Un viaggio nella materia condensata: Dalle prime tecnologie a semiconduttore alle tecnologie quantistiche

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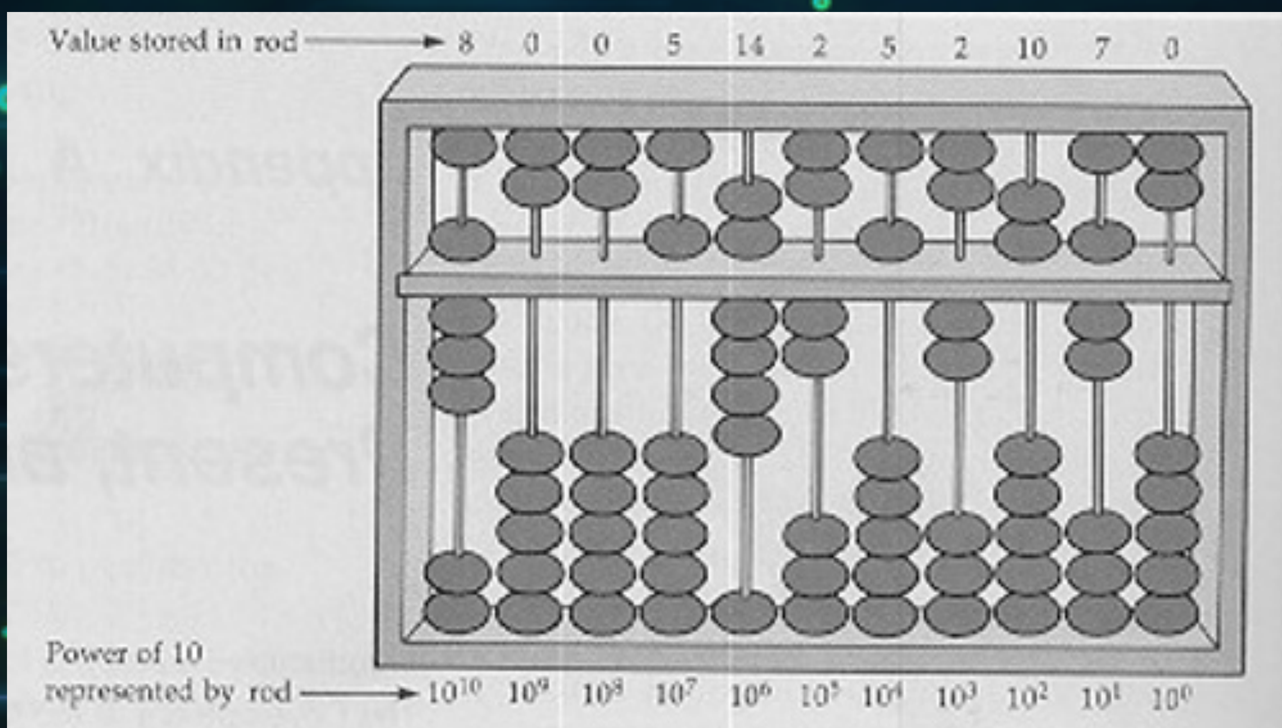
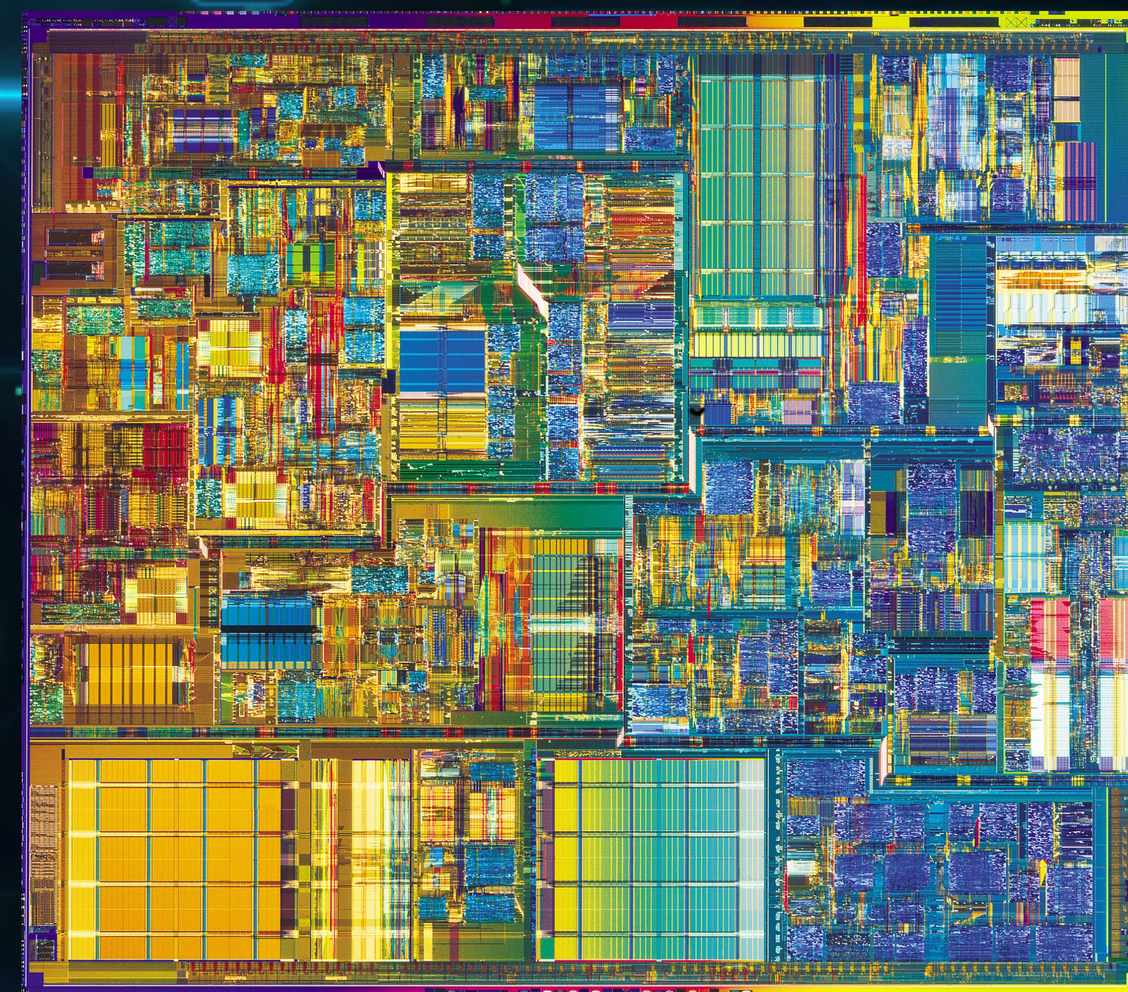
Outline

- Storia delle prime tecnologie
- Transistor e “scaling down”
- Il mondo quantistico
- Sistemi a bassa dimensione
- Fasi topologiche
- Effetto Hall quantistico
- Introduzione alla Quantum computation
- Electron Quantum Optics (EQO)
- Nuovi materiali 2D

Dall’abaco ai processori…



Abacus – XXI secolo a.C. – 10 additions / min



Pentium 4 – XXI secolo d.C. – 10^{9} additions / sec

1897: La scoperta dell’elettrone

J. J. Thomson

‘To the electron, may it never be of any use to anybody’

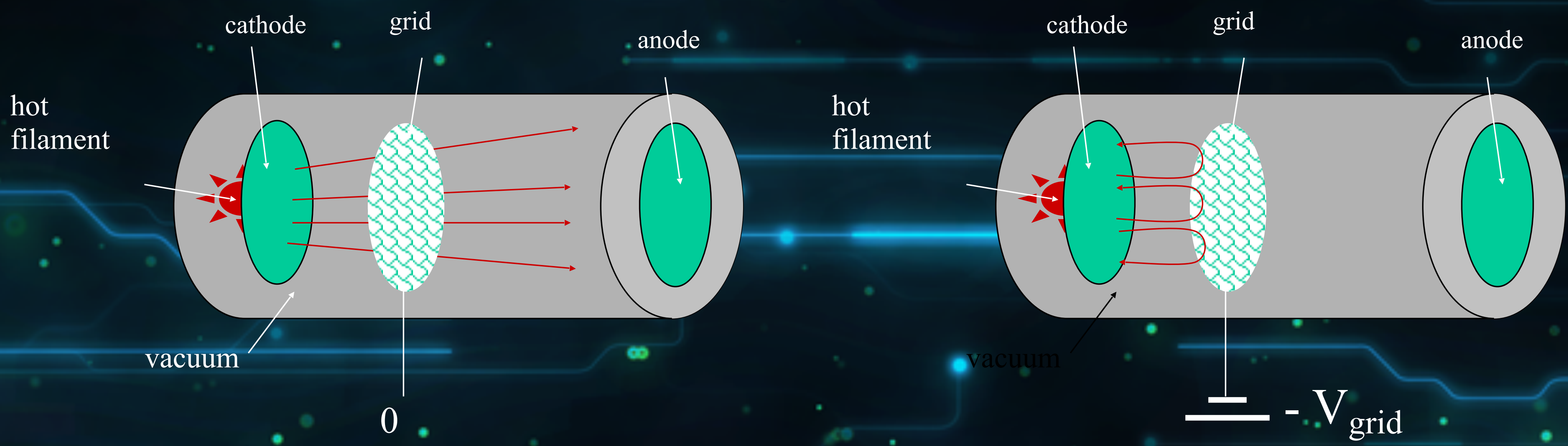
J. J. Thomson's favorite toast

The Nobel Prize in Physics 1906

"In recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"

Sir Joseph John Thomson

Il tubo a vuoto: predecessore del transistor (1906)



current flowing = ON

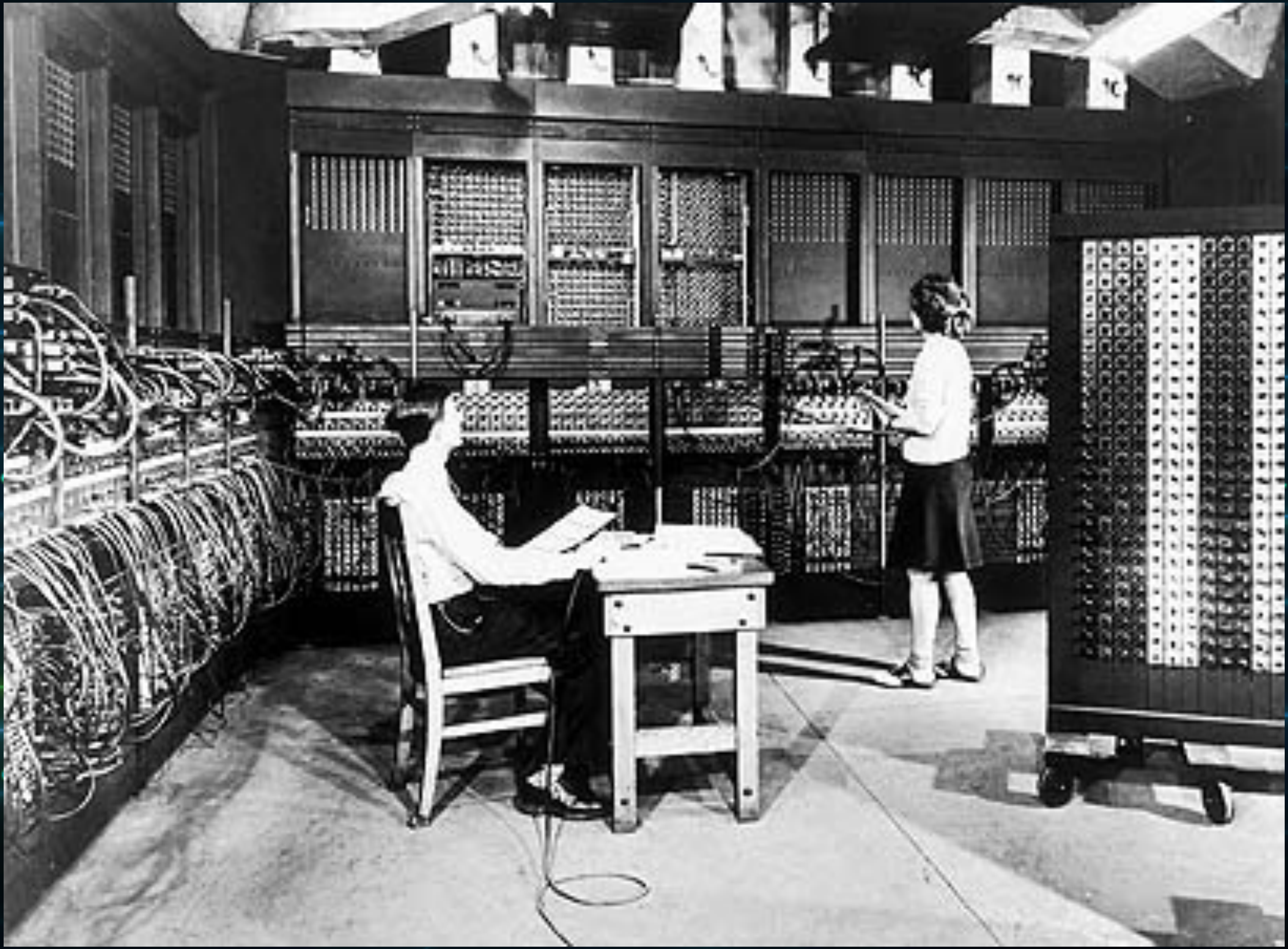
current not flowing = OFF

Switch: 0 (OFF) e 1 (ON)

Amplificatore: un piccolo cambiamento di voltaggio nella griglia provoca un grossa corrente

Primo computer elettronico con i tubi a vuoto

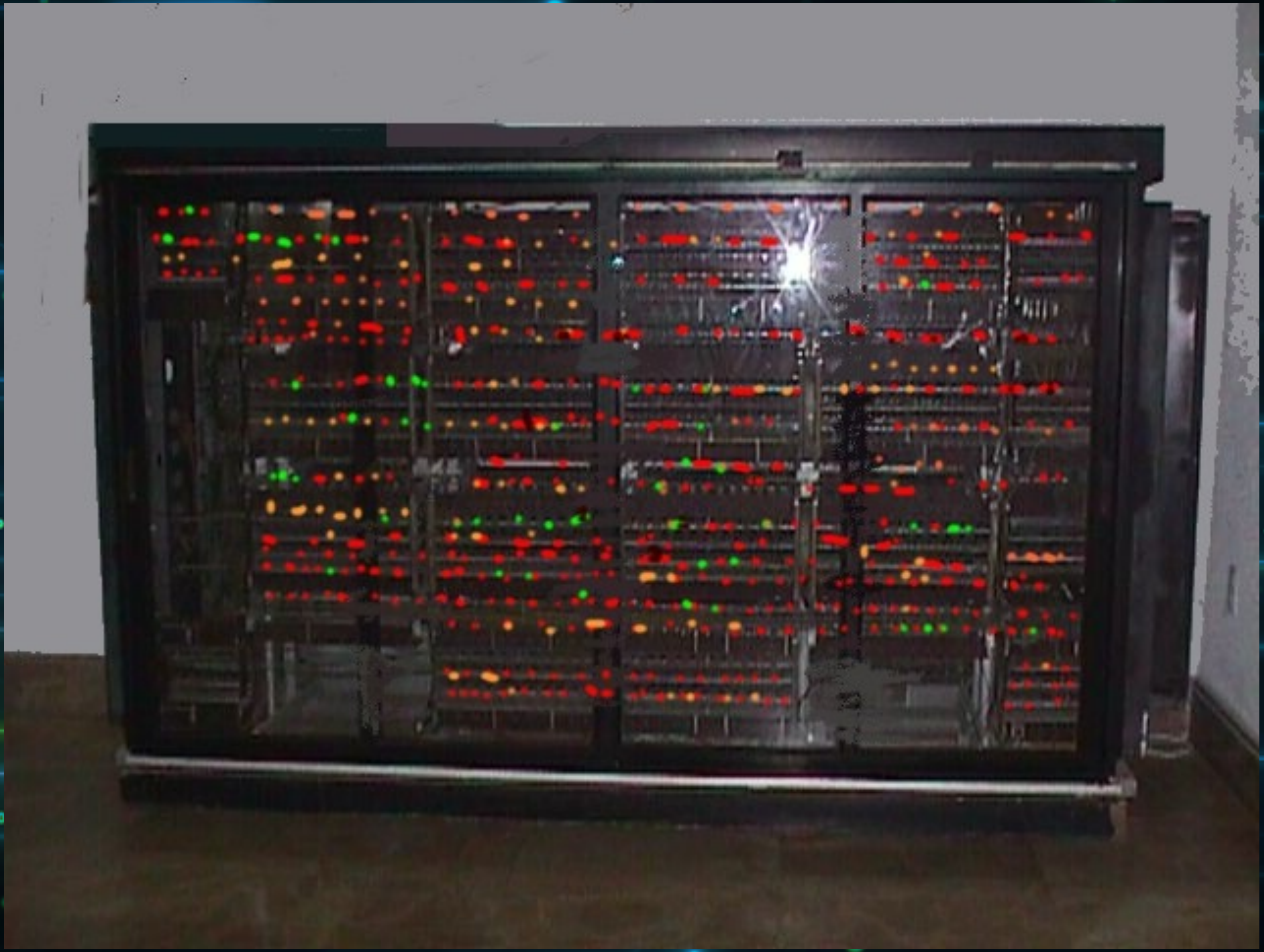
ENIAC - 1945



Speed: 5,000 additions / sec
Memory: 200 digits

18,000 vacuum tubes
weighs 30 tons
area 180 sqm

1955: Weizak – Weizmann Institute



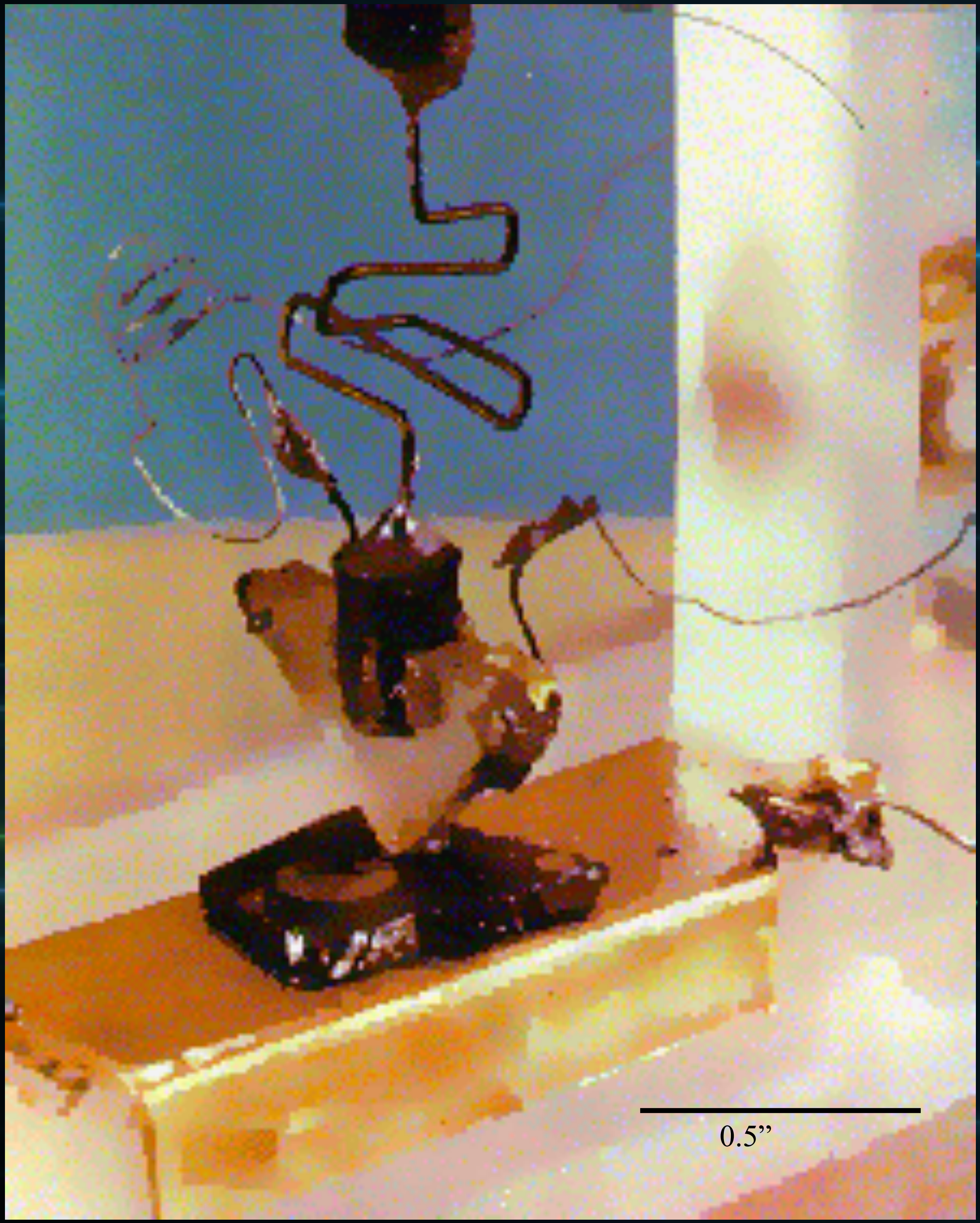
10 anni dopo il primo computer… cosa è cambiato?

Oggi…

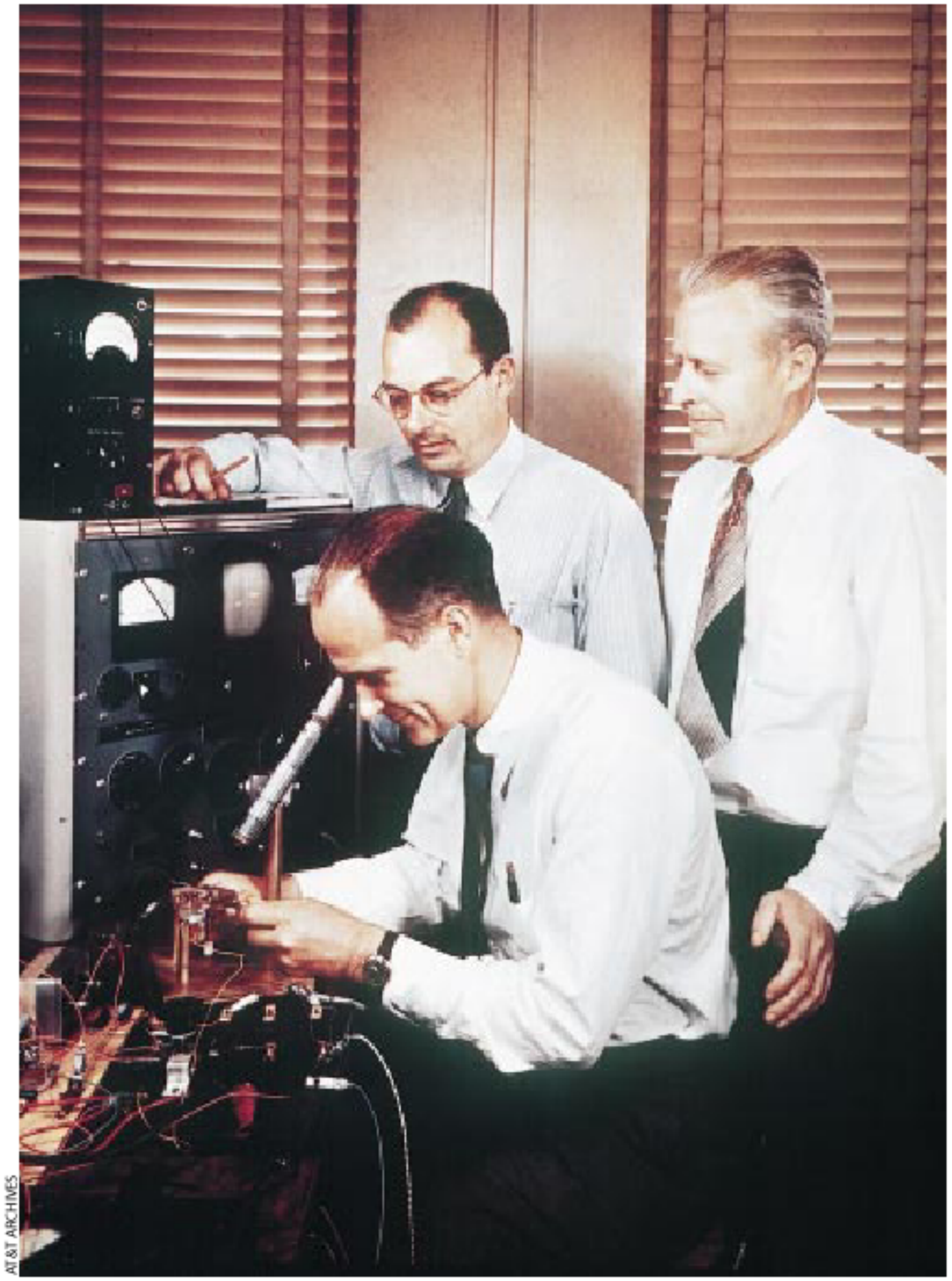
Frequenza: 2.8 GHz **RAM: 16/32 GB** **Peso: circa 1 kg**

Ma come ci siamo arrivati?

Nascita del transistor – 1947, Bell Laboratories

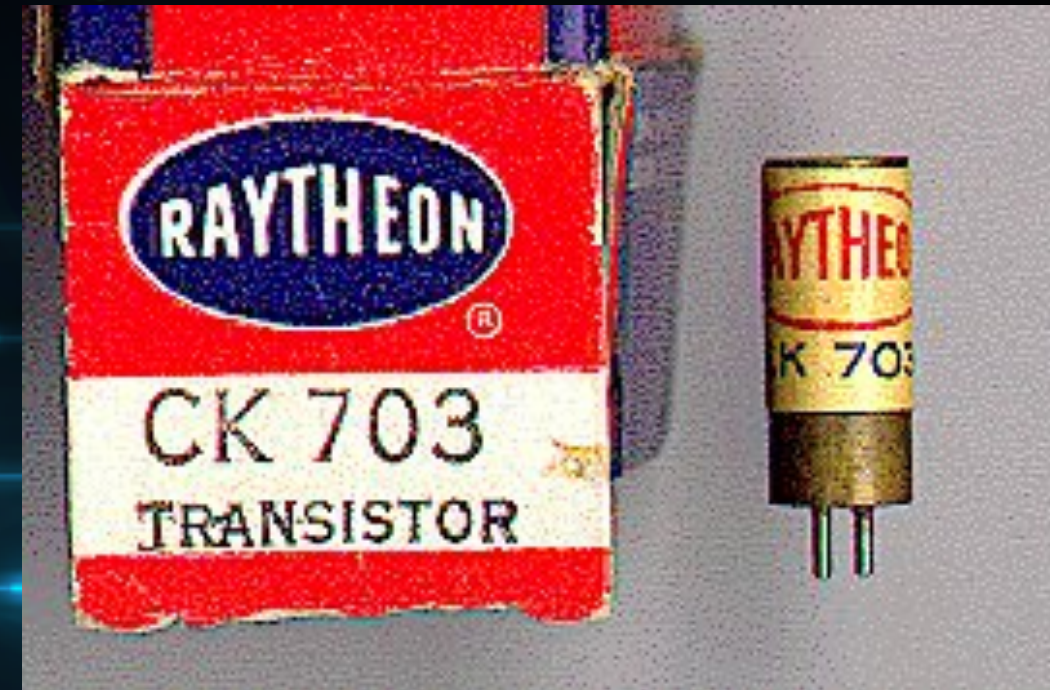


Primo transistor fatto di Germanio

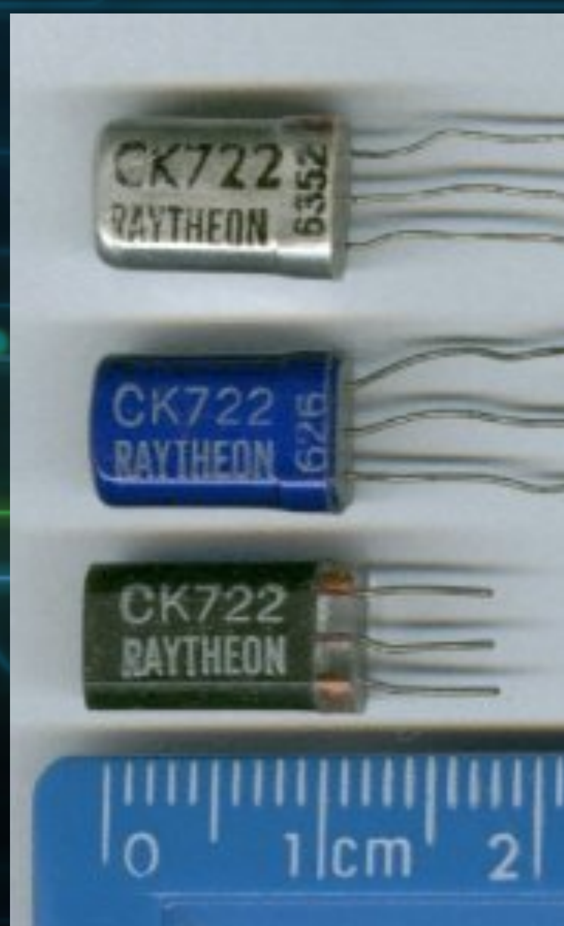


INVENTORS Shockley (*seated*), Bardeen (*left*) and Brattain (*right*) were the first to demonstrate a solid-state amplifier (*opposite page*).

