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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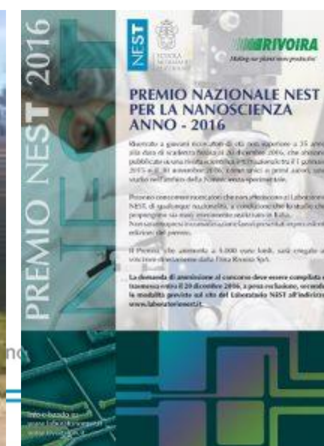
CENTRO DI COMPETENZE NEST SULLE NANOTECNOLOGIE



Nanowire-based devices

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

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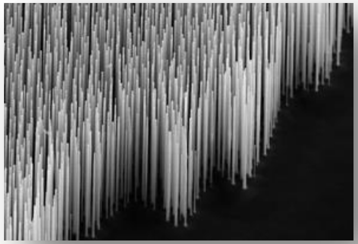
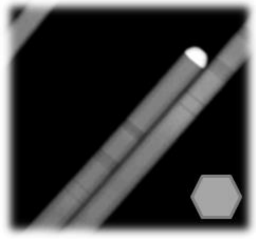
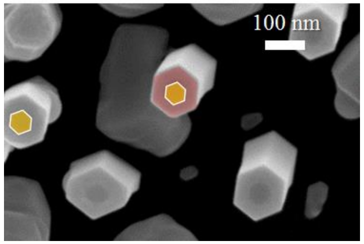

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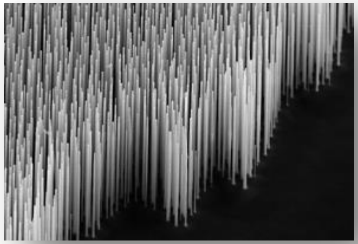
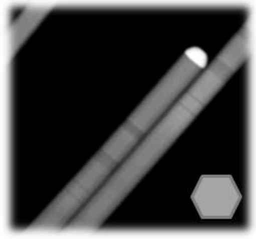
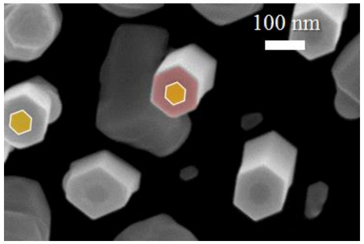
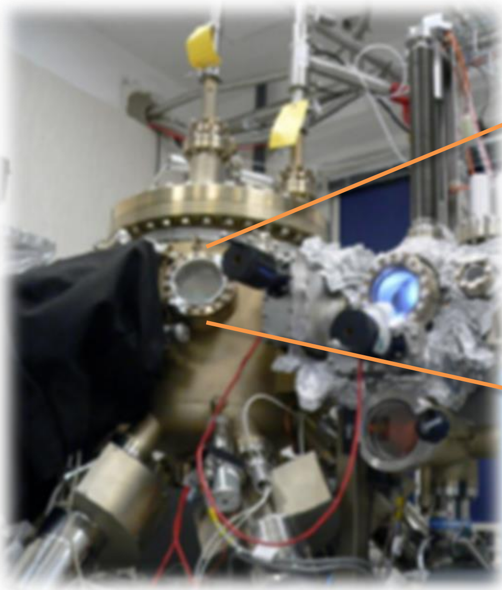
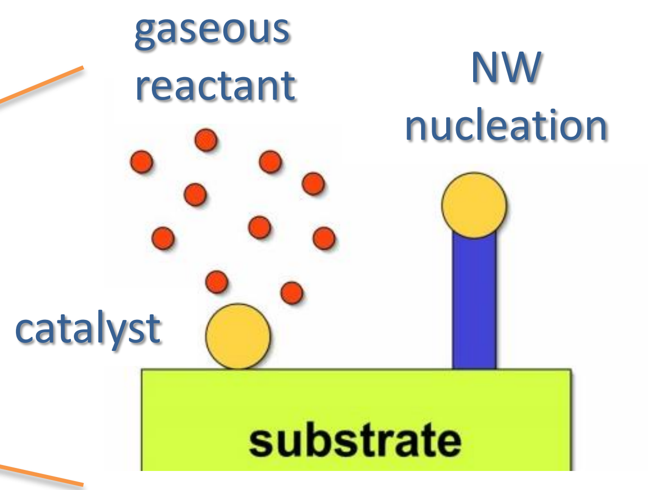






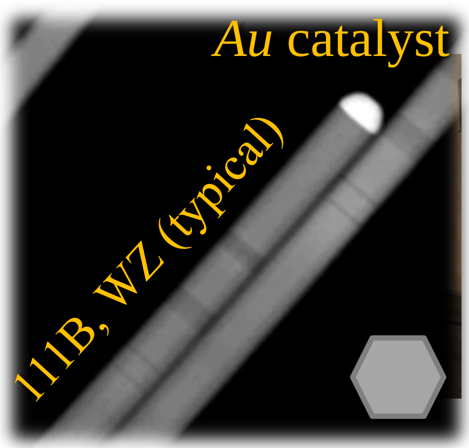
Nanowire growth by CBE





Lucia Sorba

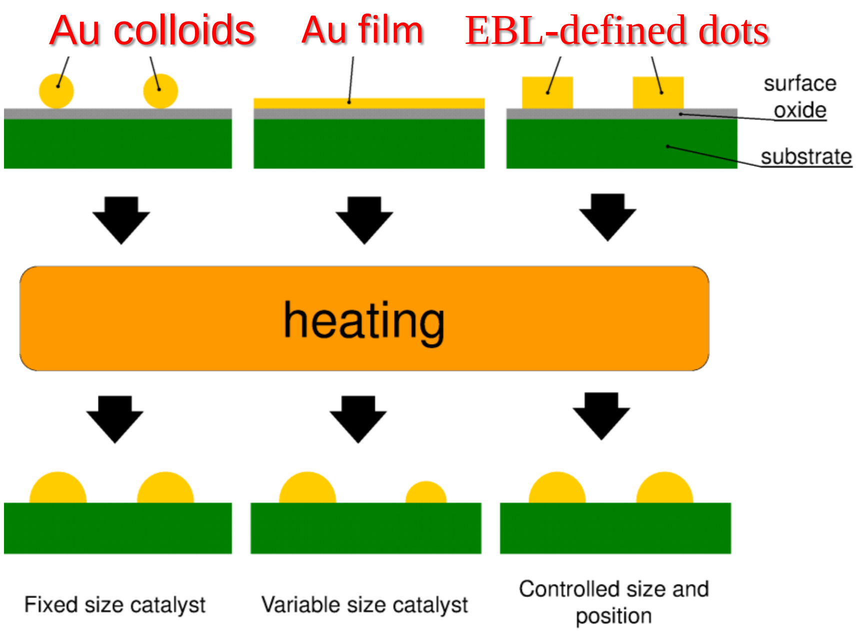
- Chemical beam epitaxy
- III-V Semiconductors
- Self-assembled nanocrystals (bottom-up approach)



Nanowire growth by CBE

Valentina Zannier

Daniele Ercolani



Isha Verma

Omer Arif

Nanowire growth by CBE

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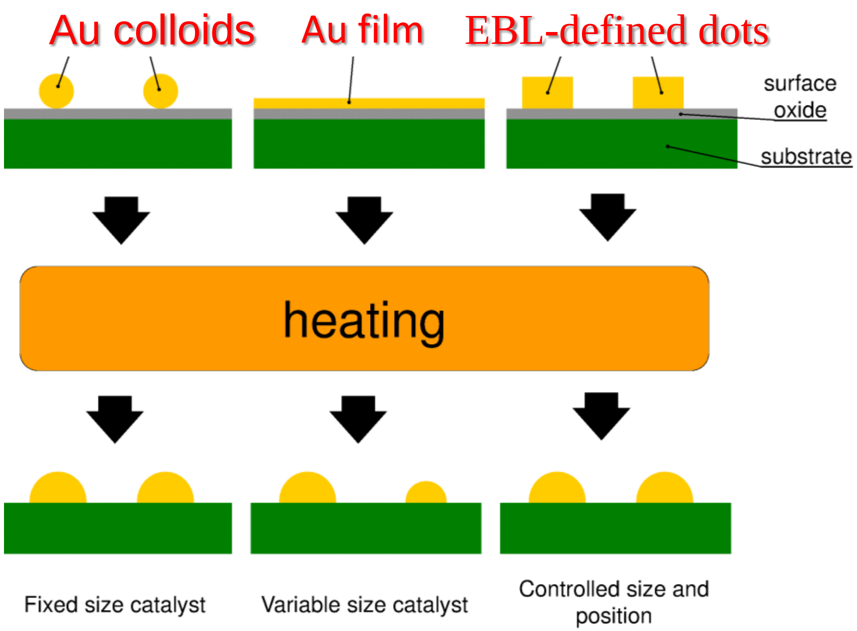
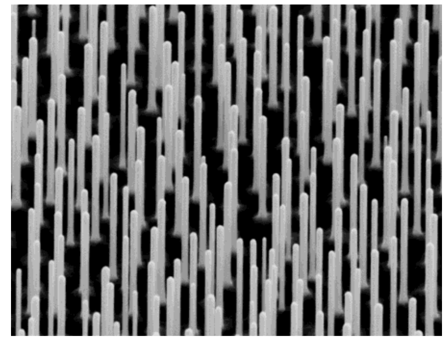
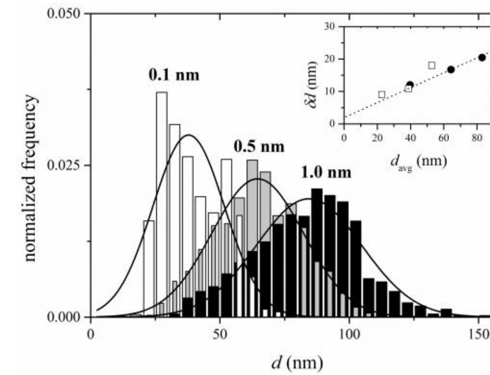


Au thin film





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

Isha Verma

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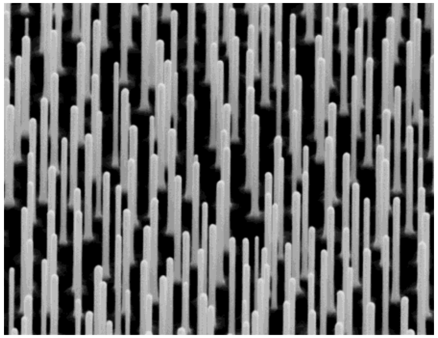

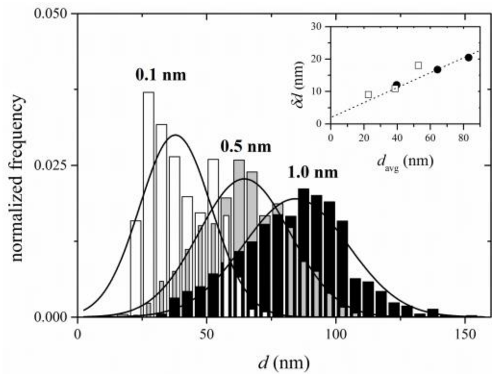

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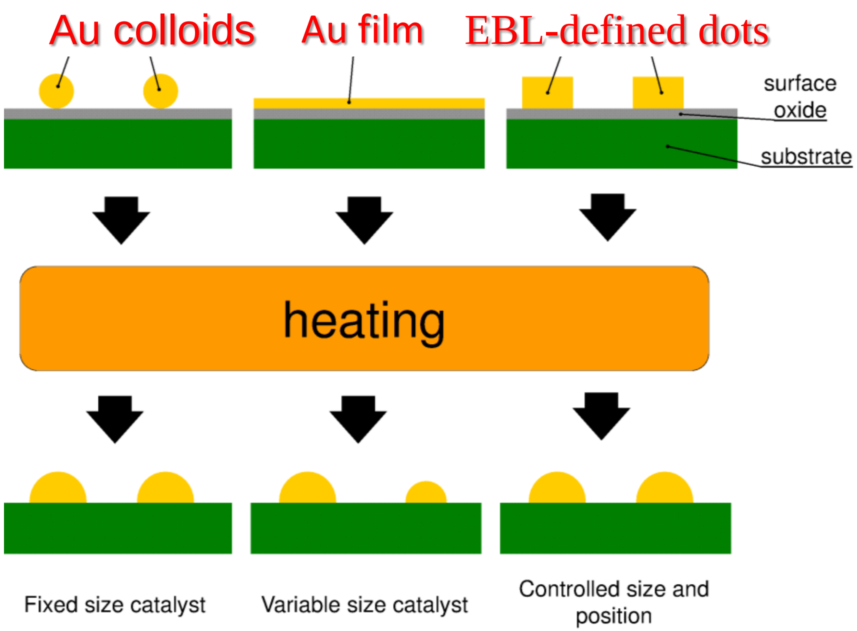
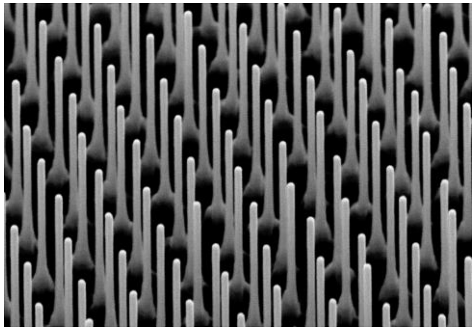
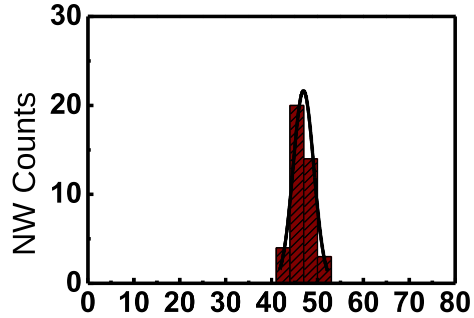


