Elettroni nel nanomondo:
carica, calore ed effetti quantici nelle nanostrutture

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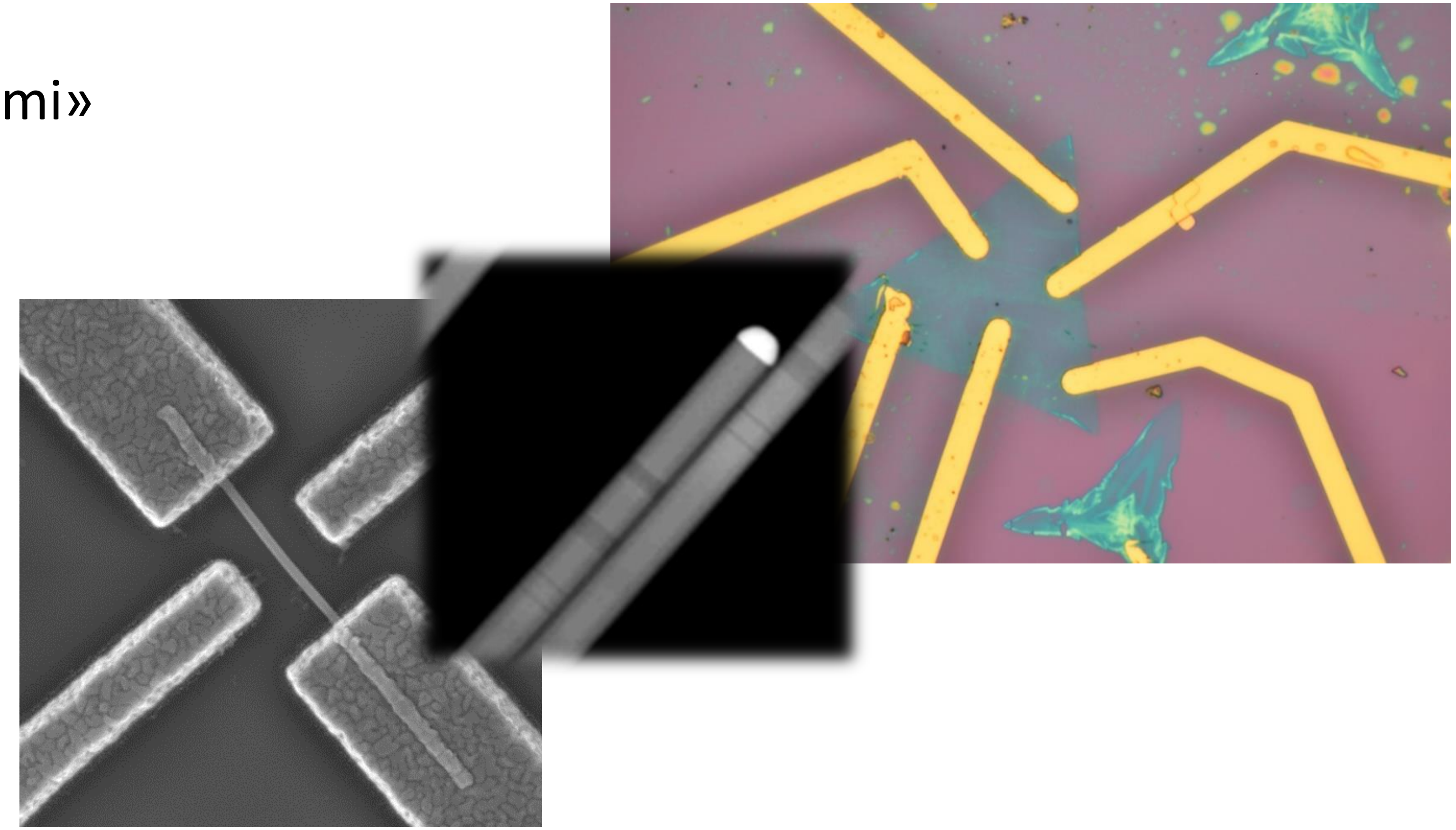
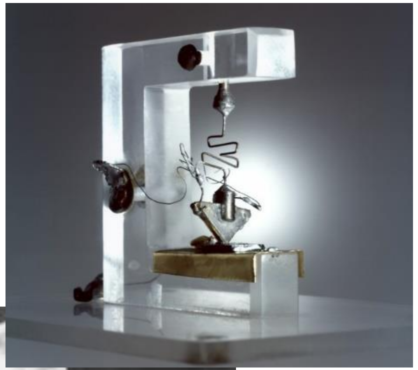
Dipartimento di Fisica «E.Fermi»
Università di Pisa



1972
BCS theory

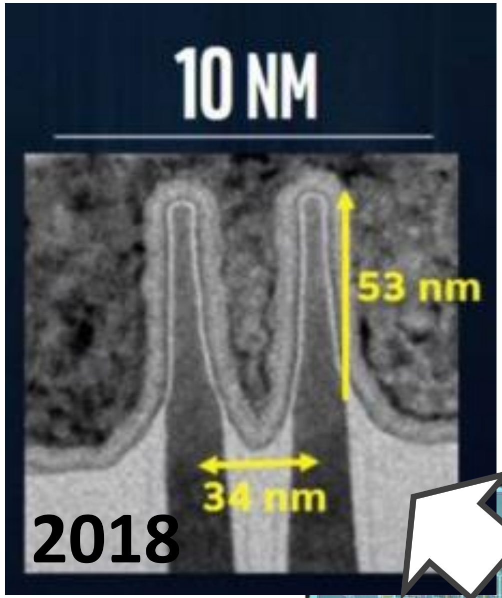
John Bardeen



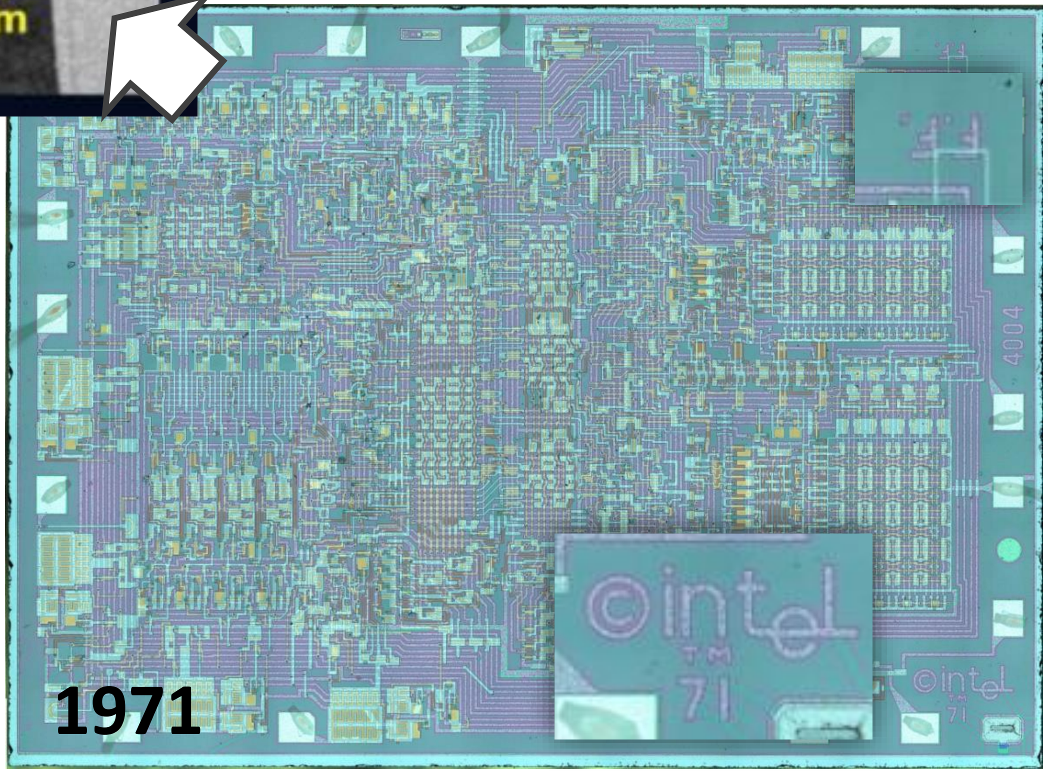
Walter Brattain

1956
transistor

William B. Shockley



Federico Faggin



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Scienza ⇄ Tecnologia

Miniaturizzazione

1959
«Plenty of room at the bottom!»

Perché studiare le nanostrutture?

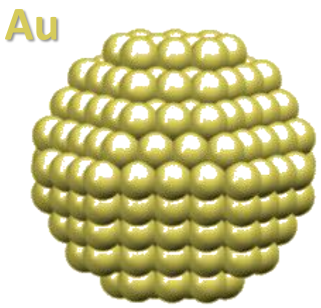
Piccolo rispetto a cosa?

Scale fisiche rilevanti:

- Distanza interatomica
- Energia di caricamento
- Lunghezza di coerenza
- Lunghezze di scattering
- …

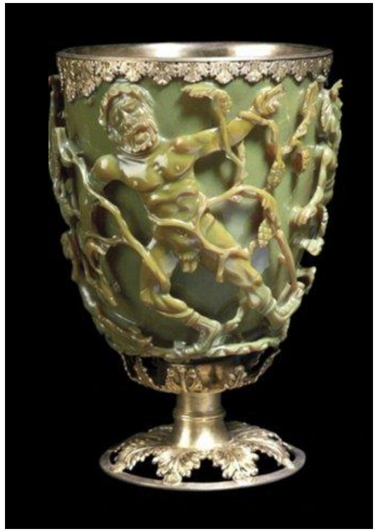
Perché studiare le nanostrutture?

Concetto #1: nanostrutture possono dare comportamenti diversi
(a volte qualitativamente diversi) dal limite «macro»



- ➢ Alto rapporto «superficie/volume»
- ➢ Temperatura di fusione ridotta (!) (legge di Thomson-Gibbs)
- ➢ Proprietà chimiche
- ➢ Proprietà ottiche
- ➢ ecc…

Coppa di Licurgo (IV secolo)
Nanotecnologia ante litteram



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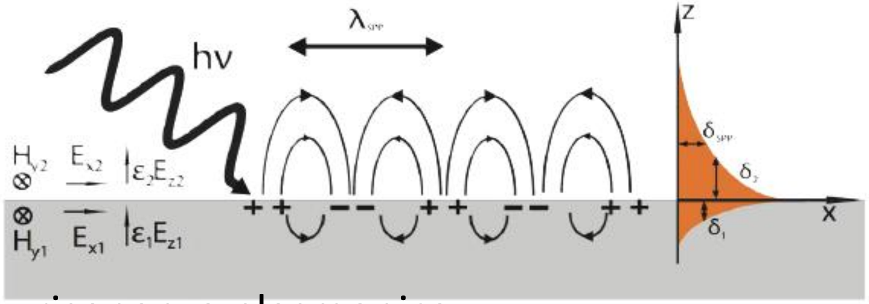
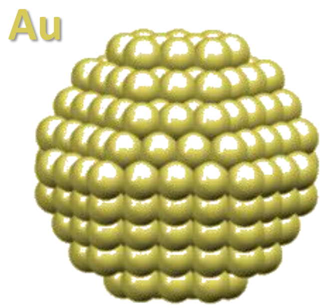


risonanza plasmonica

Perché studiare le nanostrutture?

Concetto #1: nanostrutture possono dare comportamenti diversi
(a volte qualitativamente diversi) dal limite «macro»
Concetto #2: la vera novità consiste nel controllo, comprensione, design
degli effetti nelle nanostrutture



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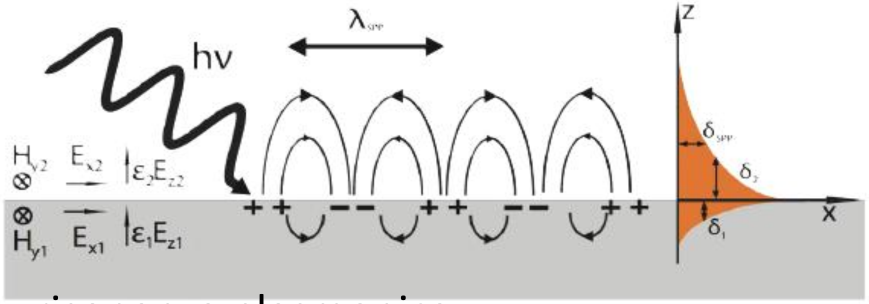