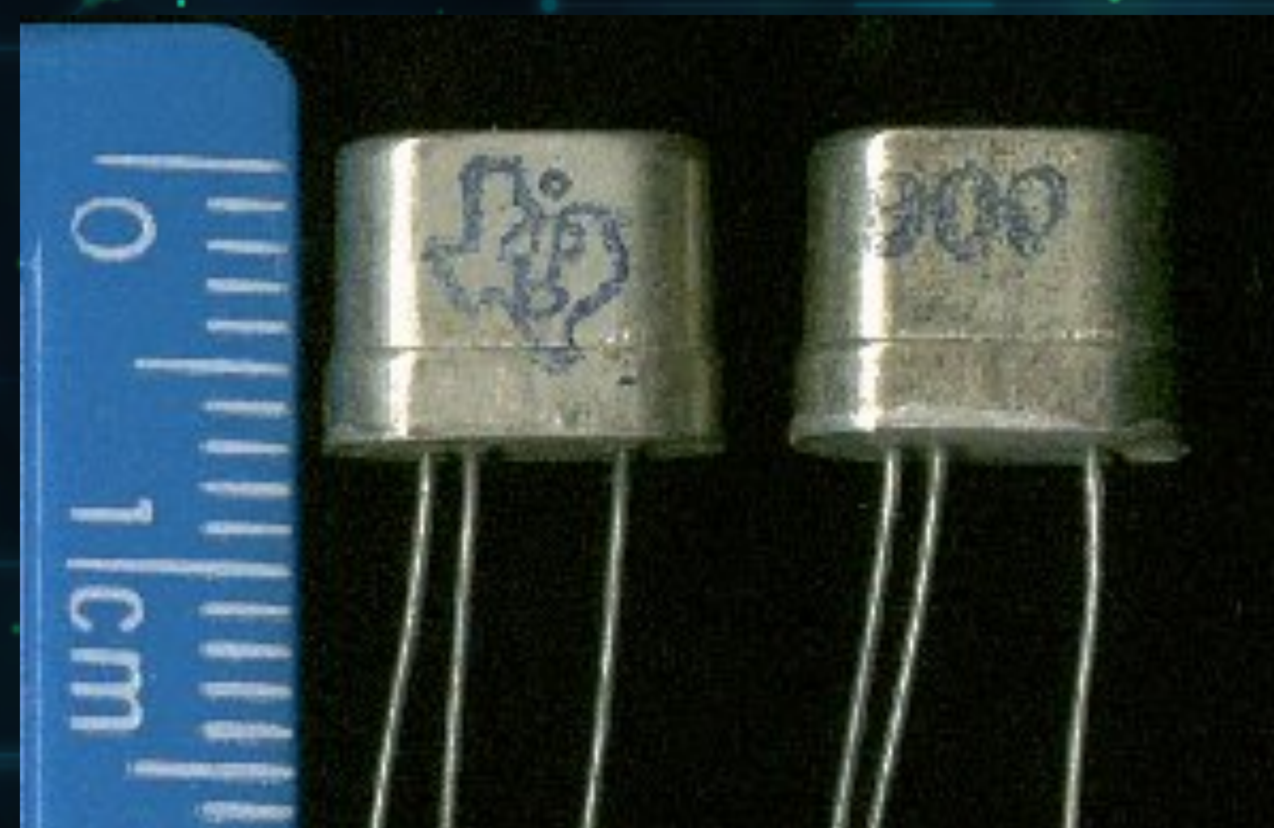
1948- Schockly
invents the Ge Junction transistor



1949- Raytheon CK703
first commercial Ge transistor

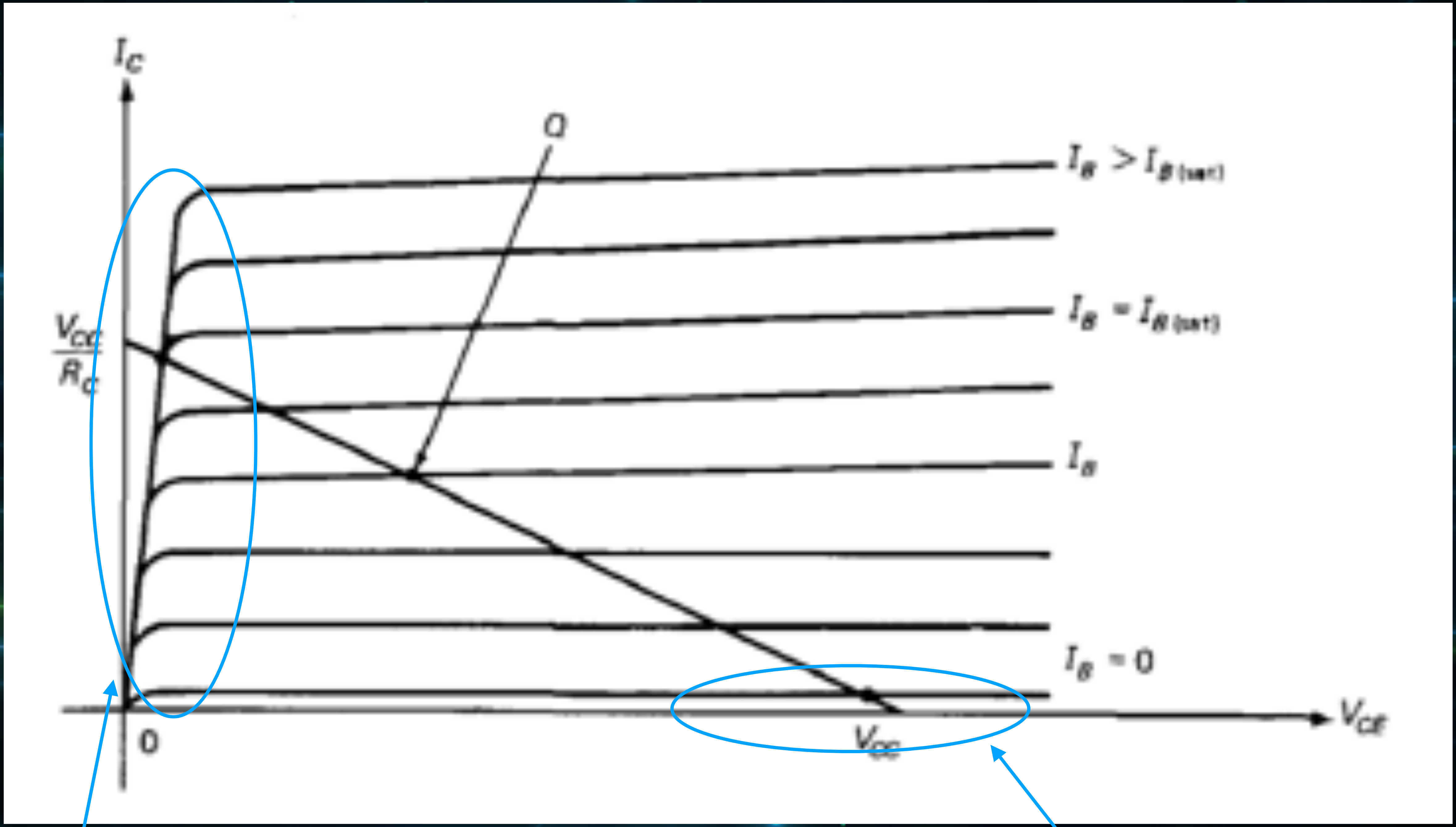


1953 - Raytheon CK722
first mass produced Ge transistor



1955 - Texas Instruments 900
first commercial Si transistor

Transistor come switch



Saturazione

Interdizione

The Nobel Prize in Physics 1956

"For their researches on semiconductors and their discovery of the transistor effect"

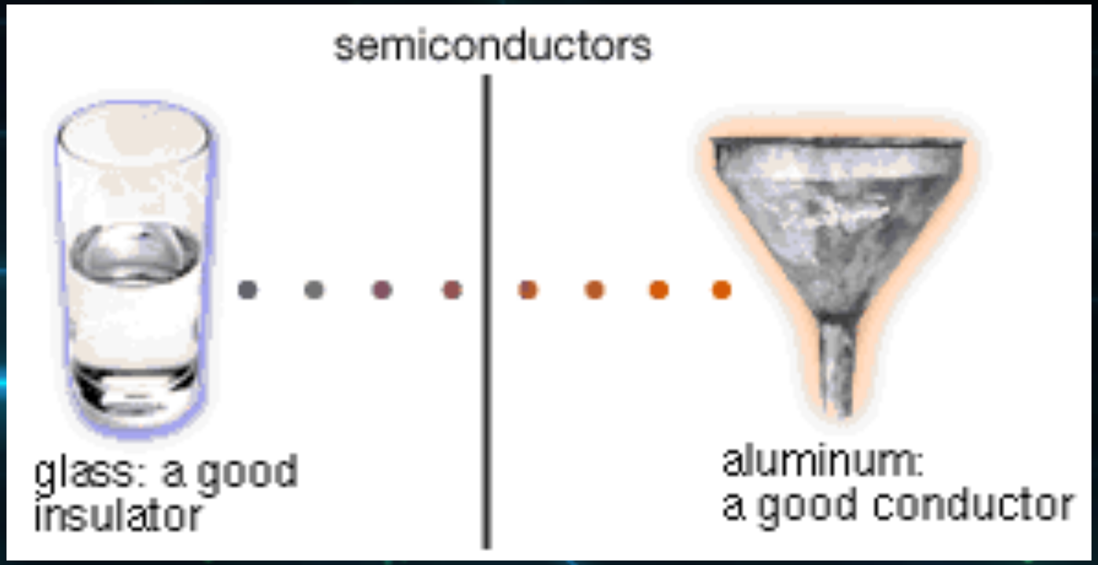
William Bradford Shockley

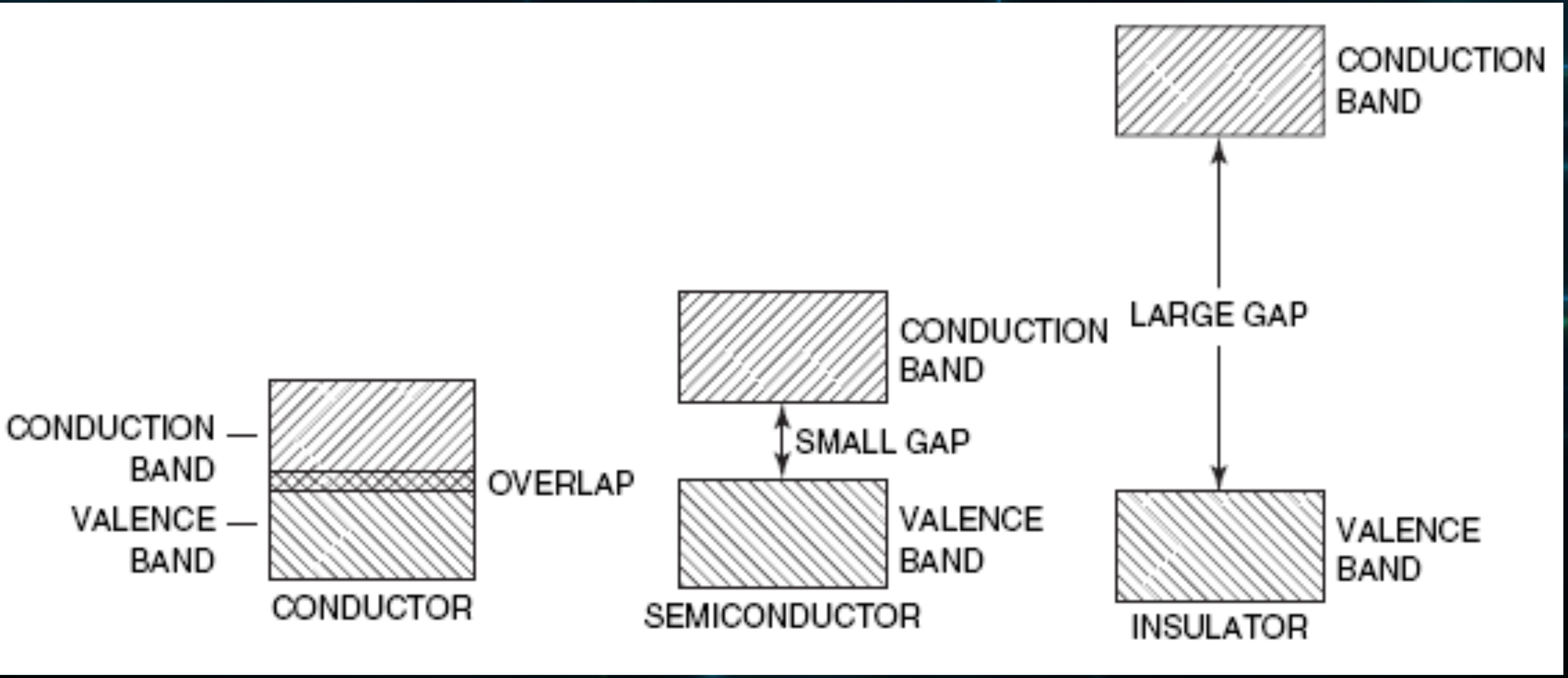
John Bardeen

Walter Houser Brattain

Cristalli semiconduttori

I transistor sono fatti da materiali semiconduttori…

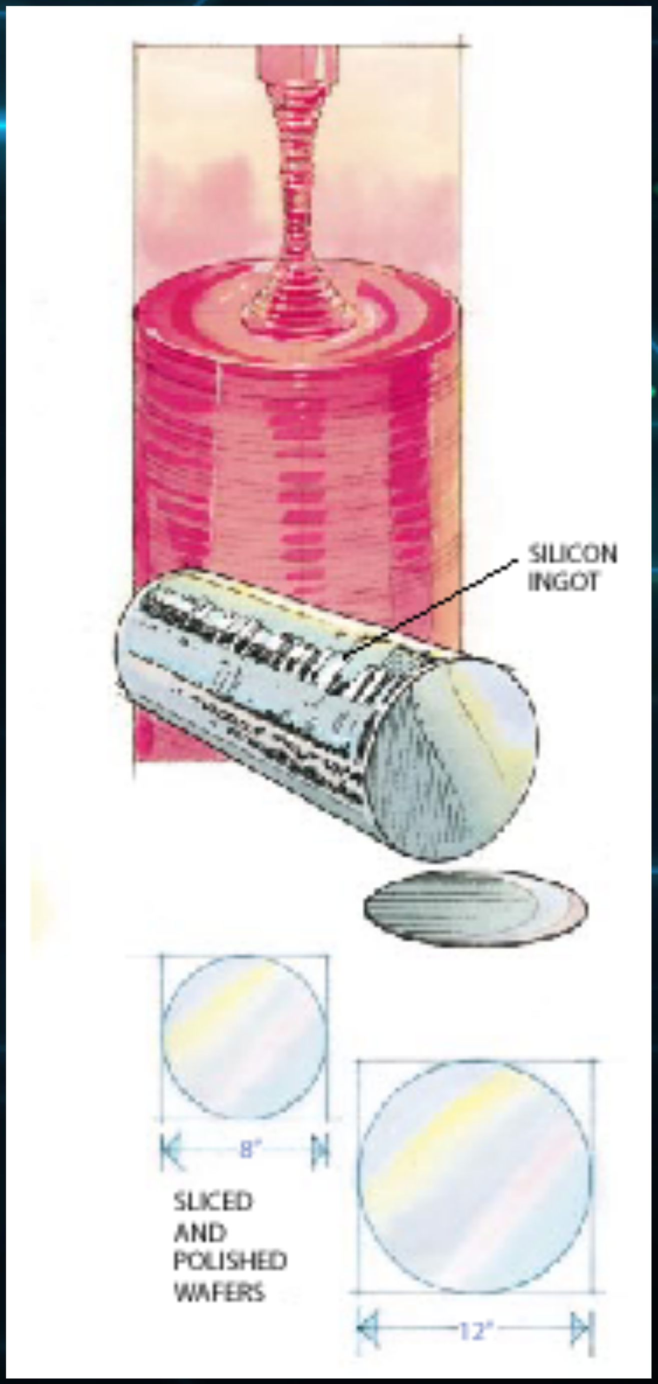




Substrati per transistor

Materiali semiconduttori policristallini purificati

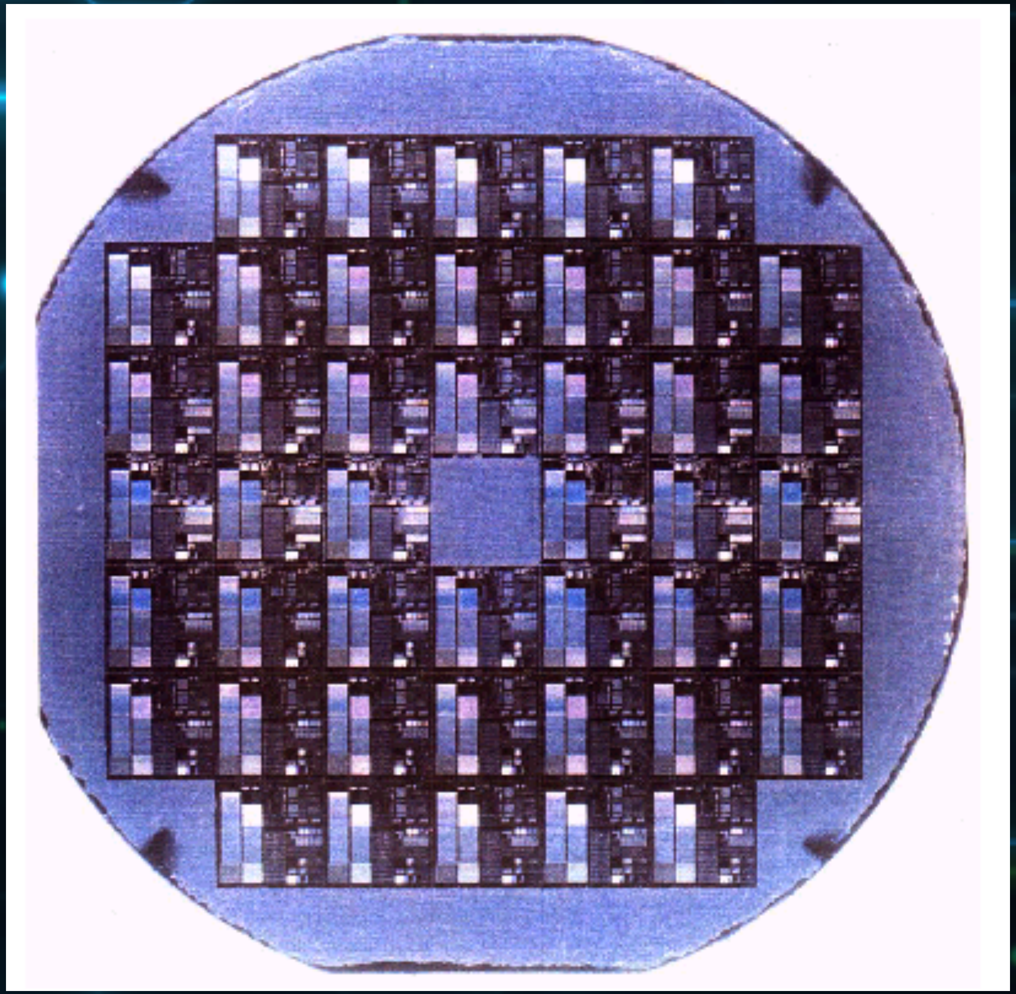
Crescita di un singolo cristallo di silicio



Il circuito integrato

Molti transistor e circuiti complicati su un unico substrato

Primo circuito integrato costruito dalla Texas Instruments nel 1958
da Jack Kirby and Robert Noyce



Circuito integrato moderno
Moltissimi chip su un unico substrato
ed ogni chip contiene milioni di transistor

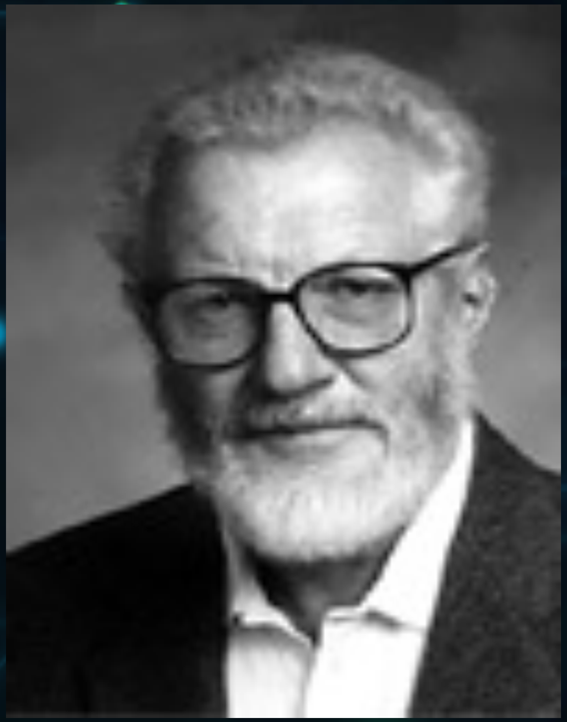
The Nobel Prize in Physics 2000

"For basic work on information and communication technology"

"For developing semiconductor heterostructures used in high-speed- and opto-electronics"

"For his part in the invention of the integrated circuit"

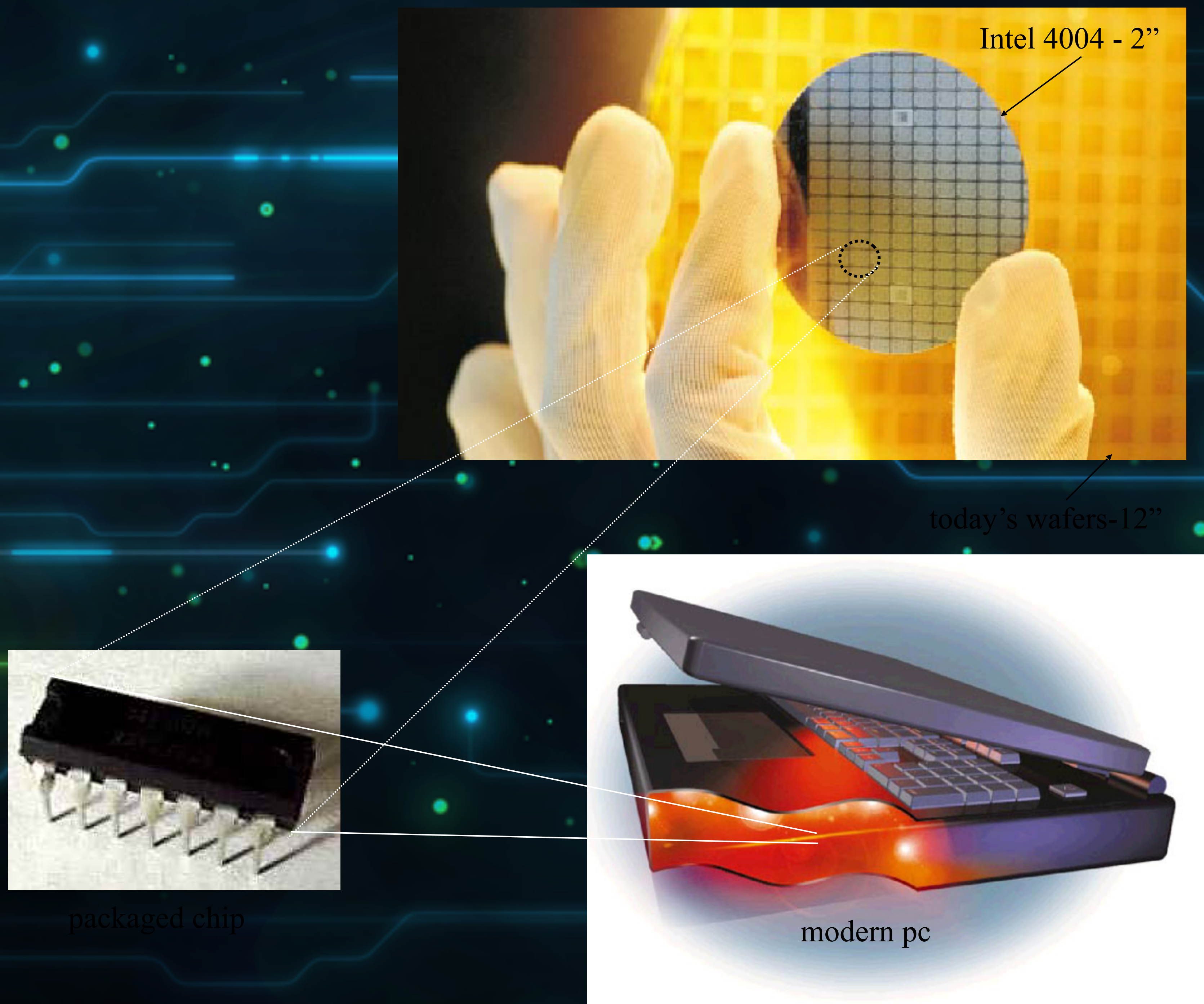
Zhores I Alferov



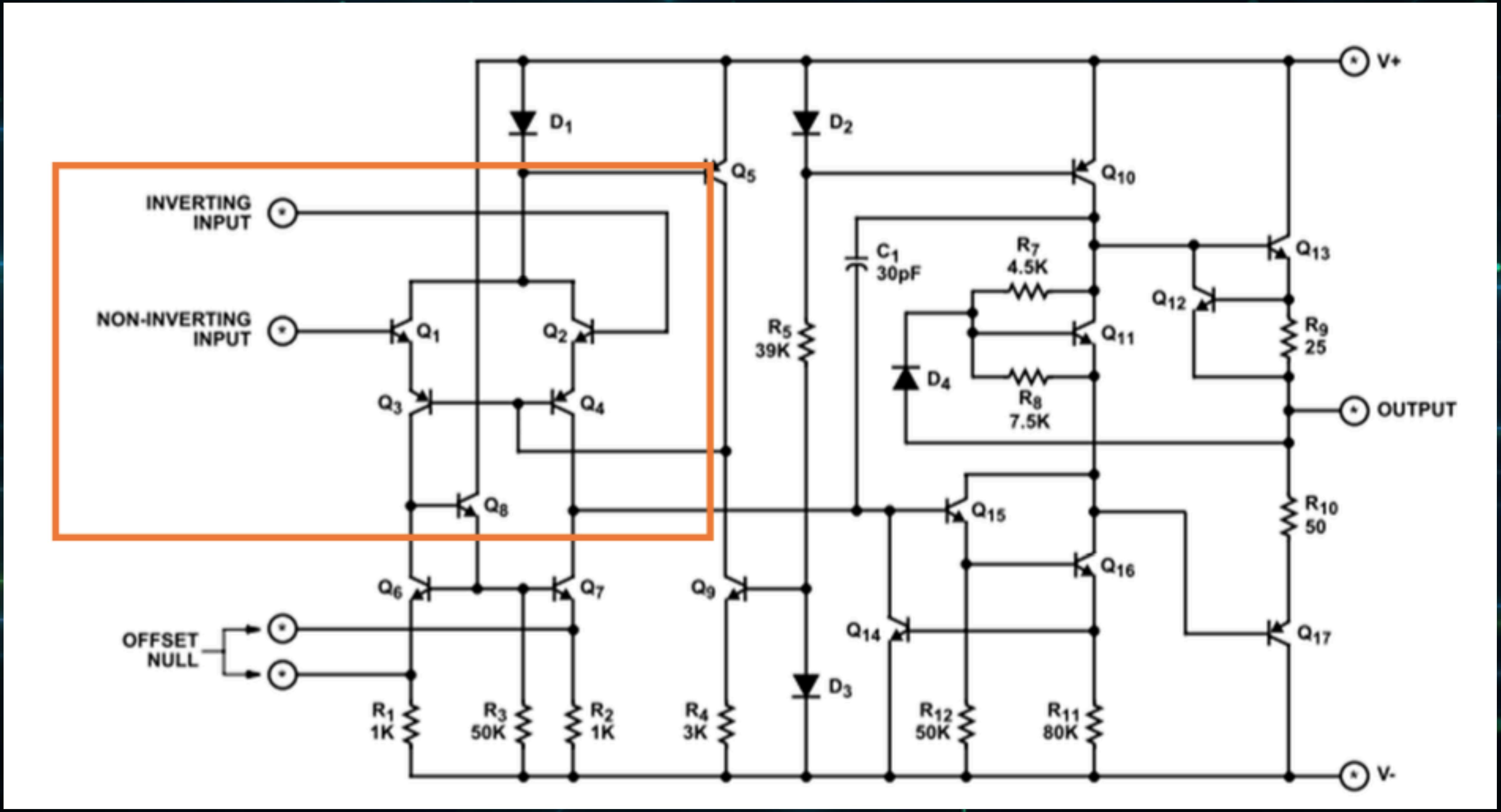
Herbert Kroemer

Jack S Kilby

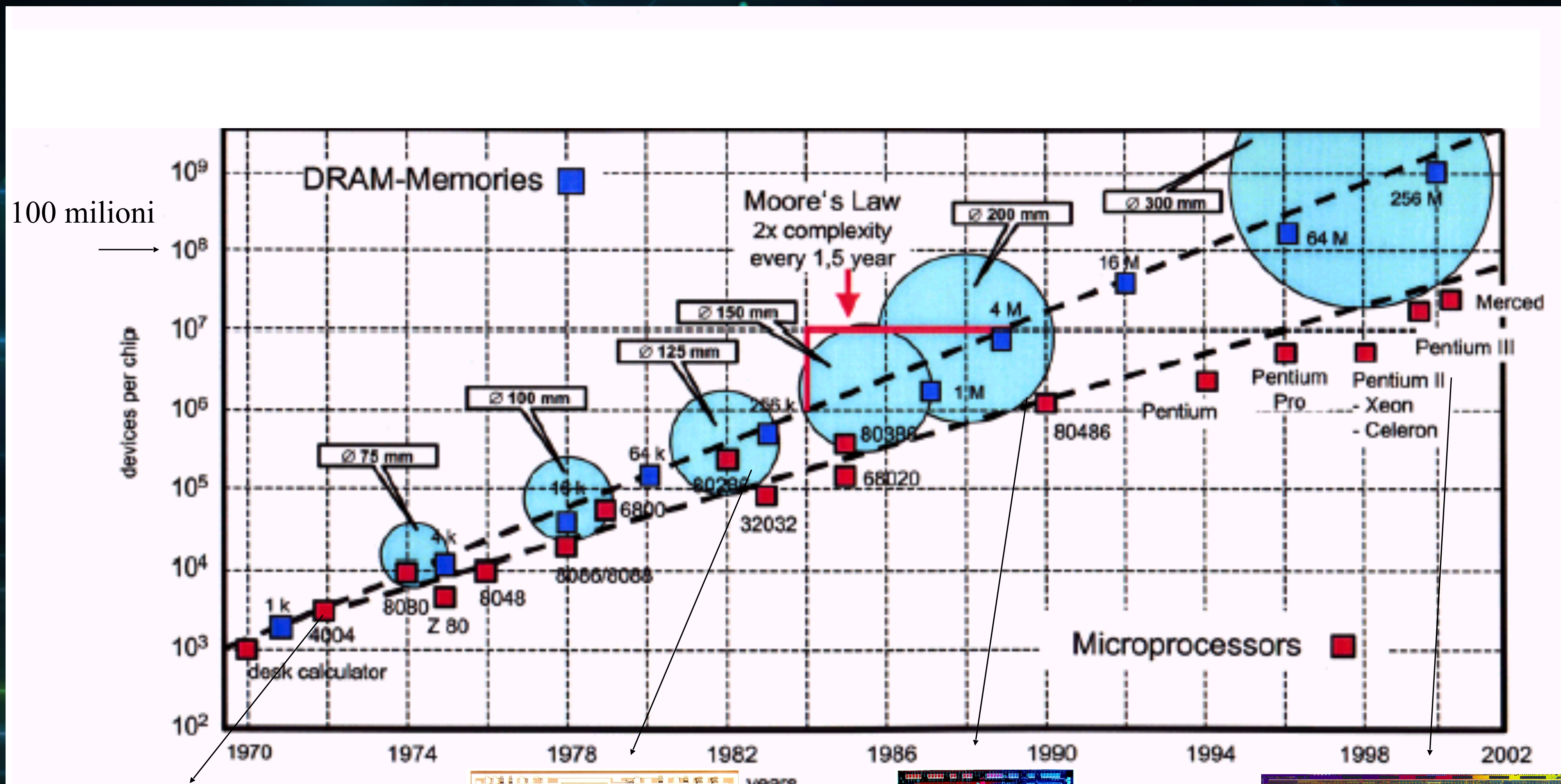
I circuiti integrati oggi…

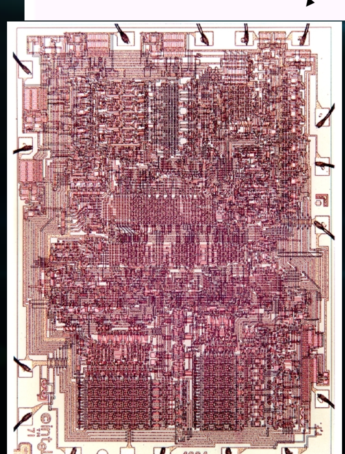


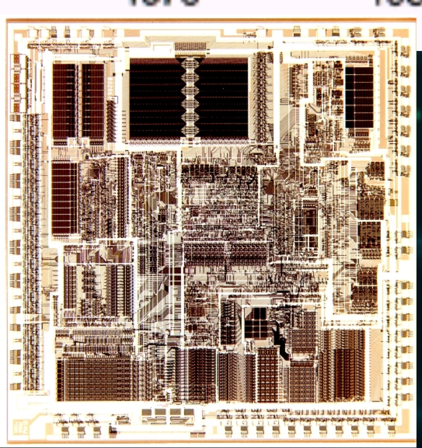
Cosa c'è all'interno di un integrato?