EBL-defined dots





Isha Verma

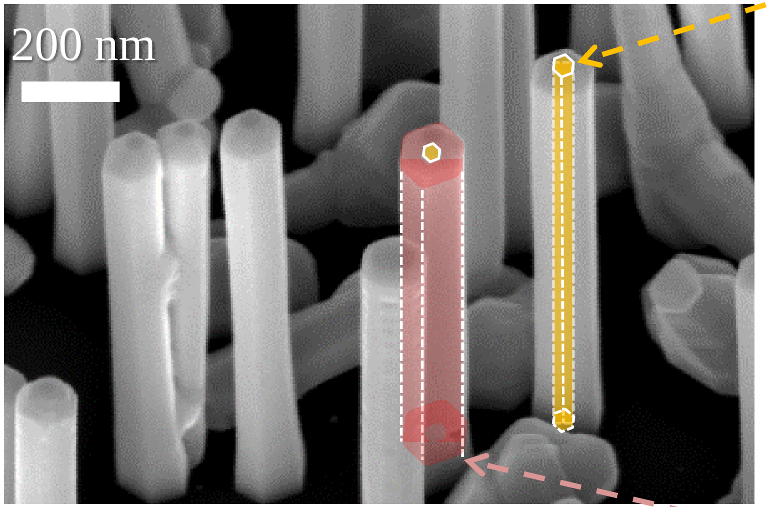
Omer Arif

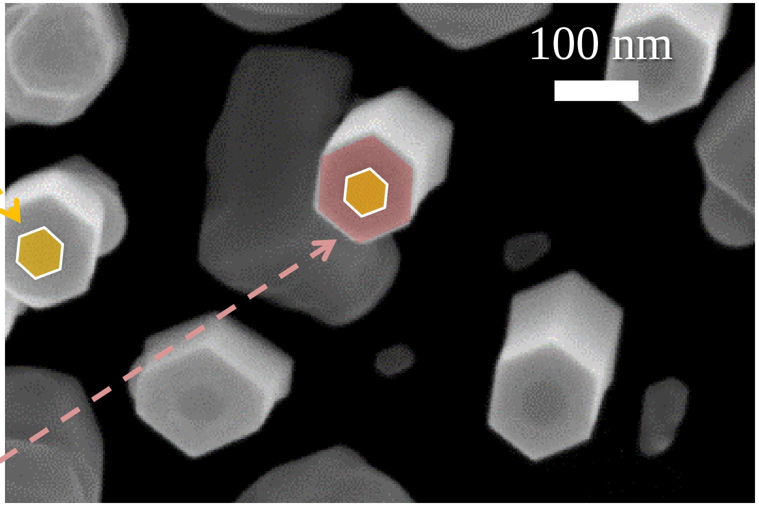
Radial heterostructures: core-shell NWs

Zhara Montmatz

InAs core

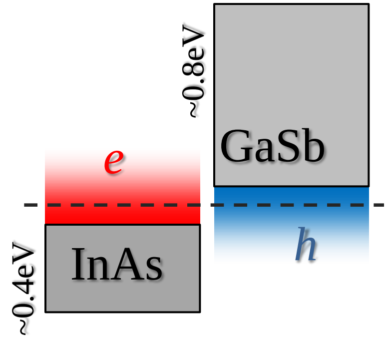
Umesh Gomes





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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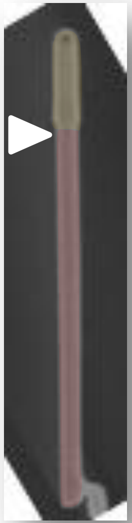
Axial heterostructures

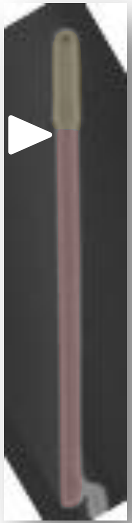
GaAs/InAs



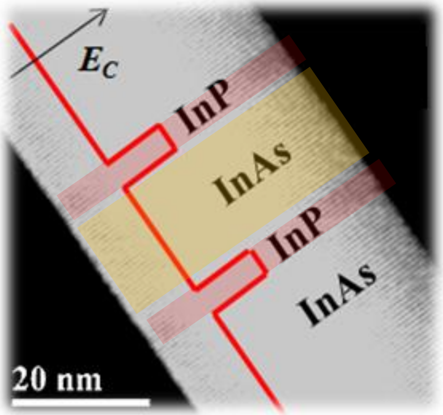
Sharp **interface**
between 2 semiconductors

Axial heterostructures

GaAs/InAs **InAs/InP**



S. Roddaro



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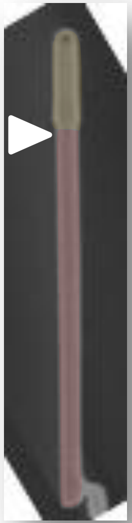
InP **barriers** few nm thick
inside an InAs NW

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

Axial heterostructures

GaAs/InAs



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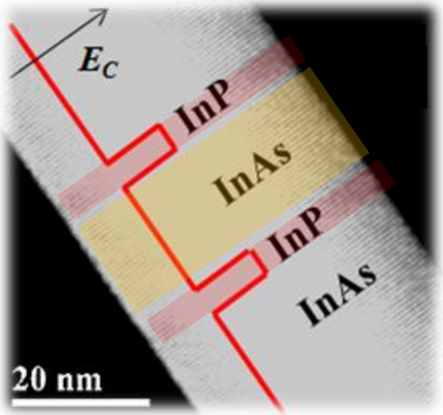
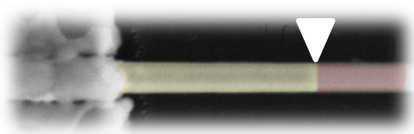
S. Roddaro



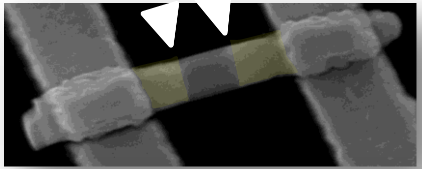
InP **barriers** few nm thick inside an InAs NW

Hybrids

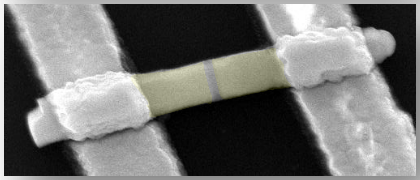
M. Gemmi



J. David



V. Piazza



Metal/semiconductor **junctions**

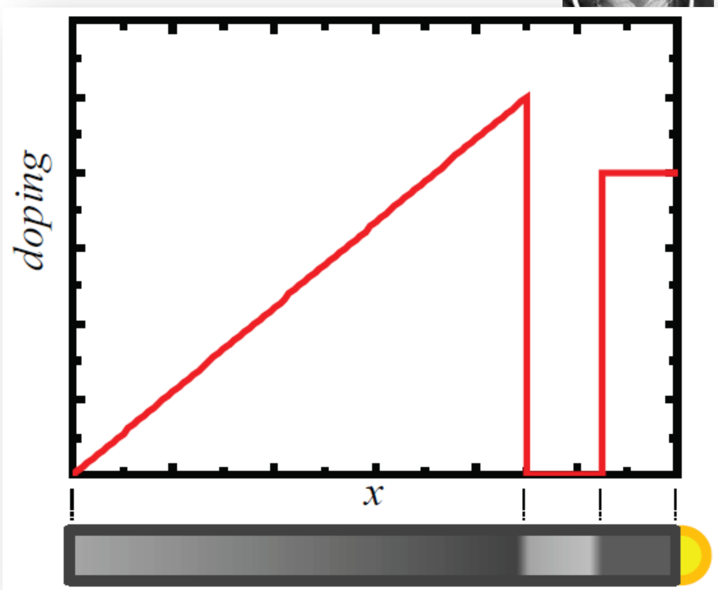
- Tunneling processes in 0D and 1D (NW-QDs)
- Shottcky barriers → light emission, optoelectronics

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)

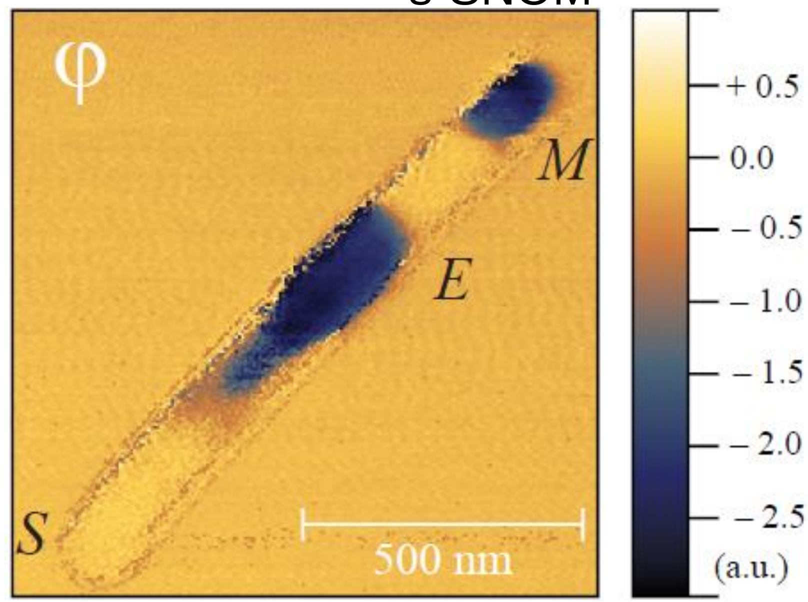
Homostructures: graded n-type doping

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)

Ionic liquid gating of InAs nanowire-based FETs

V. Demontis, V. Zannier, D. Ercolani, L. Sorba, F. Beltram and F. Rossella
S. Ono
J. Lieb and B. Sacepe

NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR, Pisa (Italy)
Central Research Institute of Electric Power Industry, Yokosuka, Kanagawa (Japan)
Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Neel, Grenoble (France)

NW Thermoelectrics

SUPPORTED NW devices: Seebeck & Power Factor

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

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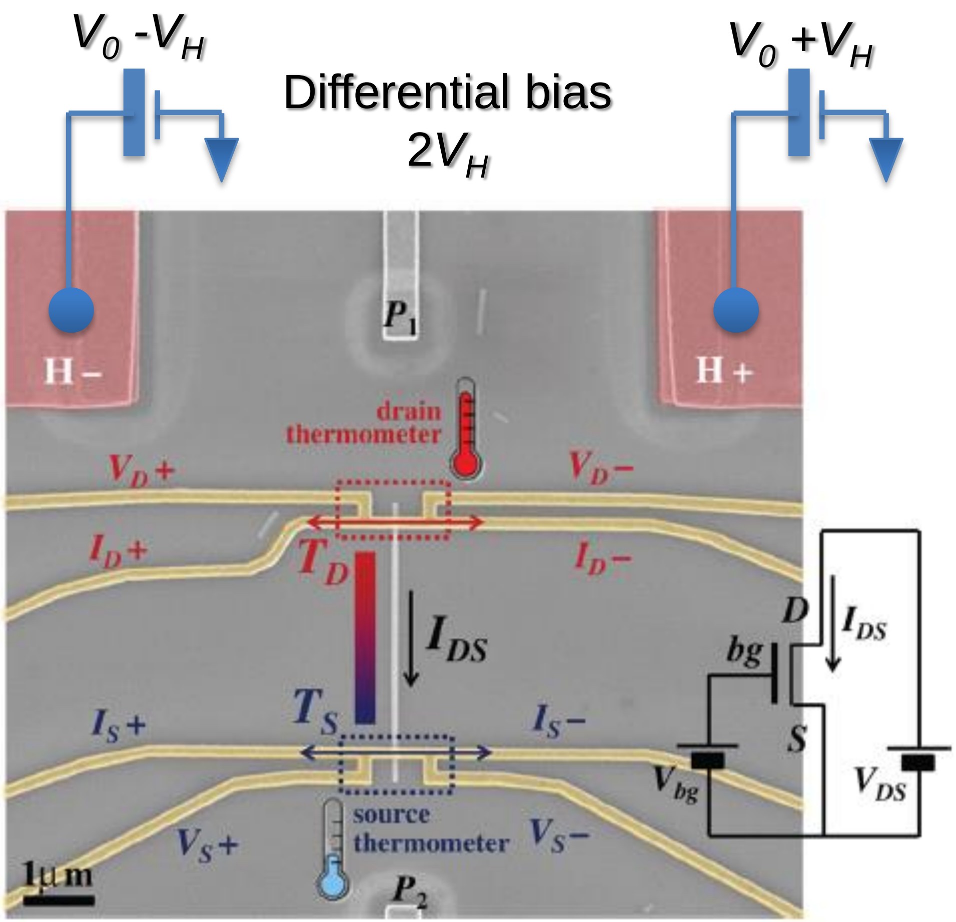

S.Roddaro, et al., Nano Research 2014

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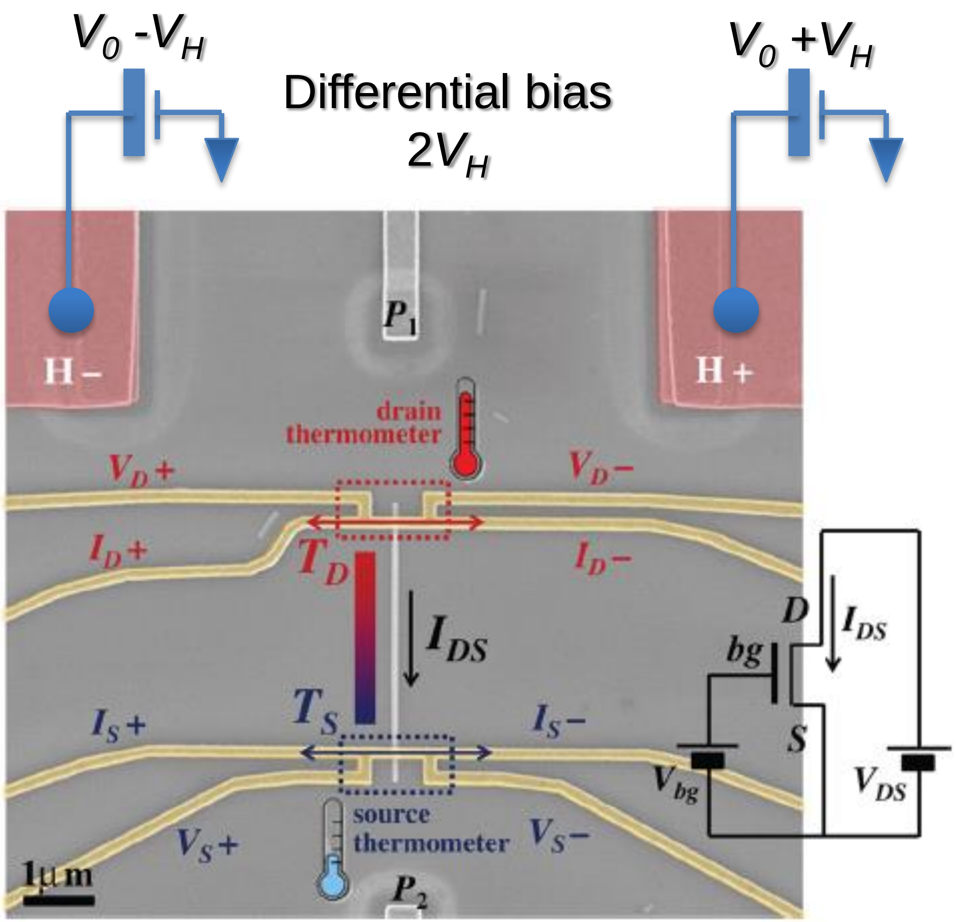

