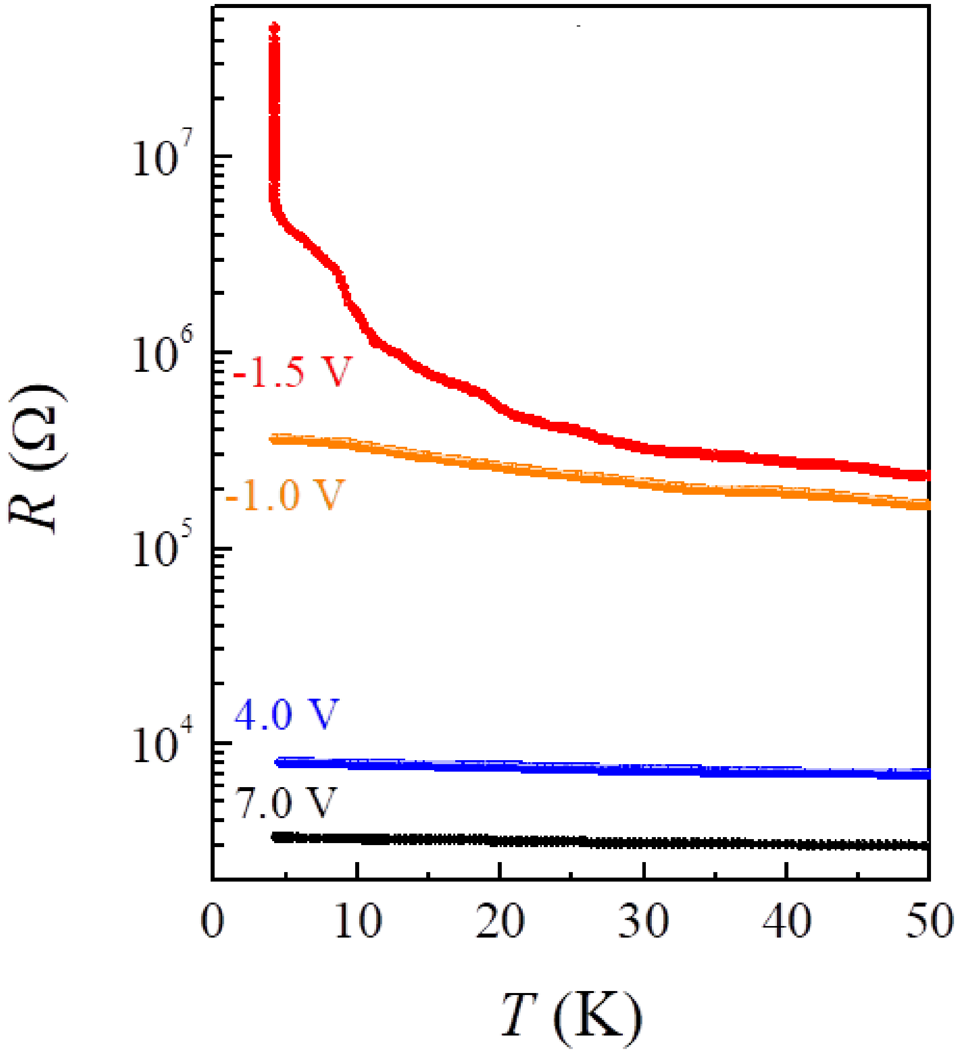
LIQUID & BACK gate
(same device!)



$C_{LIQUID\ GATE} \approx 30 * C_{BG}$

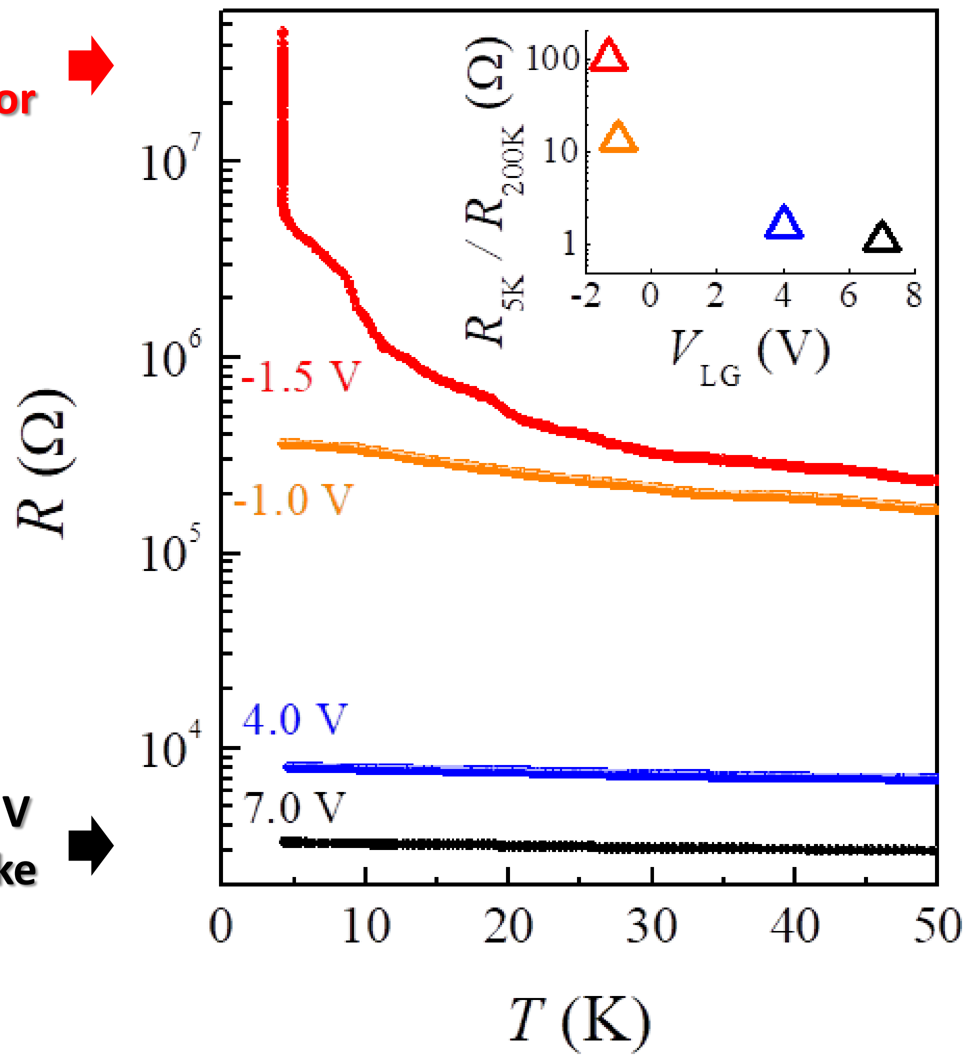
n ≈ $5*10^{17}$ cm^{-3}
μ ≈ 200 cm^2/Vs
C_{BG} ≈ 60 aF

Gate induced transition



Gate induced transition

***V_{LG}* << 0V**
semiconductor



***V_{LG}* >> 0 V**
Metal-like

J. Lieb, et al.,
Adv. Funct. Materials 2018
in press

Summary & perspectives

The happy marriage btwn III-V NWs & ionic liquids

- control of hysteresis
- FET operation demonstrated
- Ionic liquid gate versus BG: no match!
- Onset of charge induced phase transition