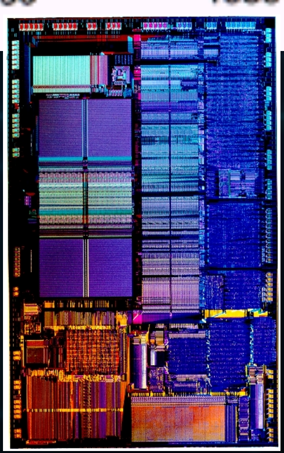


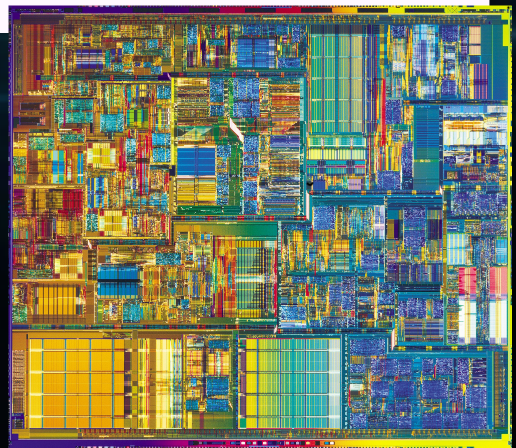
Legge di Moore




Intel - 4044


Intel - 286

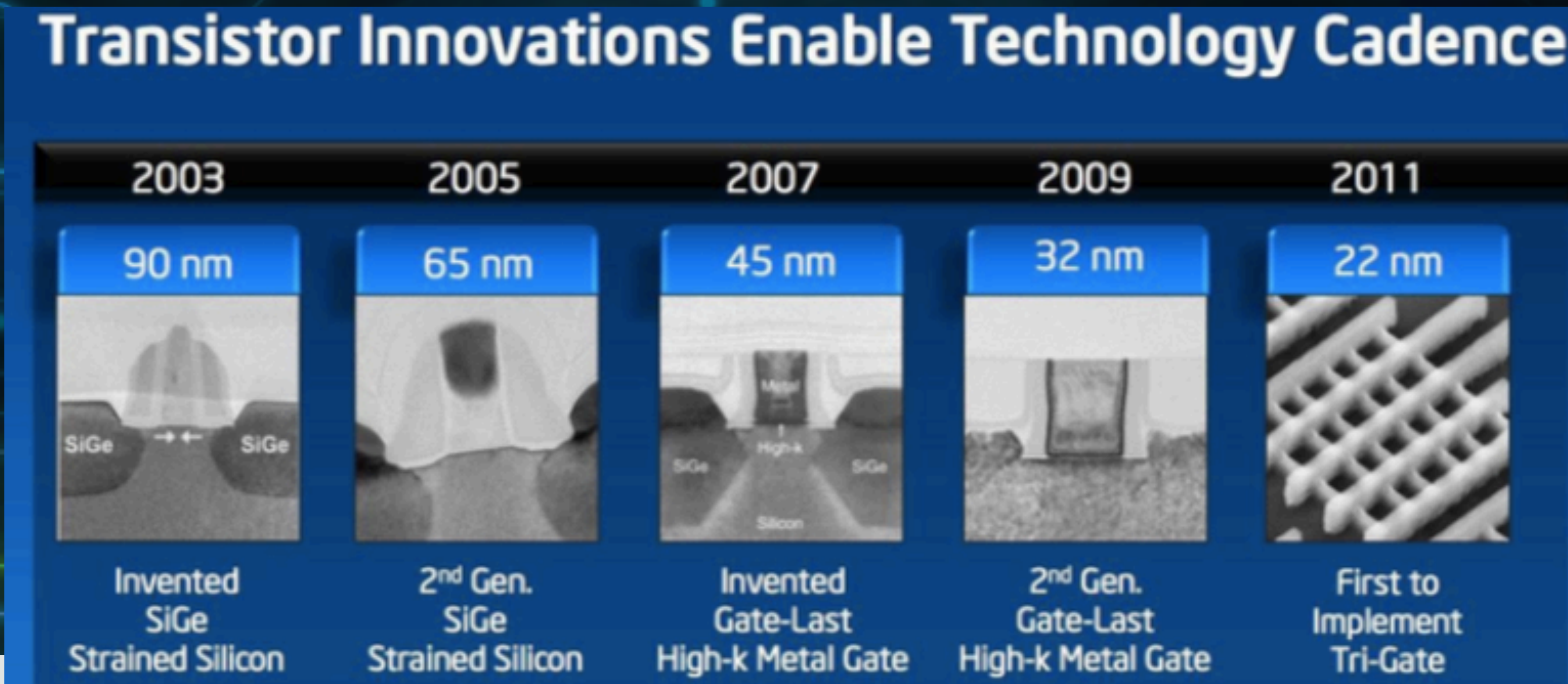

Intel - 486


Intel - Pentium III

Miniaturizzazione

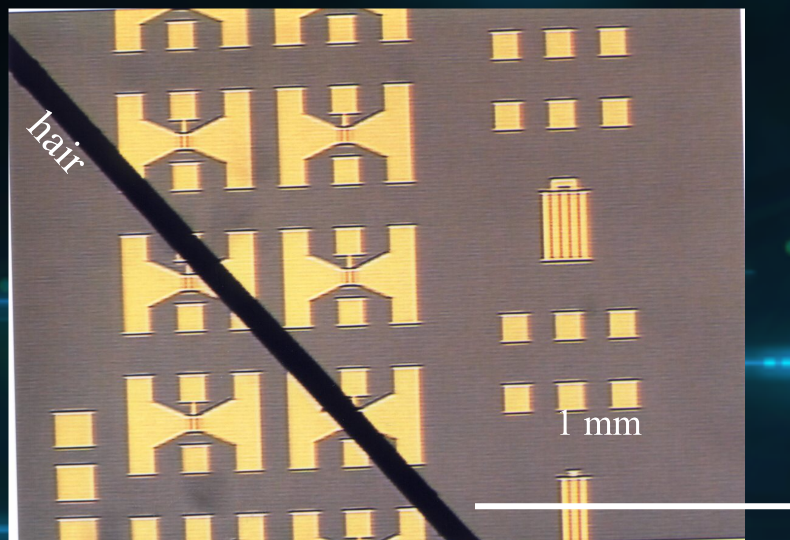
$$C = \varepsilon \cdot \frac{A}{d}$$

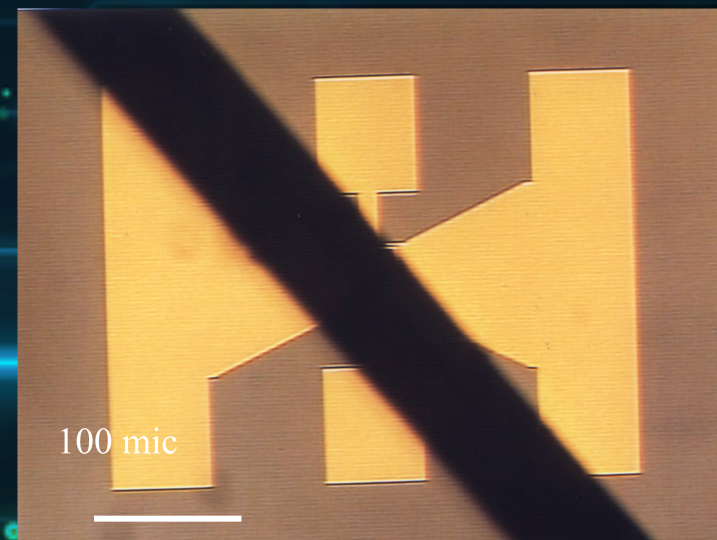
Diminuire la dimensione dei dispositivi con dei diversivi…



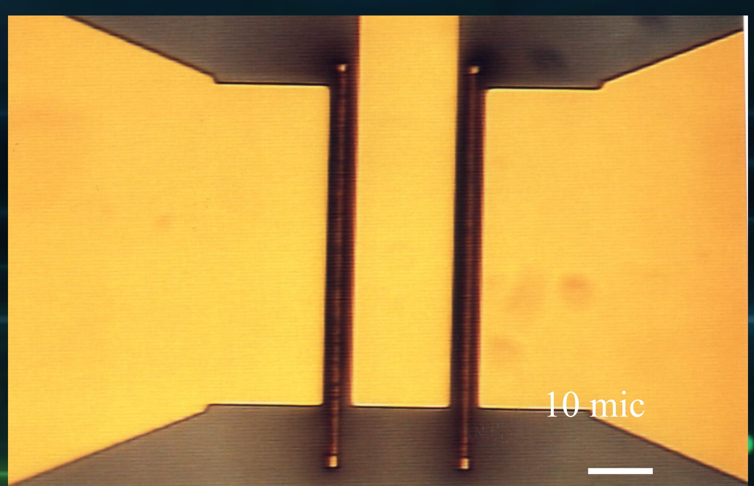
CPU	Date of Introductior	Number of Transistors
Intel486™ SL Processor	1992	1,400,000
AMD K6 (Model 6)	1997	8,800,000
Intel® Pentium® 4 Processor	2000	42,000,000
Intel® Celeron® D Processor	2004	125,000,000
Intel® Core™2 Quad Processor Q	2008	820,000,000
Intel Core i7-3970X	2012	2,270,000,000

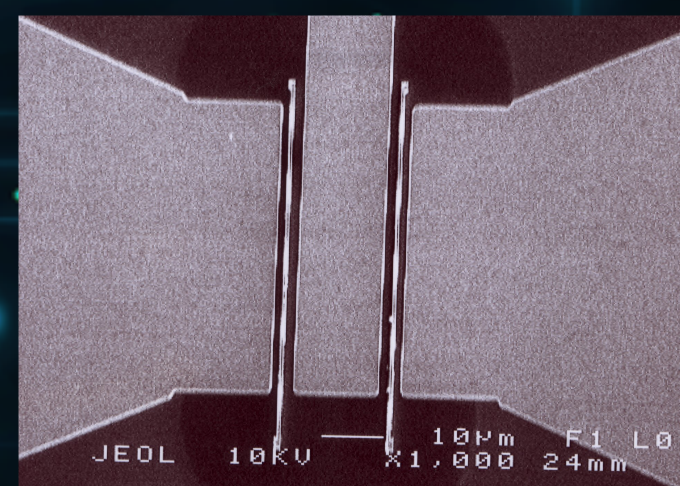
Miniaturizzazione

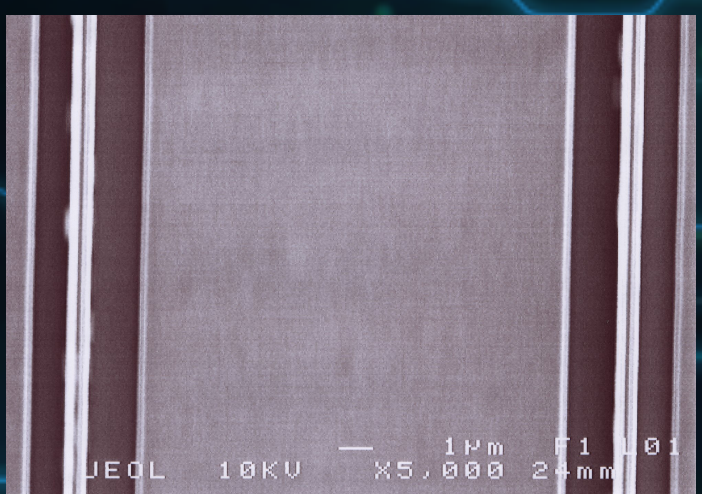


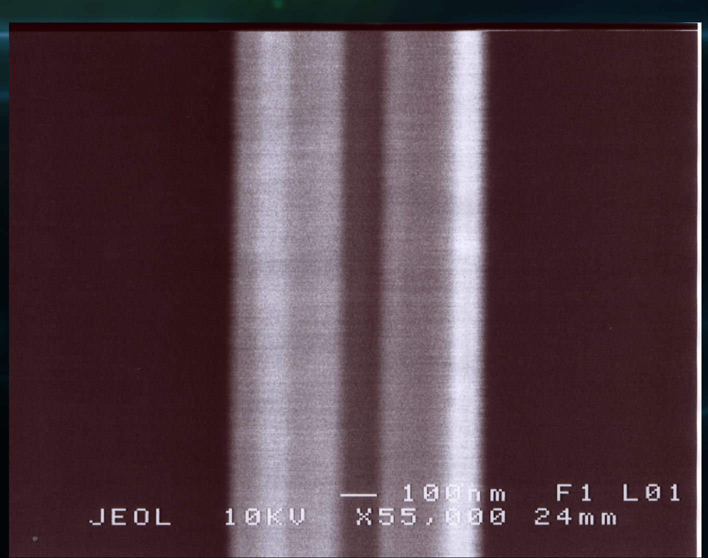


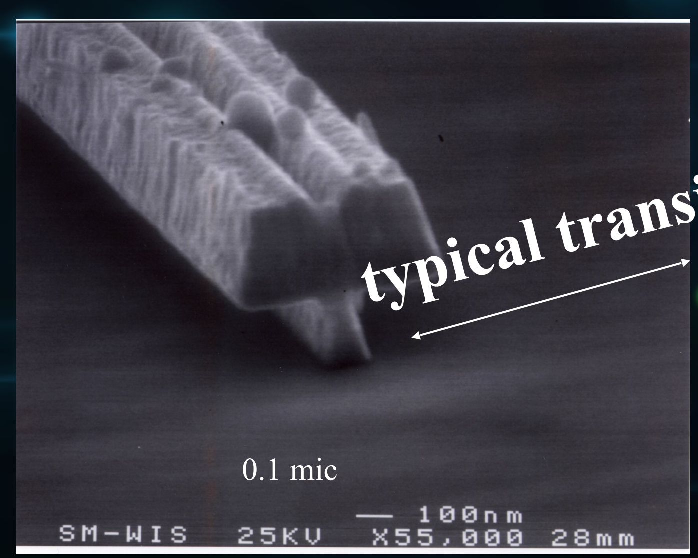
1 mm = 1,000 mic









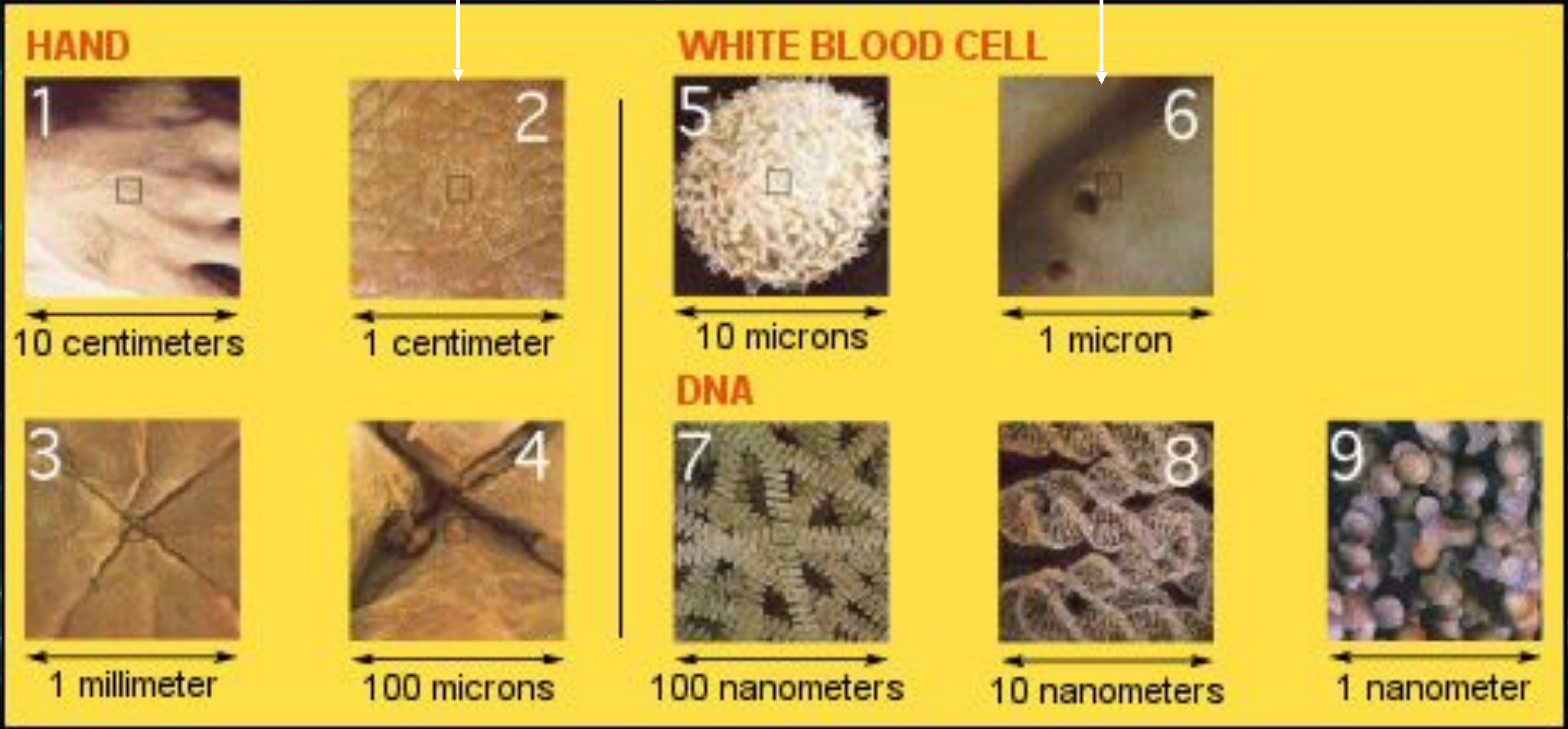


Quanto possiamo ancora diminuire le dimensioni?

Miniaturizzazione

macro-electronics in 1950's

micro-electronics today

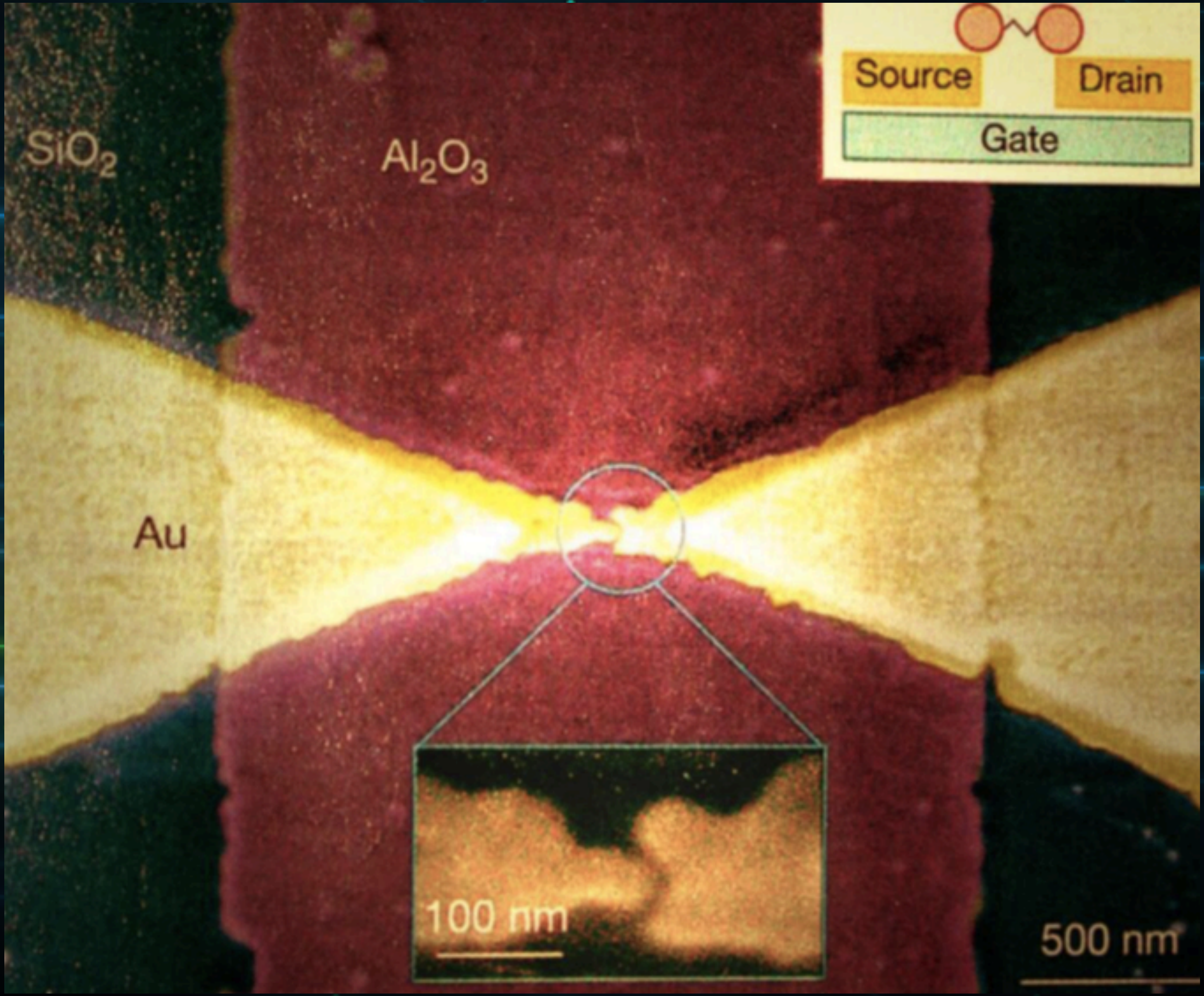


Nano-elettronica del futuro

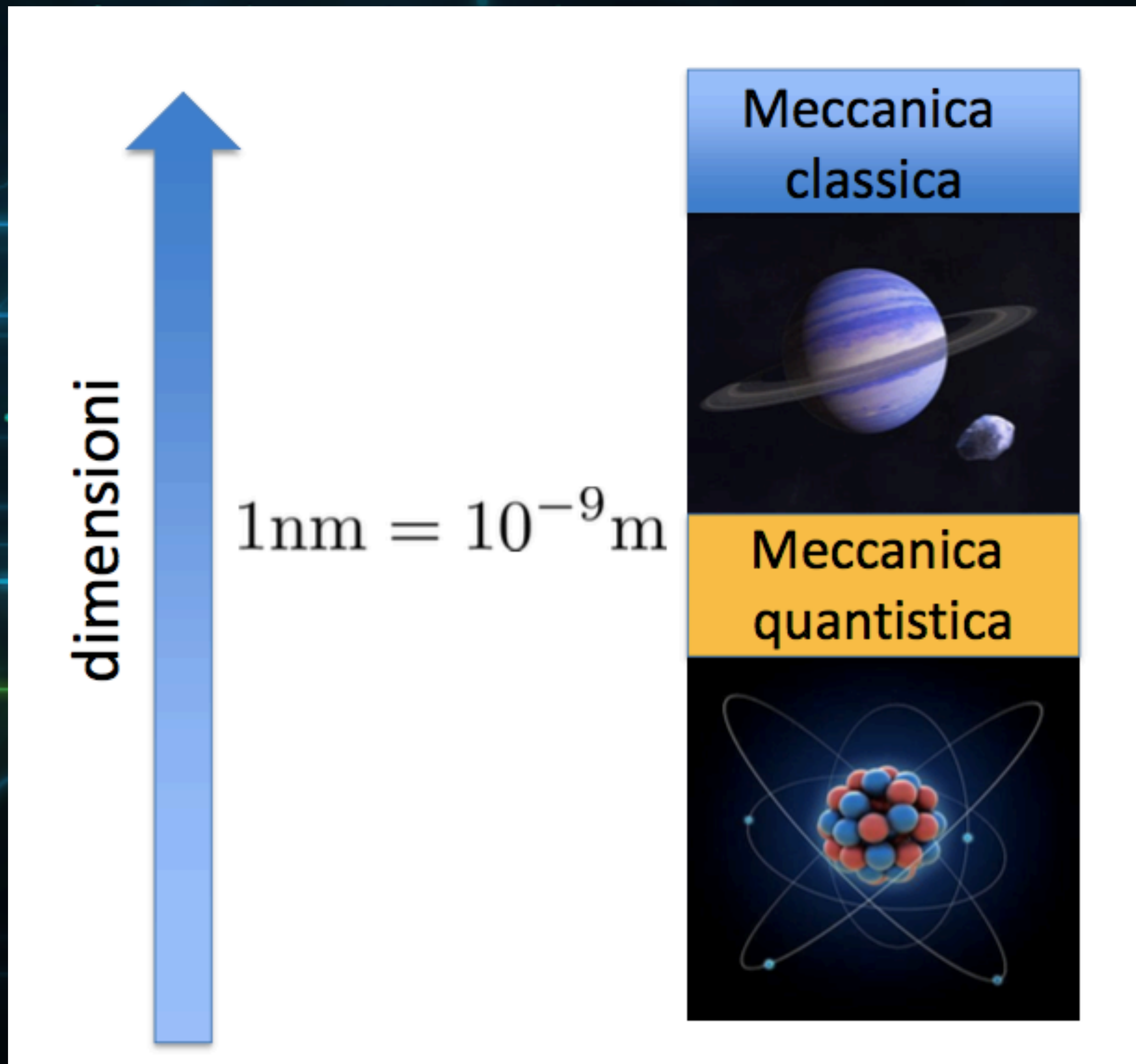
Come si potrà costruire?

Quale sarà il suo comportamento?

Primi transistor con molecole organiche

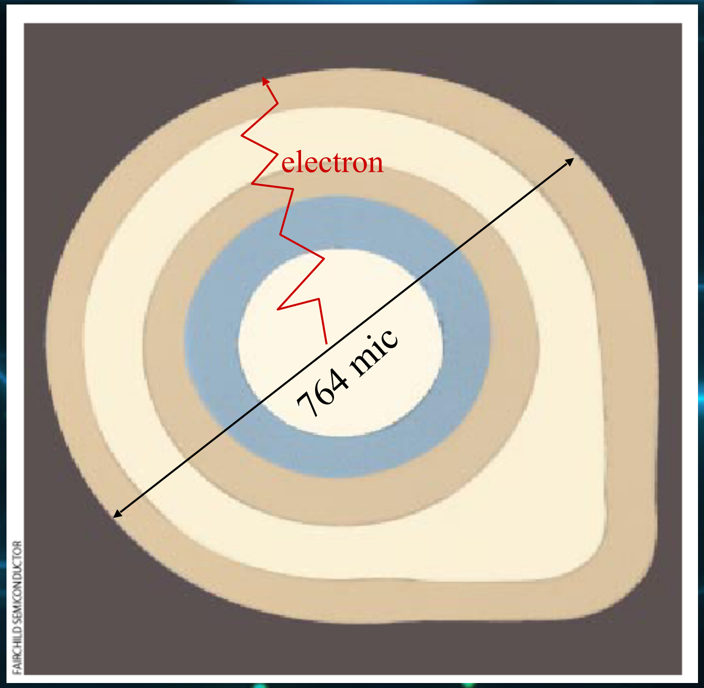


Diminuzione delle dimensioni $\longrightarrow$ Regime quantistico

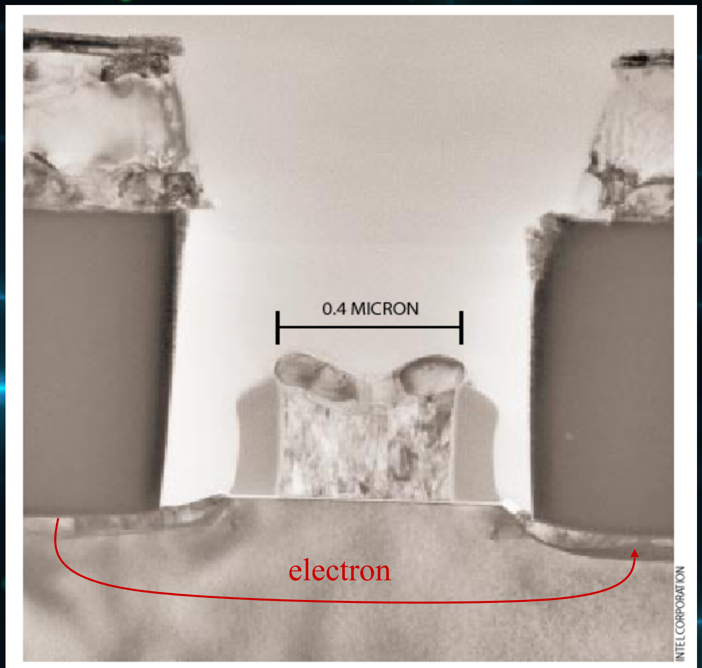


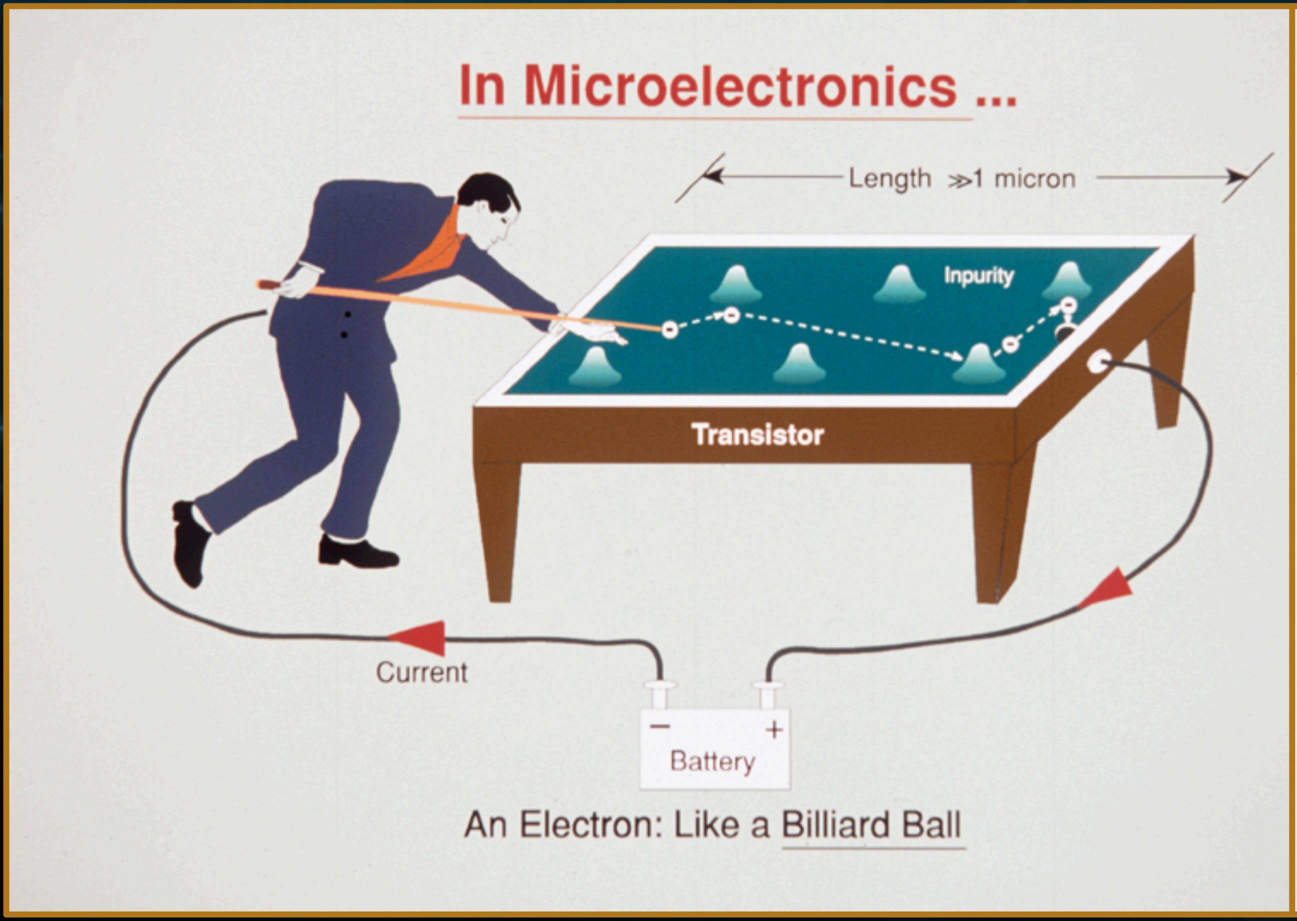
Dal mondo classico → Al mondo quantistico

