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On the ballistic one-dimensional character of semiconductor nanostructures for Majorana fermions

EXP: JC Estrada Saldaña, JP Cleuziou, EJH Lee, R. Mizokuchi, P. Torresani, S De Franceschi (*CEA)*

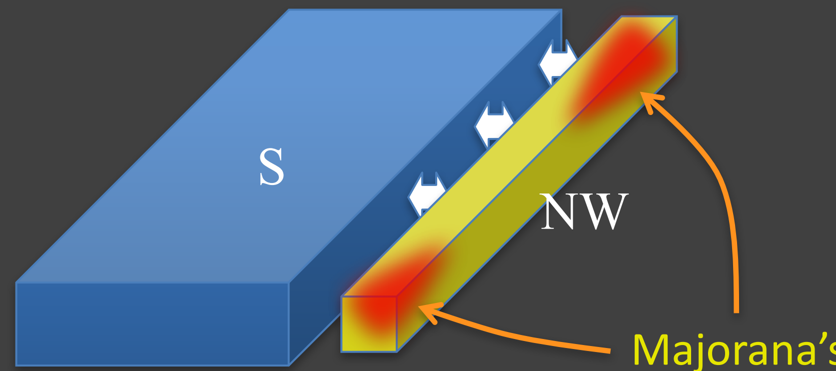
MATERIAL: *D. Ercolani, L. Sorba (NEST, Pisa);*
X Jiang, CM Lieber (*Harvard);*
D Car, E Bakkers (TU Eindhoven);
M. Myronov (Warwick)

THEORY : R Aguado (*CSIC Madrid), R Zikco (IJS);*
YM Niquet (CEA)

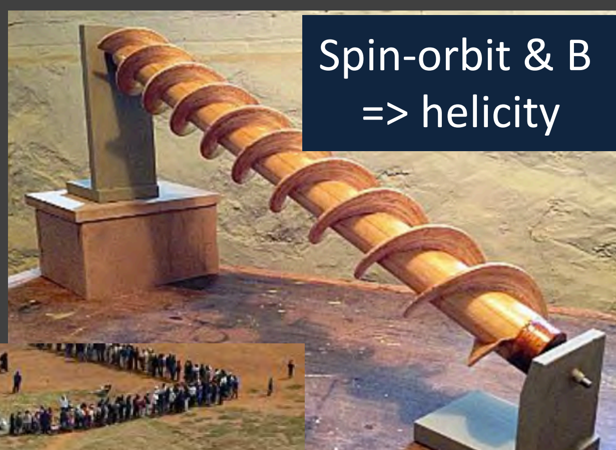
erc
MARIE CURIE ACTIONS
ANR

Majorana fermions in semiconductor nanowires

Lutchyn et al., PRL (2010)
Oreg et al., PRL (2010)



Key ingredients for Majorana edge states:

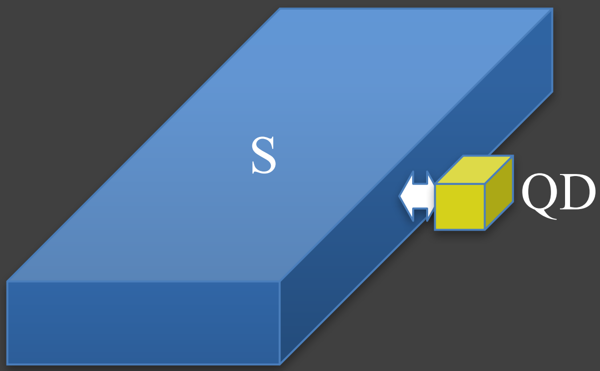


Outline

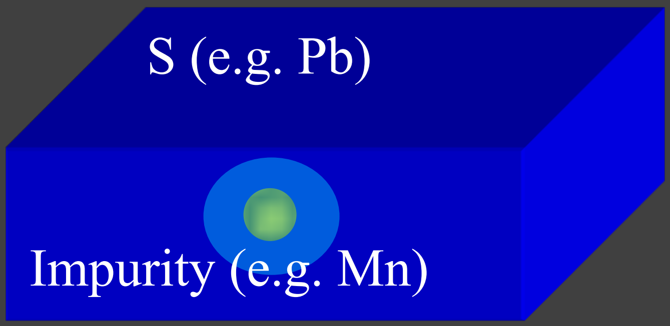
Superconducting proximity effect in:

- Strongly confined (0-D) quantum dot
- Quasi-ballistic (quasi 1D) junction

Quantum dot/impurity coupled to a superconductor

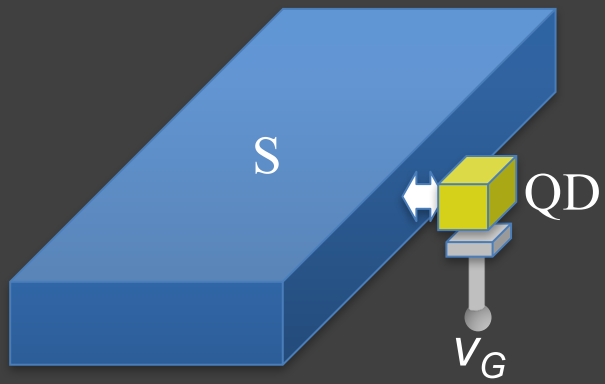


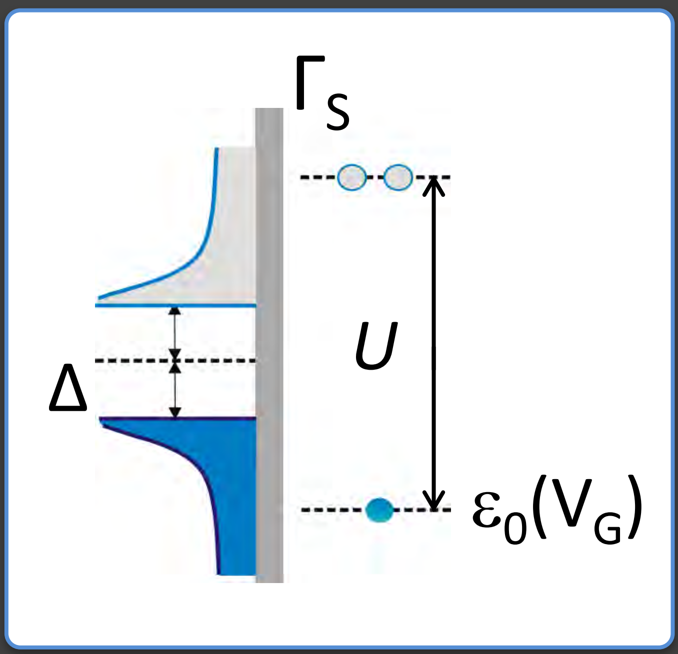
Glazman & Matveev, JETP Lett. (1989)
Vecino et al, PRB (2003)
Bauer et al., J. Phys. Cond. Matter (2007)
Meng et al., PRB (2009)
....



[see e.g. A. V. Balatsky, Rev. Mod. Phys. (2006)]

Quantum dot coupled to a superconductor





Simplest case (Anderson model):

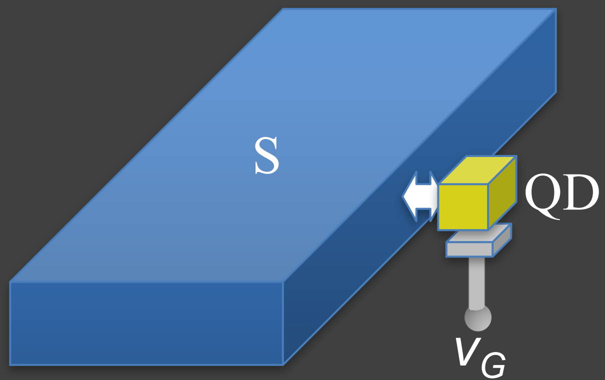
- Just **one** spin-degenerate level
- QD filling: N = 0, 1, or 2

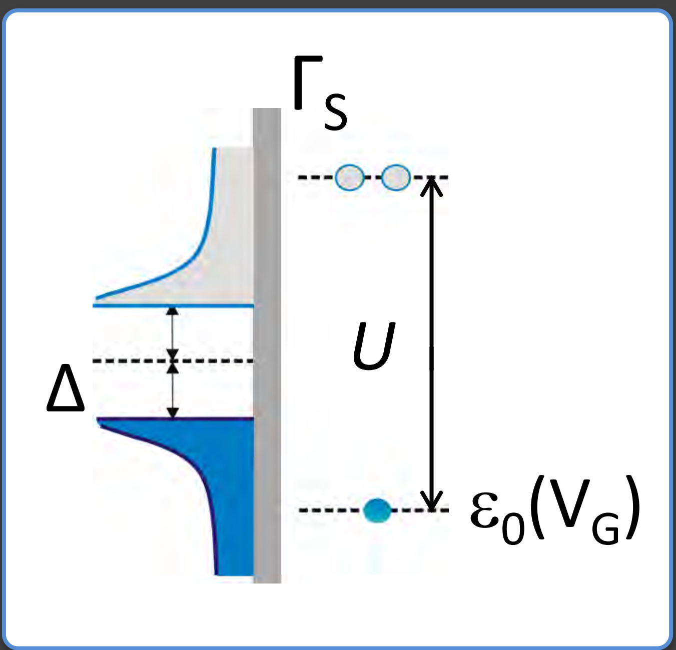
Relevant energy scales:

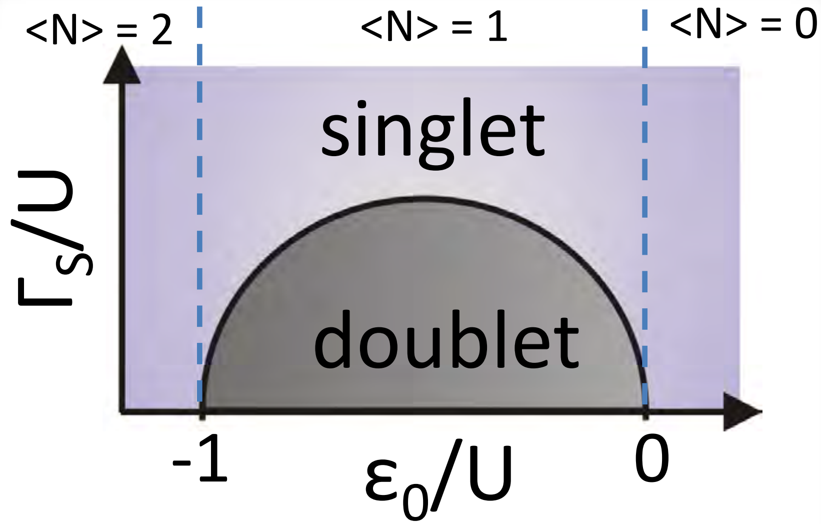
Δ, U, ε_0, Γ_S

- Δ → supercond. pairing correlations
- U → Single-electron charging
- ε_0 → Gate tunable
- Γ_S → charge fluctuations

Lowest-energy states and phase diagram







Possible ground states (large Δ limit):

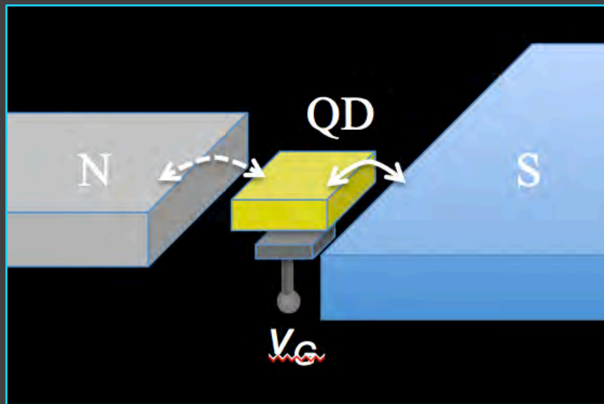
Spin doublet (odd)

$$|D\rangle = |\downarrow\rangle \; ; \; |\uparrow\rangle$$

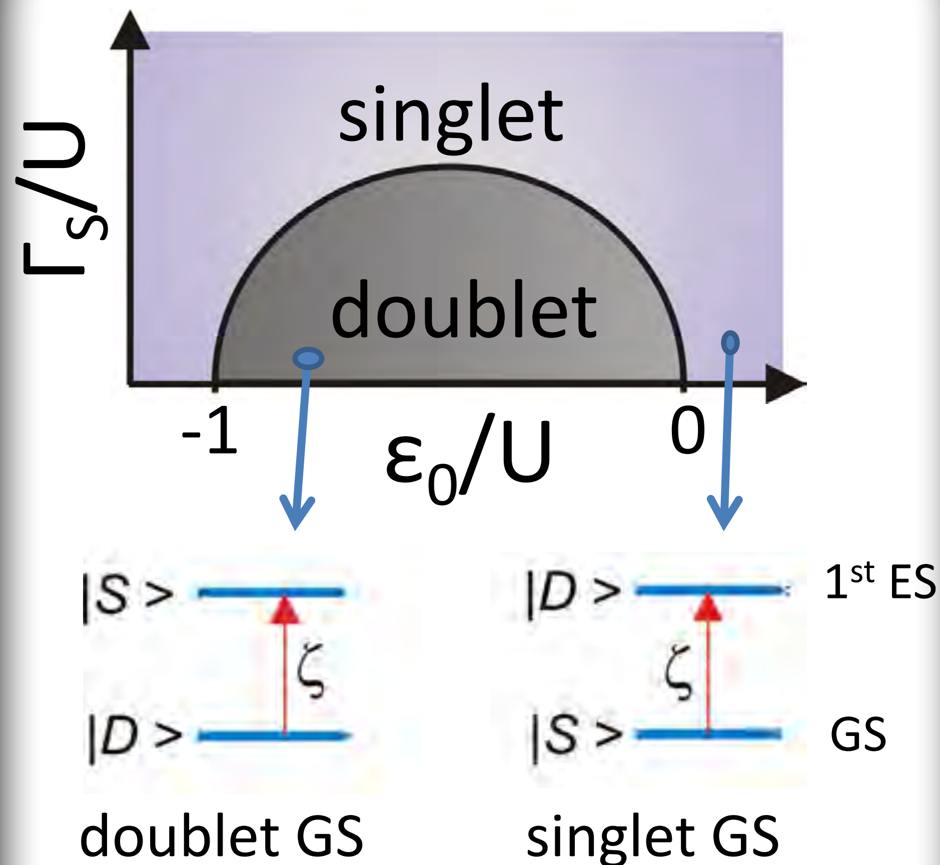
BCS-type spin singlet (even)

$$|S\rangle = -v^*|\uparrow\downarrow\rangle + u|0\rangle$$

Andreev levels as elementary sub-gap excitations



Tunnel spectroscopy of the Andreev levels

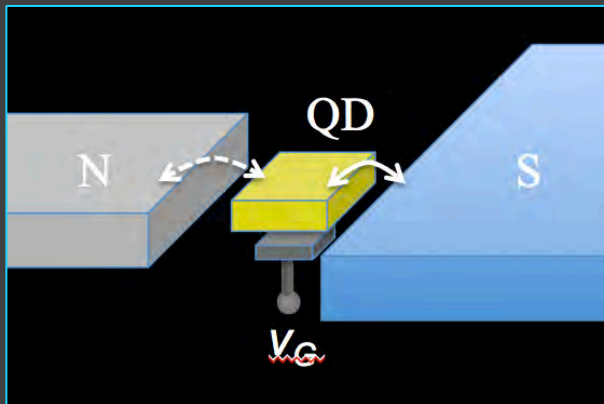


Excitations involve single charge fluctuations, i.e., odd -> even or vice-versa

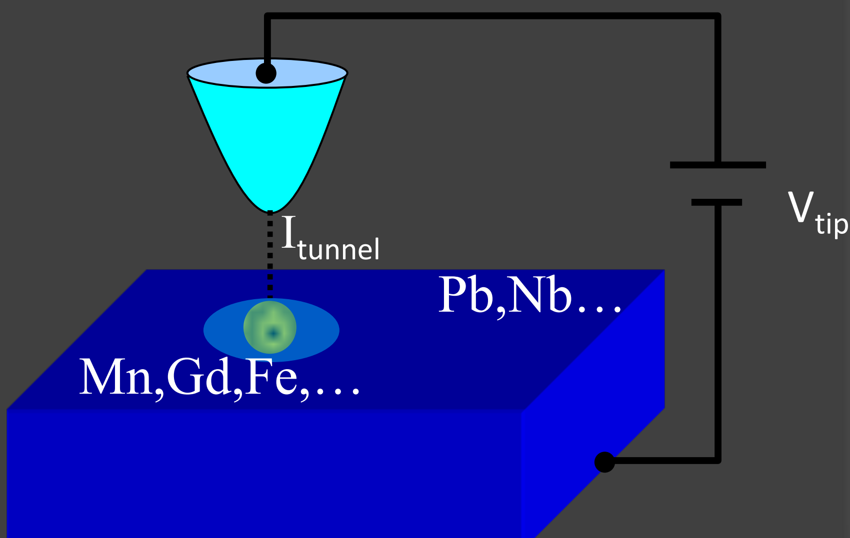
Related works on Andreev level spectroscopy:

Deacon et al., PRL (2010)
Pillet et al., Nature Phys. (2010), PRB (2013)
Dirks et al., Nature Phys. (2011)
Chang et al., PRL (2013)

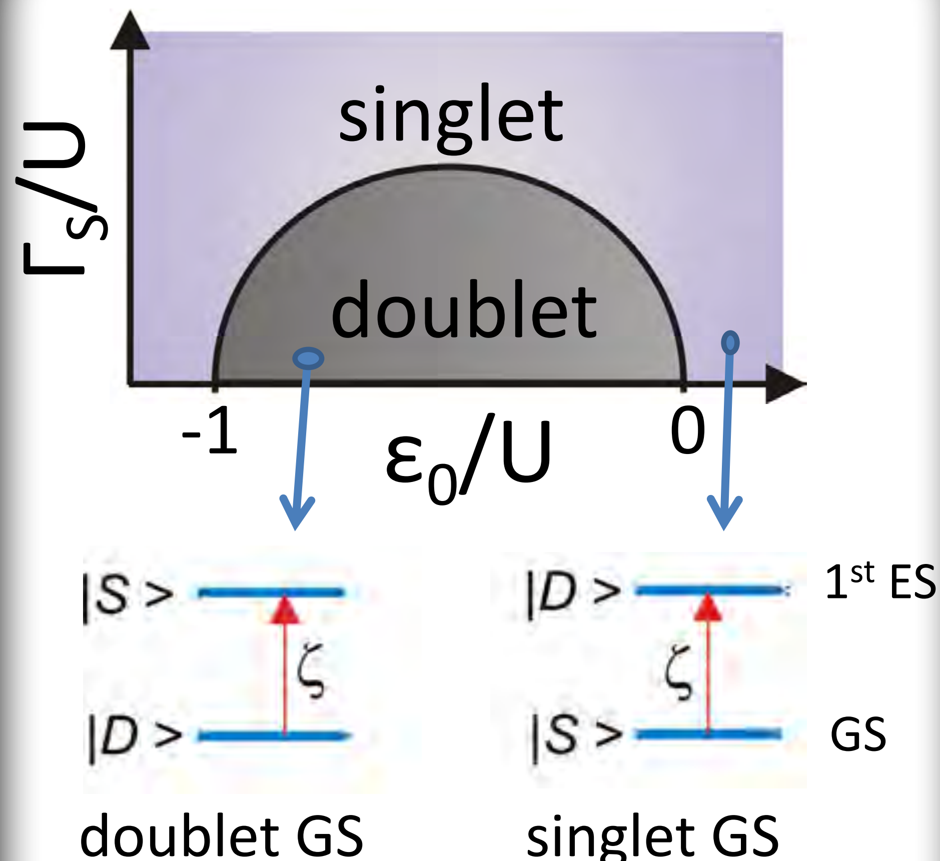
Andreev levels as elementary sub-gap excitations



Tunnel spectroscopy of the Andreev levels (or Yu-Shiba-Rusinov states)_

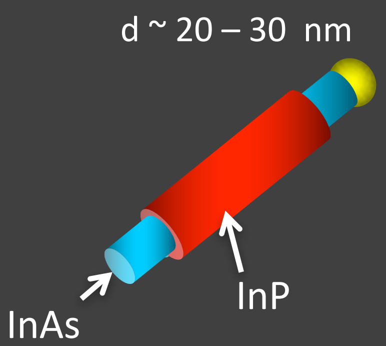


Yazdani et al. (1997), ..., Franke et al. (2011), ...