- Gate-electrode geometry optimization
- Suspended NW thermoelectrics
- Charge induced phase transition in 2D and 1D
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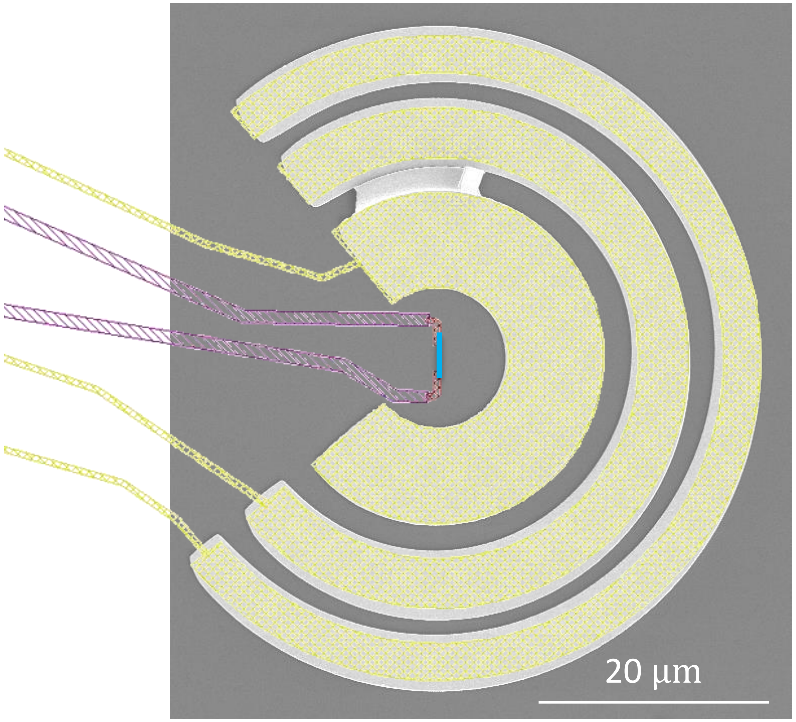
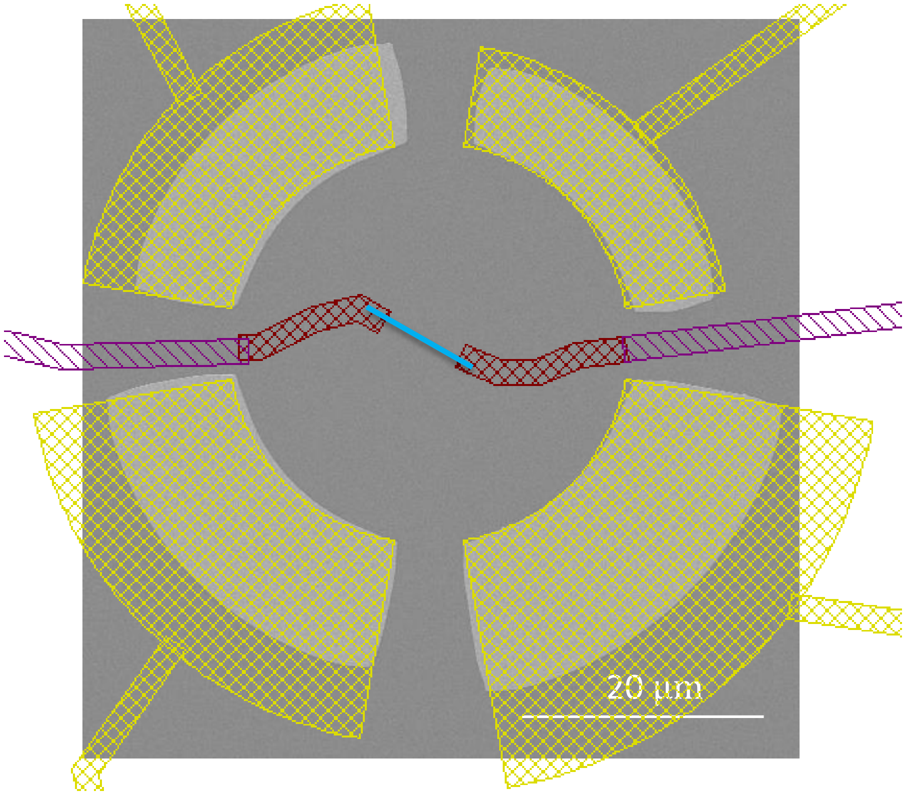
Gate-electrode geometry optimization

Liquid gating performance affected by:

gate-electrode distance from the NW ?

gate-electrode area?





SCUOLA NORMALE SUPERIORE PISA

Acknowledgements

CNRNANO PISA NEST

Valeria Demontis

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Daniele Ercolani

Stefan Heun

Lucia Sorba

Fabio Beltram

Shimpei Ono

CRIEPI Central Research Institute of Electric Power Industry

NÉEL institut

B. Sacepe
J. Lieb

V. Tozzini

L. Bellucci

NEST

SCUOLA NORMALE SUPERIORE PISA

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Pisa
(Lungarno Pacinotti)

Principles of TE: Microscopic origins

- **Electrical conductivity** $$\sigma = \frac{e^2}{3}\int \tau(E) v^2(E)\left(-D(E)\frac{df_0}{dE}\right) dE$$

  requires large area under differential conductivity (green line)

- **Seebeck** coefficient $$S = -\frac{e}{3T\sigma}\int \tau(E) v^2(E)\left(-D(E)\frac{df_0}{dE}\right)(E-E_f) dE$$

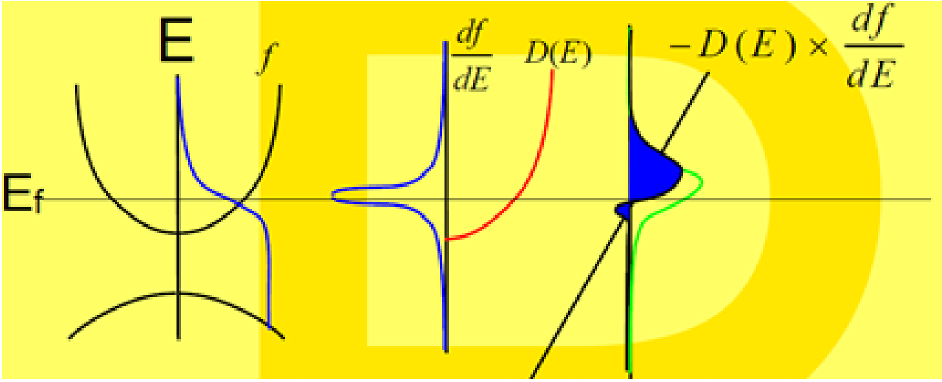
  requires asymmetry in differential conductivity at E_F (blue area)

Power factor σS^2

- **Thermal conductivity** $$k = \frac{1}{d}\frac{\partial}{\partial T}\int E f(E)\, g(E)\, \nu(E)\, \Lambda(E)\, dE$$