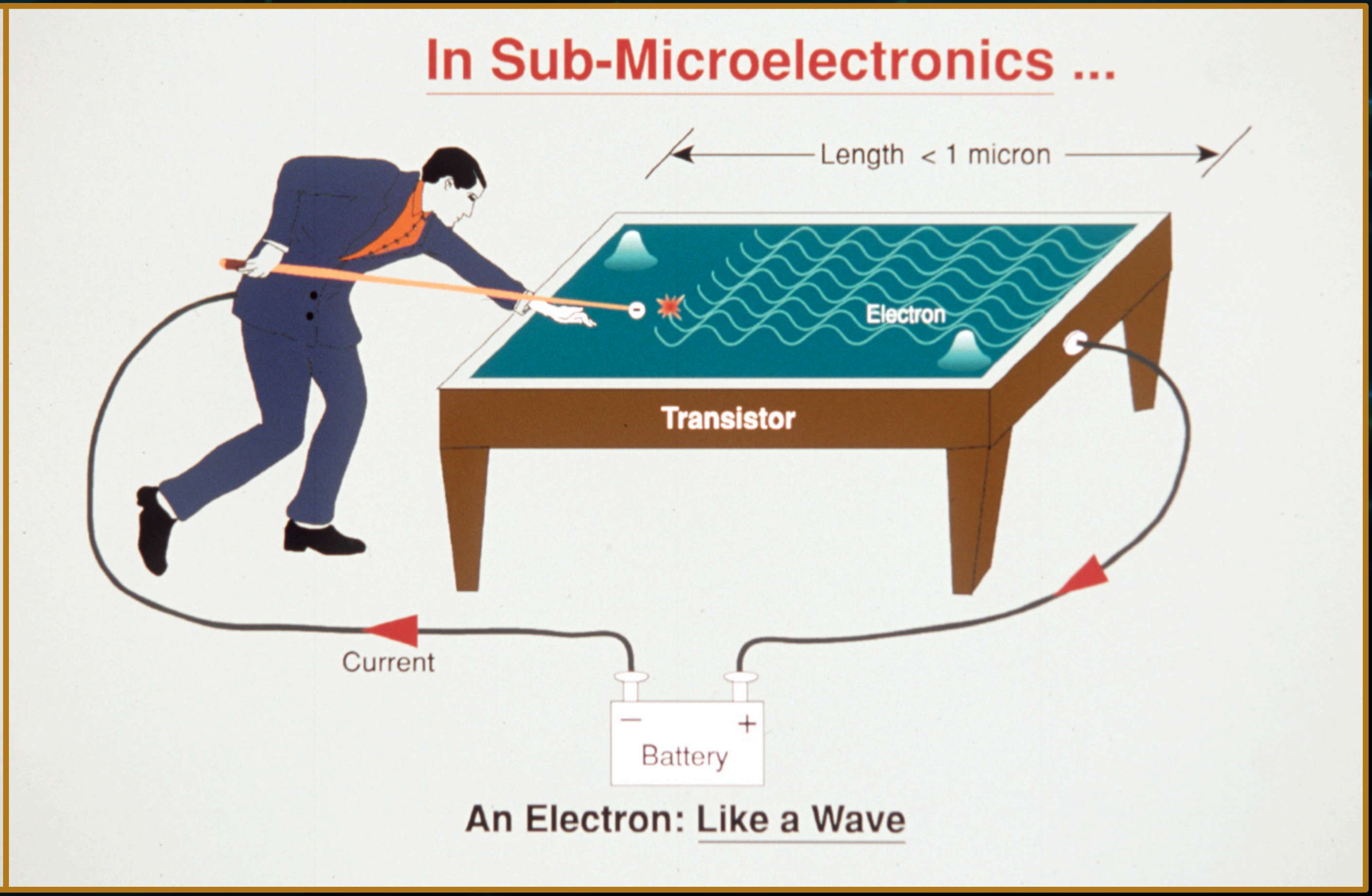
Fairchild - 1959



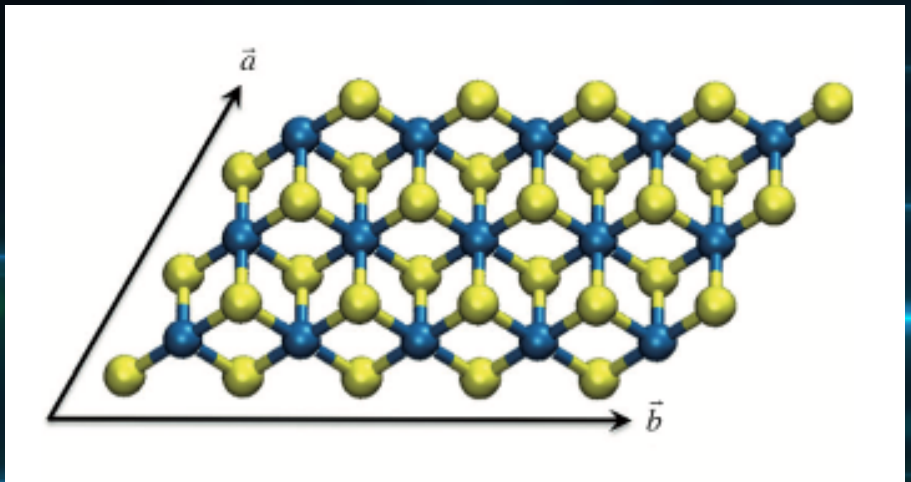
Intel - 2000





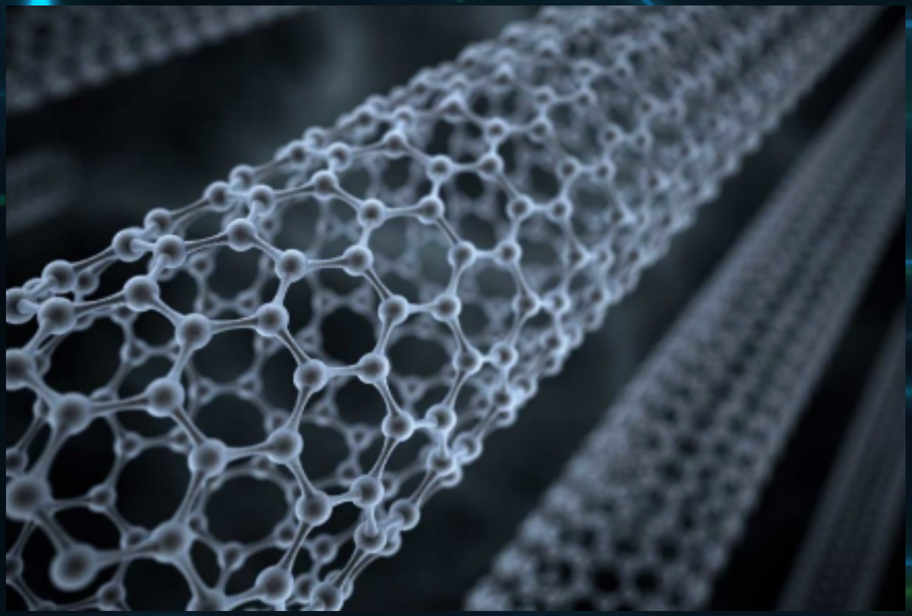


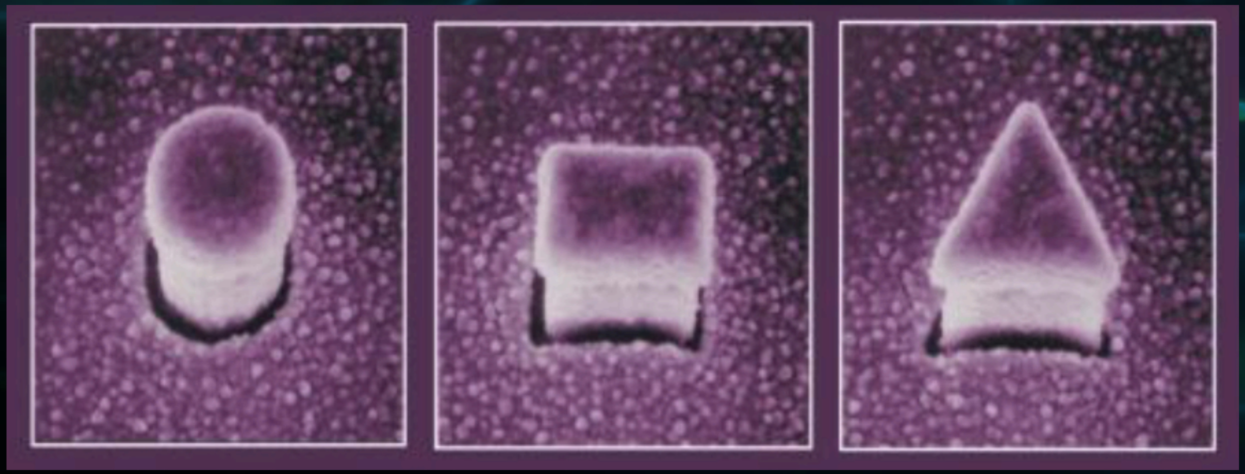
Che sistemi possiamo studiare?



Materiali 2D

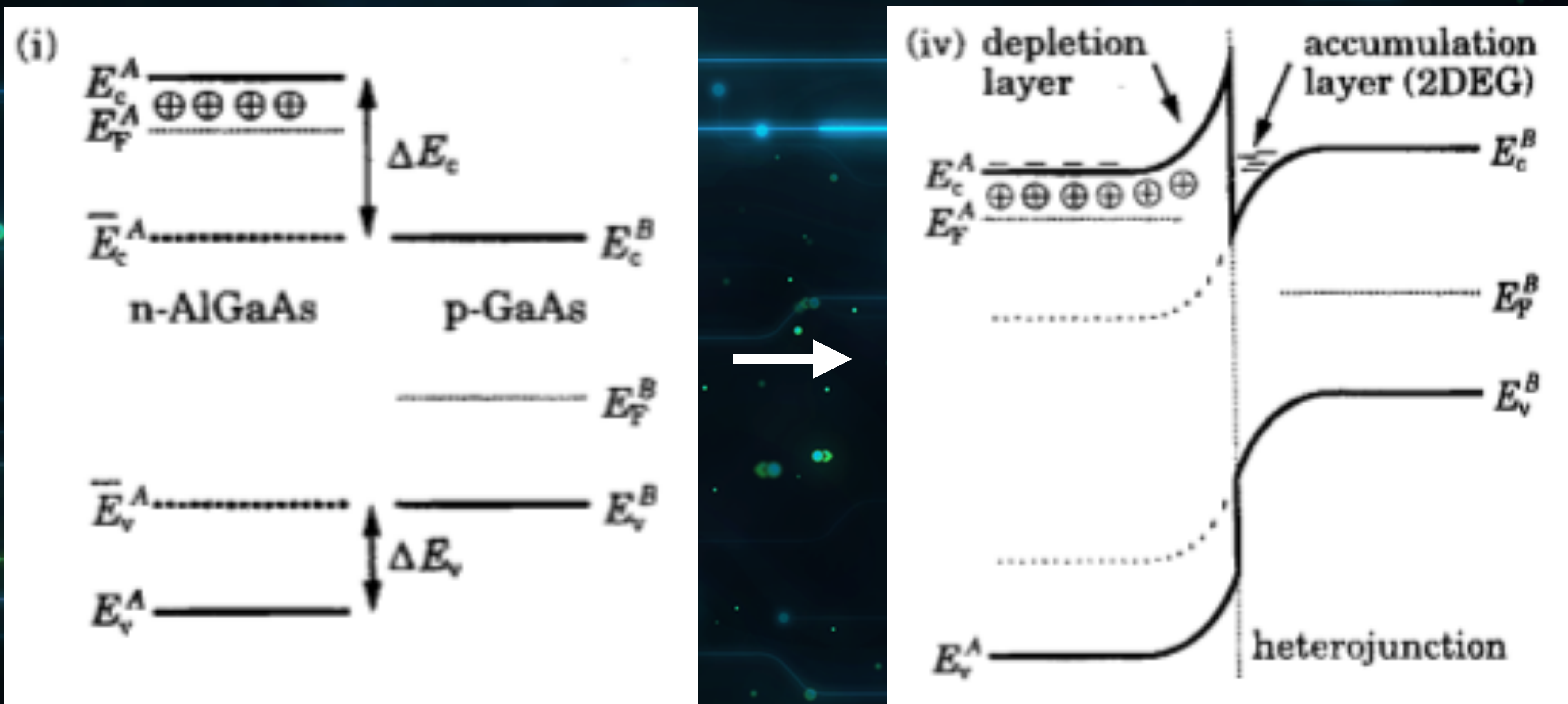
Materiali 1D





Materiali 0D

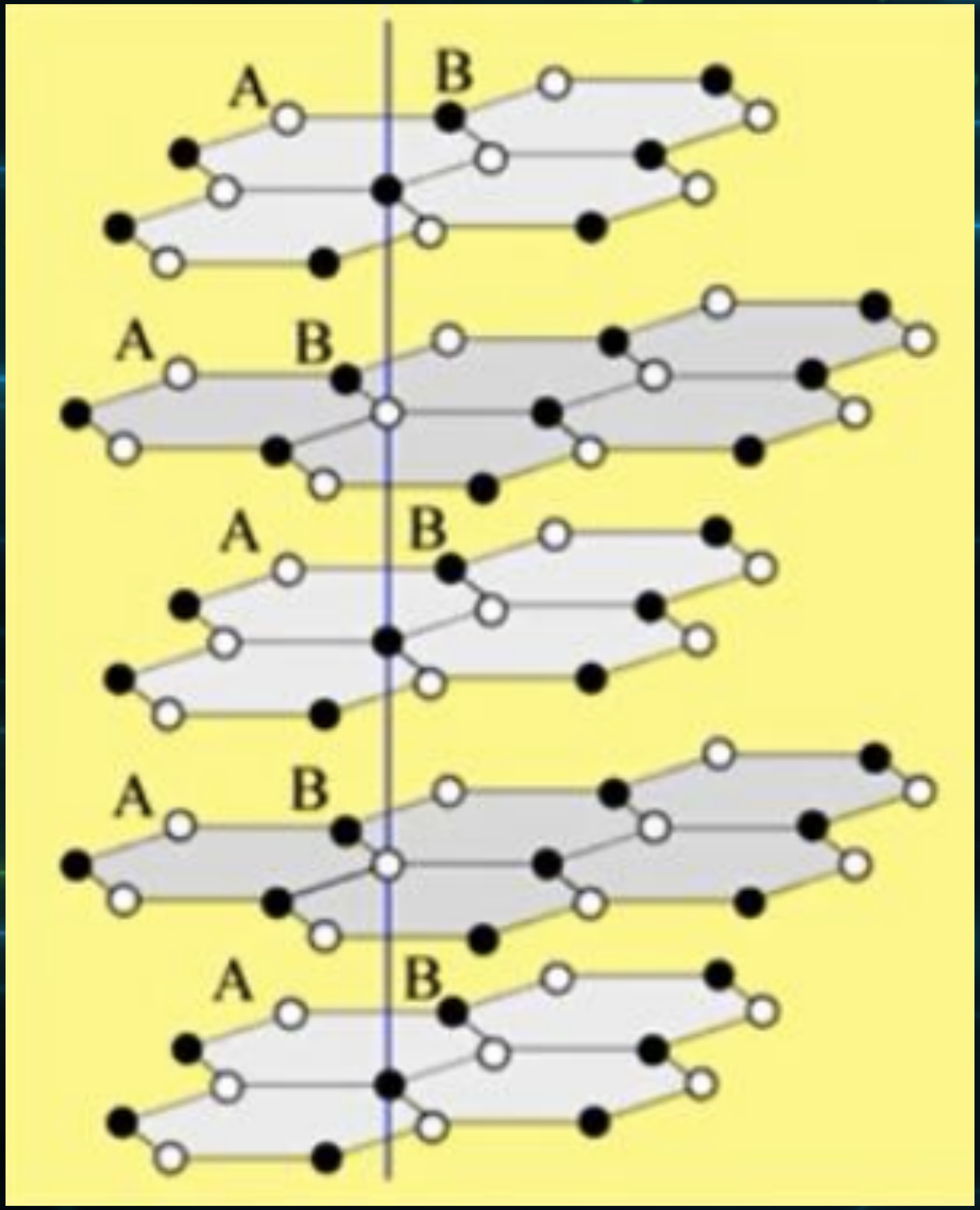
Eterostrutture a semiconduttore



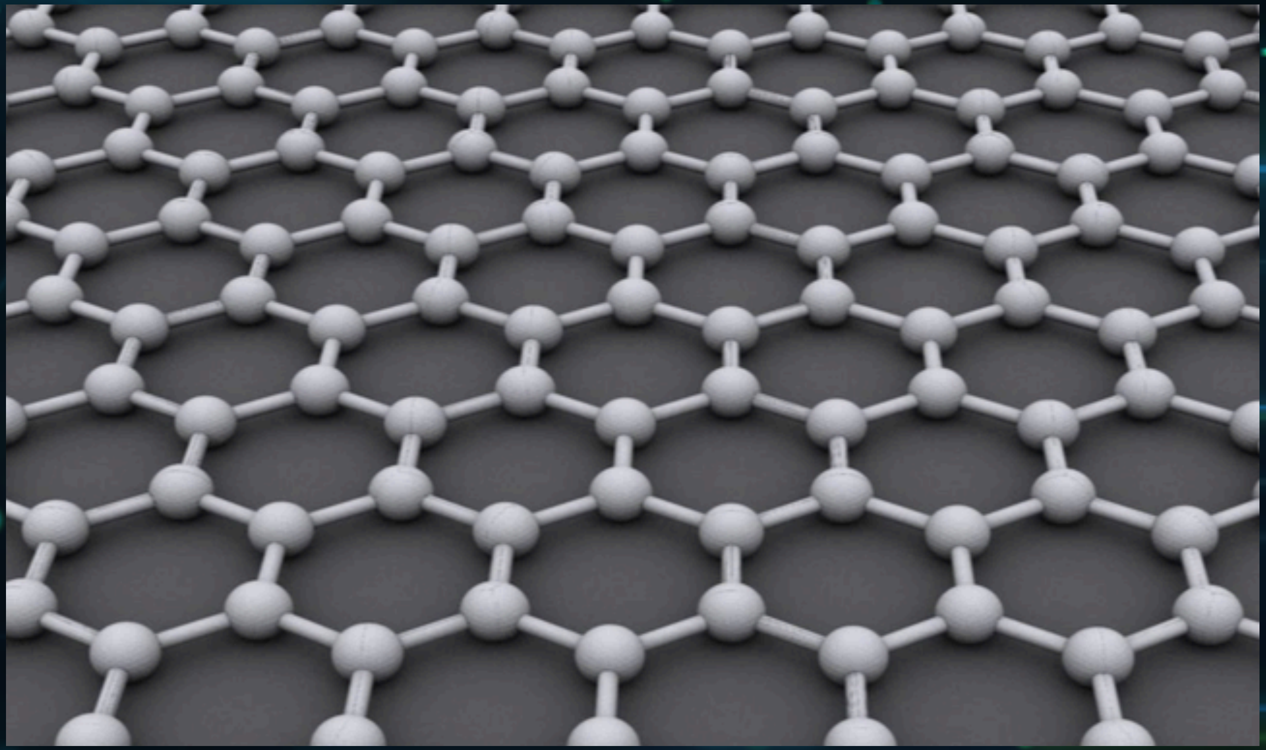
Formazione del 2DEG: elettroni vincolati in 2D

Materiali 2D - Grafene

Dalla Grafite…



…Al Grafene



Come si ottiene?

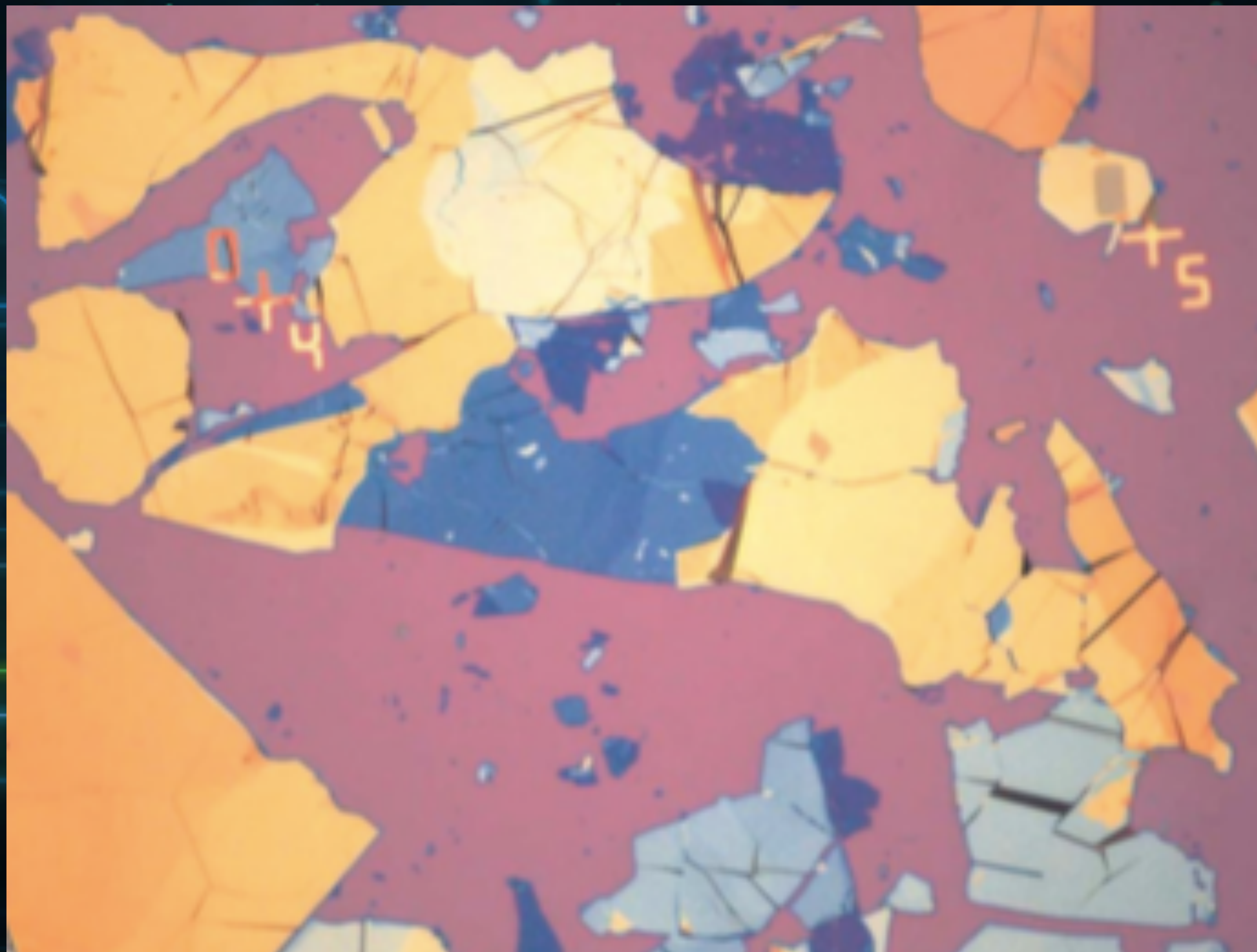
The Nobel Prize in Physics 2010

Andre Geim

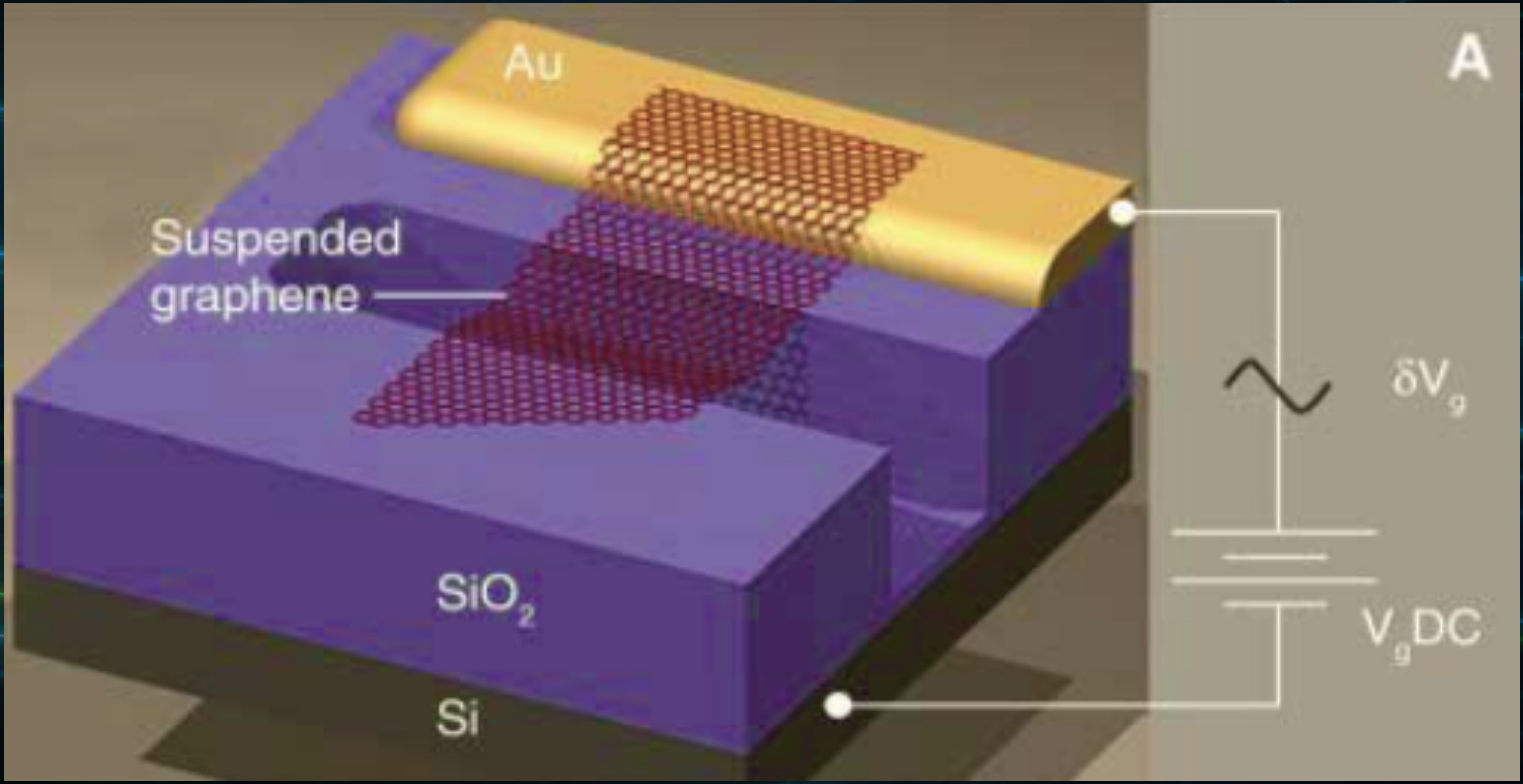
Konstantin Novoselov

"for groundbreaking experiments regarding the two-dimensional material graphene"

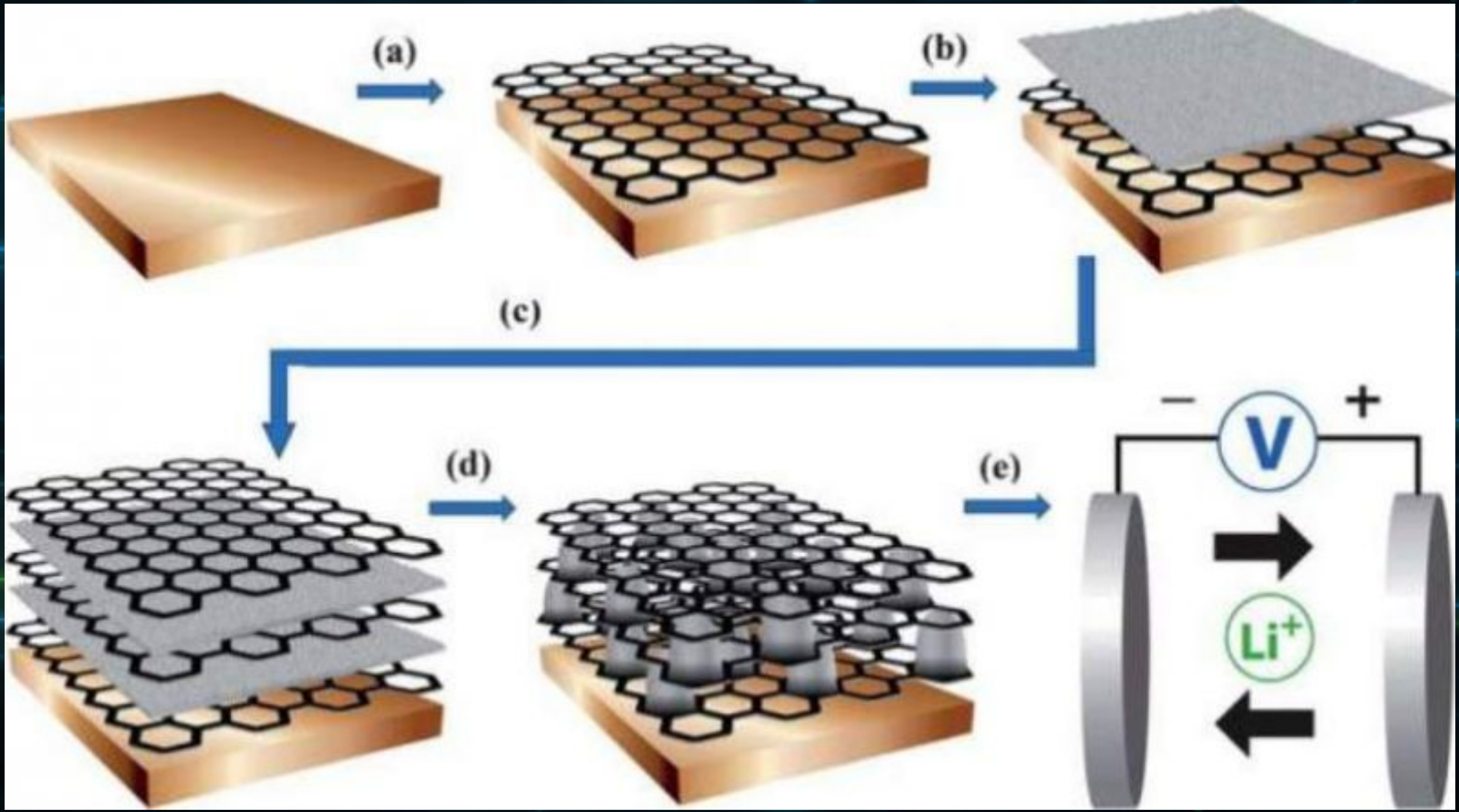
Cosa si osserva?