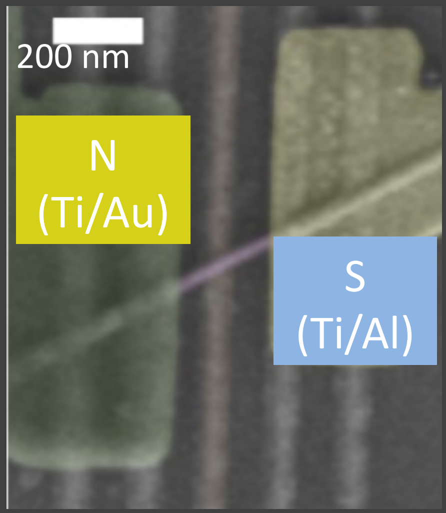


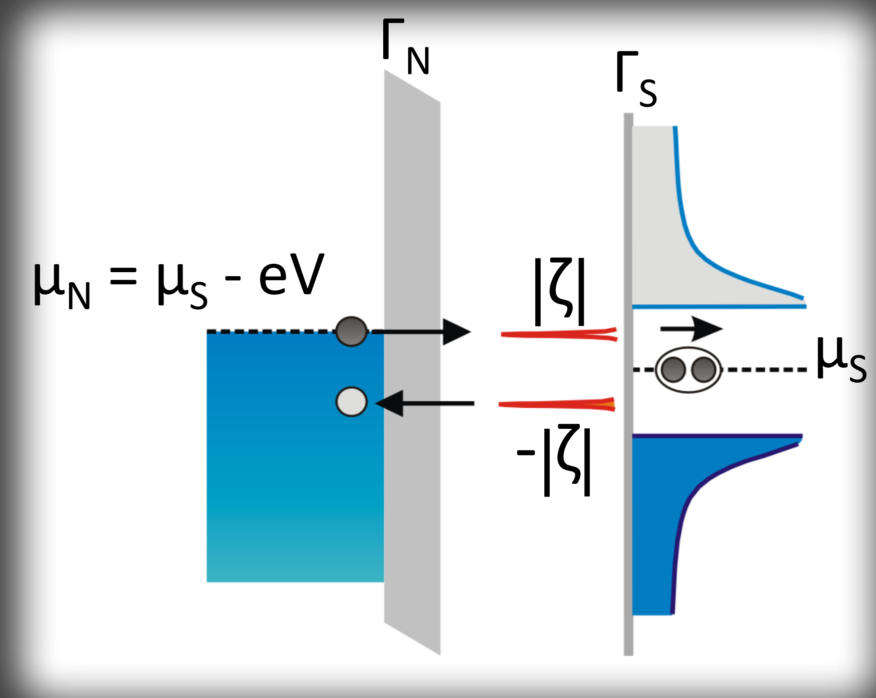
Excitations involve single charge fluctuations, i.e., odd -> even or vice-versa

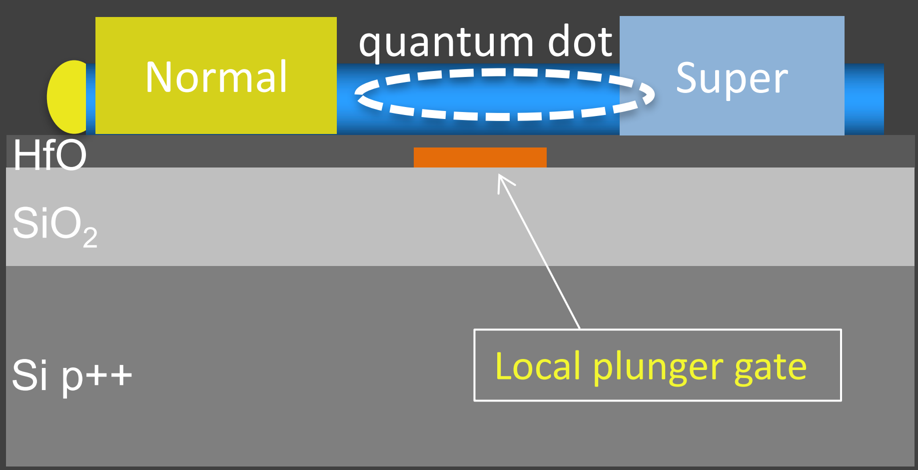
Our devices



InAs/InP core/shell nanowires
(Lieber's group)



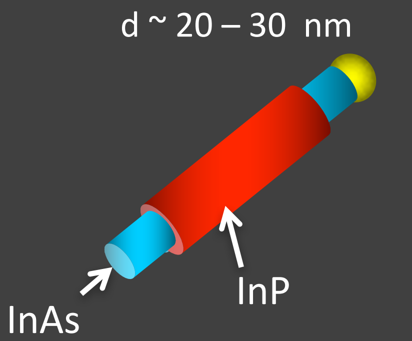




Normal contact used as a weakly coupled tunnel probe

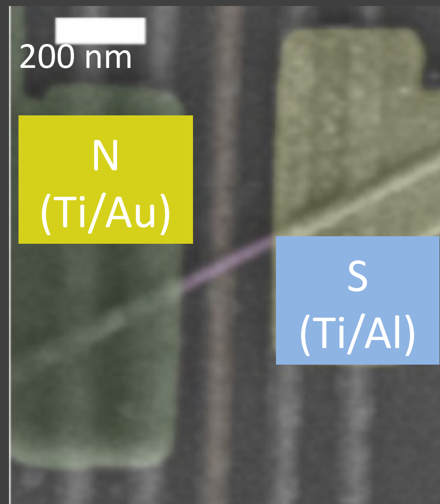
i.e. $\Gamma_N << \Gamma_S$

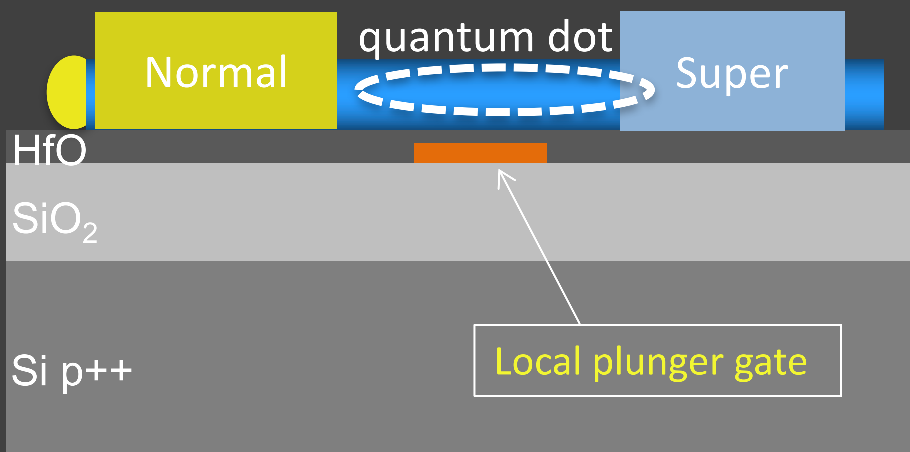
S-QD-N geometry and Andreev level spectroscopy

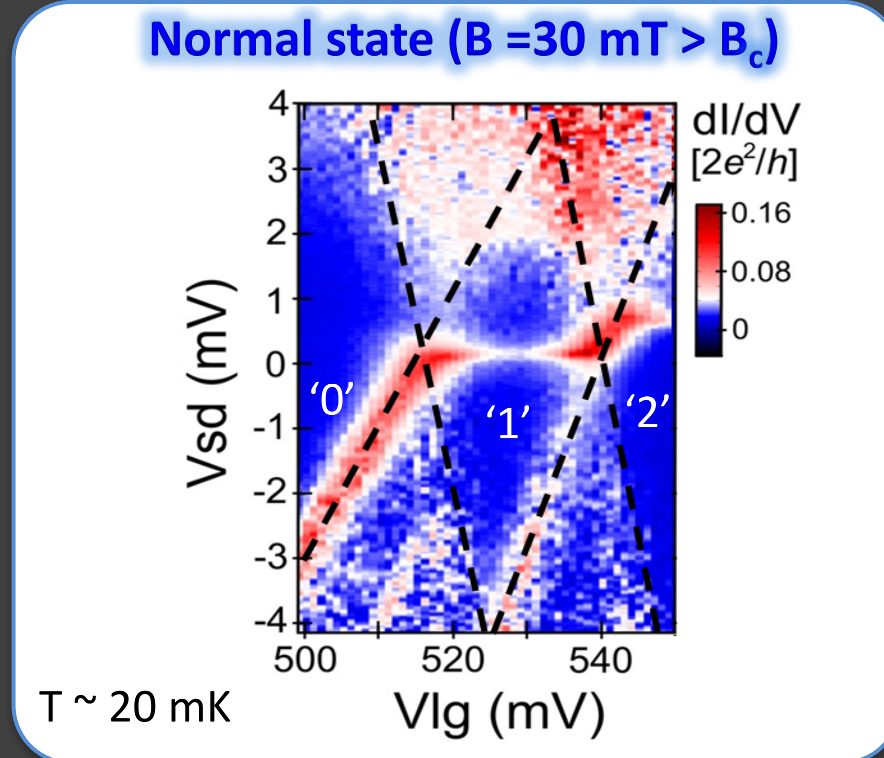


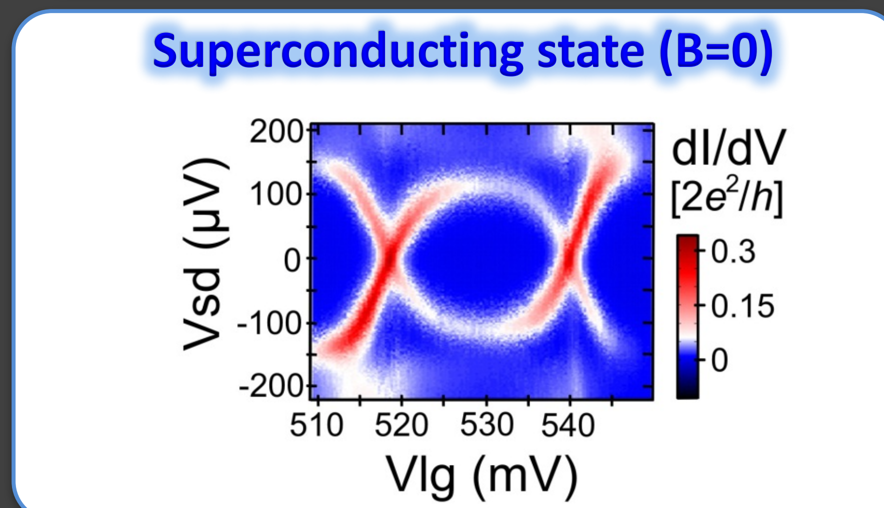
InAs/InP core/shell nanowires

(Lieber's group)

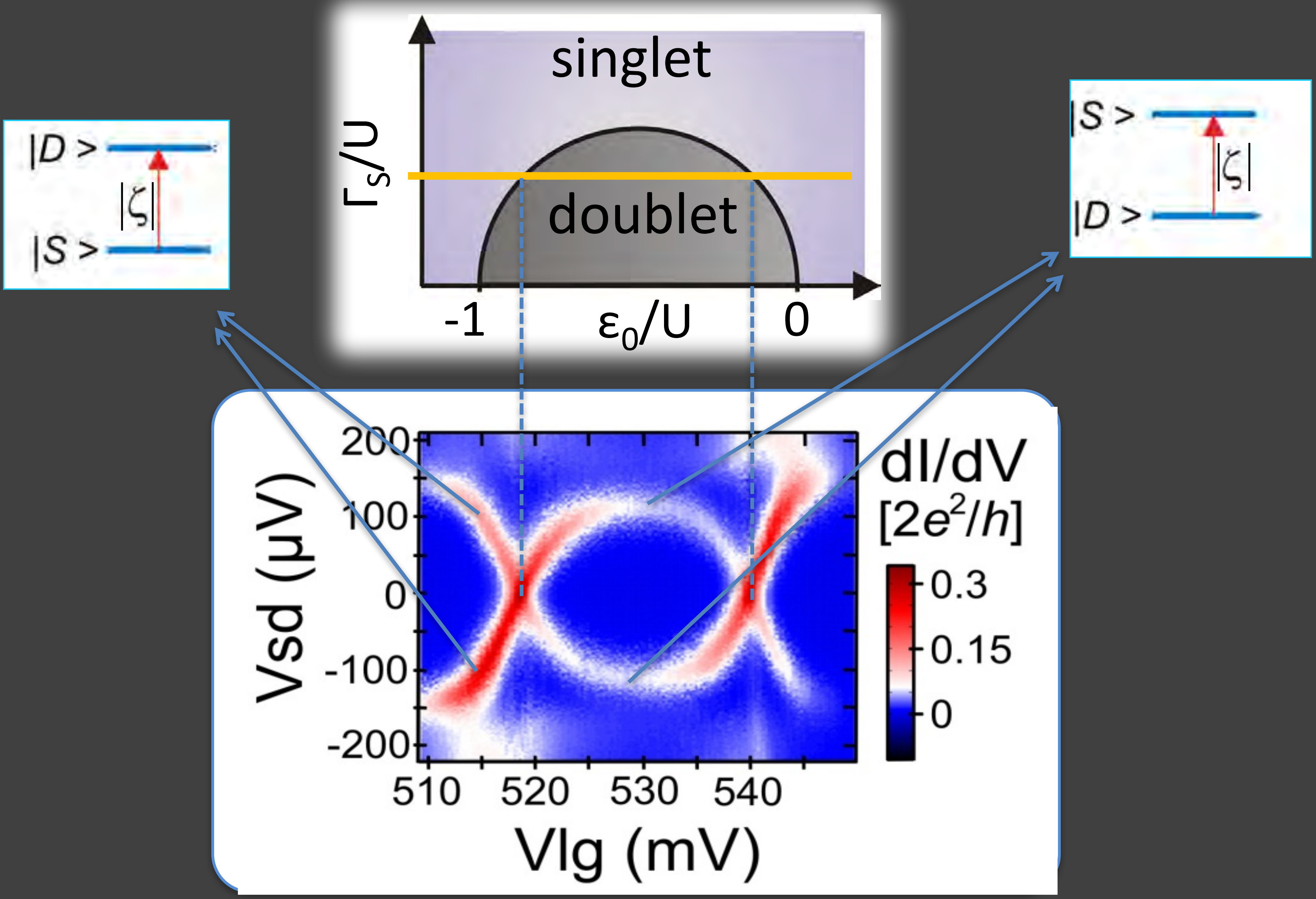




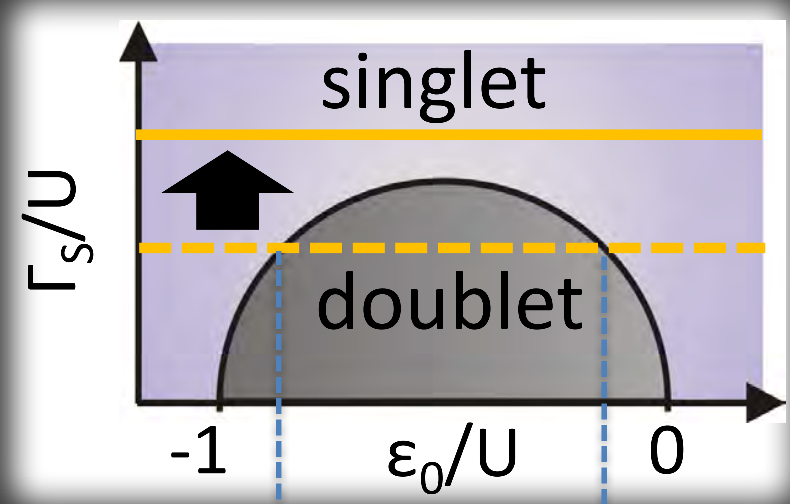


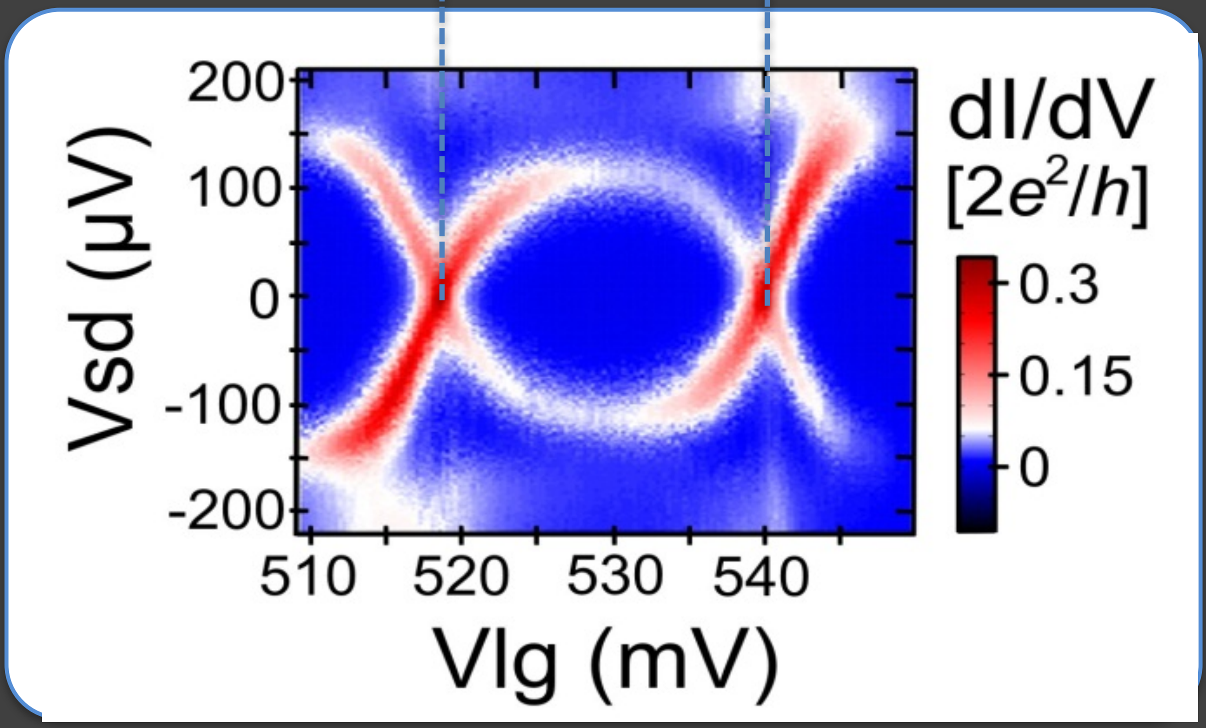


Tunnel spectroscopy of sub-gap states in the "weak" coupling regime

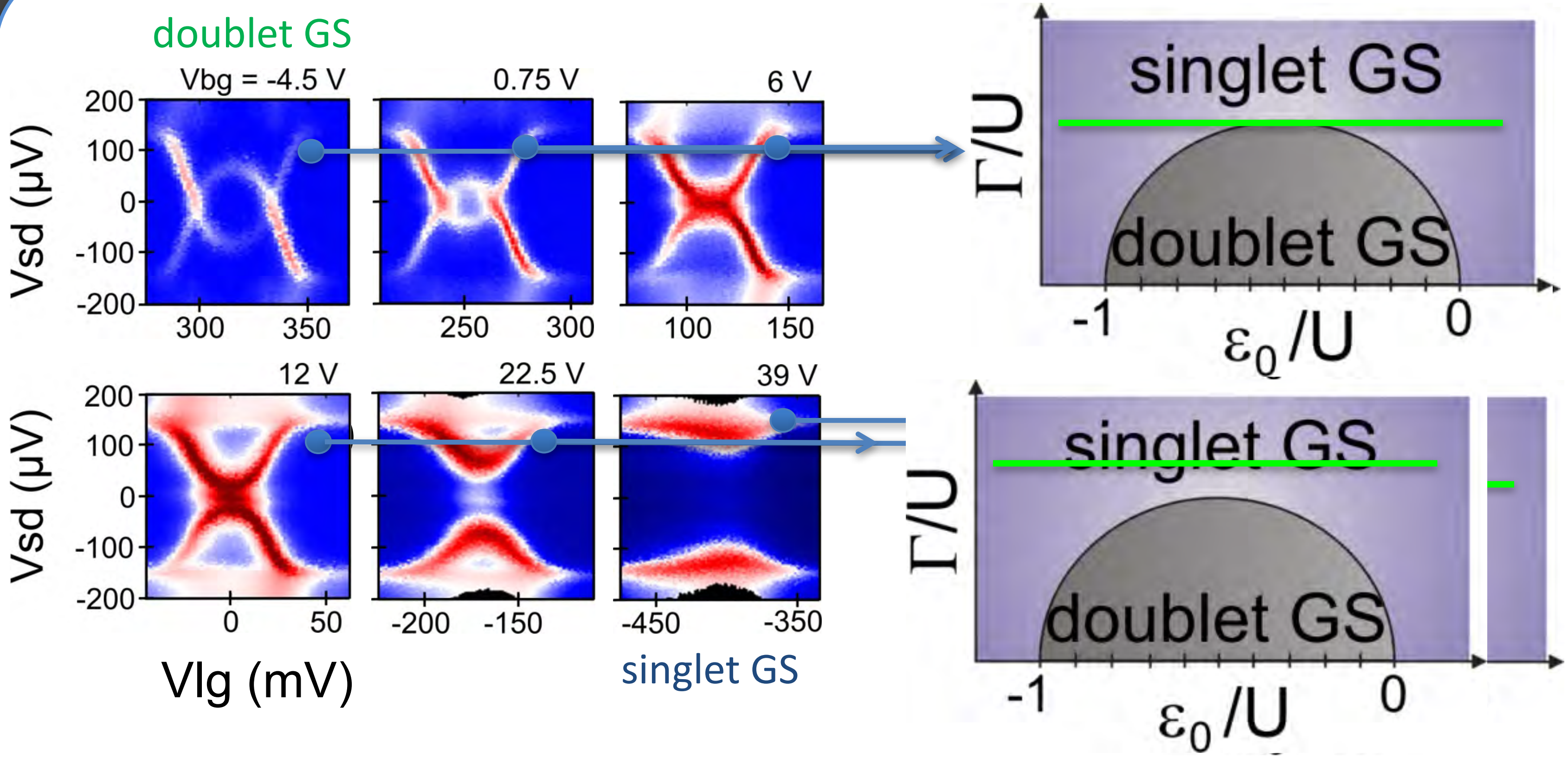


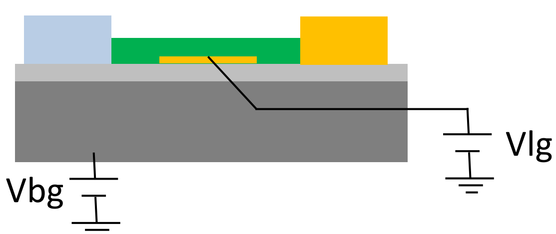
Let's increase the S-QD coupling….