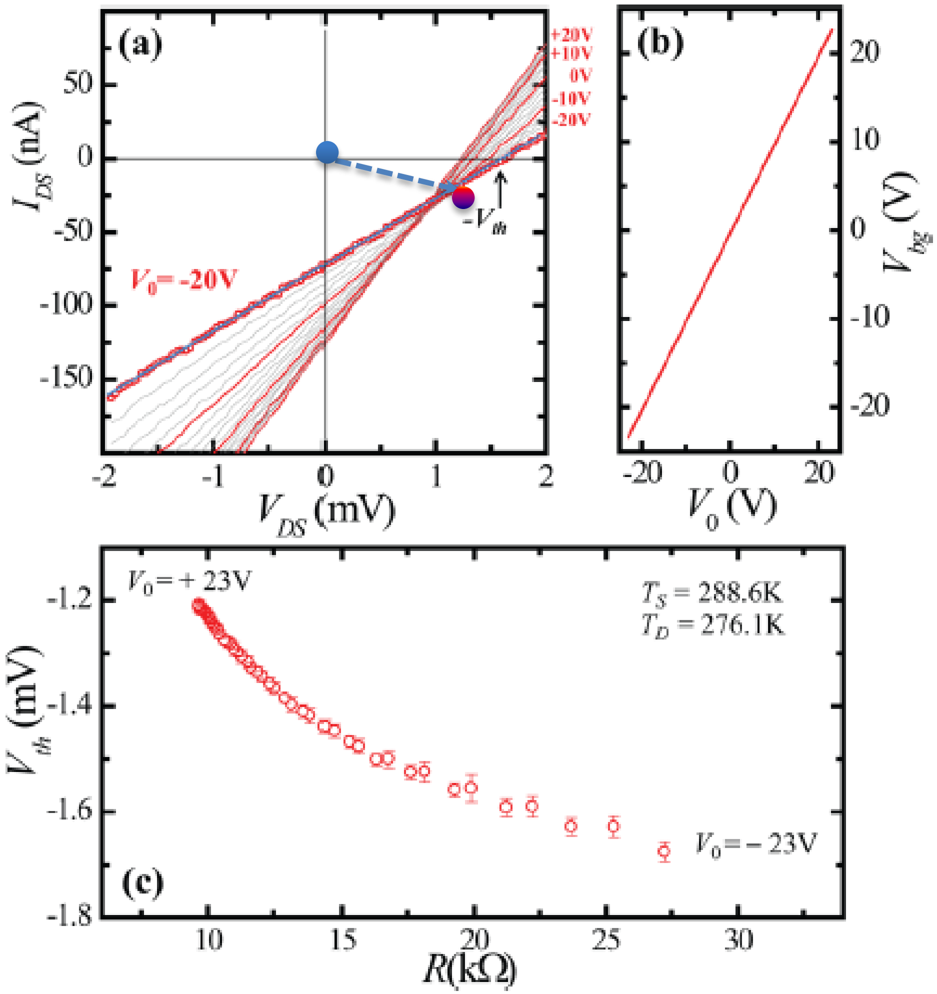
Bulk Semiconductor

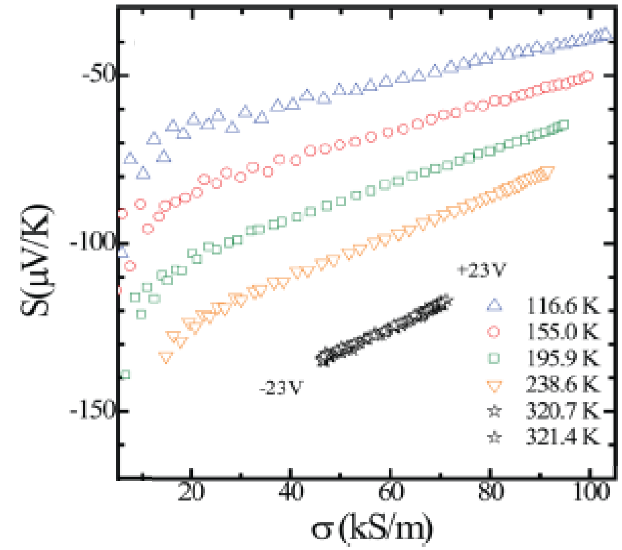
σ,S, k entangled

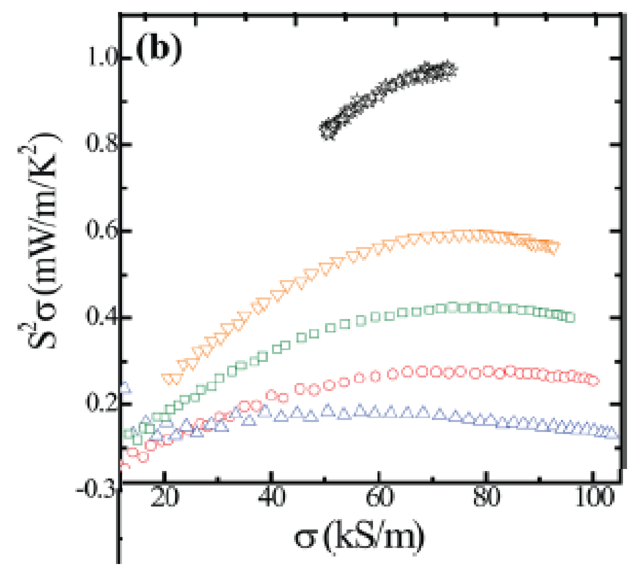


Quantum confinement !?
S ↑
k ↓

InAs NW Thermoelectric properties







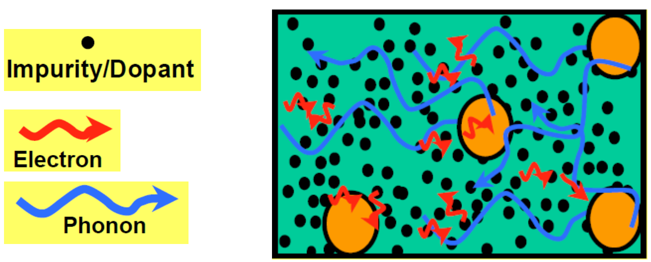
Approaches to k lowering

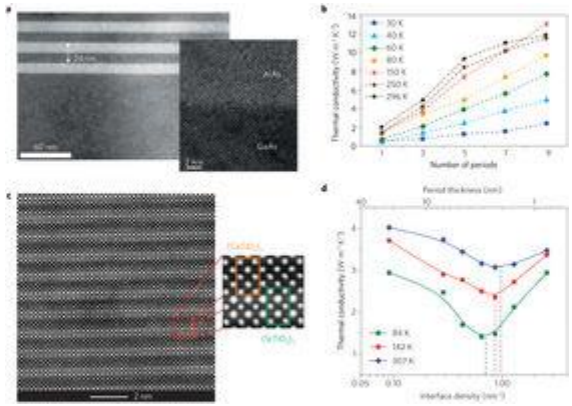
$$ZT = \frac{S^2 \sigma}{k_e + k_l} T$$

- Materials with structural disorders and phonon scattering centers (es. grain boundaries, nanocomposites, superlattices etc)
- Nanostructures with one or more dimensions smaller than the phonon mean free path $\Lambda(E)$ but larger than that of electrons and holes
- …

Electron crystal - phonon glass

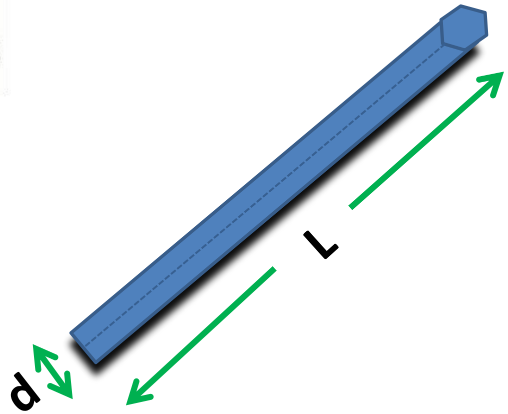
Nanostructured semiconductor





Nature Materials 14, 667–674 (2015)

Advantages of NANOWIRES



1-D material: d<<L

electron mean free path < d < phonon mean free path

σ is basically the same as in the bulk material

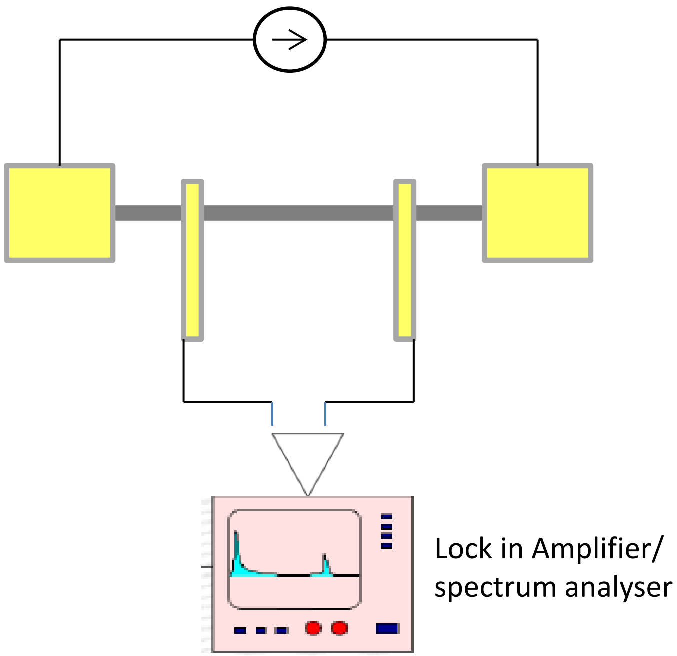
- In **NWs** low dimensionality allows to reduce k thanks to the **increased phonon-boundary scattering**

- NWs can be "easily" further nanostructured in their length, in order to exploit other quantum effects useful in TE field, such as confinement, phonon scattering in superlattices, field effect etc.

