Hybrid superconducting – semiconducting devices based on nanowires

leo kouwenhoven

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Kun Zuo, David van Woerkom, Daniel Szombati, Stijn Balk,
Michiel de Moor, Attila Geresdi, Maja Cassidy
Stevan Nadj-Perge, John Watson

wires: Diana Car, Emanuele Uccelli & Erik Bakkers

theory: Michael Wimmer

FOM Microsoft TU Delft Delft University of Technology QUTech

Materials

&

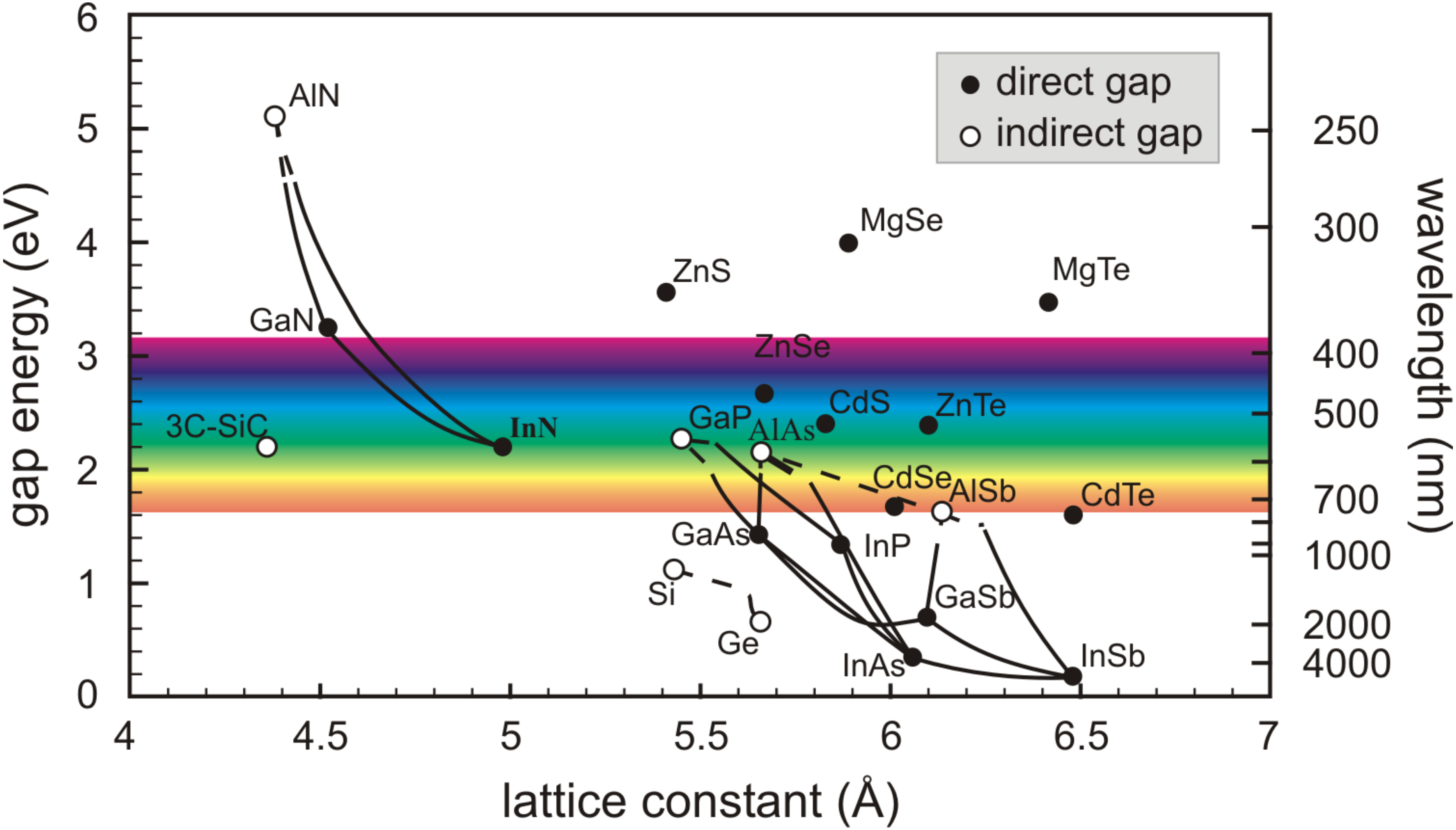
Growth

Periodic system of the elements

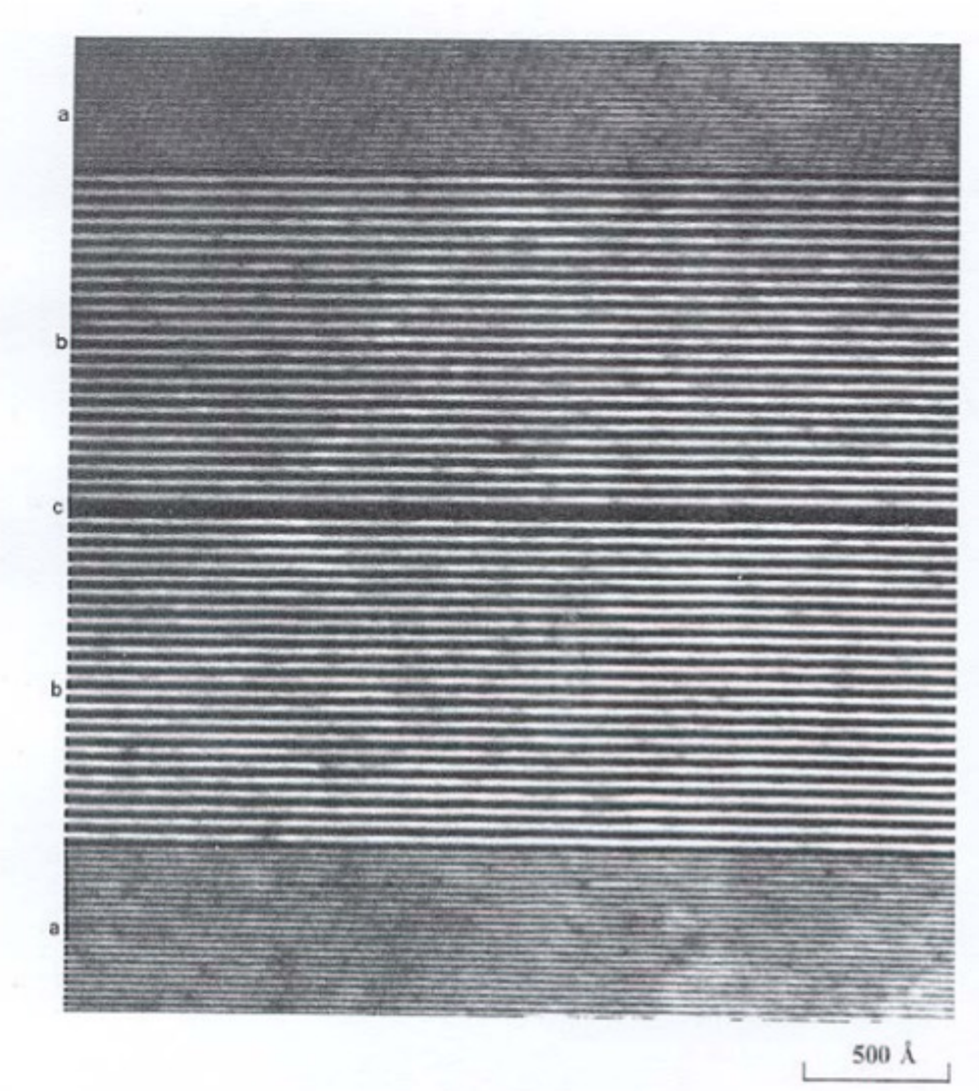
												II	III	IV	V	VI		
hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	89-102 * *	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [261]	dubnium 105 **Db** [262]	seaborgium 106 **Sg** [266]	bohrium 107 **Bh** [264]	hassium 108 **Hs** [269]	meitnerium 109 **Mt** [268]	ununnilium 110 **Uun** [271]	unununium 111 **Uuu** [272]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]				

*Lanthanide series	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
* *Actinide series	actinium 89 **Ac** [227]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]

Band engineering



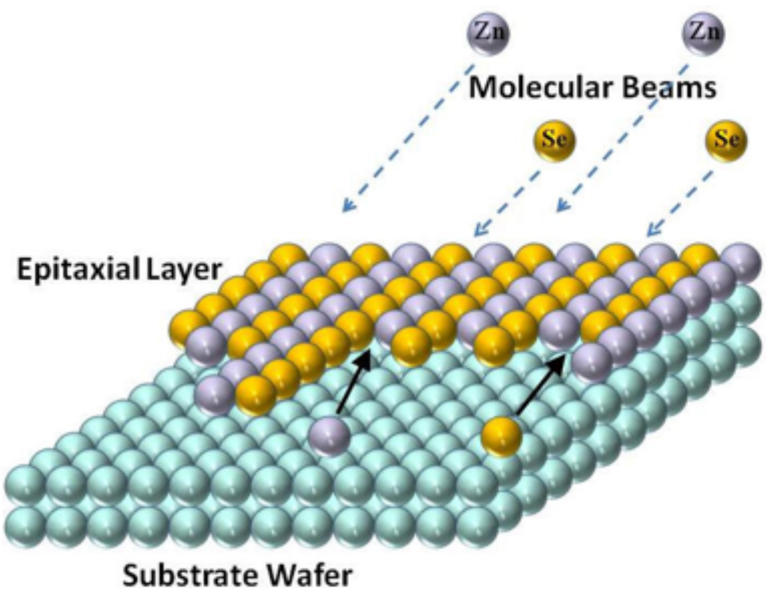
Heteroepitaxy of III-V

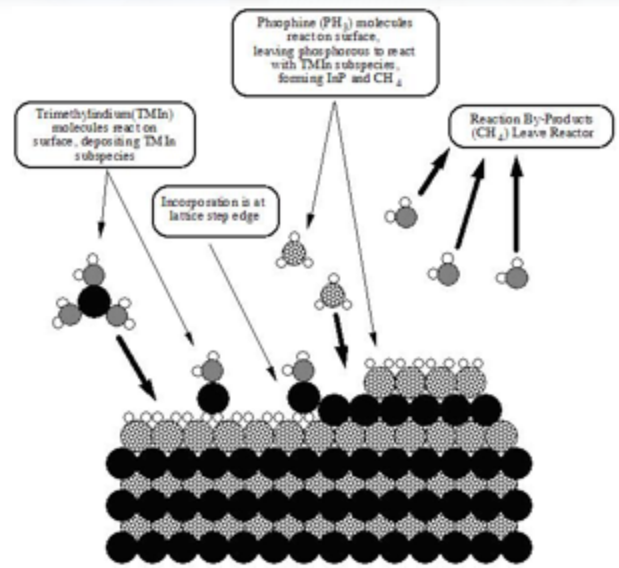


GaAs (dark regions) AlAs (lighter regions) superlattice: interesting for laser

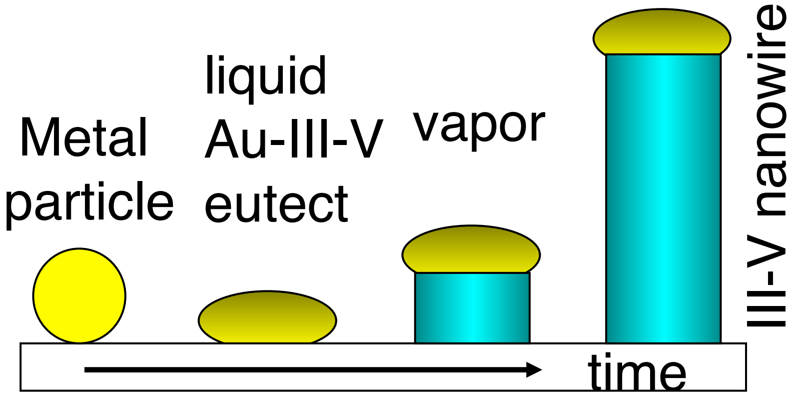
Molecular beam epitaxy (MBE)

Metal organic vapor phase epitaxy (MOVPE)

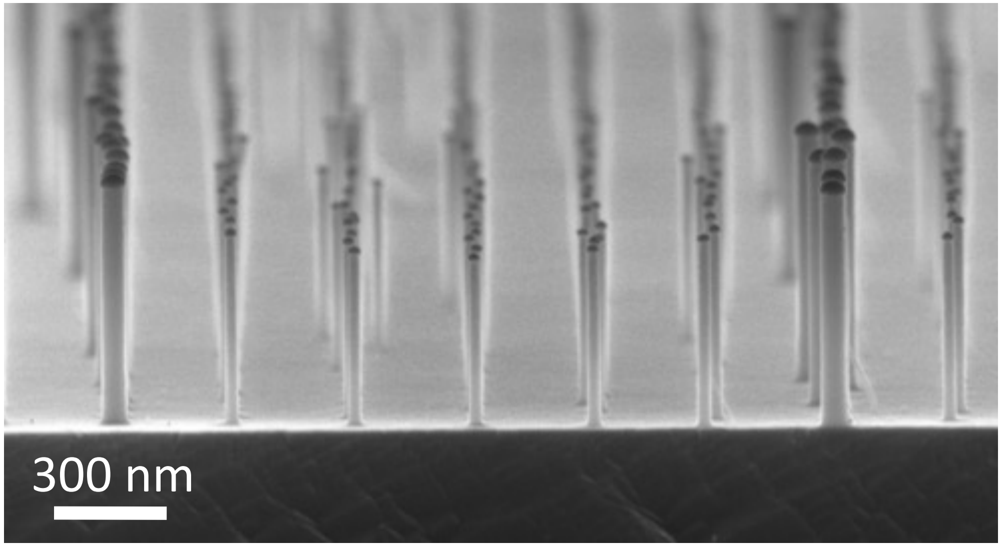




How nanowires grow…



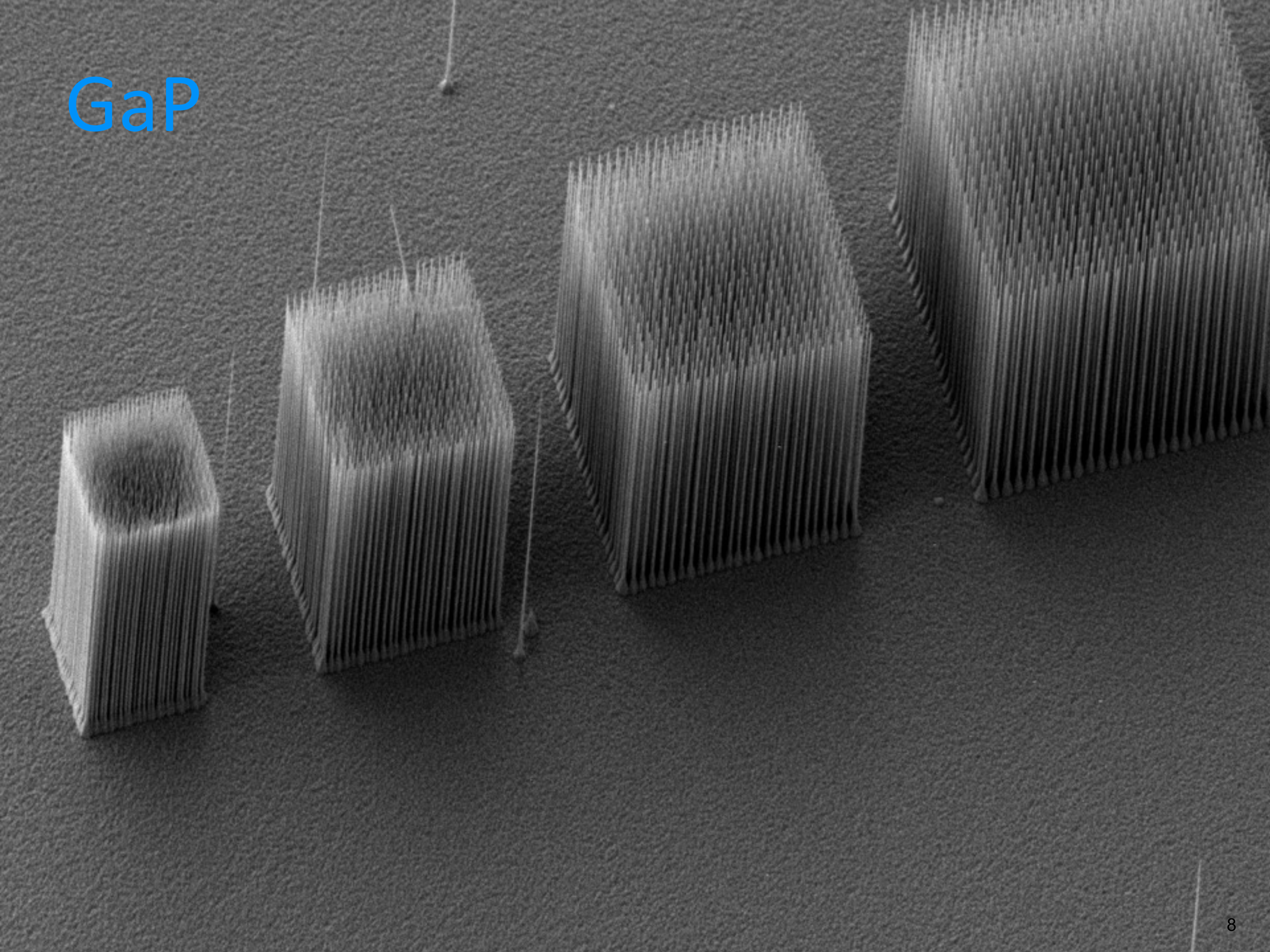
Wagner and Ellis, *APL*, 1964



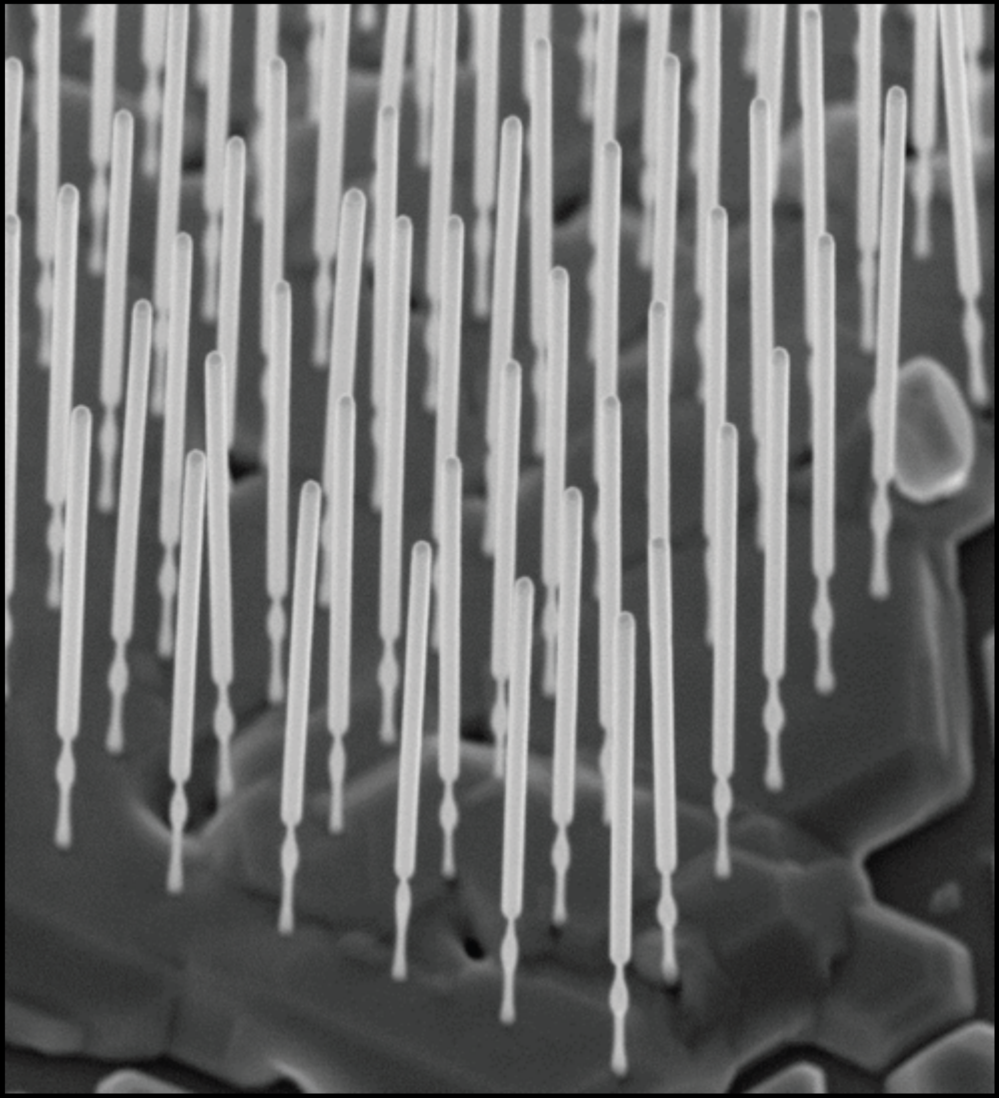
Nature Nanotechnology 2, 541 (2007)

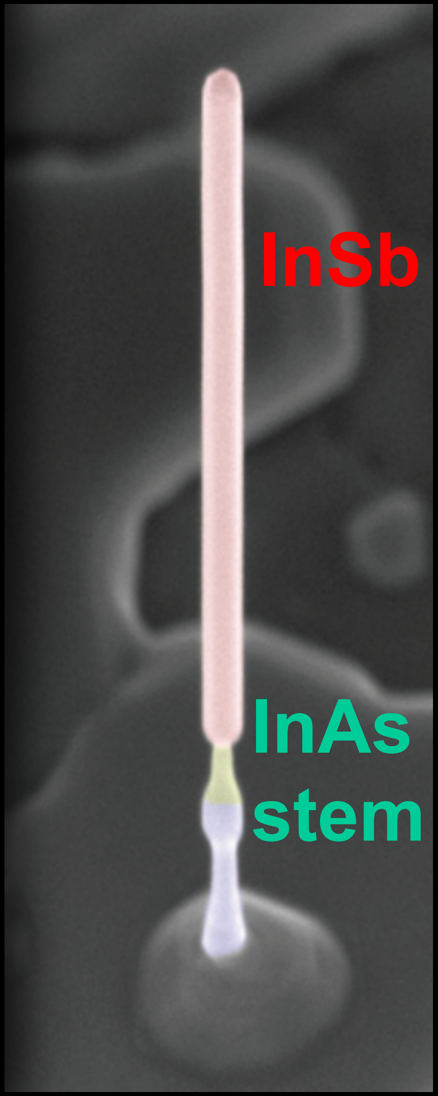
Different semiconductor classes:

- IV: Si, Ge
- III-V: GaAs, InP, etc.
- II-VI: ZnO, CdSe, etc.