Increasing S-QD coupling induces a doublet-to-singlet quantum phase transition

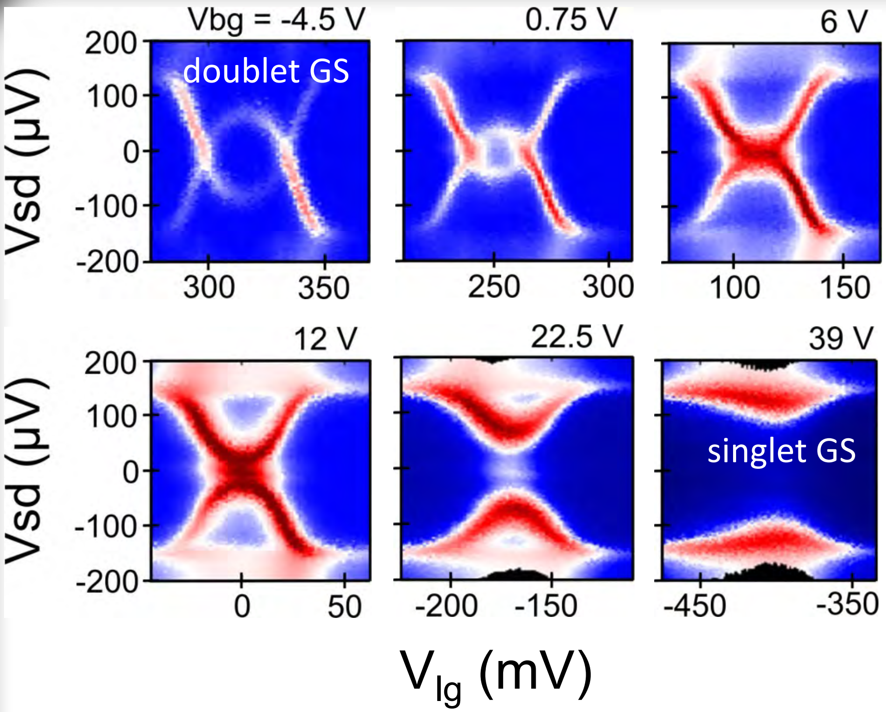


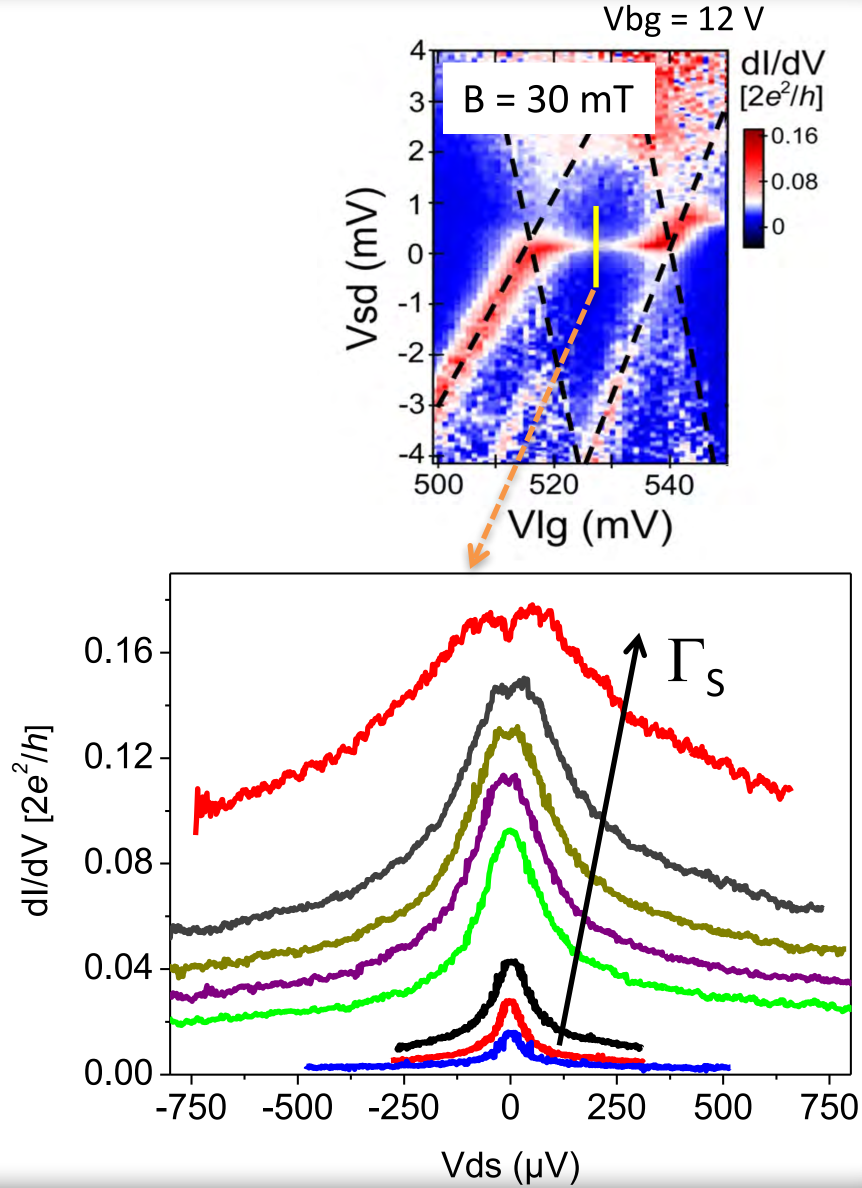


Back-gate voltage used to tune S-QD coupling

(always $\Gamma_N << \Gamma_S$)

Corresponding normal-state Kondo regime



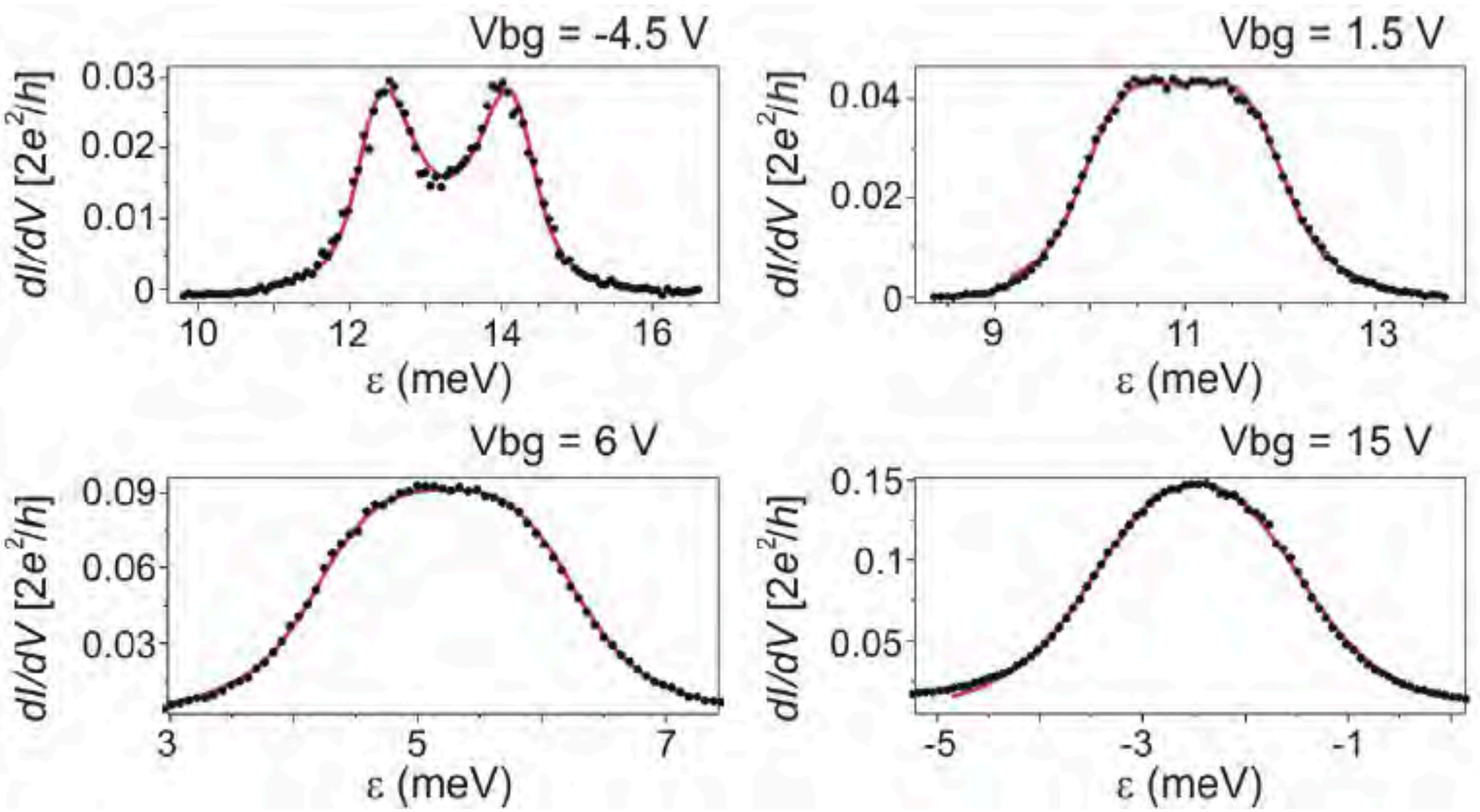


Note: $T_K \sim \exp(-U/\Gamma_S)$

NRG fitting of the normal-state linear conductance

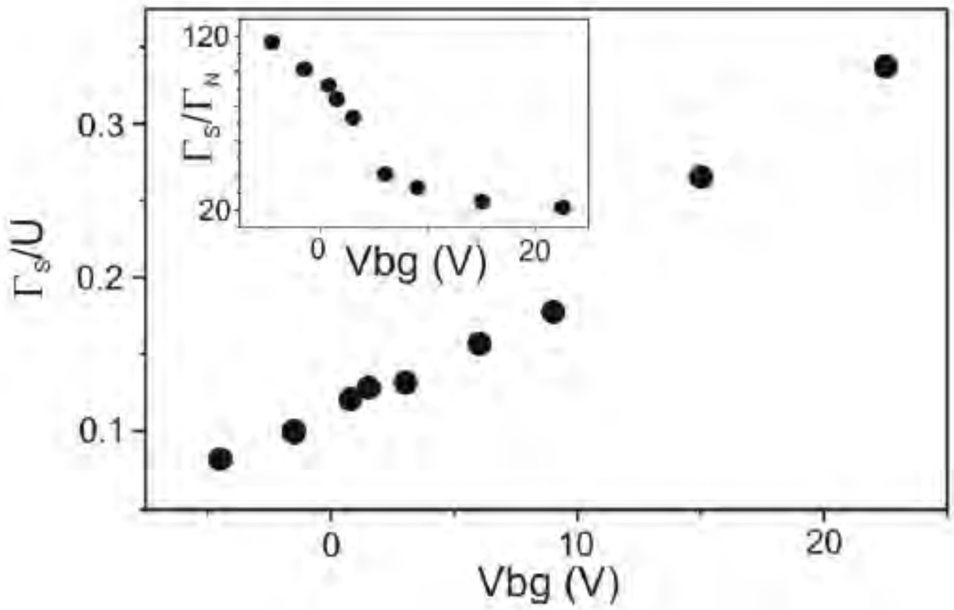
$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \epsilon_0 n + U/2(n-1)^2 + V \sum_{k\sigma} d^\dagger_\sigma c_{k\sigma} + \mathrm{H.c.}$$

$$+ g\mu_B B S_z \quad \text{with} \quad S_z = (1/2)(d^\dagger_\uparrow d_\uparrow - d^\dagger_\downarrow d_\downarrow)$$

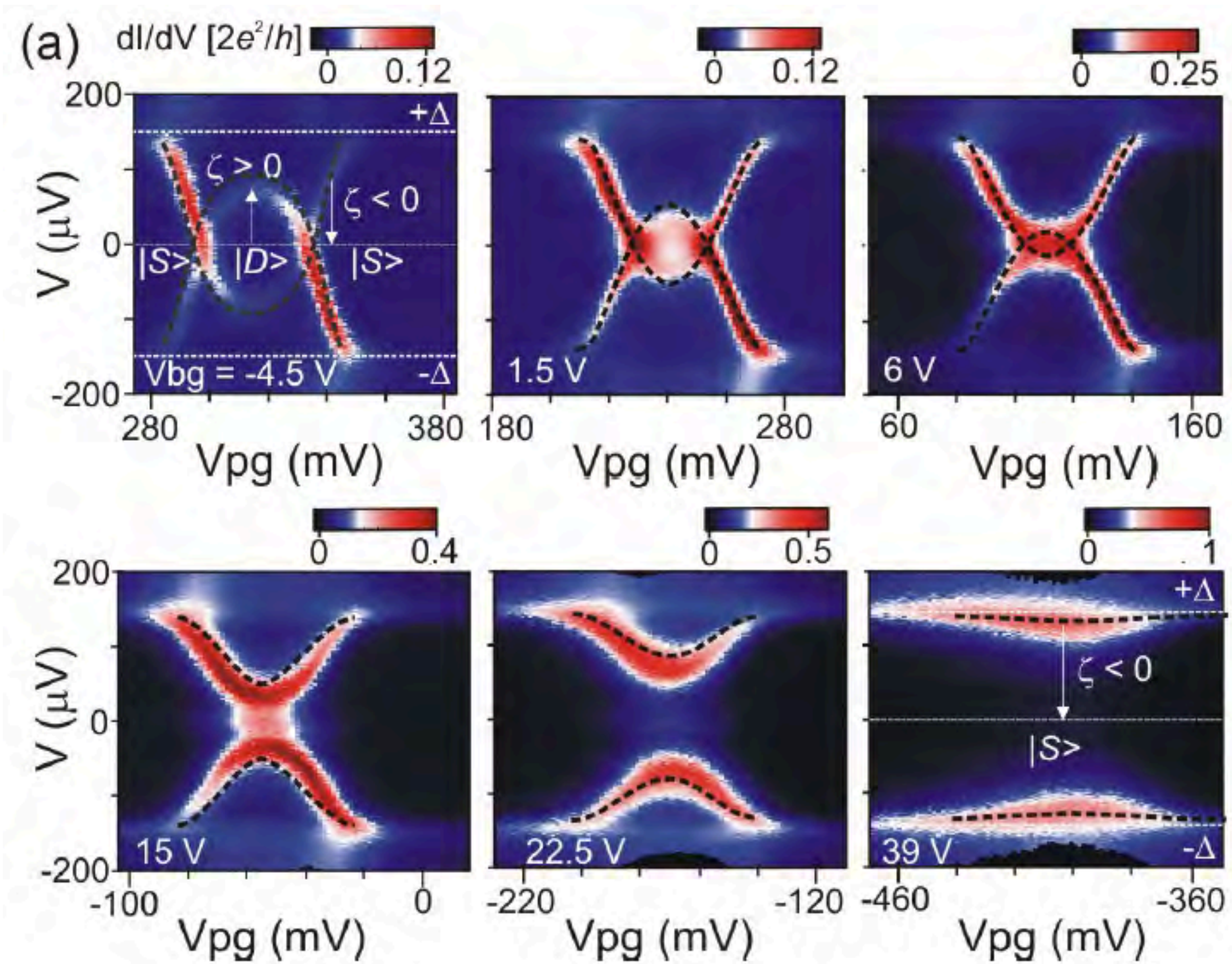


NRG fitting of the normal-state linear conductance

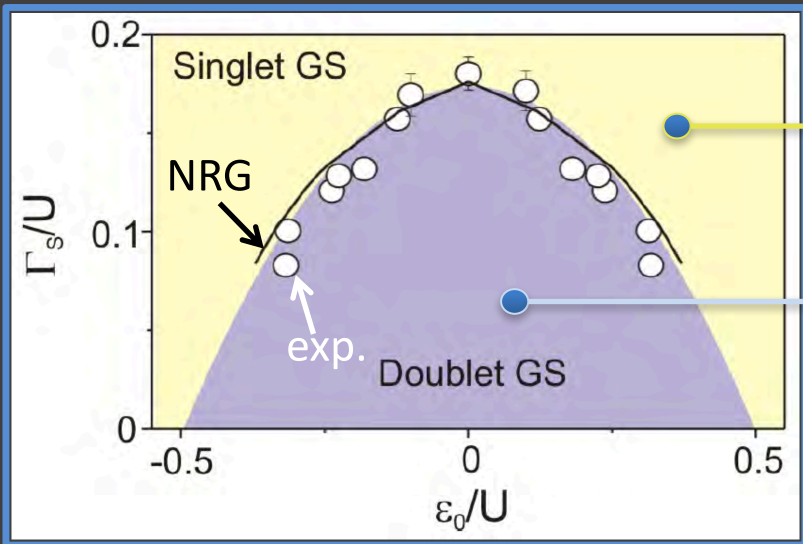
V_{bg} (V)	Γ_S/U	U (meV)	Γ_S/Γ_N	T_K (mK)
-4.5	0.07222	2.50753	121.92	31.58
-1.5	0.0904	2.33457	104.85	95.02
0.75	0.1125	2.31231	94.38	254.5
1.5	0.1206	2.23428	85.98	327.54
3	0.12496	2.26679	74.77	383.95
6	0.15356	2.18159	41.07	803.045
9	0.1758	2.14117	33.42	1247.49
15	0.26431	1.9835	25.03	3761.59
22.5	0.33782	1.95634	21.49	6079.83



Superconducting regime: experimental data vs NRG (dashed lines)



QD-S phase digram: experimental vs NRG (dashed lines)