Nanowires are ideal nanostructures to explore the effects of low-dimensionality on thermoelectric behavior

All-Electrical Measure of *k*: 3ω-Method

$i(t) = I_o \sin(\omega t)$



$V_{3\omega} = V_{0,3\omega} \sin(3\omega\text{-}\varphi)$

The fit of the experimental curve using:*

$$V_{0,3\omega} \approx \frac{4 I_0^3 R R' L}{\pi^4 k_t A}$$

where L = conductor lenght
A = conductor section area

provides the value of k

L. Lu, et al., Rev. Sci. Instrum., 72, 2996 (2001)
J. Kimling, et al., Rev. Sci. Instrum. 82, 074903 (2011)
G. Pennelli, et al., J. Appl. Phys. 115, 084507 (2014)

$$R' = \frac{\Delta R}{\Delta T}$$ Need to be determined

* valid for high aspect ratio conductors

Convection Heat Losses

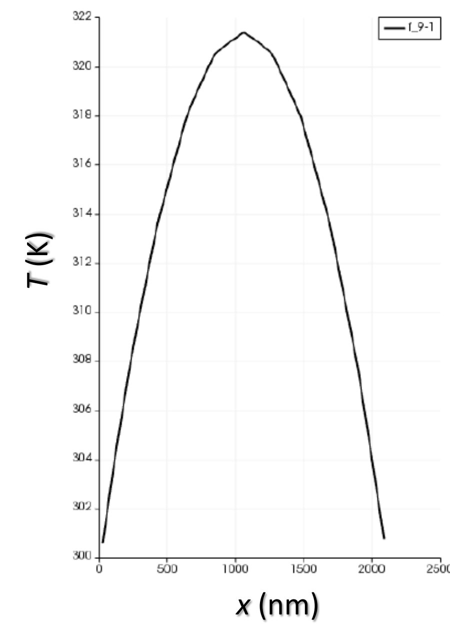
Convective Power Exchange: $P_{conv} = \lambda * \Delta T_{NW\text{-}environment} * \text{NW area}$

80nm, 2um

ΔT_{max}(NW center) = 20°C (from FEM)