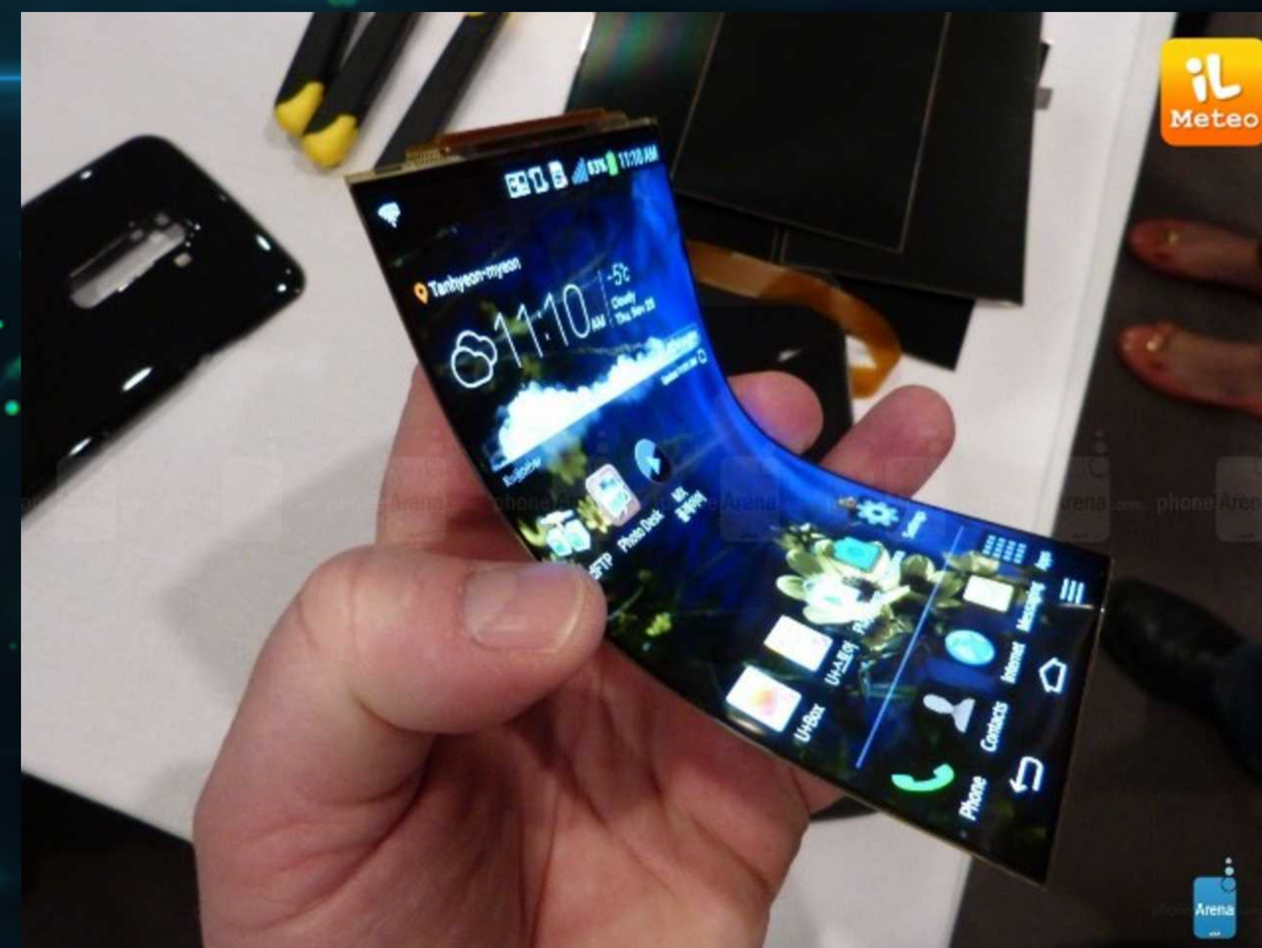
Utilizzi: Risuonatore



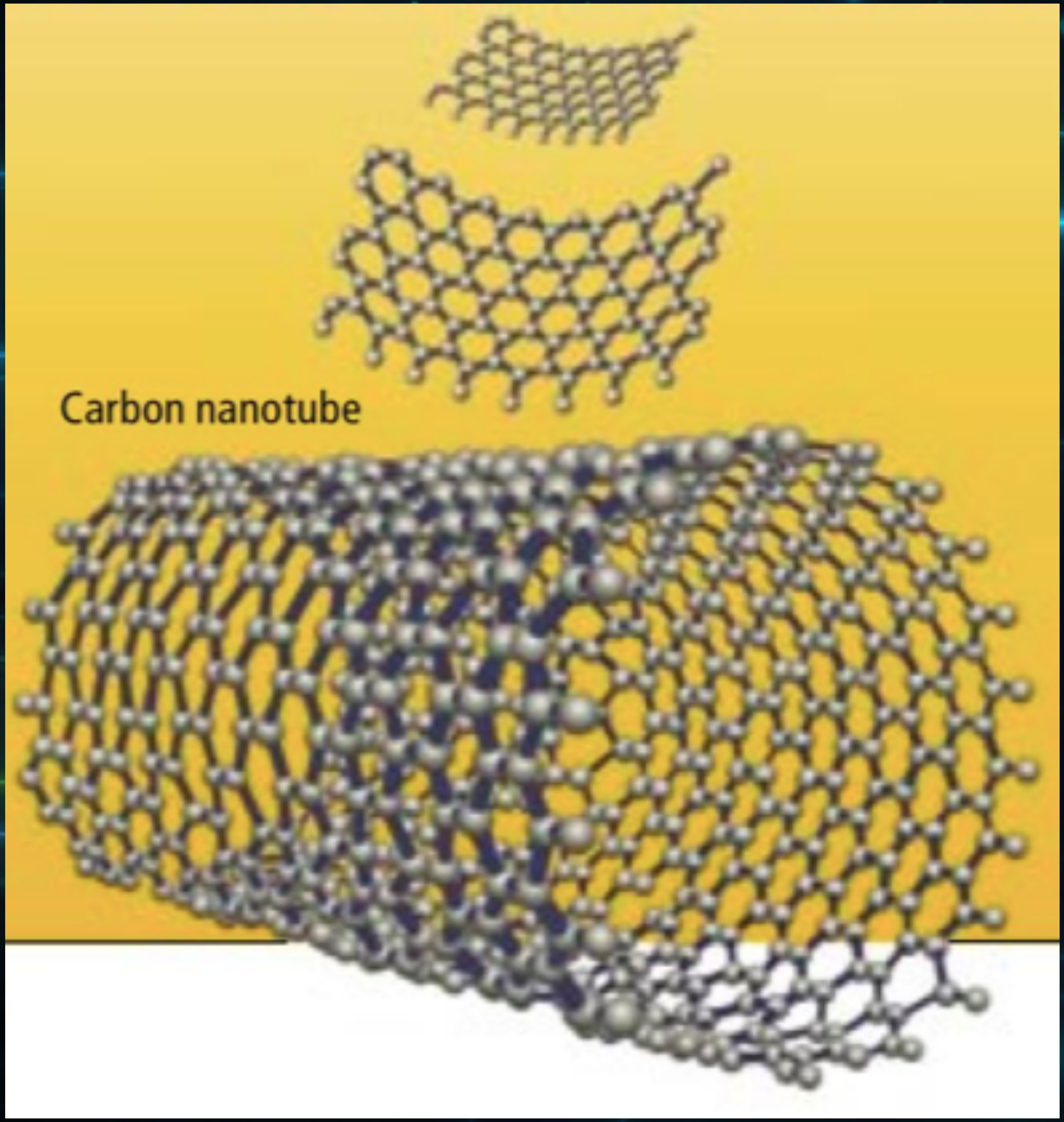
Utilizzi: Batterie



Utilizzi: Tecnologie flessibili

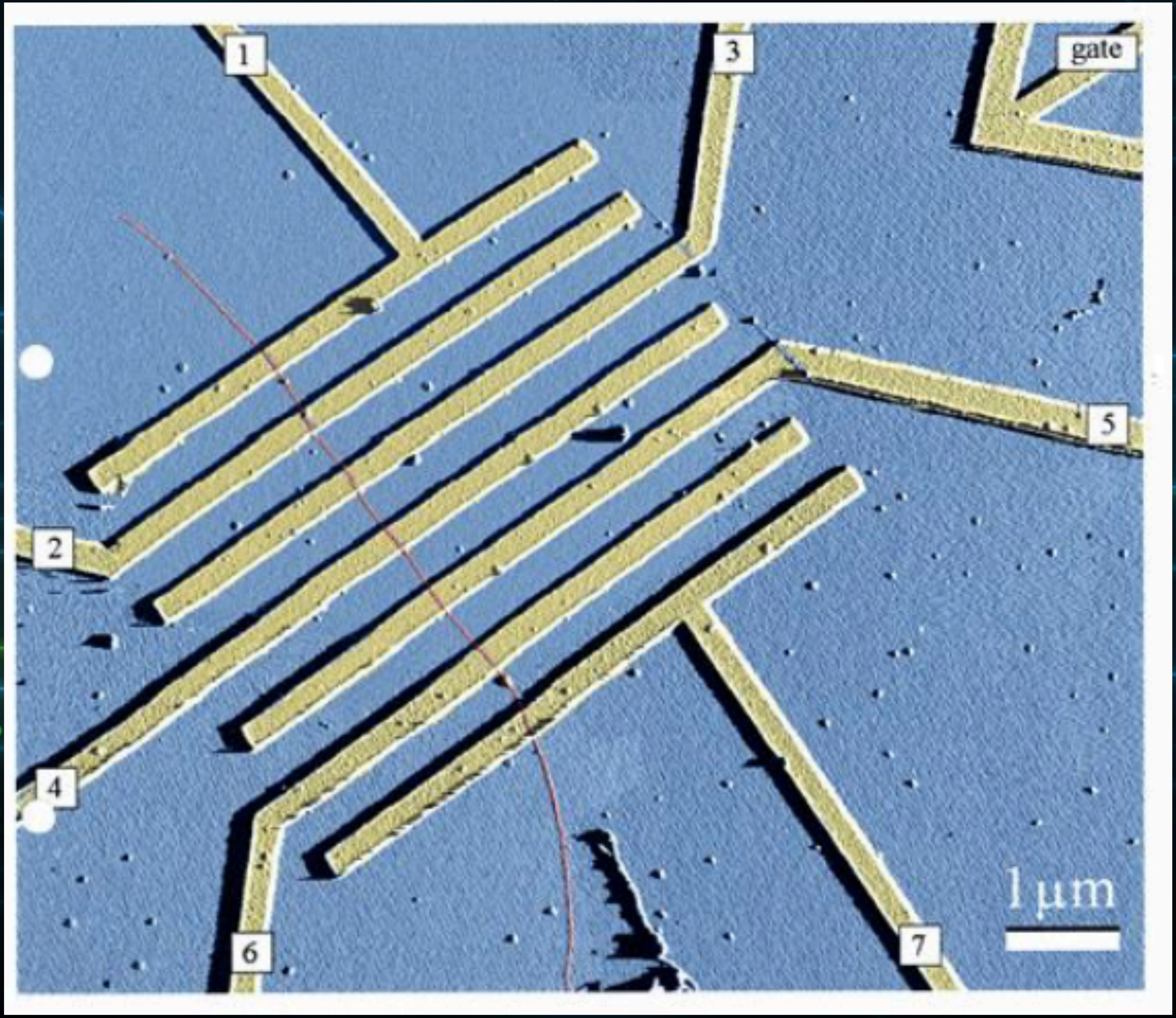


Materiali 1D

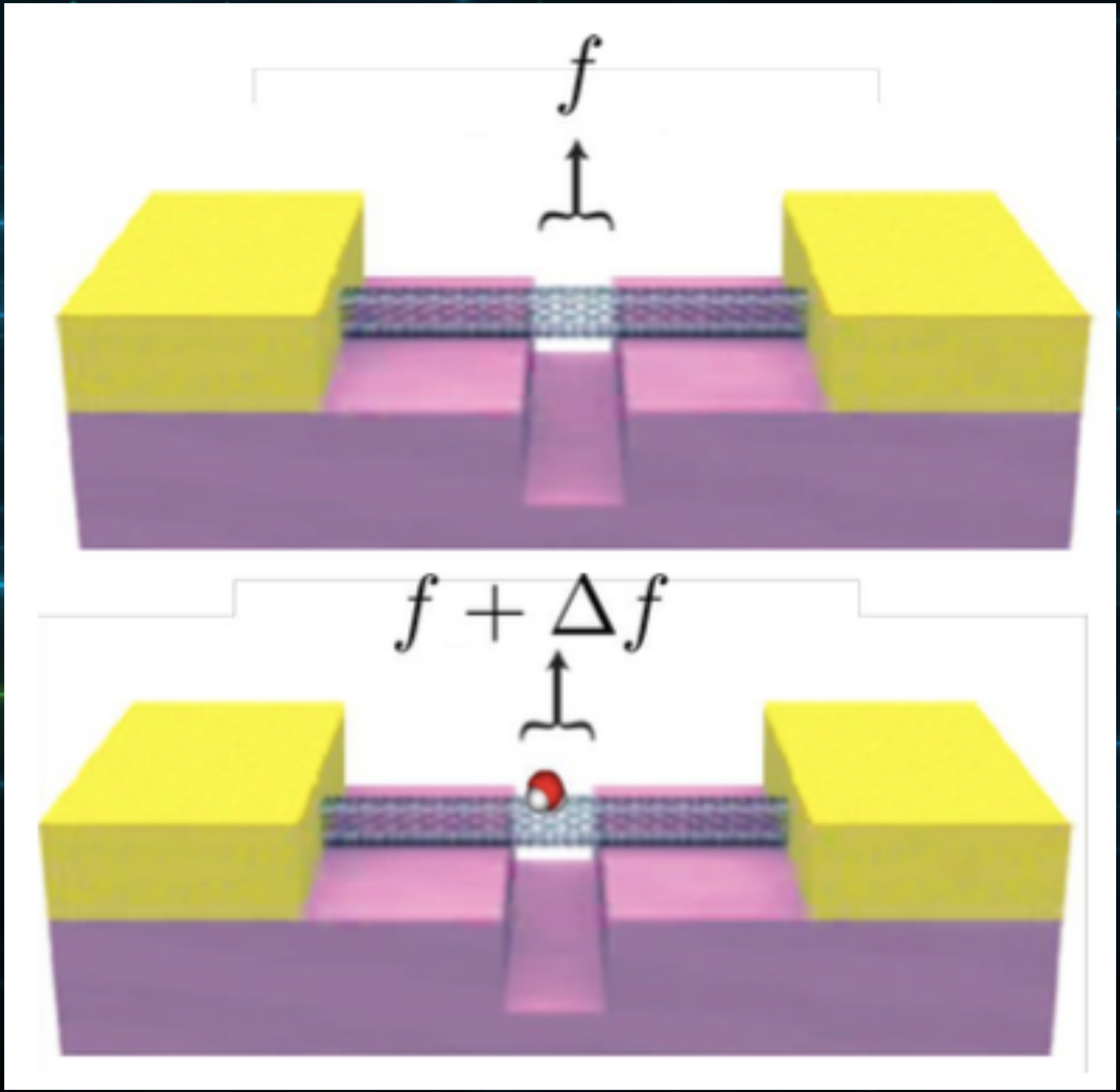


Nanotubi di Carbonio

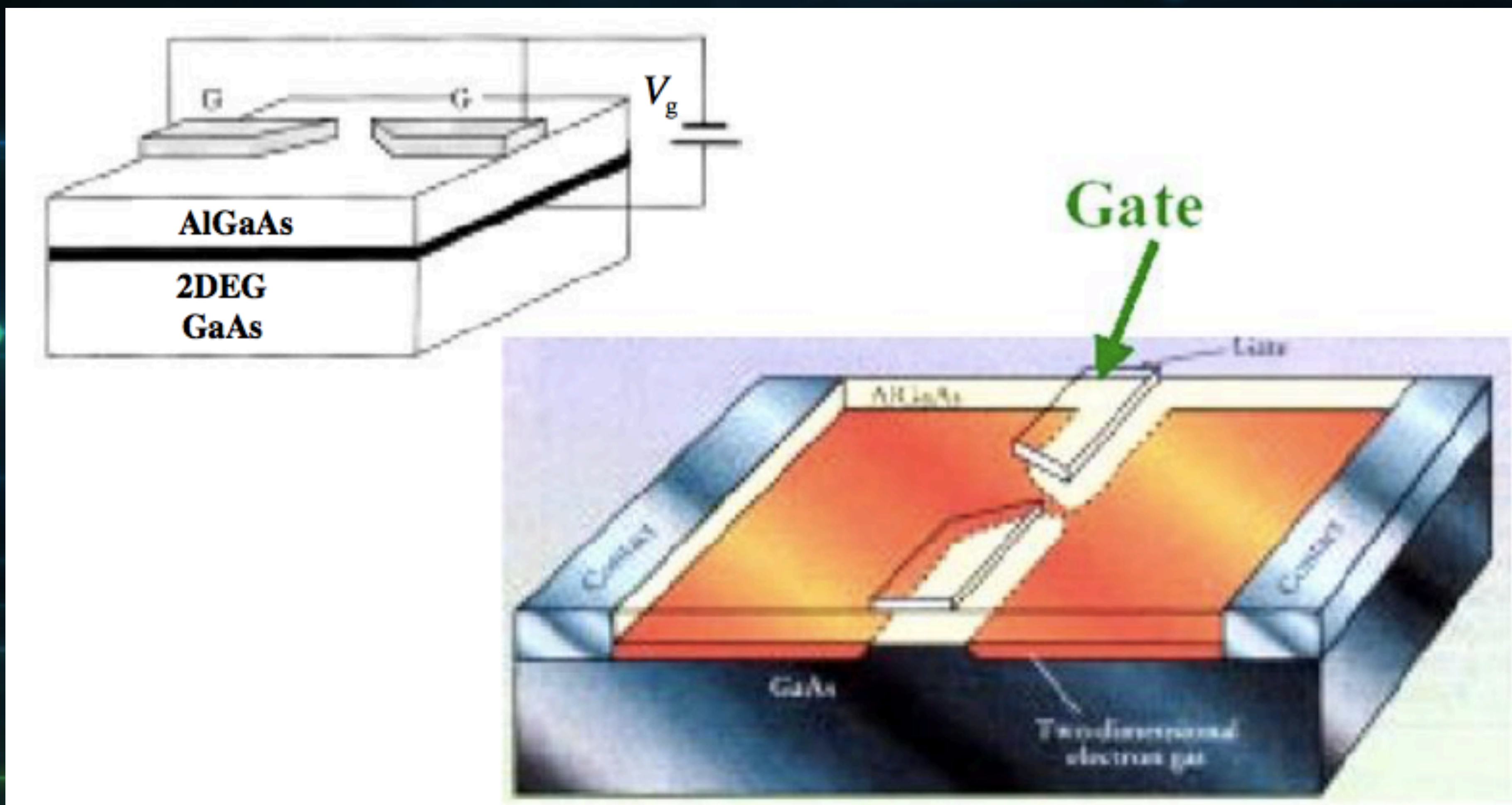
Quanto è piccolo?



Utilizzi: Sensori di massa



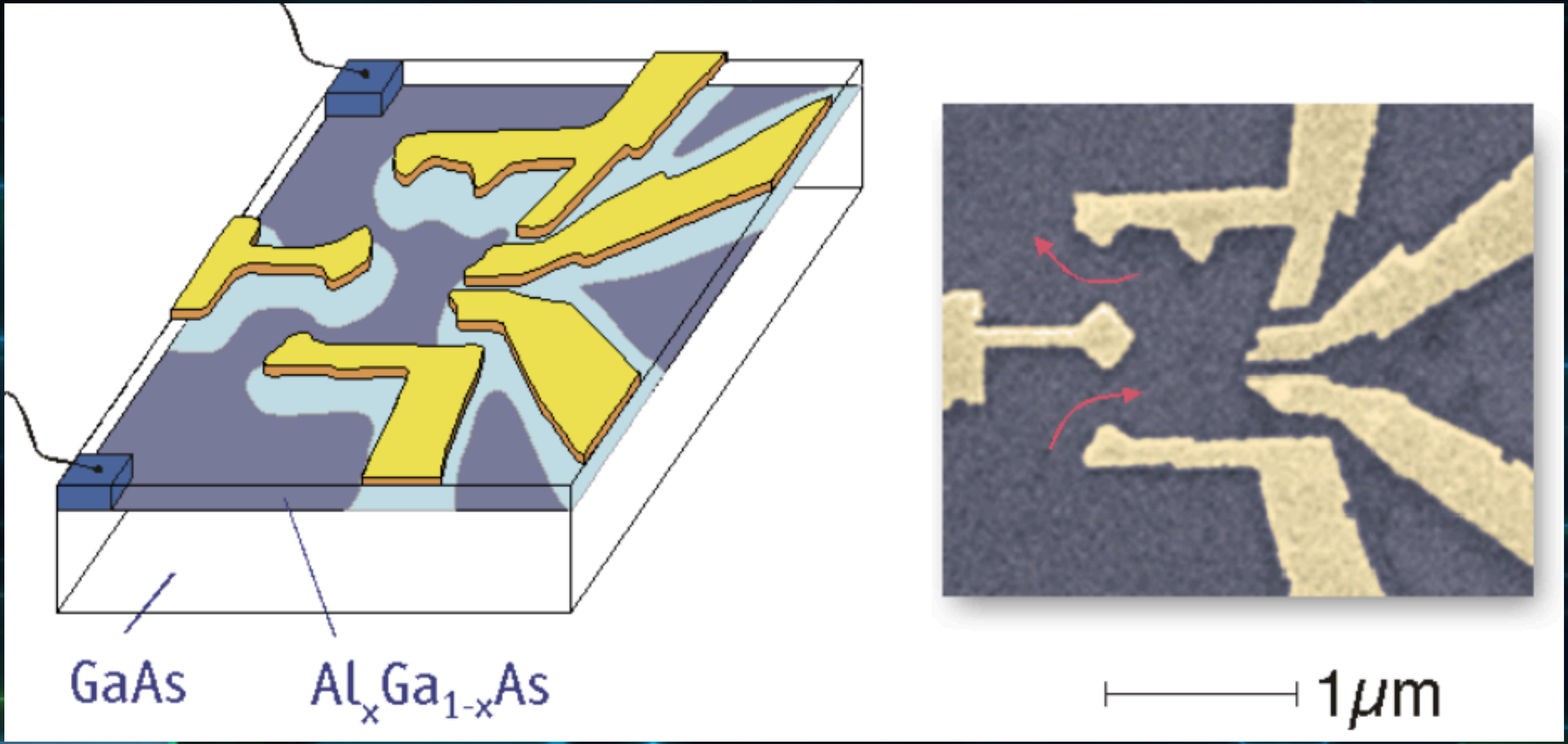
Quantum wire



Quantum Point Contact (QPC)

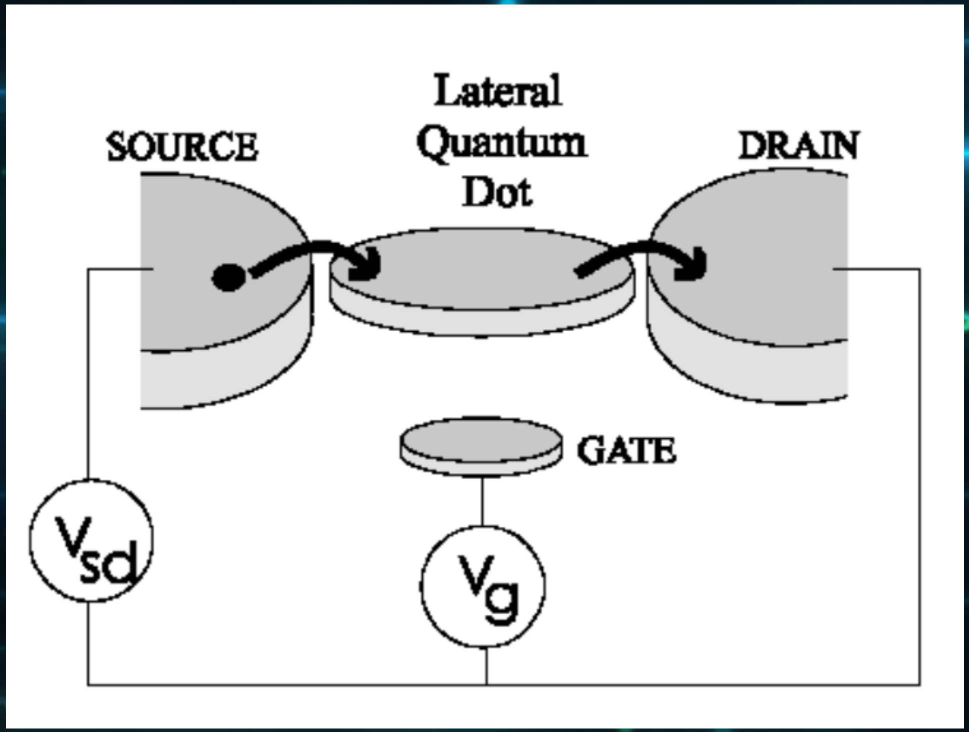
Applicando un voltaggio a due gate si crea un canale in cui gli elettroni sono vincolati

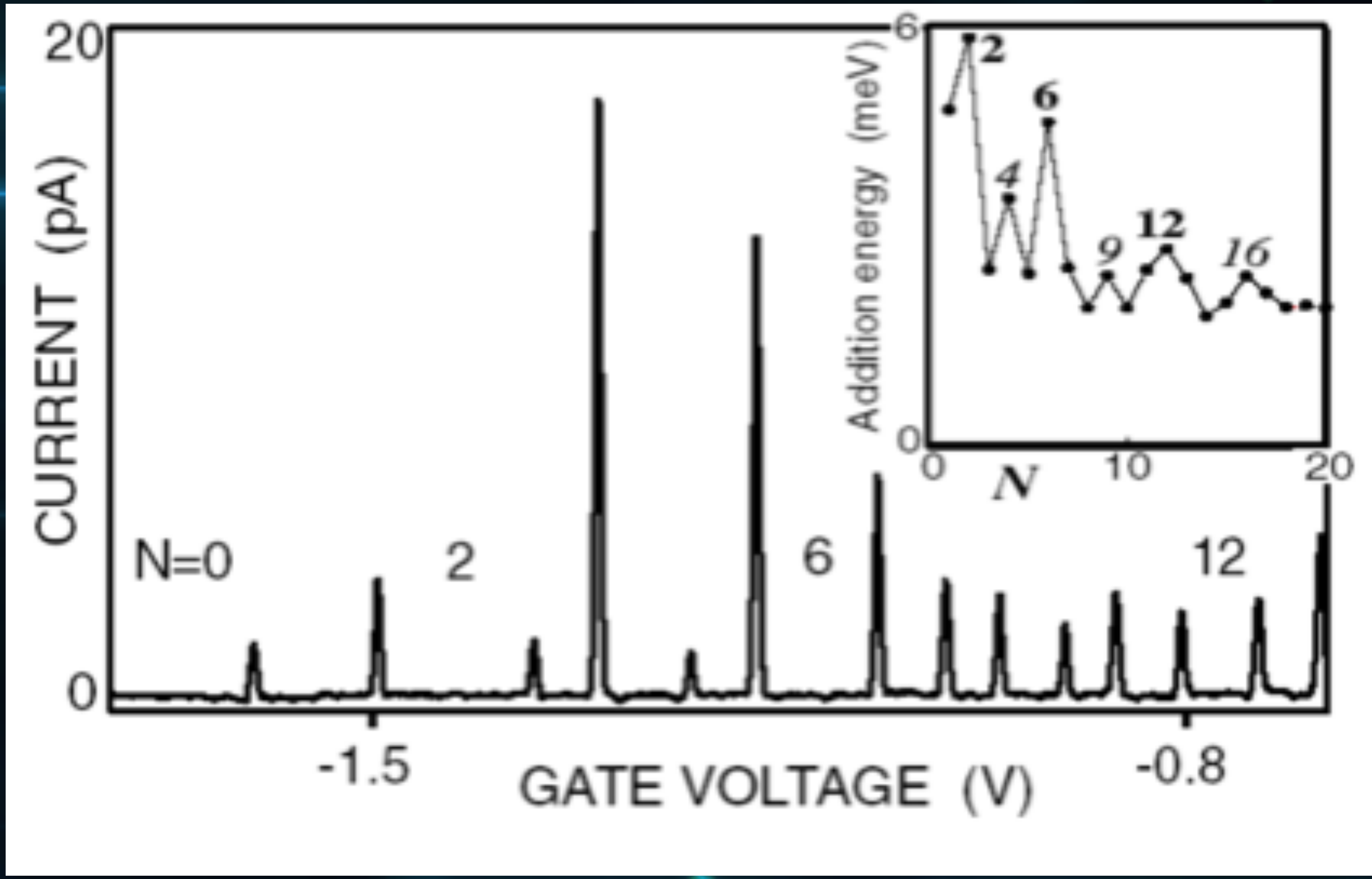
Materiali 0D



Quantum Dots: elettroni vincolati in un punto usando degli elettrodi

Schema del Quantum Dot





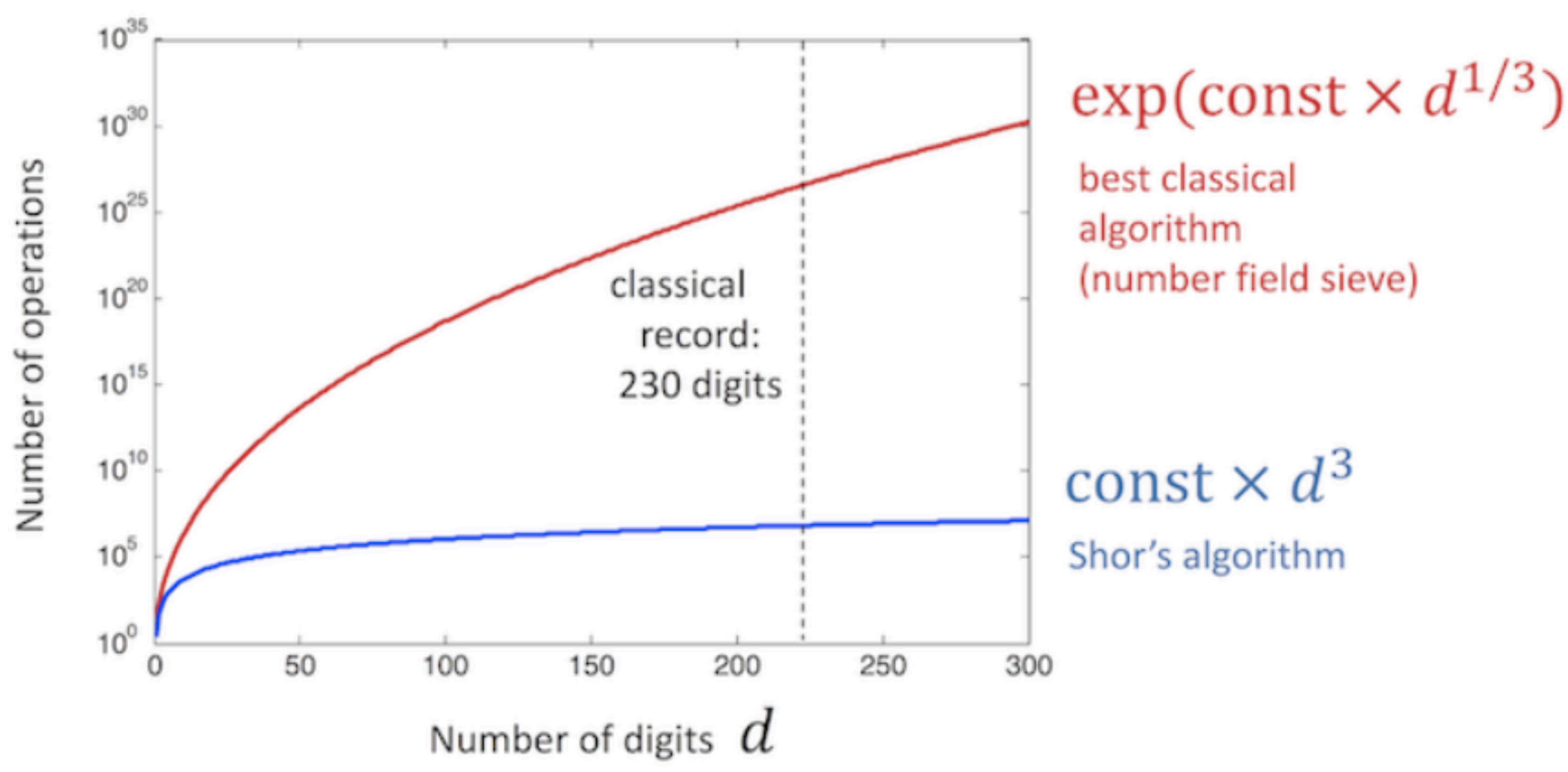
Si ha trasporto solo per certi potenziali di gate → Transistor perfetto!