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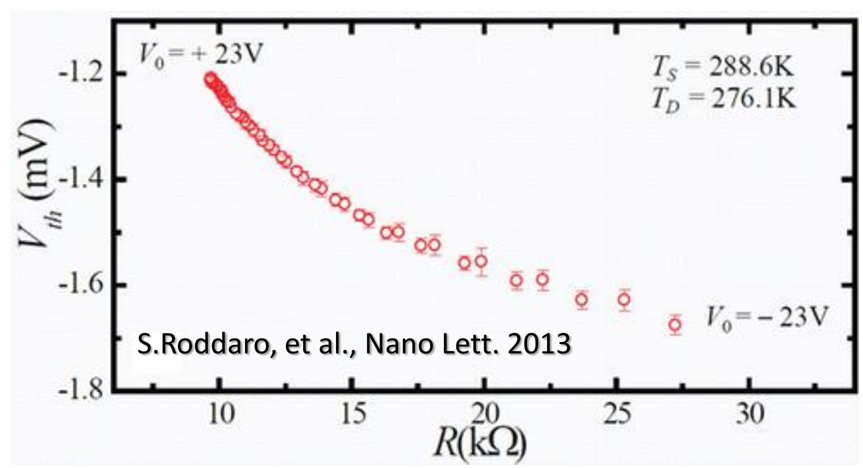

S.Roddaro, et al., Nano Lett. 2013

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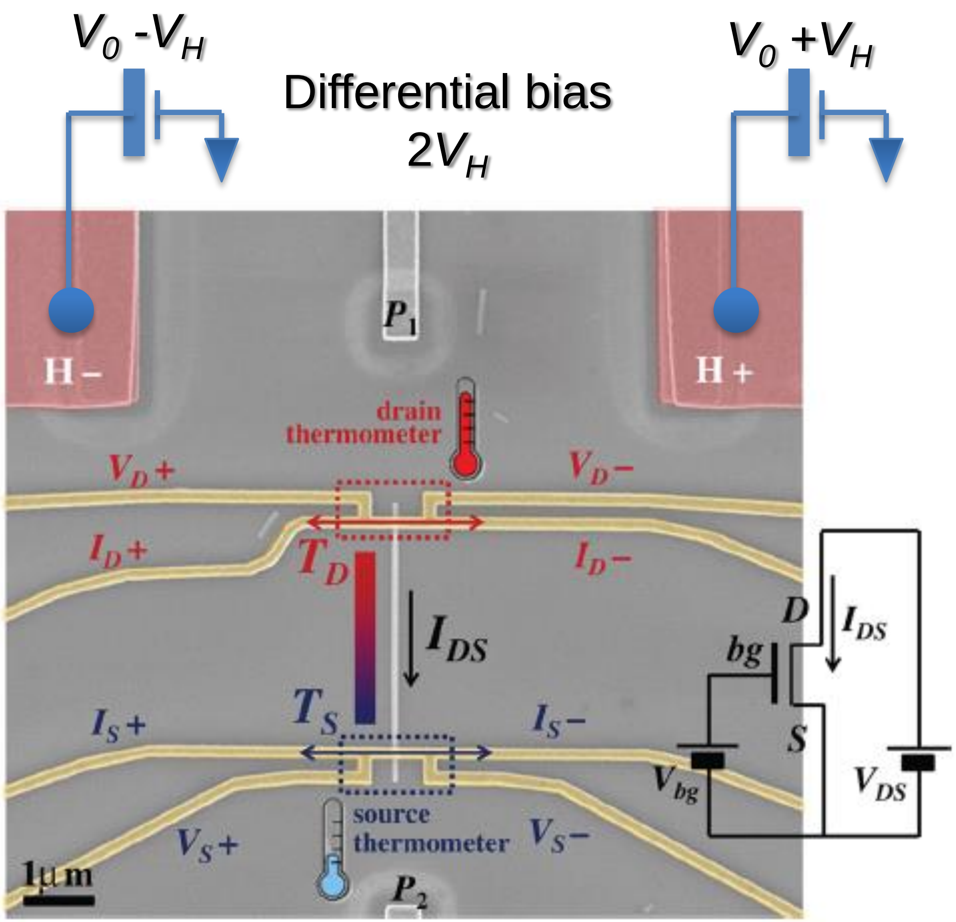
D.Prete et al, in preparation 2018
E. Tickonov, et al. Sci. Rep. 2016
E. Tickonov, et al. SST 2016



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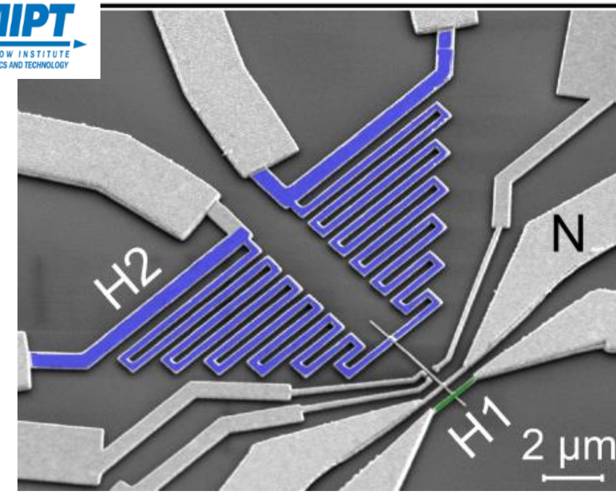

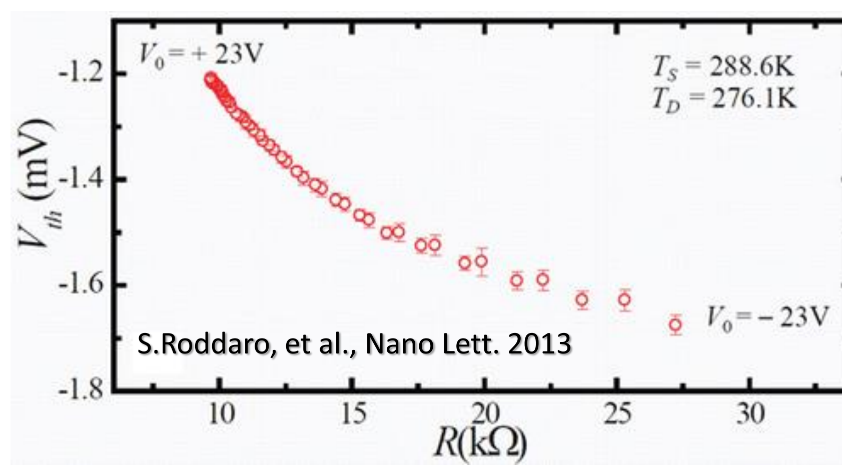

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SUSPENDED NW devices: thermal conductivity

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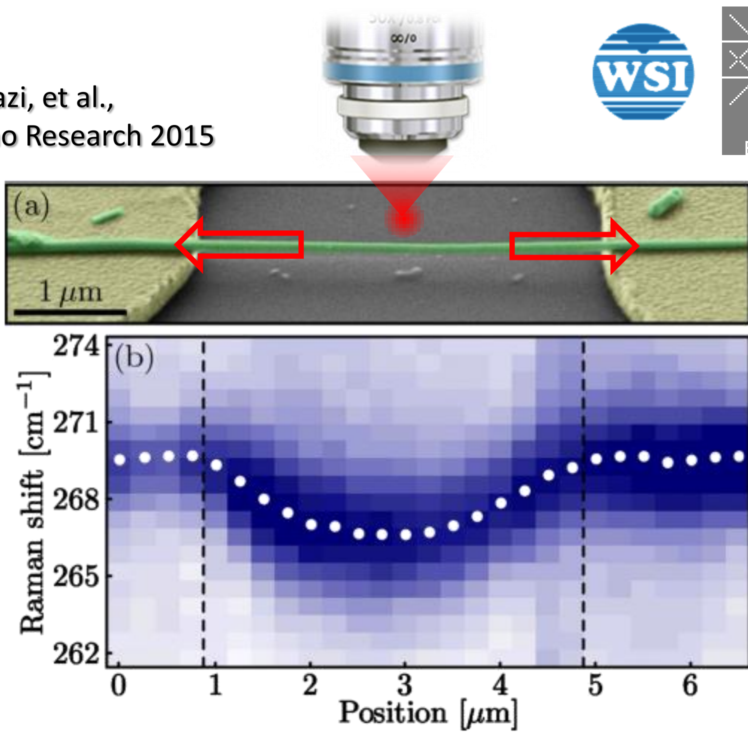
Optical approach

S. Yazi, et al.,
Nano Research 2015



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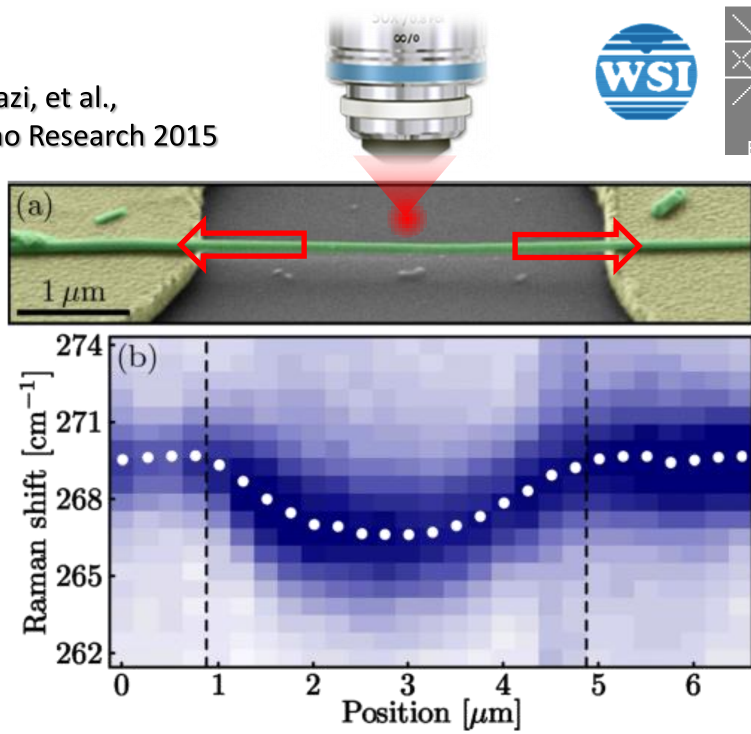
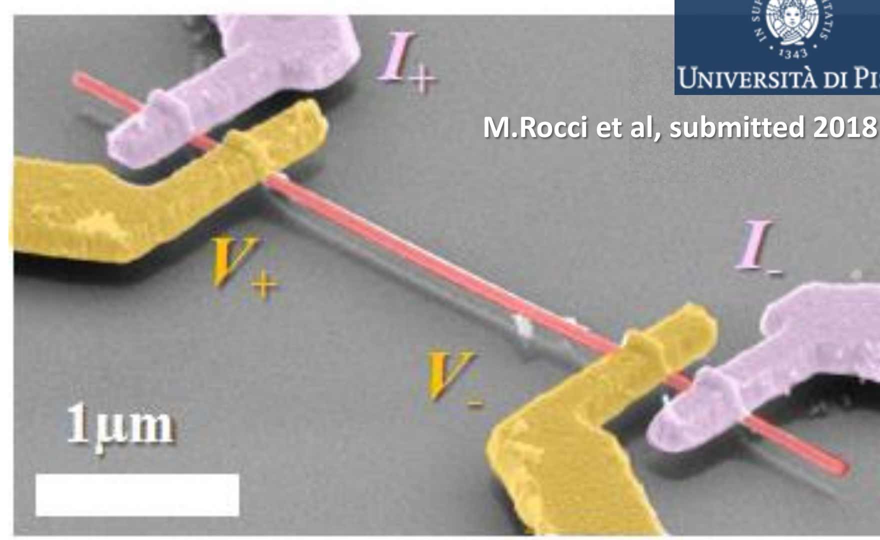


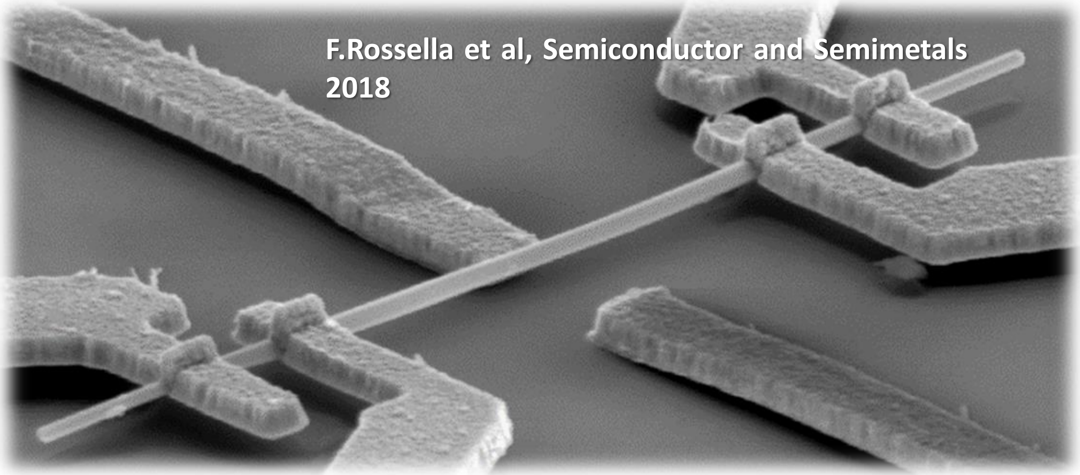
All-electrical method:
Current injection at freq ω
Voltage probing at freq 3ω

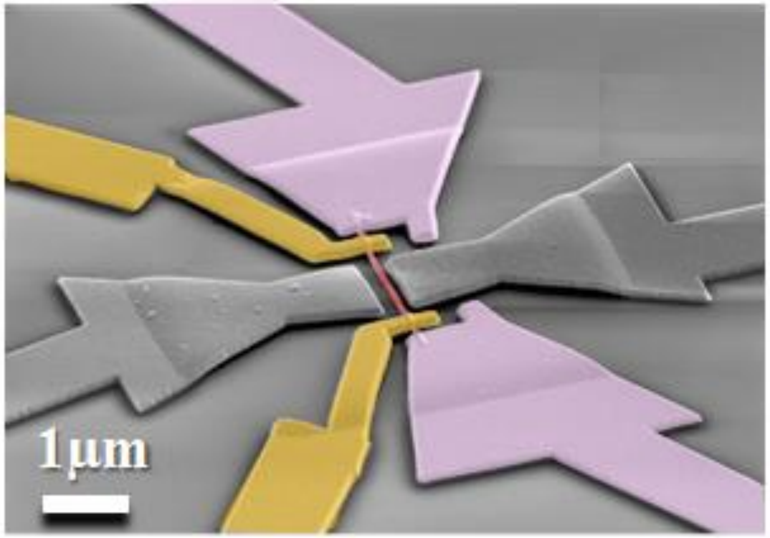
M.Rocci et al, submitted 2018



Suspended NW devices: strategies for gating?