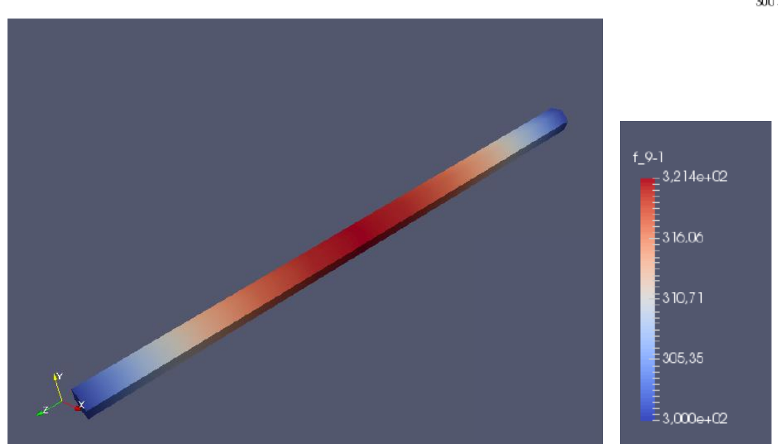
λ_{air} =100

upper threshold P_{conv} = e-9 W



R = 4 kOhm, I = 50 uA → P = RI^2 = e-5 W

$P_{joule} / P_{conv.}$ = e4

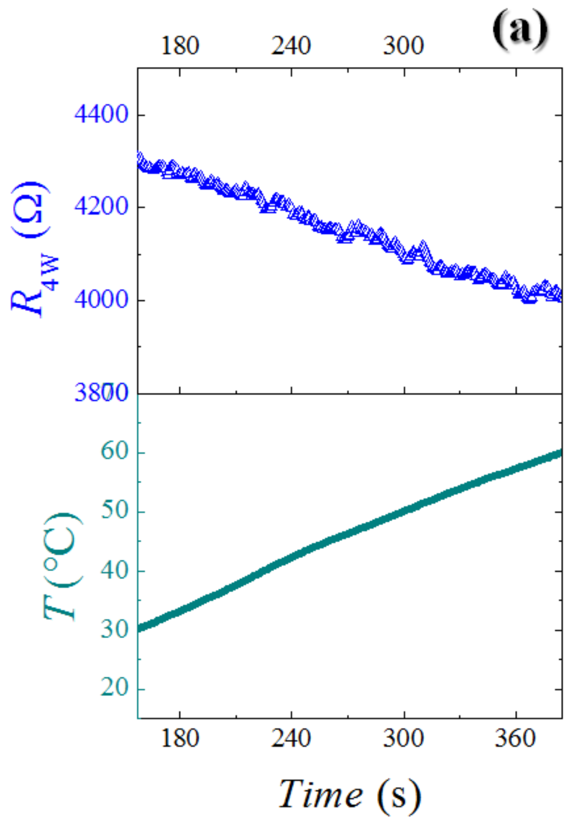


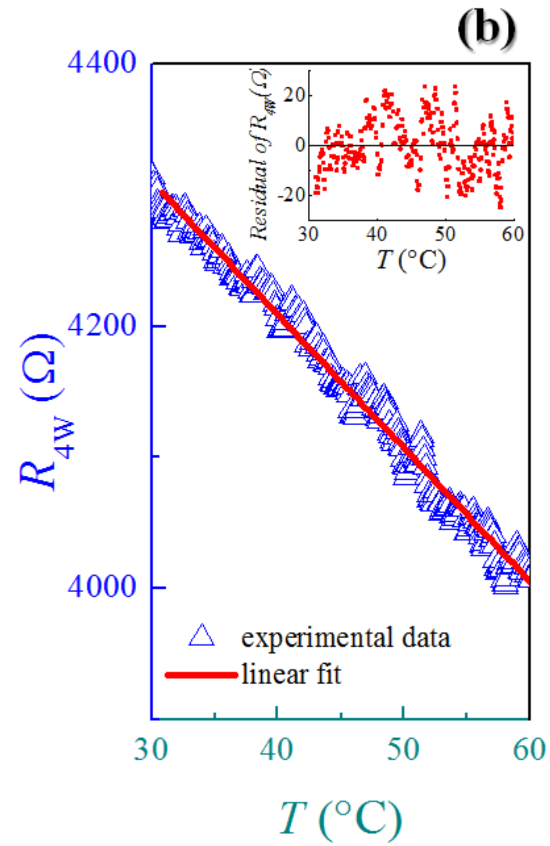
T-dependence of R

ΔT given by local or non-local heater

$$\frac{\Delta R}{\Delta T} = R' \approx 10\ \Omega/\text{K}$$

$$V_{03\omega} \approx \frac{4 I_0^3 R R' L}{\pi^4 k_t A}$$



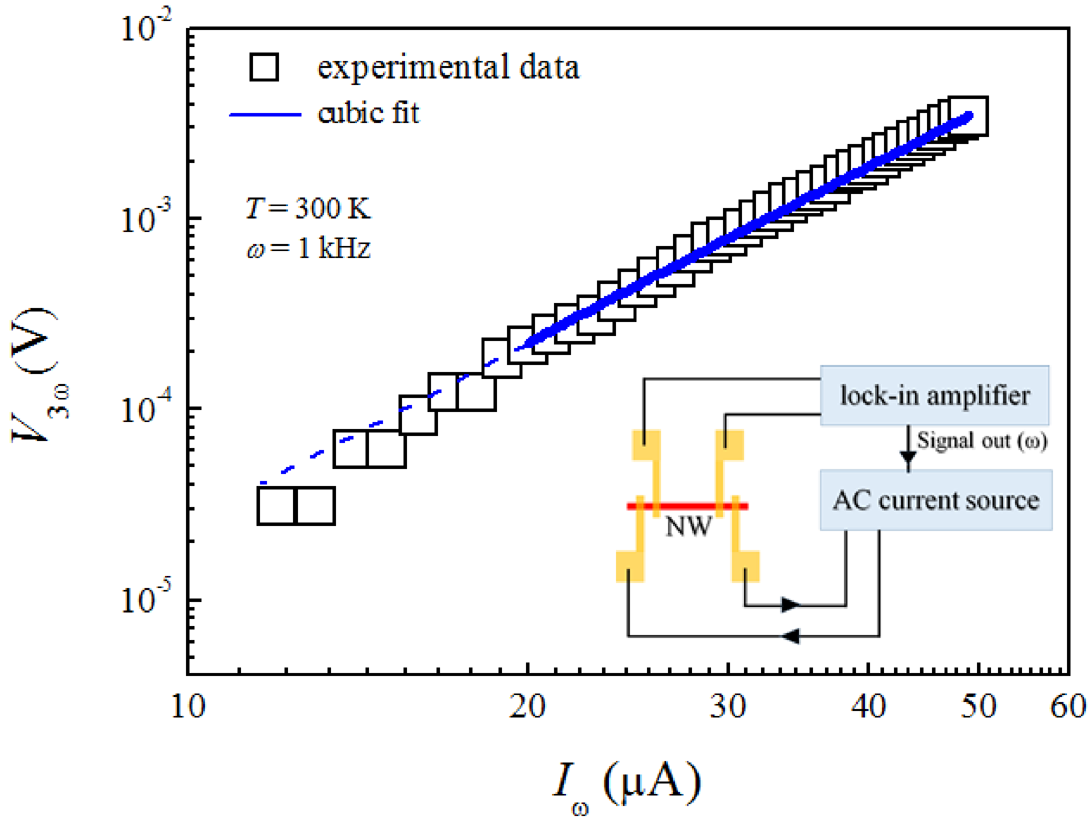


$V_{3\omega}$ versus I_0 : estimate of k

Preliminary k estimate
20 W/mK

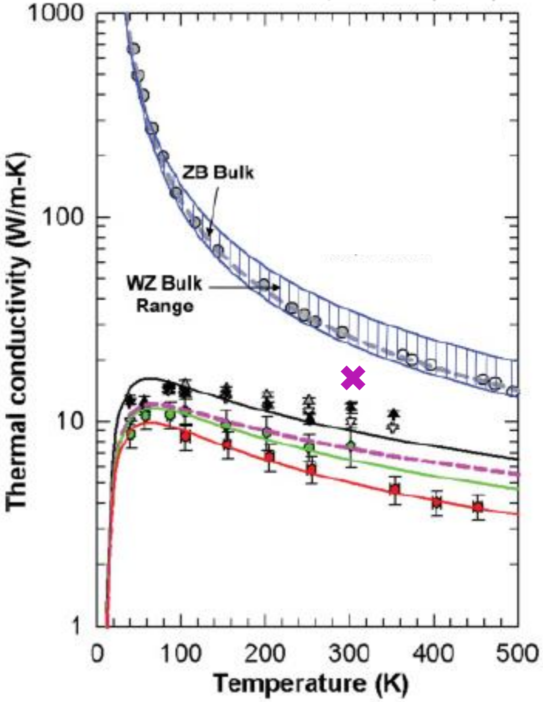
Model refinement:
Aspect ratio ≈ 20

K ≈ 16 W/mK

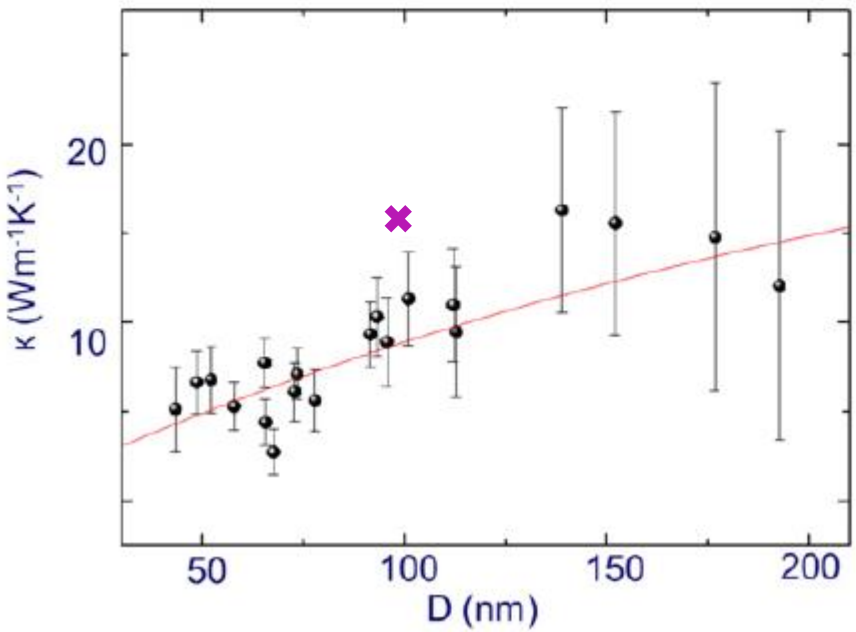


Estimate of *k*

FENG ZHOU et al.
PHYS. REV. B 83, 205416 (2011)



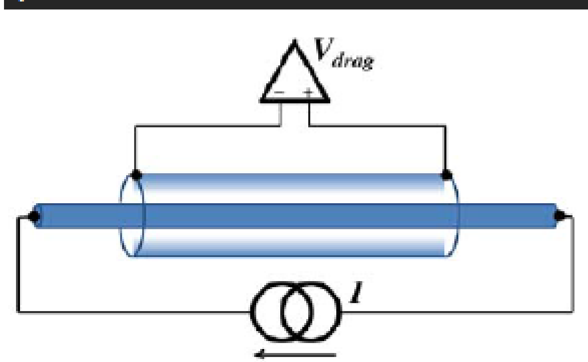
M Y Swinkels et al
Nanotechnology 26 (2015) 385401



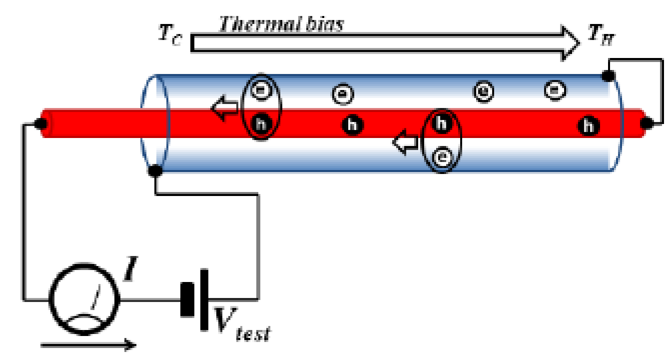
The whole protocol for measuring thermal conductivity in suspended NW devices is tested, works fine

CS-NW device

Demonstration of 1D-1D-drag phenomena in self-assembled NWs



Unveiling TE effects in Coulomb-coupled 1D systems



Ionic liquid gating of InAs nanowire-based FETs

Francesco Rossella
NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR
Pisa, Italy

National Enterprise for nanoScience and nanoTechnology

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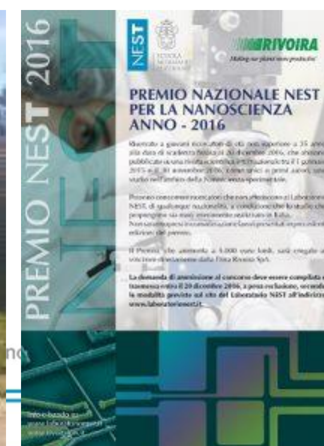
CENTRO DI COMPETENZE NEST SULLE NANOTECNOLOGIE