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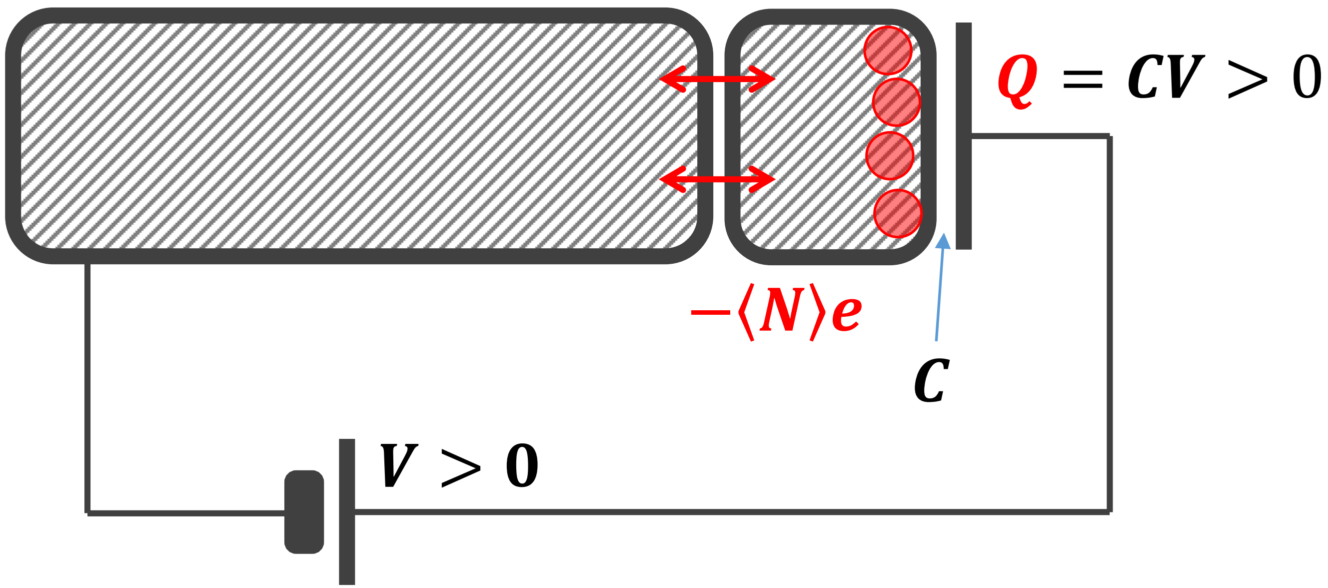
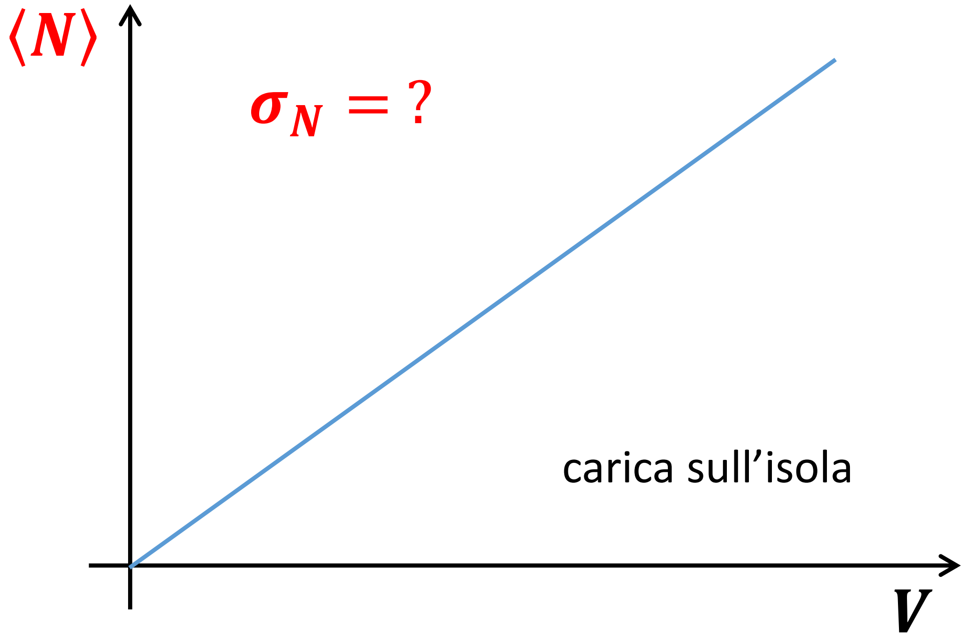
Sistemi a «singolo elettrone»

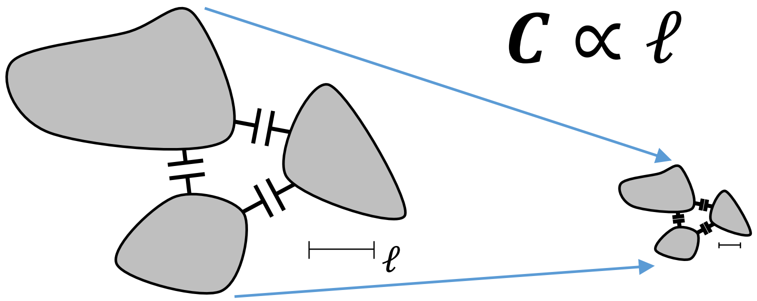




Energia di caricamento dell'isola

$$E_c = \frac{e^2}{C_\Sigma}$$

$$C \propto \ell$$



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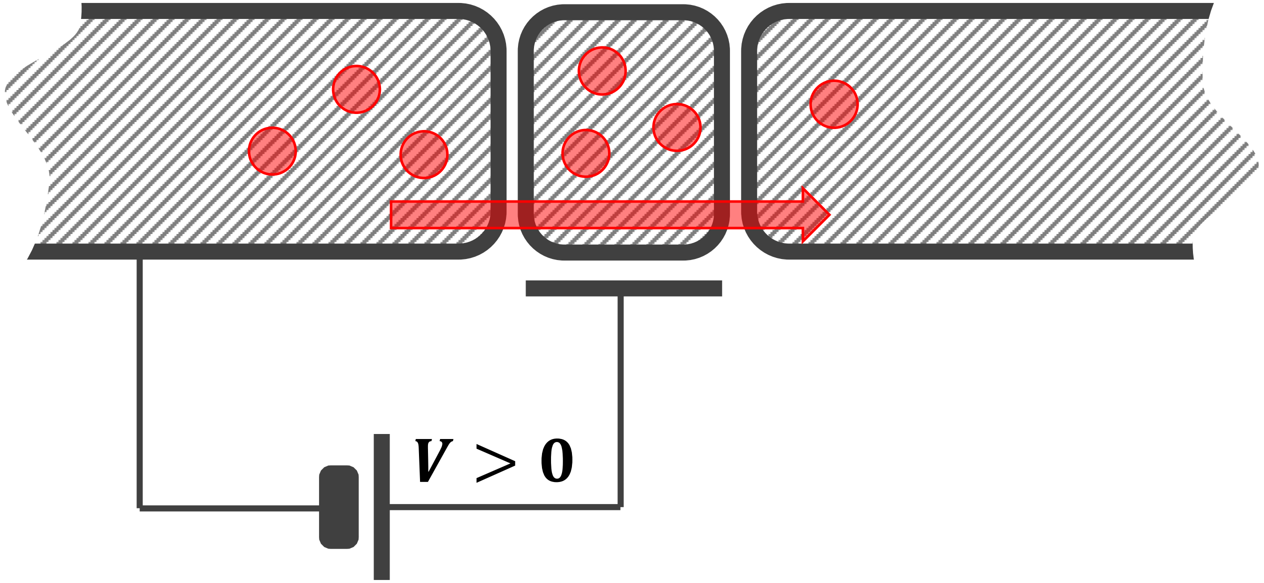
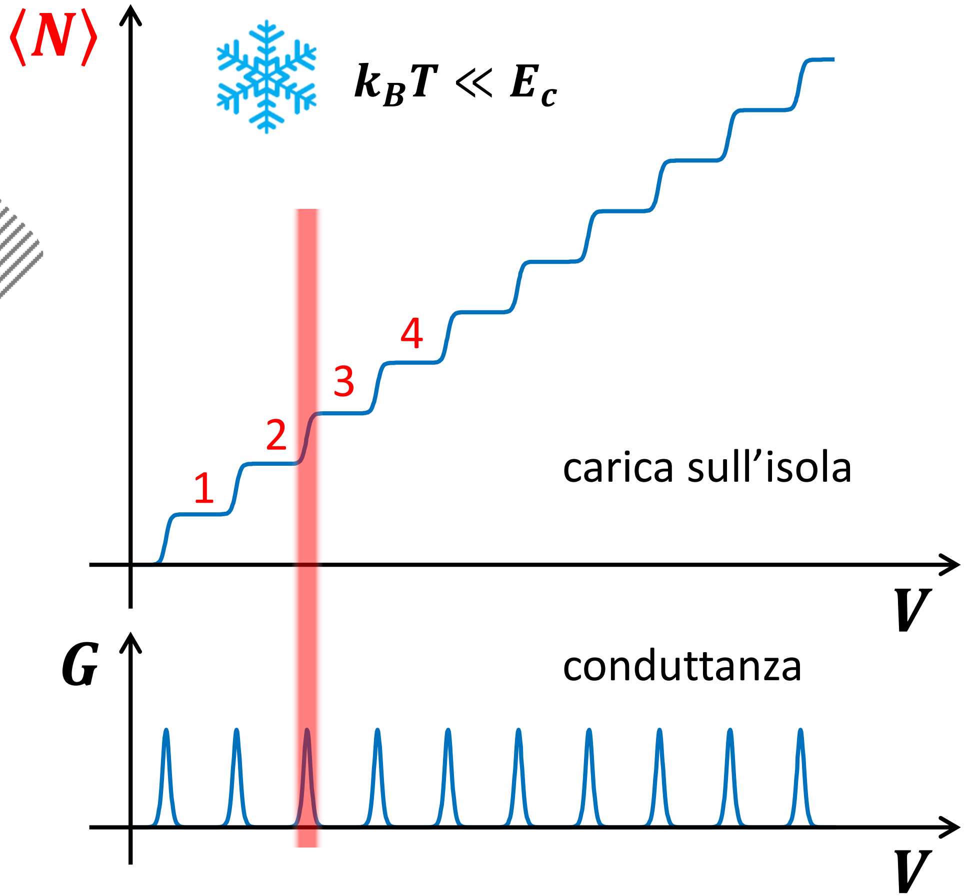




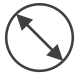
Energia di caricamento dell'isola

$$E_c = \frac{e^2}{C_\Sigma}$$

se usiamo…
300K (≈25meV)

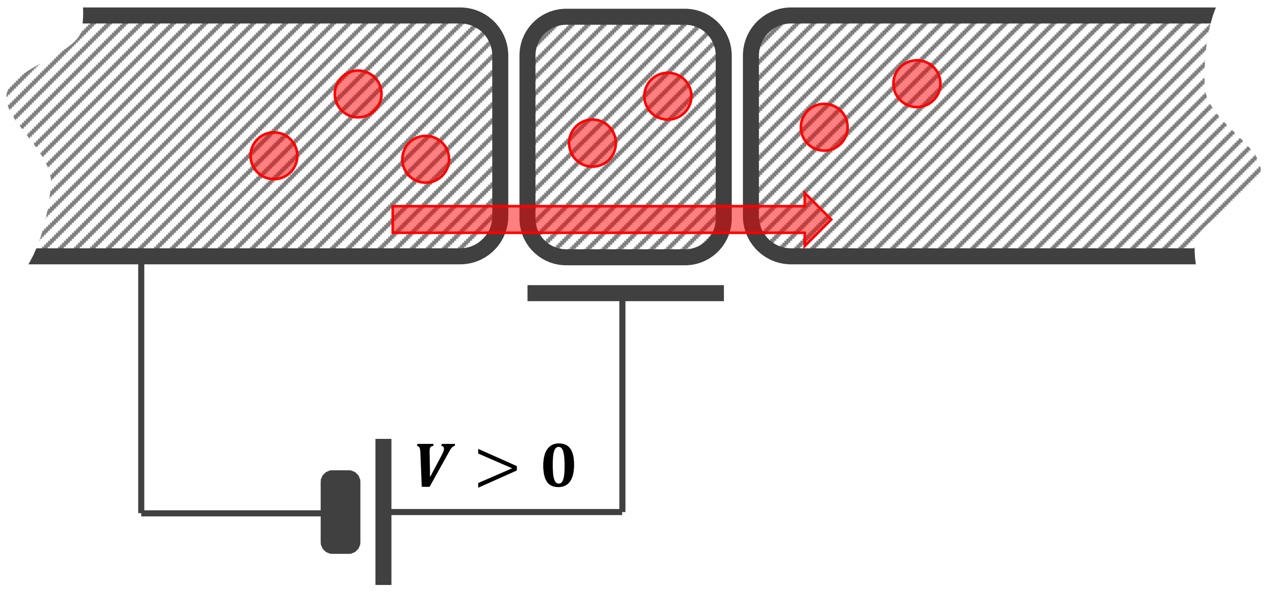
la scala corrispondente è
≈6aF (6e-18F!)

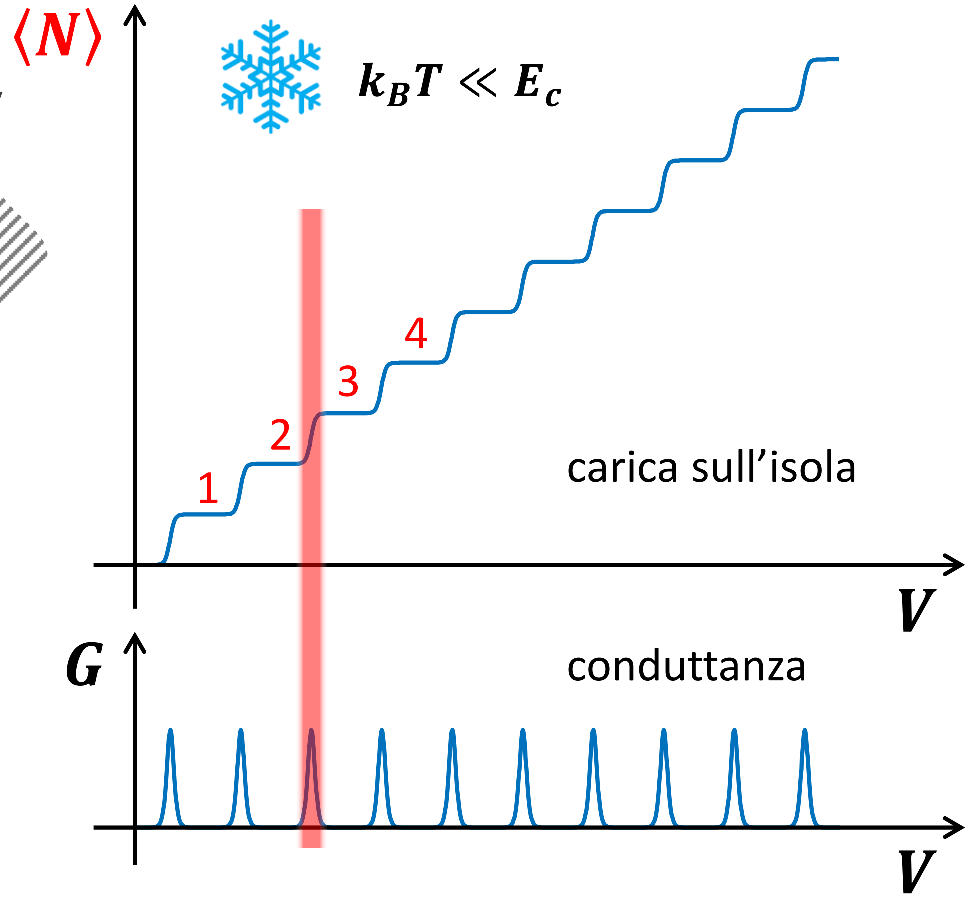
100nm



Self-capacitance ≈6aF

Sistemi a «singolo elettrone»