GaP

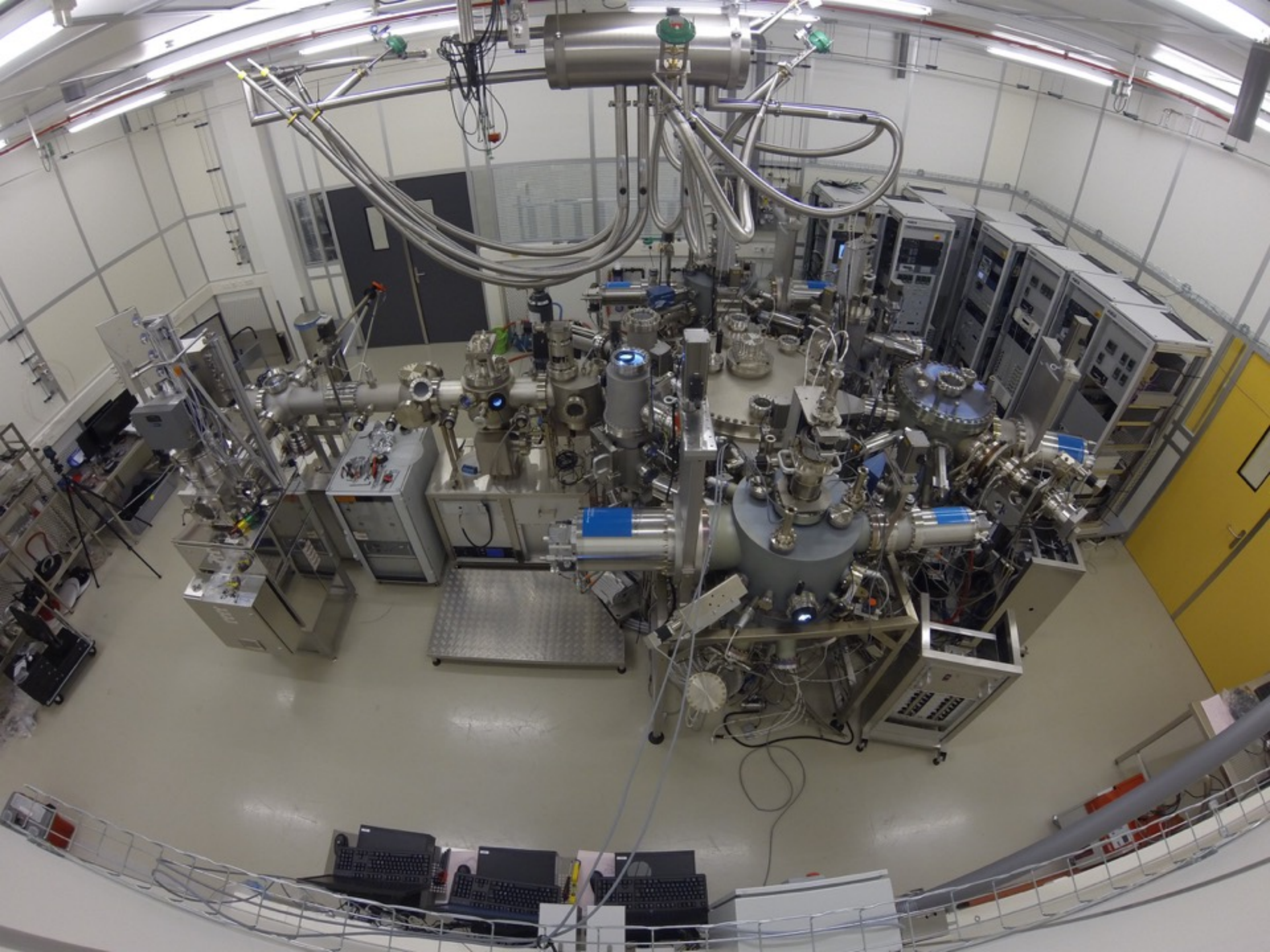
InSb Zinc Blende nanowires, growth along [111] length ~2-3 μm, diameter ~100 nm





Plissard, Bakkers et al., Nanoletters (2012)

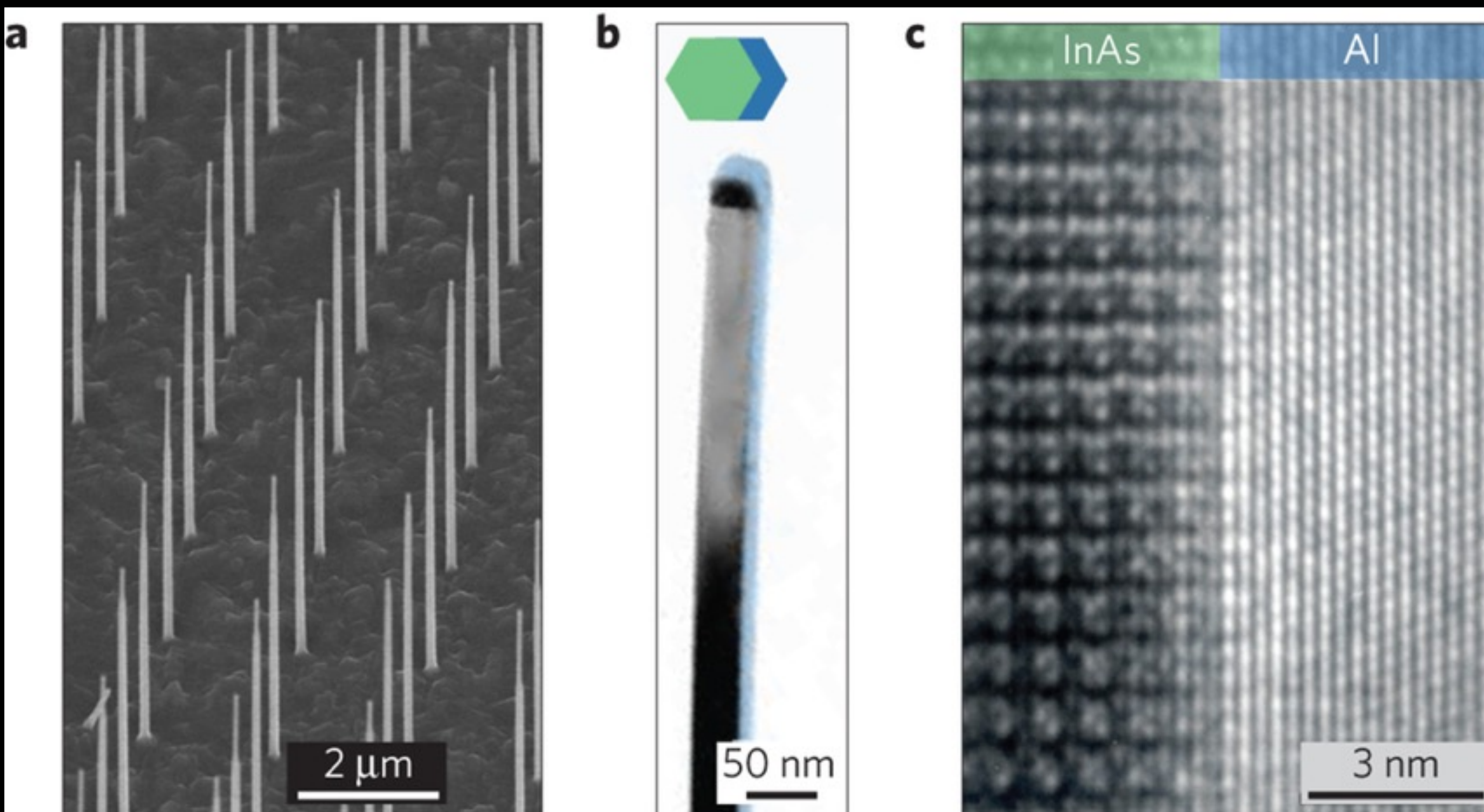
Nanowire Epi & Shadows



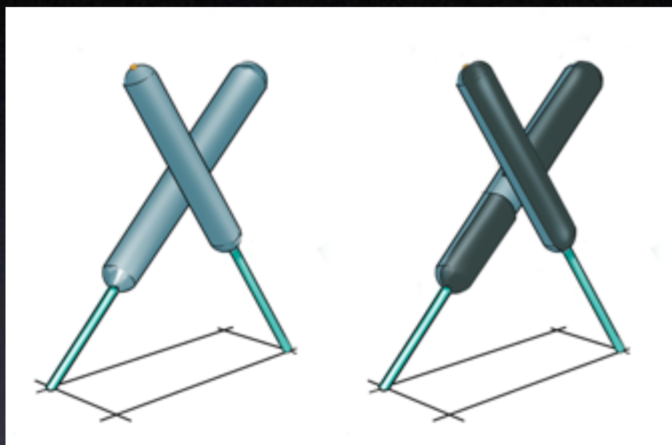
nature materials
ARTICLES
PUBLISHED ONLINE: 12 JANUARY 2015 | DOI: 10.1038/NMAT4176

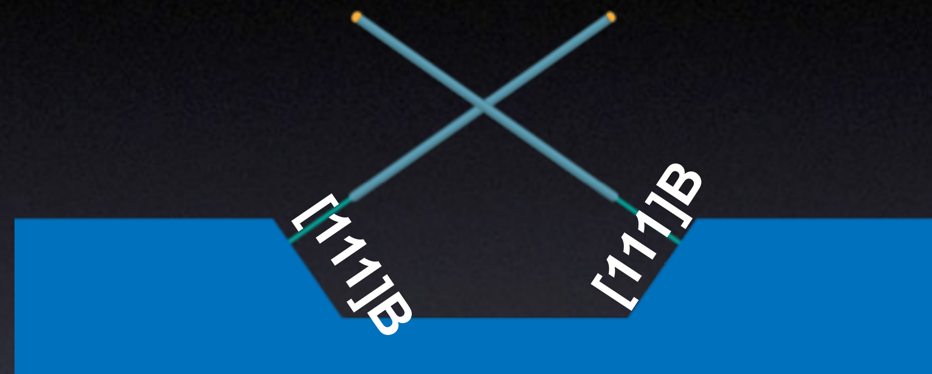
Epitaxy of semiconductor–superconductor nanowires

P. Krogstrup[1]*, N. L. B. Ziino[1], W. Chang[1], S. M. Albrecht[1], M. H. Madsen[1], E. Johnson[1,2], J. Nygård[1,3]*, C. M. Marcus[1] and T. S. Jespersen[1]*

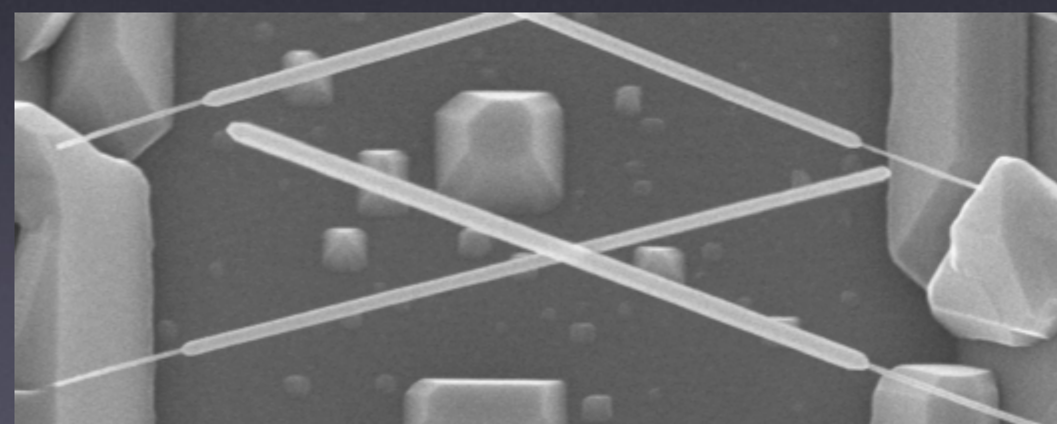


ΣΗΑΔΟΩ ΓΡΟΩΤΗ

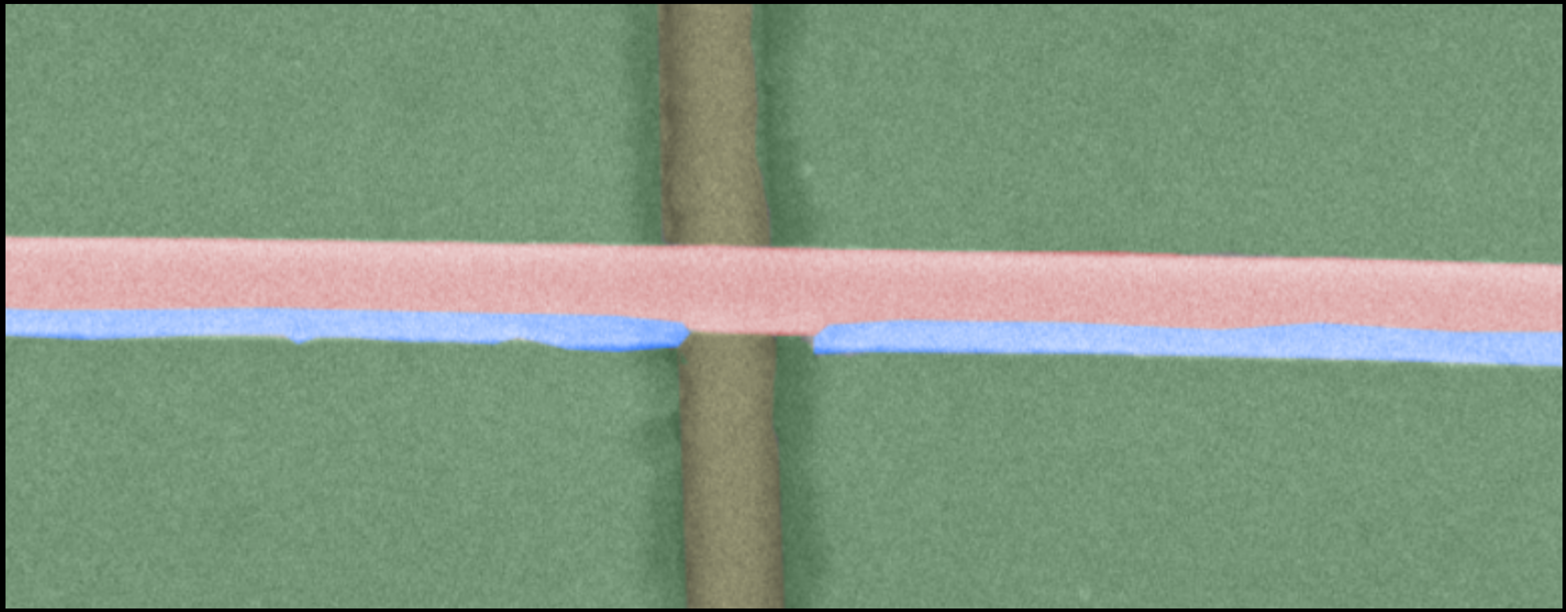


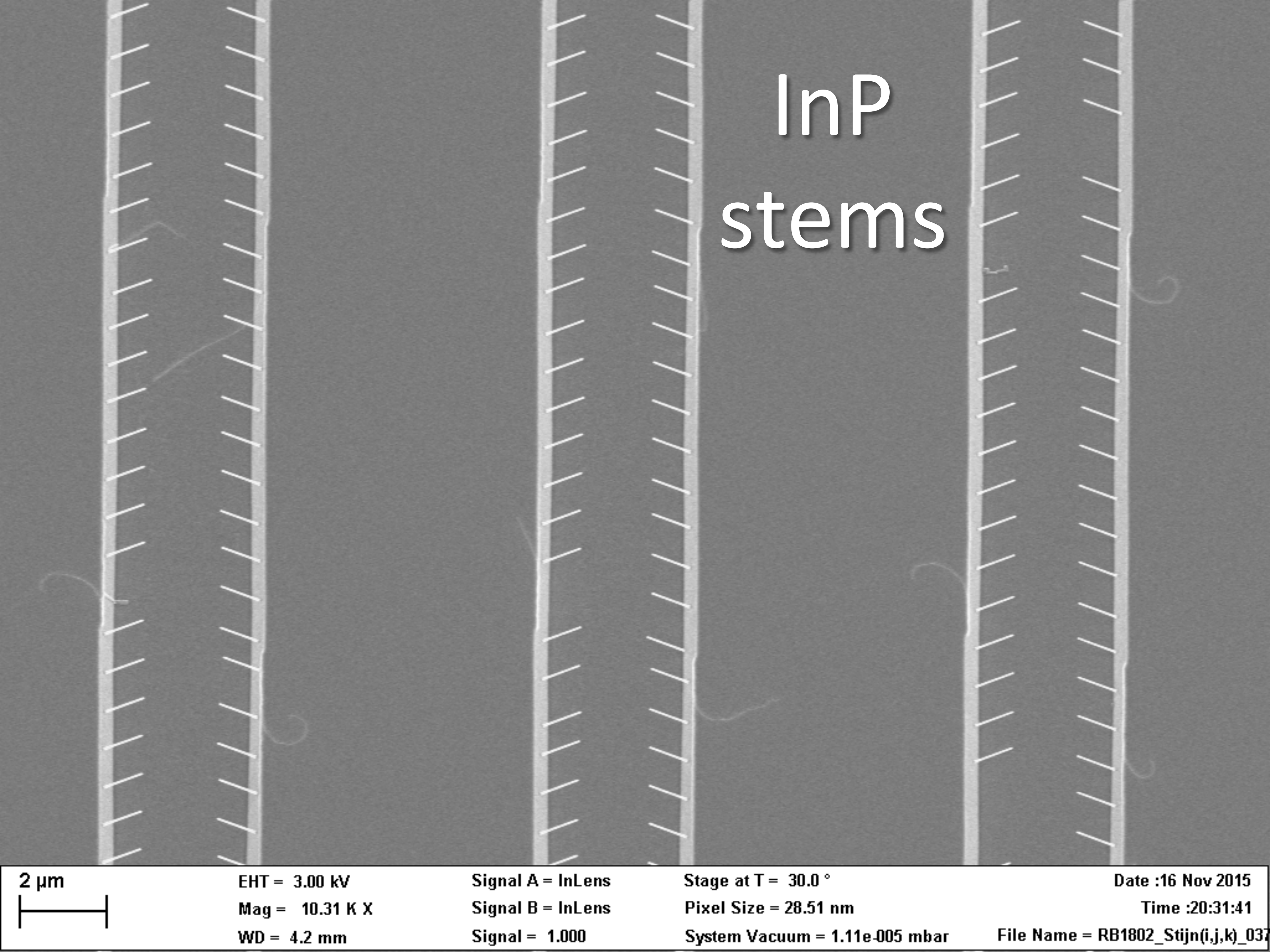


Balk et al 2016



Results from Peter Krogstrup (Growth in Copenhagen) and
David van Woekom, Attila Gersdi & John Watson (Device fab in Delft)




InP
stems
2 µm
EHT = 3.00 kV
Mag = 10.31 K X
WD = 4.2 mm
Signal A = InLens
Signal B = InLens
Signal = 1.000
Stage at T = 30.0 °
Pixel Size = 28.51 nm
System Vacuum = 1.11e-005 mbar
Date :16 Nov 2015
Time :20:31:41
File Name = RB1802_Stijn(i,j,k)_03