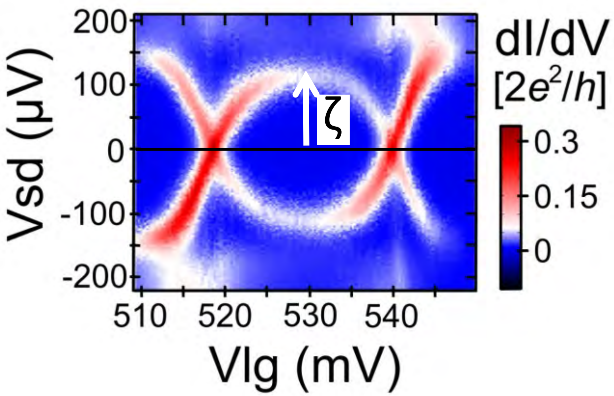


$I_s = I_c \sin[\Delta\varphi]$

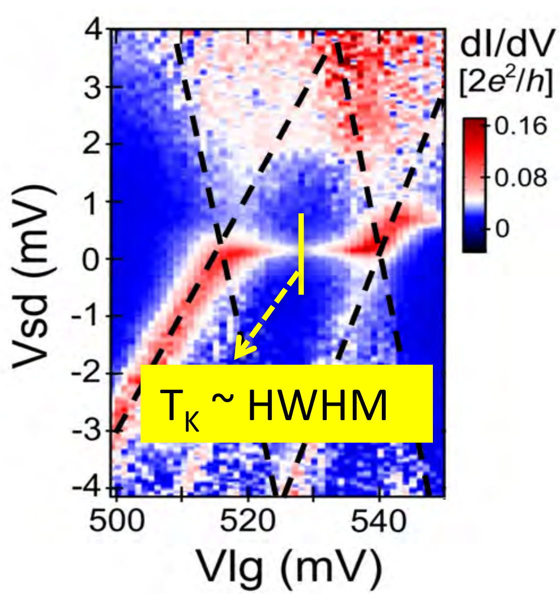
$I_s = I_c \sin[\Delta\varphi + \pi]$

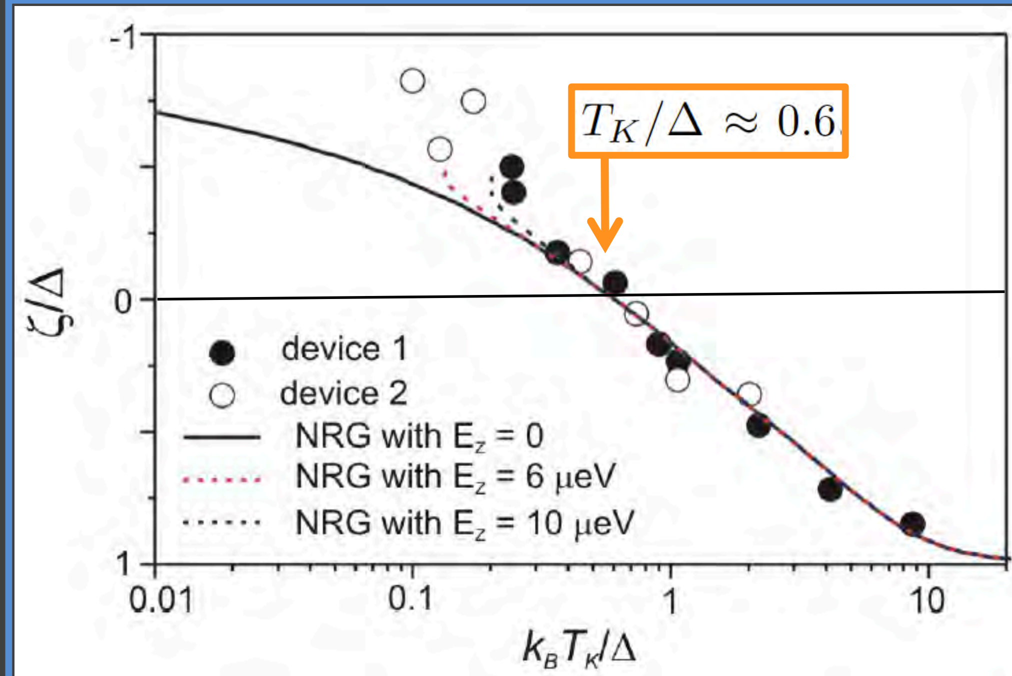
Van Dam et al., Nature (2006)
Maurand et al, PRX (2012)
Delagrange et al., PRB (2016)

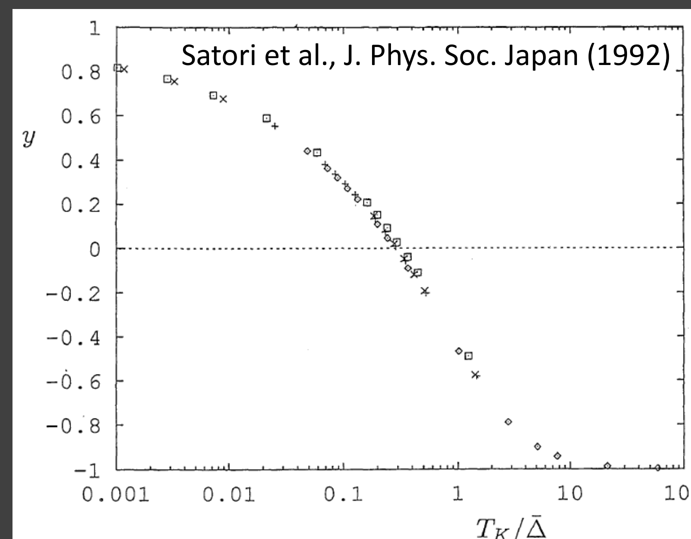
Superconducting state (B=0)



Normal state (B =30 mT > B_c)

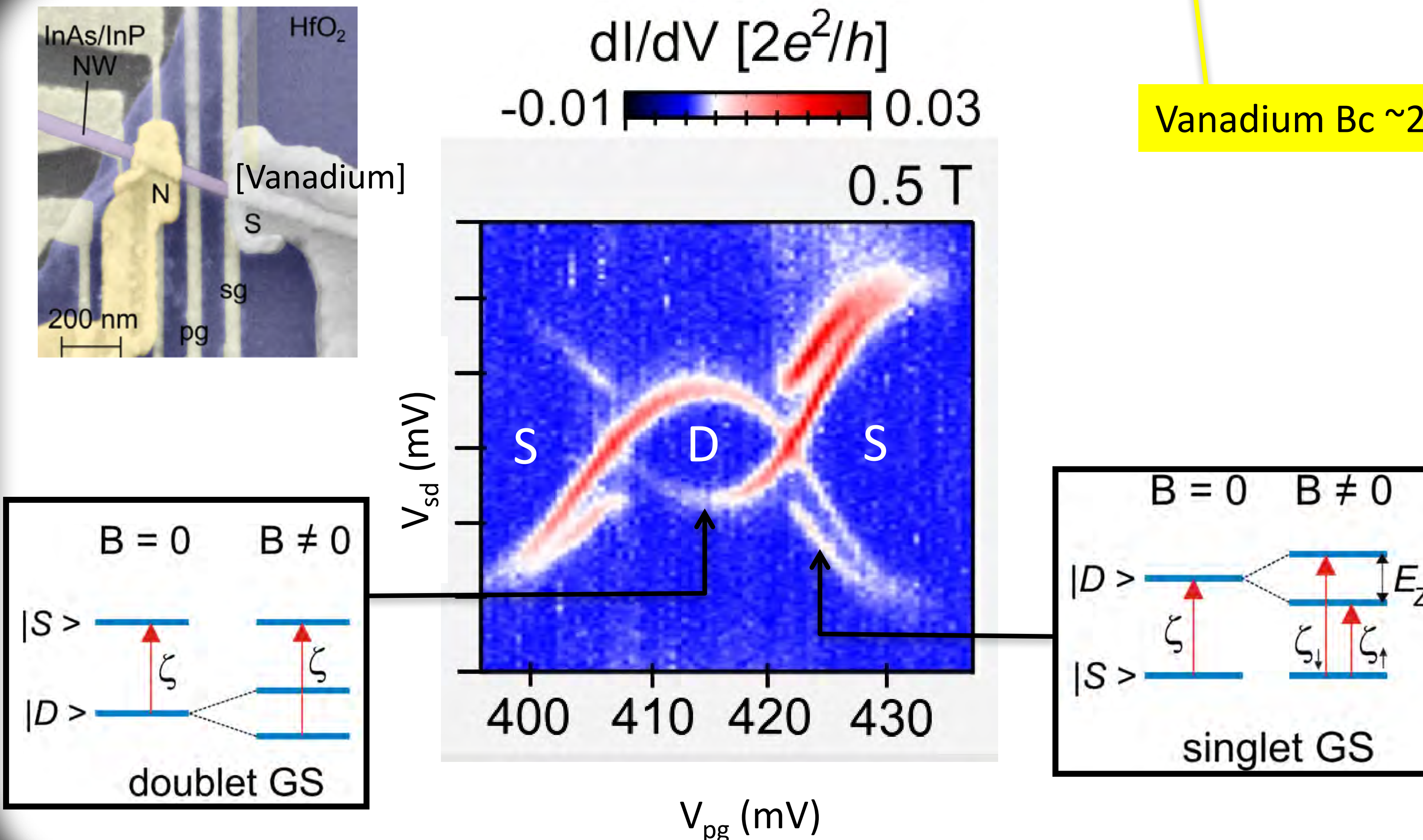






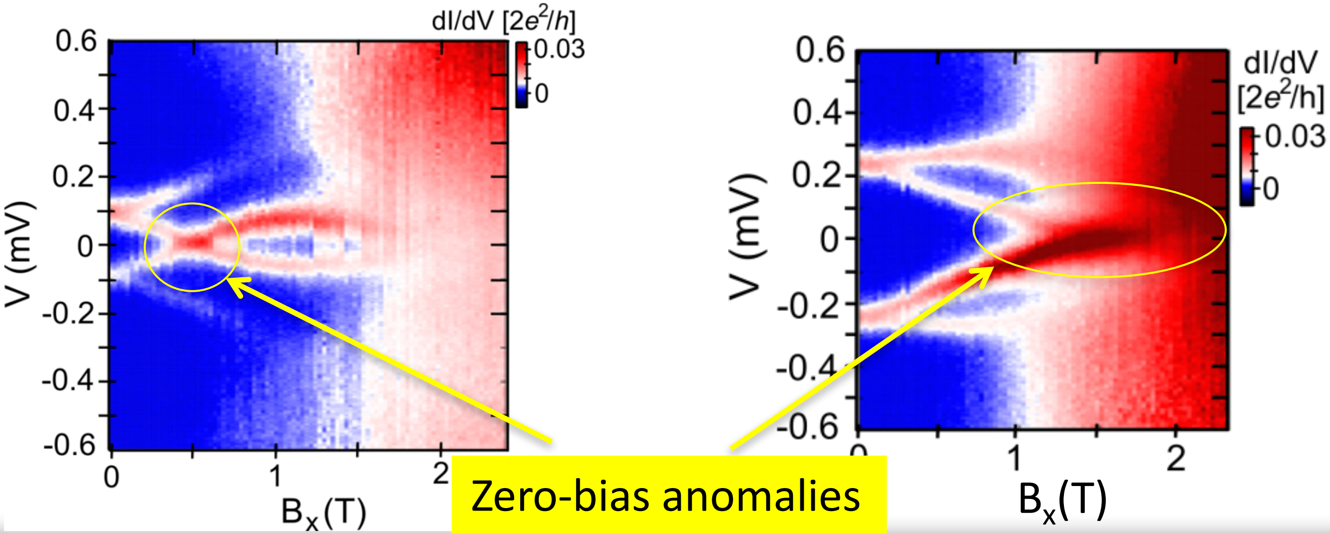
Observation of Zeeman splitting in the singlet regime (Al/InAs/V device)

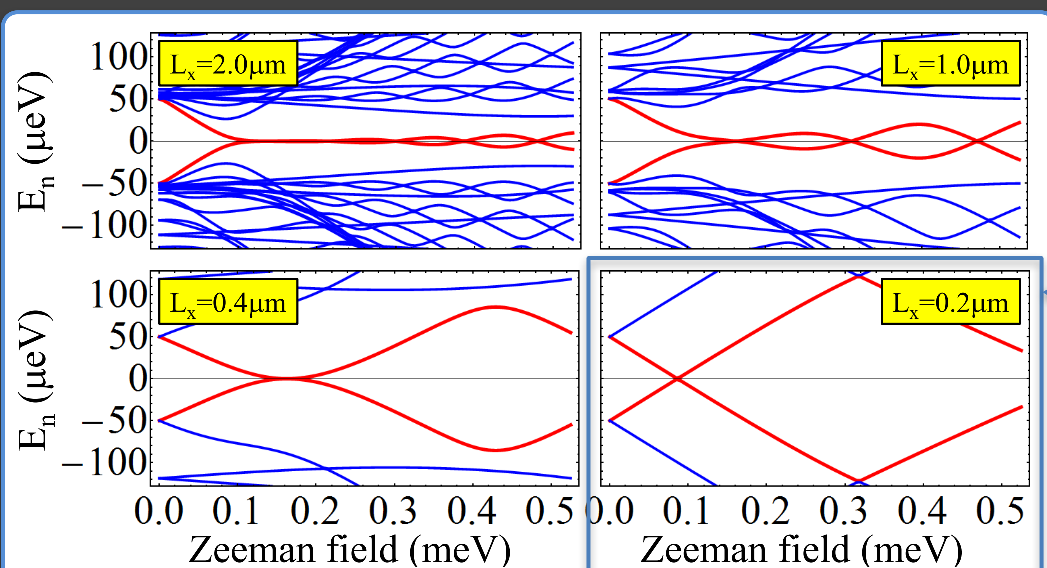
Vanadium Bc ~2T



Tunnel-spectroscopy experiments in S-nanowire-N devices

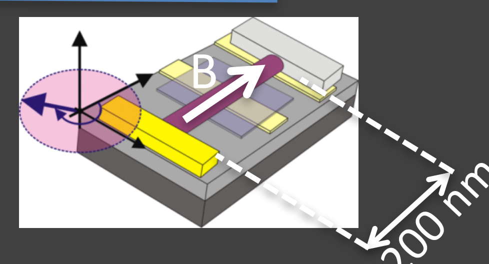
Au/InAs NW/V device





Stanescu, Lutchyn, Das Sarma, PRB (2013)

Short-channel limit



Superconducting proximity effect in:

- Strongly confined (0-D) quantum dot
- Quasi-ballistic (quasi 1D) junction

One-dimensionality in InSb nanowires

NANO LETTERS
Letter
pubs.acs.org/NanoLett

Quantized Conductance in an InSb Nanowire

Ilse van Weperen,[†] Sébastien R. Plissard,[‡] Erik P. A. M. Bakkers,[†,‡] Sergey M. Frolov,[†,§] and Leo P. Kouwenhoven*[,†]

[†]Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands
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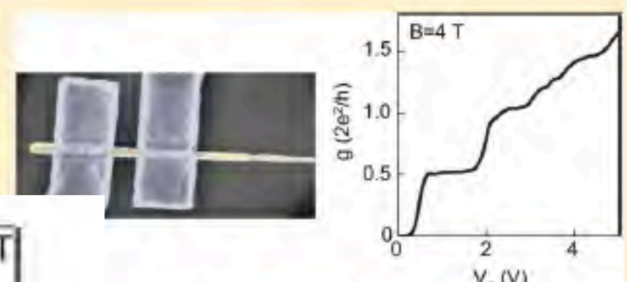
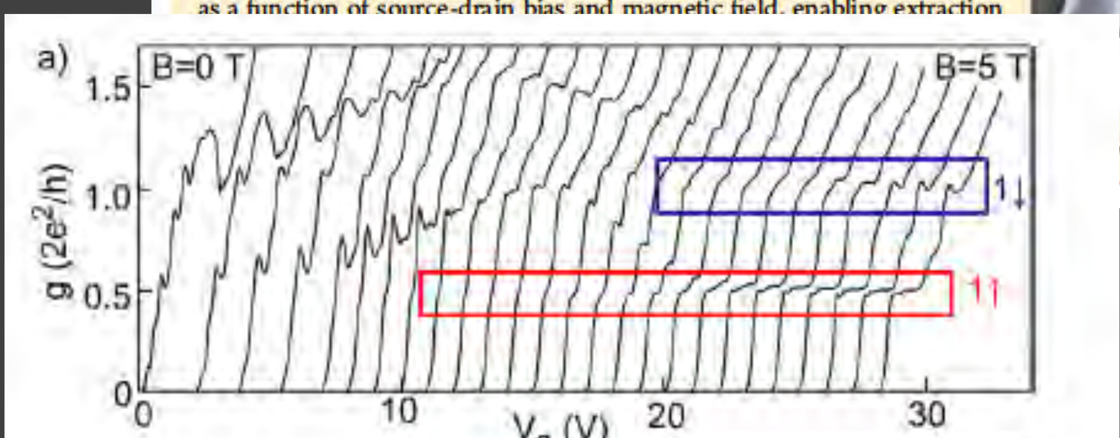
Supporting Information

ABSTRACT: Ballistic one-dimensional transport in semiconductor nanowires plays a central role in creating topological and helical states. The hallmark of such one-dimensional transport is conductance quantization. Here we show conductance quantization in InSb nanowires at nonzero magnetic fields. Conductance plateaus are studied as a function of source-drain bias and magnetic field, enabling extraction



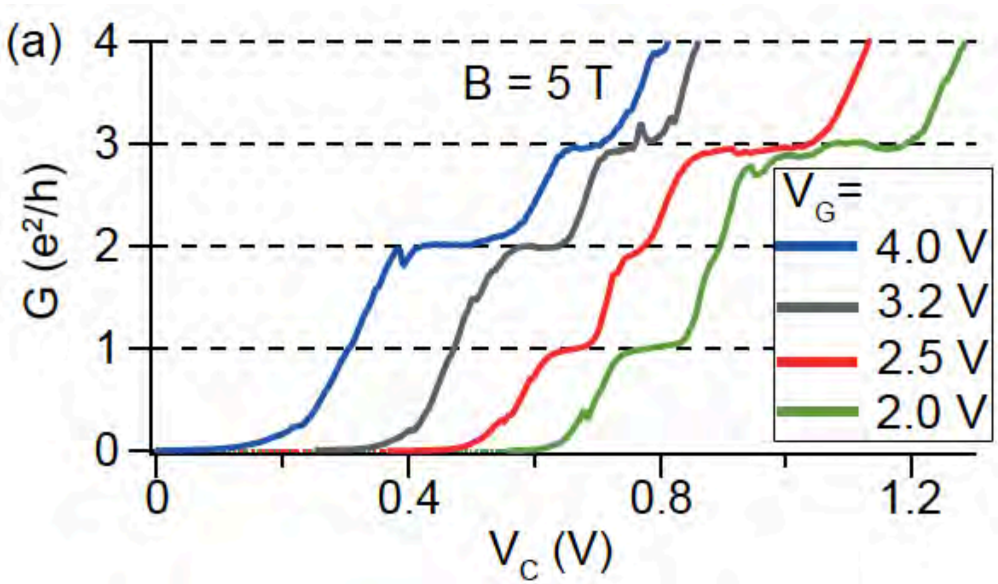
, *subband, nanowire, InSb*

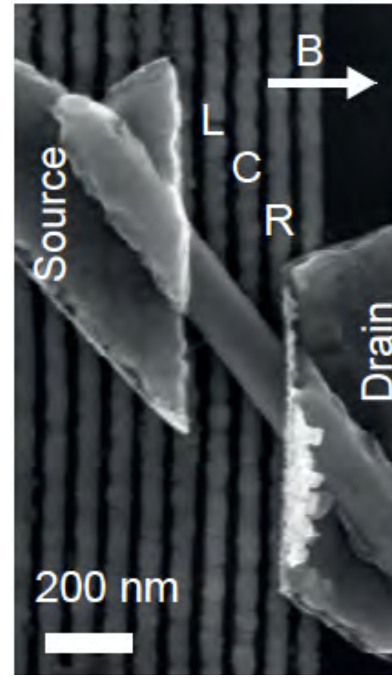


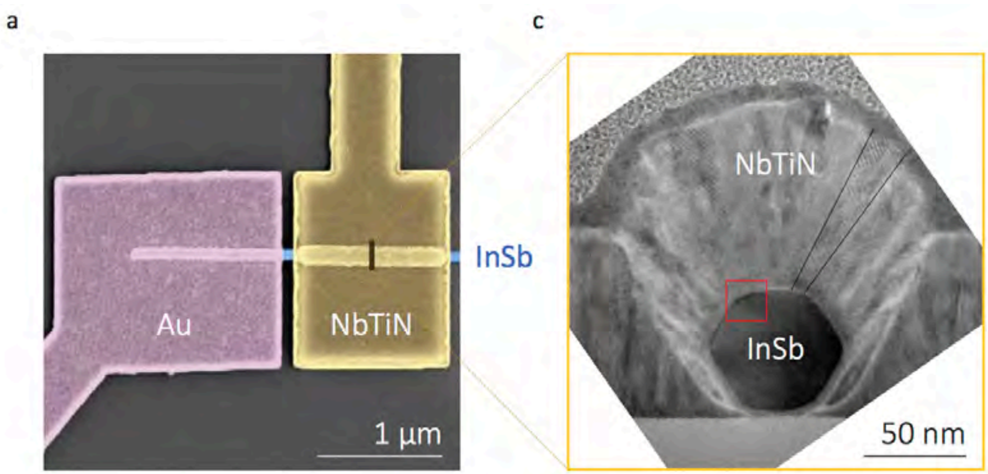
(2013)