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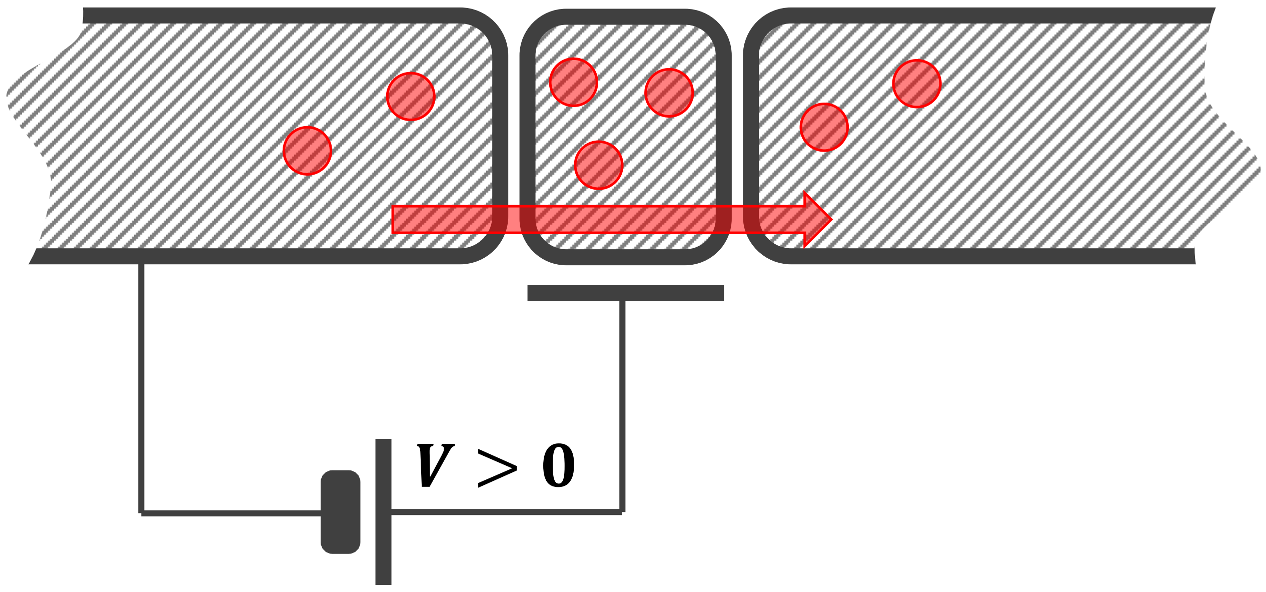

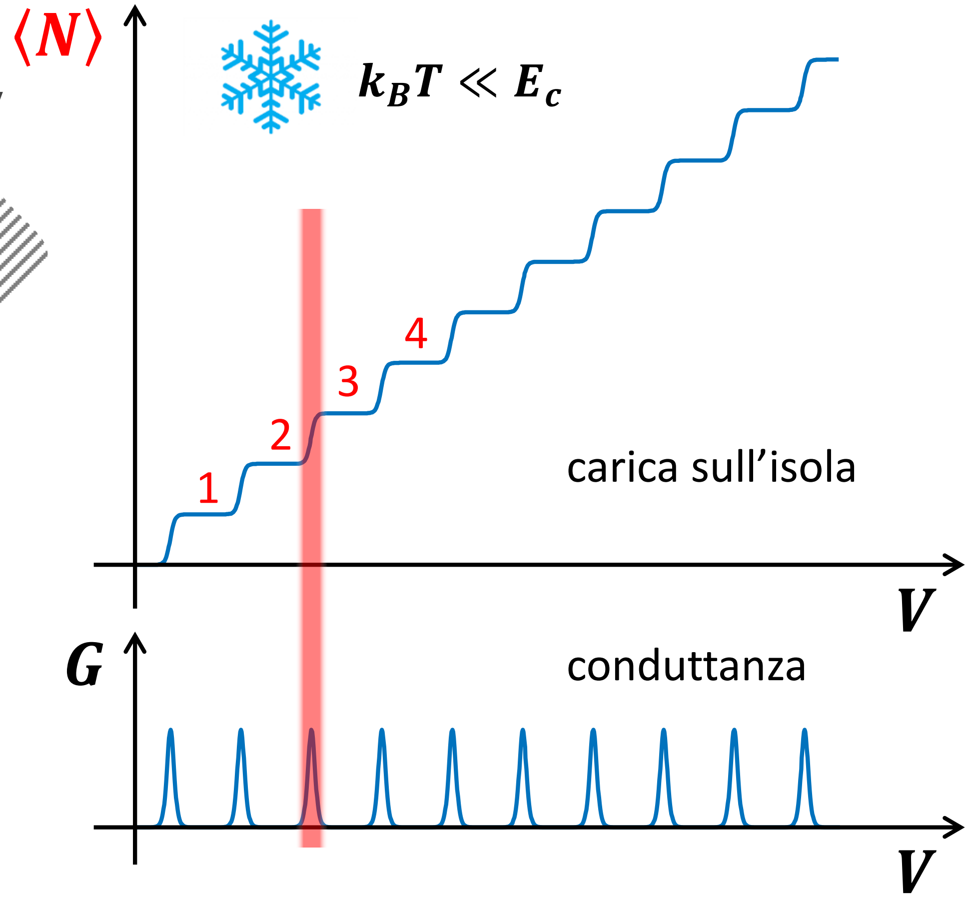

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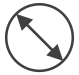

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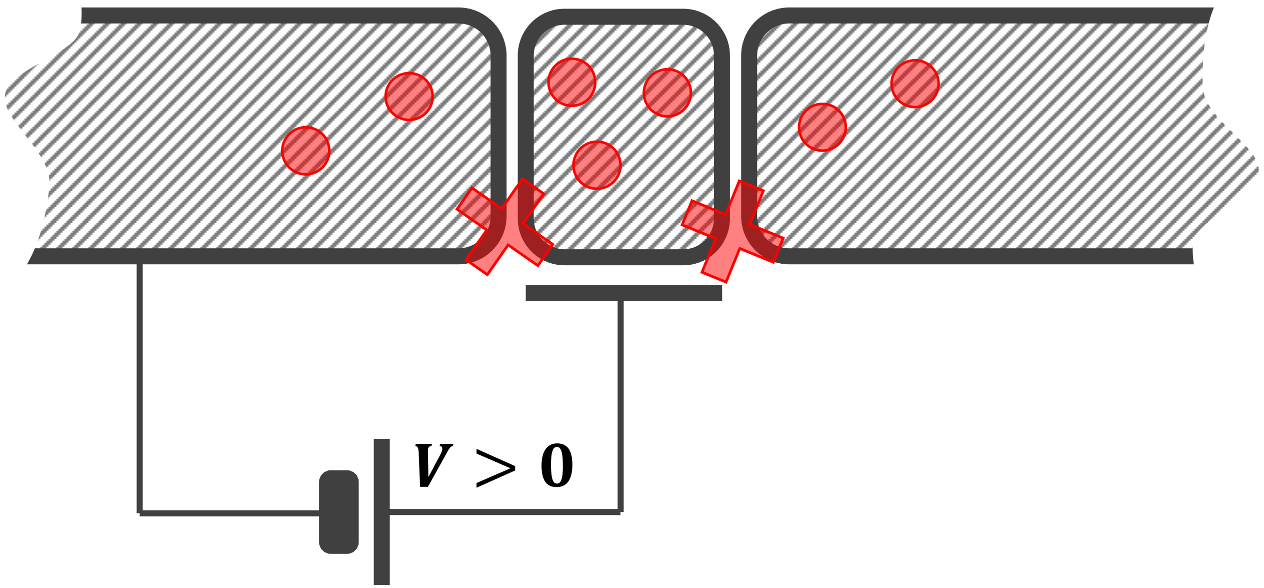

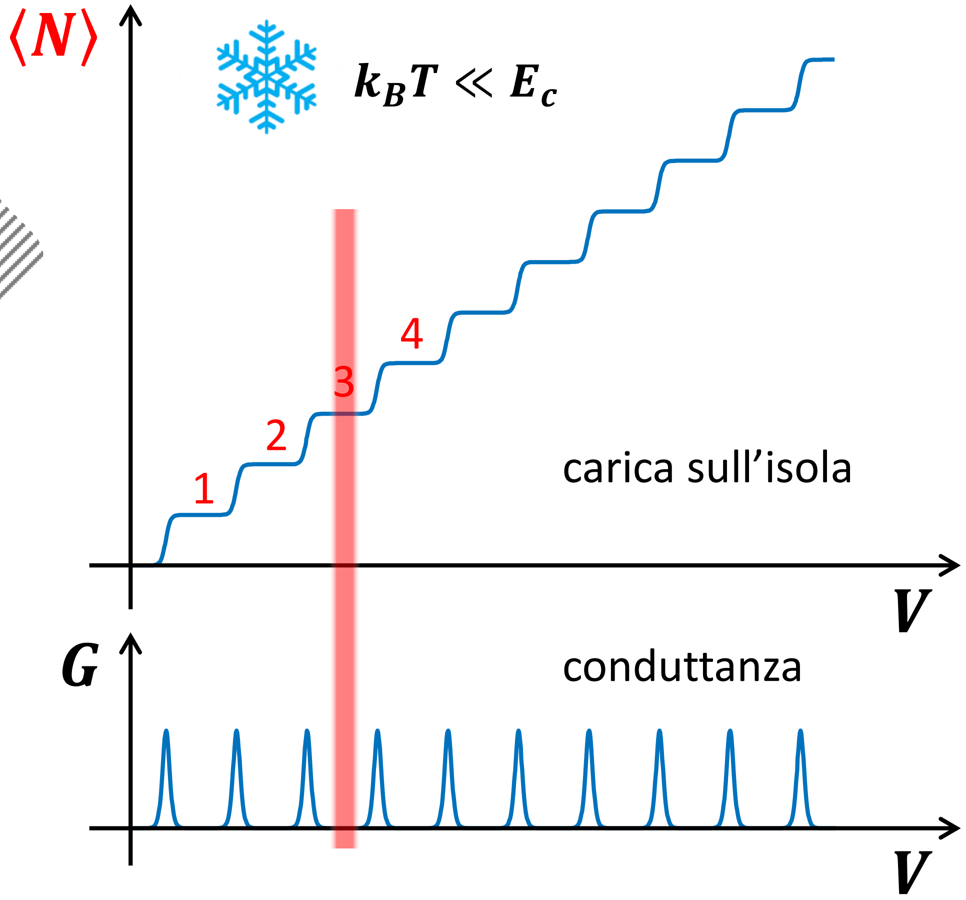

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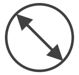

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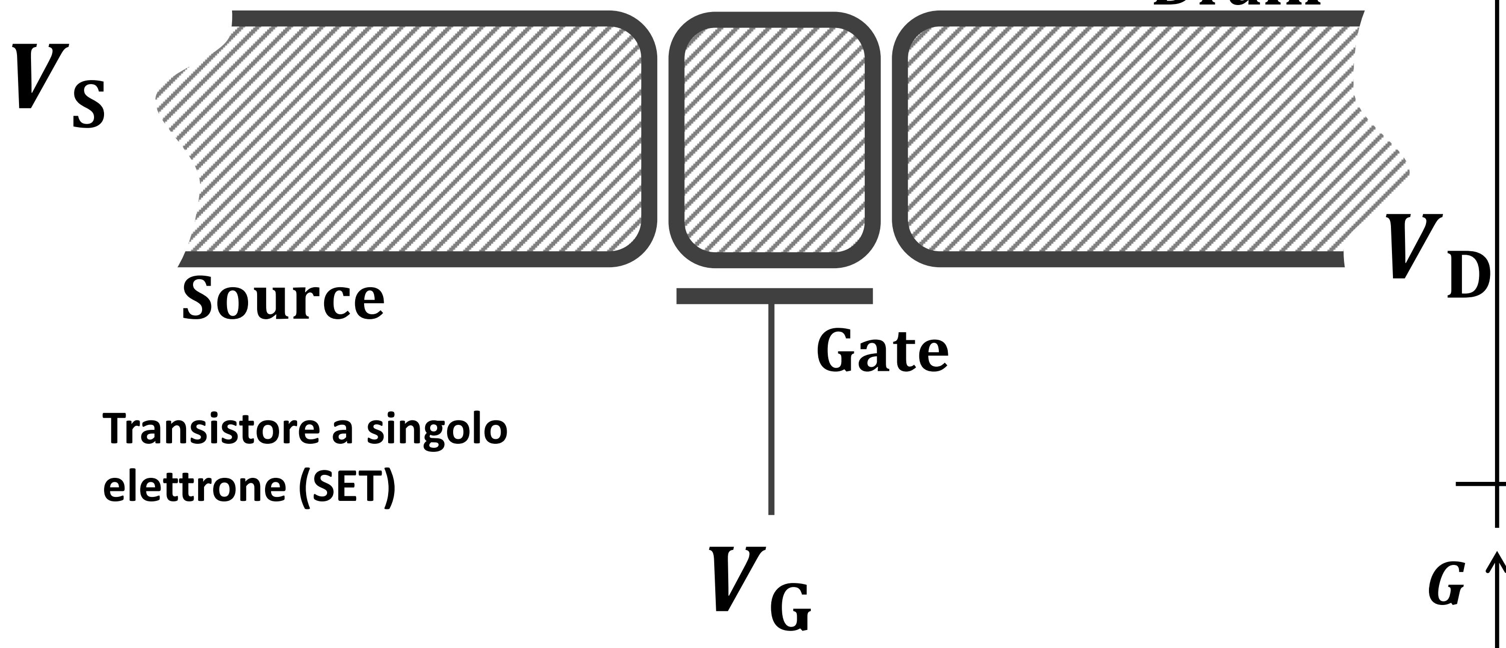
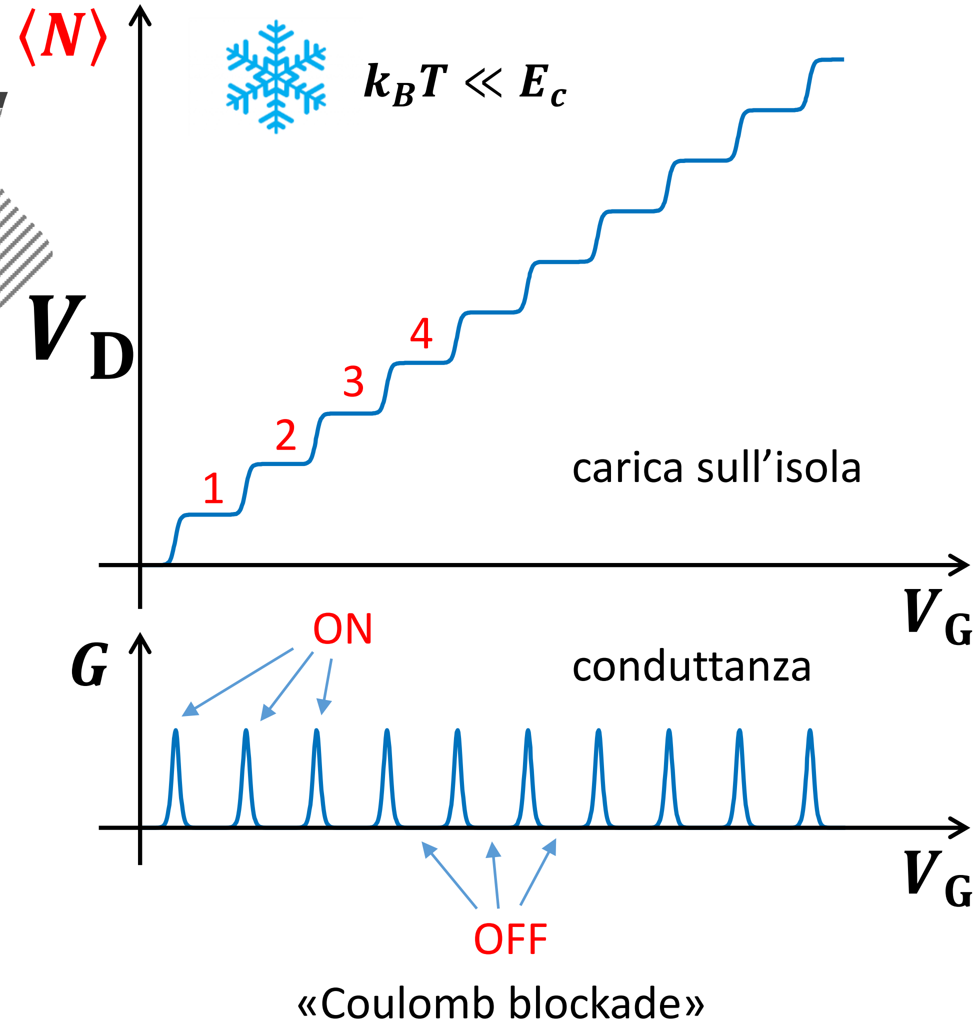