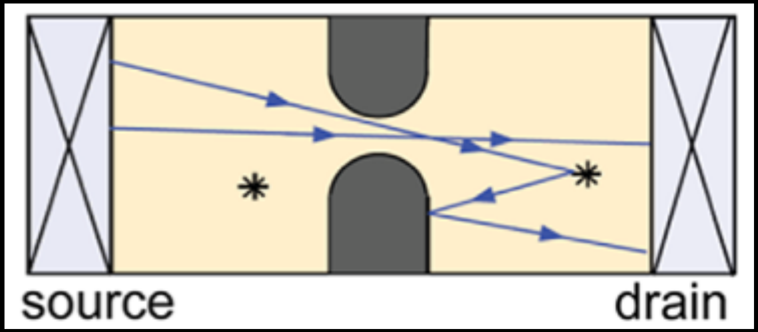
CONTACTS

1D quantum wire

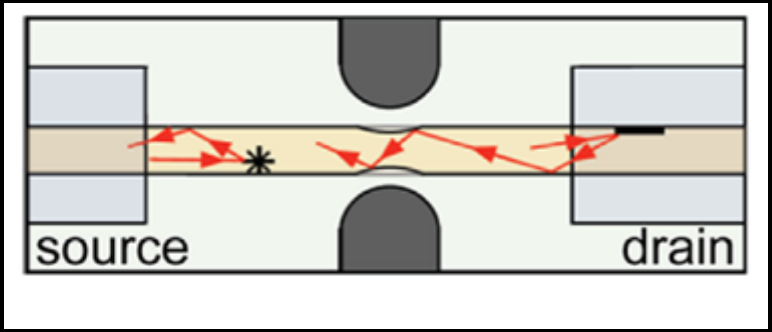
- discrete modes
- ballistic transport

= quantized conductance

2D

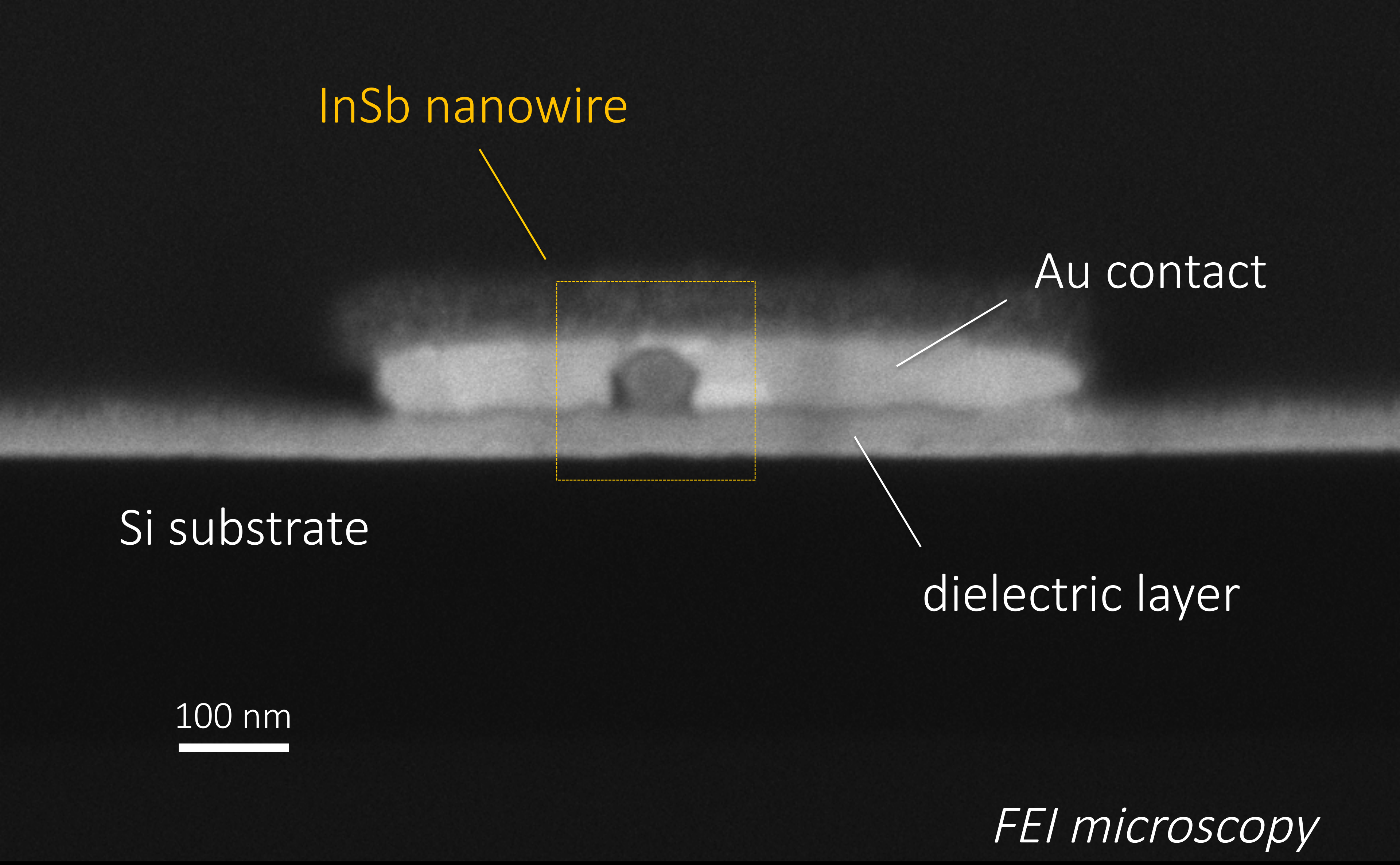


1D

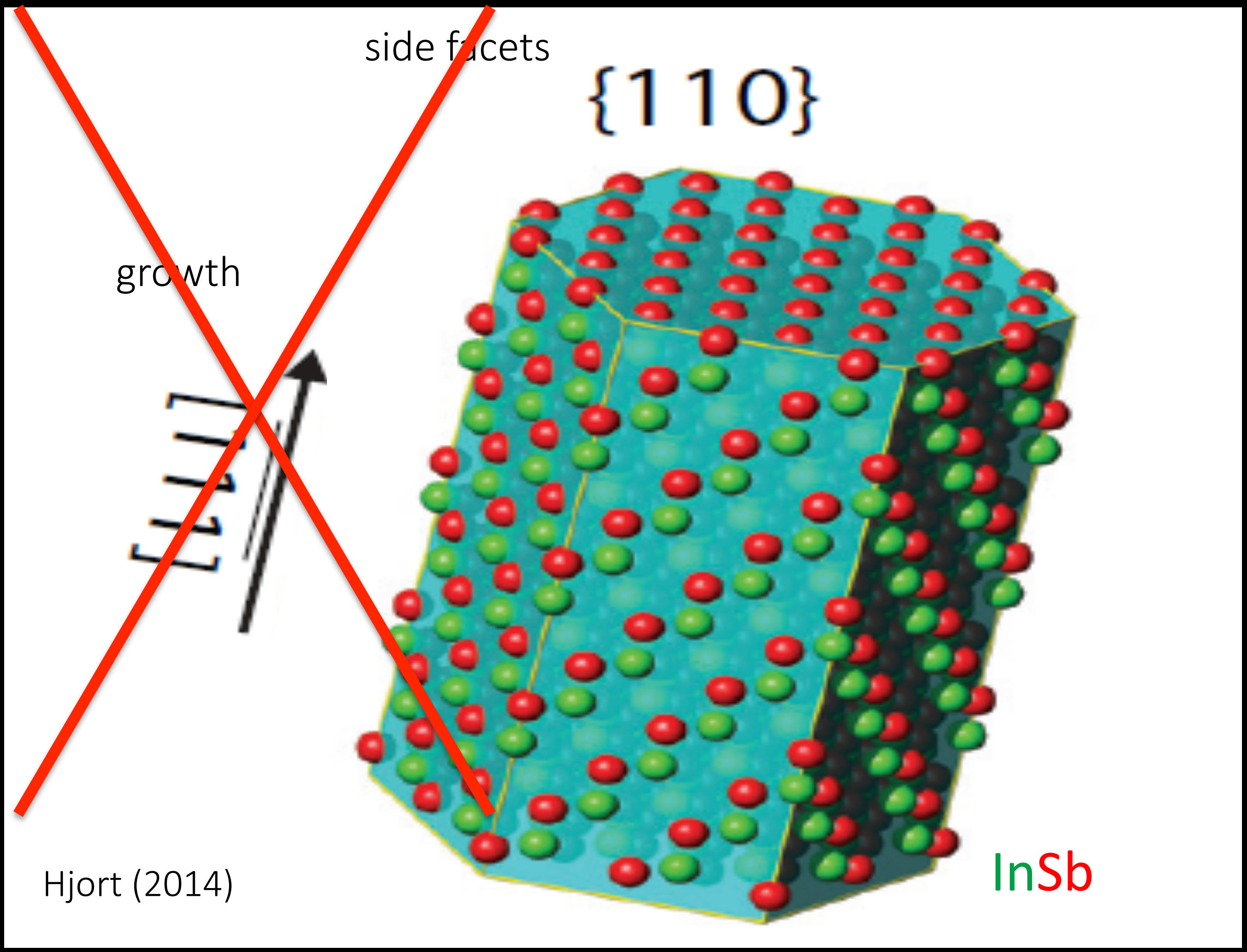


quantized conductance in 1D requires transparent contacts

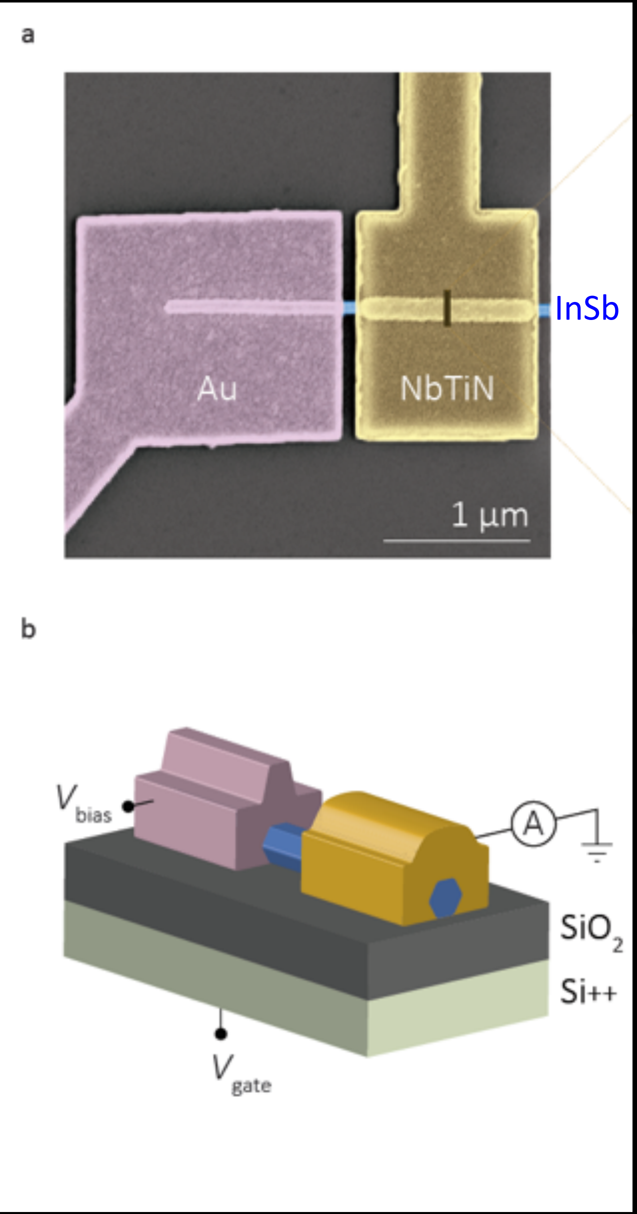
surface treatment/oxide removal



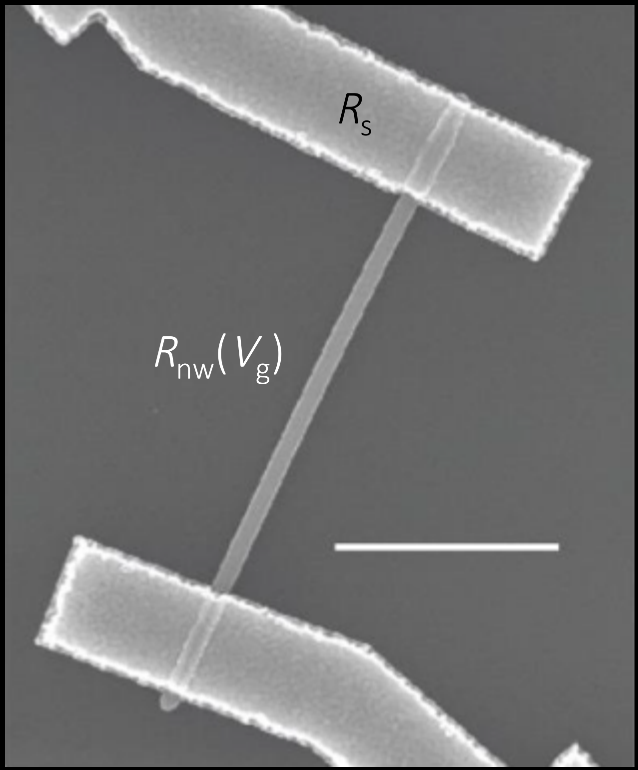
nanowire contact areas

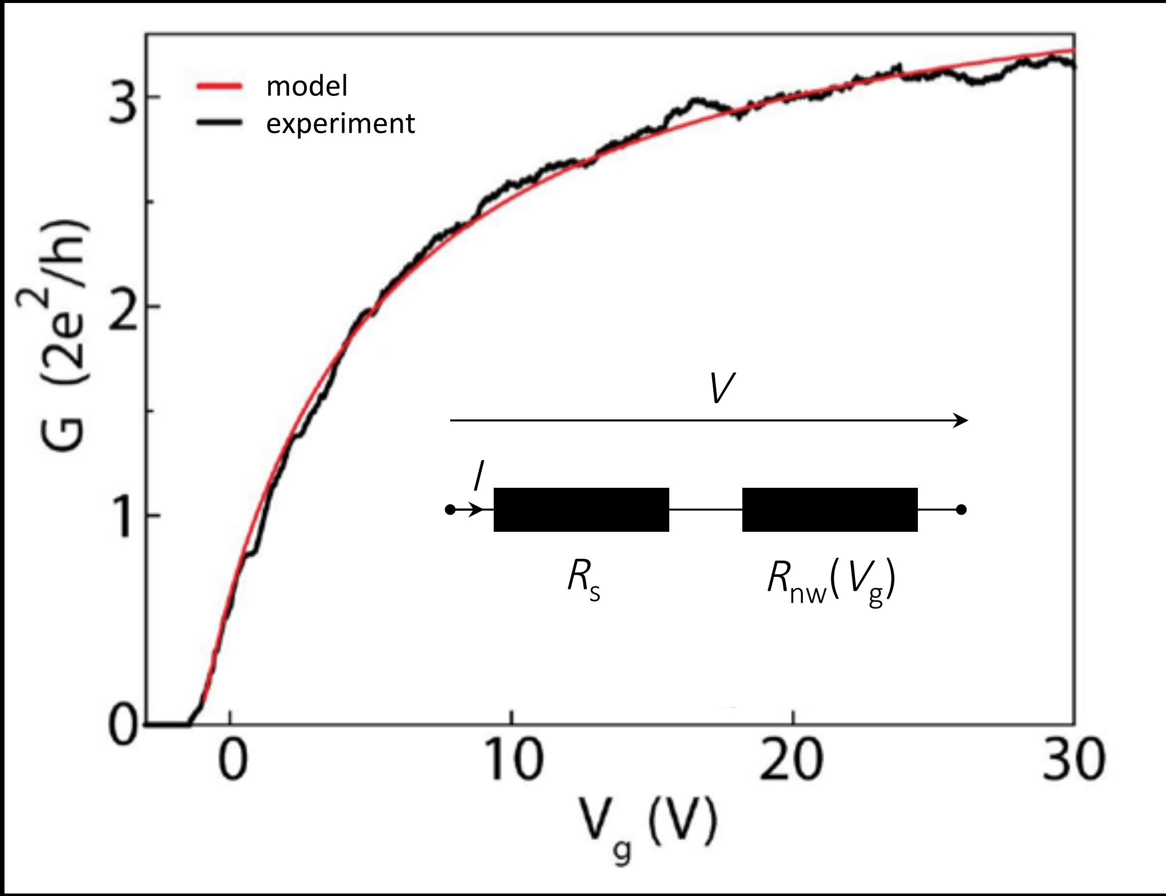


interface



how to extract mobility

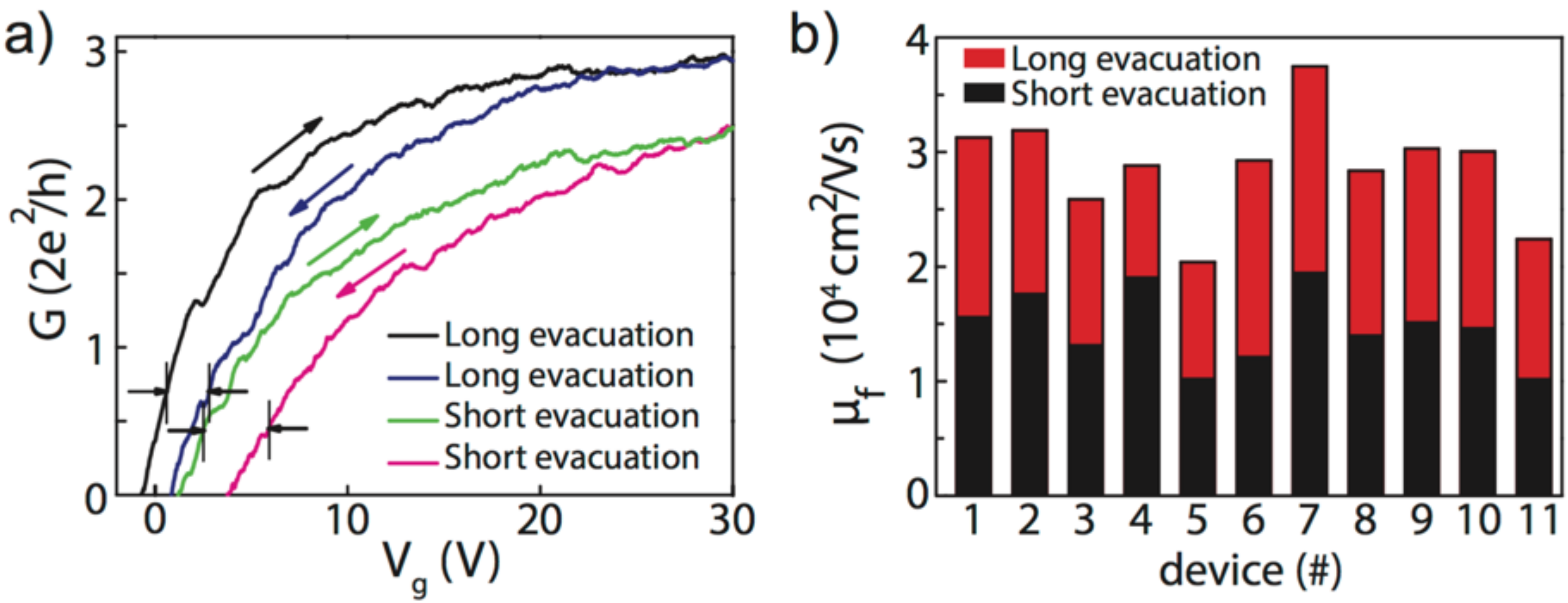




http://arxiv.org/pdf/1411.7285.pdf

$$G(V_g) = \left(R_s + \frac{L^2}{\mu C \left(V_g - V_{th}\right)} \right)^{-1}$$

how to extract mobility

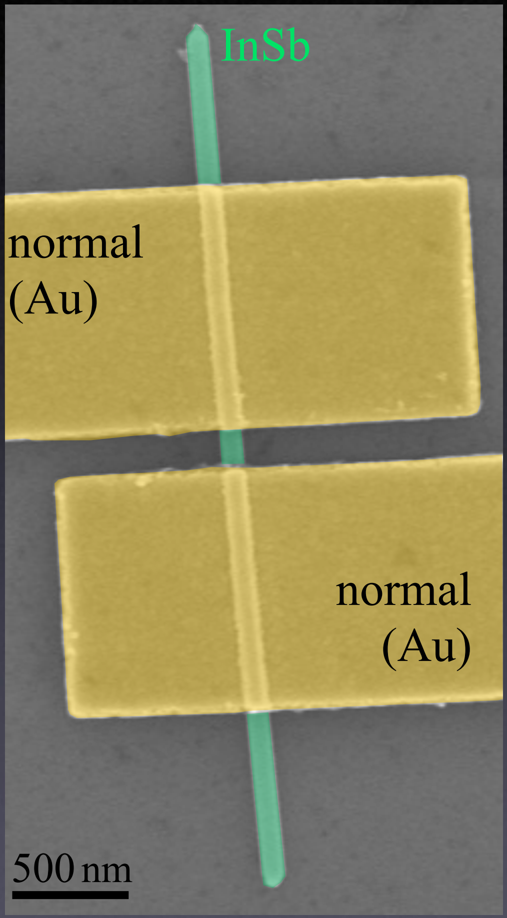


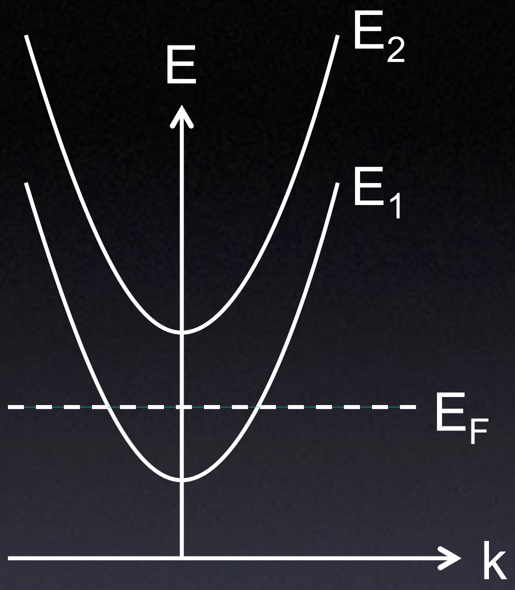
http://arxiv.org/pdf/1411.7285.pdf

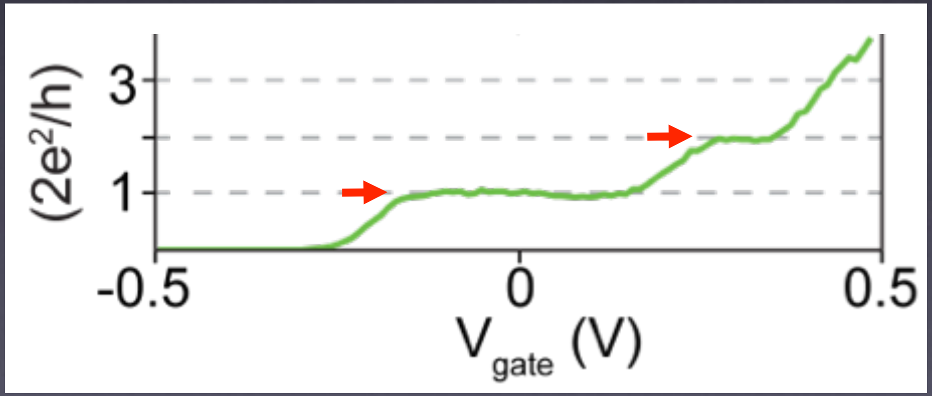
Note: Extracted field effect mobility is not the same as mobility and mean-free-path used by theorists in e.g. lattice models!