Ballistic transport in InSb NWs

[Estrada Saldaña et al., arXiv:1709.02614]

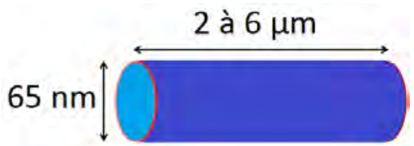




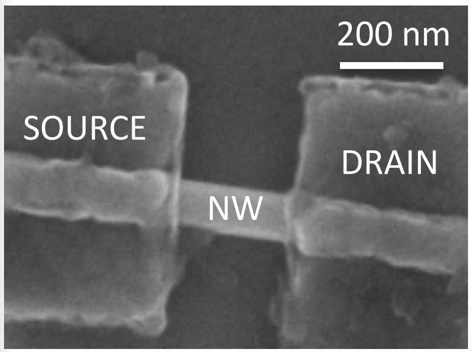


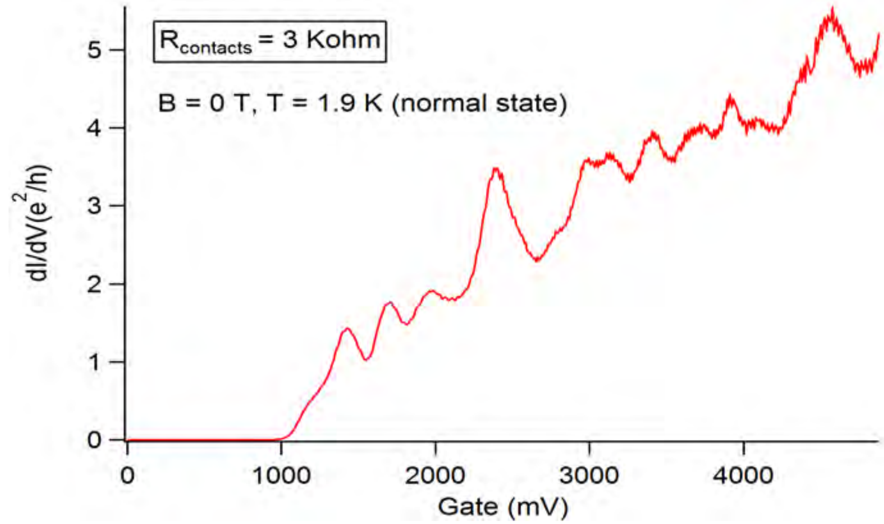
[reproduced from Zhang et al., Nat. Comm. 8, 16025 (2017)]

Assessing 1D character of InAs nanowires

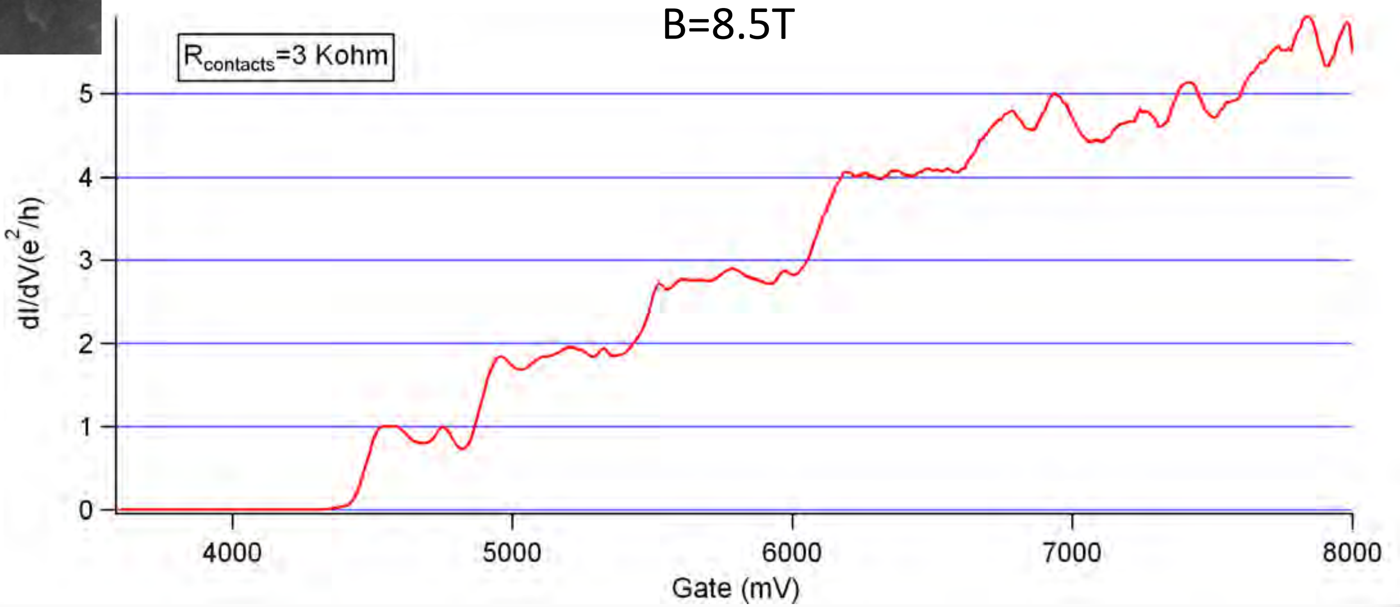


Material from Sorba's group (Pisa)





B=8.5T

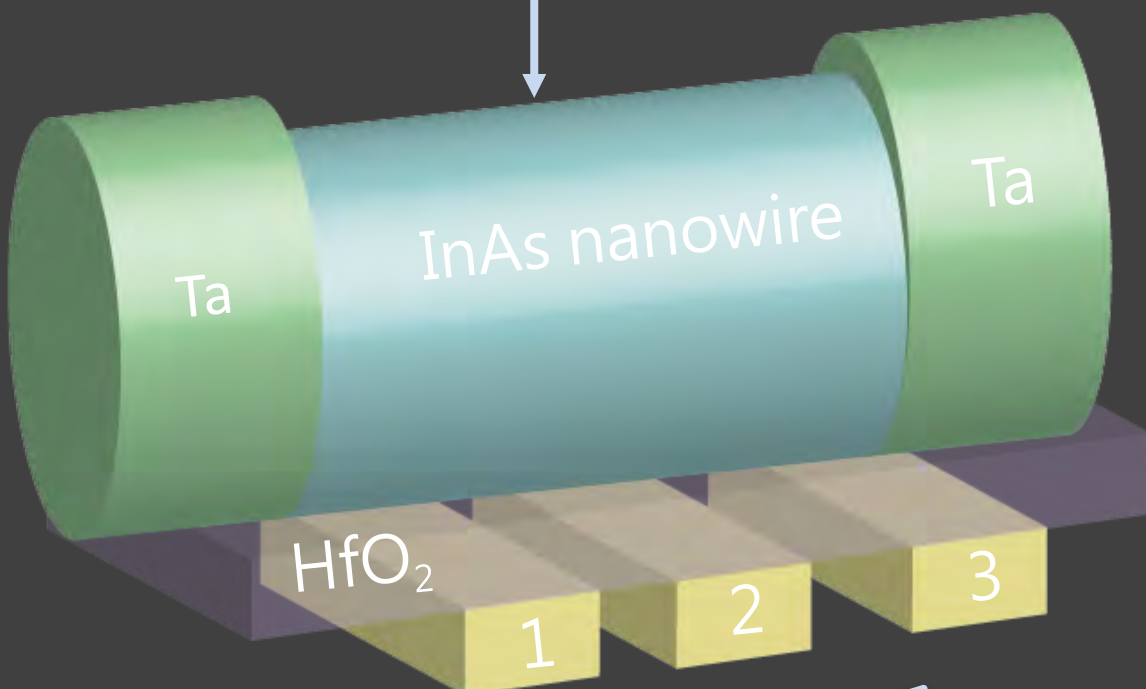


(unpublished)

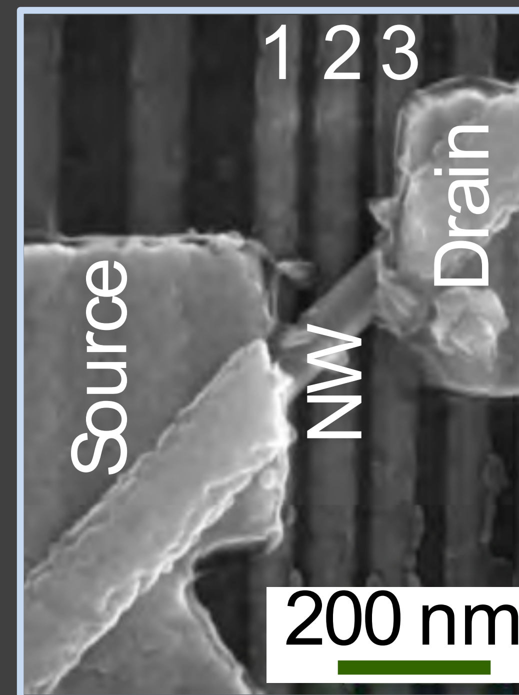
Device description

High critical field
(B_c~1.8 T, T_C~0.8K, Δ^*~80 μeV)

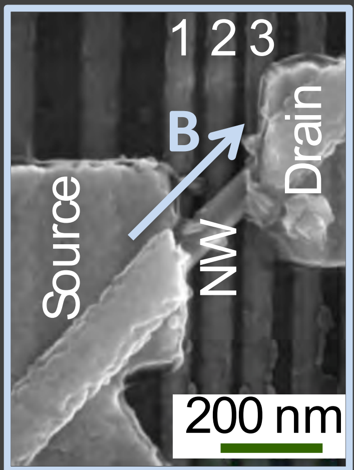
Large g-factor



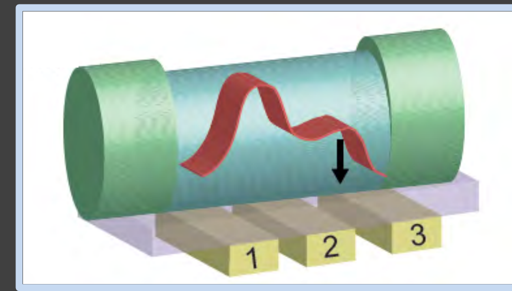
Bottom finger gates



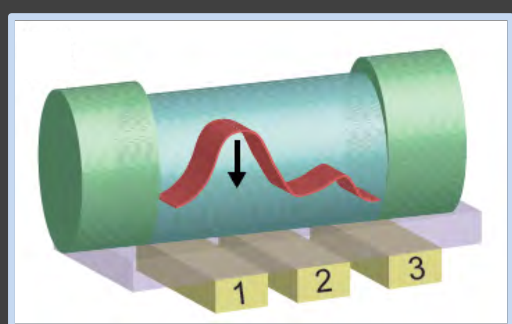
CBE-grown InAs NWs from Sorba's group (Pisa)



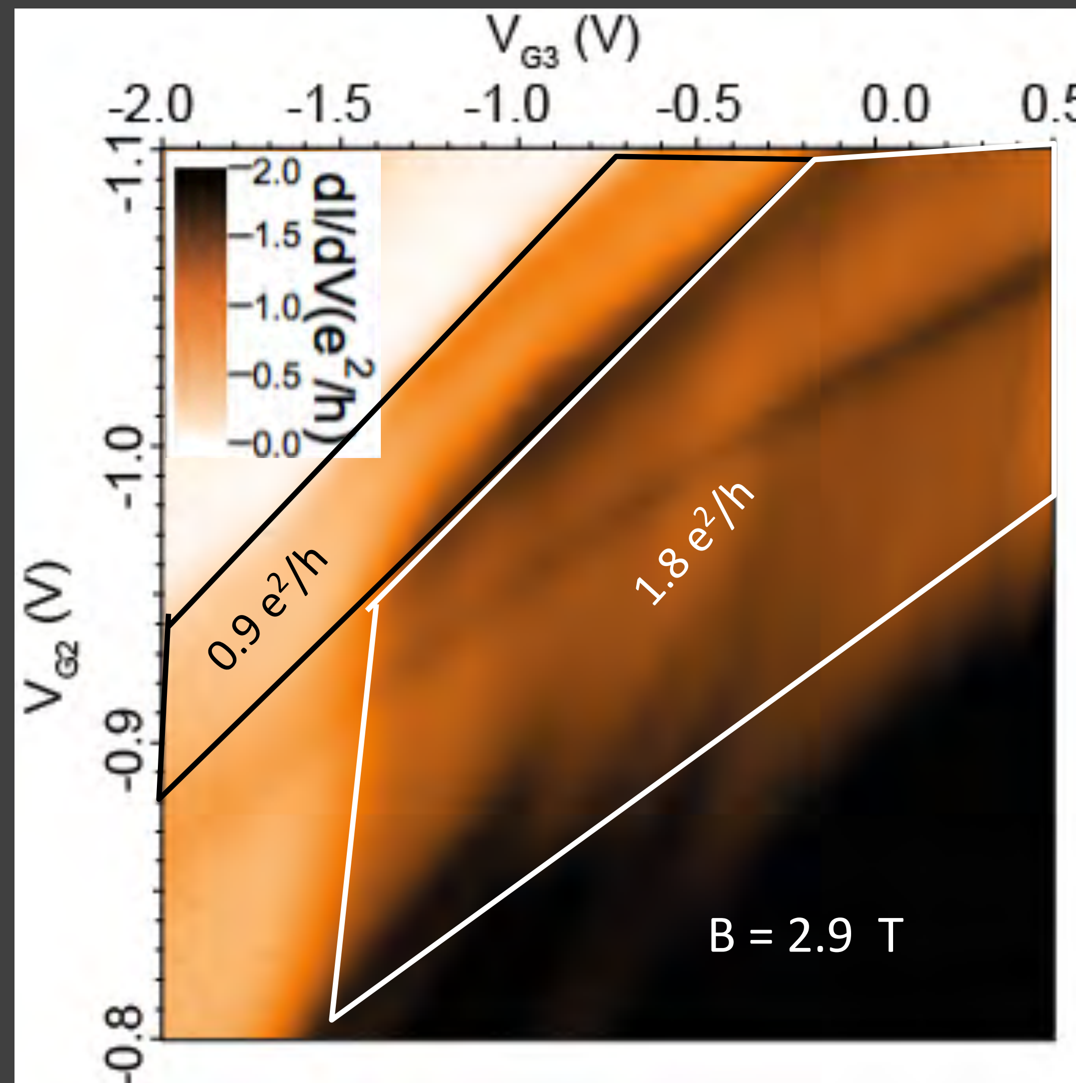
1 2 3
B
Source
NW
Drain
200 nm



1
2
3

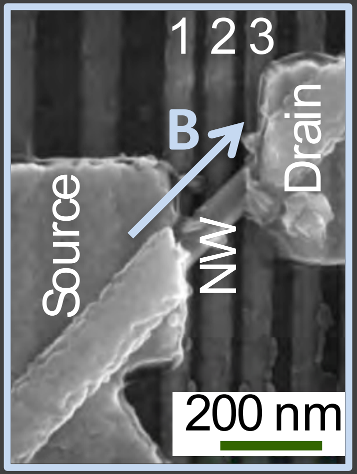


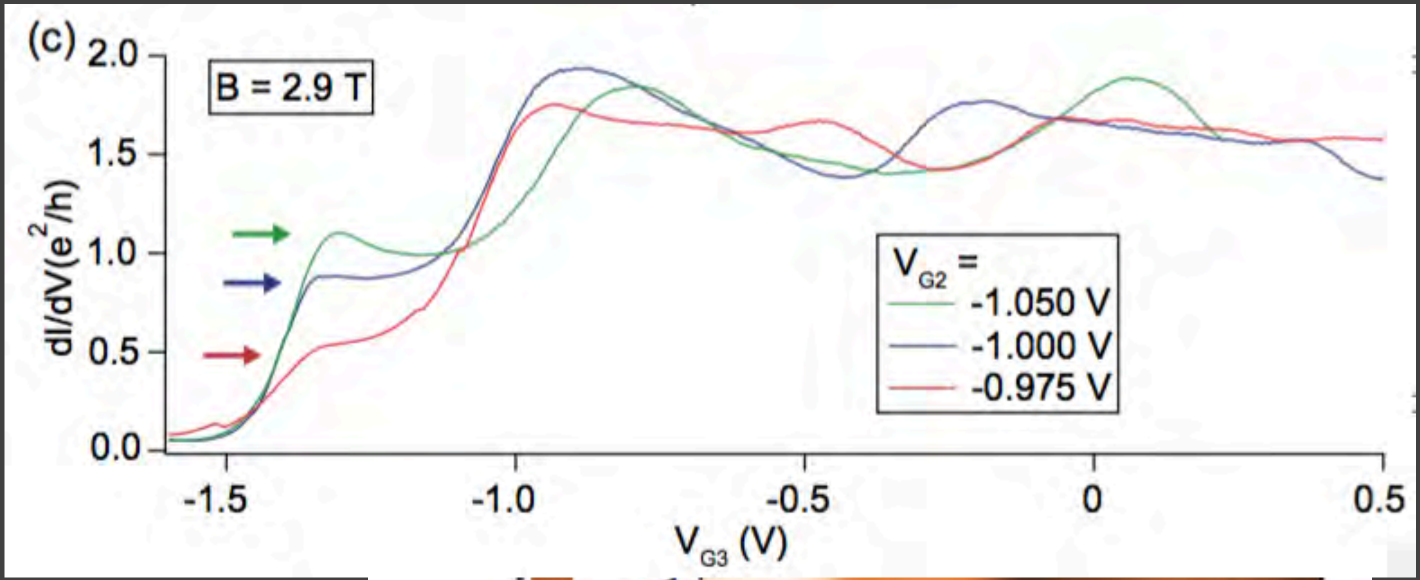
1
2
3

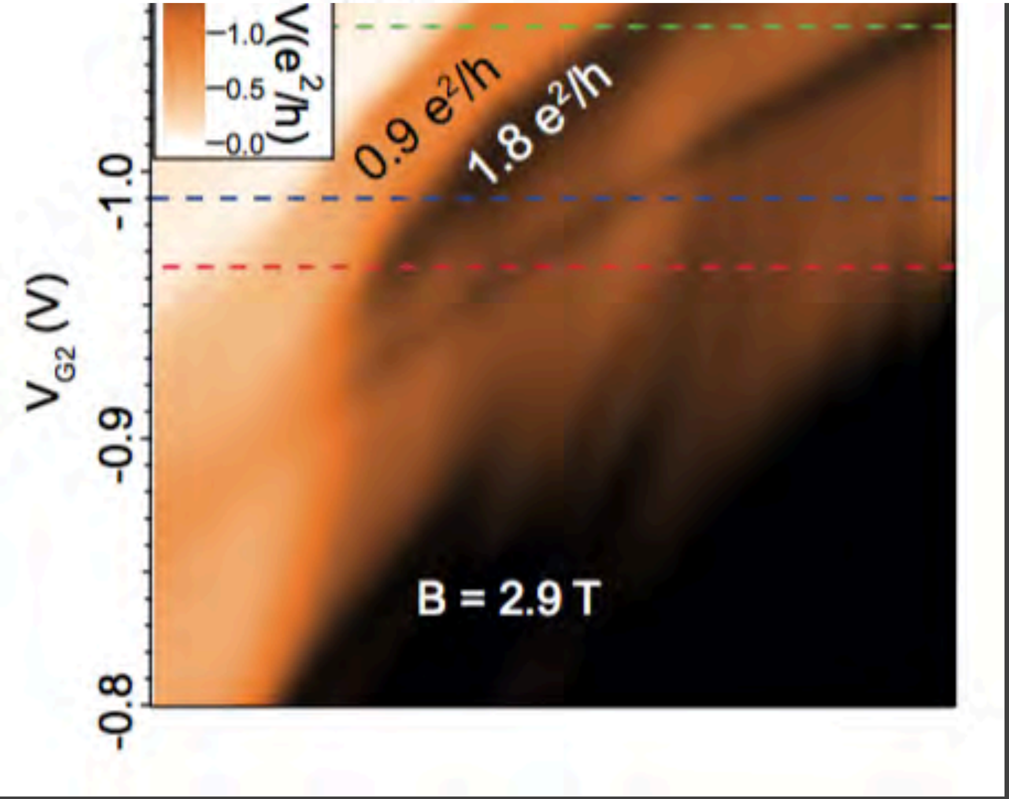


V_G3 (V)
-2.0 -1.5 -1.0 -0.5 0.0 0.5
V_G2 (V)
-1.1 -1.0 -0.9 -0.8
dI/dV(e^2/h)
2.0 1.5 1.0 0.5 0.0
0.9 e^2/h
1.8 e^2/h
B = 2.9 T