Transistore a singolo elettrone (SET)



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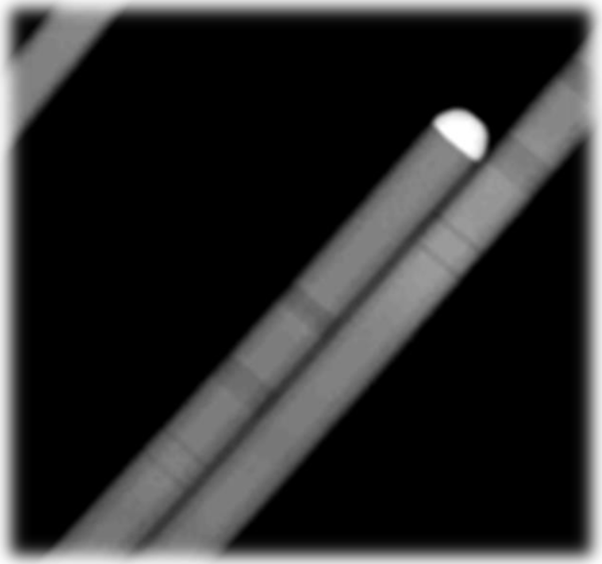

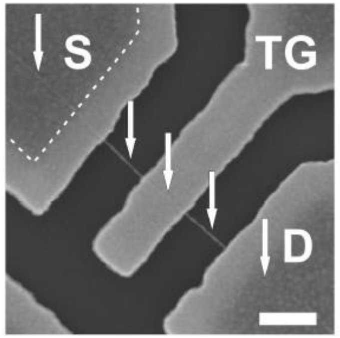

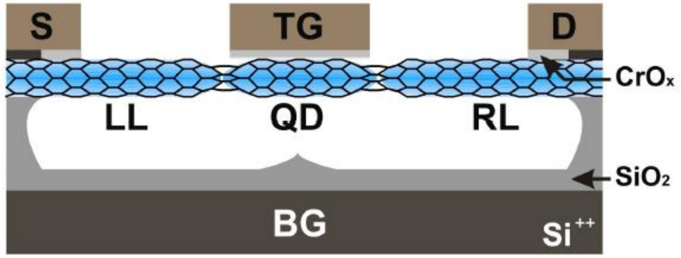

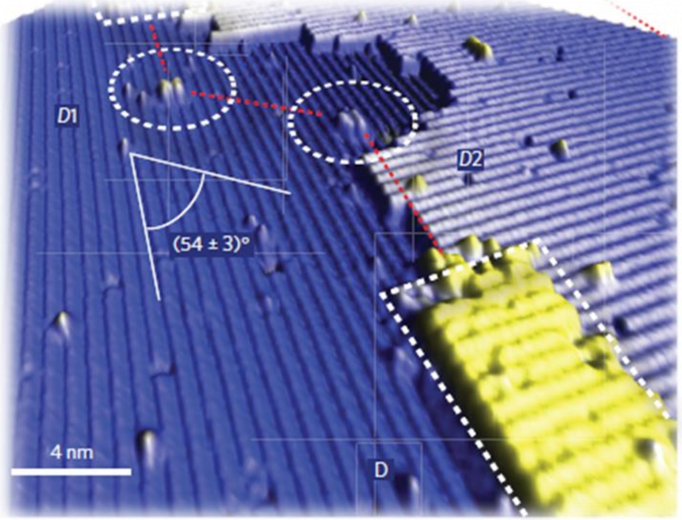

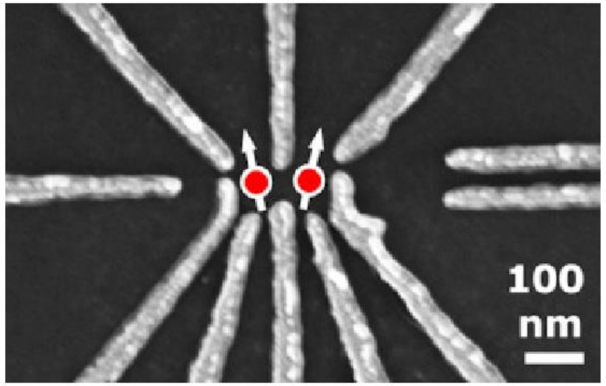

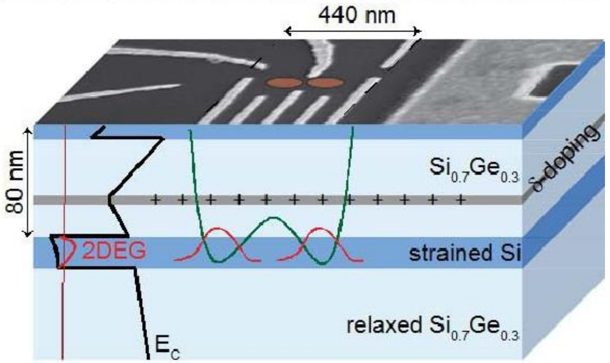

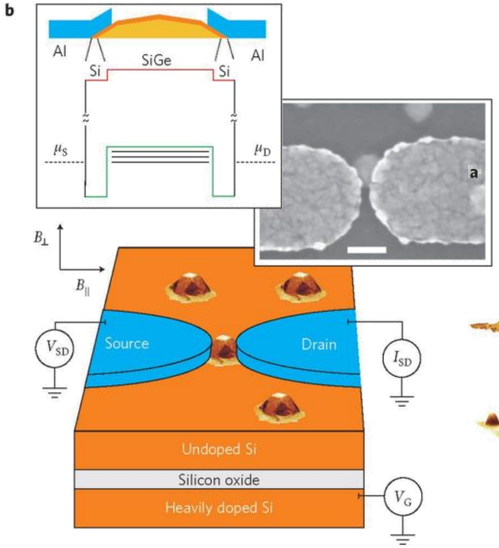

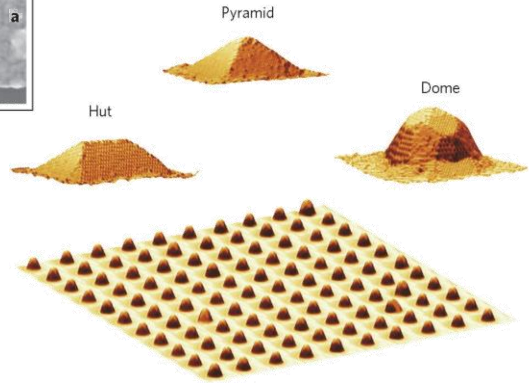

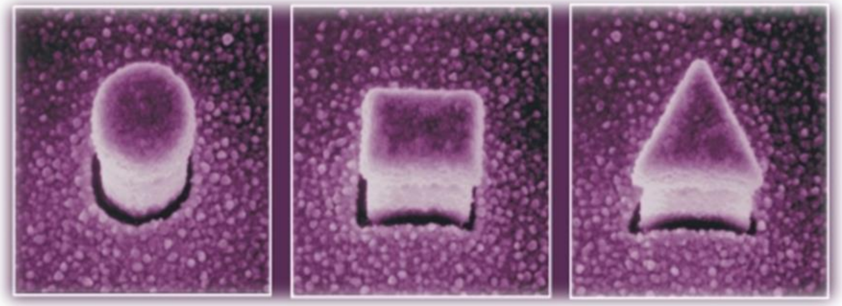

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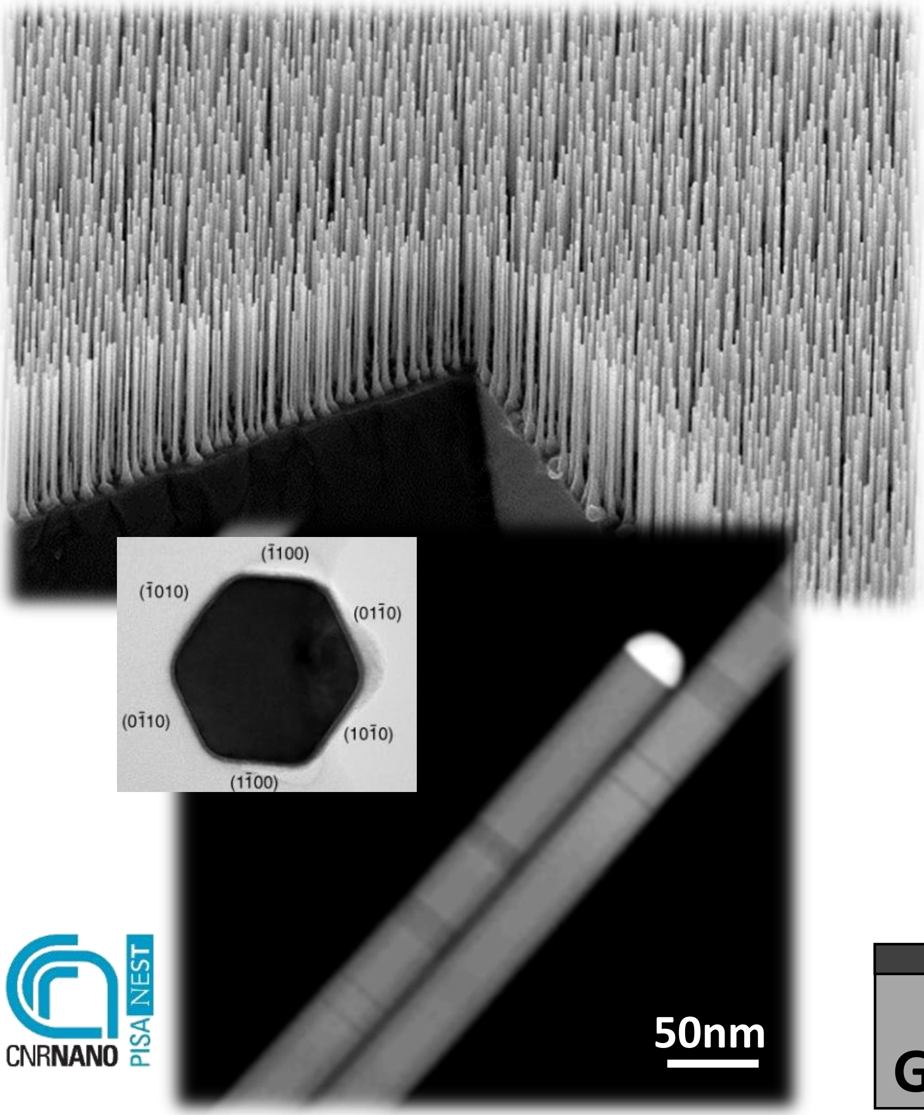