QUANTIZED CONDUCTANCE

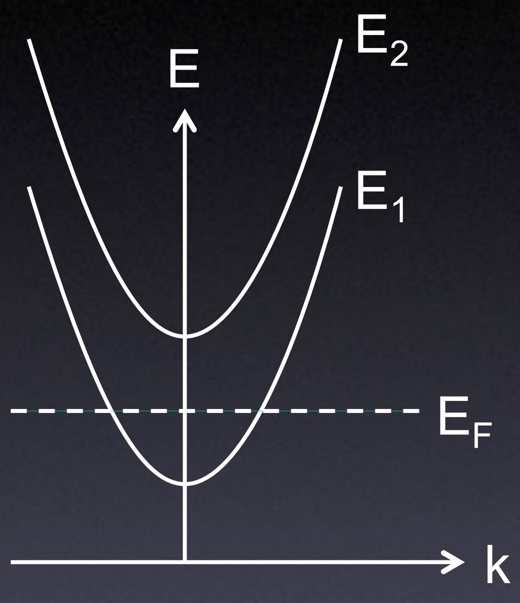
Ballistic one-dimensional nanowire

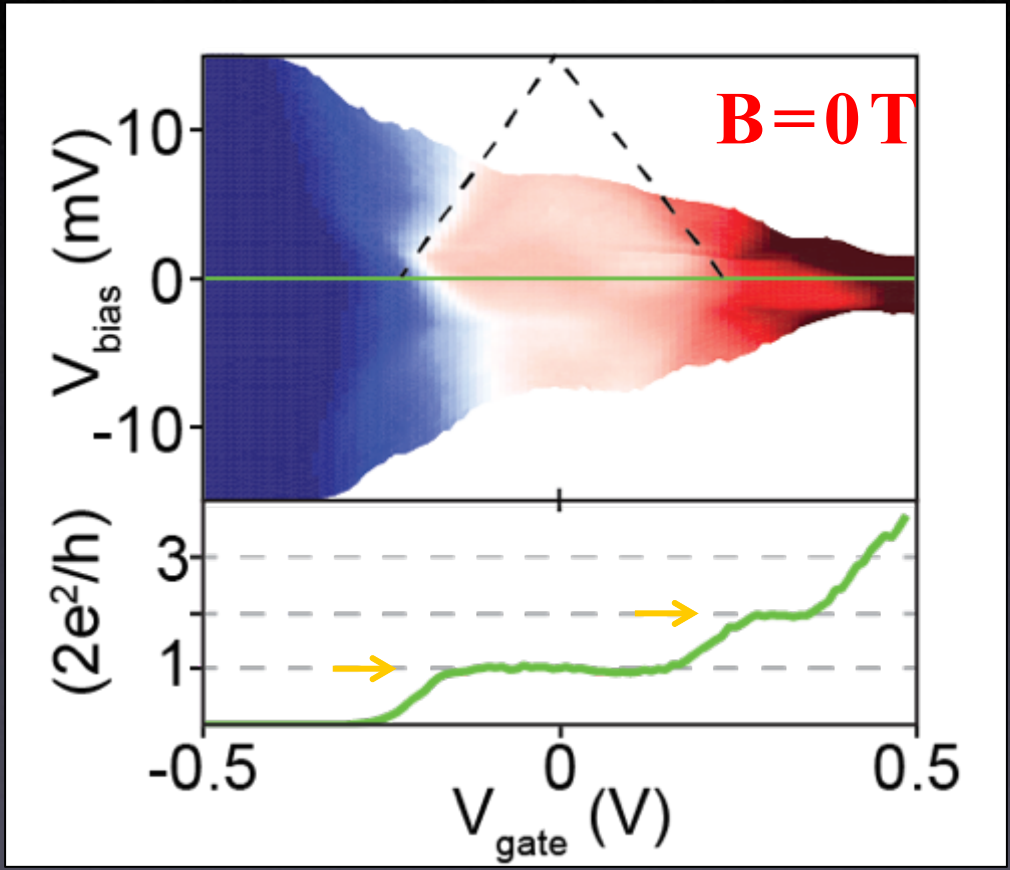






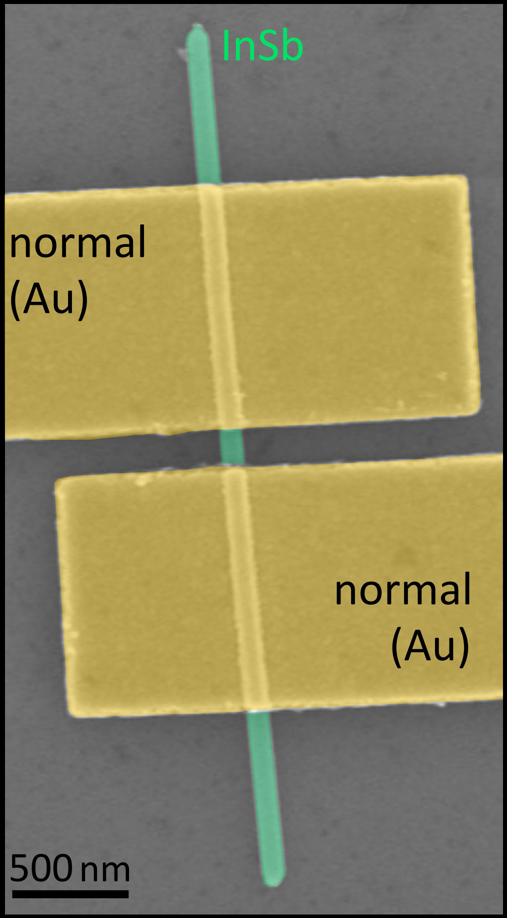
Ballistic one-dimensional nanowire

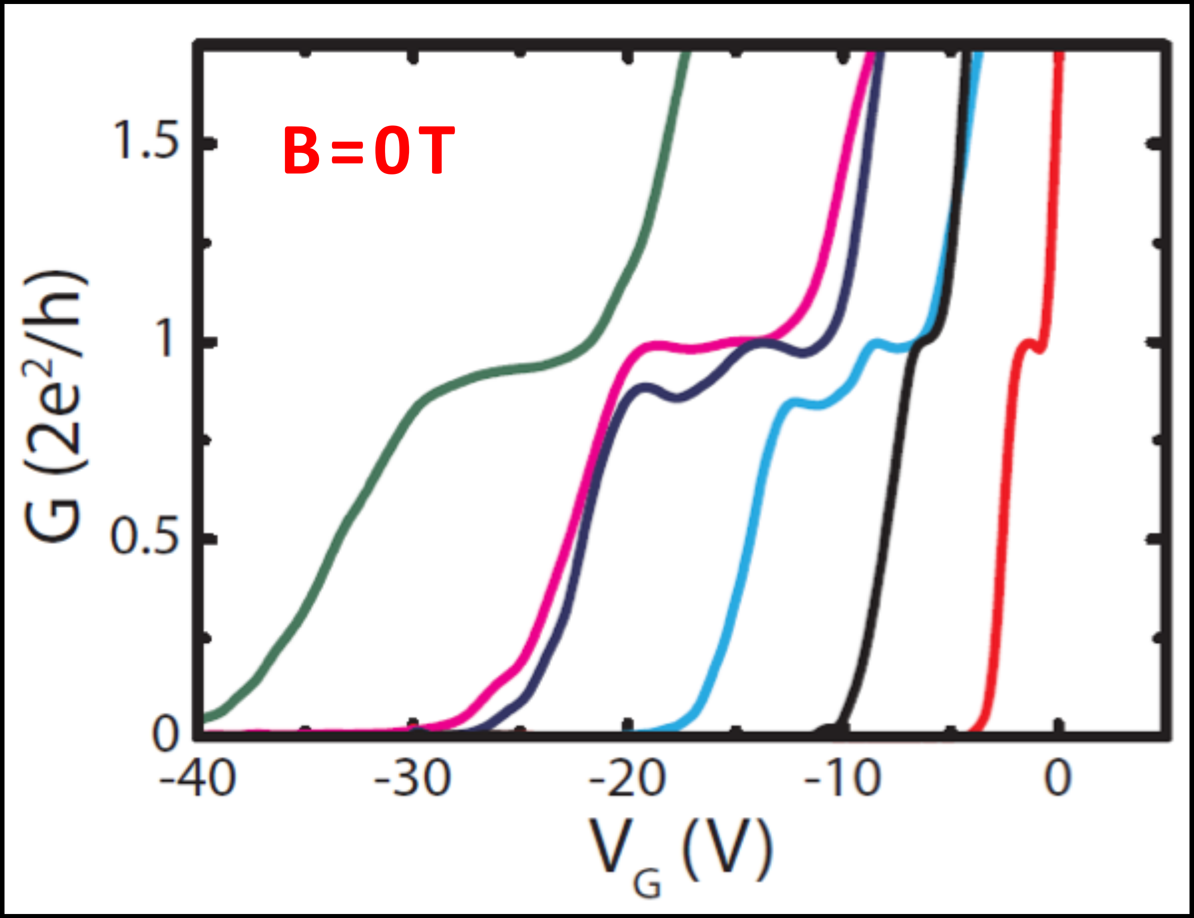




- Subband spacing~15meV

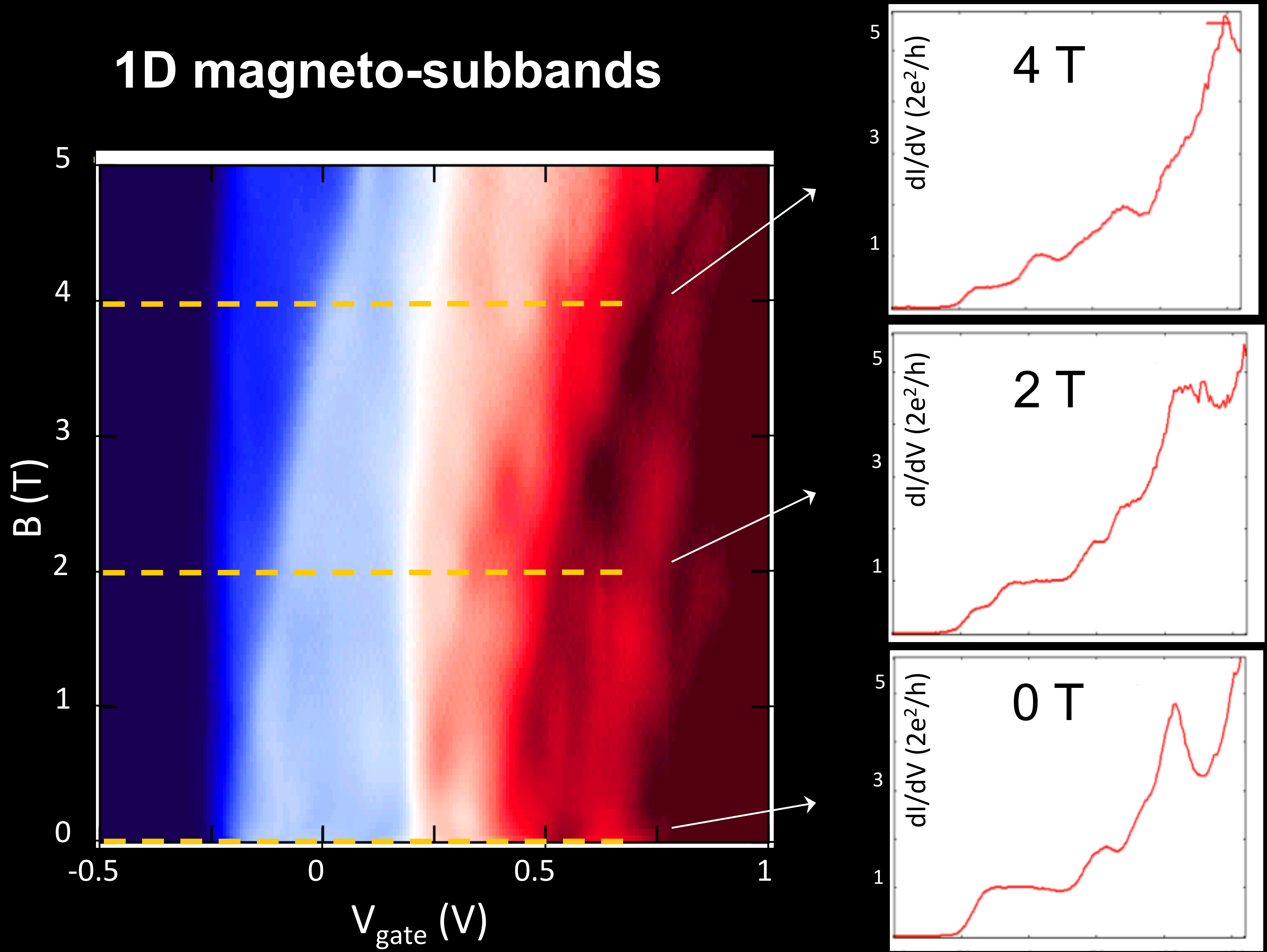
Ballistic one-dimensional nanowire



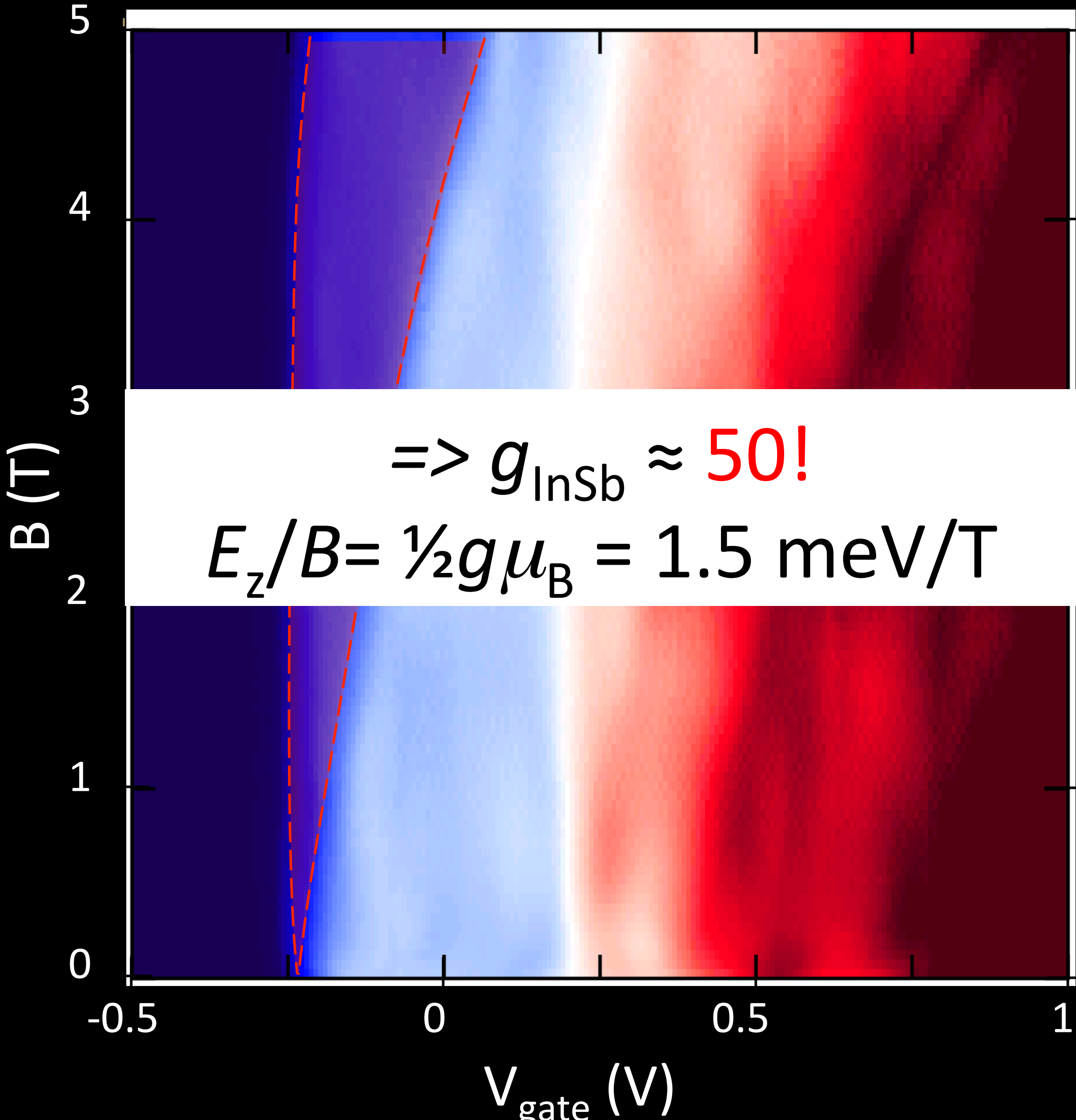


quantized conductance at zero field for all wires

1D magneto-subbands

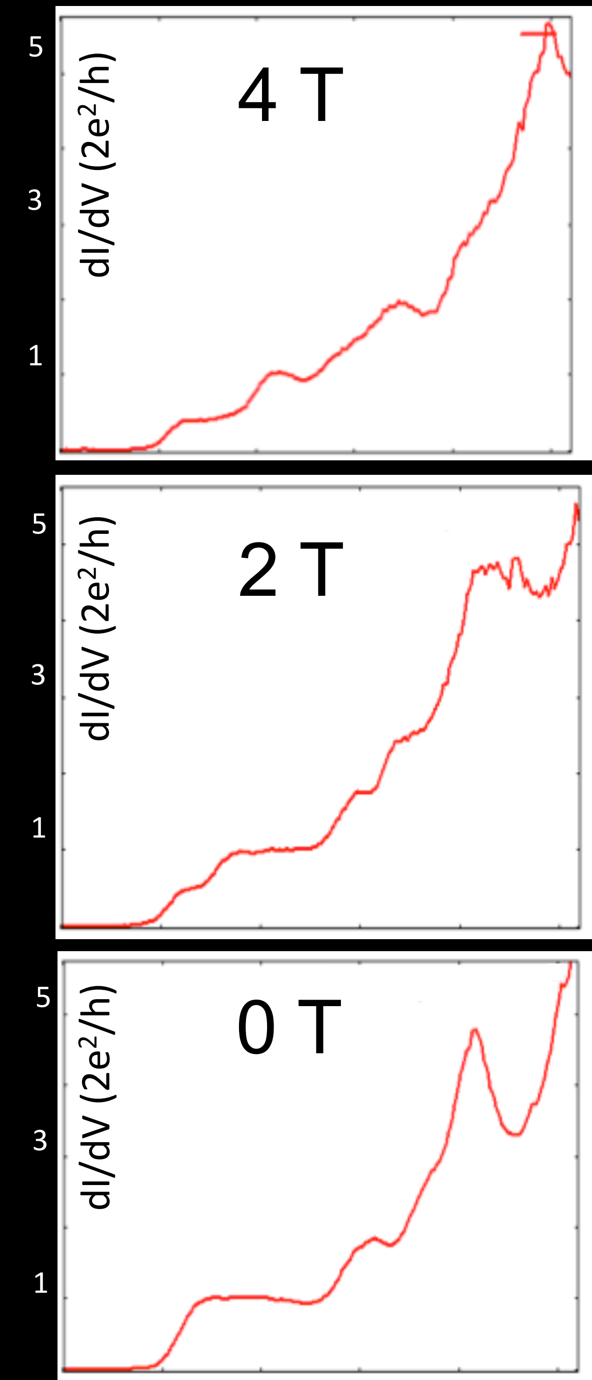


1D magneto-subbands



$\Rightarrow g_{InSb} \approx$ 50!

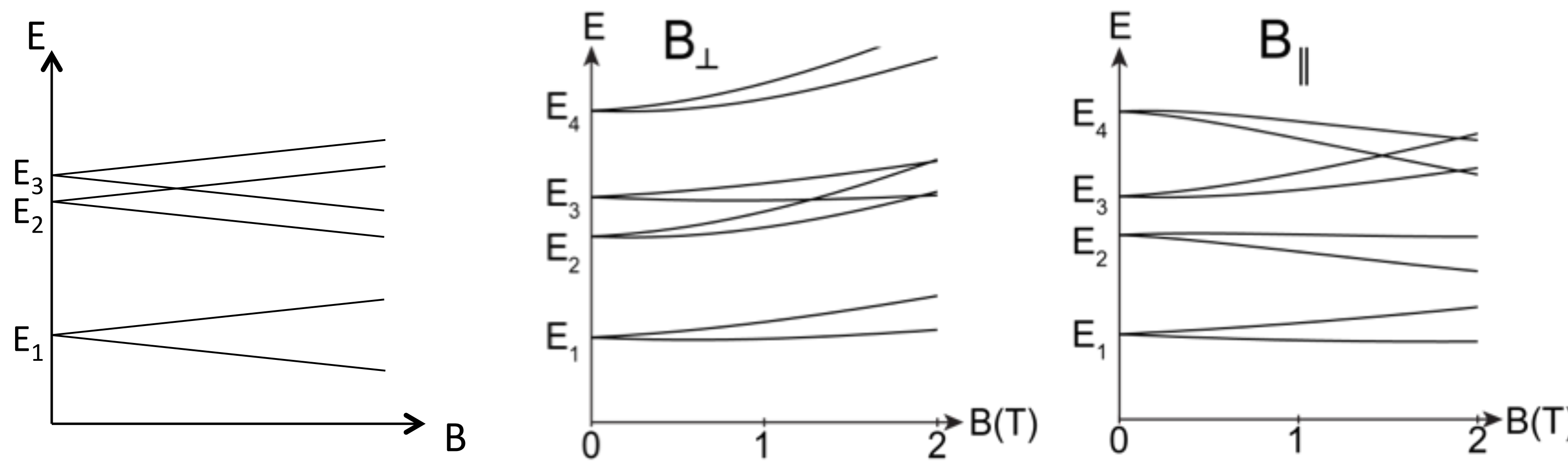
$E_z/B = \frac{1}{2} g\mu_B = 1.5$ meV/T



Orbital effect

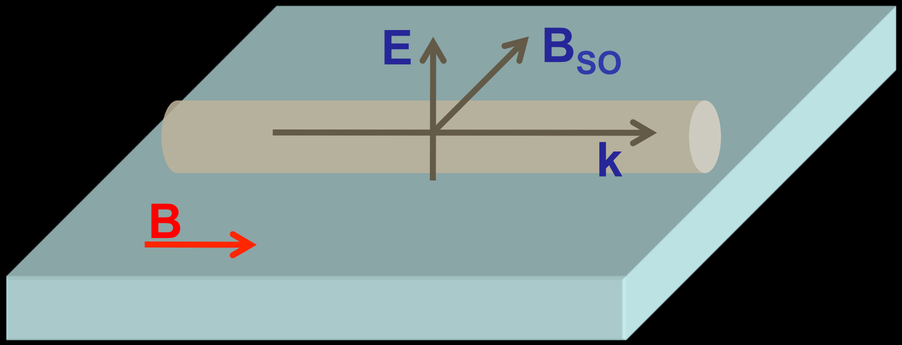
- Orbital effects dominate sub-band dispersion
- B-field orientation important
- Orbital sub-band degeneracies possible

arXiv:1603.03751

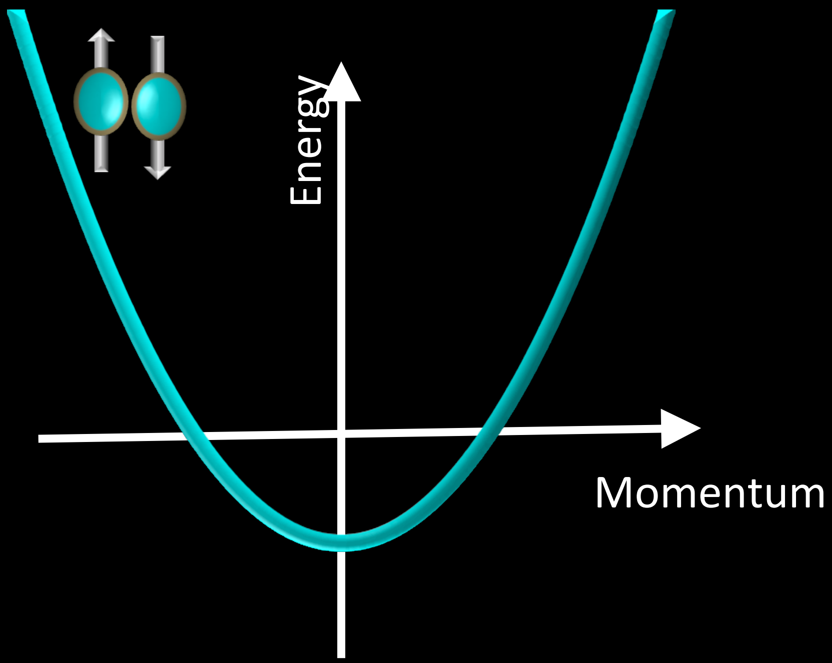


SPIN-ORBIT

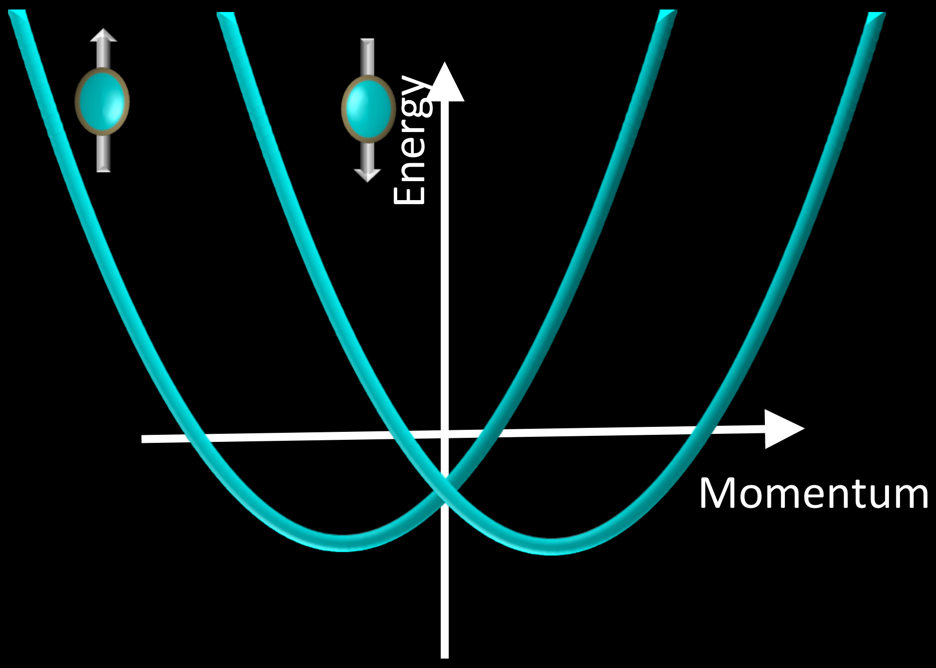
1D subbands with Rashba spin-orbit interaction ➔ *helical liquid*