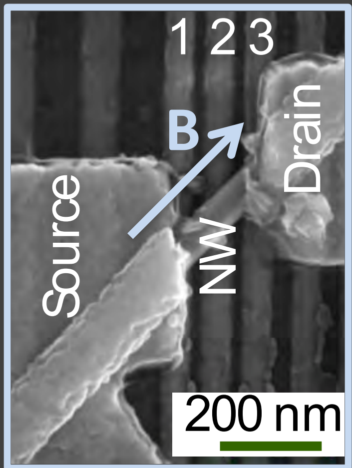
T = 15 mK

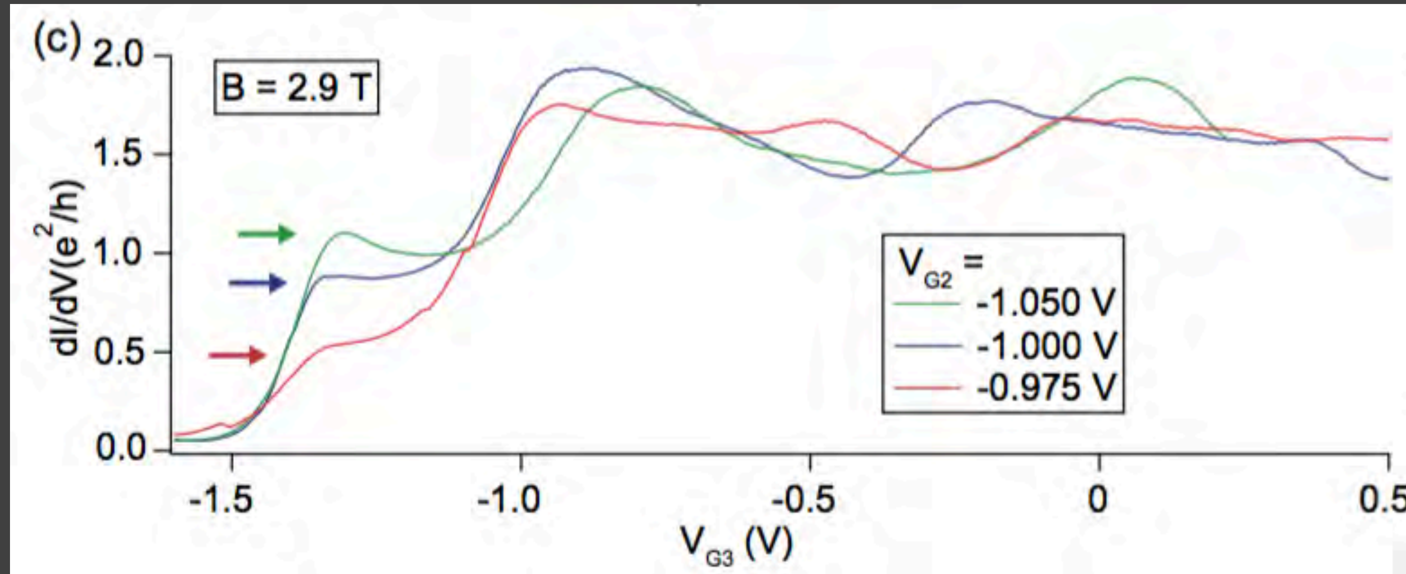

1 2 3
B
Source
NW
Drain
200 nm


(c)
B = 2.9 T
dI/dV(e^2/h)
2.0
1.5
1.0
0.5
0.0
-1.5
-1.0
-0.5
0
0.5
V_G3 (V)
V_G2 =
-1.050 V
-1.000 V
-0.975 V

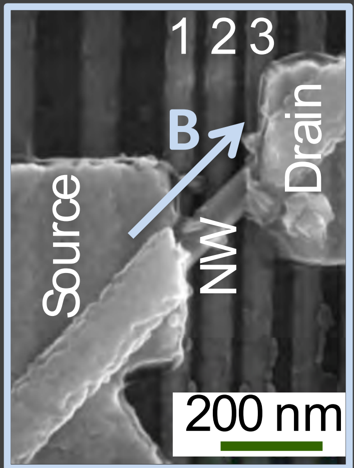

V_G2 (V)
-1.0
-0.9
-0.8
1.0
0.5
0.0
V(e^2/h)
0.9 e^2/h
1.8 e^2/h
B = 2.9 T

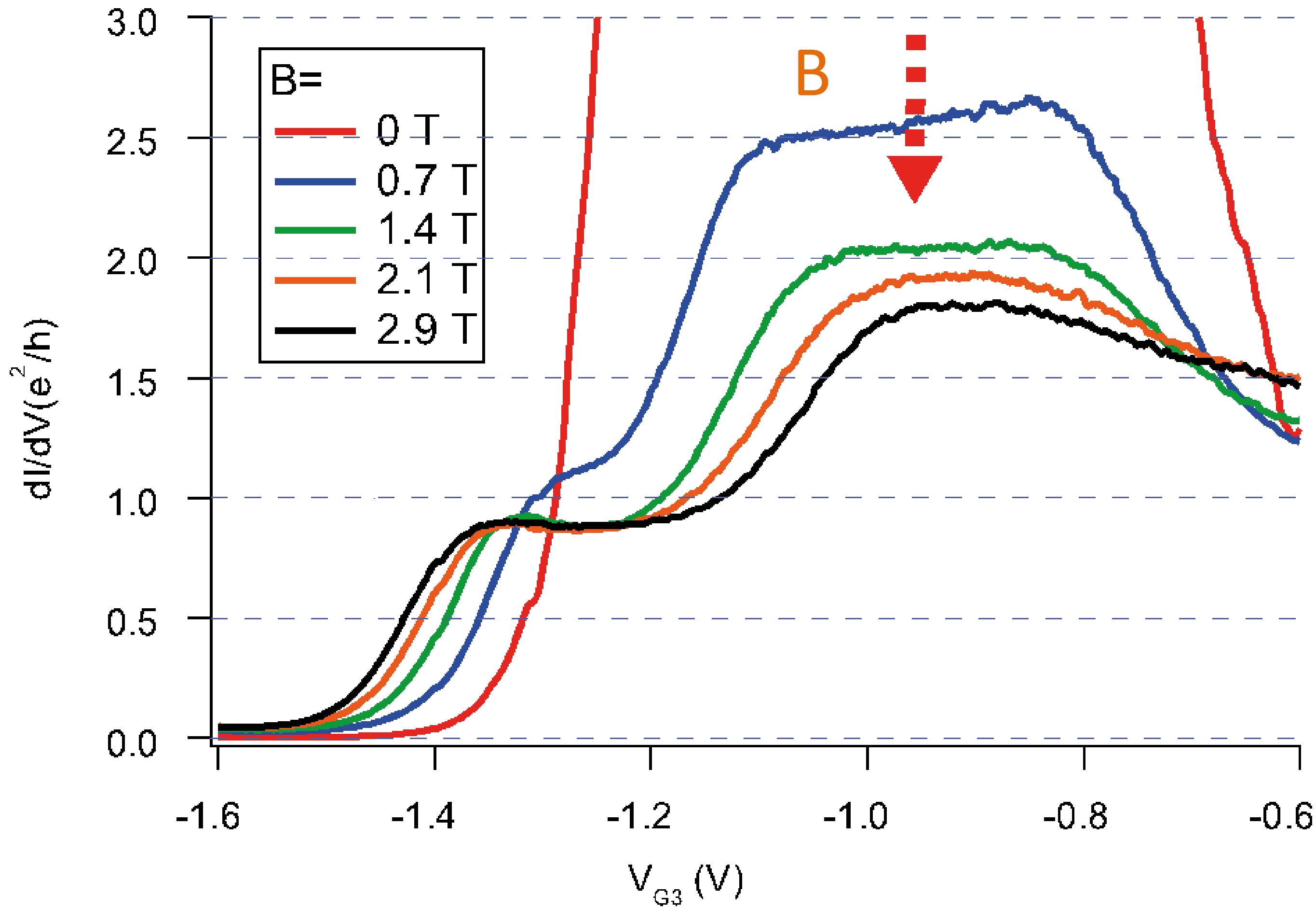
T= 15 mK

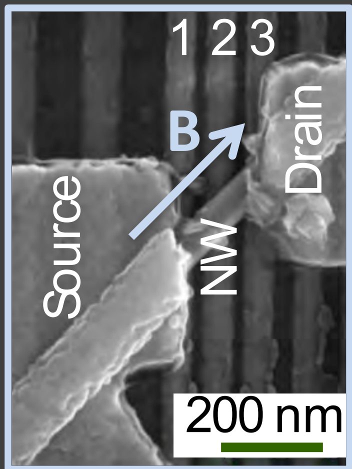

1 2 3
B
Source
NW
Drain
200 nm


(c)
B = 2.9 T
dI/dV(e^2/h)
2.0
1.5
1.0
0.5
0.0
-1.5
-1.0
-0.5
0
0.5
V_G3 (V)
V_G2 =
-1.050 V
-1.000 V
-0.975 V

T= 15 mK

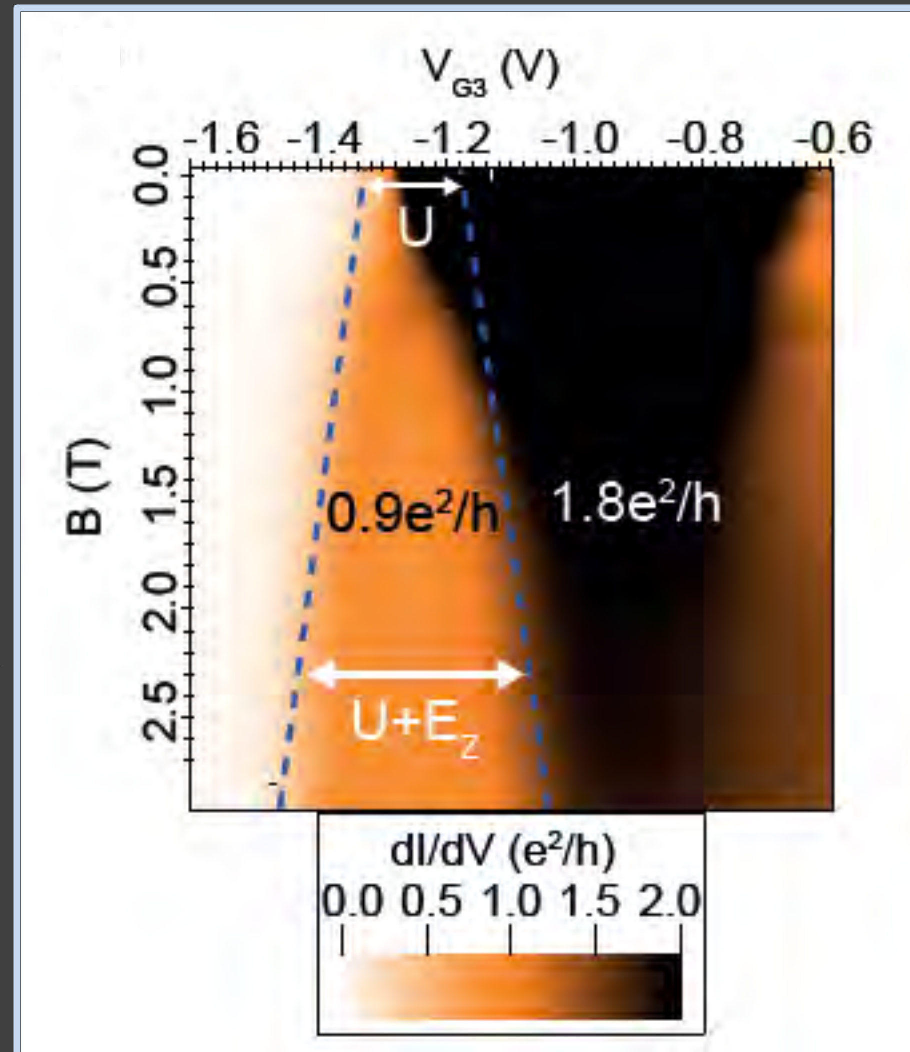

1 2 3
B
Source
Drain
NW
200 nm

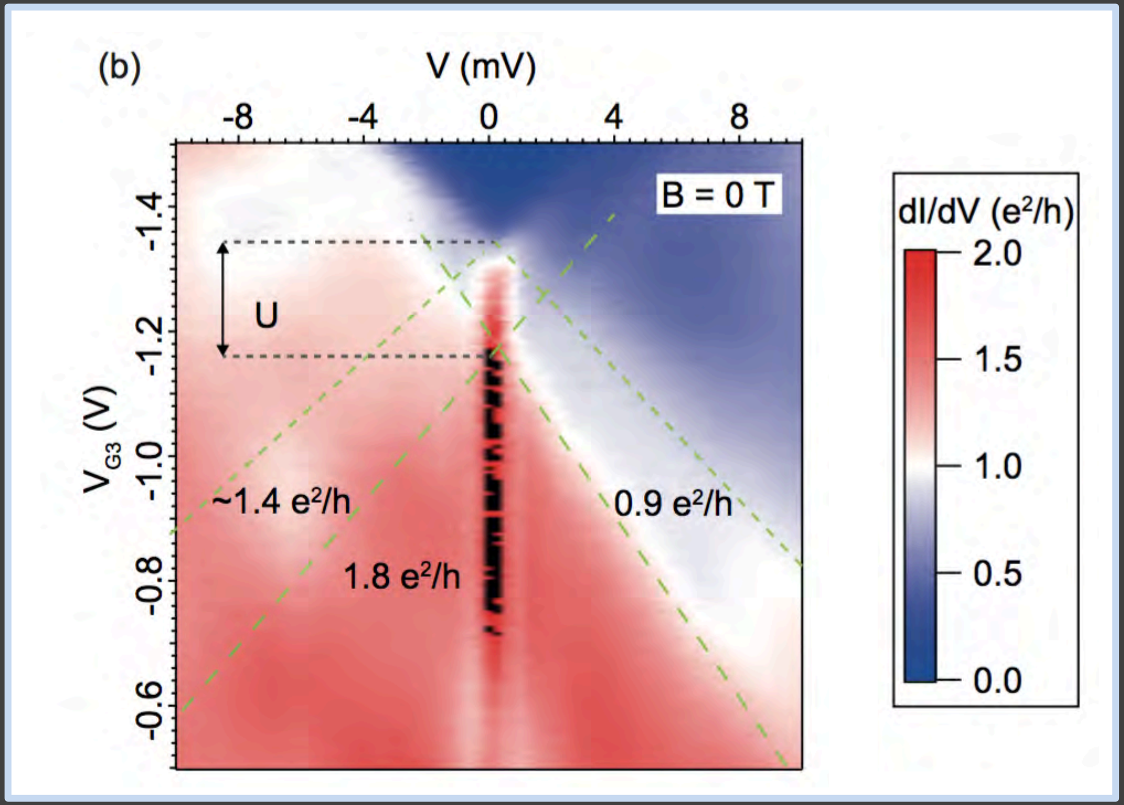

B=
0 T
0.7 T
1.4 T
2.1 T
2.9 T
B
3.0
2.5
2.0
1.5
1.0
0.5
0.0
dI/dV(e^2/h)
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
V_G3 (V)