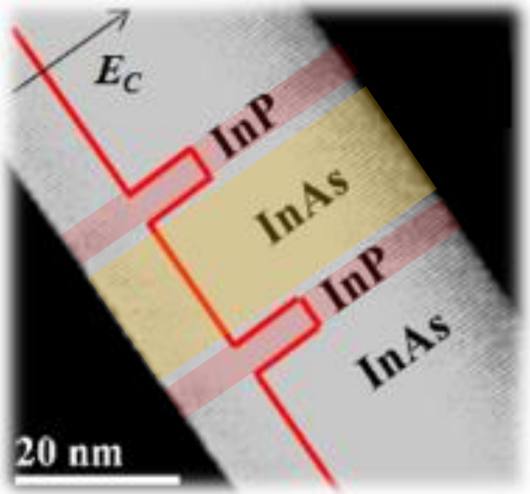

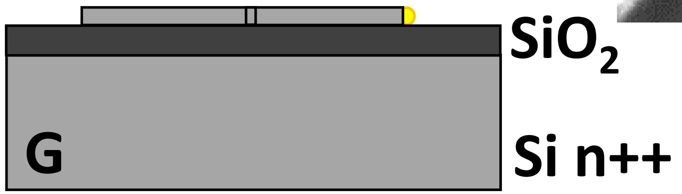

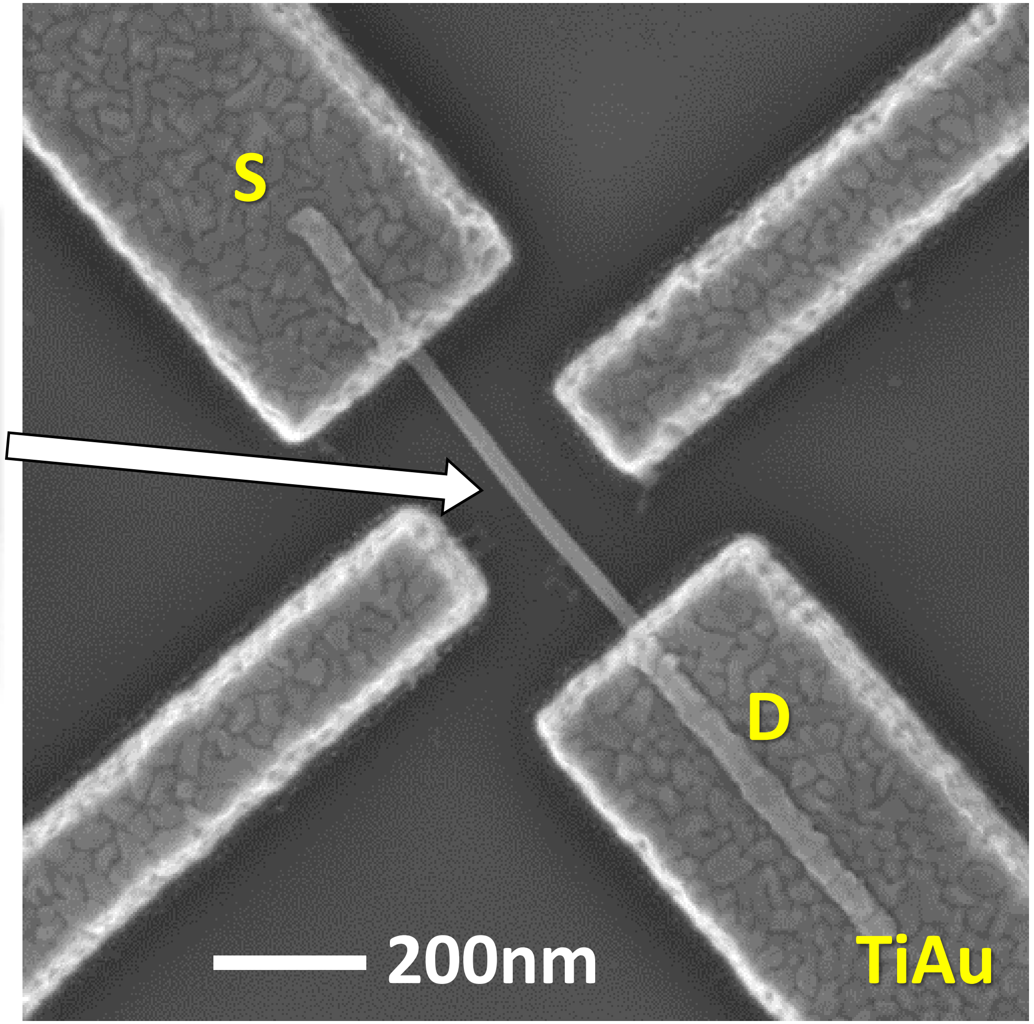

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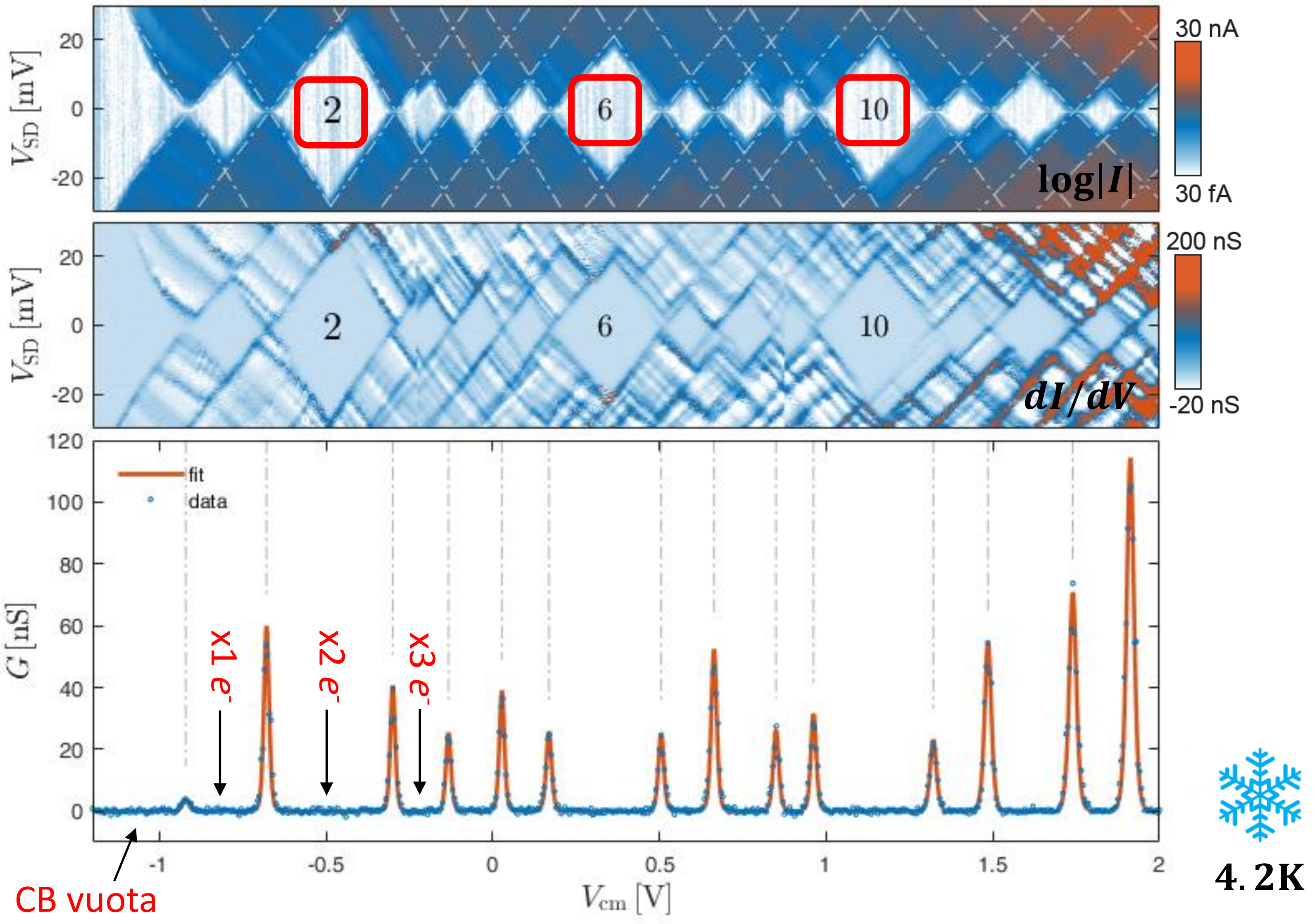
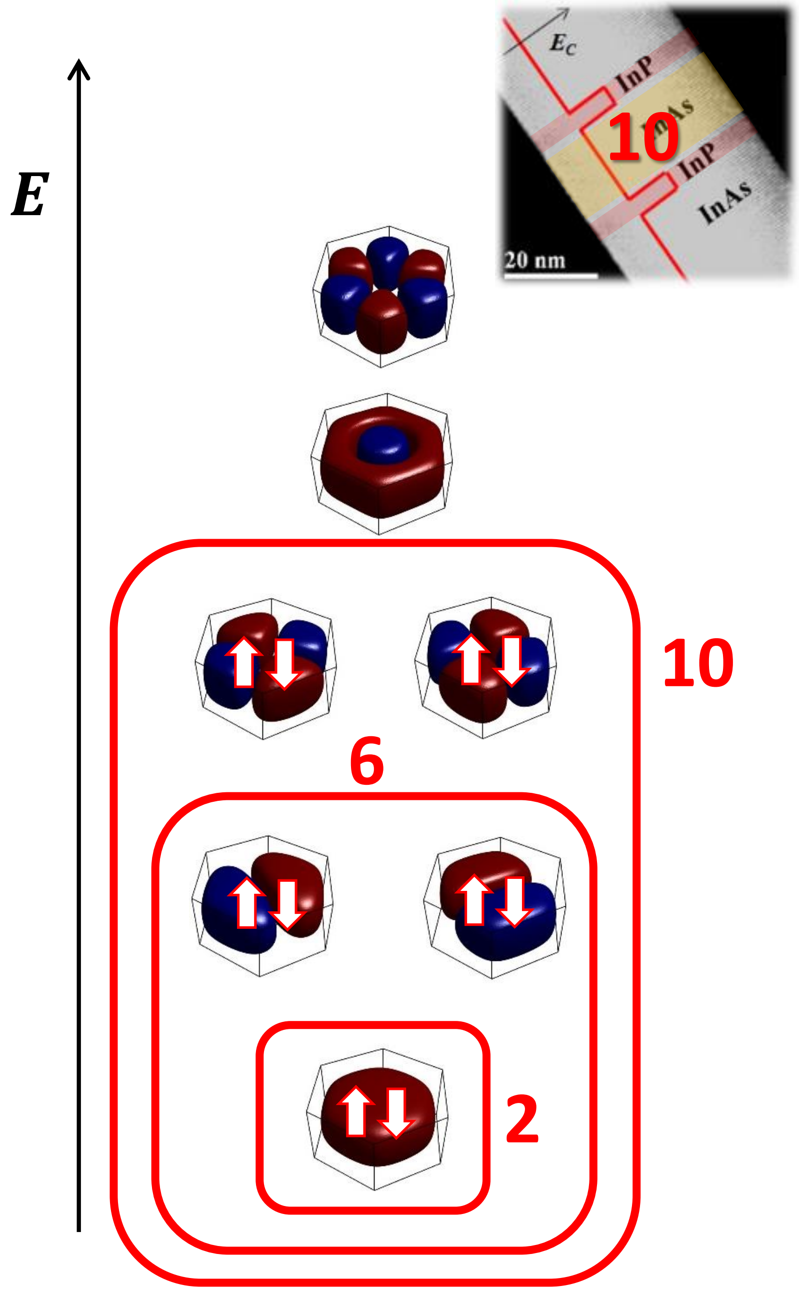
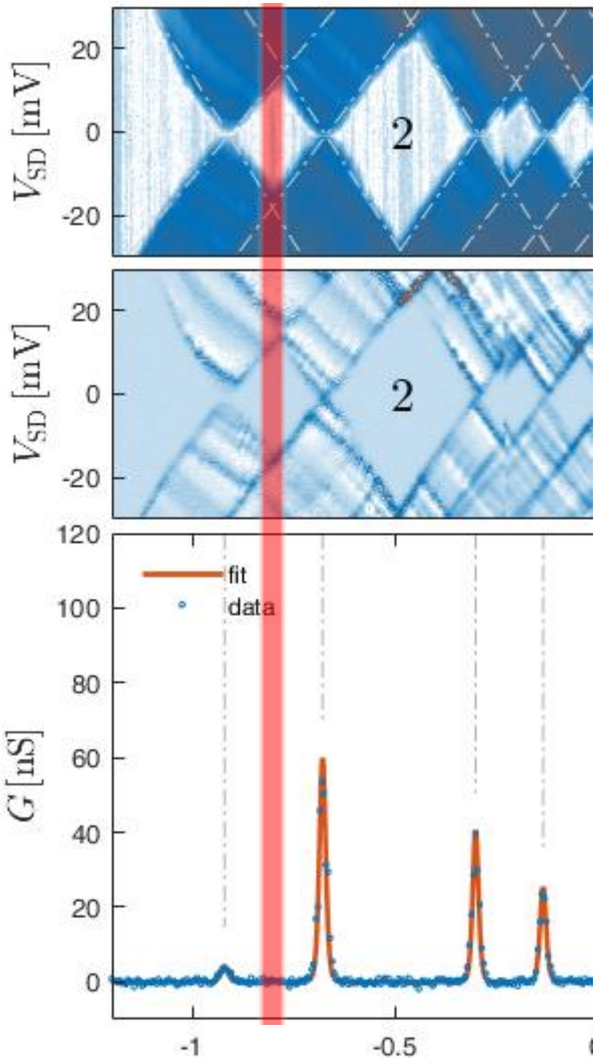
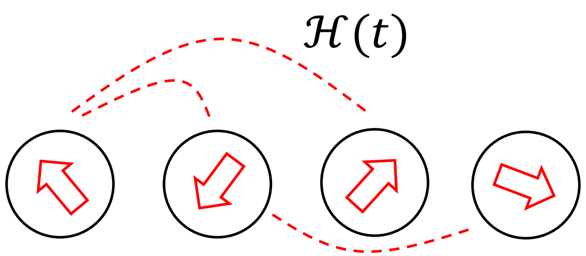




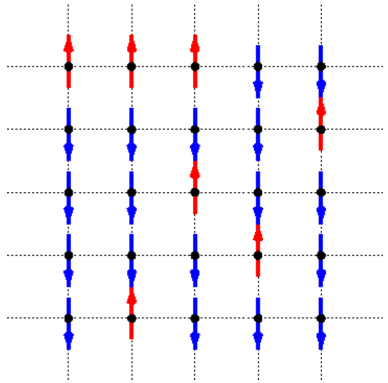
A che serve?!