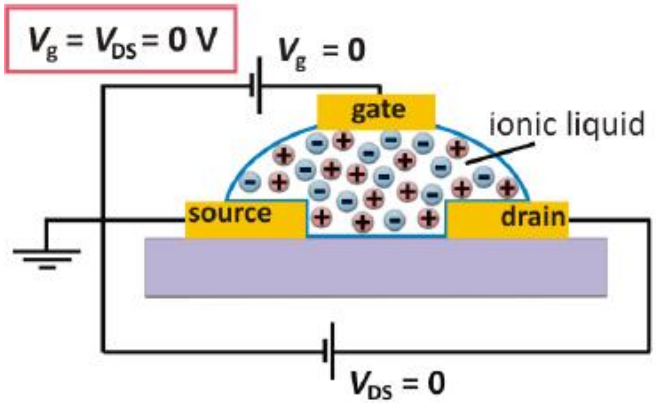
backgate, side gates ➔ poor modulation of σ at temperatures of interest

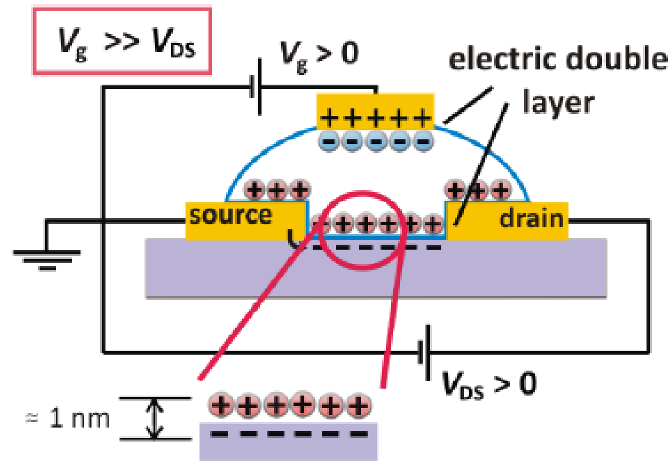


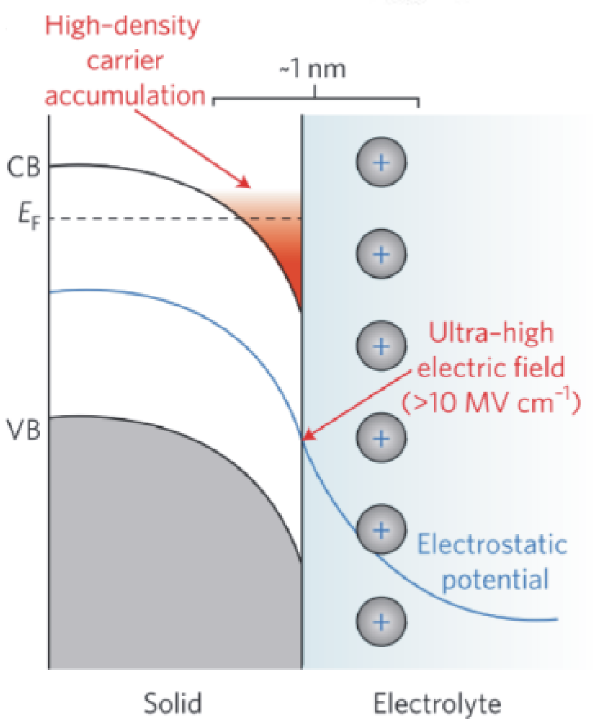


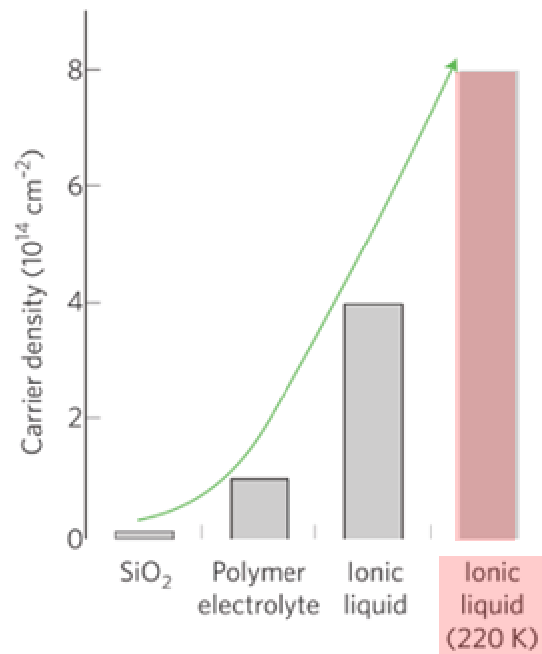
15% *R* modulation
within +/- 20V
(combining BG and SG)

Ionic liquid gating



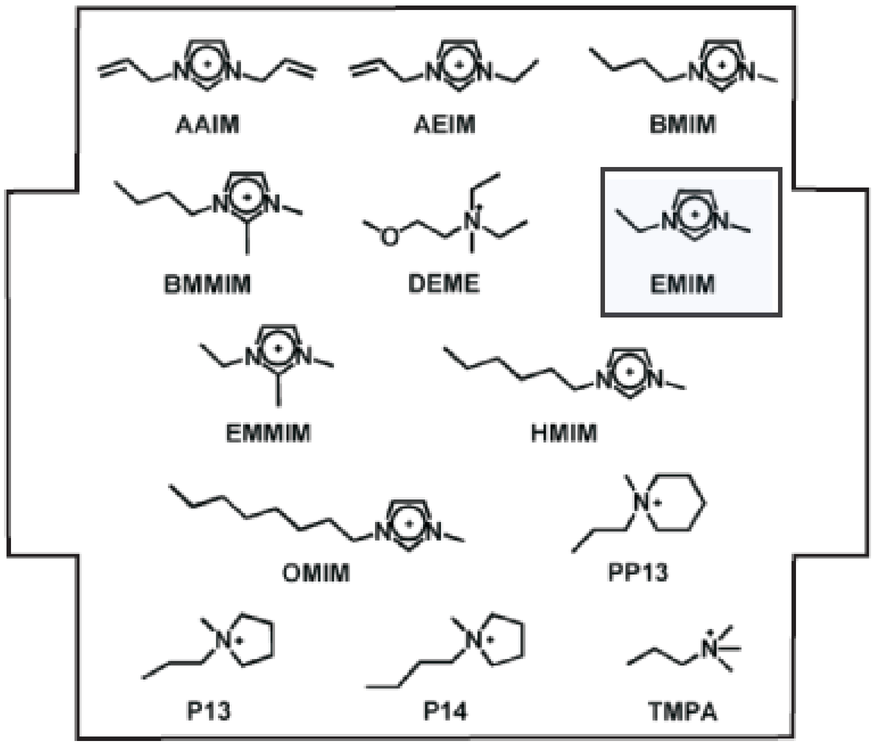




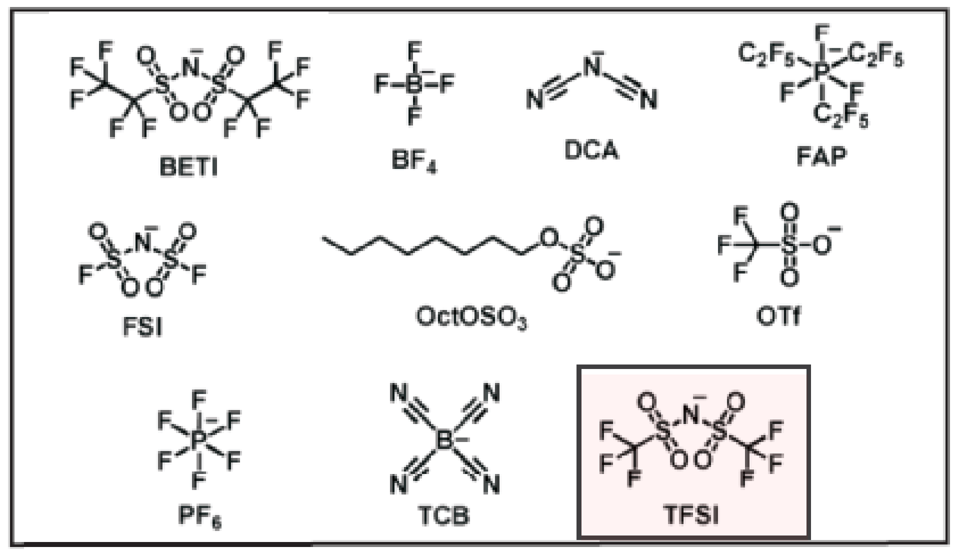


Zoology of ionic liquids

CATIONS

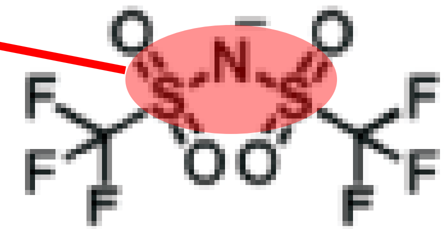


ANIONS



Zoology of ionic liquids

Made for each other!



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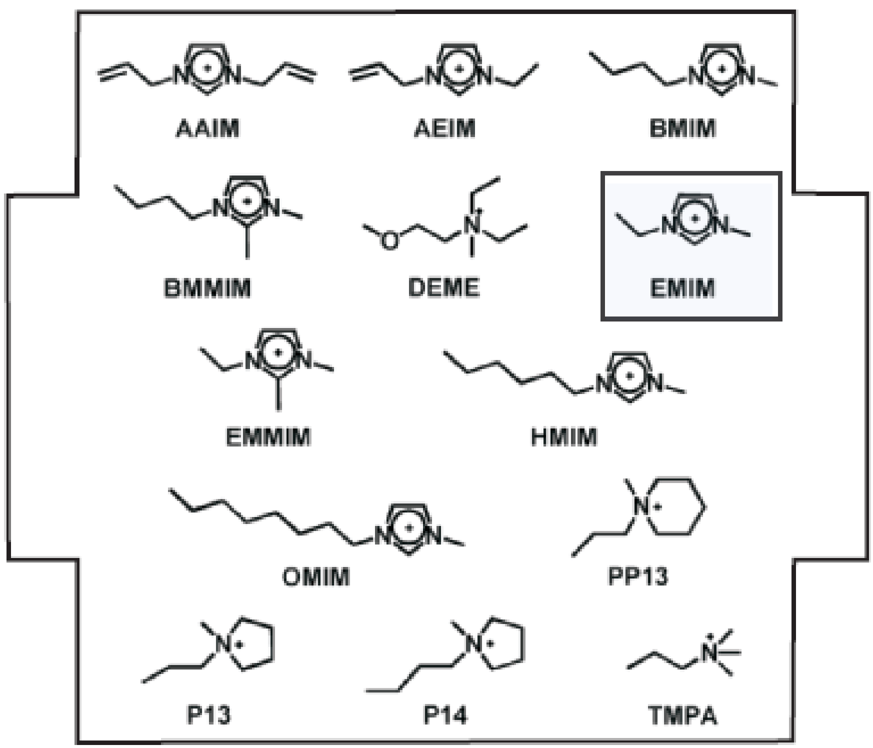
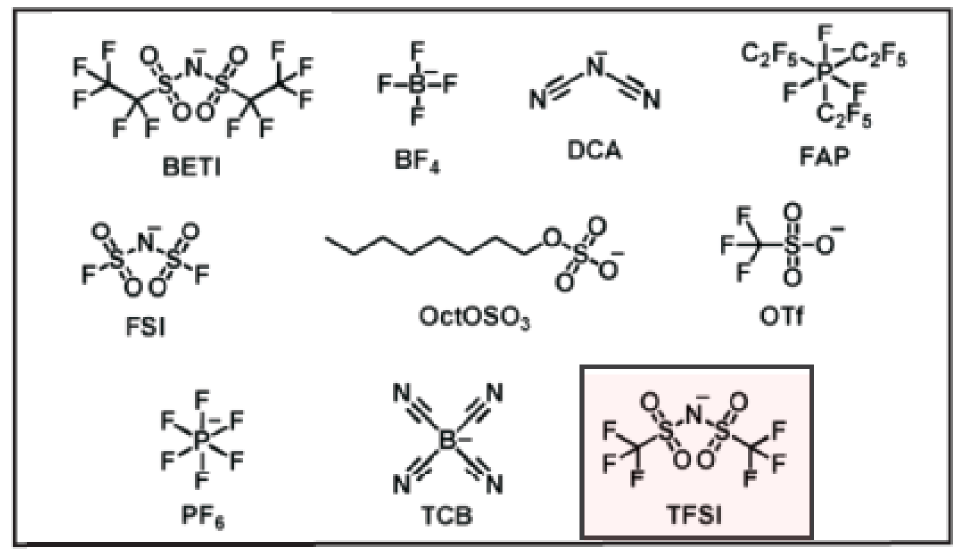
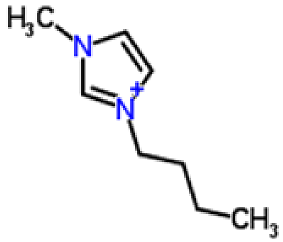
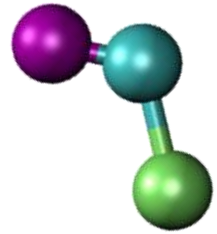
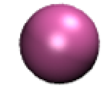