Electron g-factor: –11

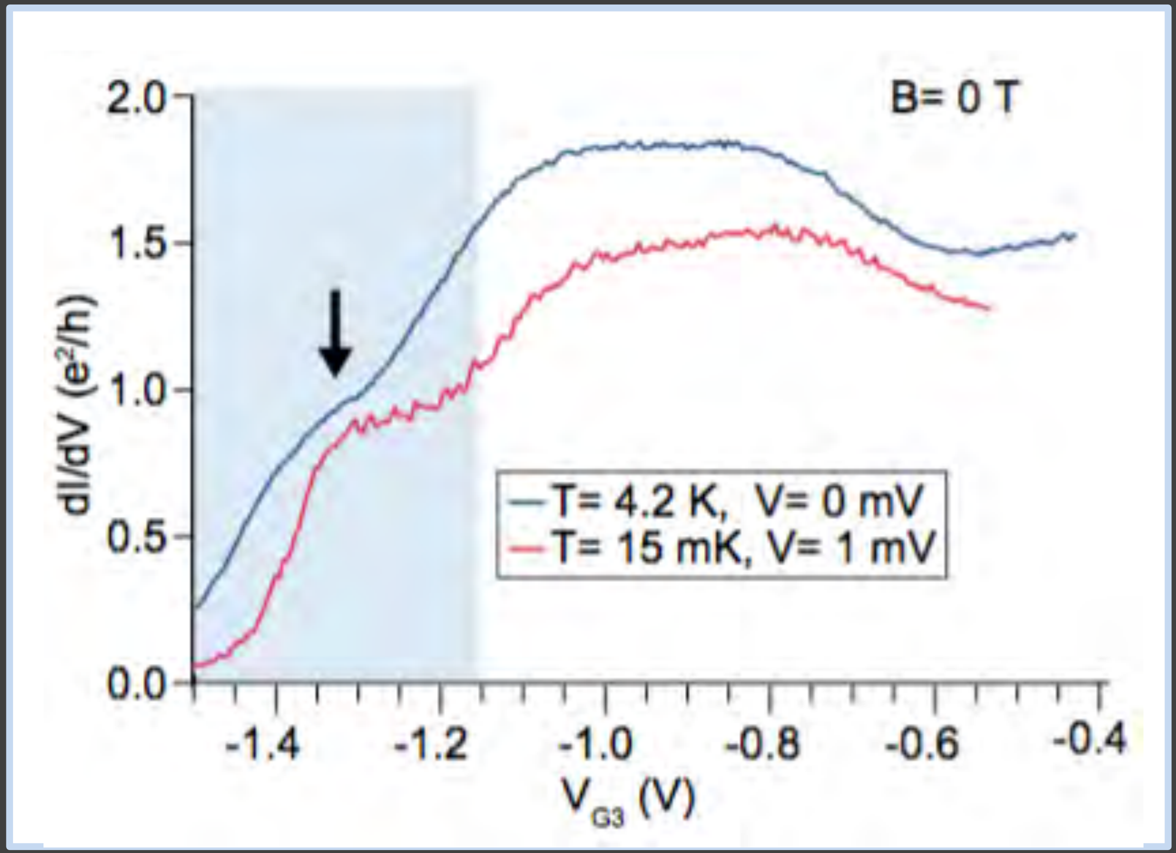
Localized state: U ~ 1.3 meV



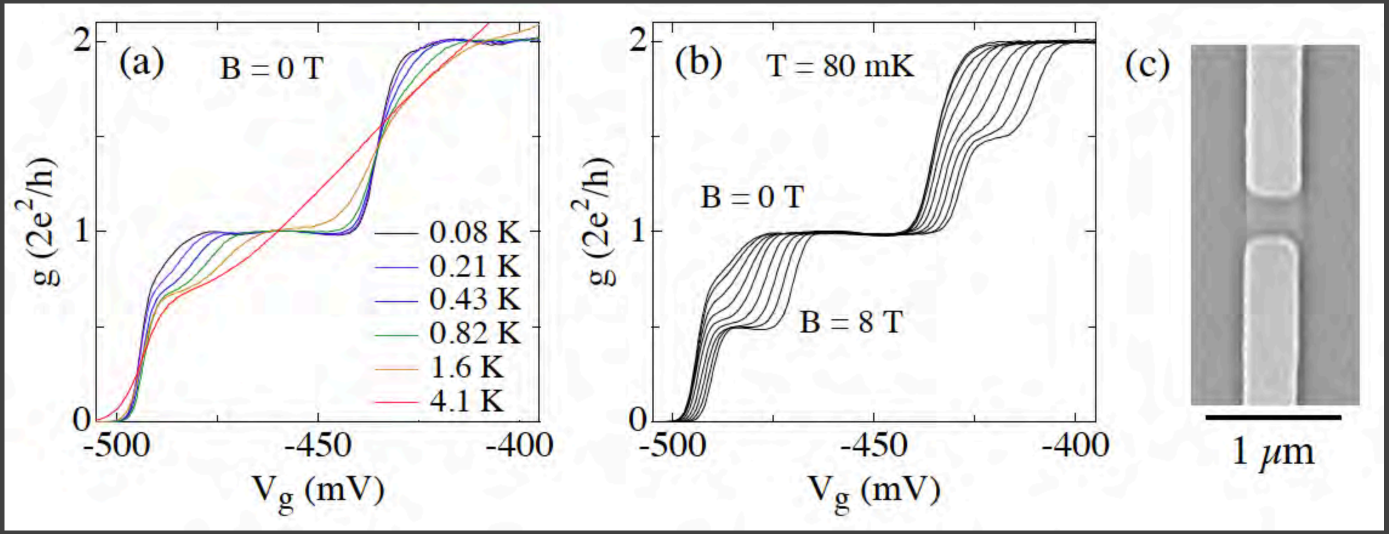


=> Lever-arm parameter α = 0.008 meV/mV

“0.7”- type anomaly at B=0

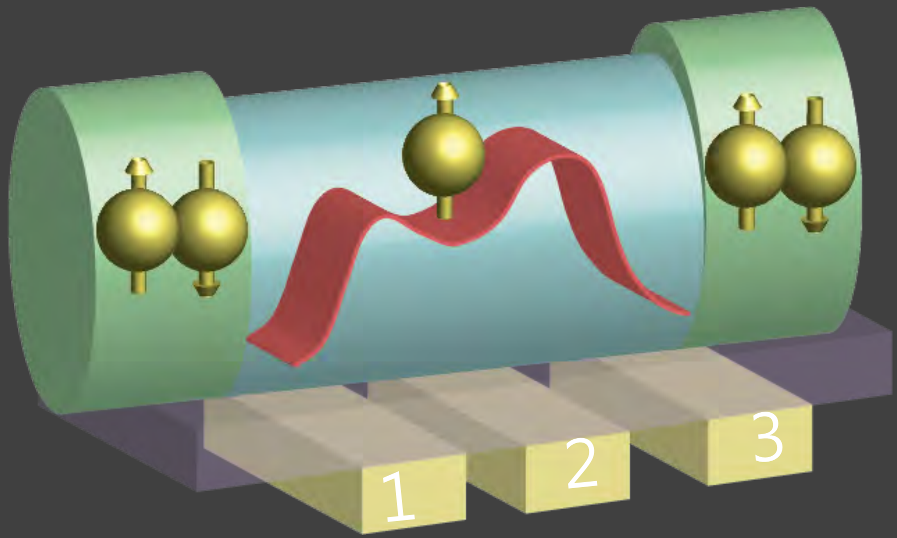


“0.7” anomaly in quantum point contacts

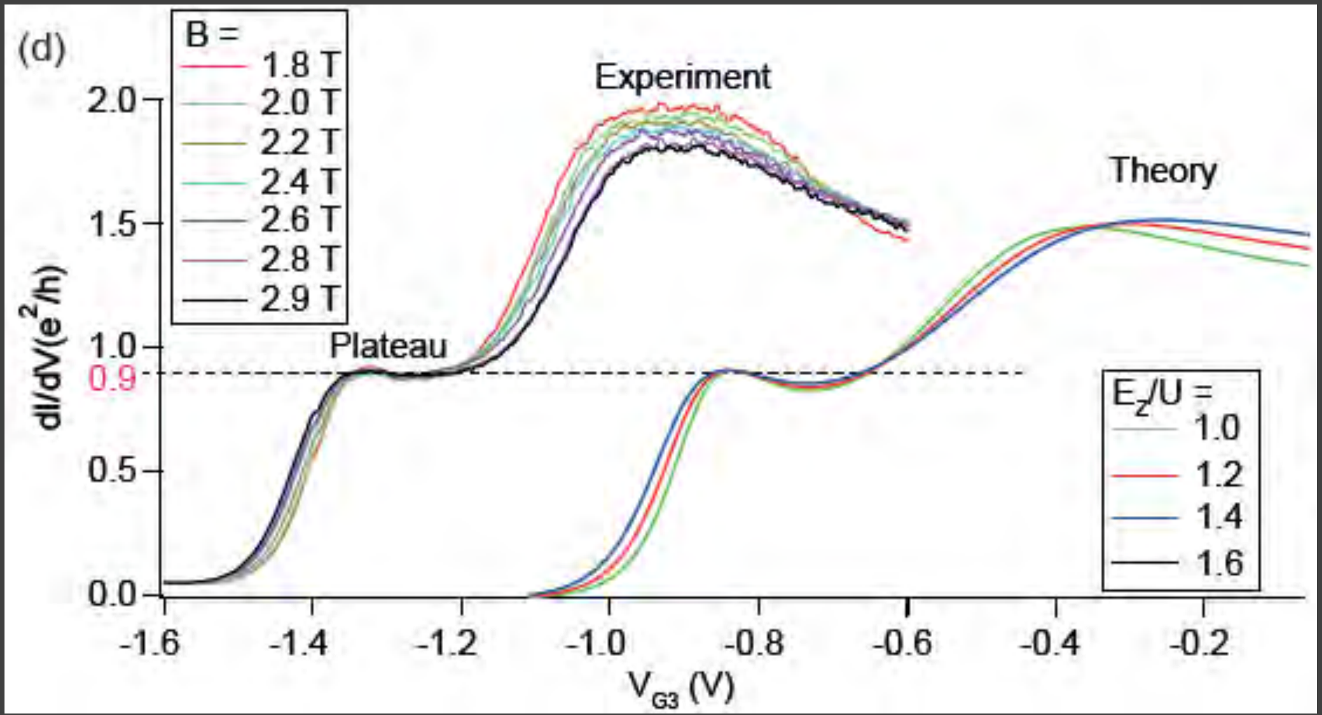


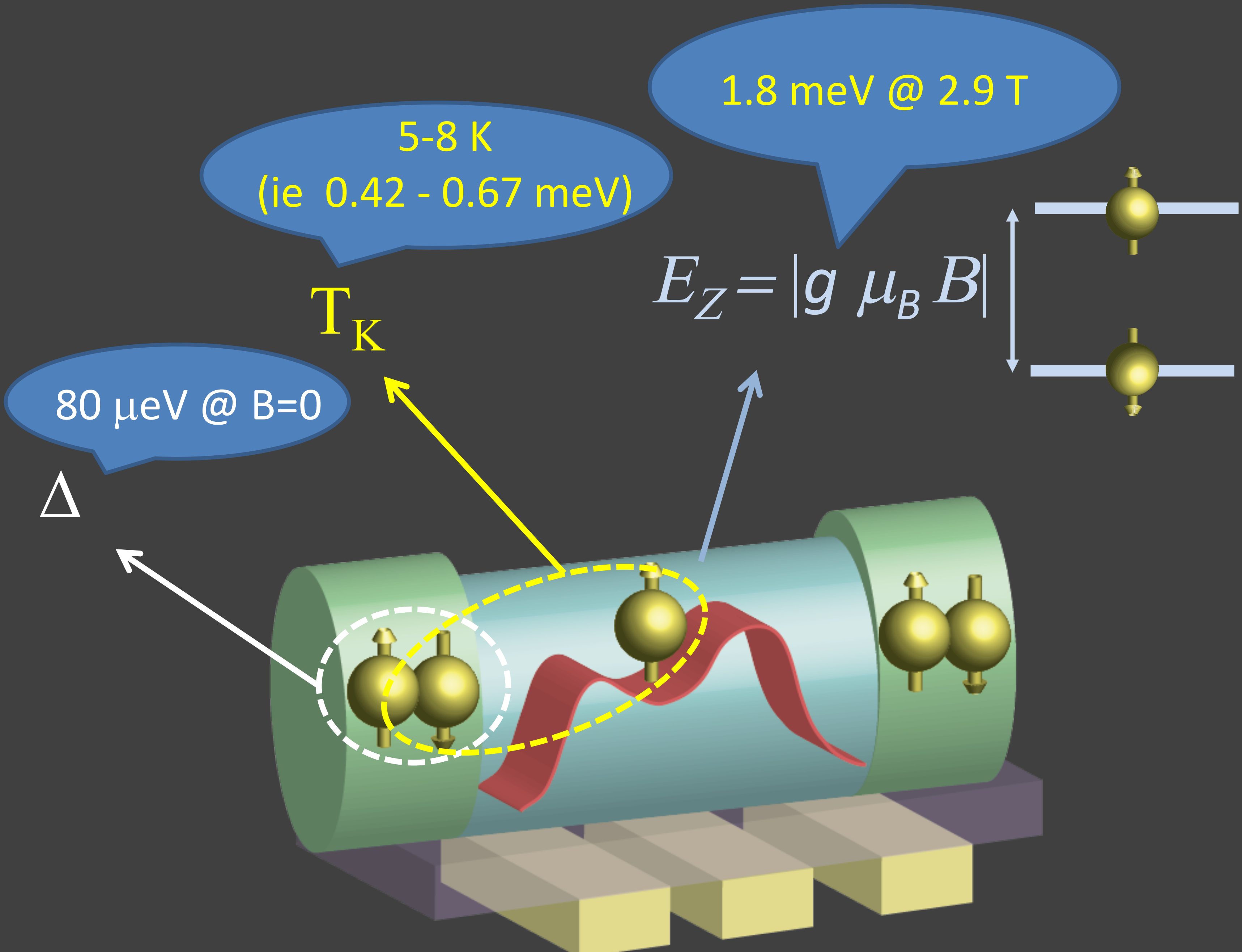
[From Cronenwett et al. PRL 2002]

Possible origin:
Kondo-effect associated with a quasi-localized spin-1/2 state
[Theory: Meir, Hirose, Wingreen, PRL 2002]

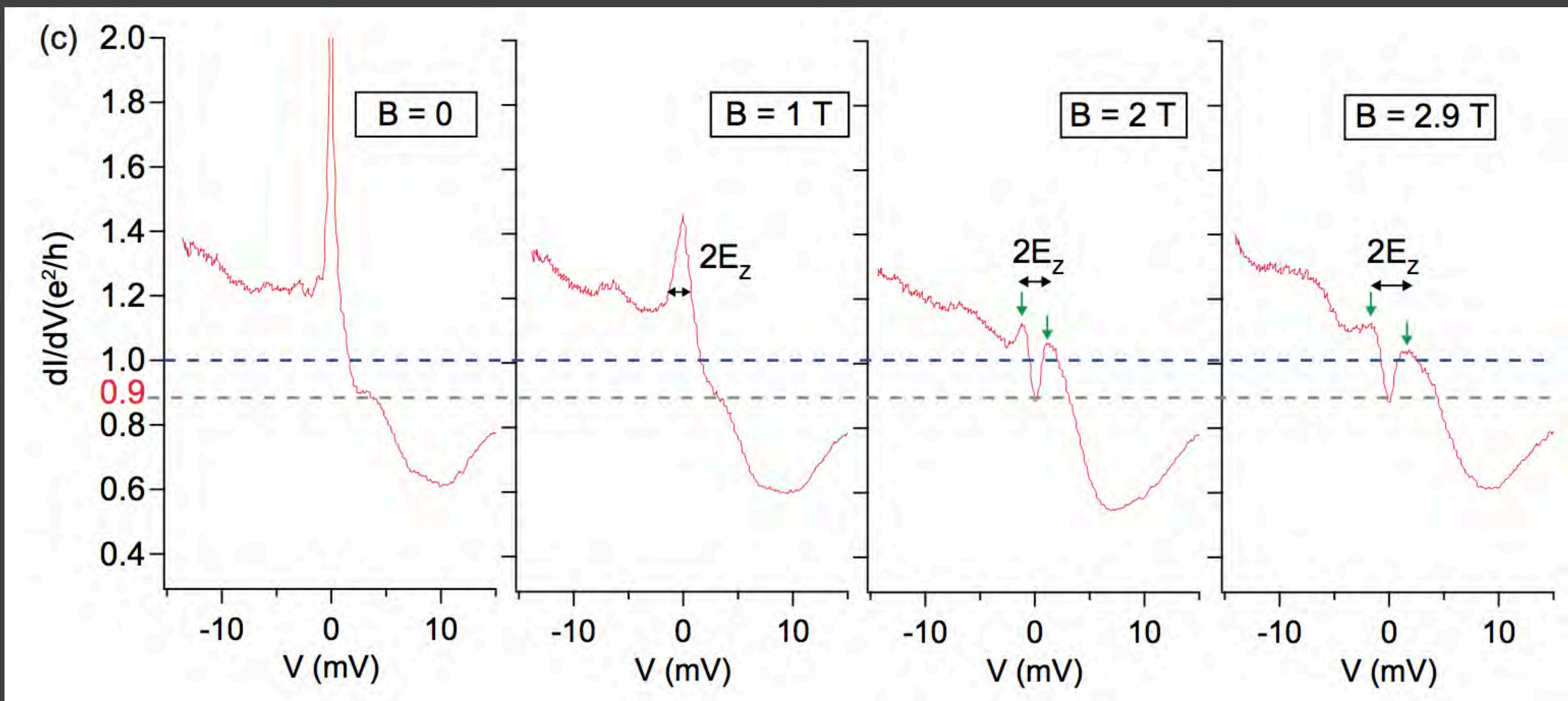


Model:
Quantum dot with Gamma quadratically increasing with V_{G3}

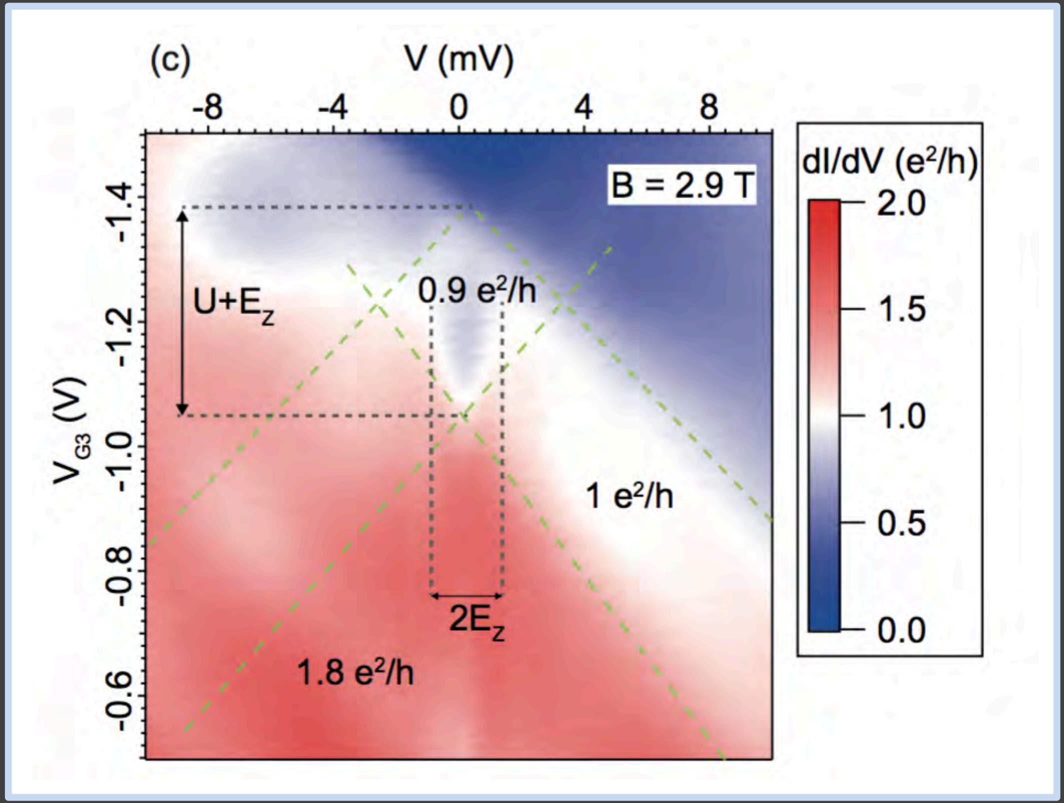




1.8 meV @ 2.9 T
5-8 K
(ie 0.42 - 0.67 meV)
$E_Z = |g\ \mu_B\ B|$
T_K
80 μeV @ B=0
Δ

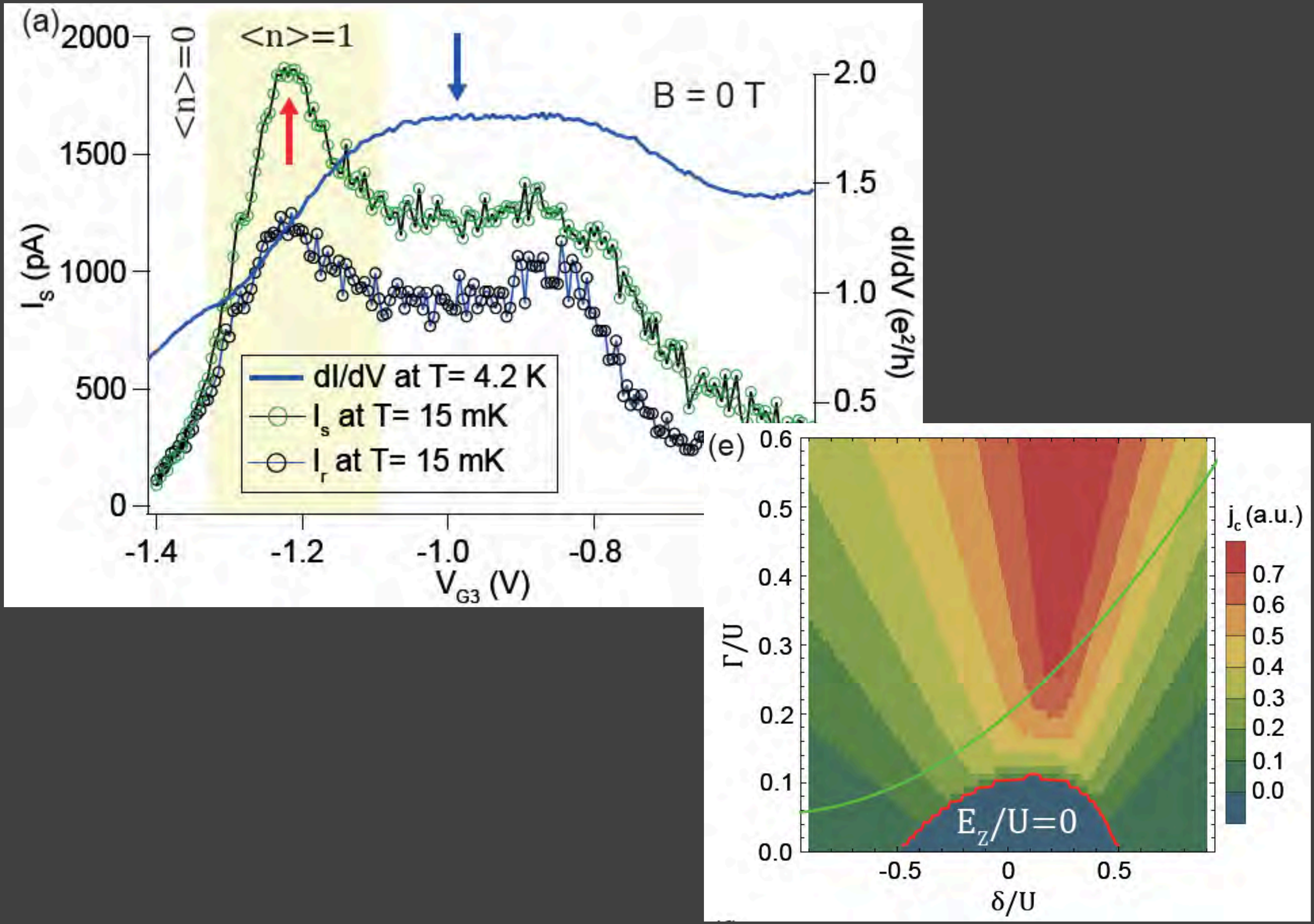


(c)
dI/dV(e²/h)
2.0
1.8
1.6
1.4
1.2
1.0
0.9
0.8
0.6
0.4
B = 0
B = 1 T
B = 2 T
B = 2.9 T
2E_z
2E_z
2E_z
-10
0
10
V (mV)
V (mV)
V (mV)
V (mV)