Qual è allora il problema?

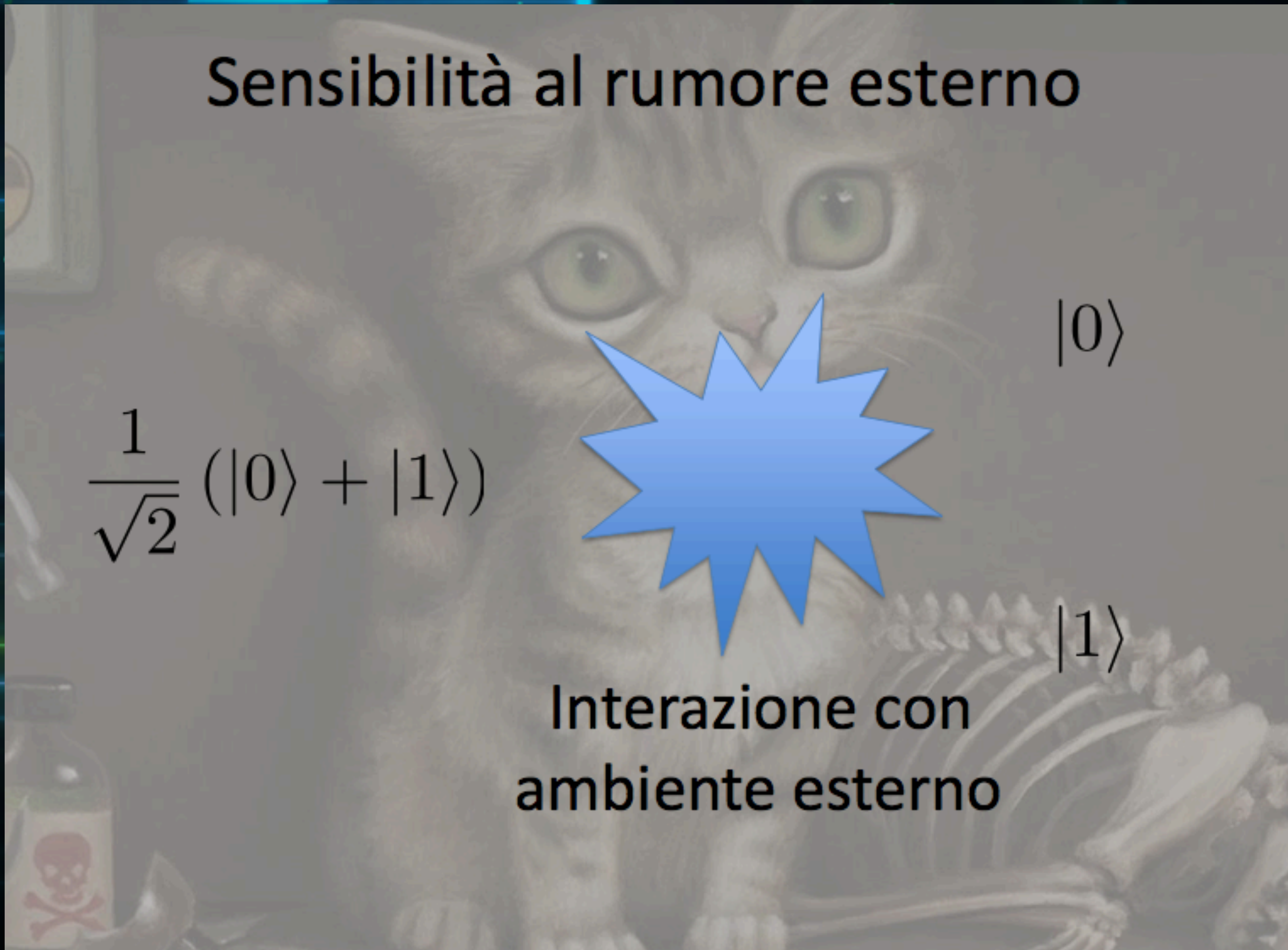
Gli stati quantistici possono contenere molte più informazioni…

Imbattibile in alcuni settori!

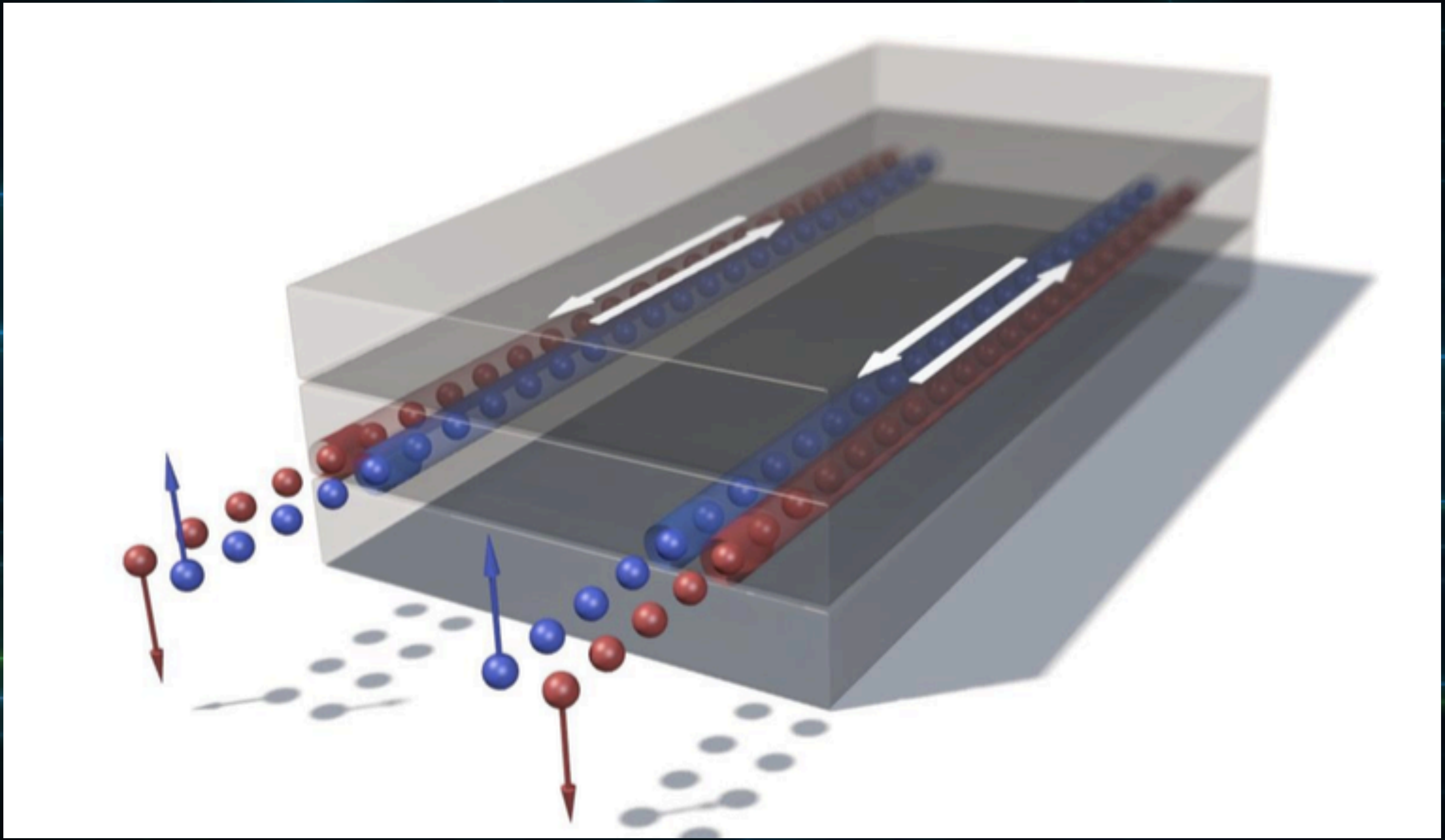
fattorizzazione di un numero intero in numeri primi



Però…


Sensibilità al rumore esterno
$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$
$|0\rangle$
$|1\rangle$
Interazione con ambiente esterno

La soluzione?



SISTEMI TOPOLOGICI

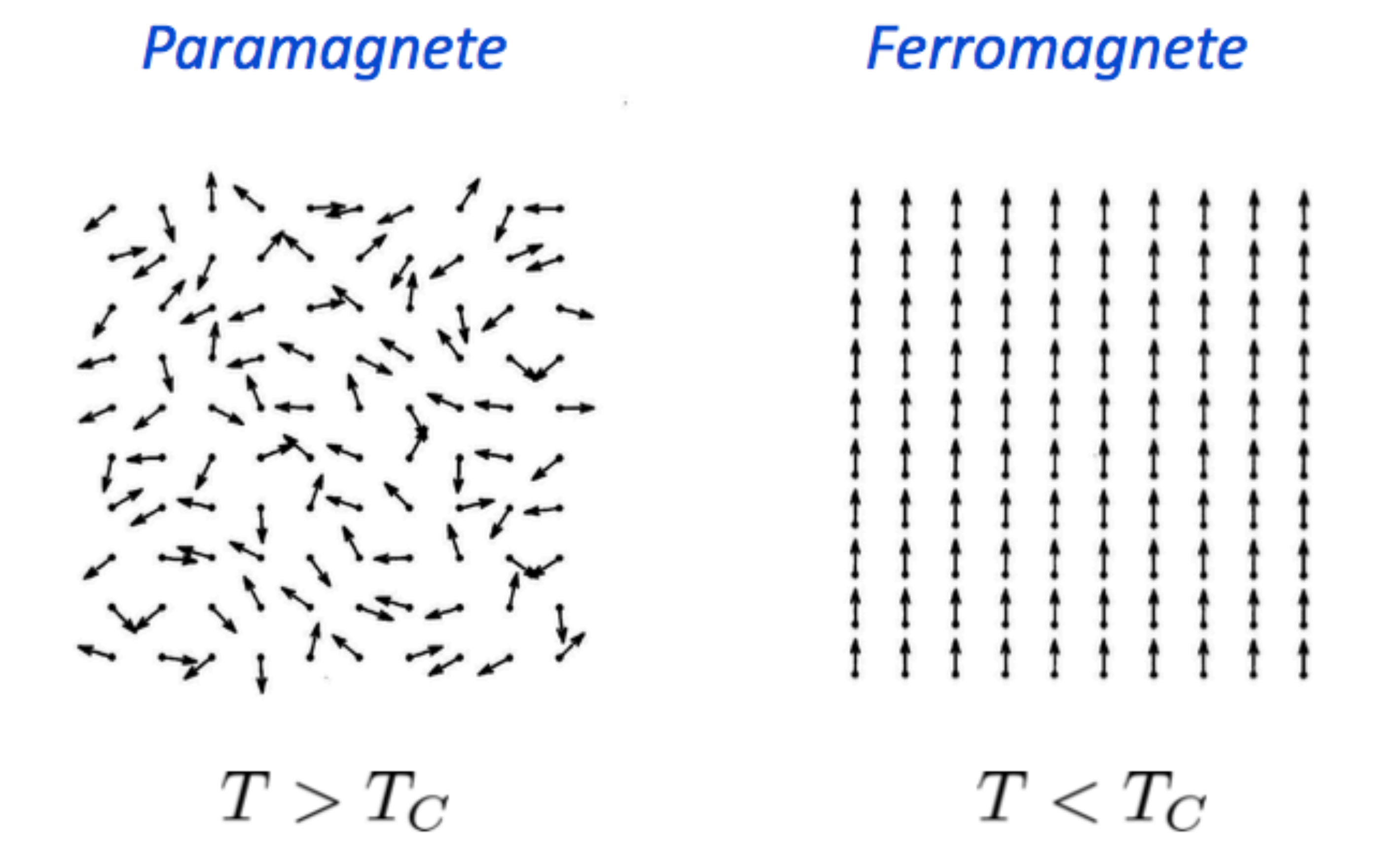
Fino al 1970…

Classificazione delle fasi della materia:

Simmetria

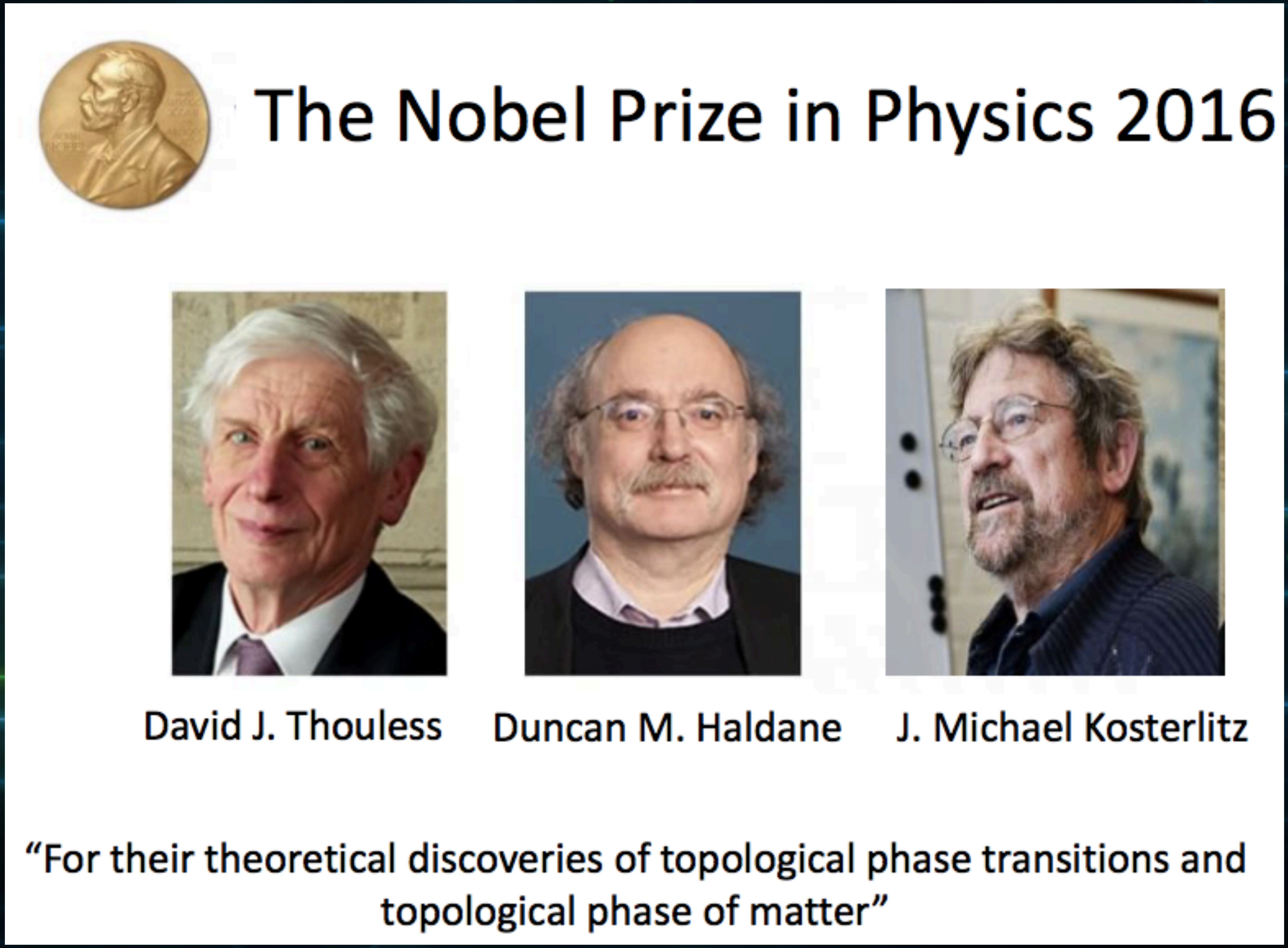
Identifica la proprietà dei fenomeni fisici di ripetersi sostanzialmente identici nel tempo e nello spazio

Fasi della materia fino al 1970…



Dagli anni ’70…

Nuova classificazione delle fasi della materia!



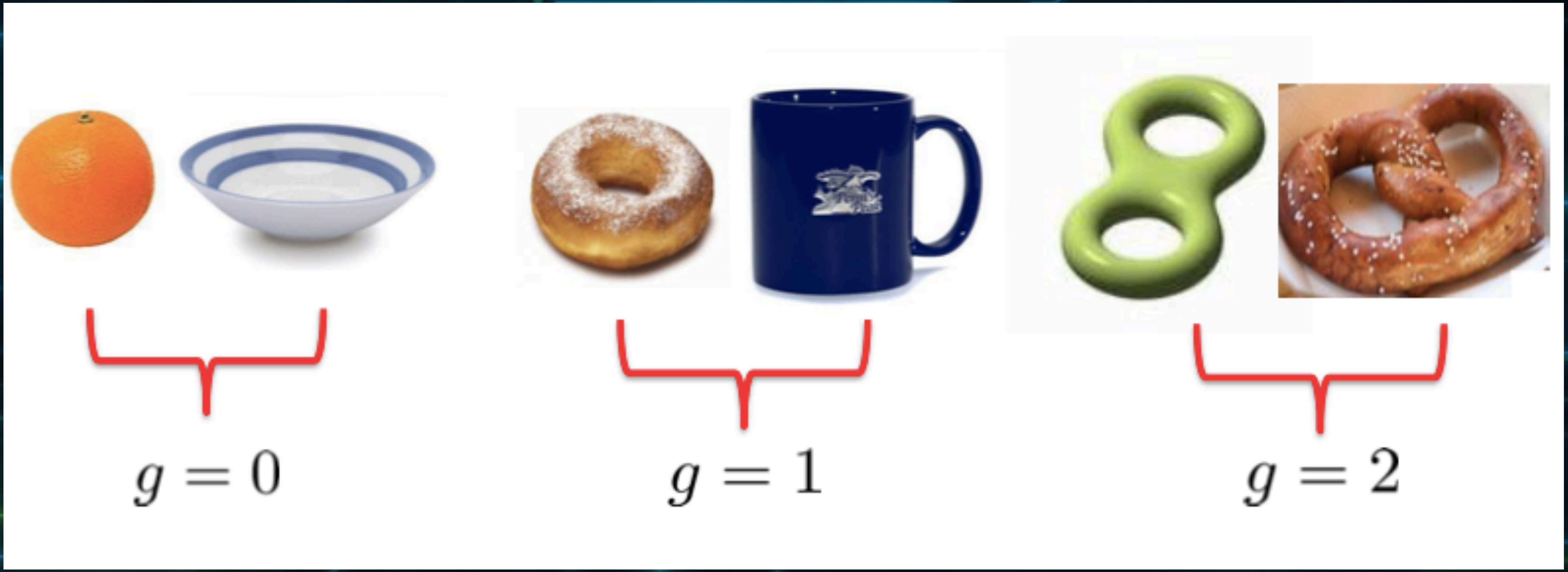
TOPOLOGIA!

Topologia

Studio delle proprietà preservate sotto l'azione di deformazioni senza strappi e rotture

Invariante topologico: quantità “conservata” sotto l’azione di una deformazione

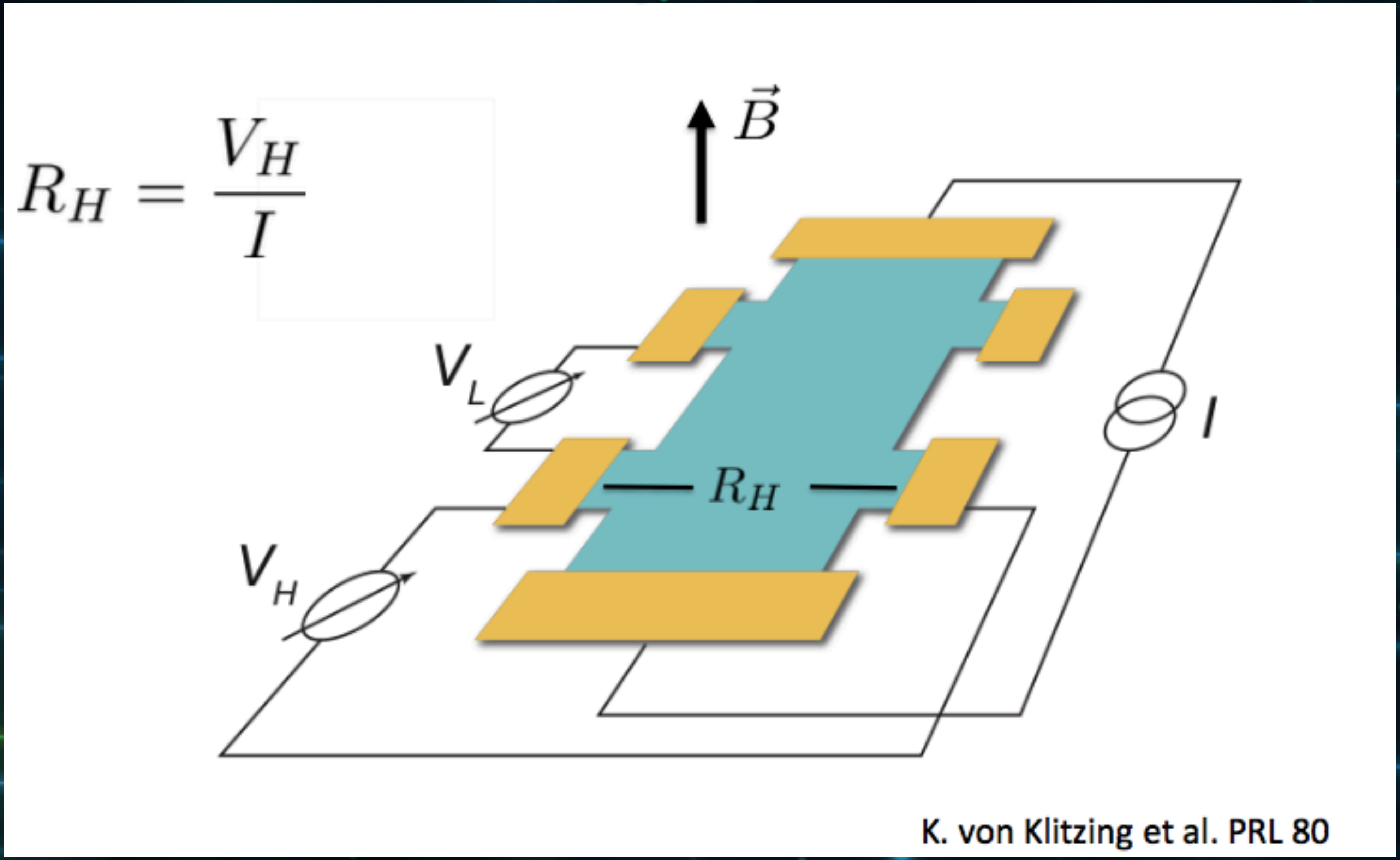
Classificazione topologica di figure e forme



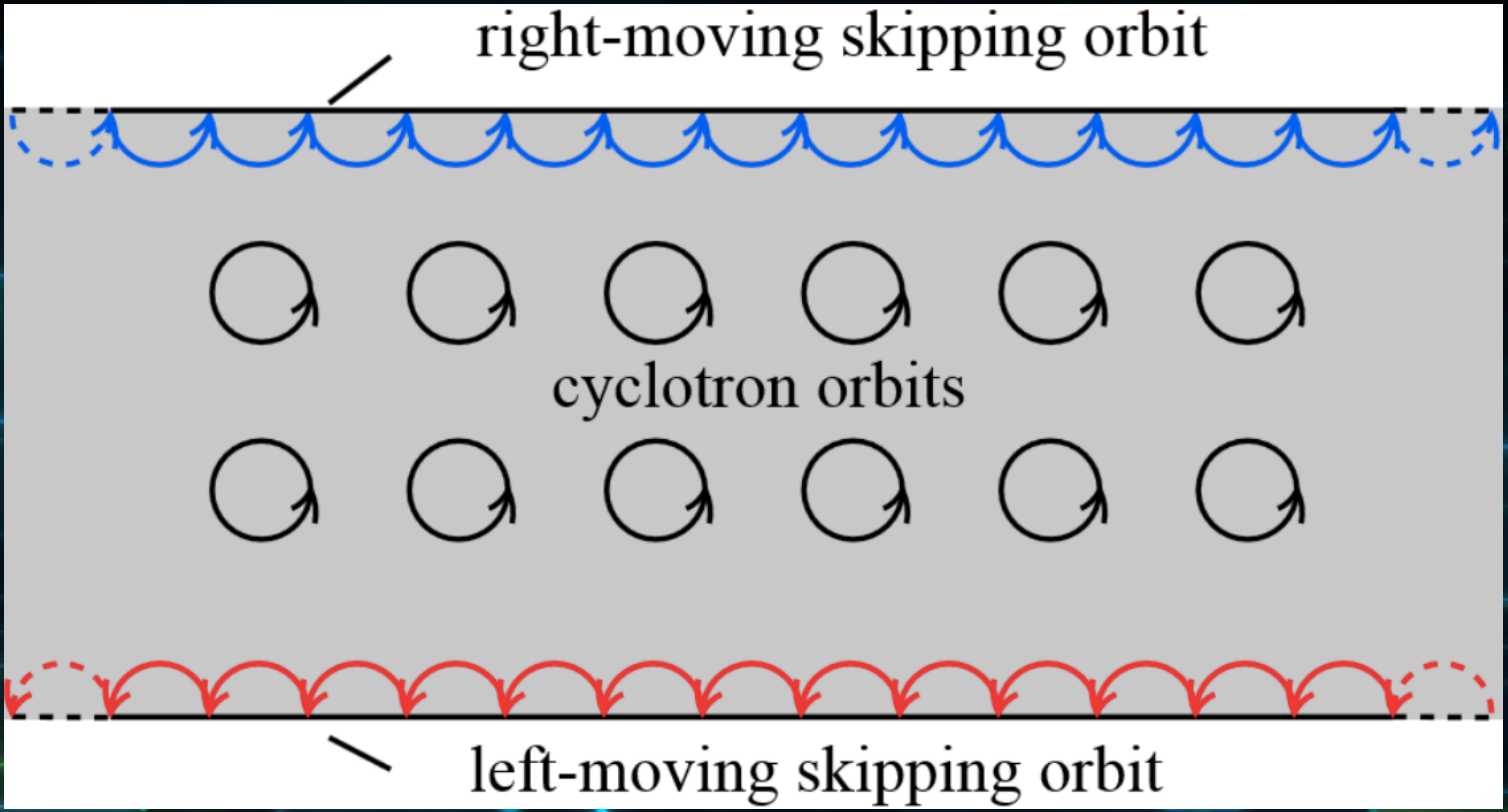
g: invariante topologico

Invariante topologico ⟷ **Fase topologica**

Prime conferme sperimentali…

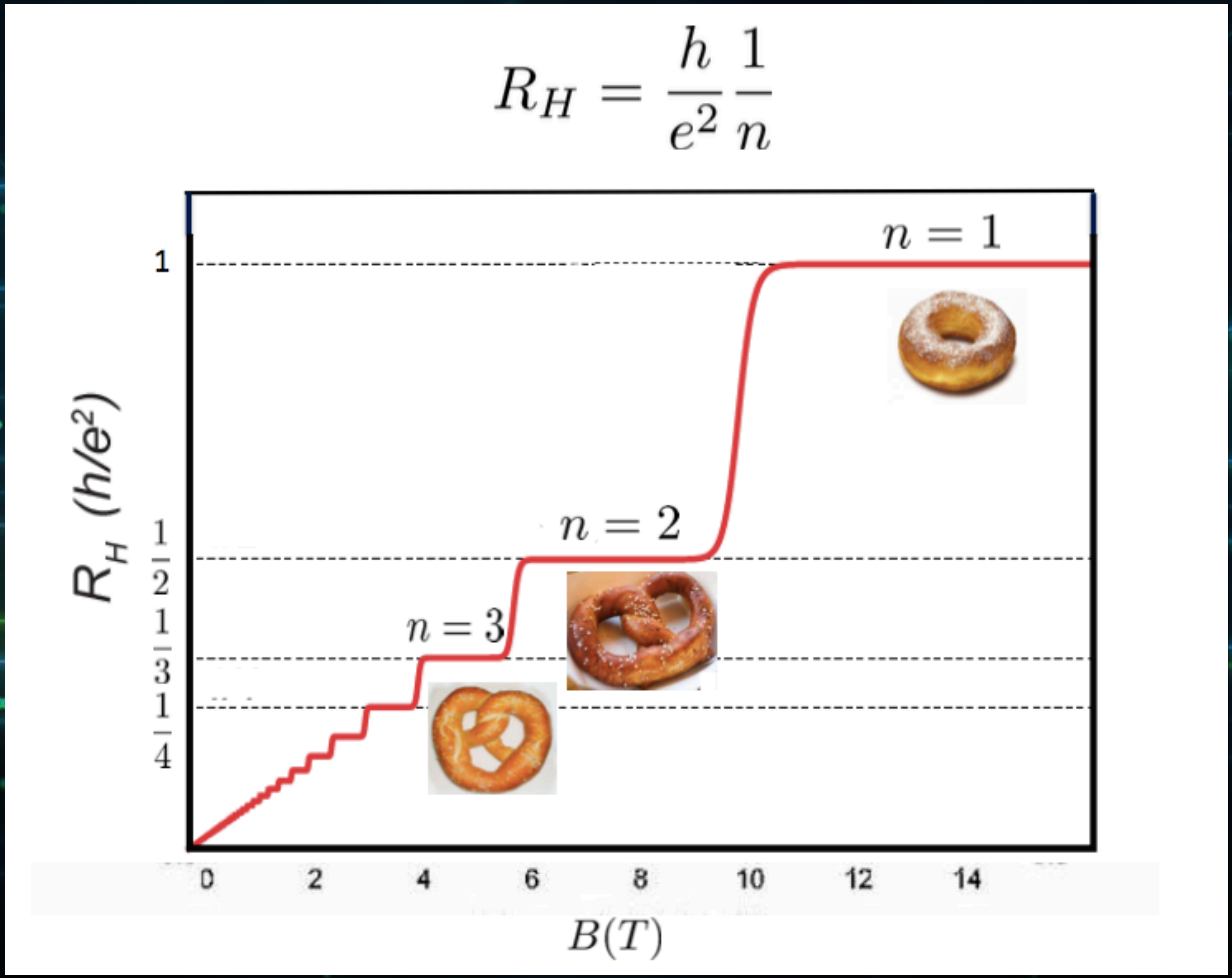


Effetto Hall Quantistico



Stati di bordo topologicamente protetti!