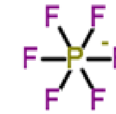


SCUOLA NORMALE SUPERIORE PISA



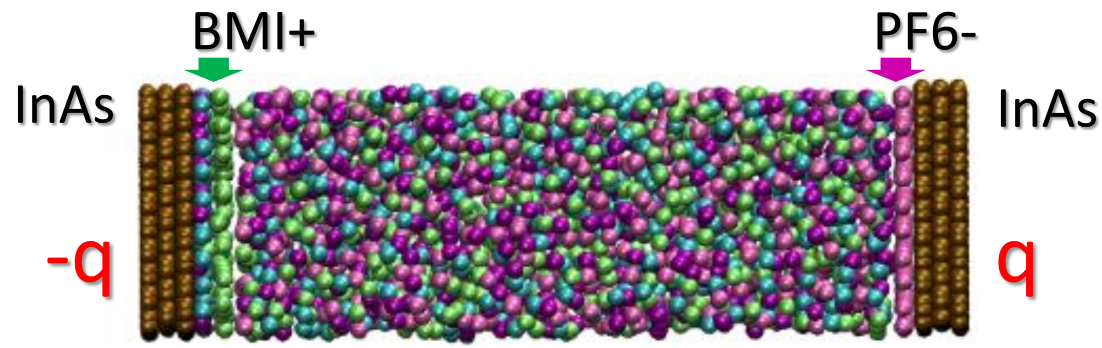


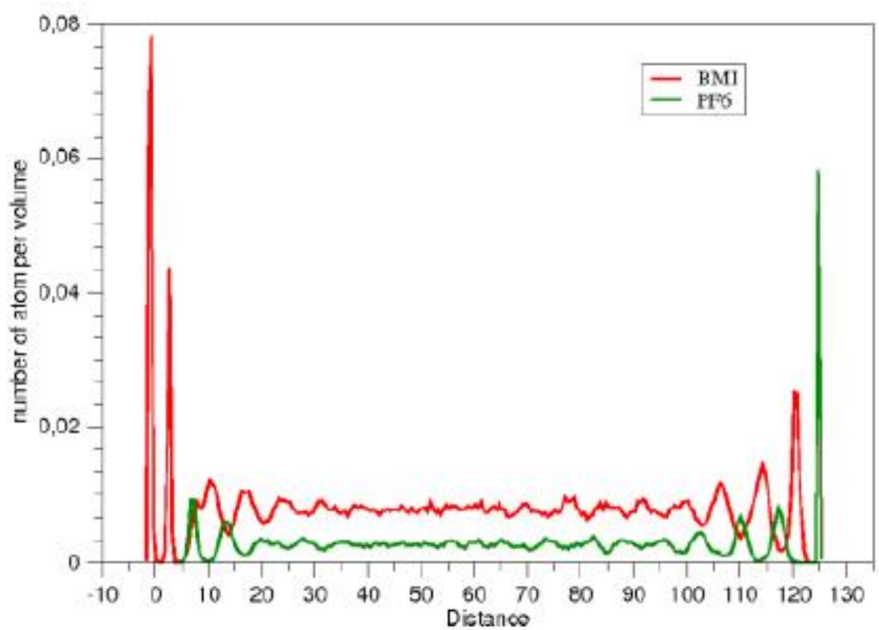




DFT
Hexafluorophosphate
(coarse grain)
+ layered electrodes
+ porosity

Molecular dynamics
diffusion coefficients





V. Tozzini

L. Bellucci

Many additional problems in simulations!

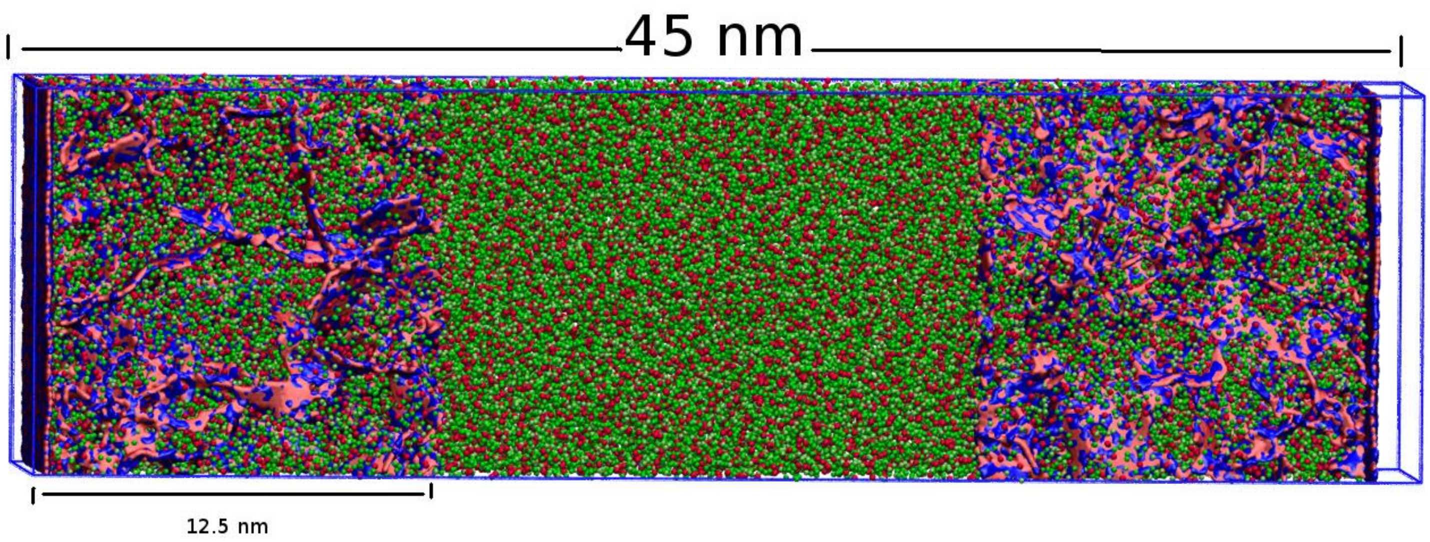
- ✓ realistic structure of the porosity (→ sponge builder)
- ✓ Size of the system
- ✓ The model of electrode must be polarizable

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

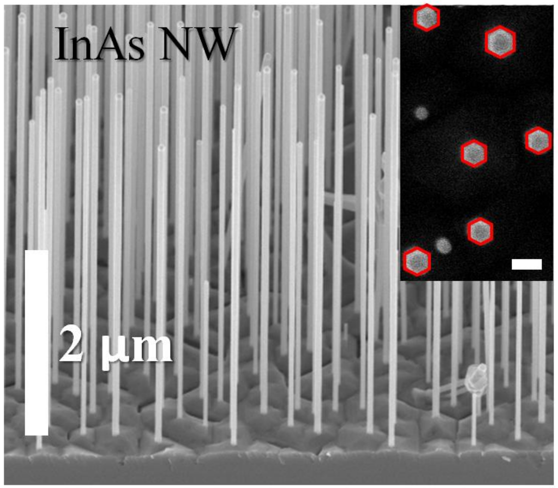


Electric Double Layer Transistors & Thermoelectrics

- Test-bed for confinement effects (DOS discretization) → ZT, $S^2\sigma$ enhancement

- oxides (SrTiO3, ZnO, Cu2O)
  Thin films
  2D materials
  SWCNTs
  NWs ??

Ionic liquid gated InAs NW FET: realization



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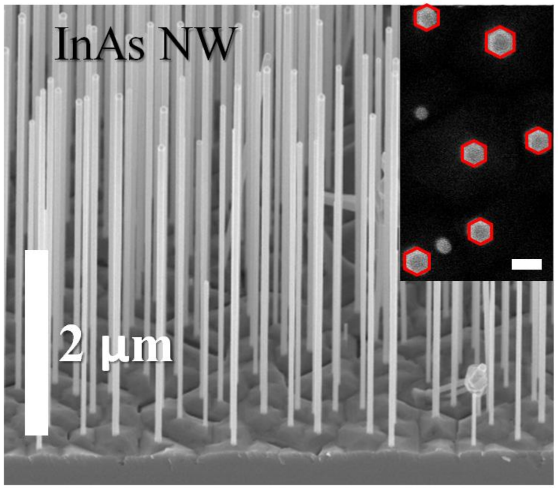

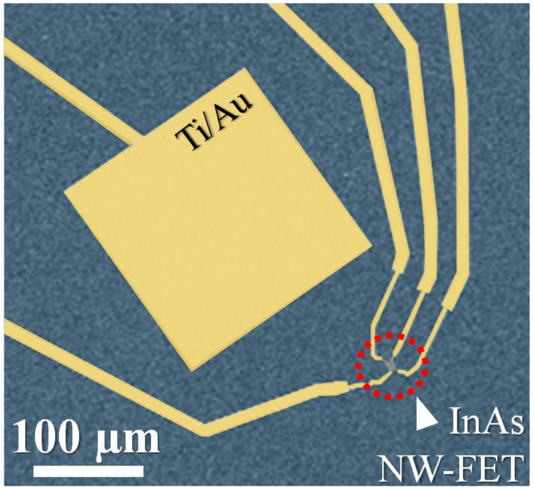

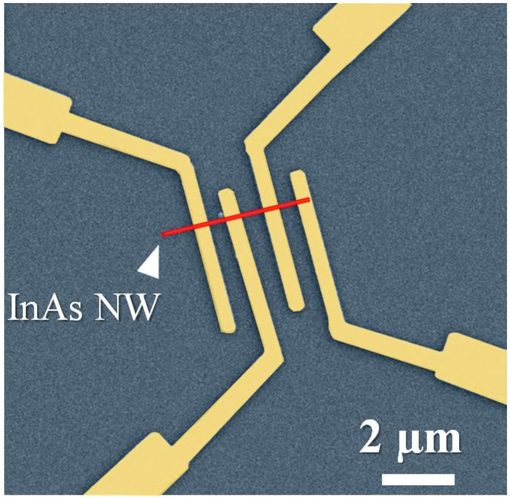

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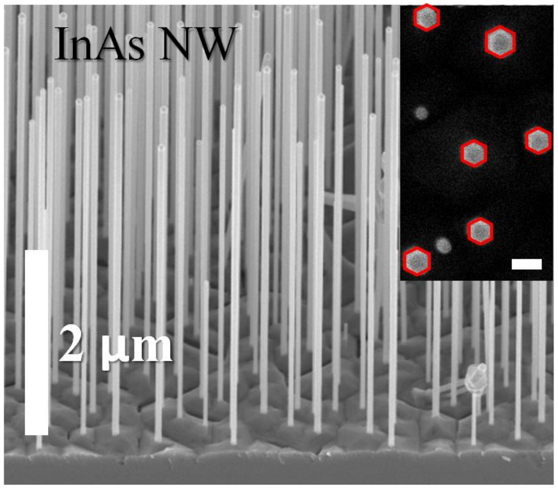

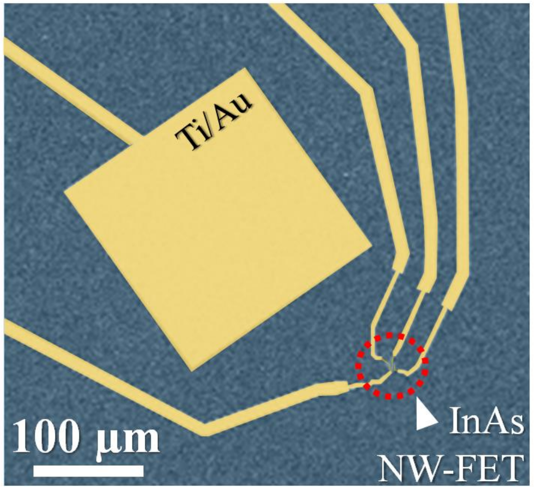

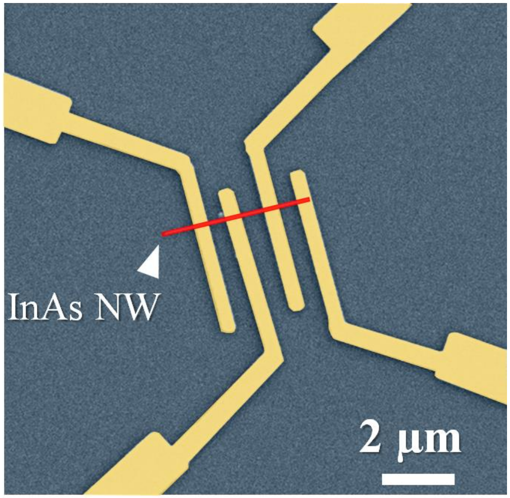

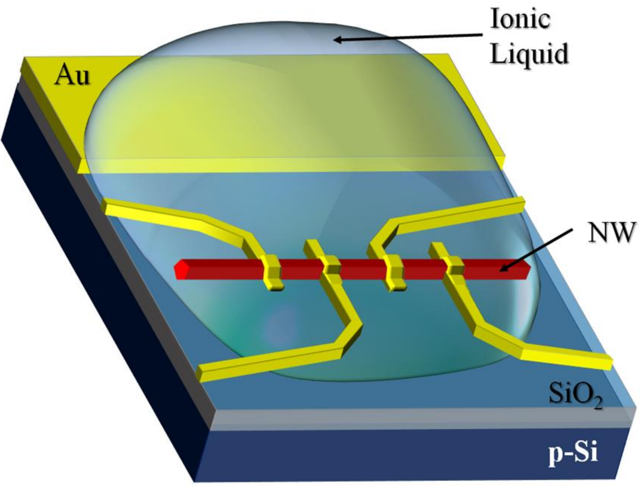

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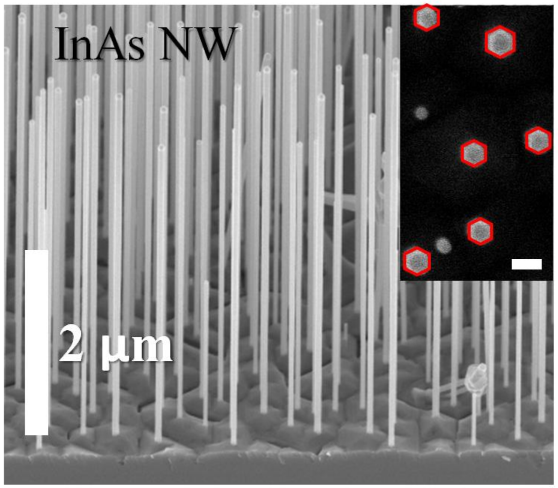