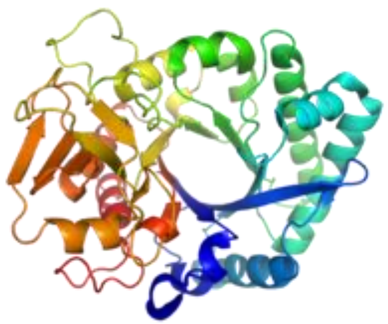


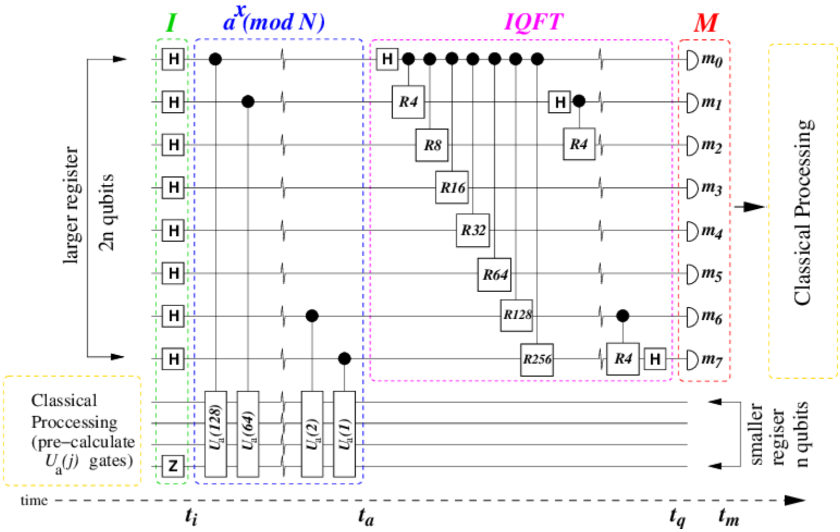
«quantum computer»

2^N livelli



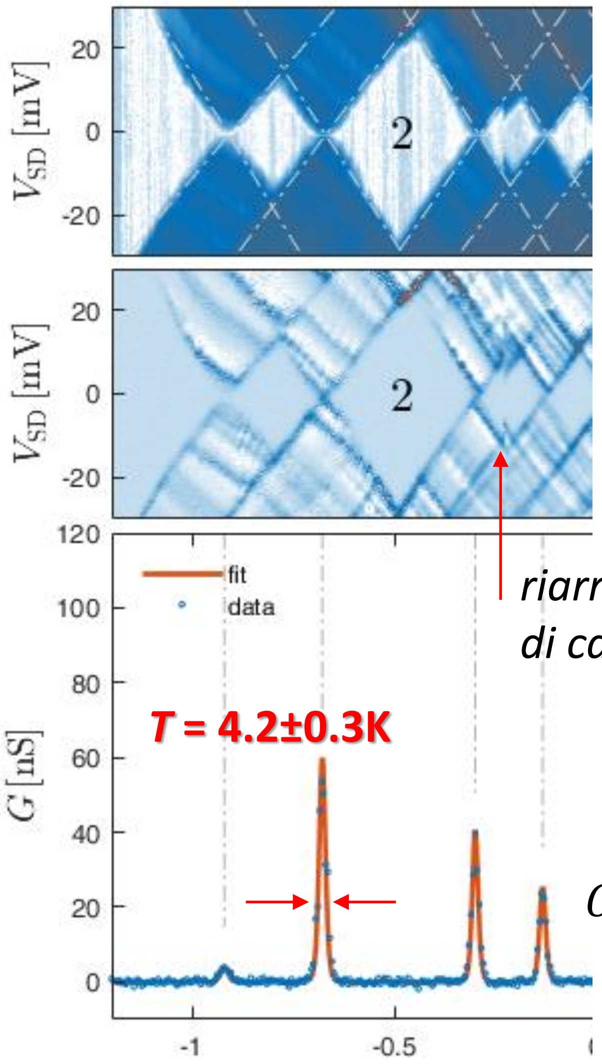
- Simulazione di sistemi quantici
- Problemi di ottimizzazione
- Calcolo numerico





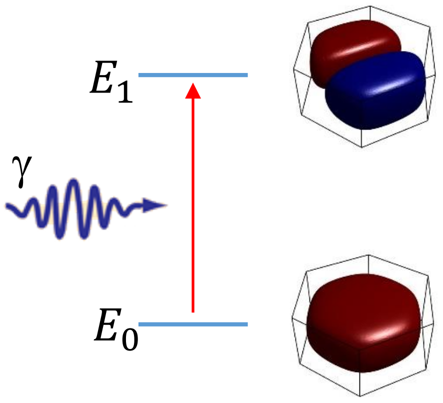
Esempio
algoritmo di Shor
(quantum FT)

A che serve?!



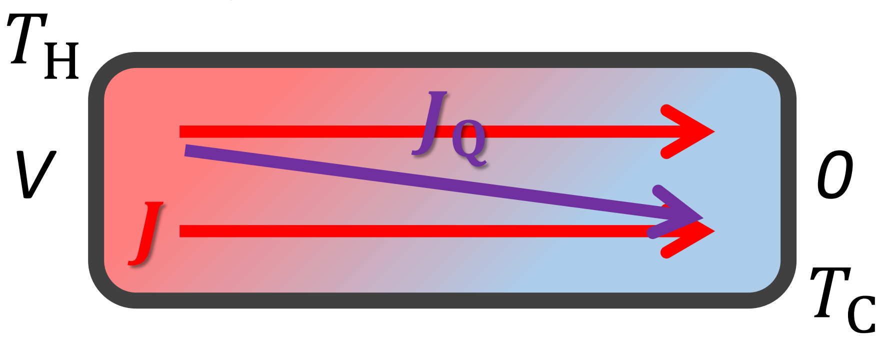
riarrangiamento di carica

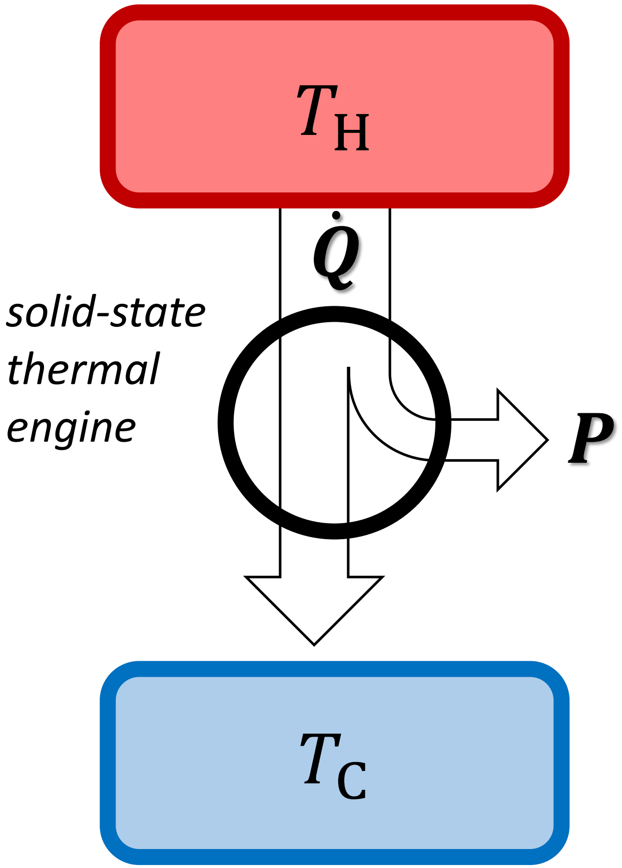
- Sistema estremamente sensibile alle cariche nelle vicinanze: CHARGE DETECTOR
- Larghezza di riga: TERMOMETRO ELETTRONICO PRIMARIO
- Orbitali «ingegnerizzati»: DETECTOR DI RADIAZIONE
- …



$$G = \frac{e^2}{h} \cdot \frac{h\Gamma}{k_B T} \cdot \frac{1}{4\cosh^2\left(\alpha_g (V - V_0)/2k_B T\right)}$$

Trasporto di carica… e il calore?





effetto Seebeck

«drift» (legge Ohm)

diffusione (legge Fick)

$$\boldsymbol{J} = \sigma(\boldsymbol{E} - S\nabla T) - qD\nabla n$$
$$\boldsymbol{J}_{\mathbf{Q}} = \Pi \boldsymbol{J} - \kappa_e \nabla T$$

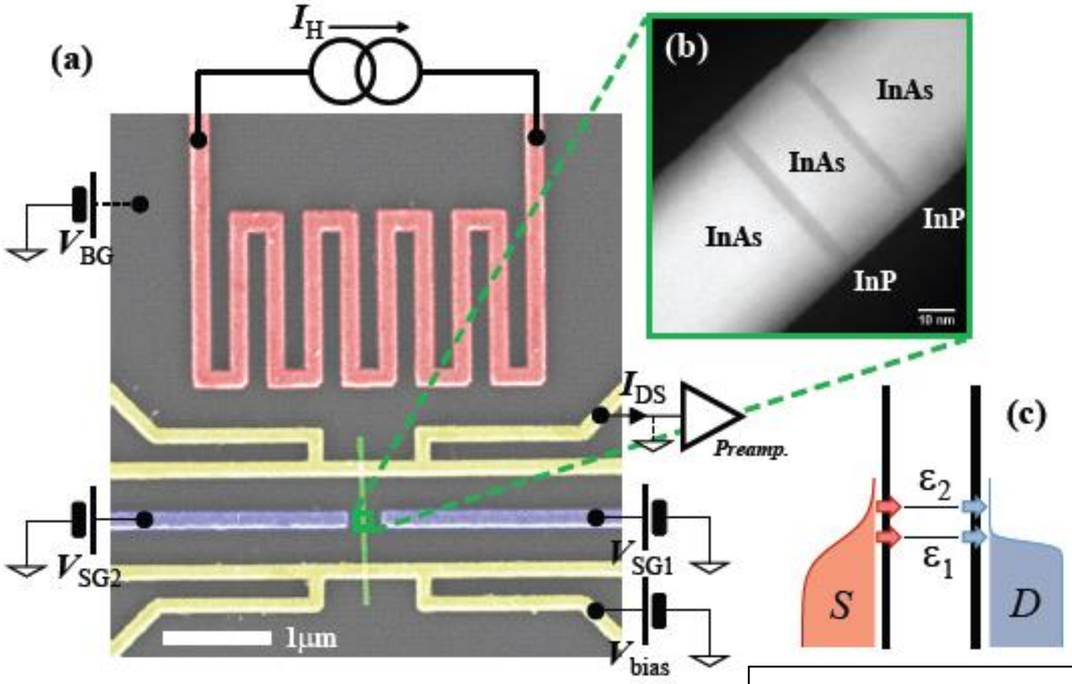
effetto Peltier

conduzione termica (legge Fourier)

(*) NB descrizione ancora largamente semplificata:

1. *Solo risposta lineare*
2. *Sostanzialmente, fisica classica*
3. *E i fononi?*
4. *Effetti fuori equilibrio? In che limite ha senso parlare di una «temperatura» su scala nano?*

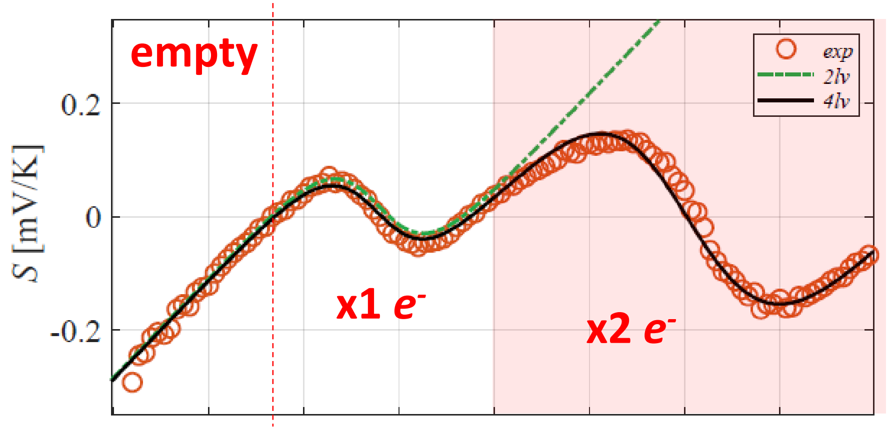
Termoelettricità nelle nanostrutture



$$\Delta V = S\Delta T$$

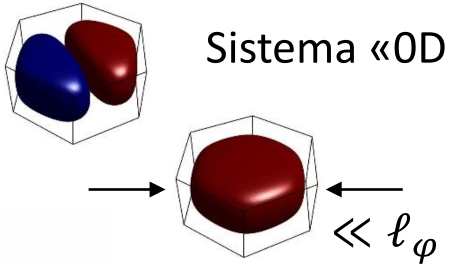
Prospettive:

- Possiamo creare nuovi materiali termoelettrici?
- Usare la risposta termoelettrica come strumento di indagine per le nanostrutture?
- Studio della statistical thermodynamics (full counting statistics su motore termico in operazione, etc)
- Quantum thermodynamics



Perché studiare le nanostrutture?