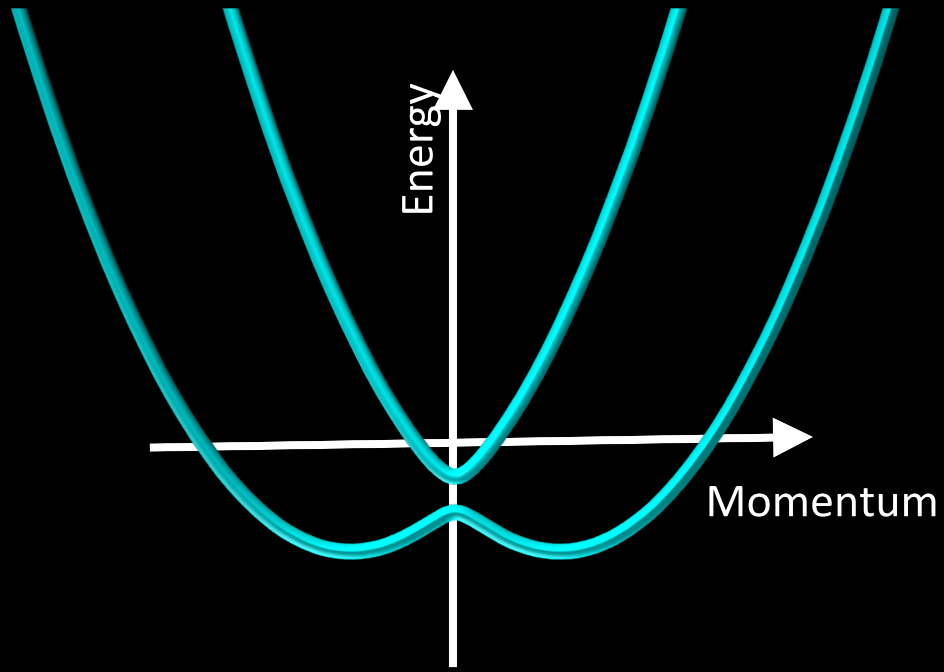
SPIN ORBIT INTERACTION (SOI)



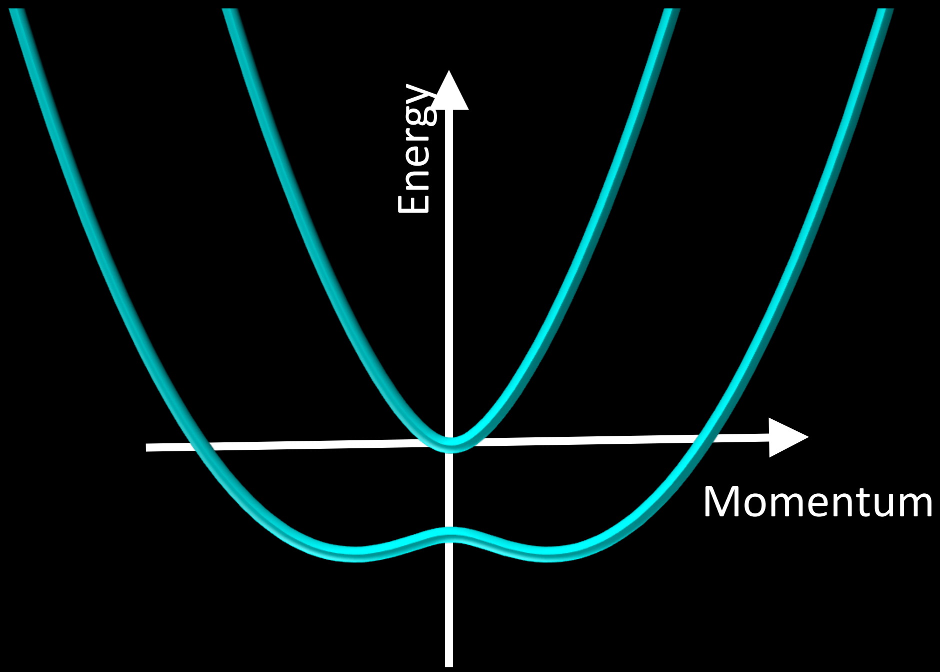
SPIN ORBIT INTERACTION (SOI)



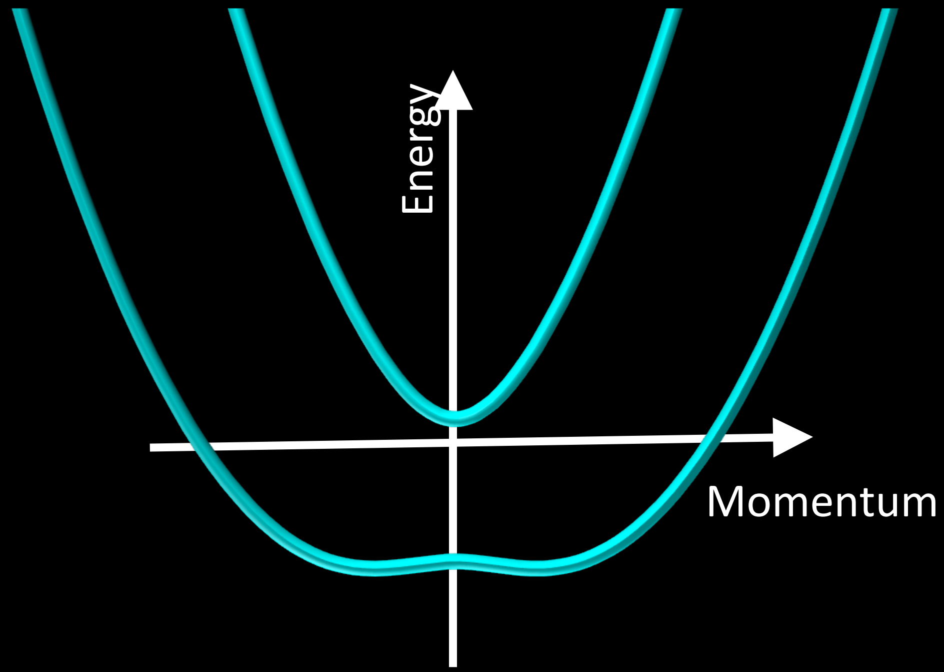
SOI+Magnetism



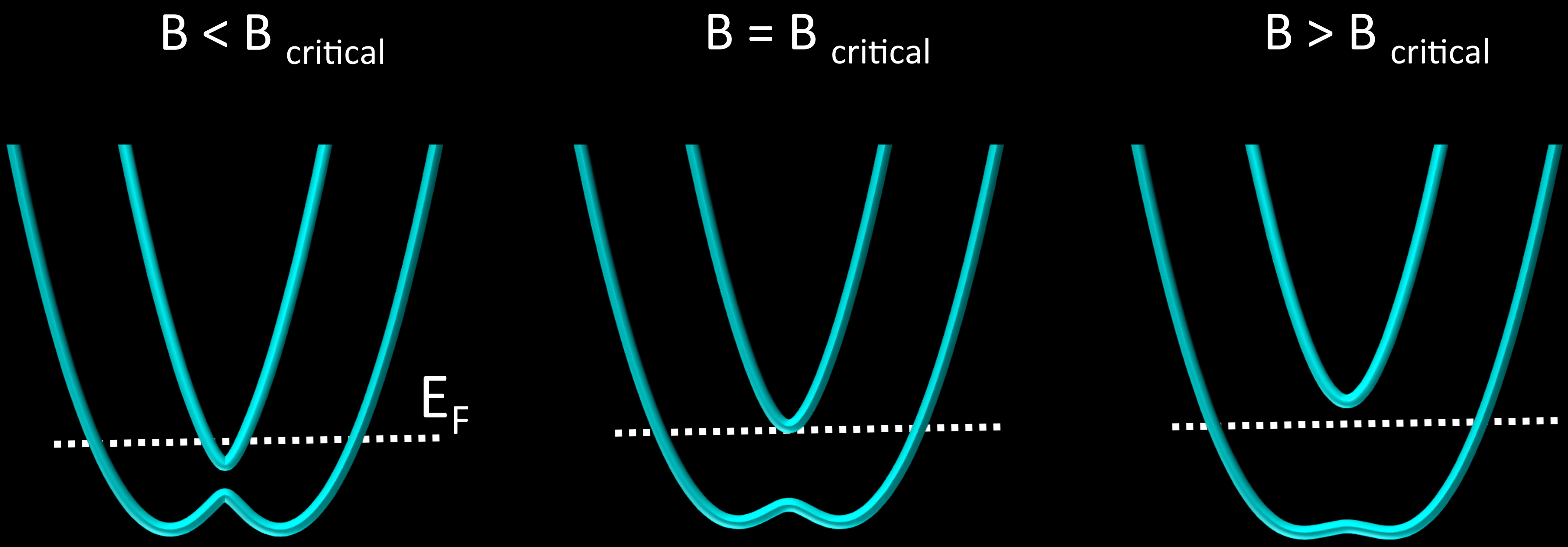
SOI + Magnetism



SOI + Magnetism

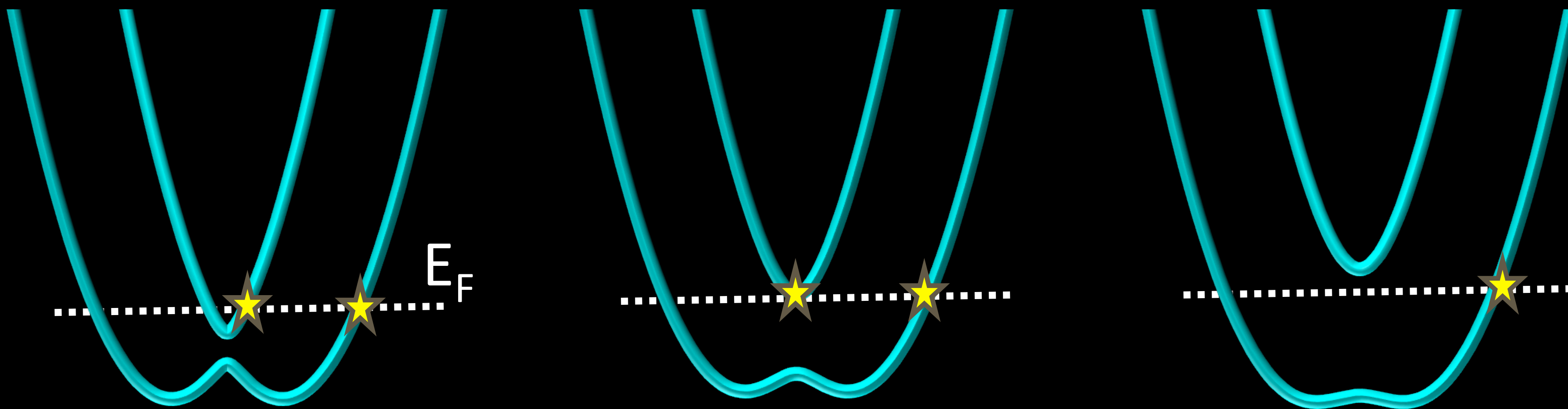


SOI + Magnetism



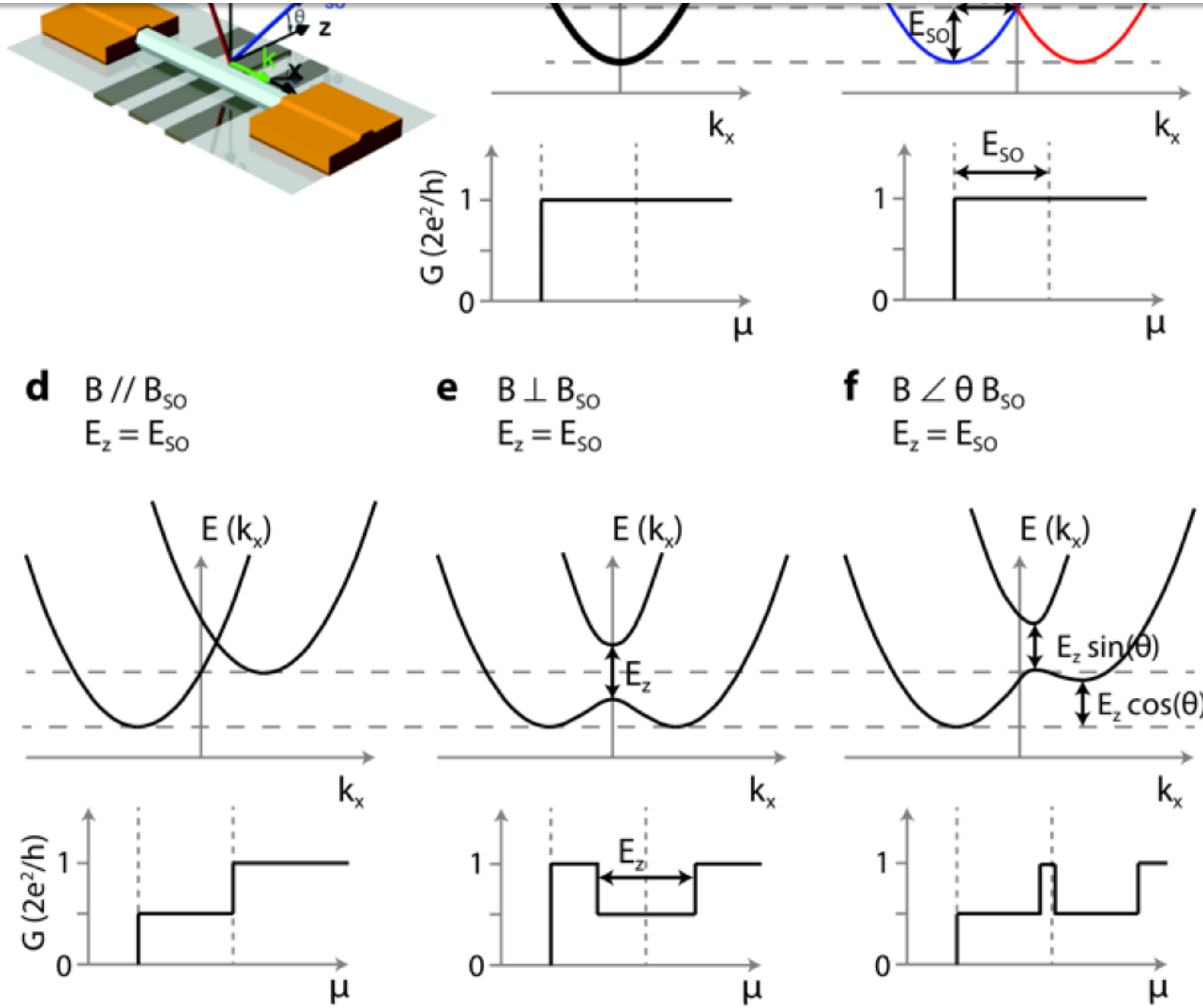
SOI + Magnetism

$B < B_{critical}$ $B = B_{critical}$ $B > B_{critical}$



TOPOLOGICALLY DISTINCT

Number of crossing different in parity


z
k
x
k_x
E_{SO}
k_x
G (2e²/h)
1
0
μ
E_{SO}
1
0
μ
d
$B \parallel B_{SO}$
$E_z = E_{SO}$
e
$B \perp B_{SO}$
$E_z = E_{SO}$
f
$B \angle \theta\ B_{SO}$
$E_z = E_{SO}$
E (k_x)
k_x
E (k_x)
E_z
k_x
E (k_x)
E_z sin(θ)
E_z cos(θ)
k_x
G (2e²/h)
1
0
μ
E_z
1
0
μ
1
0
μ

PHYSICAL REVIEW B **90**, 235415 (2014)

Conductance behavior in nanowires with spin-orbit interaction: A numerical study

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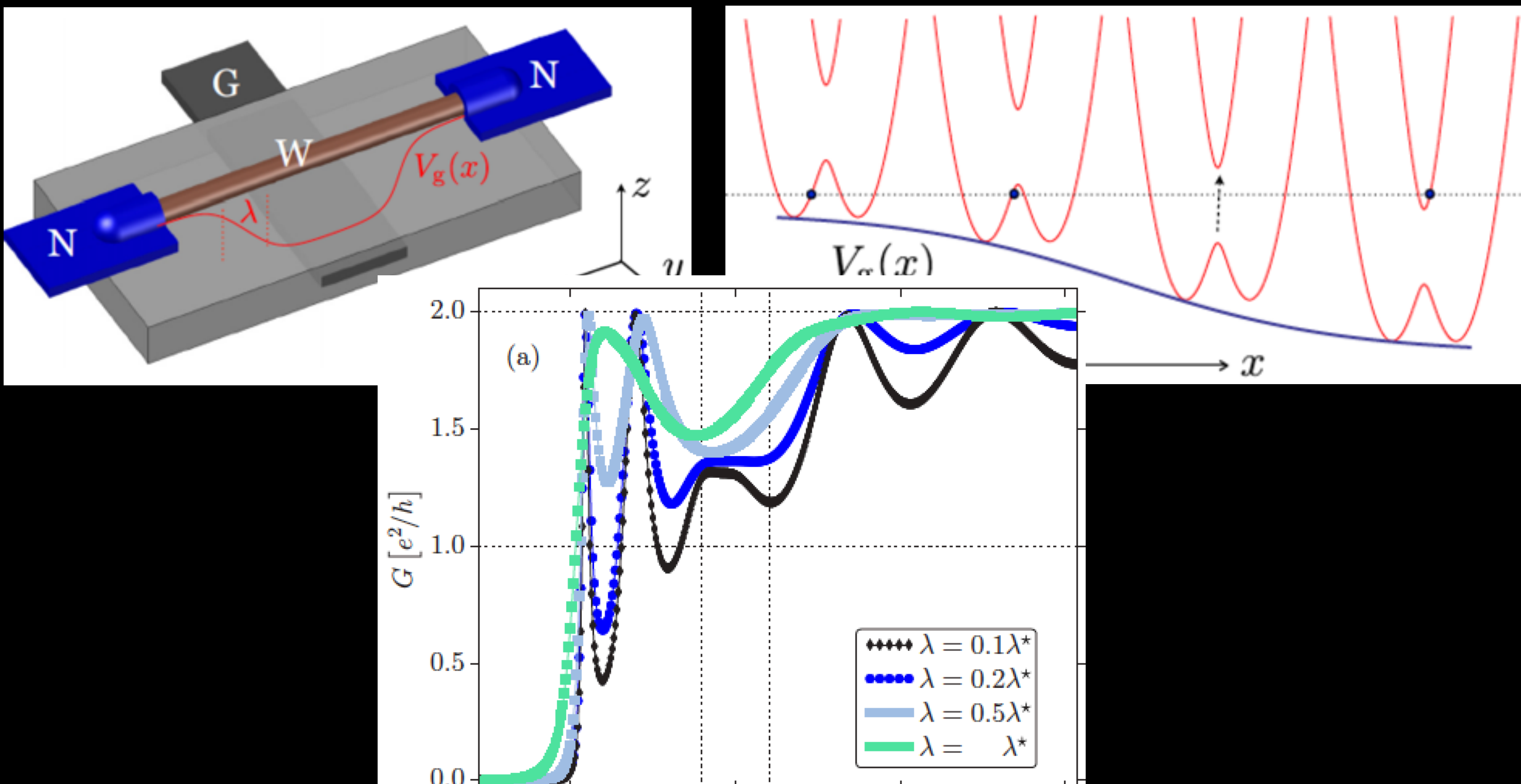
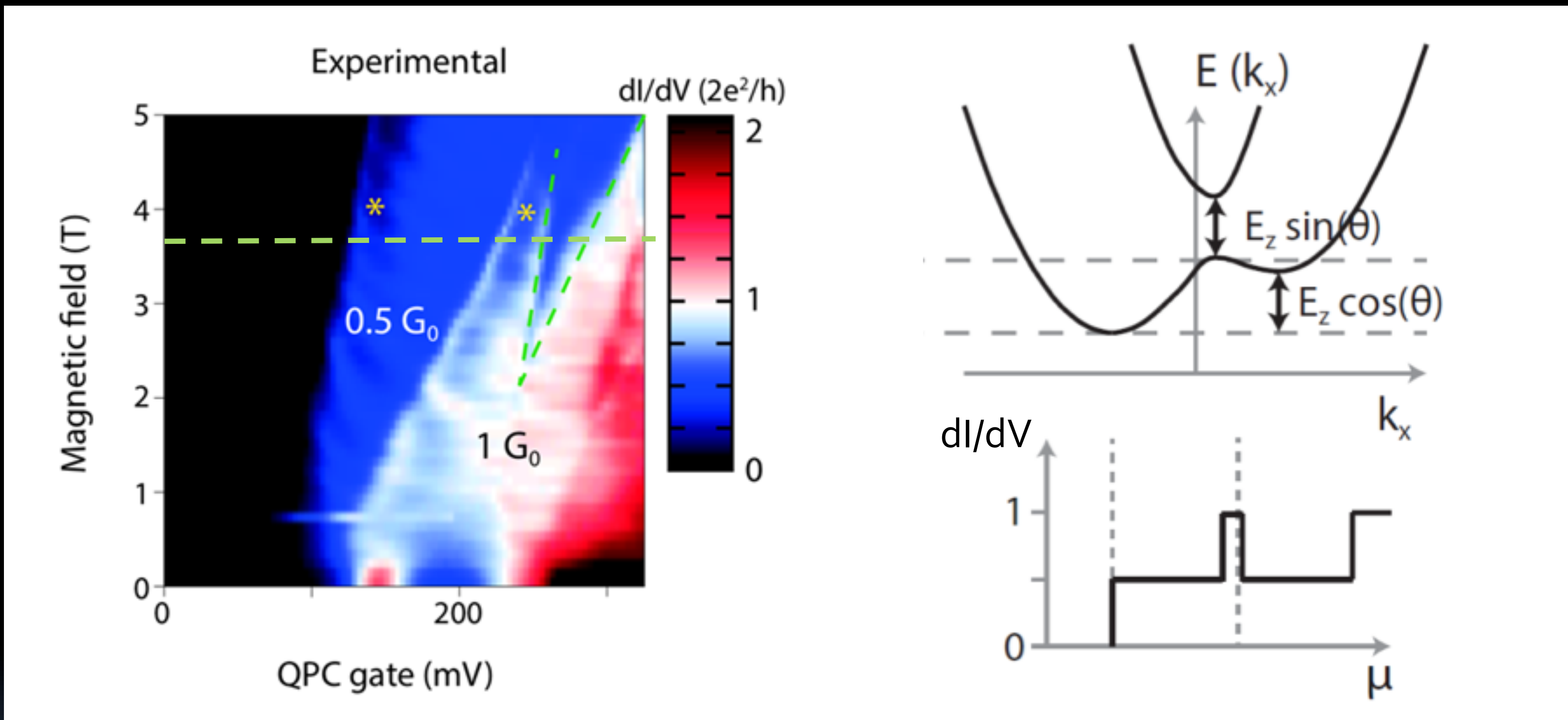
(Received 4 August 2014; revised manuscript received 14 October 2014; published 5 December 2014)