Nanowire-based devices

- **Materials:** **self-assembled NW heterostructures**

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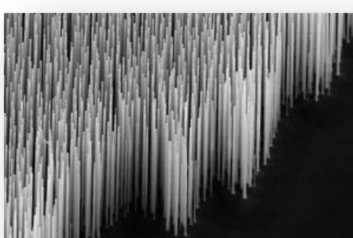
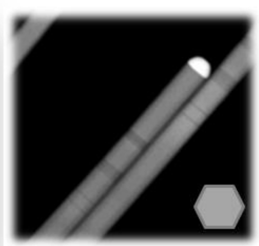
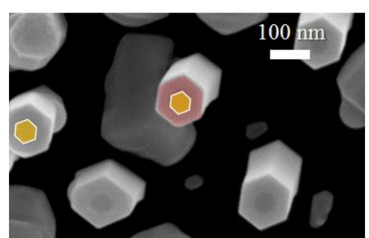
- **Implementation:**
  - I. **hemogeneous nanowires**
  - II. **InAs/InP axial heterostructures**
  - III. **InAs/InP/GaSb radial heterostructures**
  - IV. **Hybrid metal/semiconductor axial heterostrictures**







National Enterprise for nanoScience and nanoTechnology

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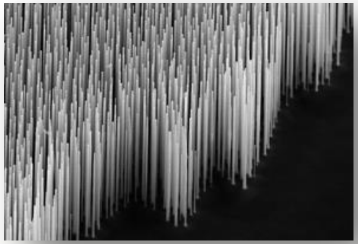
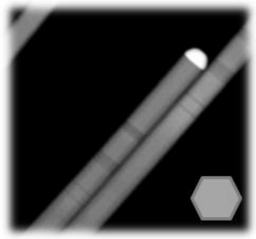
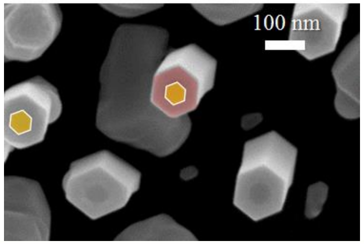
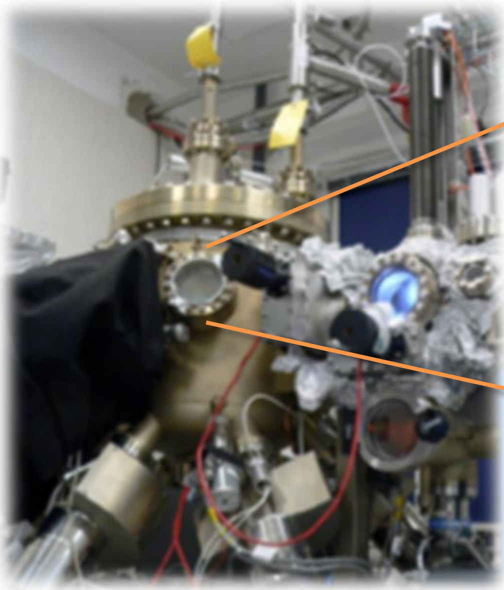
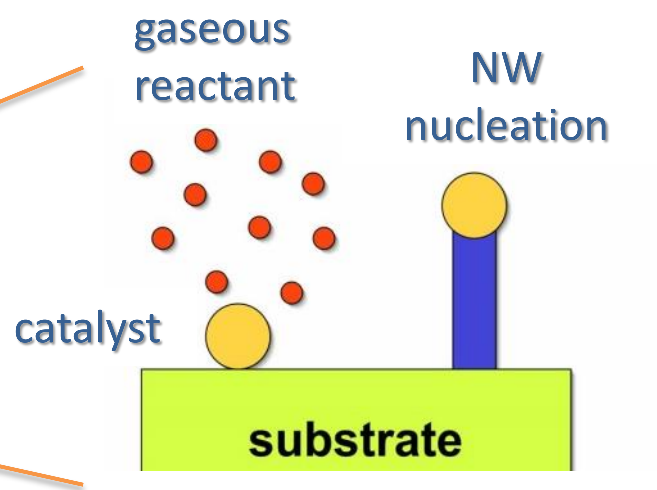






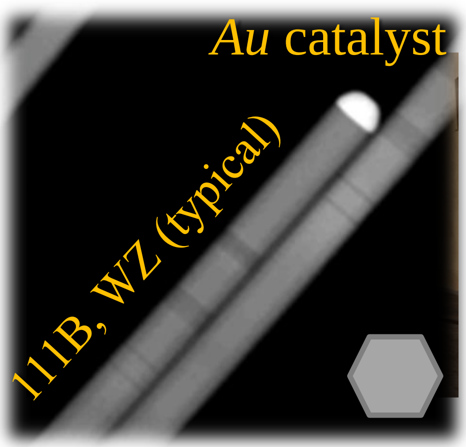
Nanowire growth by CBE





Lucia Sorba

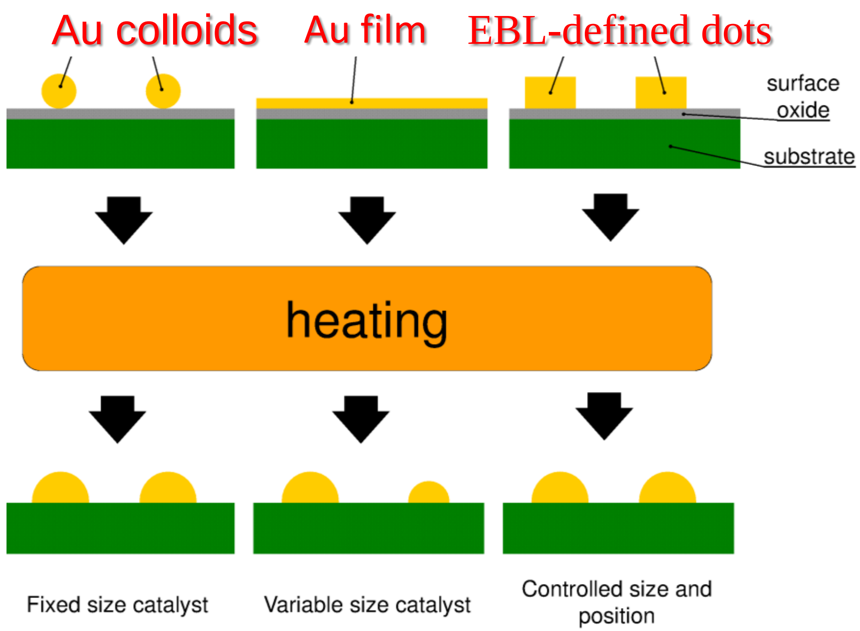
- Chemical beam epitaxy
- III-V Semiconductors
- Self-assembled nanocrystals (bottom-up approach)



Nanowire growth by CBE

Valentina Zannier

Daniele Ercolani



Isha Verma

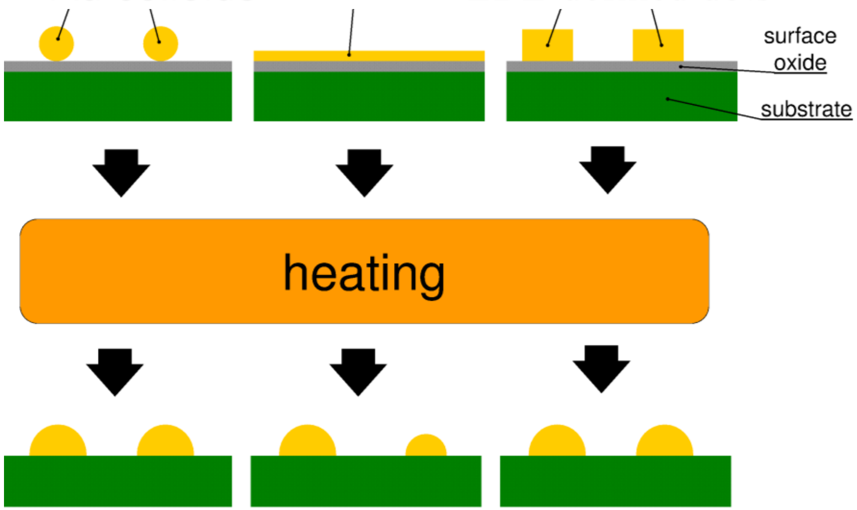
Omer Arif

Nanowire growth by CBE

Valentina Zannier

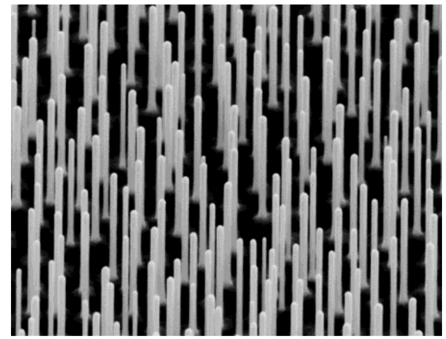
Daniele Ercolani

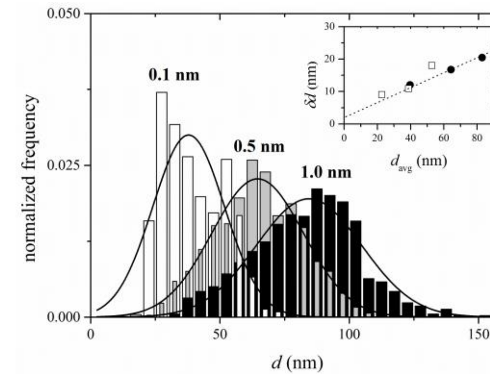
Au colloids | Au film | EBL-defined dots