«Quantum dot»



Sistema «0D»

Scale fisiche rilevanti:

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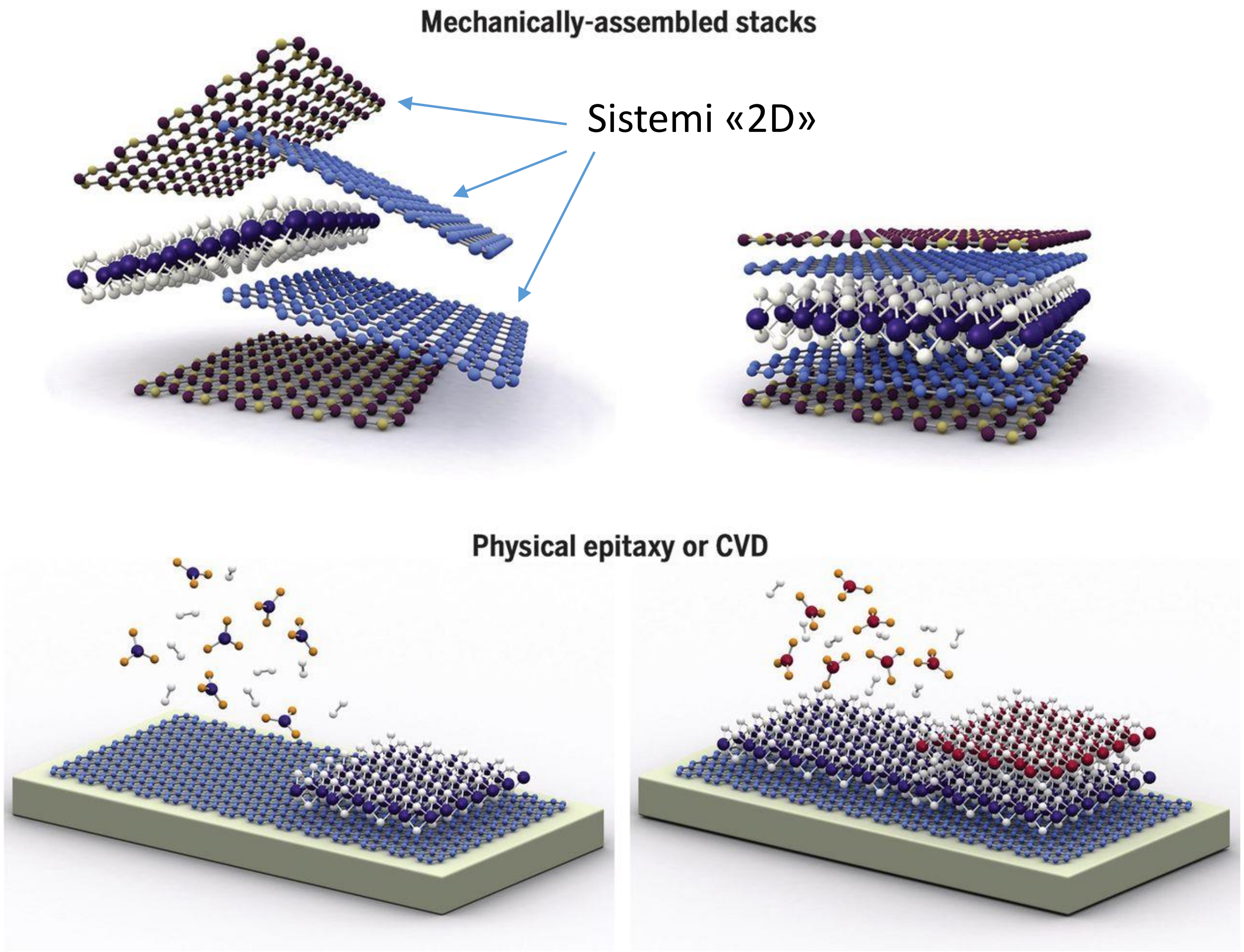
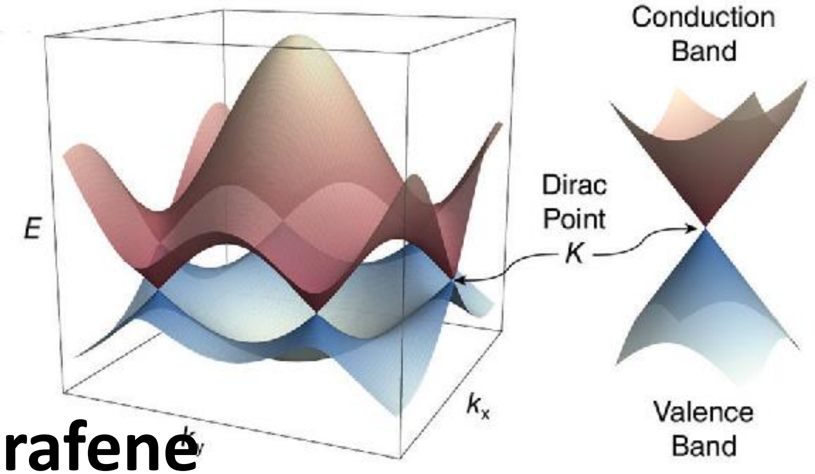
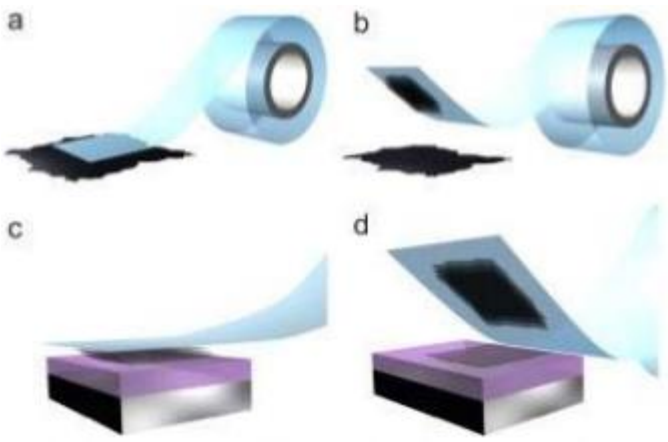
- Energia di caricamento
- Lunghezza di coerenza
- Lunghezze di scattering
- …

Materiali a dimensionalità ridotta

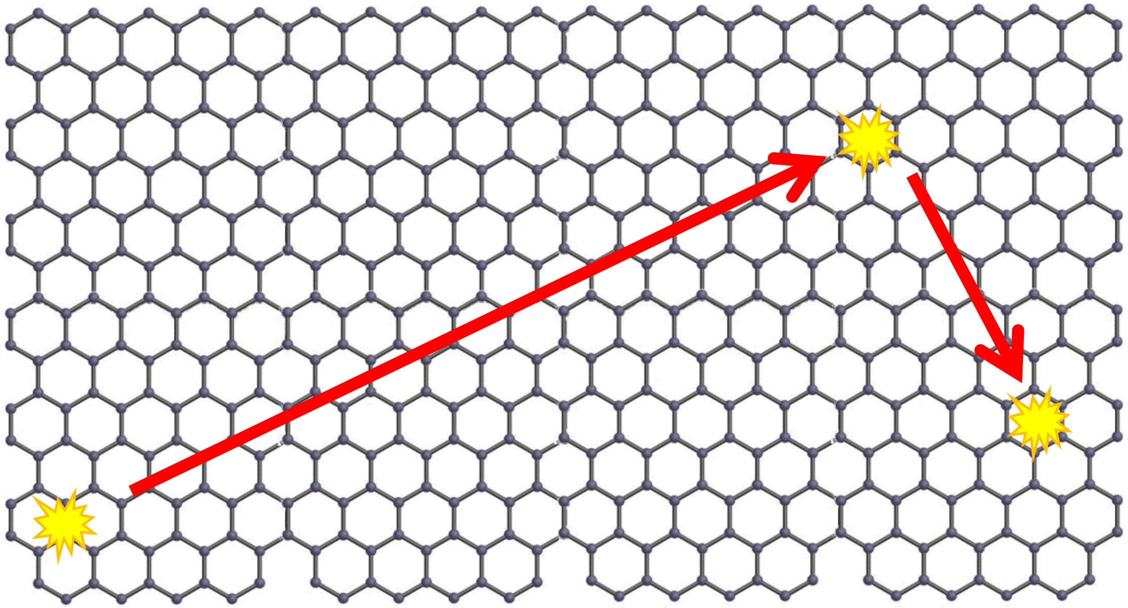


Materiali 2D





Grafene



Distanza interatomica C-C: 0.142nm

- cammino libero medio
  - Trasporto balistico vs diffusivo
  - $V = RI$ con $R \propto lunghezza$

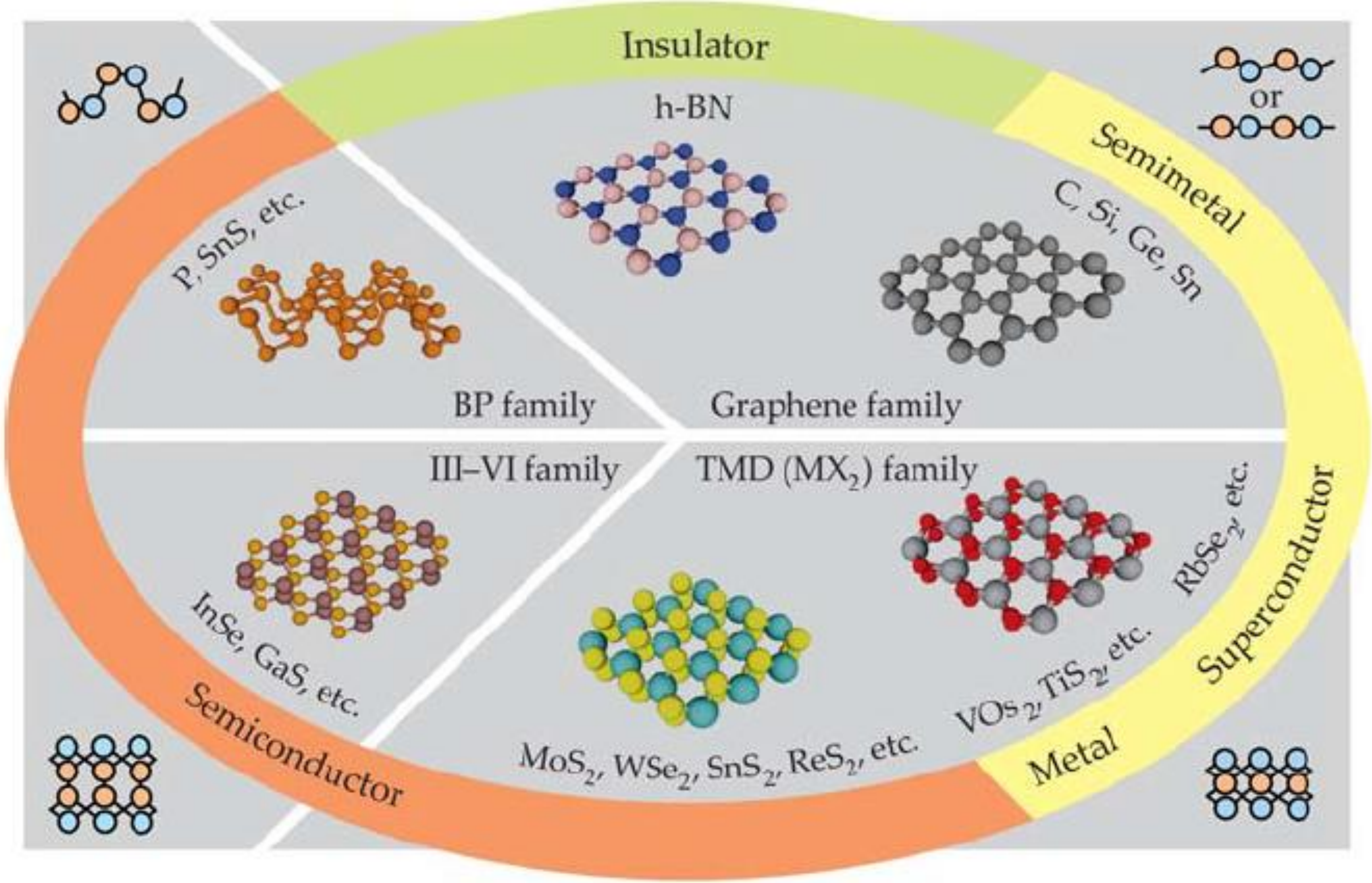
Forget it!

$$J = \sigma E$$

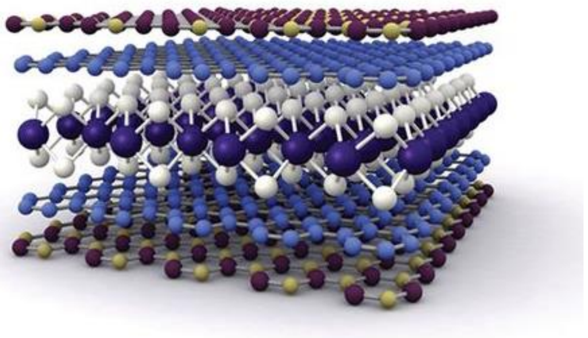
- lunghezza di coerenza
  - Trasporto coerente