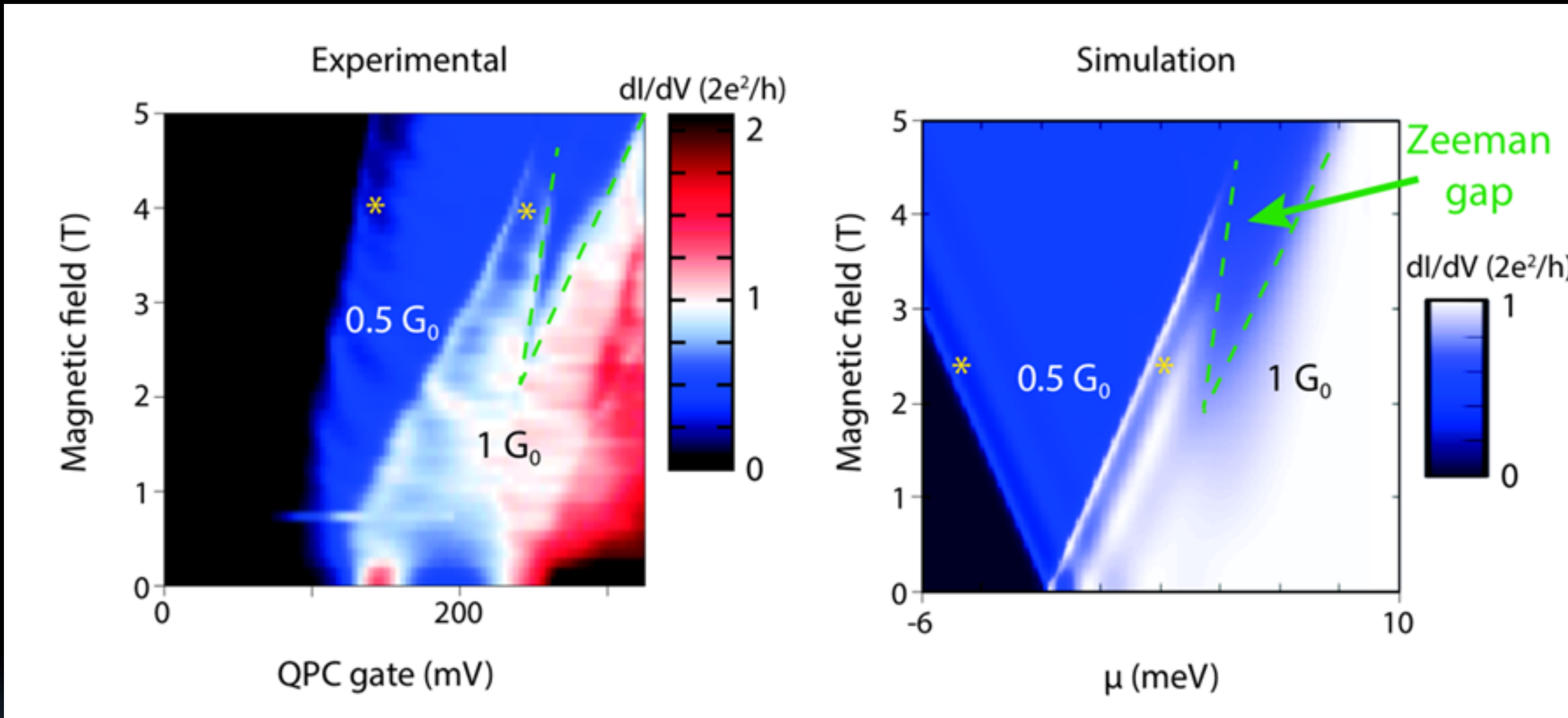


Spin-orbit interaction, helical gap



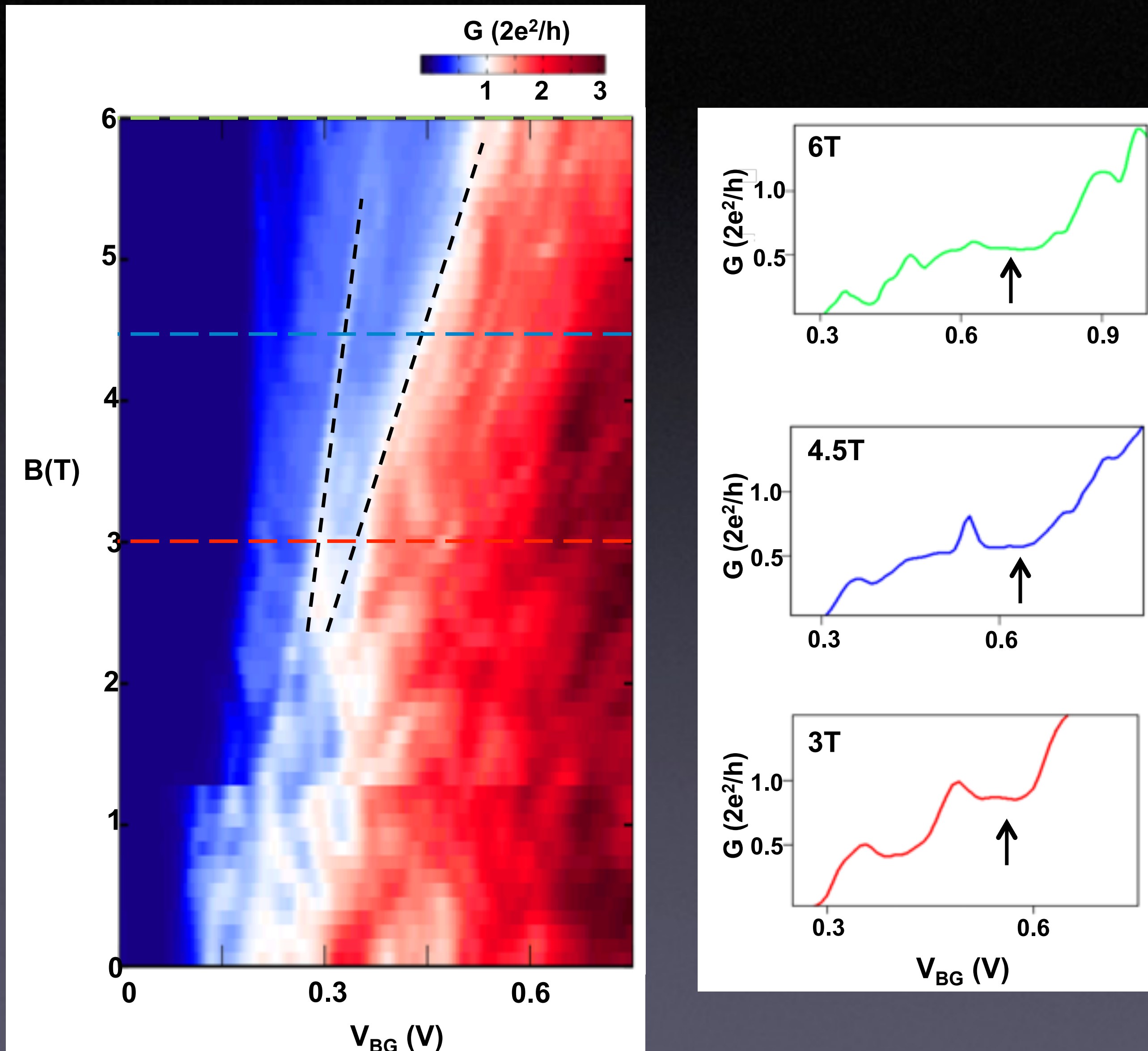
Spin-orbit coupling from helical gap :
$E_{SO} = 1 \ldots 4\ meV = 10 \ldots 40\ K$ on multiple devices

Spin-orbit interaction, helical gap

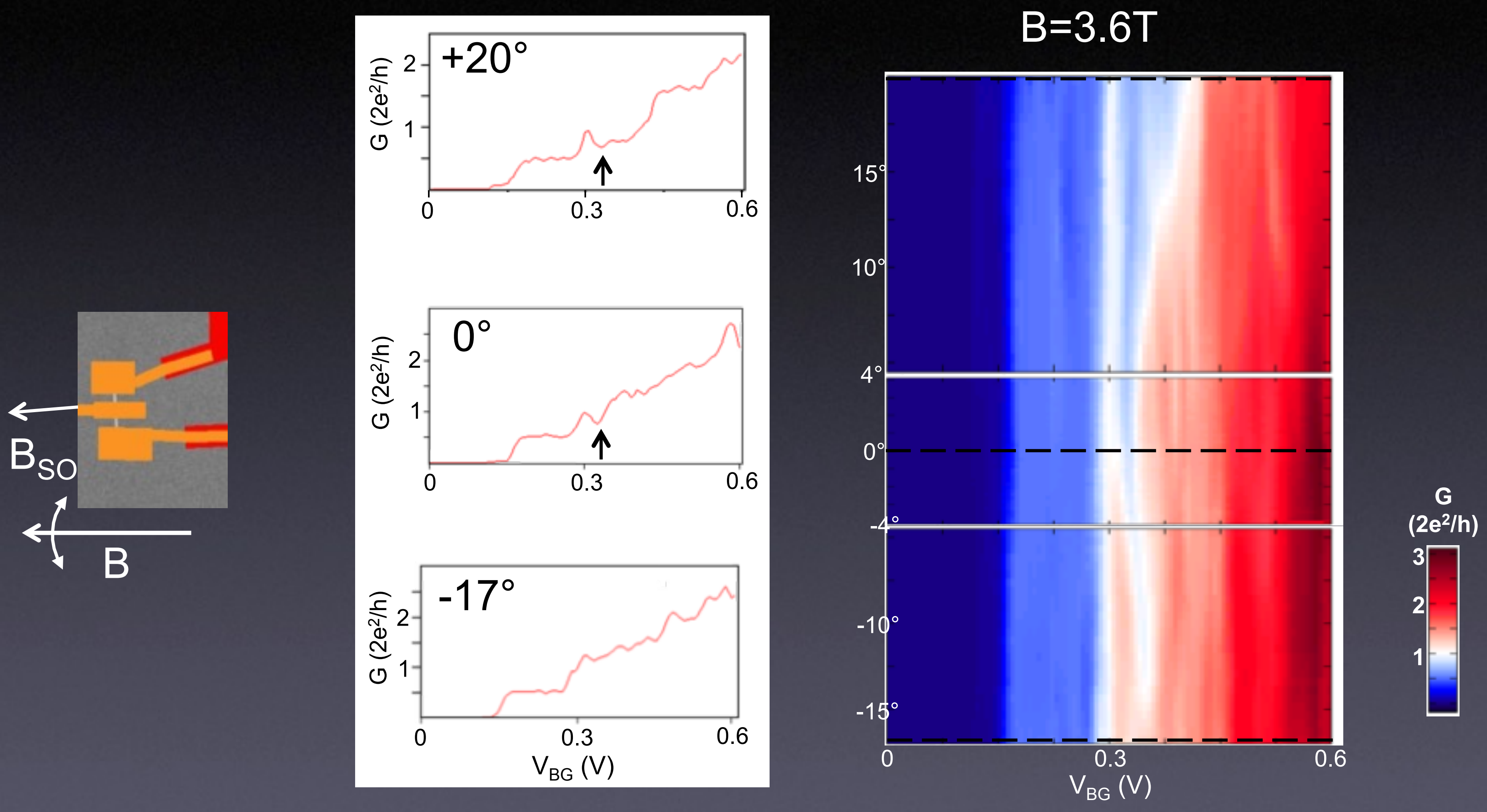


theory and simulation by Michael Wimmer,
preliminary data

Spin-orbit coupling from helical gap :
$E_{SO} = 1 \ldots 4\ meV = 10 \ldots 40\ K$ on multiple devices



G (2e²/h)
1 2 3
6
5
4
B(T)
3
2
1
0
0 0.3 0.6
V_BG (V)
6T
4.5T
3T
G (2e²/h)
1.0
0.5
0.3 0.6 0.9
V_BG (V)



B=3.6T
B
SO
B
+20°
0°
-17°
G (2e²/h)
V
BG
(V)
0
0.3
0.6
15°
10°
4°
0°
-4°
-10°
-15°
G
(2e²/h)
3
2
1

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Spin-orbit interaction in InSb nanowires

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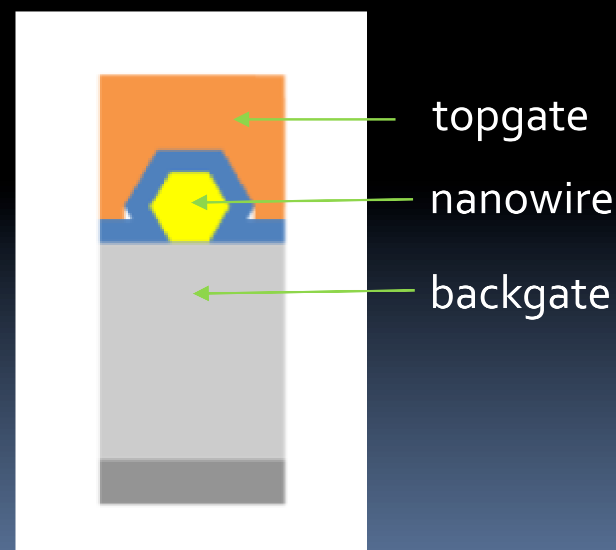
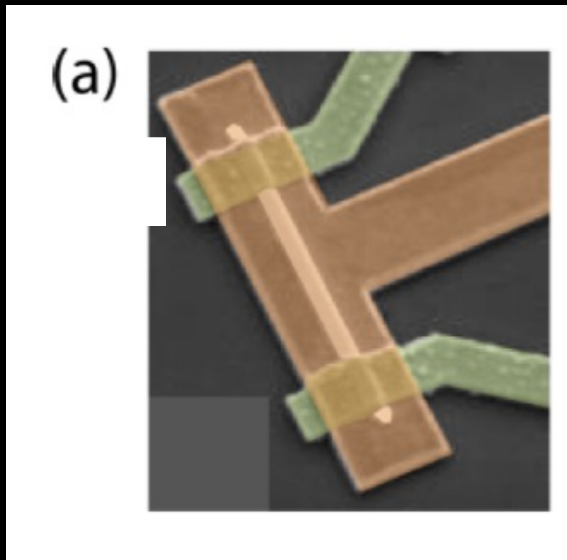
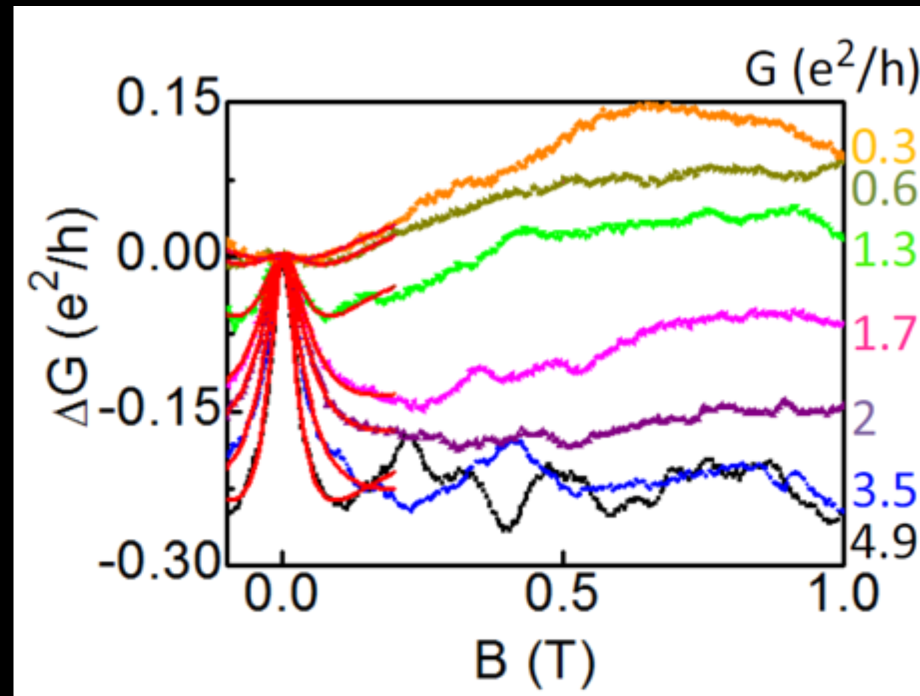
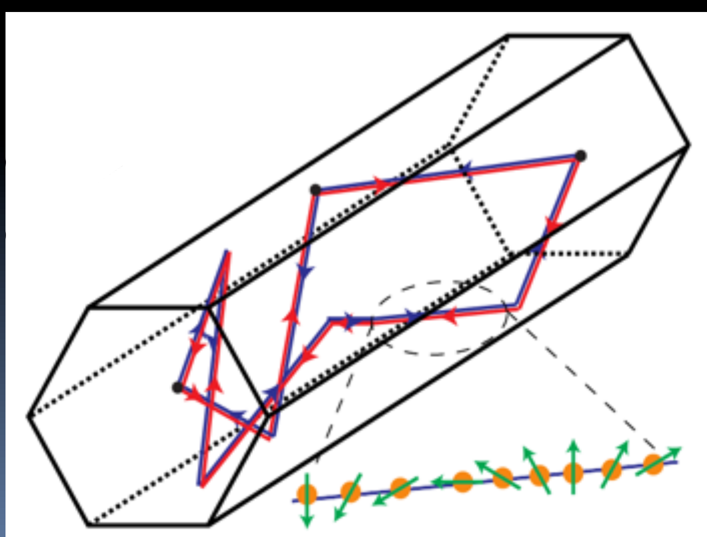
We use magnetoconductance measurements in dual-gated InSb nanowire devices, together with a theoretical analysis of weak antilocalization, to accurately extract spin-orbit strength. In particular, we show that magnetoconductance in our three-dimensional wires is very different compared to wires in two-dimensional electron gases. We obtain a large Rashba spin-orbit strength of 0.5–1 eV Å corresponding to a spin-orbit energy of 0.25–1 meV. These values underline the potential of InSb nanowires in the study of Majorana fermions in hybrid semiconductor-superconductor devices.



Spin-orbit interaction, W(A)L data





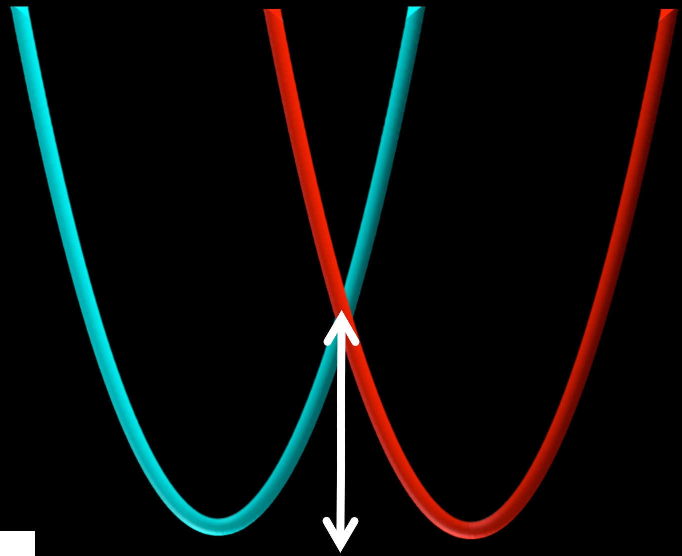


Spin-orbit coupling from magnetoconductance:
$E_{SO} = 0.25 \ldots 1\ meV = 3K \ldots 10K$