Fixed size catalyst | Variable size catalyst | Controlled size and position

Au thin film





Gomes et al.,
SST **30**, 115012 (2015)

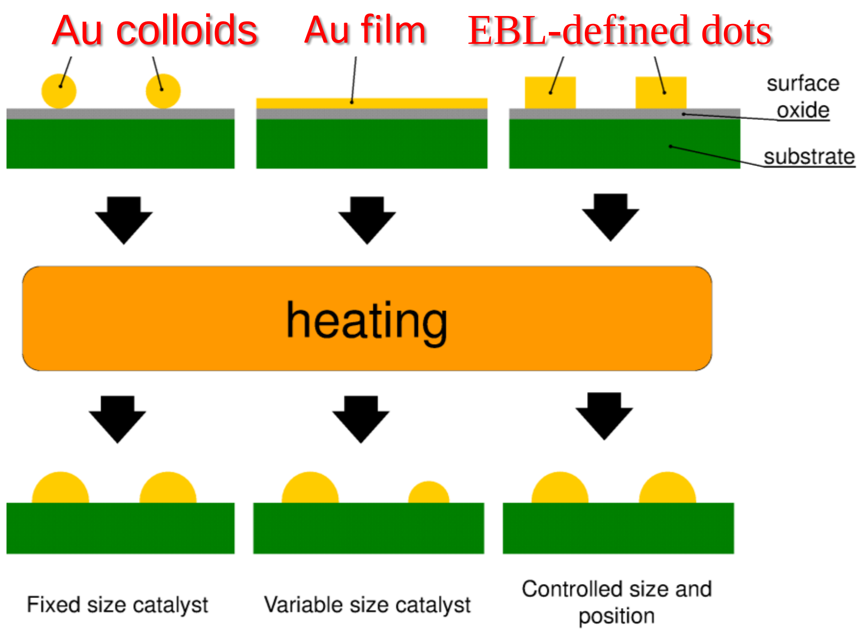
Isha Verma

Omer Arif

Nanowire growth by CBE

Valentina Zannier

Daniele Ercolani



Isha Verma

Omer Arif

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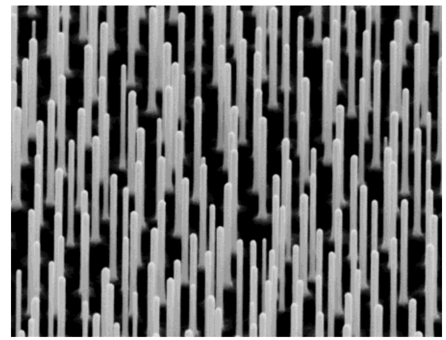

Gomes et al.,
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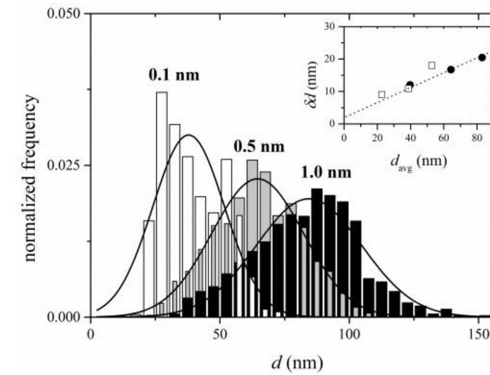
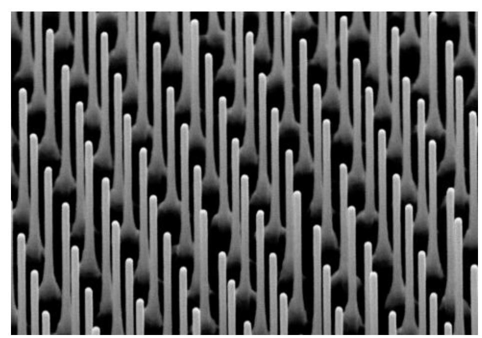
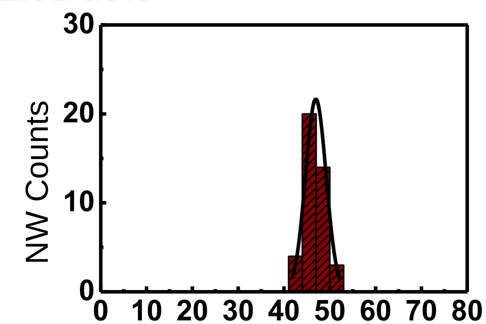


EBL-defined dots



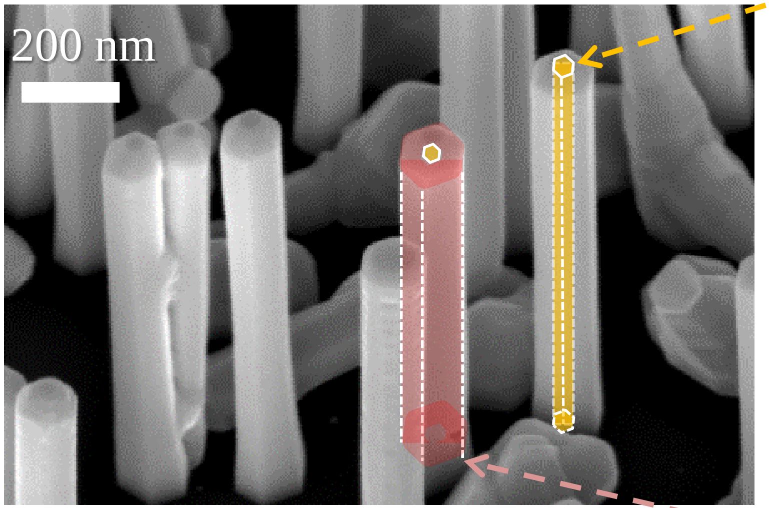


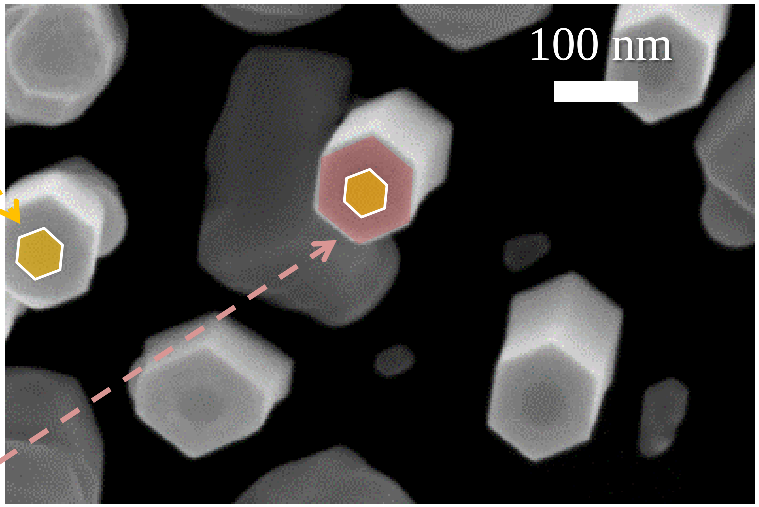
Radial heterostructures: core-shell NWs

Zhara Montmatz

Umesh Gomes

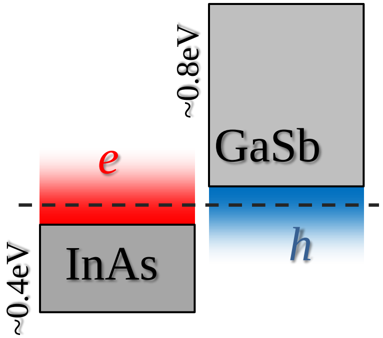
InAs core





Mirko Rocci

GaSb shell



- Tunable Esaki effect
- Thermoelectrics in coupled 1D systems
- 1D-1D Coulomb drag