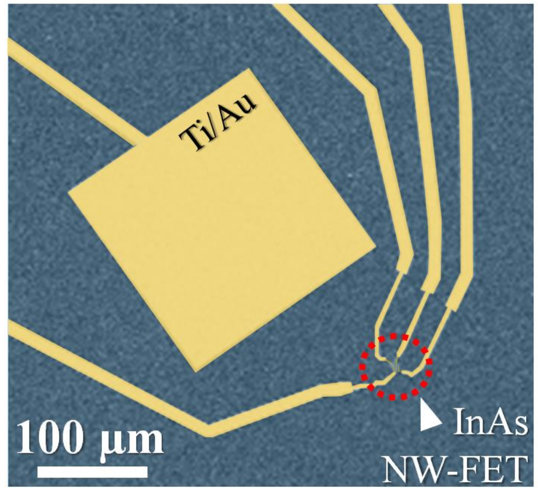

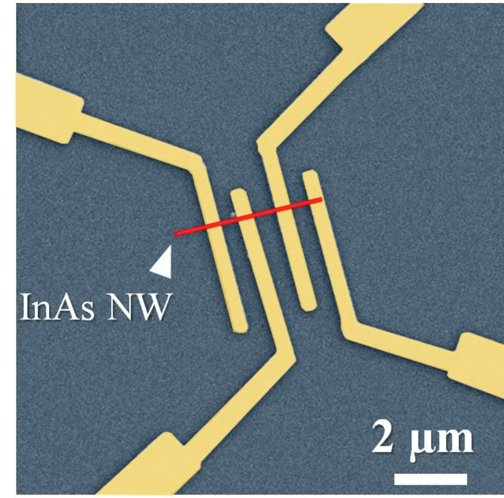

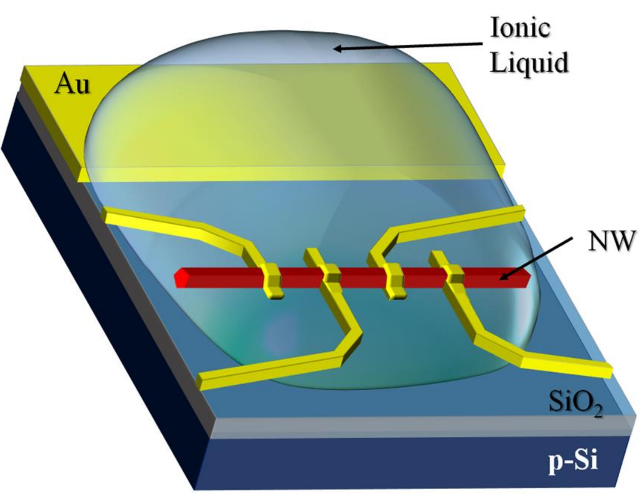

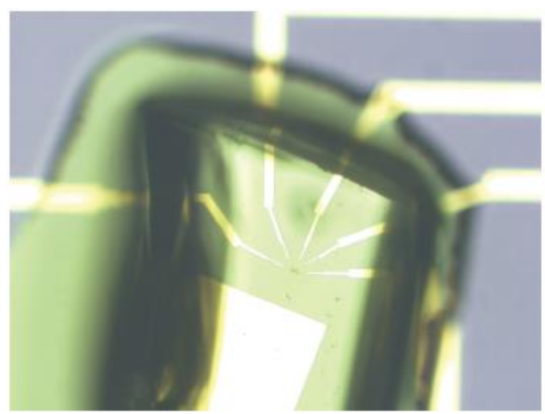

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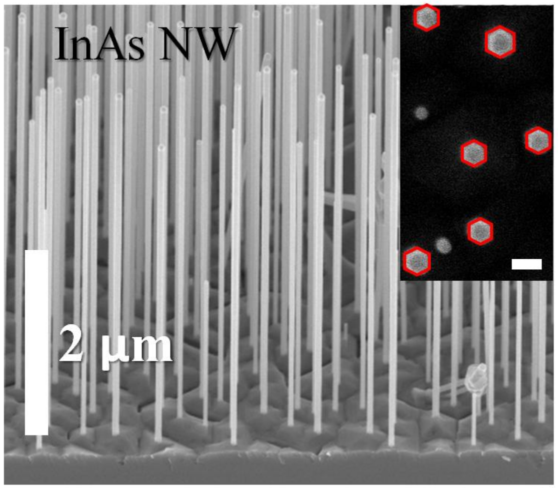
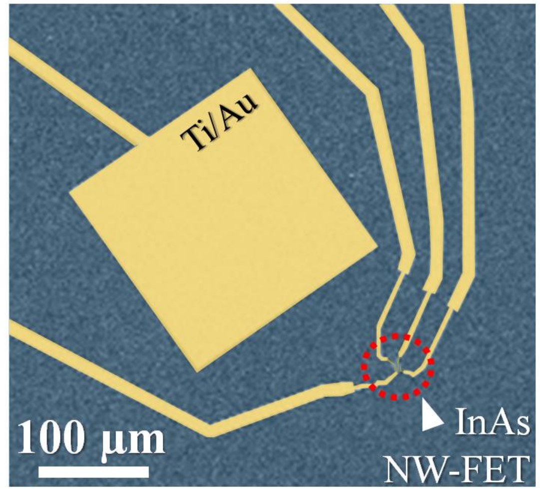
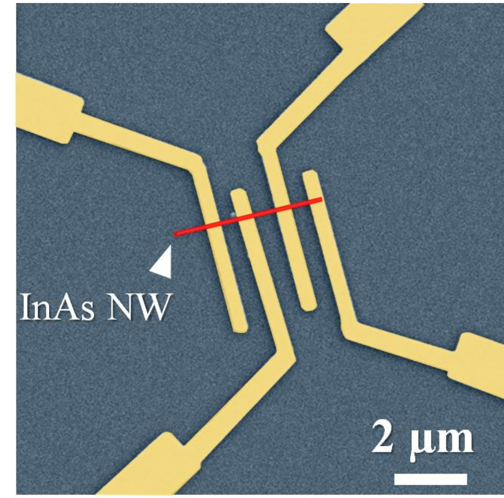
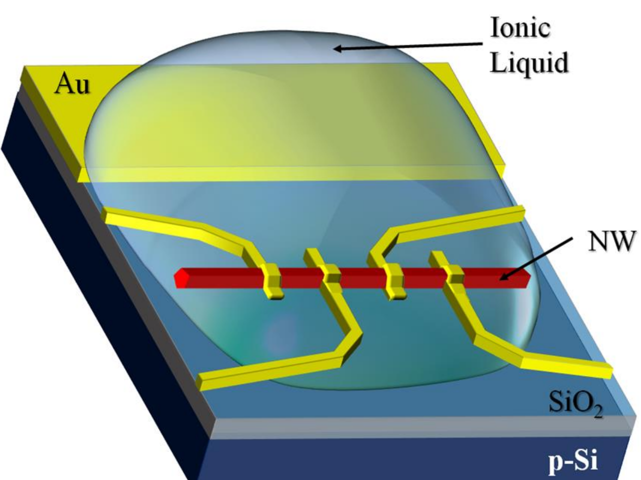
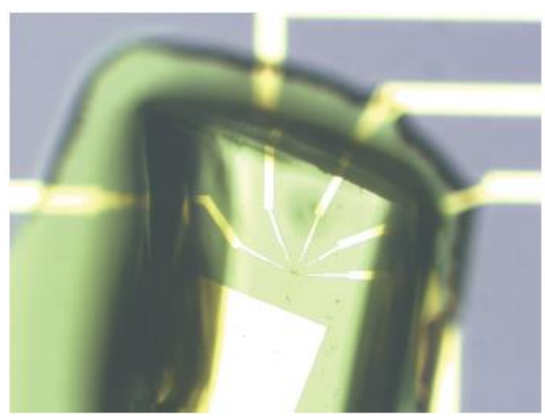


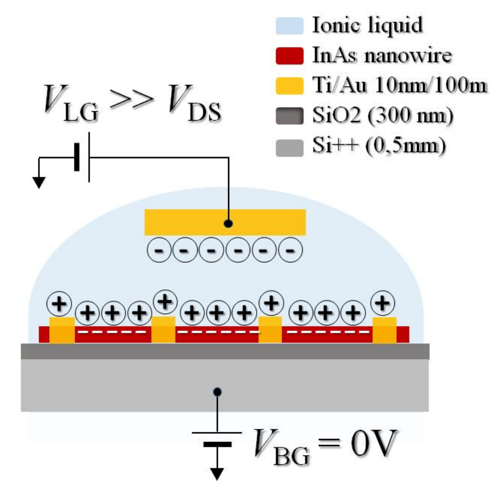




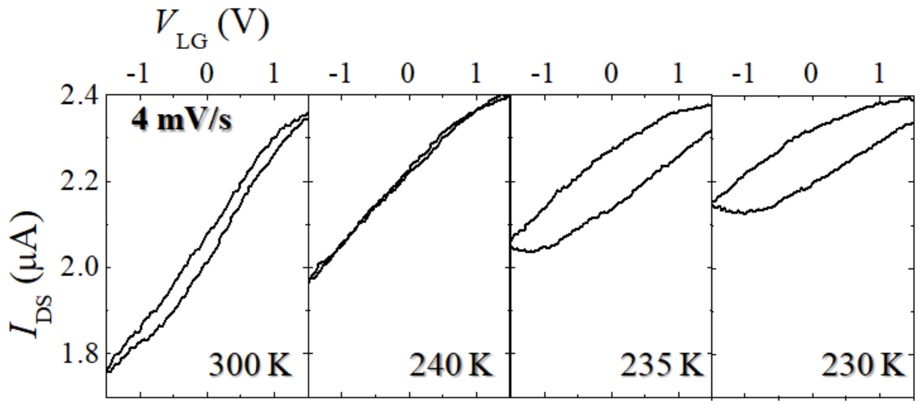
J. Lieb, … and F.Rossella, *submitted*







Hysteresis (getting rid of)



Parameter space:

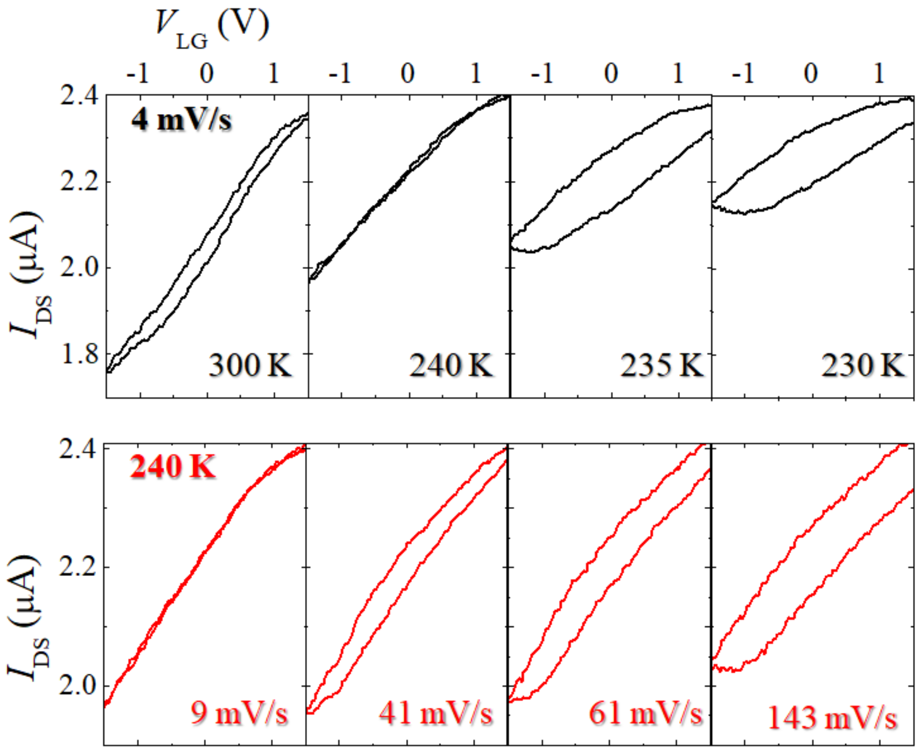
- Temperature

Hysteresis (getting rid of)

Parameter space:

- Temperature
- dV_{LG}/dt

(liquid gate voltage Sweep rate)



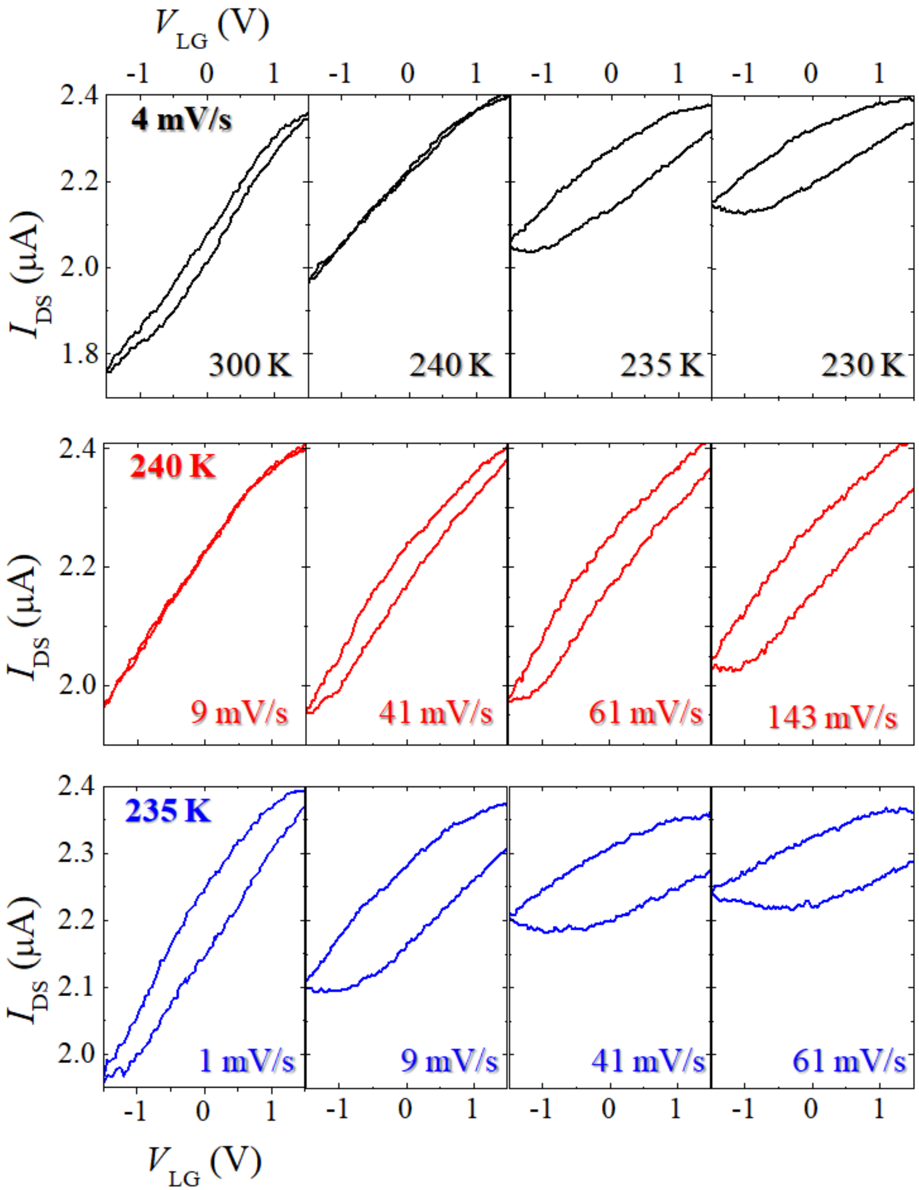
Hysteresis (getting rid of)

Parameter space:

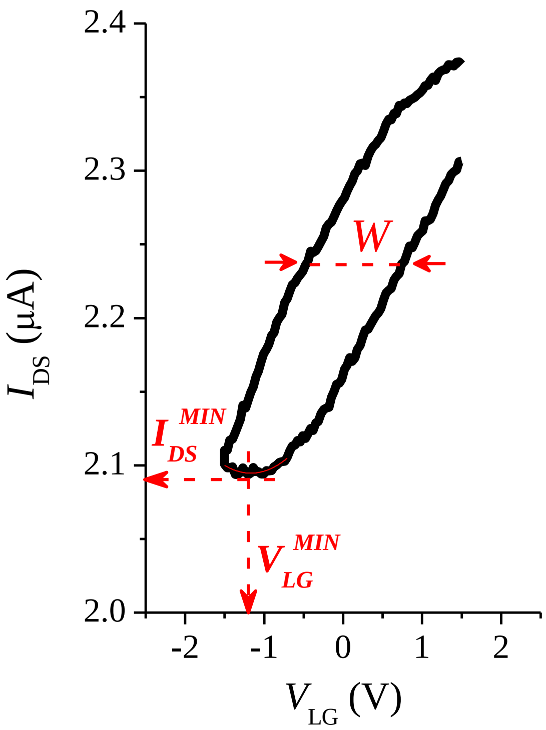
- Temperature
- dV_{LG}/dt

(liquid gate voltage Sweep rate)

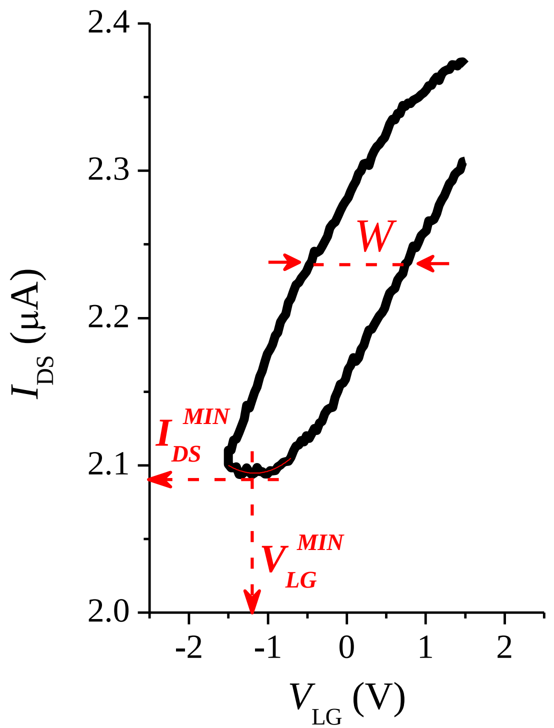
T = 240 K
$dV_{LG}/dt < 10$ mV/s

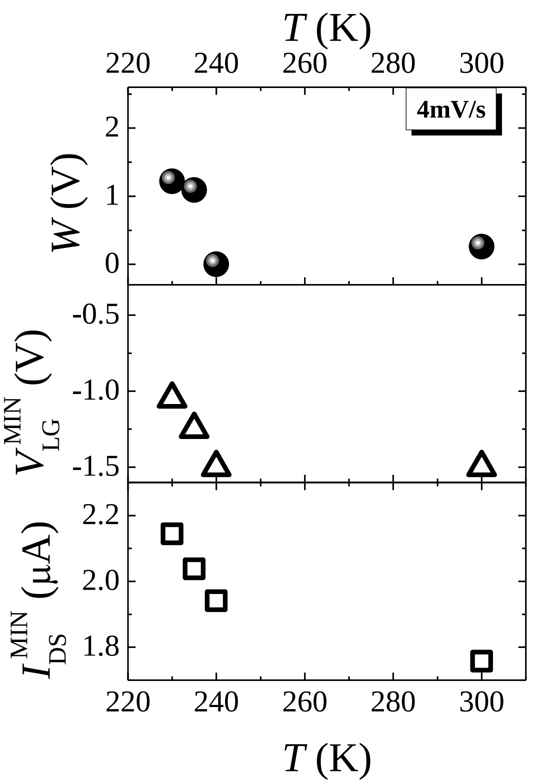


Hysteresis (getting rid of)



Hysteresis (getting rid of)





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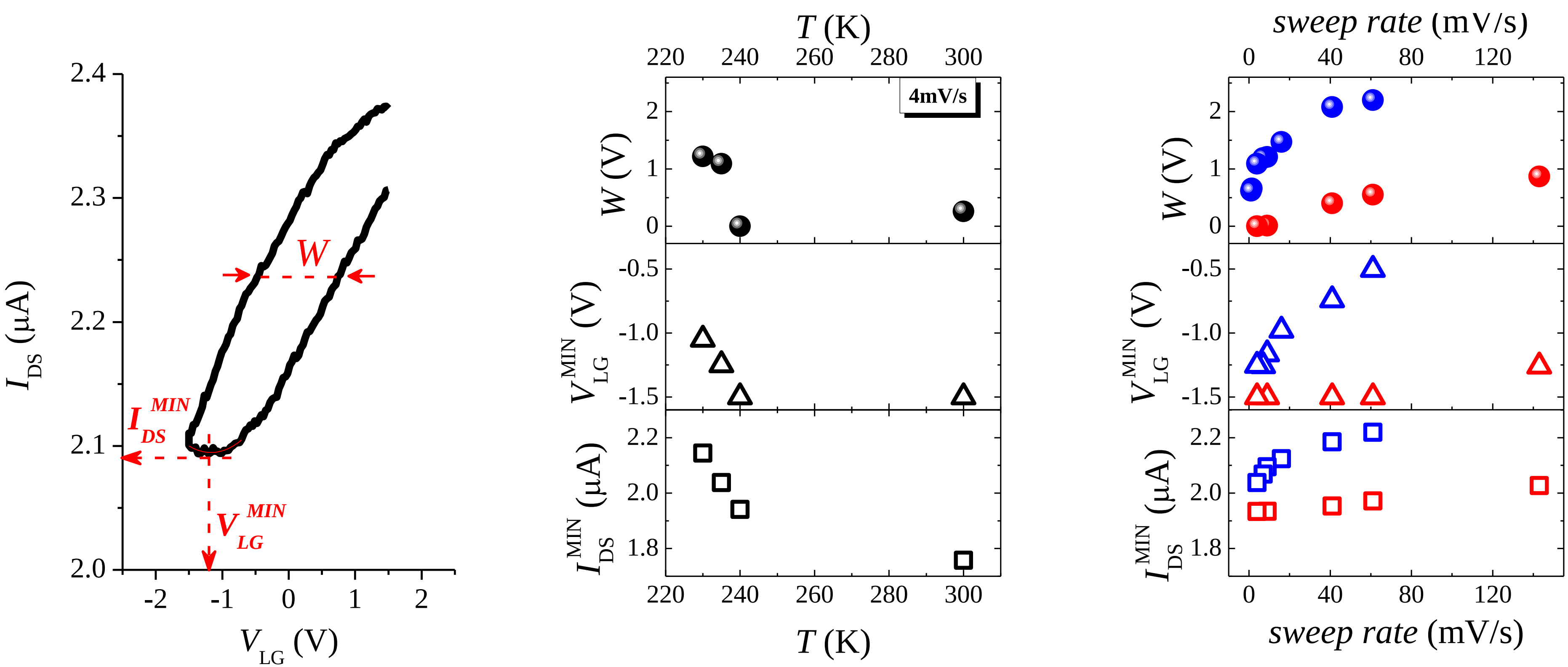
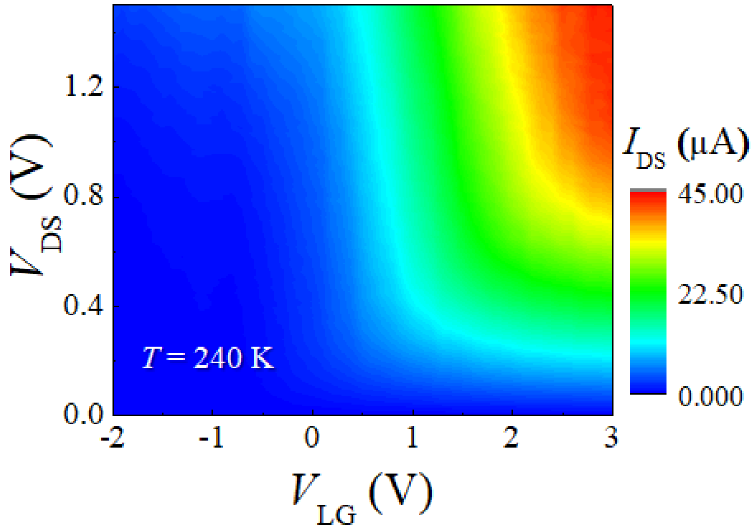
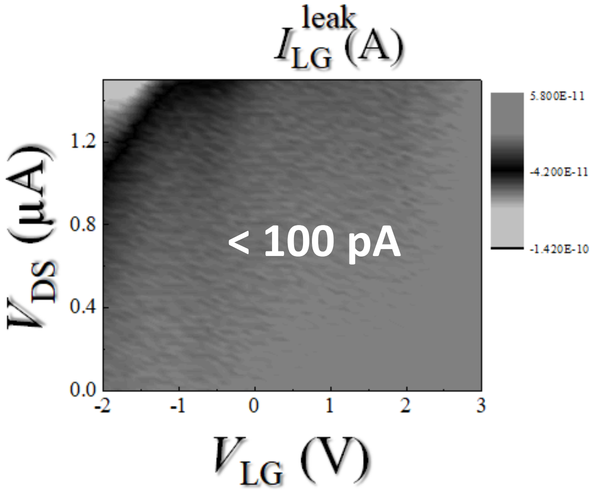


Ionic liquid gated InAs NW FET: operation

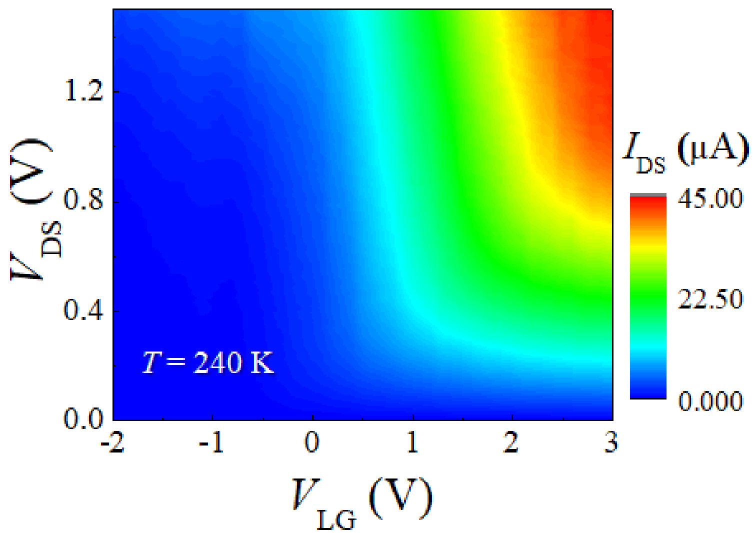
Full pinch-off

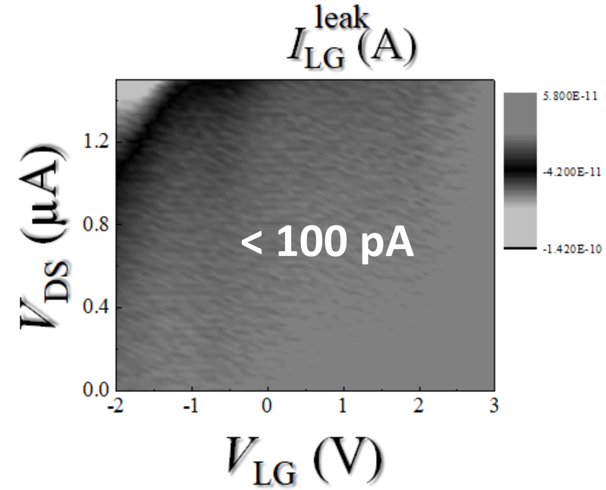




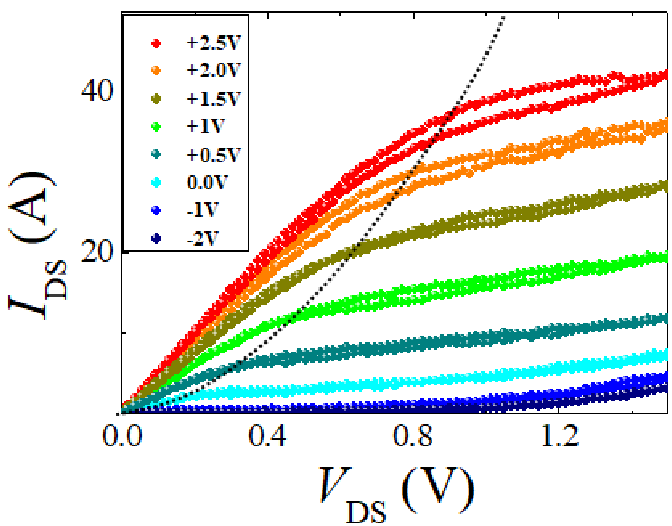
Ionic liquid gated InAs NW FET: operation