Strength spin-orbit interaction

$$E_{so} = \frac{\hbar^2}{2m\lambda_{so}^2} \approx 1meV$$

$$\lambda_{so} = \frac{1}{k_{so}} = \frac{\hbar^2}{\alpha m} \approx 50nm$$

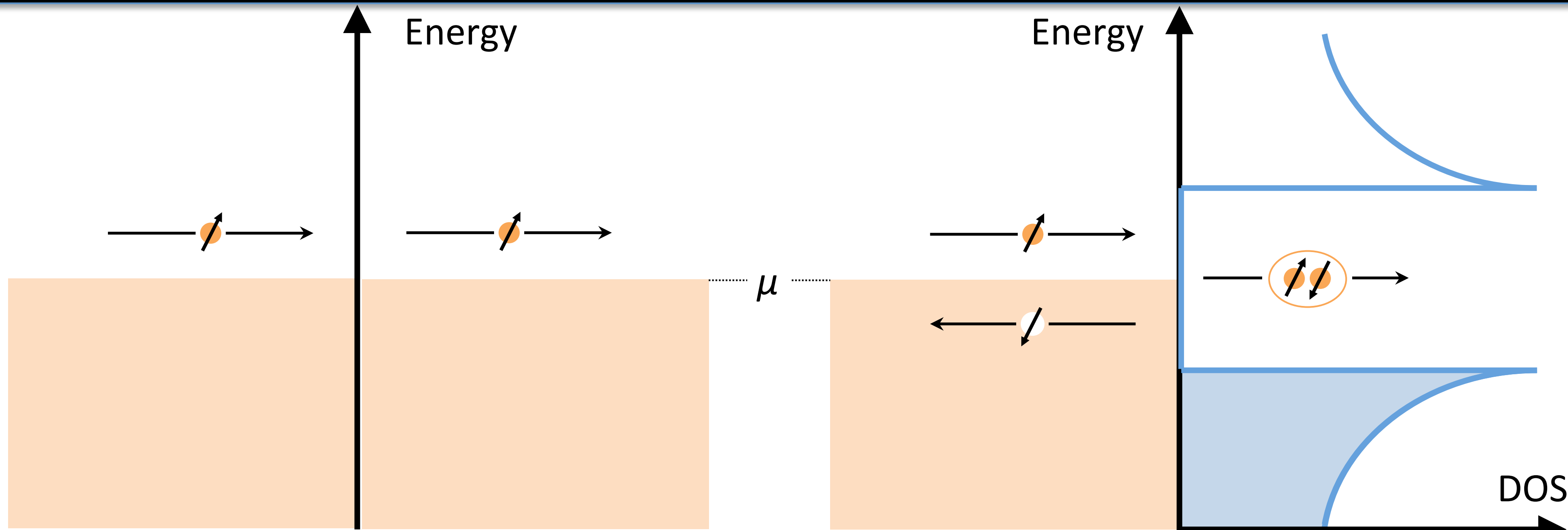


$E_{so} \sim E_Z$ @ 1T ~ 10 Kelvin

ANDREEV

normal - normal interface

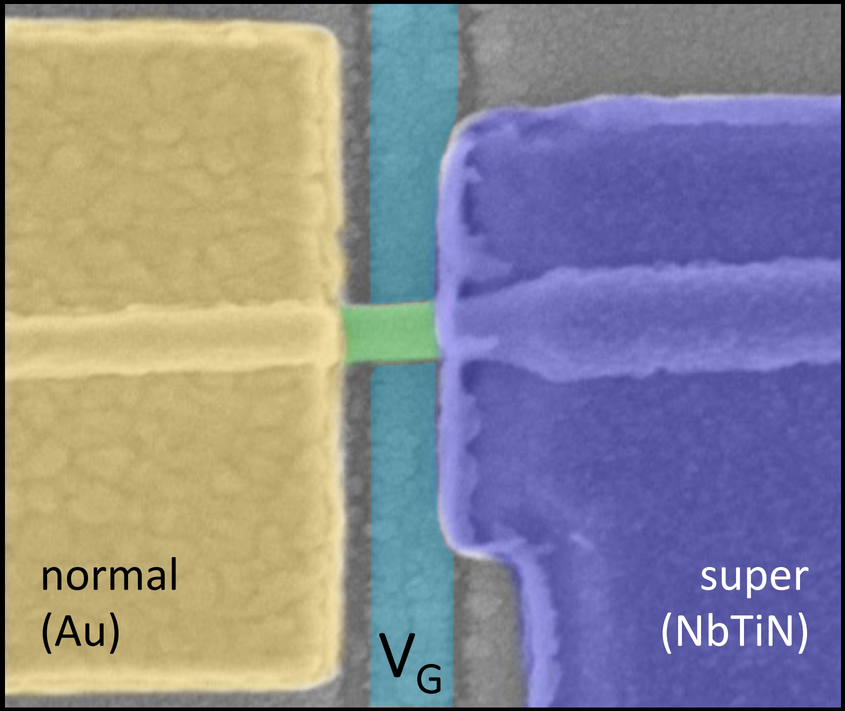
normal - superconductor interface

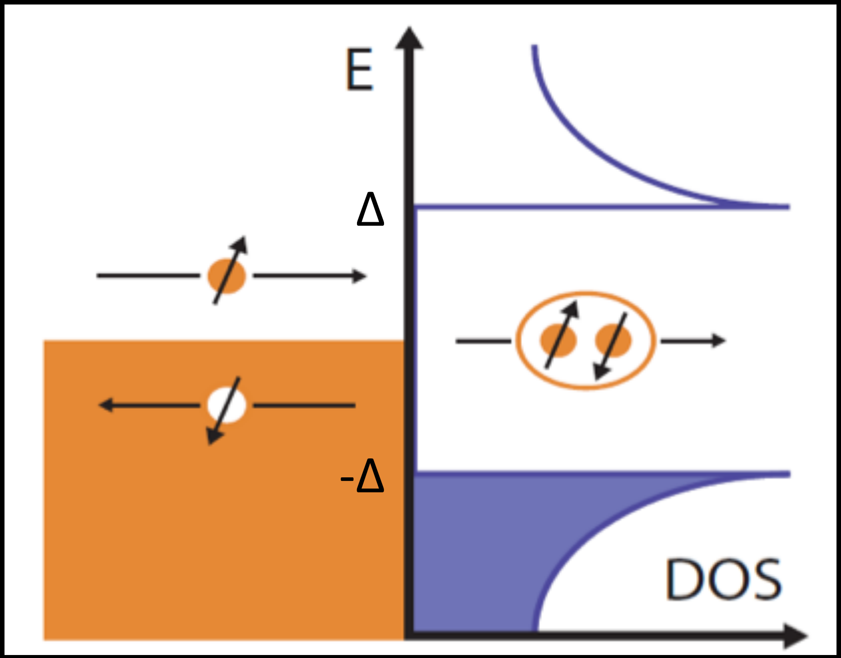


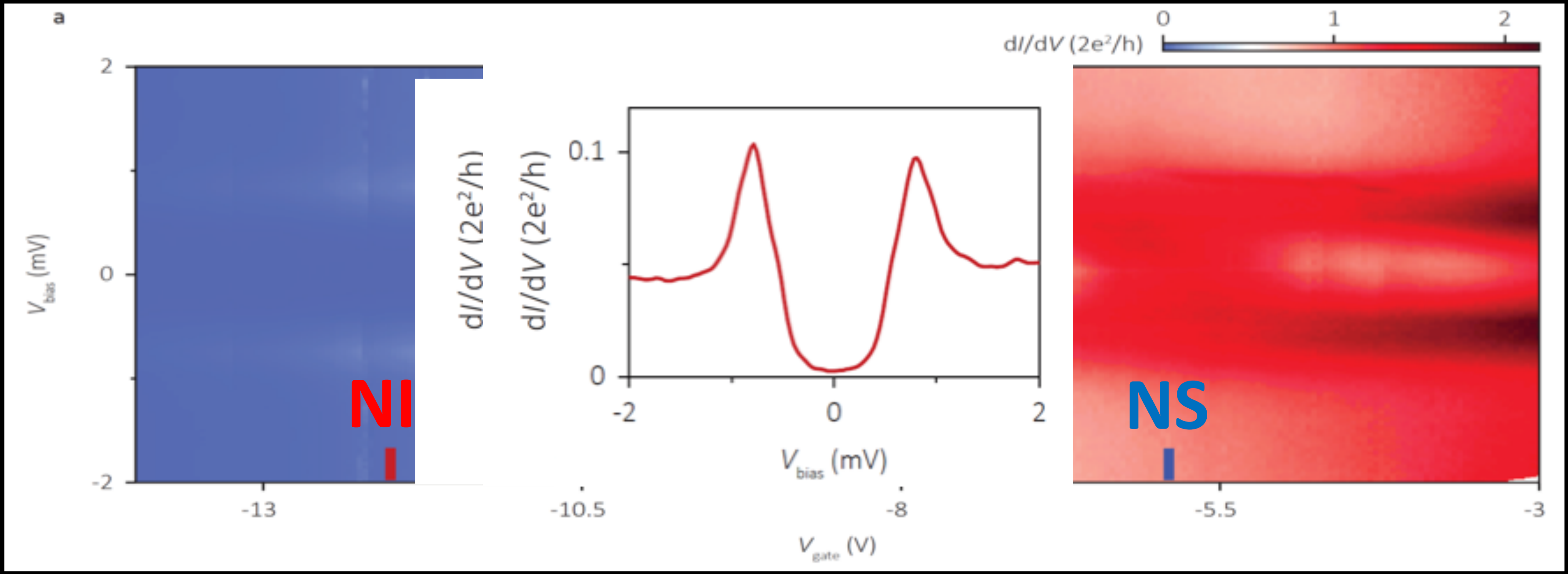
single 1D subband and $T = 1$:

$dI/dV = 2e^2/h$

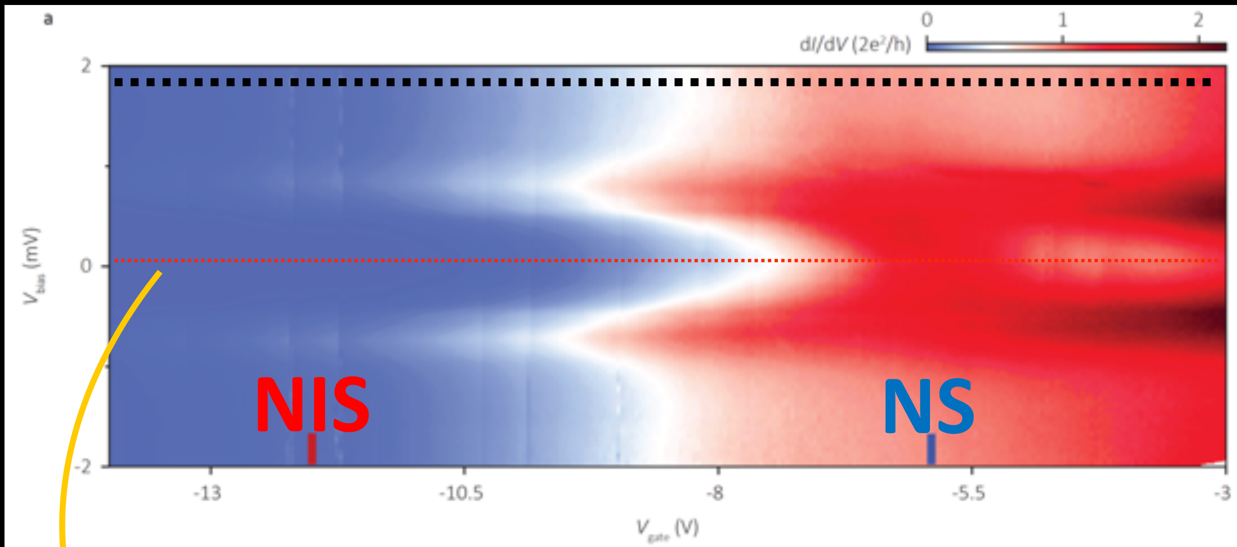
$dI/dV = 4e^2/h$

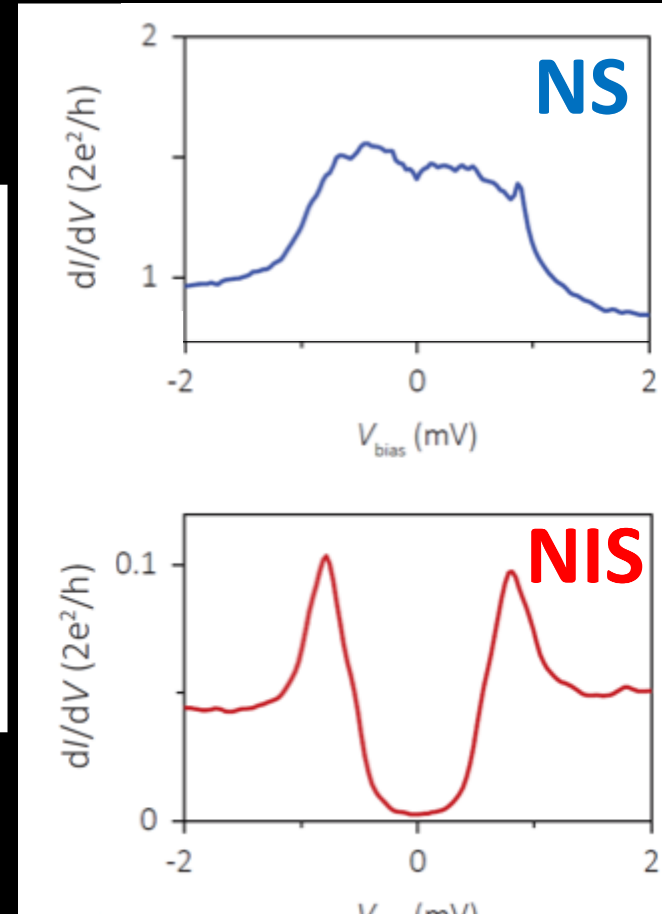

normal
(Au)
V_G
super
(NbTiN)


E
Δ
-Δ
DOS

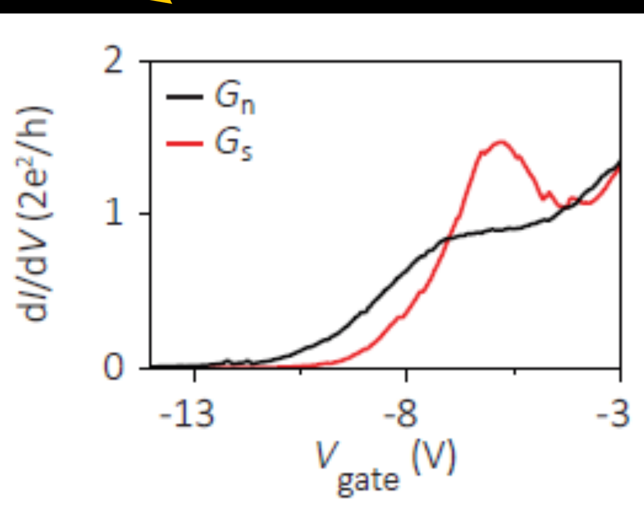

a
dI/dV (2e²/h)
0
1
2
V_{bias} (mV)
NI
NS
dI/dV (2e²/h)
0.1
0
-2
0
2
V_{bias} (mV)
-13
-10.5
-8
-5.5
-3
V_{gate} (V)

enhancement & *hard*-gap



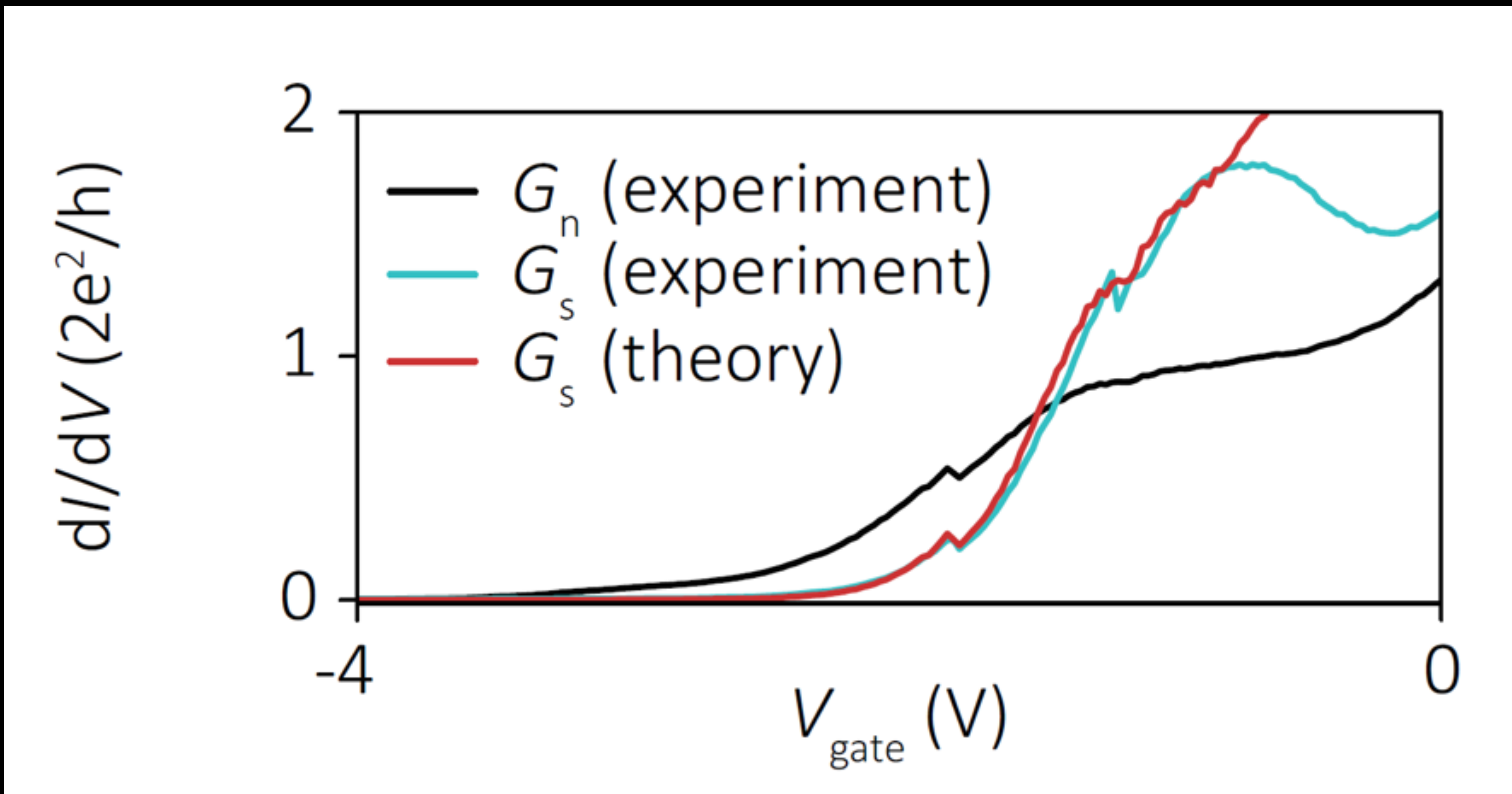


quantized plateaus

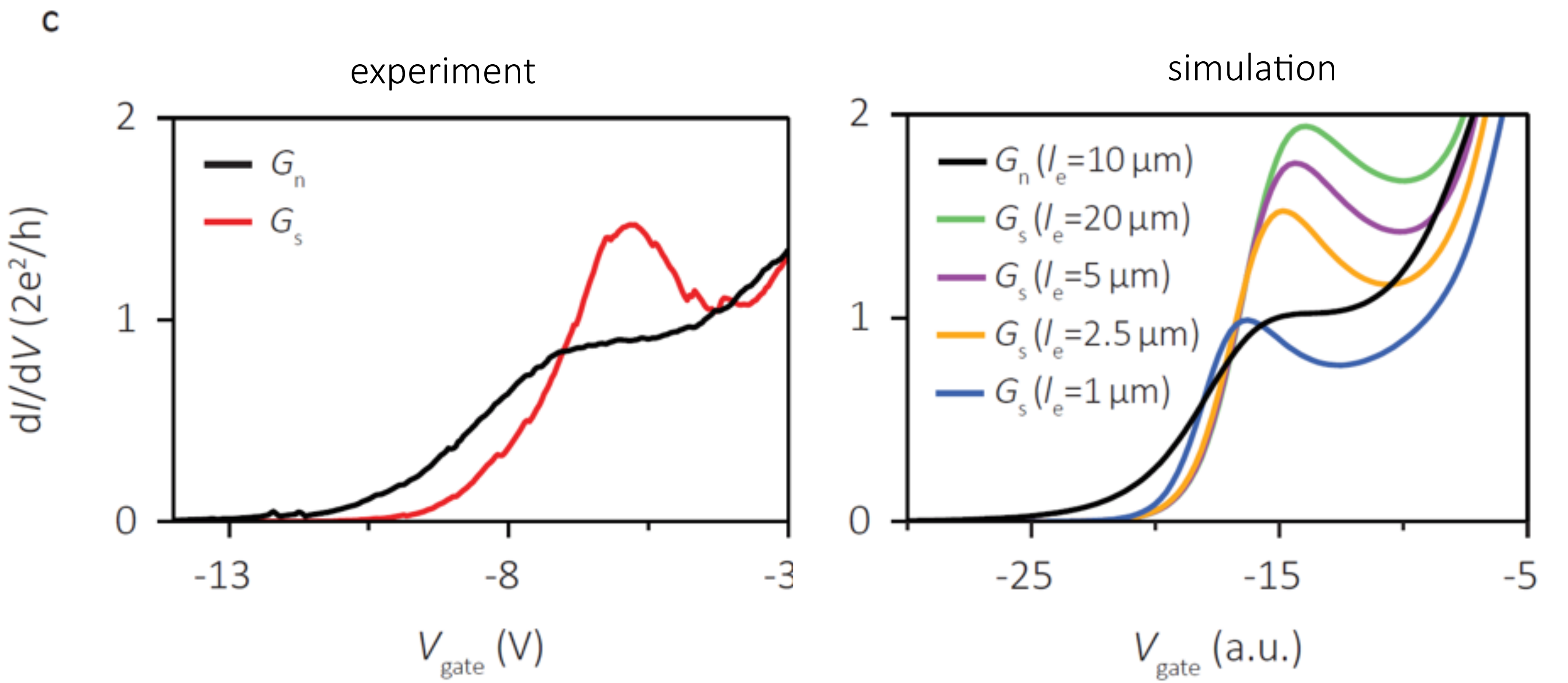


theory: $G_s = 4e^2/h \; G_n^2 / (2-G_n)^2$

Beenakker *PRB* (1992)

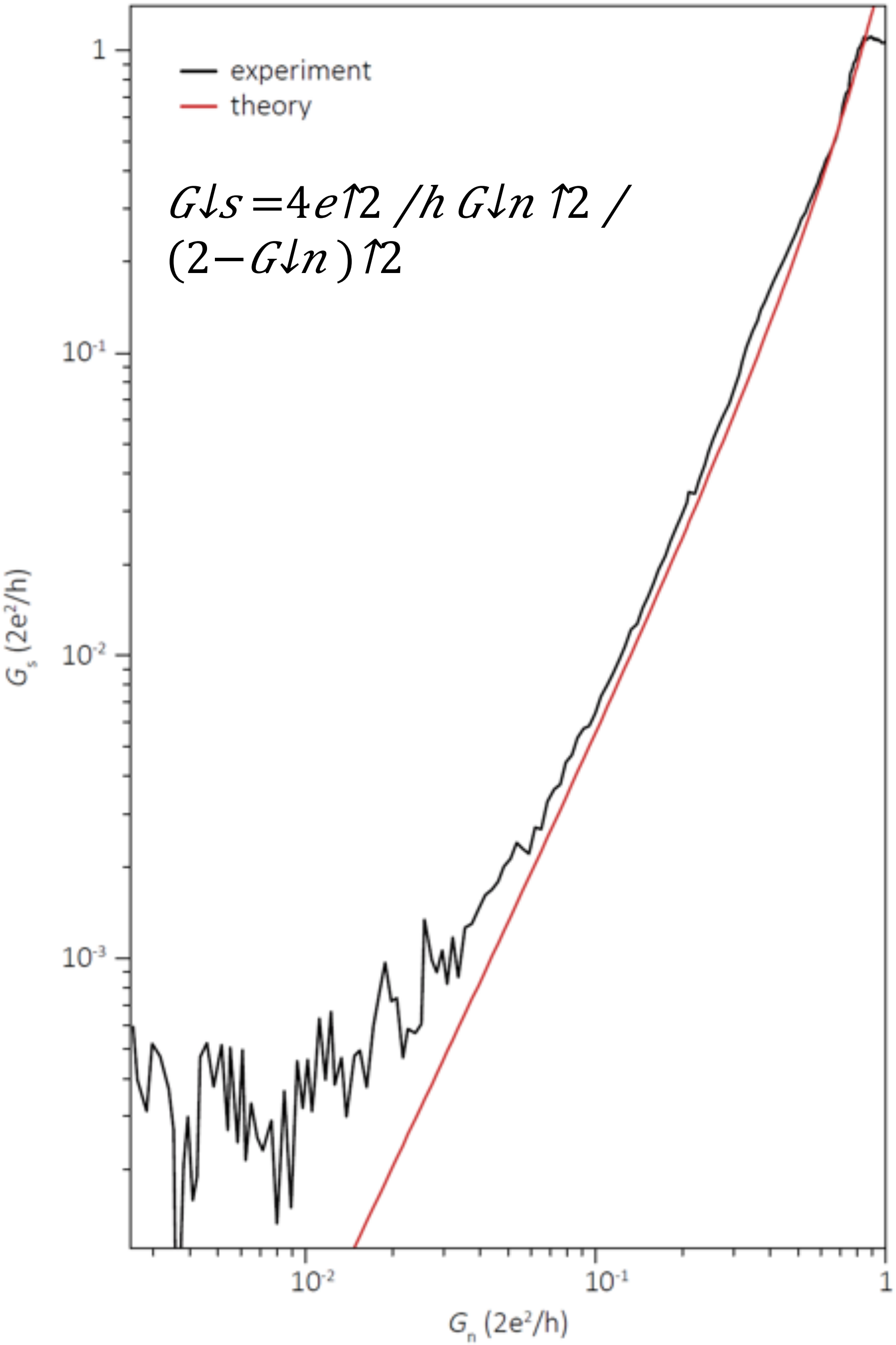


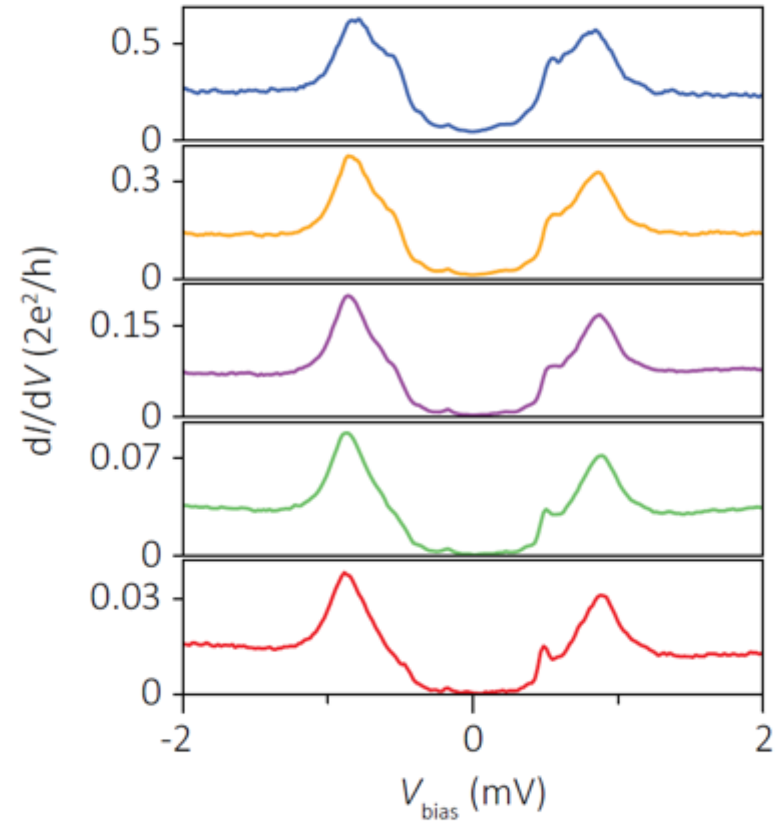
Comparison to numerics (Michal Nowak, KWANT)