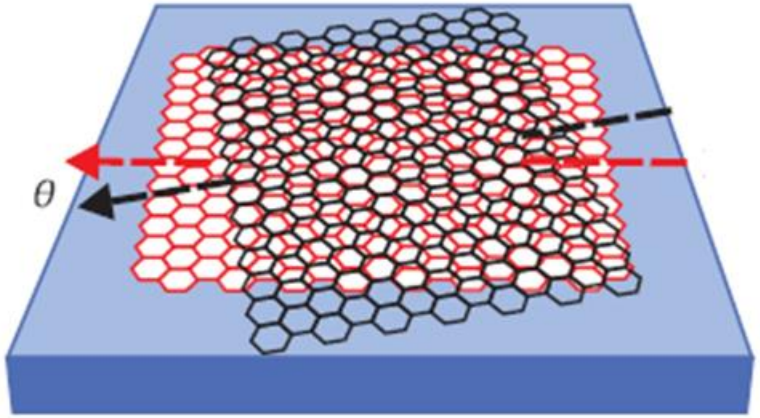
Materiali 2D

GRM = Graphene Related Materials

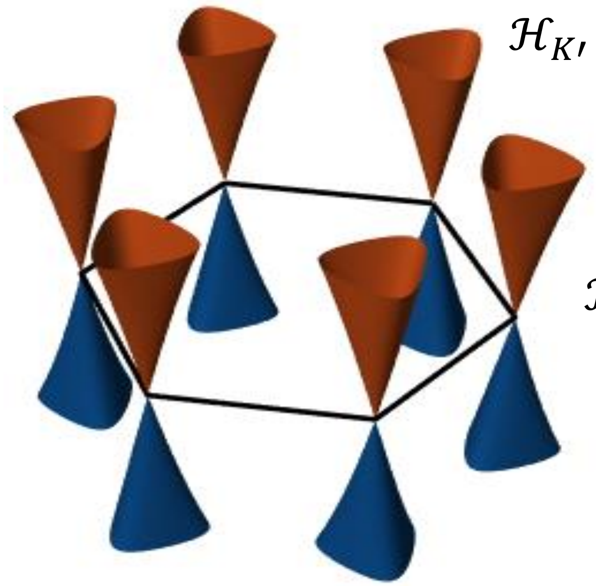


Van der Waals heterostuctures





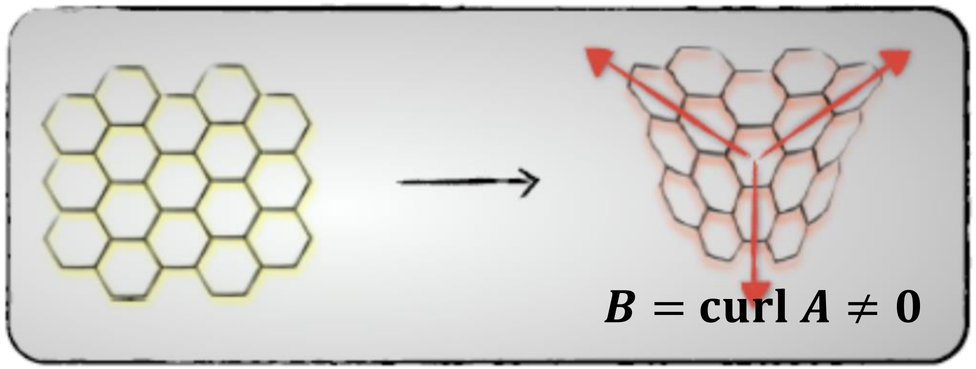
Materiali 2D

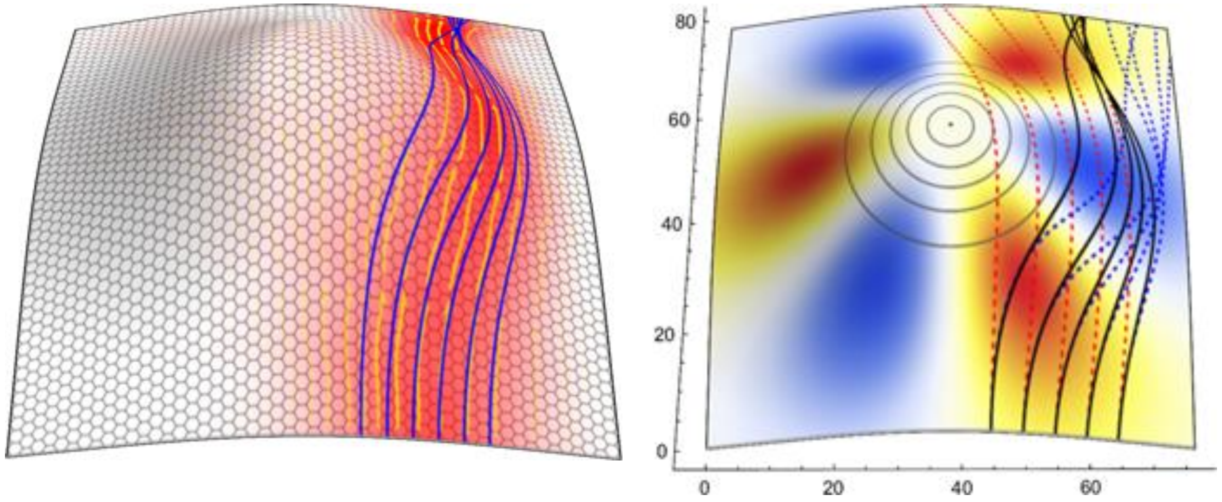


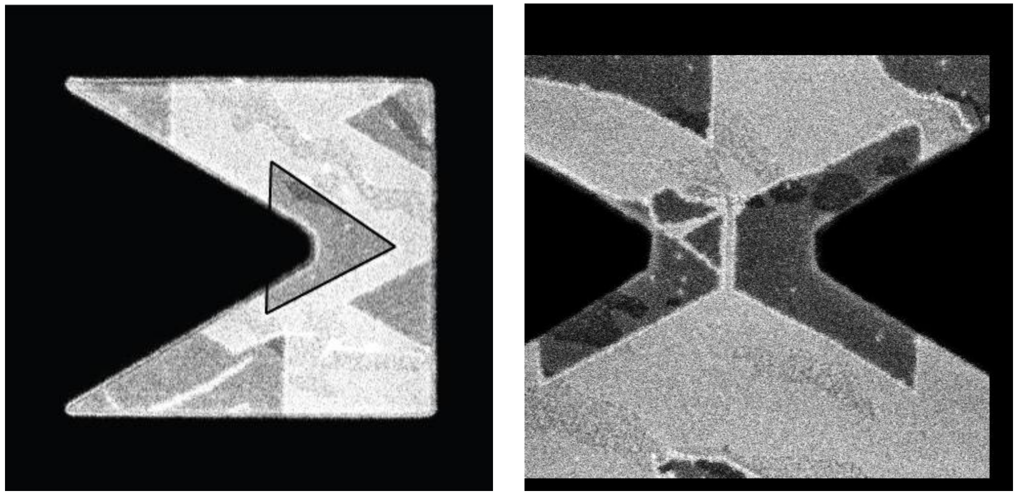
$$\mathcal{H}_{K'} = v_F \boldsymbol{\sigma}^* \cdot (\hbar \boldsymbol{q} + e\boldsymbol{A}^{(p)}/c)$$

$$\mathcal{H}_{K} = v_F \boldsymbol{\sigma} \cdot (\hbar \boldsymbol{q} - e\boldsymbol{A}^{(p)}/c)$$

$$\boldsymbol{A}_{\boldsymbol{x}}^{(p)} \propto \boldsymbol{\varepsilon}_{\boldsymbol{xx}} - \boldsymbol{\varepsilon}_{\boldsymbol{yy}}$$
$$\boldsymbol{A}_{\boldsymbol{y}}^{(p)} \propto -2\boldsymbol{\varepsilon}_{\boldsymbol{xy}}$$

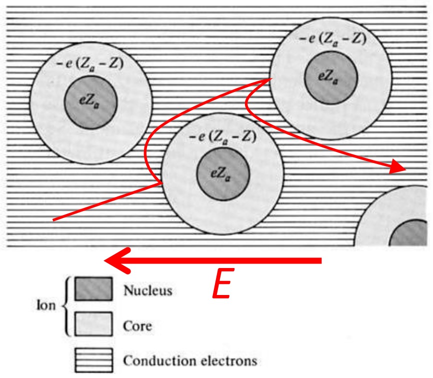






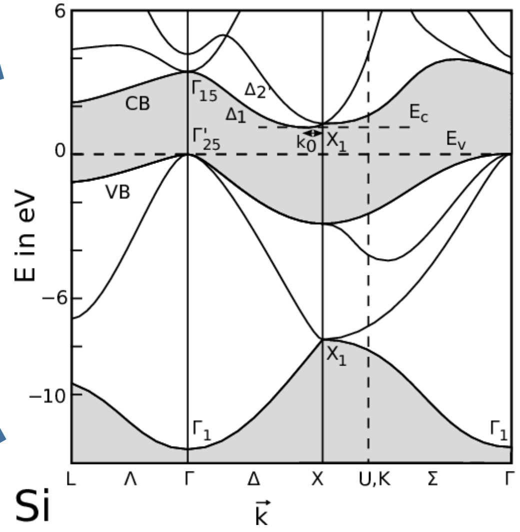
Prospettiva conclusiva

1900 Drude

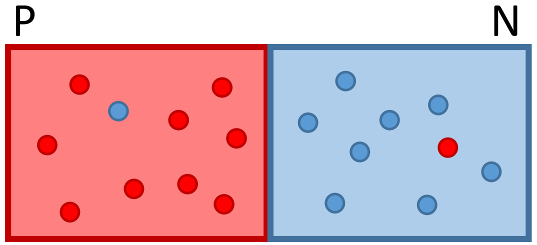


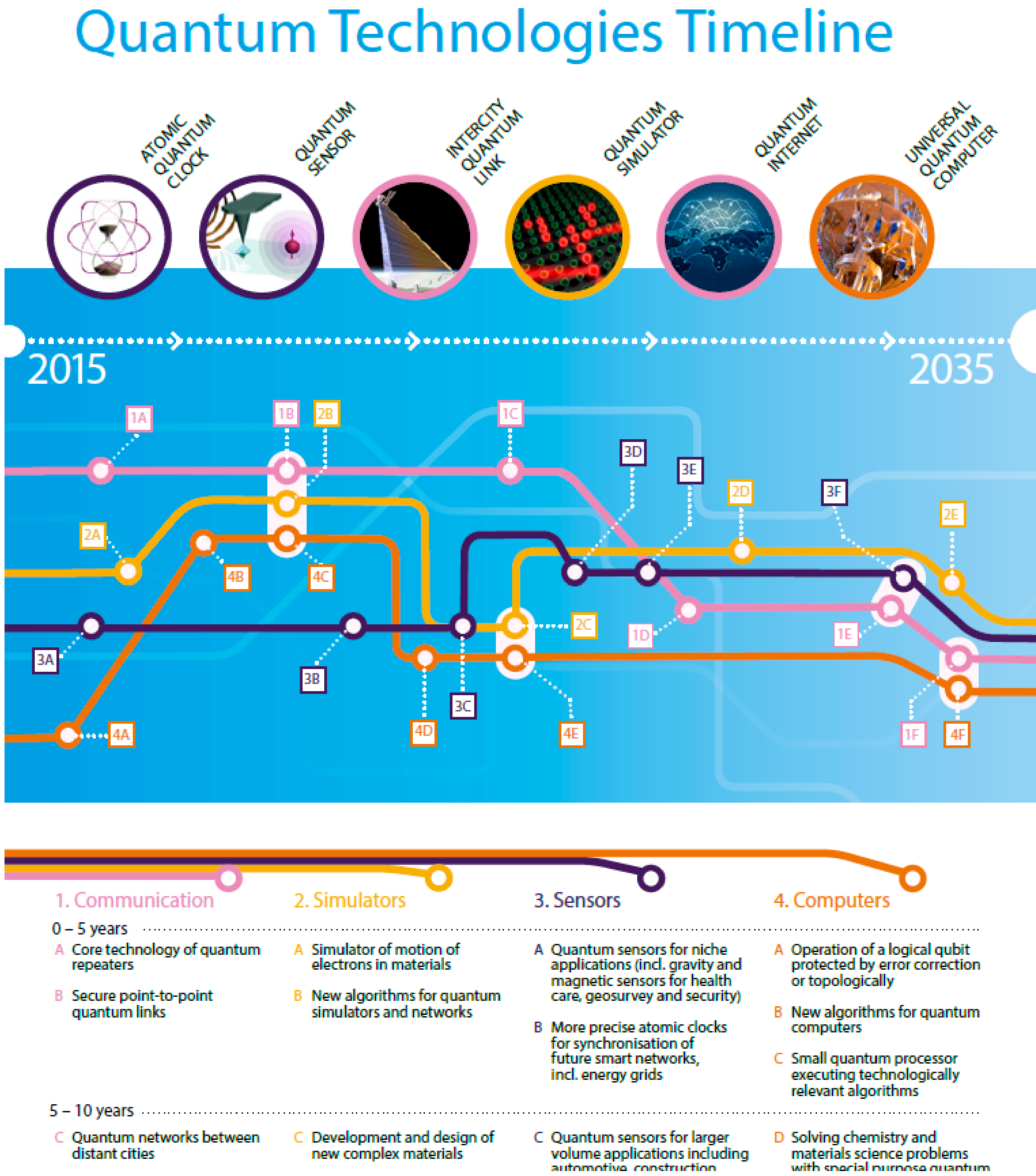
$$d\langle \mathbf{p}\rangle/dt = -e\mathbf{E} - \langle \mathbf{p}\rangle/\tau$$

QM



- «electrons» $-e$ m_e^* τ_e
- «holes» $+e$ m_h^* τ_h





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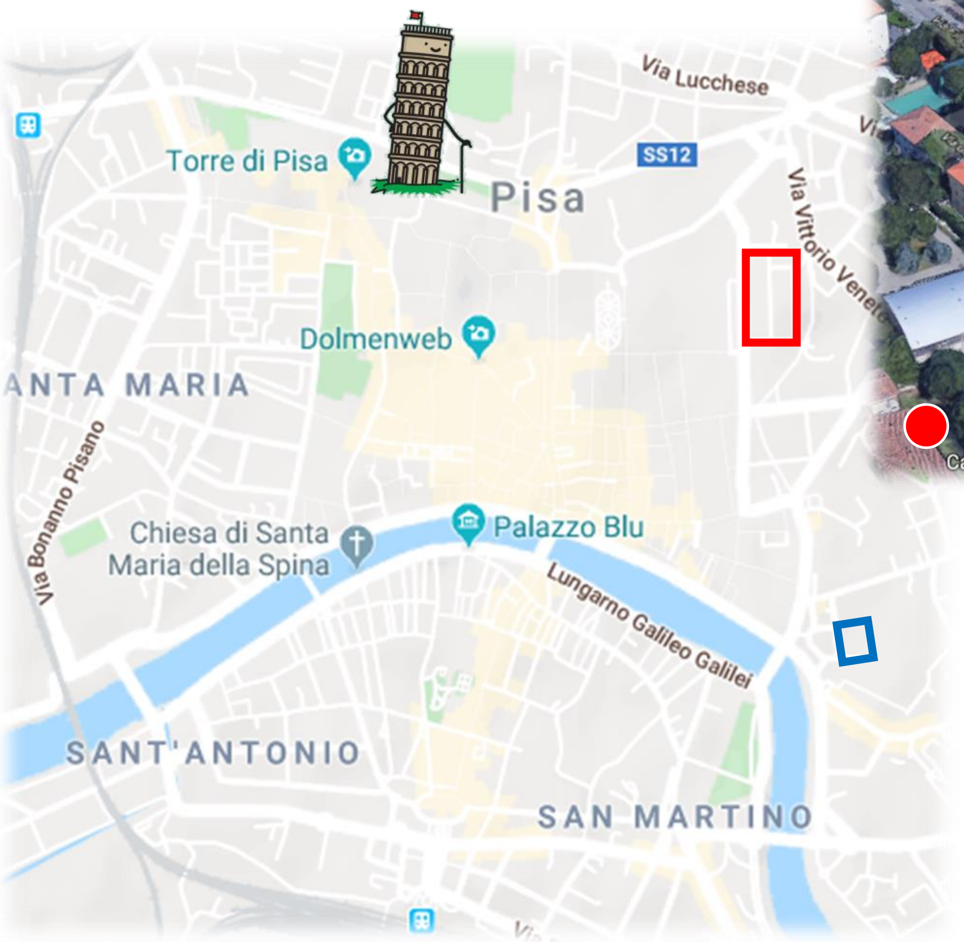

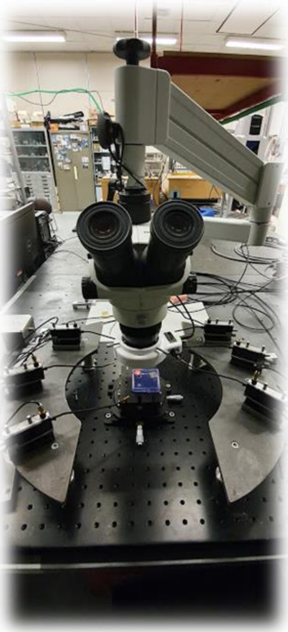

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