Il risultato?

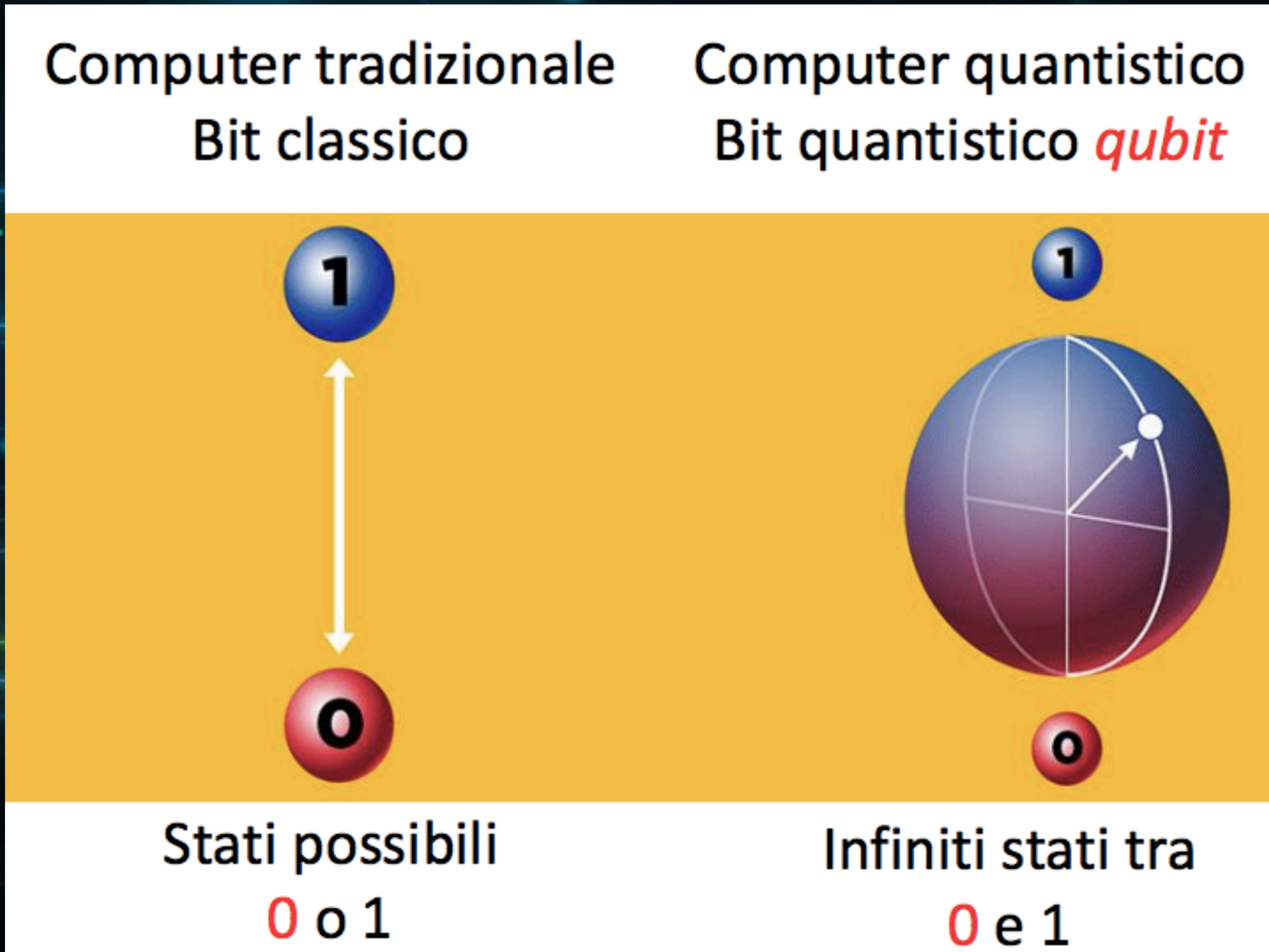


The Nobel Prize in Physics 1985

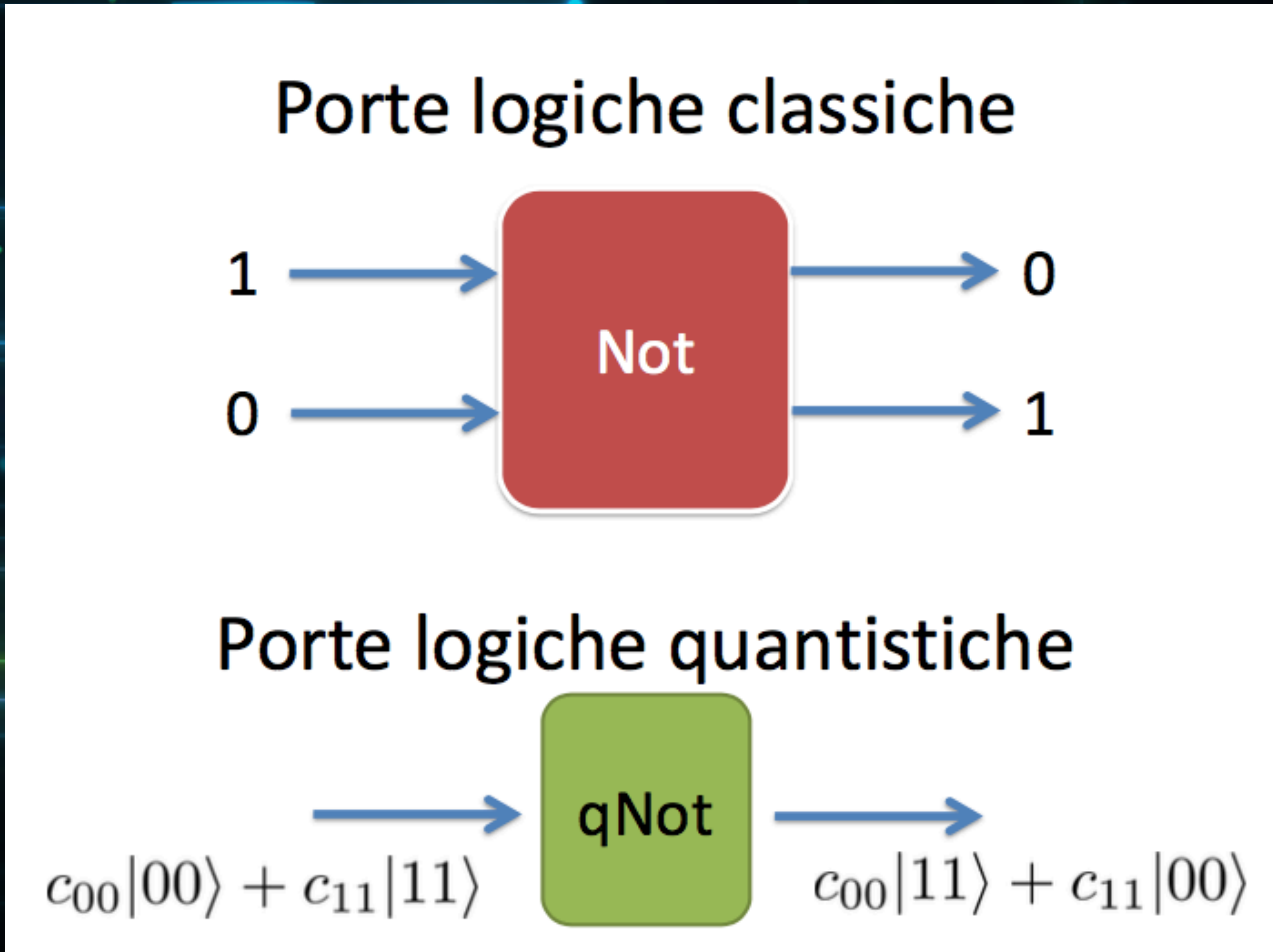
Klaus von Klitzing

"For the discovery of the quantized Hall effect"

Applicazioni: Computazione quantistica



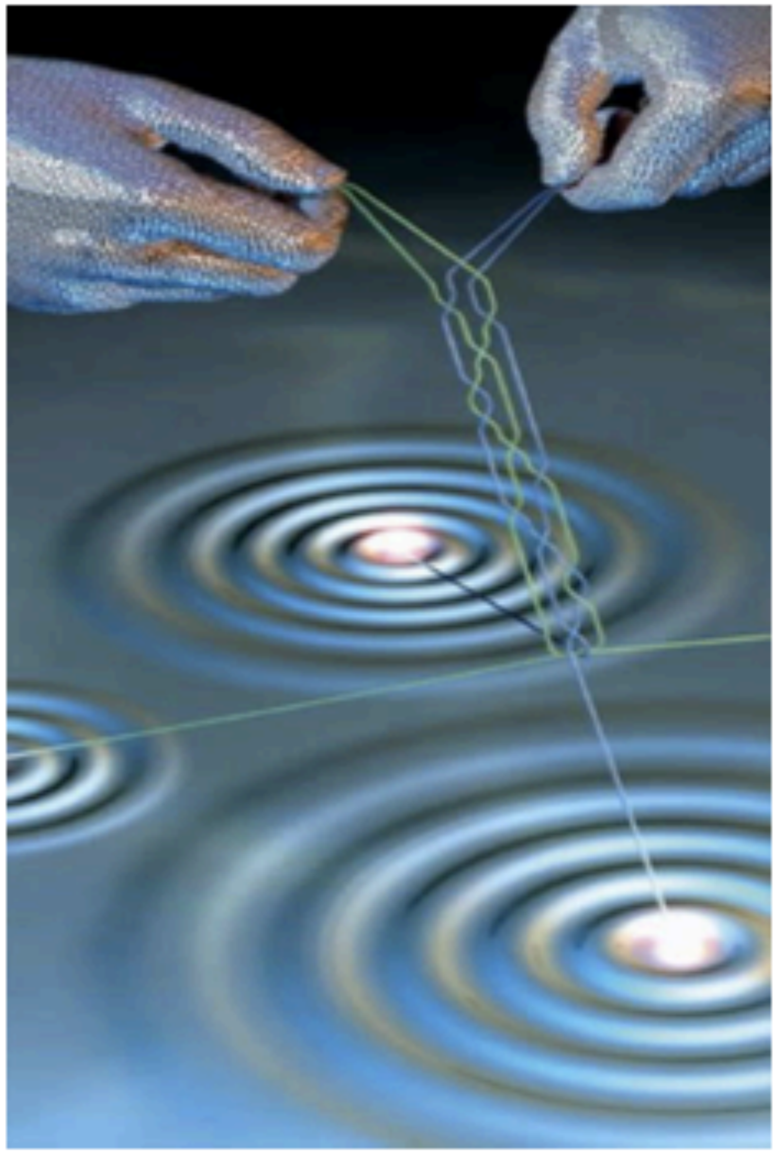
Un semplice esempio…



Operazioni simultanee…Parallelismo quantistico

Computer quantistico topologico

Manipolazione topologicamente robusta al rumore

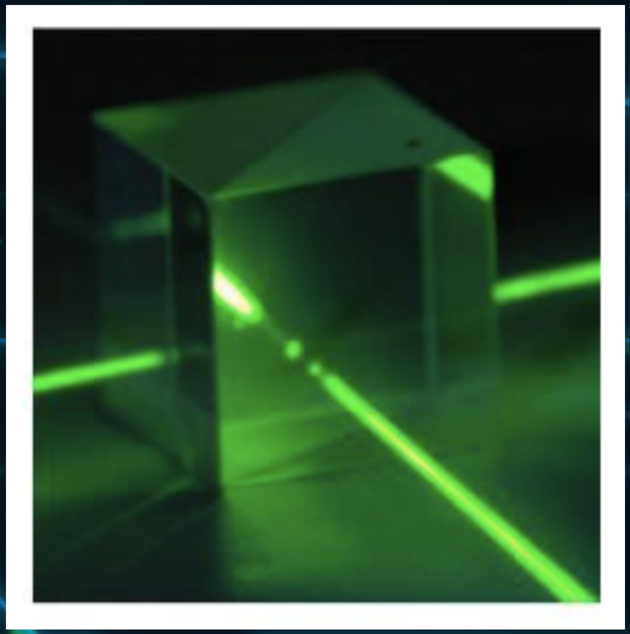


Fluido topologico: intreccio di qubit
Ogni intreccio codifica diversi codici quantistici computazionali

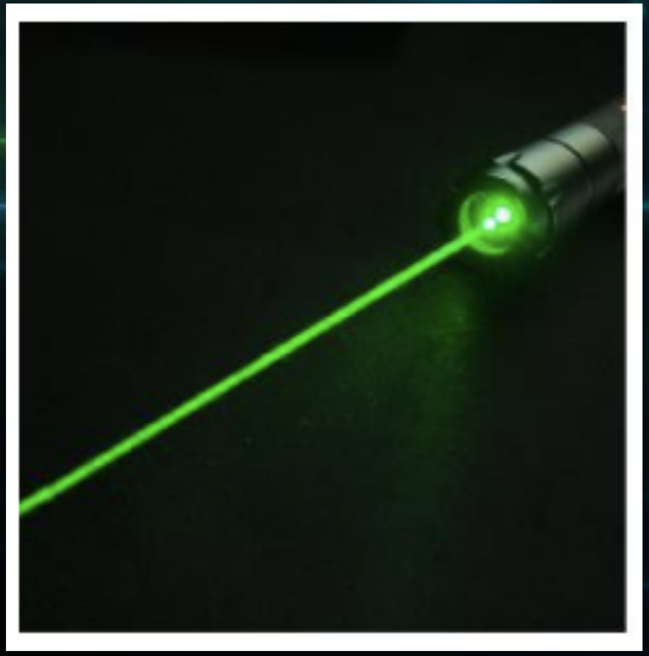
Applicazioni: Electron Quantum Optics (EQO)

Caratteristiche dell'ottica classica:

Guide d'onda



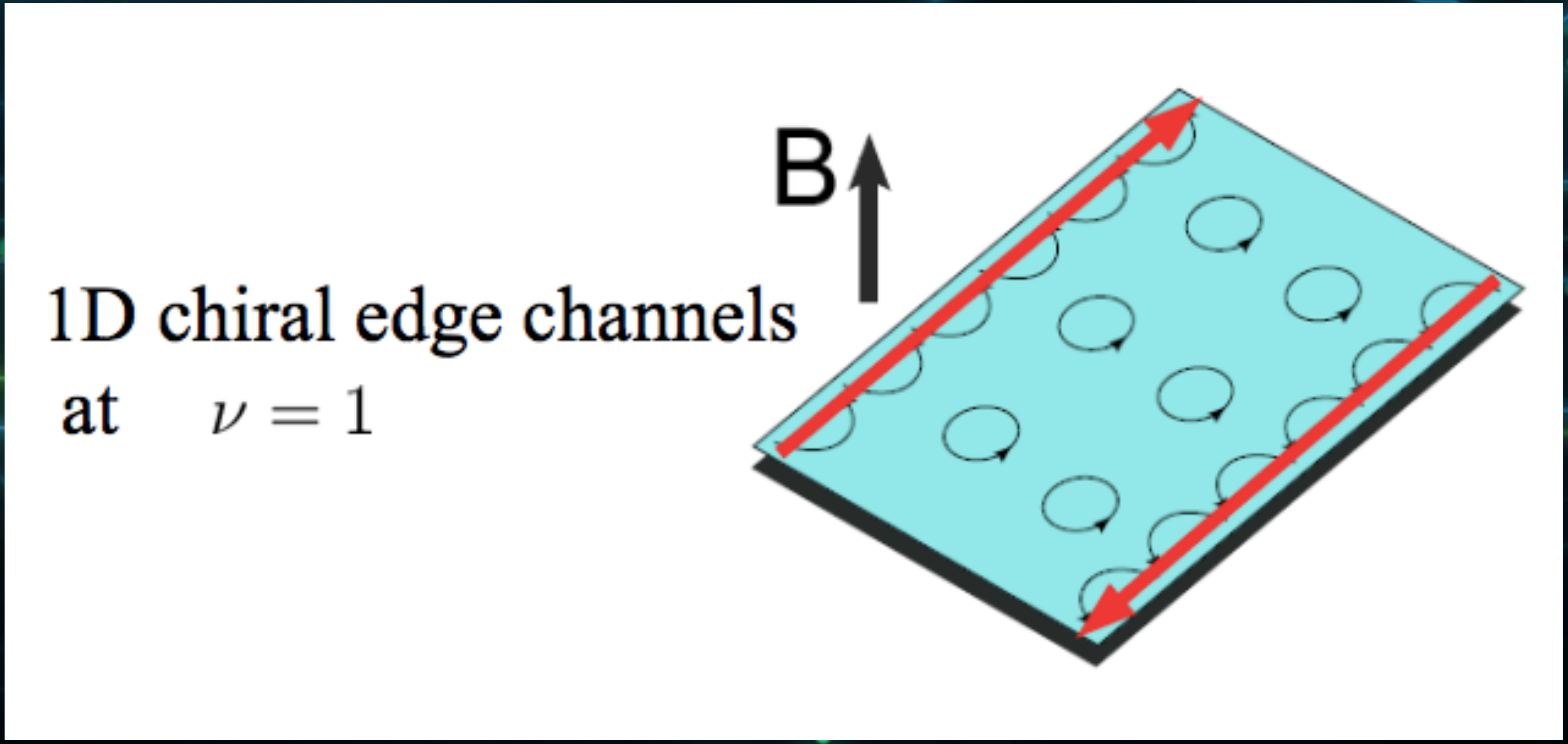
Beam splitter



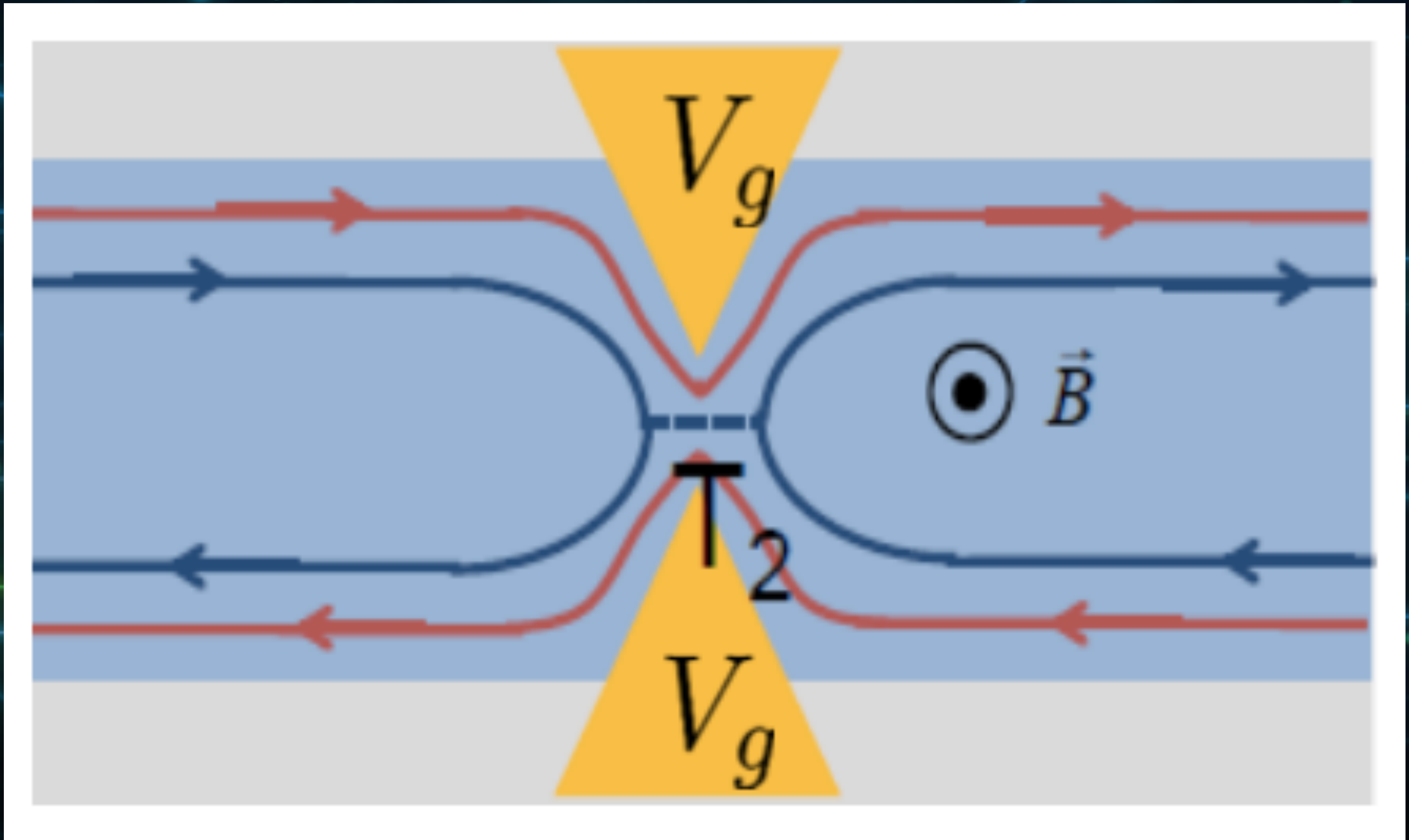
Luce coerente

Come si riflette ciò in un sistema che usa elettroni al posto di fotoni?

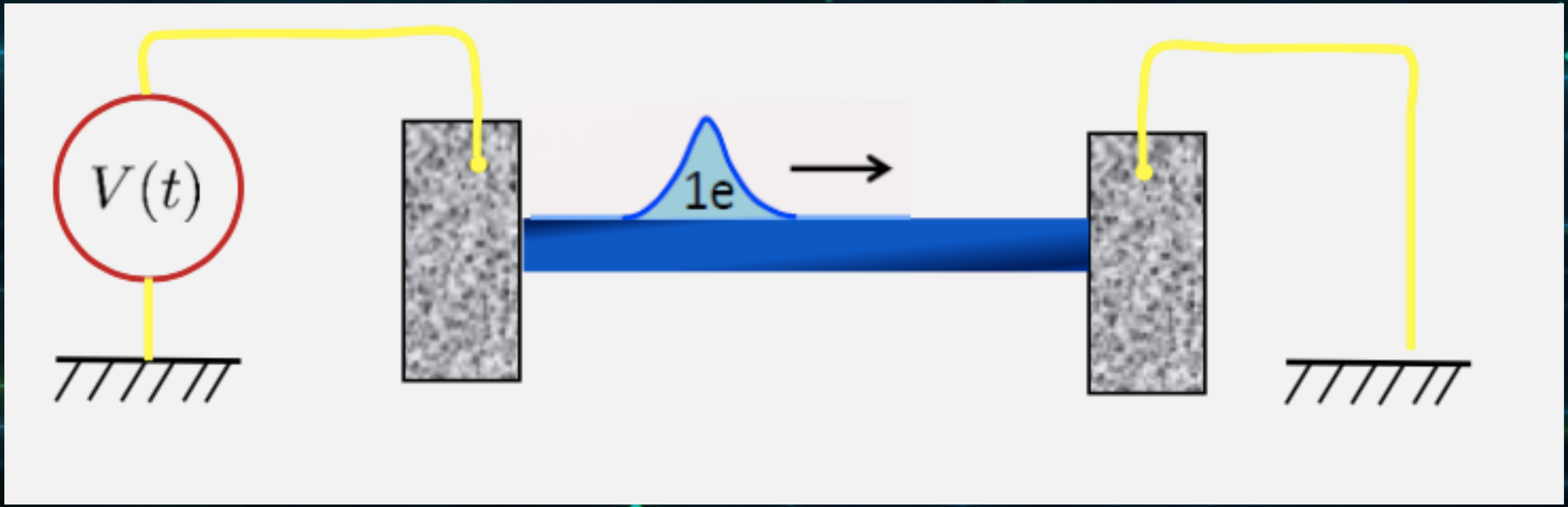
Guide d'onda $\longrightarrow$ Canali topologicamente protetti dell'effetto Hall quantistico



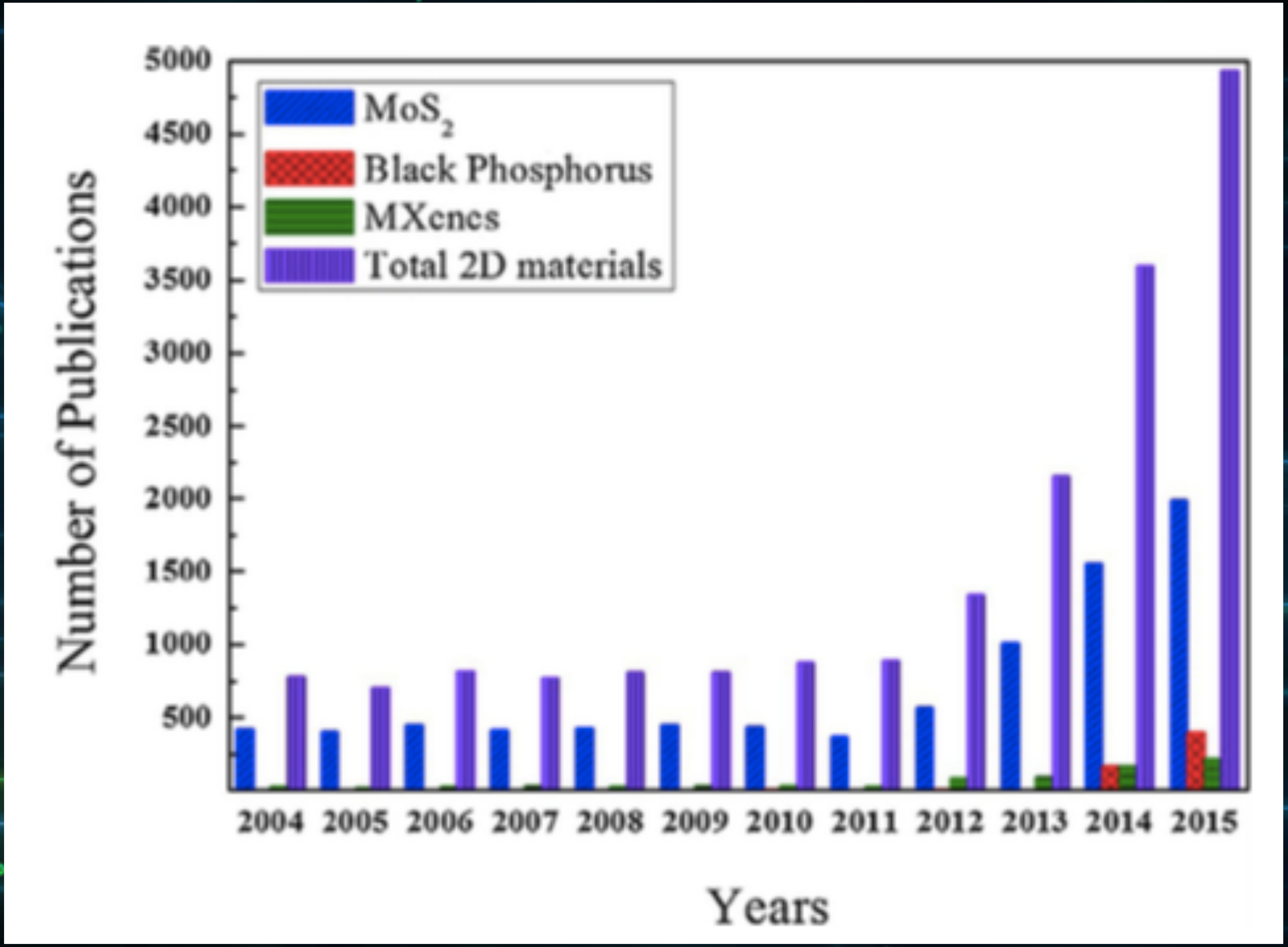
Beam splitter ⟶ Quantum point contact



Luce coerente $\longrightarrow$ Iniezione di singoli elettroni nel sistema

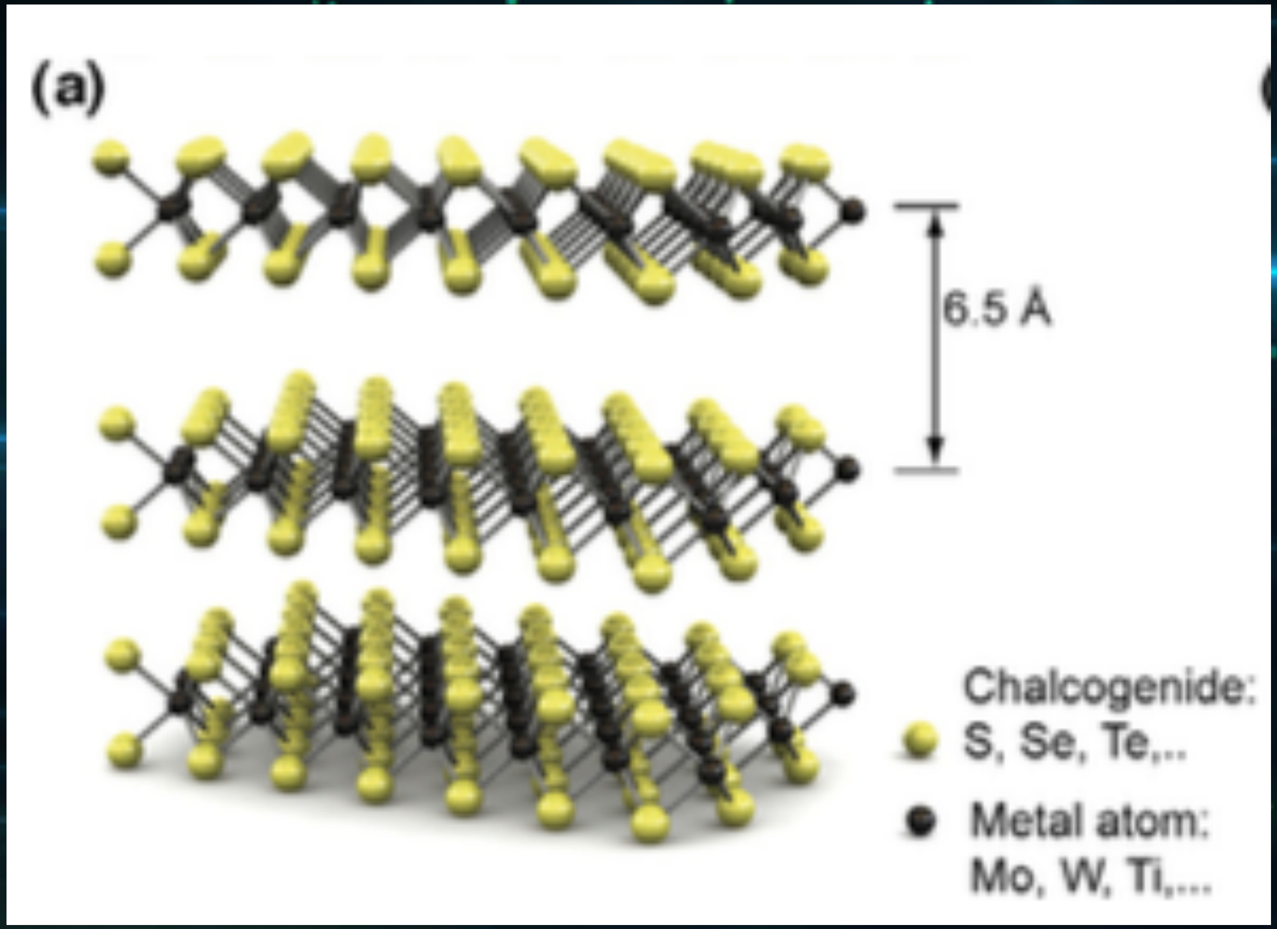


Nuovi materiali 2D



Indagine per future tecnologie e ricerca di base in grandissima crescita

Dicalcogenuri dei metalli di transizione - TMDs

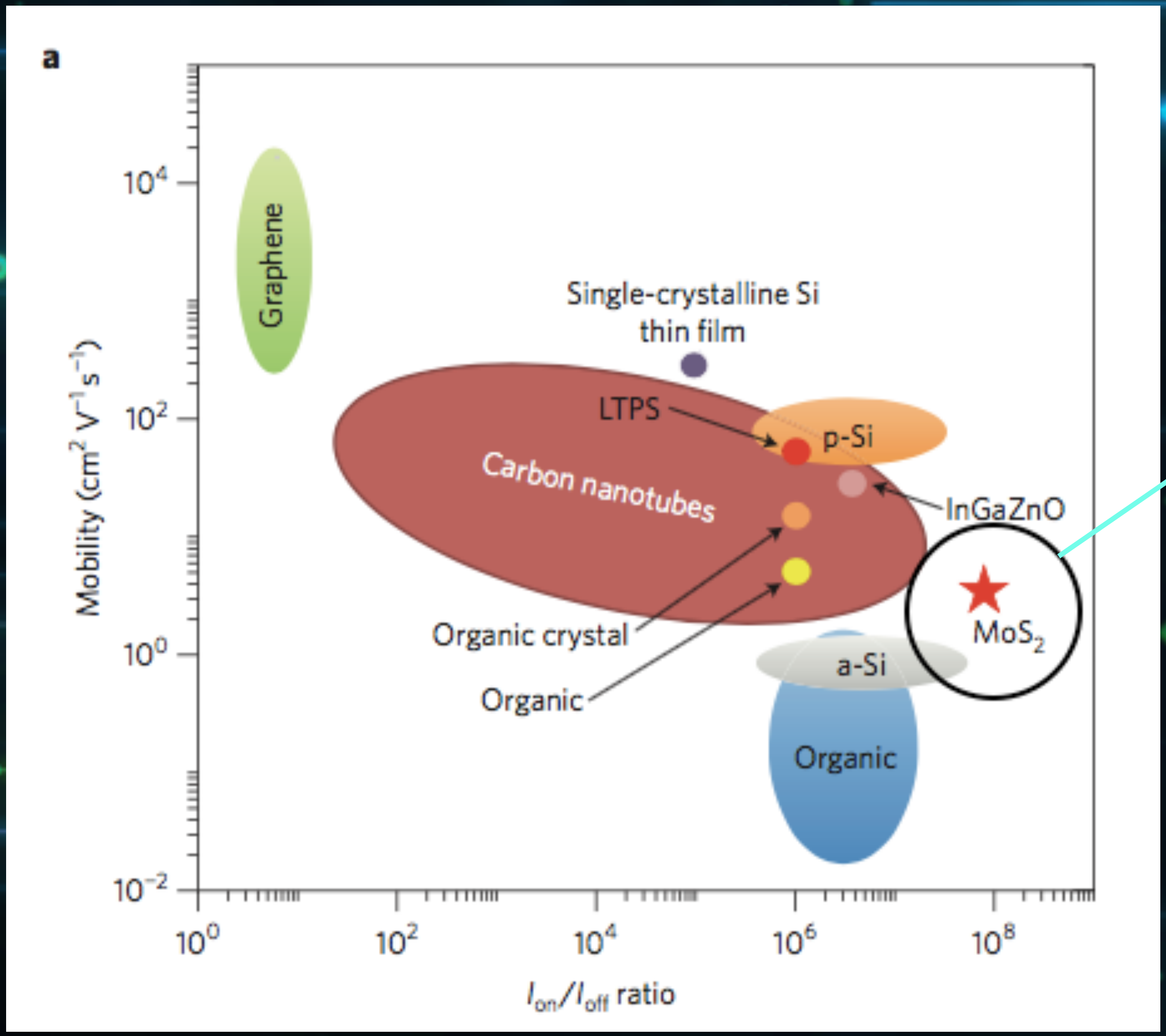


Forma MX_2

M: metallo di transizione
X: calcogeno

Materiali bidimensionali con ottime proprietà → Possibile utilizzo nell'elettronica del futuro