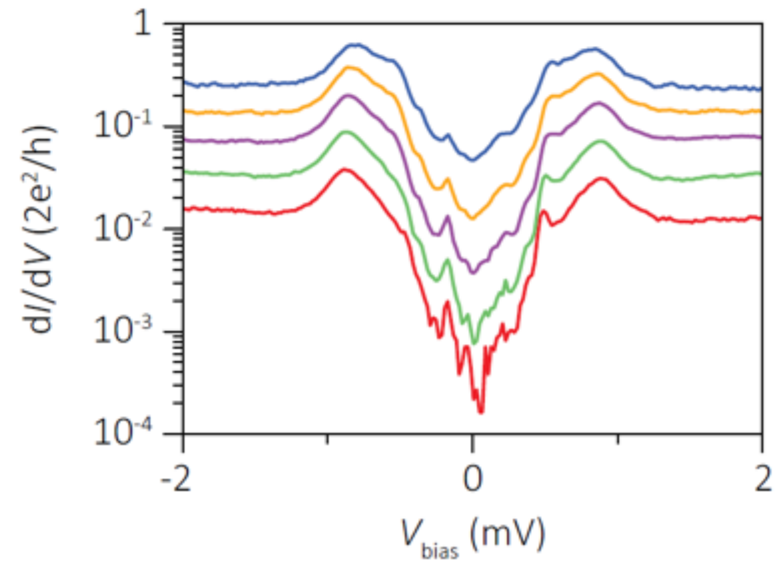
l_e ~ few micron => ballistic Andreev transport

b


experiment
theory
G↓s =4e↑2 /h G↓n ↑2 /
(2−G↓n)↑2
1
10⁻¹
10⁻²
10⁻³
G_s (2e²/h)
10⁻²
10⁻¹
1
G_n (2e²/h)


0.5
0
0.3
0
0.15
0
0.07
0
0.03
0
dI/dV (2e²/h)
-2
0
2
V_bias (mV)

d


1
10⁻¹
10⁻²
10⁻³
10⁻⁴
dI/dV (2e²/h)
-2
0
2
V_bias (mV)

SNS, Jo-FET & ABS

On-chip microwave spectroscopy of semiconductor nanowire Josephson junctions

David van Woerkom

Attila Geresdi, Alex Proutski
Daniel Bouman, Dominique Laroche
Leo Kouwenhoven

TU Delft — Delft University of Technology

TU/e — Technische Universiteit Eindhoven University of Technology

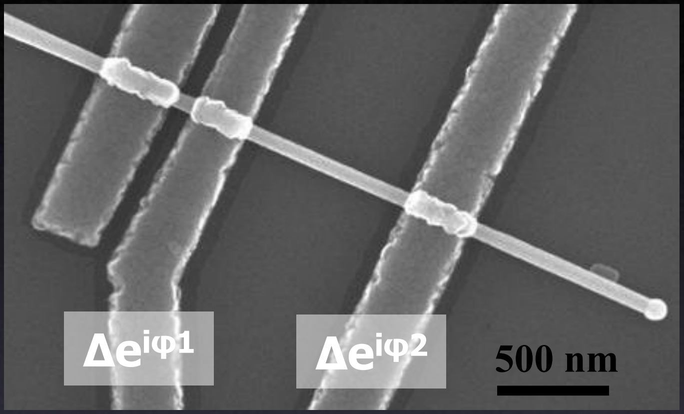
Diana Car, Sebastian Plissard,
Erik Bakkers

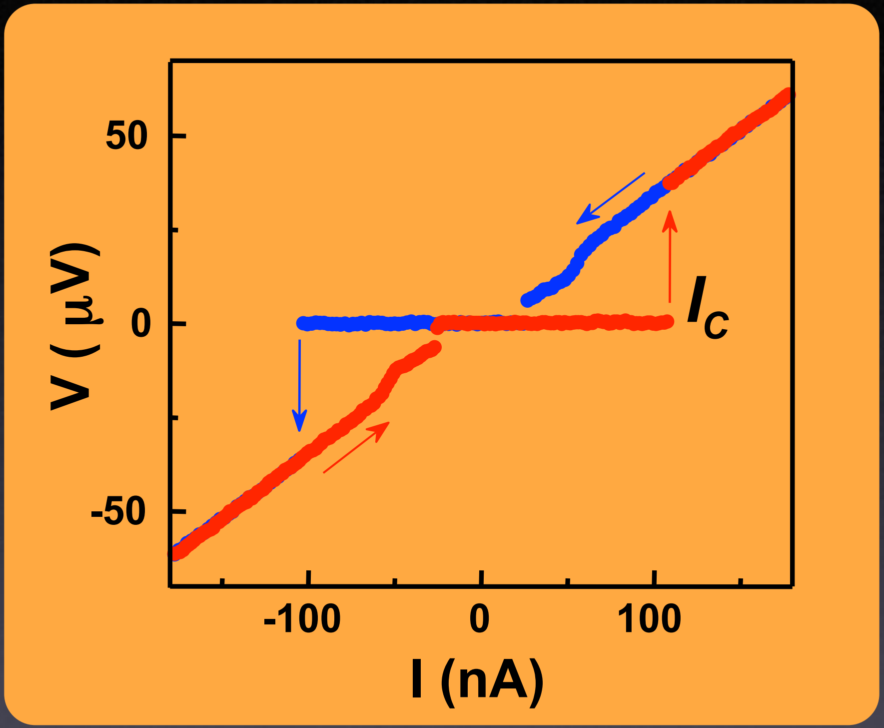
Peter Krogstrup, Mingtang Deng, Thomas Jespersen,
Jesper Nygard, Charles Marcus

Center for Quantum Devices

QuTech NWO FOM Microsoft KAVLI INSTITUTE of Nanoscience Delft

Superconductor-Semiconductor-Superconductor Josephson junctions





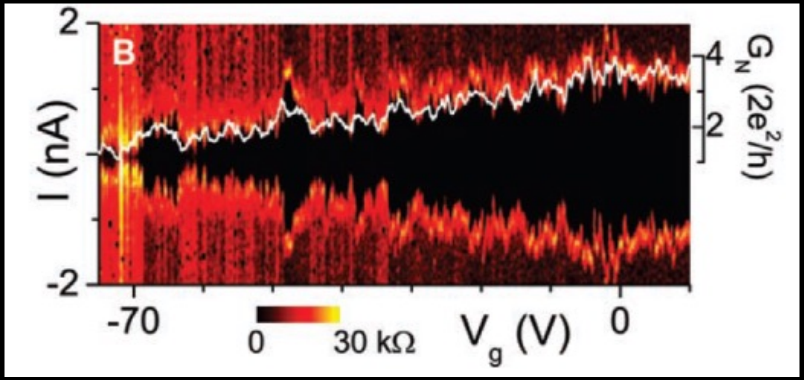
- InAs nanowires
- Ti/Al superconducting contacts
- Spacing ~< 800 nm
  → supercurrent

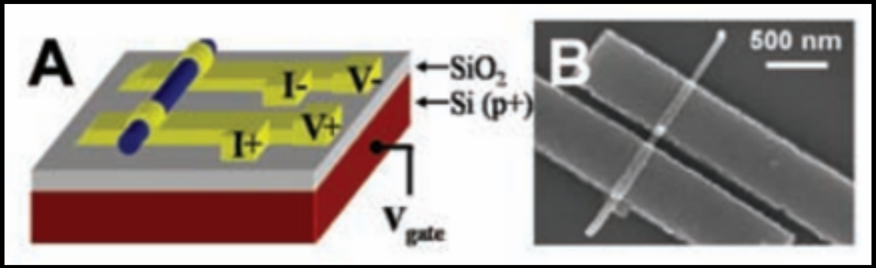
DC Josephson effect: $I_s = I_C \sin(\varphi_2 - \varphi_1)$

Science **309**, 272 (2005)
Nature **442**, 667 (2006)
Review Nature Nano 2010

SNS Josephson junction

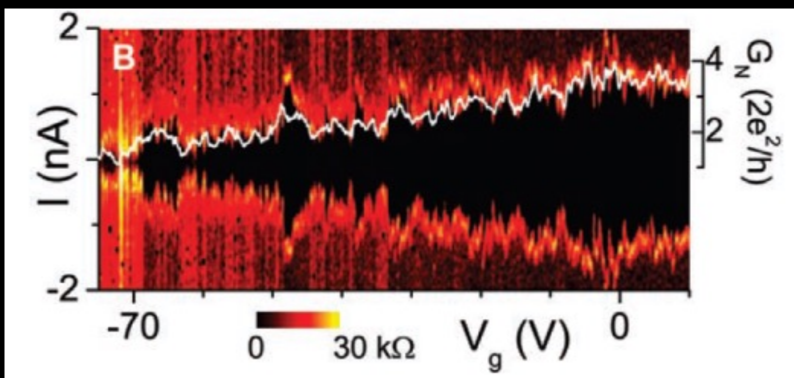
Doh et al, *Science*, **309**, 272 (2005)

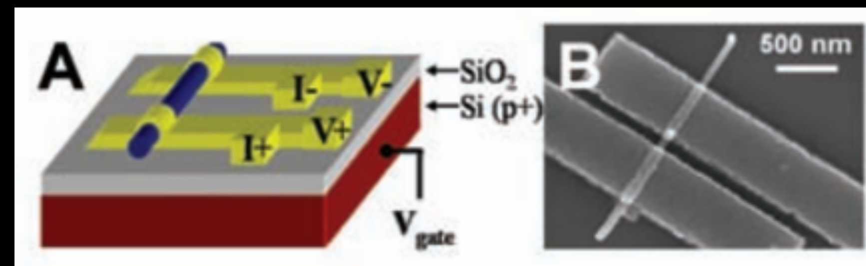


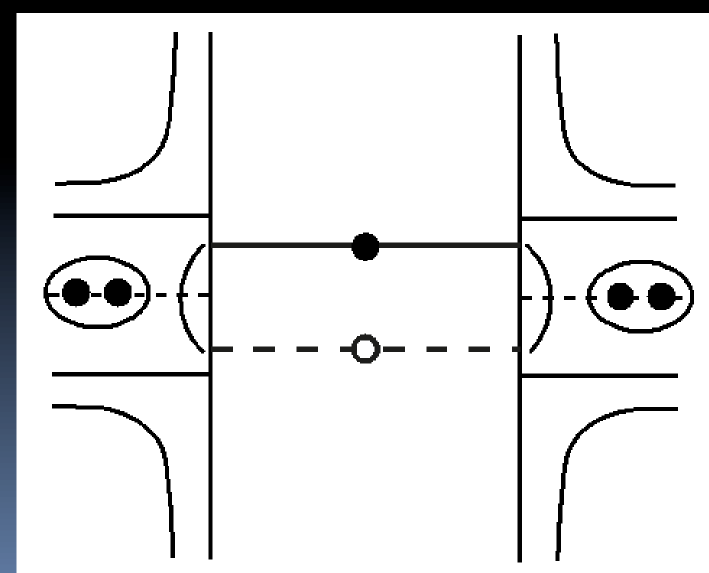


SNS Josephson junction

Doh et al, *Science*, **309**, 272 (2005)







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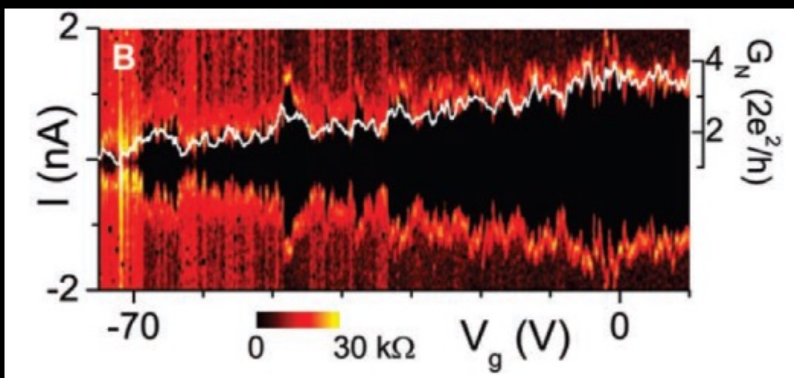
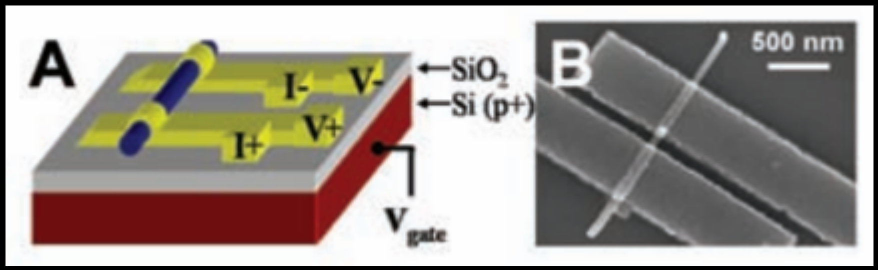
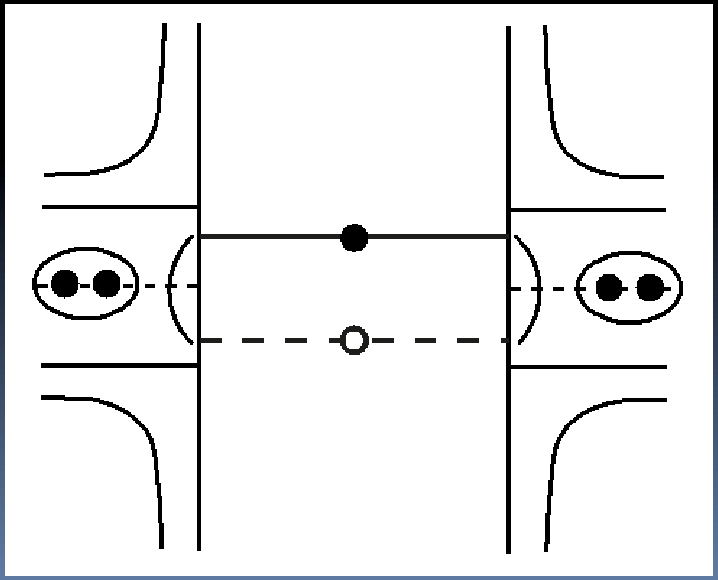


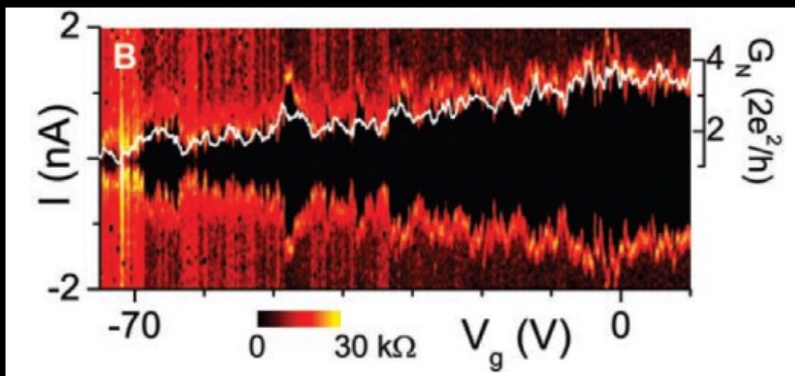


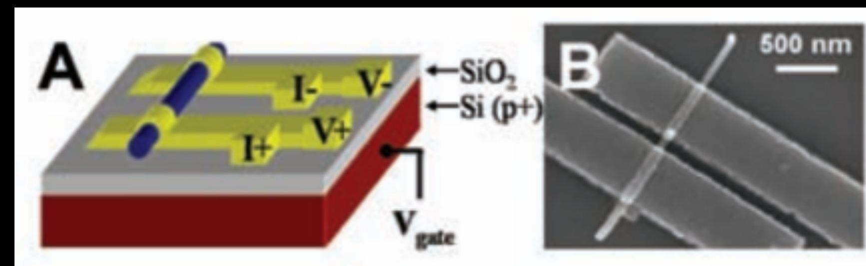
$$E_{ABS} = \pm\Delta\sqrt{1-\tau\sin^2 \varphi/2}$$



SNS Josephson junction

Doh et al, *Science*, **309**, 272 (2005)





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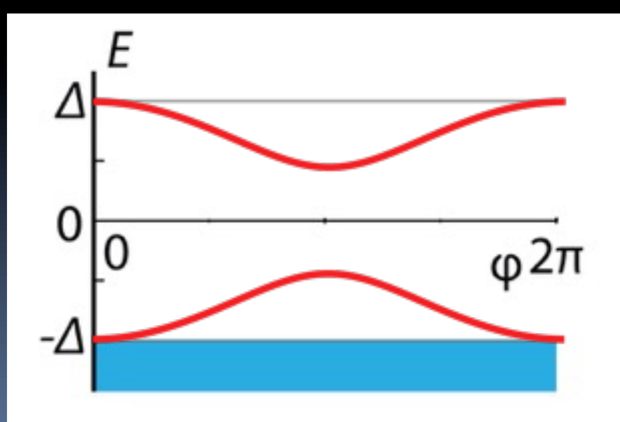

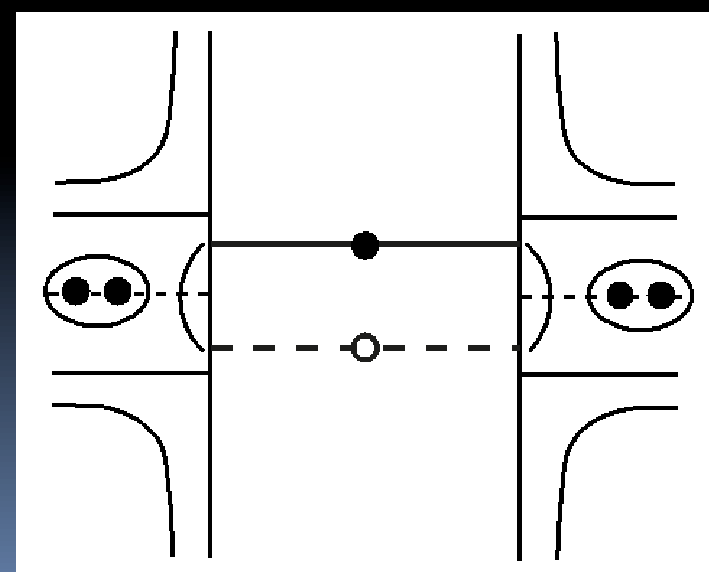

SNS Josephson junction

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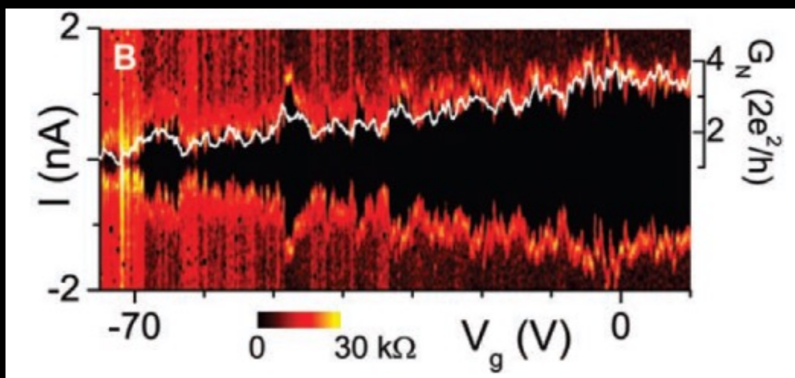

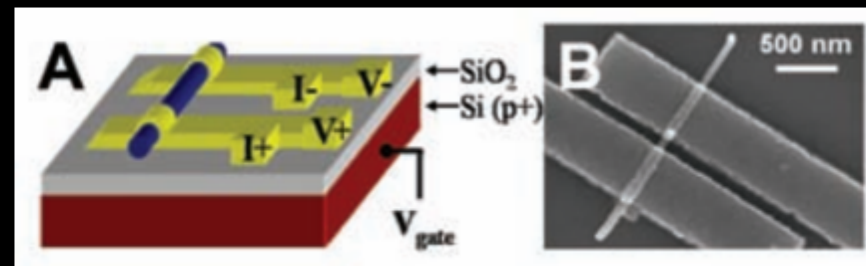

$E_{ABS} = \pm\Delta\sqrt{1-\tau\sin^2\varphi/2}$ → $I_s \sim \partial E_{ABS}/\partial\varphi$