S.Pezzini, … and F.Rossella, *in preparation*
M.Rocci, F.Rossella* *et al., Nano Lett.* **16**, 7950 (2016)

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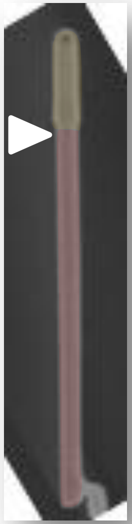
Axial heterostructures

GaAs/InAs

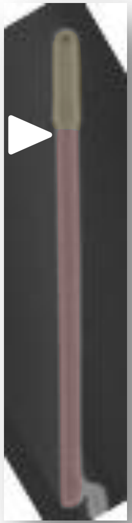


Sharp **interface**
between 2 semiconductors

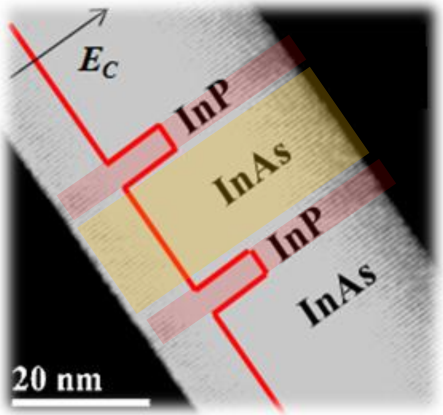
Axial heterostructures

GaAs/InAs

InAs/InP



S. Roddaro



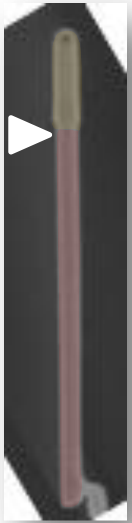
Sharp **interface** between 2 semiconductors

InP **barriers** few nm thick inside an InAs NW

- Tunneling processes in 0D and 1D (NW-QDs)

Axial heterostructures

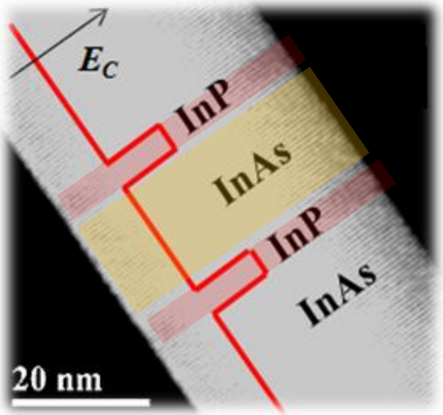
GaAs/InAs



Sharp **interface** between 2 semiconductors

InAs/InP

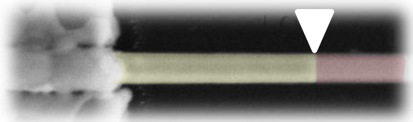
S. Roddaro



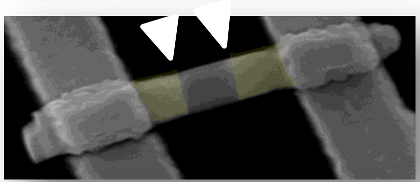
InP **barriers** few nm thick inside an InAs NW

Hybrids

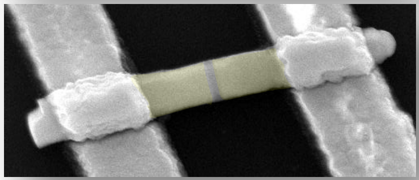
M. Gemmi



J. David



V. Piazza



Metal/semiconductor **junctions**

- Tunneling processes in 0D and 1D (NW-QDs)
- Shottcky barriers → light emission, optoelectronics

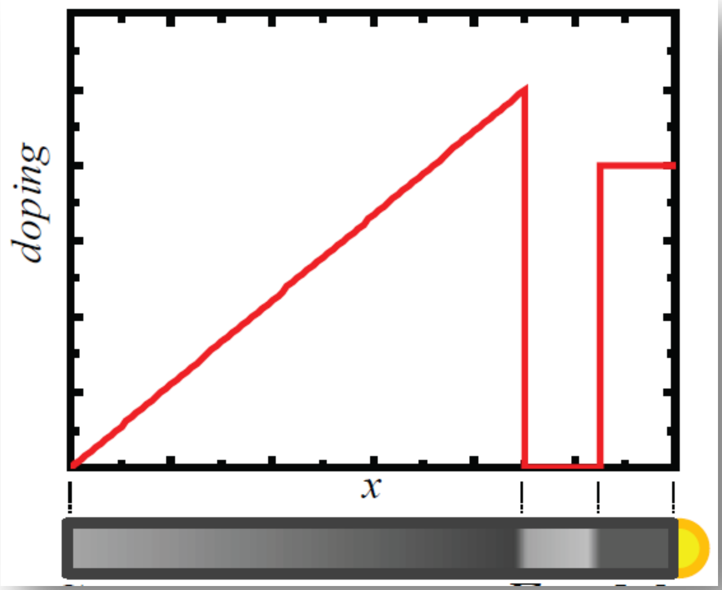
J. David, F. Rossella* *et al, Nano Lett.* ***17****, 2336 (2017)*
F. Rossella* et al, *Nano Lett*. **16**, 5521 (2016)
F. Rossella et al, *Nat. Nanotech.* **9**, 997 (2014); F. Rossella et al, *J. Phys. D: Appl. Phys*. **47** 394015 (2014)
L. Romeo et al., Nano Lett. **12,** 4490 (2012); S. Roddaro et al., *Nano Lett.* **11**, 1695 (2011)

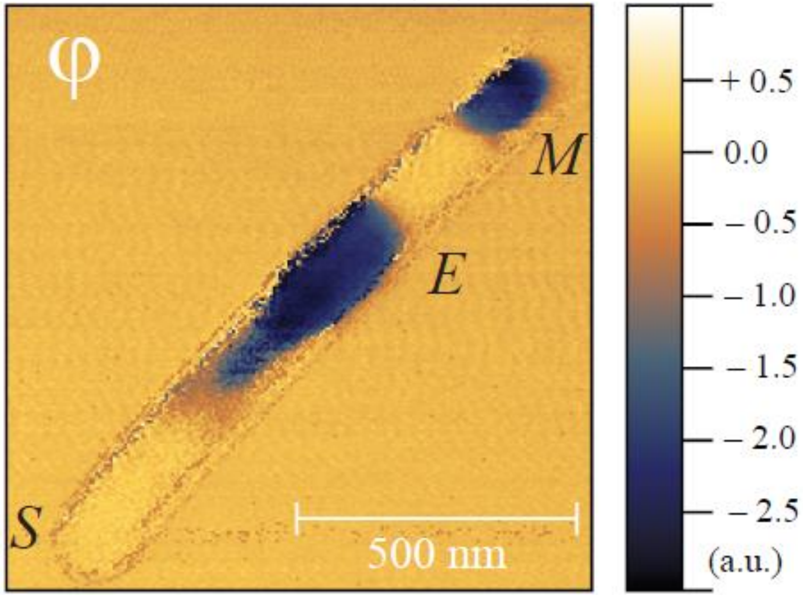
Homostructures: graded n-type doping

A. Tredicucci

A. Arcangeli

s-SNOM





- n(x) → ε(x) → tailoring dielectric response
- Semiconductor → gate-tunable nano-plasmonics

A.Arcangeli, F. Rossella* *et al, Nano Lett.* **16**, 5688 (2016)