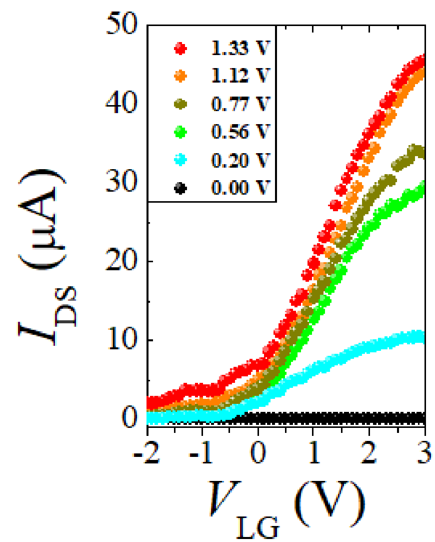
Full pinch-off





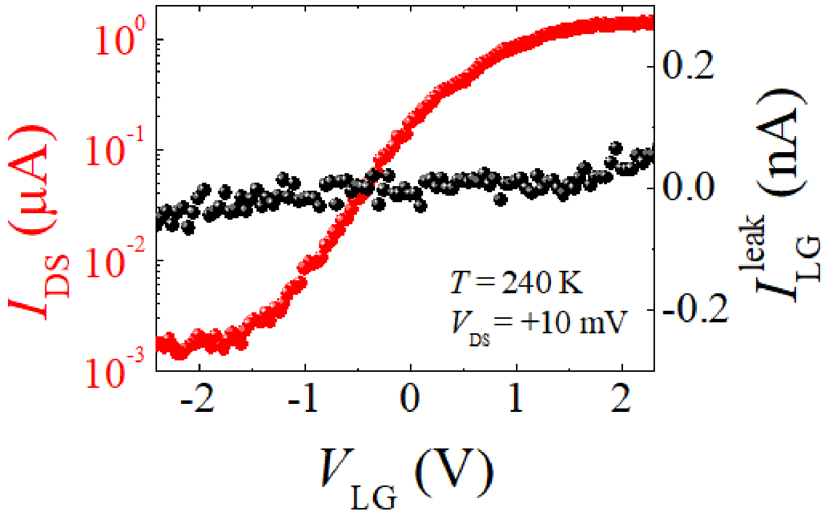
Linear & saturation regions





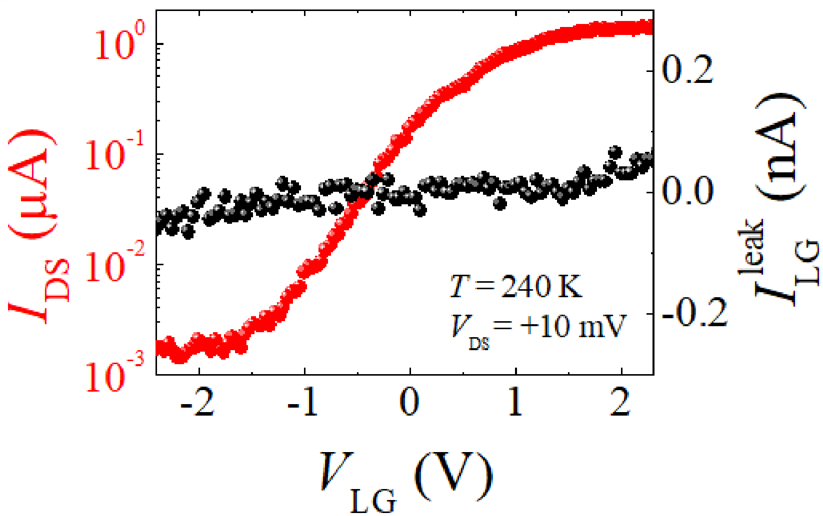
Ionic Liquid Gate vs back gate

LIQUID GATE

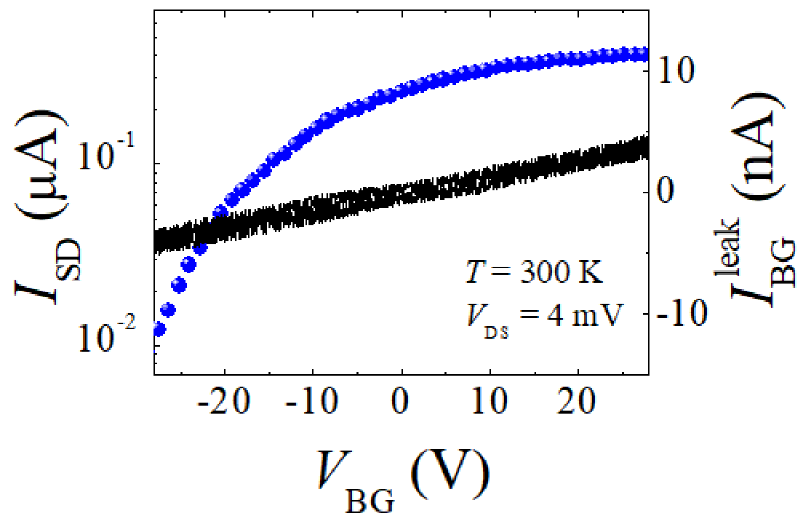


Ionic Liquid Gate vs back gate

LIQUID GATE



BACK GATE (no liquid)



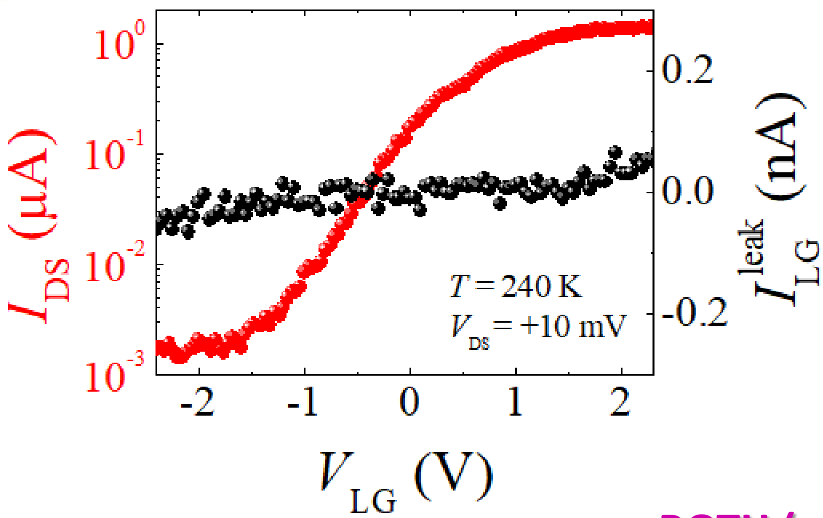
n ≈ $5*10^{17}$ cm^{-3}

μ ≈ 200 cm^2/Vs

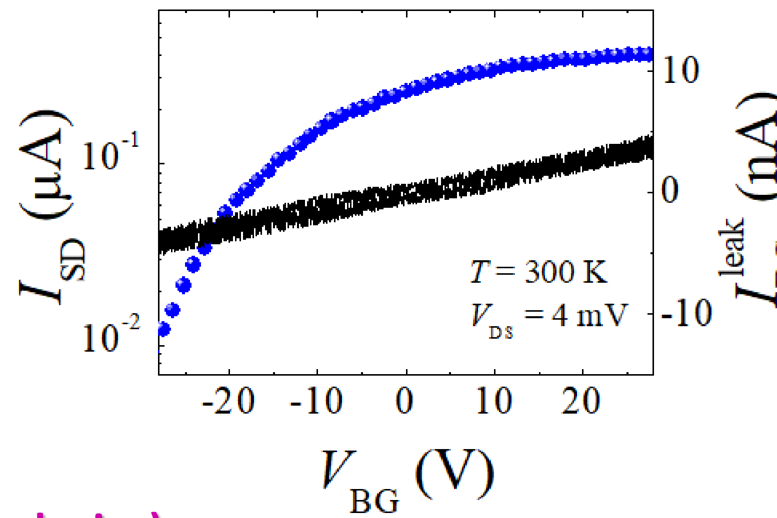
C_{BG} ≈ 60 aF

Ionic Liquid Gate vs back gate

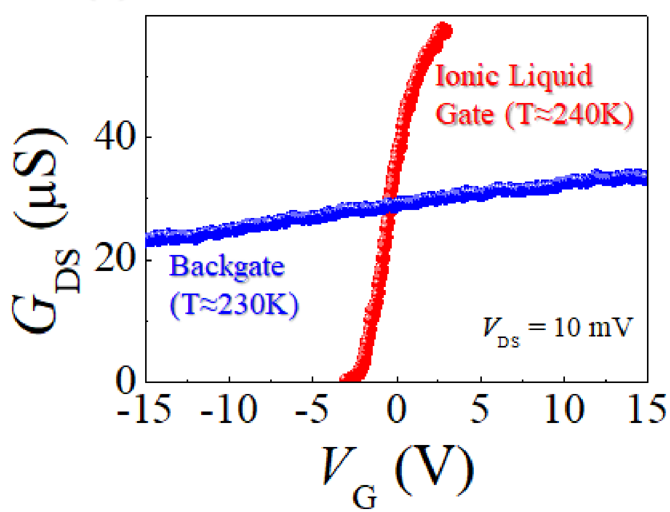
LIQUID GATE



BACK GATE (no liquid)



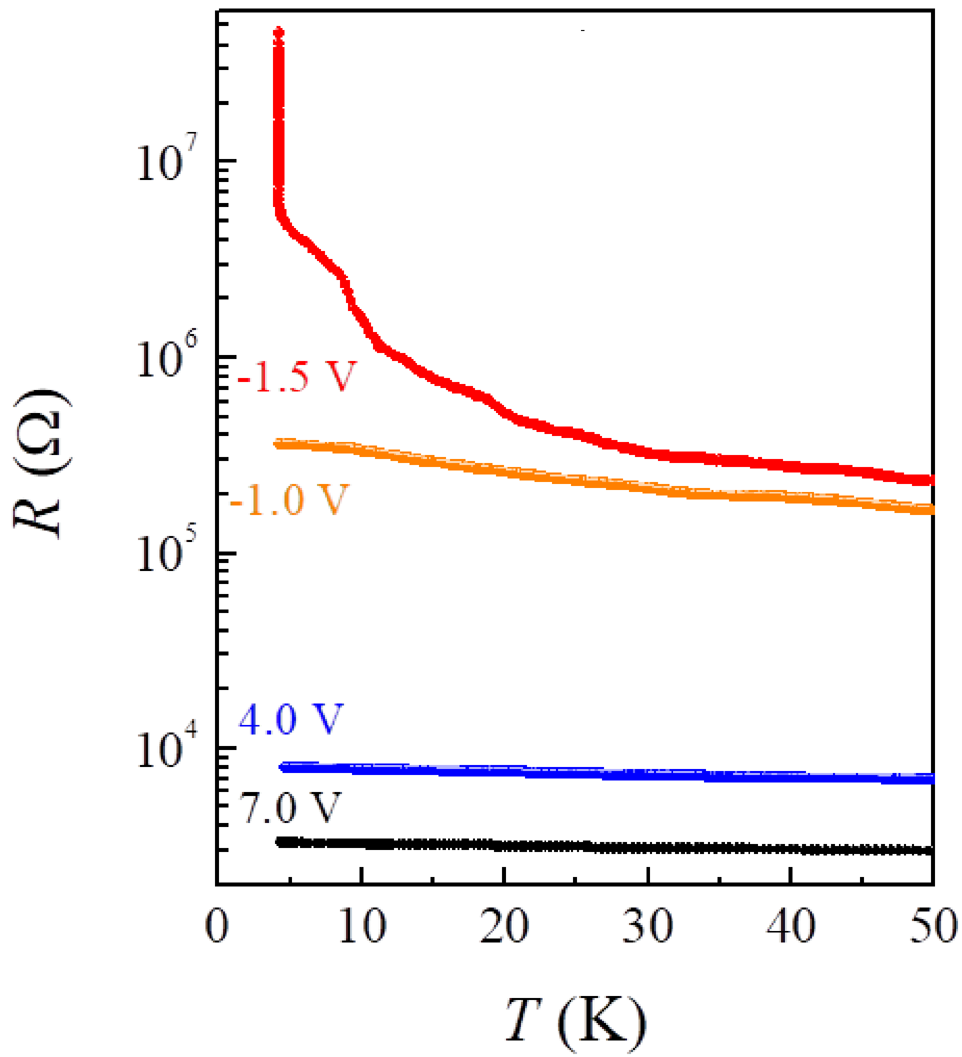
BOTH (same device)



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

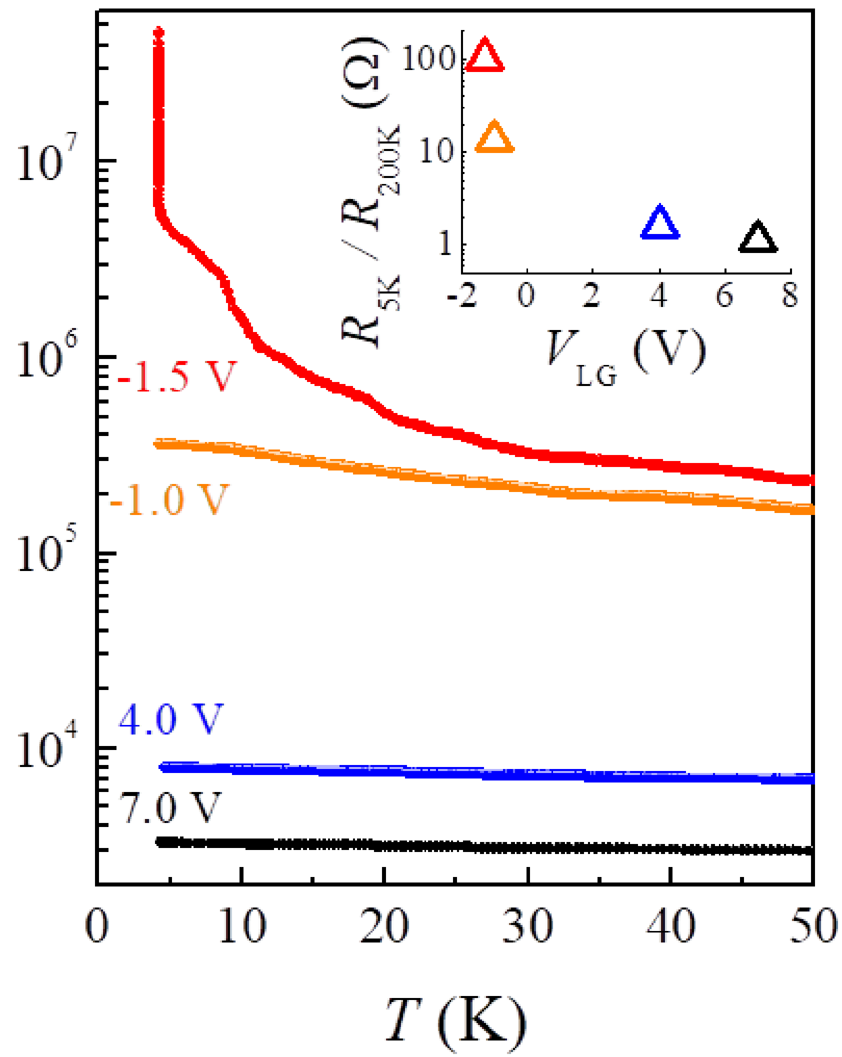
n ≈ 5*10^{17} cm^{-3}
μ ≈ 200 cm^2/Vs
C_{BG} ≈ 60 aF

Gate induced transition



Gate induced transition

V_{LG} << 0V
semiconductor



V_{LG} >> 0 V
Metal-like

Summary

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

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

- Suspended NW thermoelectrics
- Charge induced phase transition in 2D and 1D
- Ambipolar transport
- Dynamically controlled p-n junctions

SCUOLA NORMALE SUPERIORE PISA

CNR NANO PISA NEST


Valeria Demontis


Domenic Prete


Valentina Zannier


Daniele Ercolani


Lucia Sorba


Fabio Beltram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CRIEPI
Central Research Institute of Electric Power Industry

NÉEL institut



B. Sacepe
J. Lieb

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QUANTUM HALL EDGE STATE TUNNELING

Pisa
(Lungarno Pacinotti)