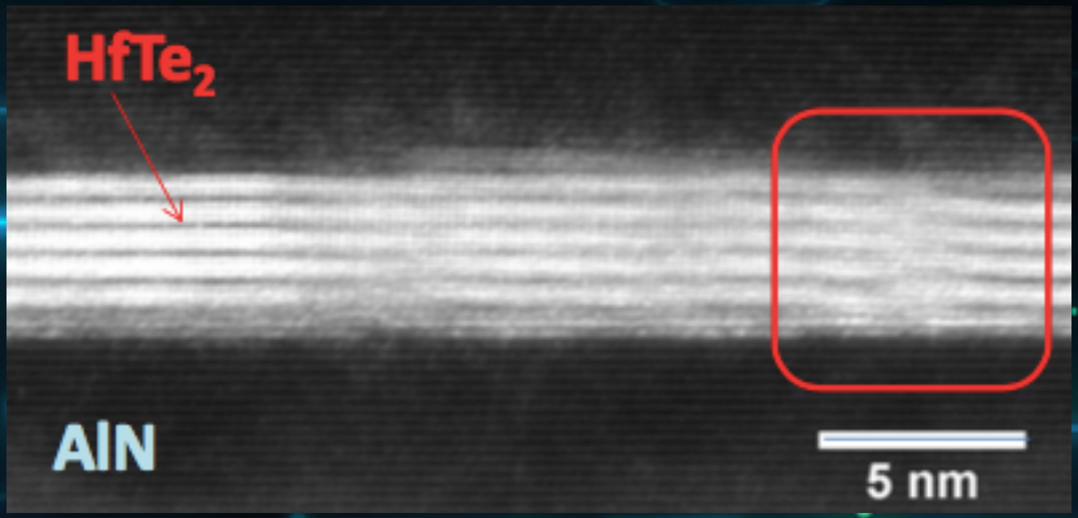
Confronto con altri materiali

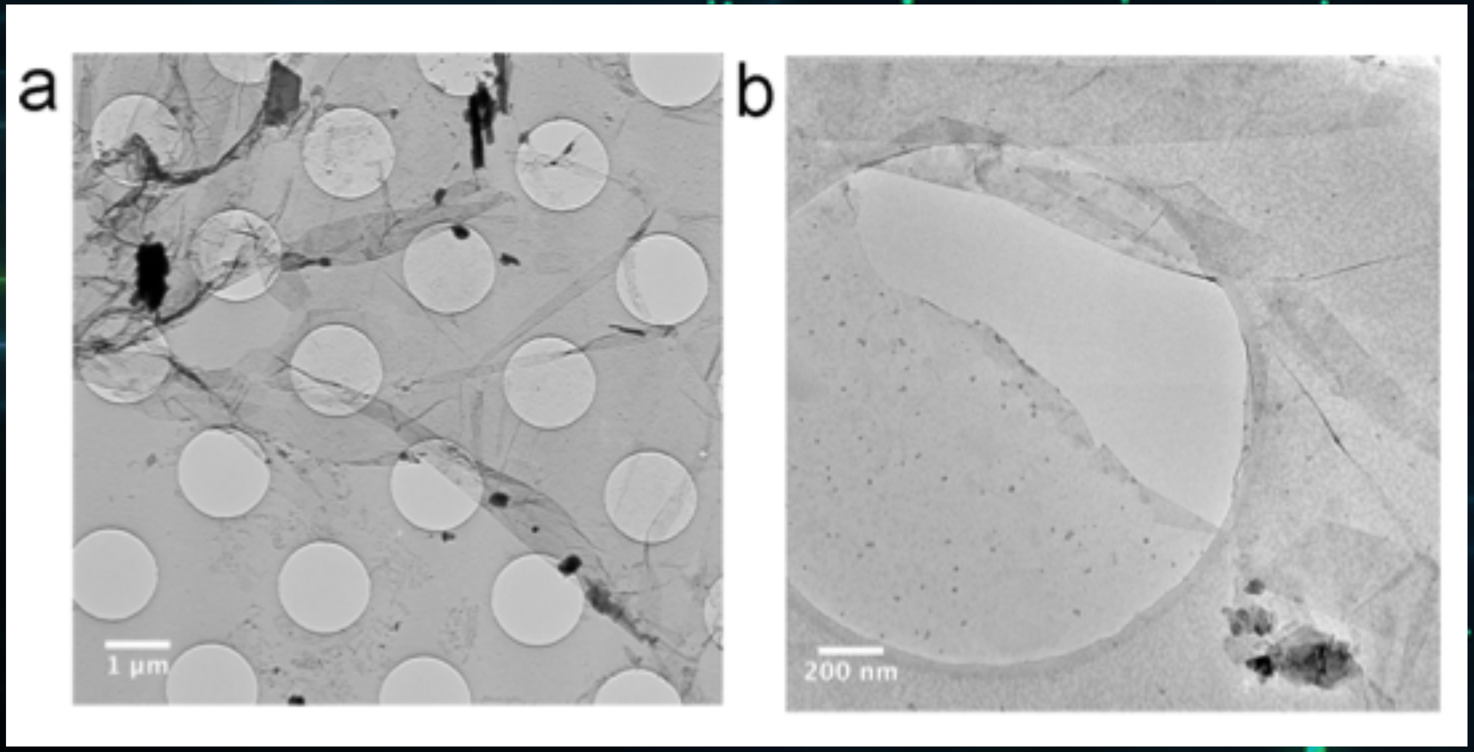


Mobilità abbastanza elevate (almeno comparabili con quelle del silicio) e frazione I_{on}/I_{off} maggiore

Problemi ad oggi…

Difficoltà di deposizione e perciò difetti



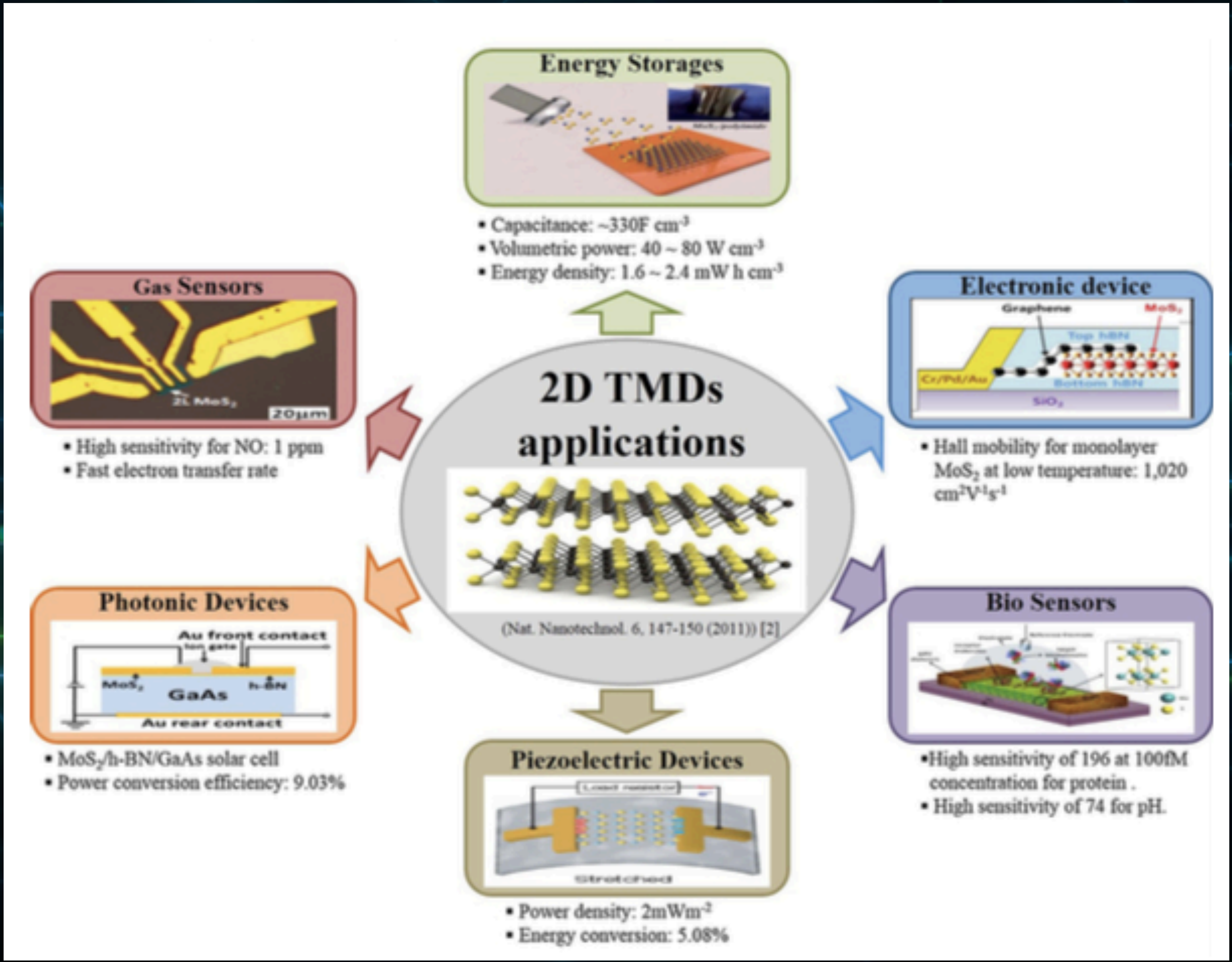


Difetti = mancata connessione nel materiale

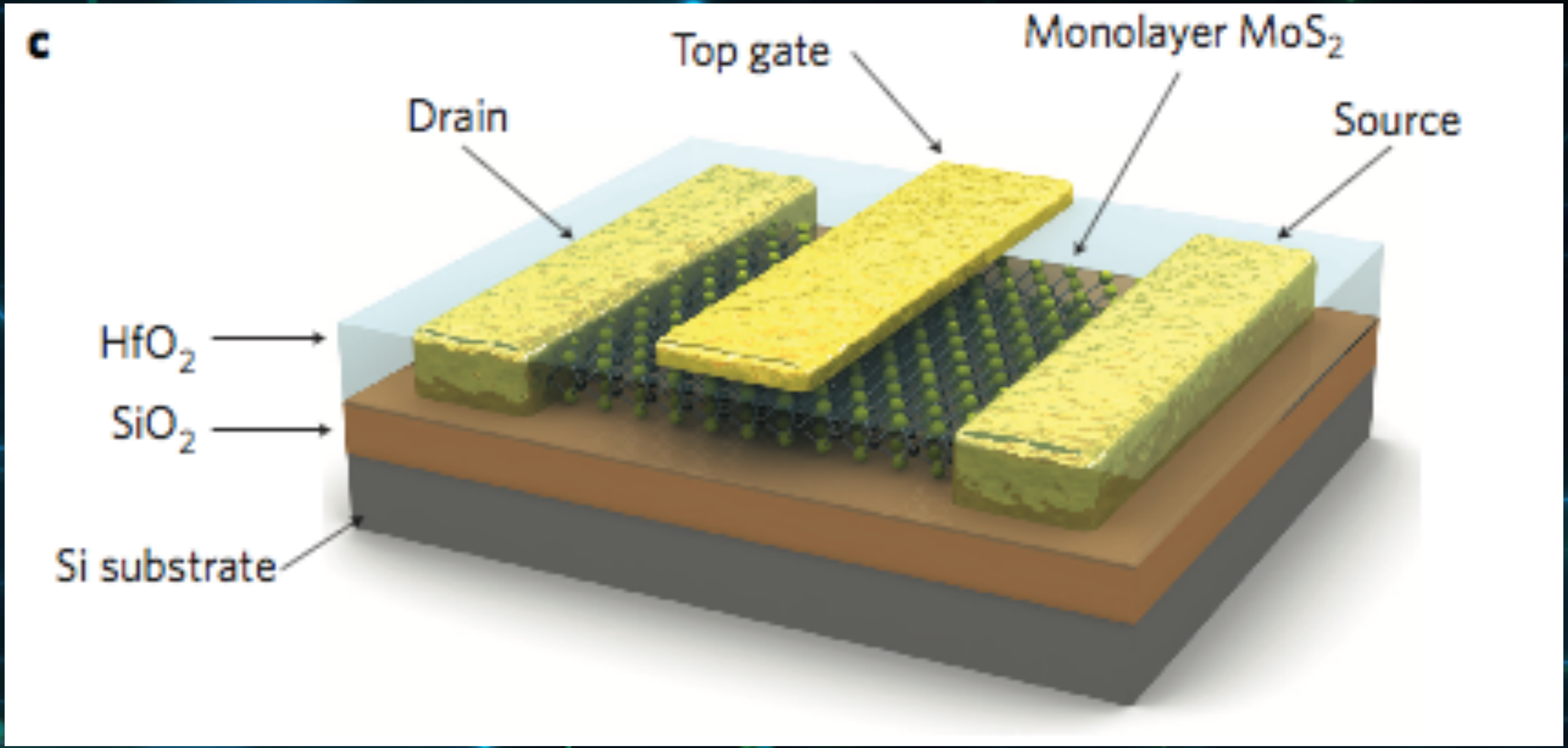
↓

Isolante

Applicazioni



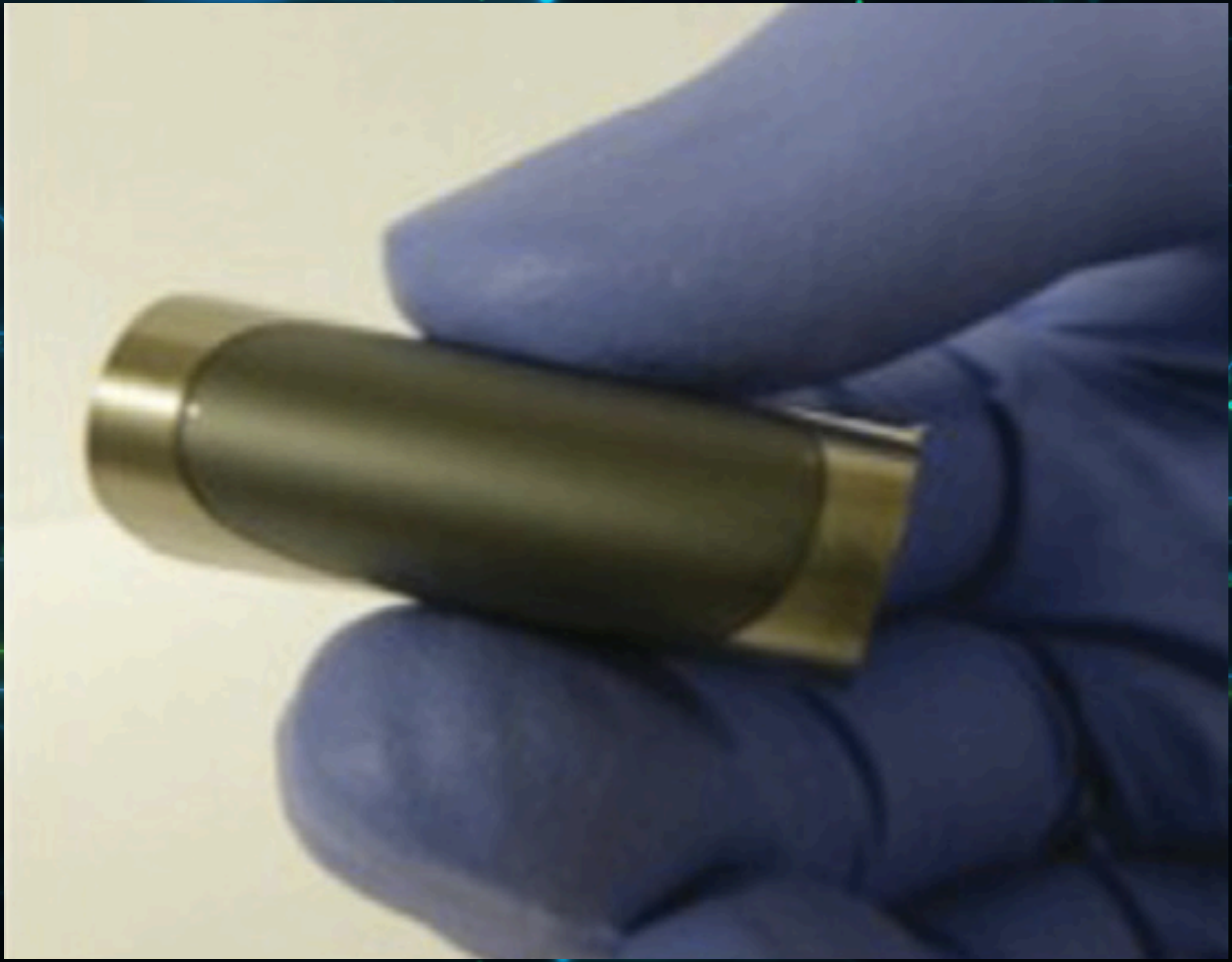
Primi prototipi di transistor con TMDs:



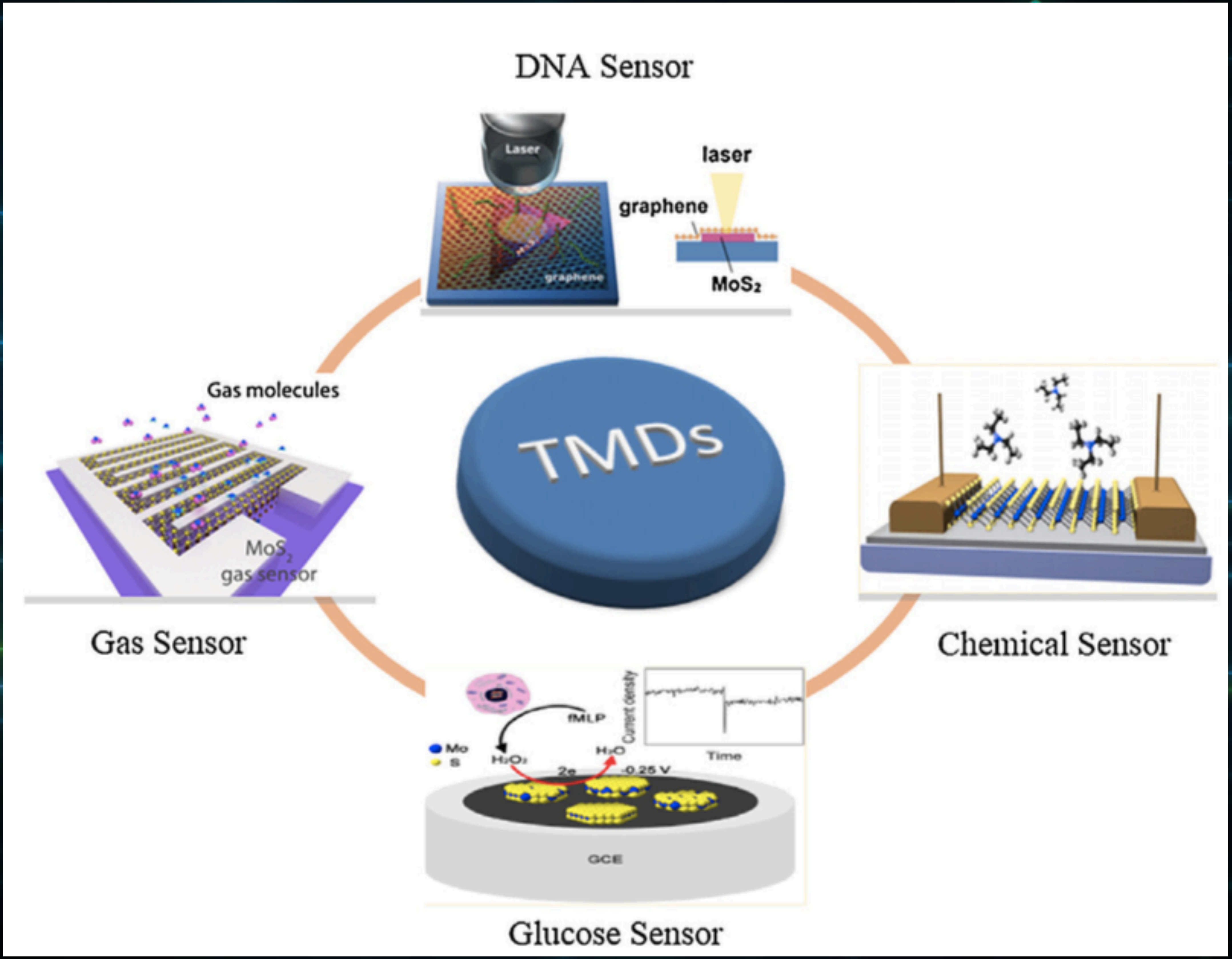
MoS2 bulk: gap indiretto 0.88 eV
MoS2 monolayer: gap diretto 1.71 eV

! Transistor con frazione corrente on/off di 10^8

Devices ad alta flessibilità



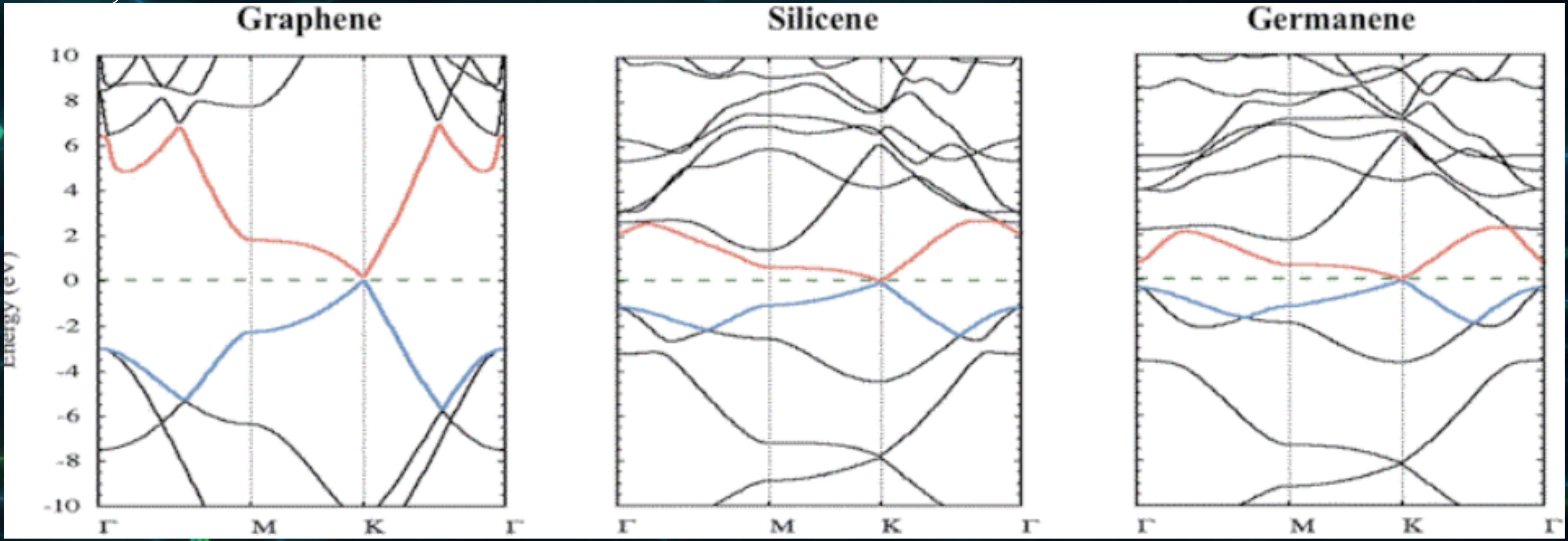
Sensoristica



X-eni

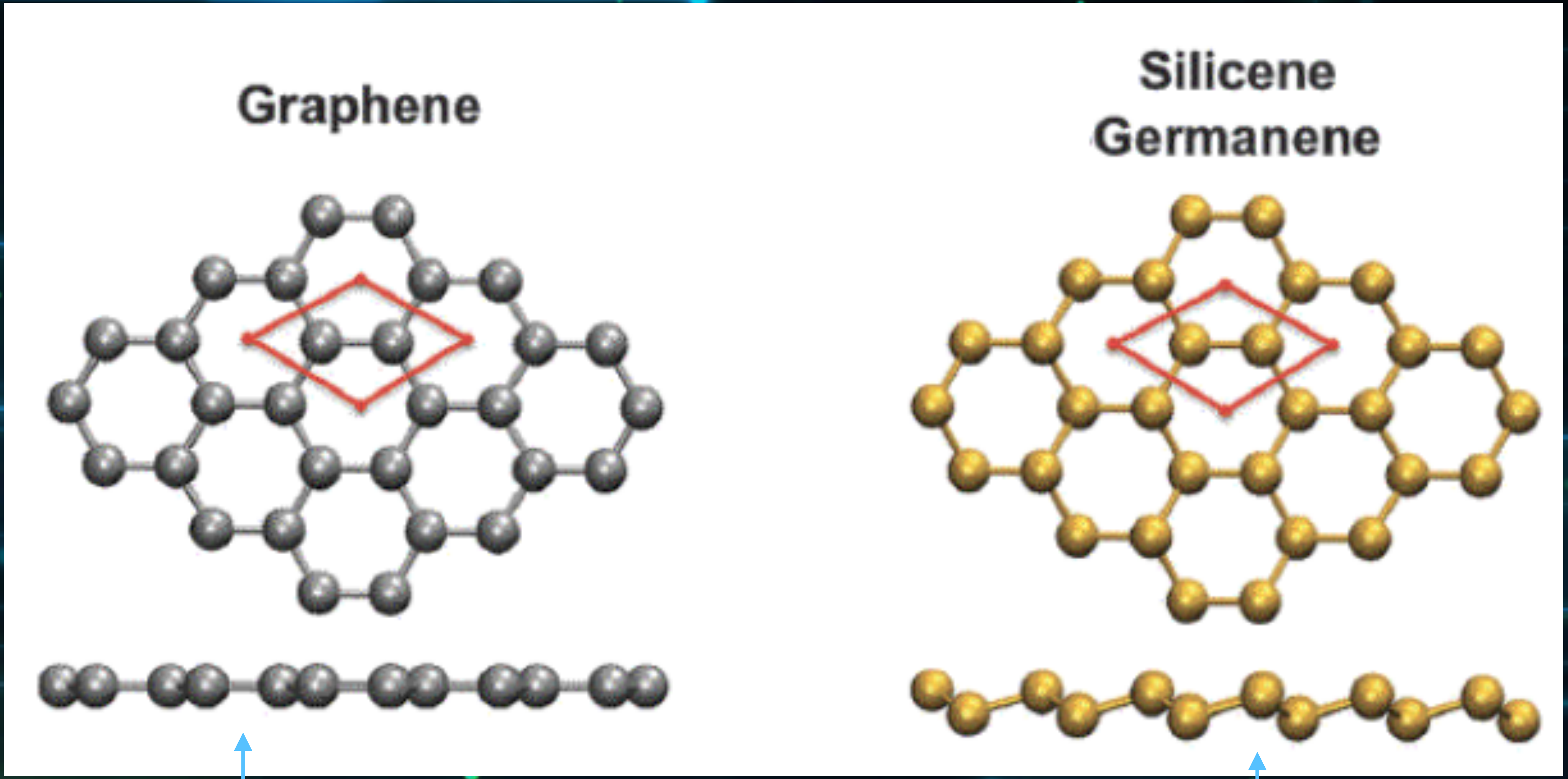
Parenti del grafene ma con caratteristiche più favorevoli per l'elettronica

X: Si, Ge



Possibilità di gap e quindi di frazione corrente on/off maggiori

Principale problema…



Legami in piano

Problema legami non in piano

Primo transistor in Silicene (2015)