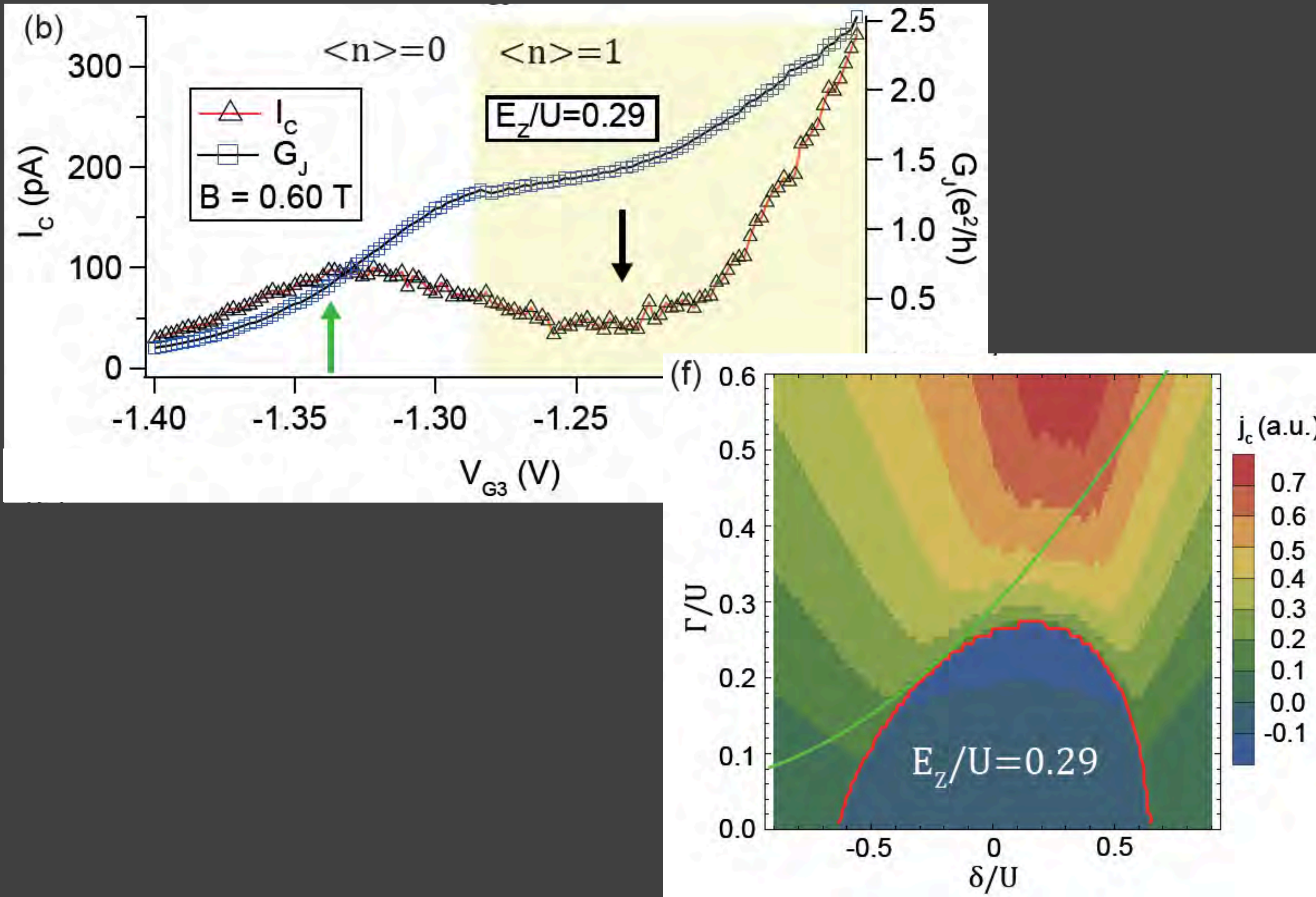


=> Lever-arm parameter α = 0.008 meV/mV

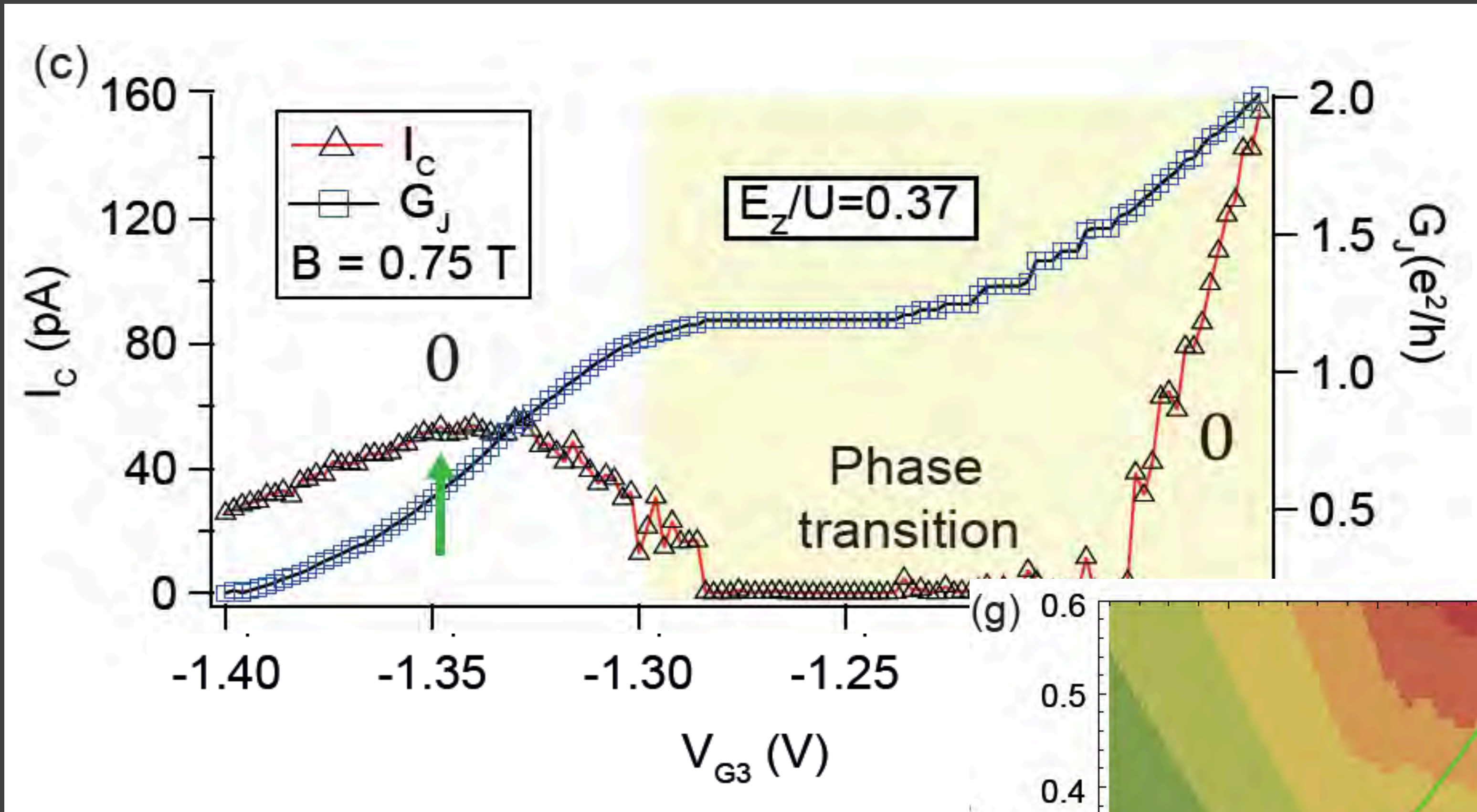
Critical current vs gate voltage: Experiment (fit with RCSJ model) vs Theory (NRG)

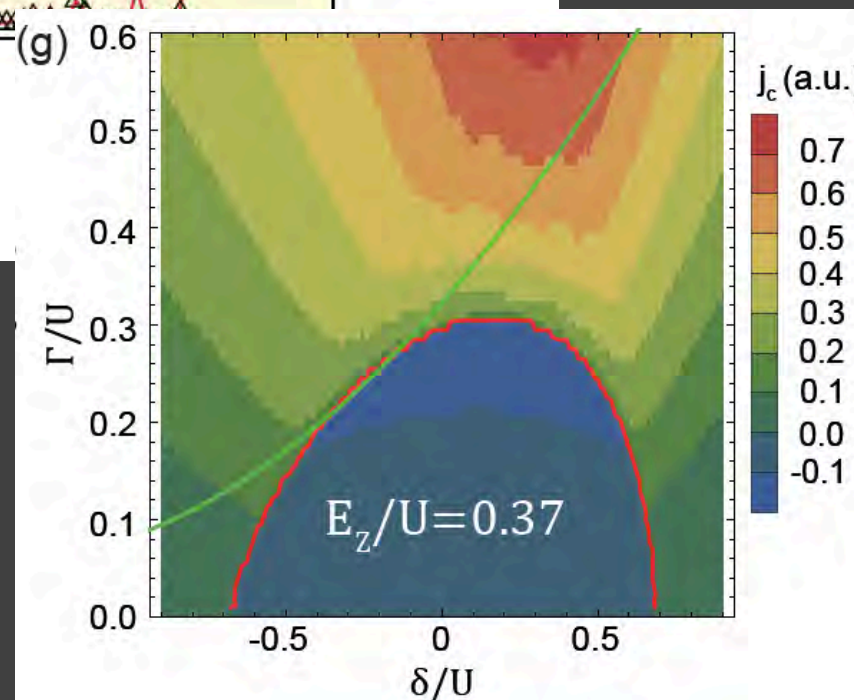


Critical current vs gate voltage: Experiment (fit with RCSJ model) vs Theory (NRG)

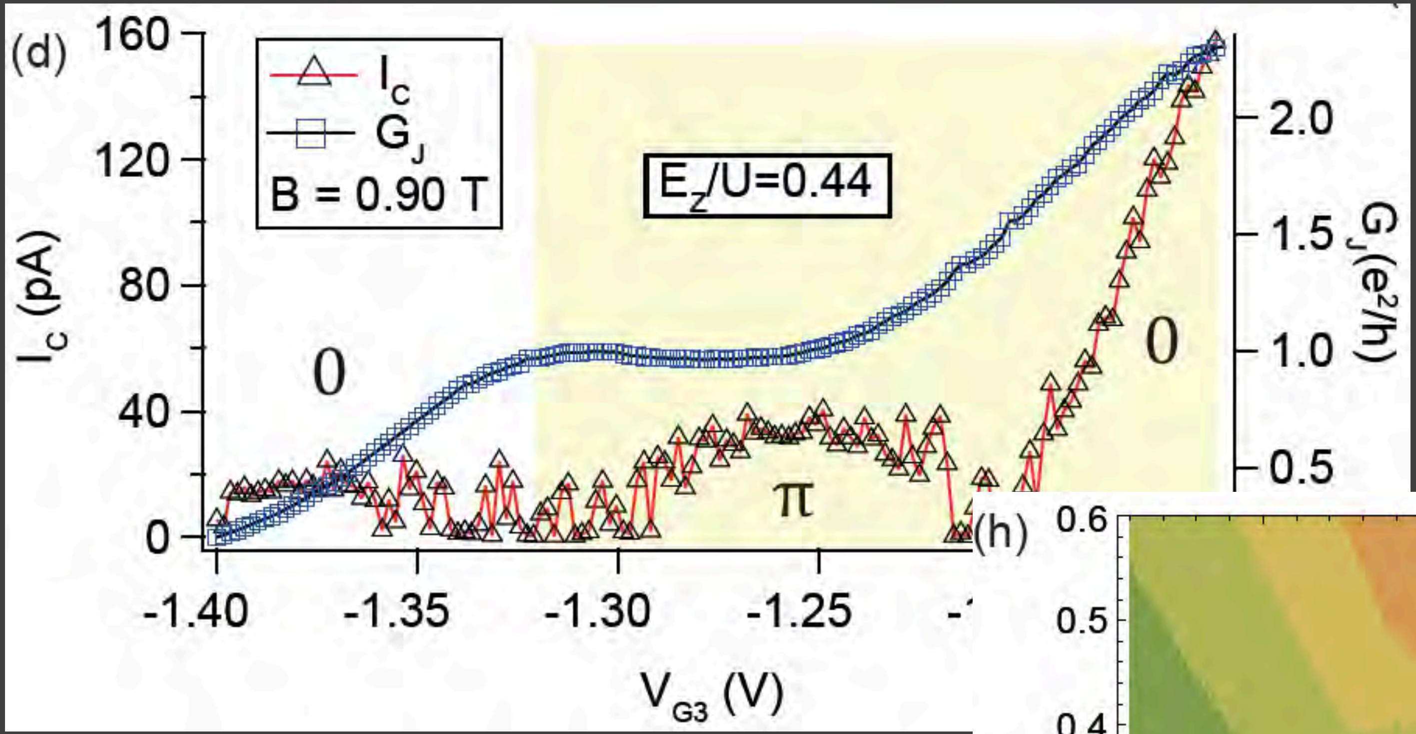


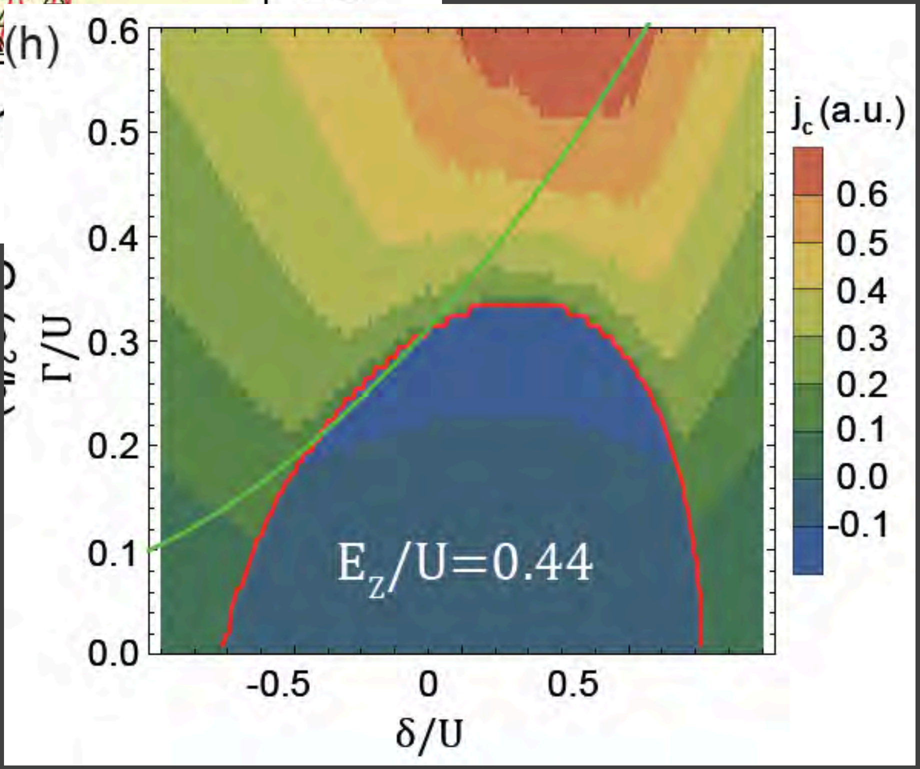
Critical current vs gate voltage: Experiment (fit with RCSJ model) vs Theory (NRG)





Critical current vs gate voltage: Experiment (fit with RCSJ model) vs Theory (NRG)





Conclusions

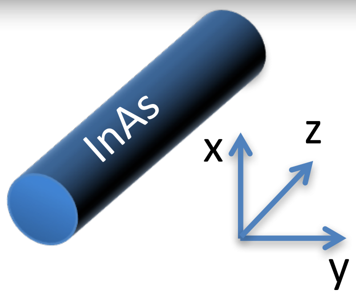
- Strongly confined (0-D) quantum dot coupled to a superconductor [Lee et al., Phys. Rev. B 95, 180502(R), 2017]

  - ➢ Accurately reproduced by a “simple” Anderson impurity model

- Quasi-ballistic (quasi 1D) junction with superconducting leads [Estrada Saldaña et al., in preparation]

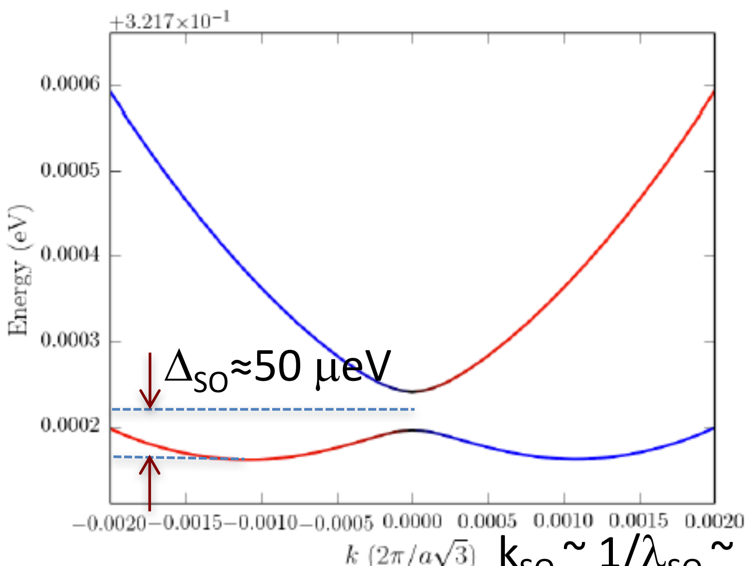
  - ➢ Coulomb interaction relevant also for short, quasi-ballistic one-dimensional wires
  - ➢ Demonstrated B-induced re-emergence of a proximity supercurrent

Tight-binding calculations (Y.M. Niquet)



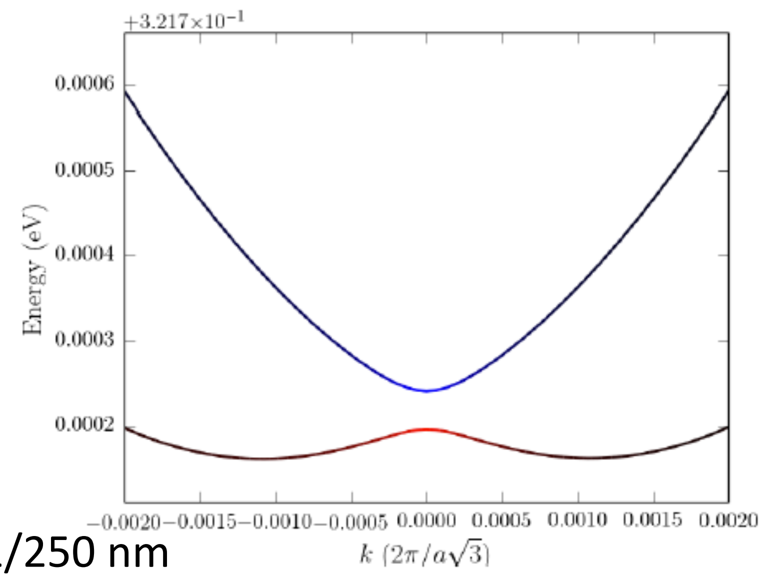
B_z = 100 mT
E_x = 20 mV/nm

Rashba Hamiltonian:
$H_{SO} = \alpha\, \sigma_y\, E_x$



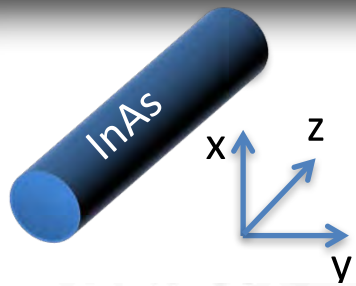
k_{SO} ~ $1/\lambda_{SO}$ ~ 1/250 nm

σ_y *(red = +1 ; black = 0 ; blue = -1)*



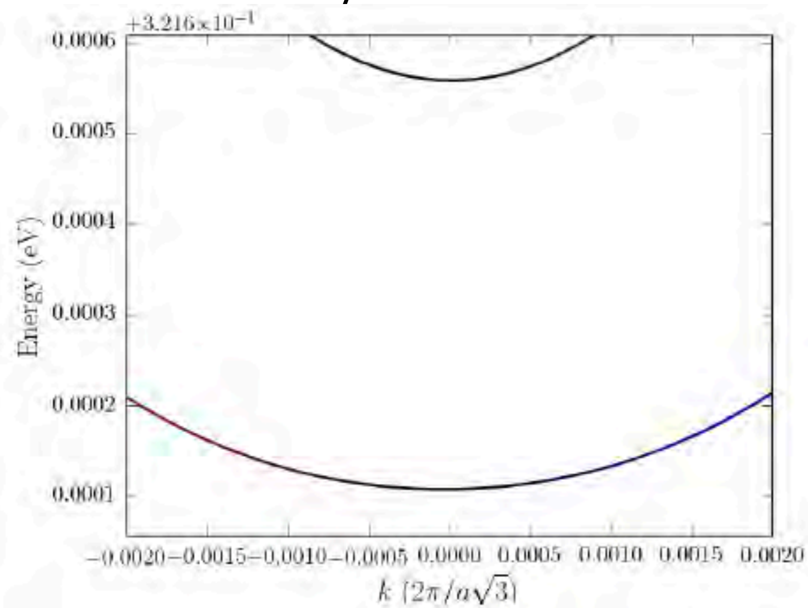
σ_z *(red = +1 ; black = 0 ; blue = -1)*

Tight-binding calculations (Y.M. Niquet)

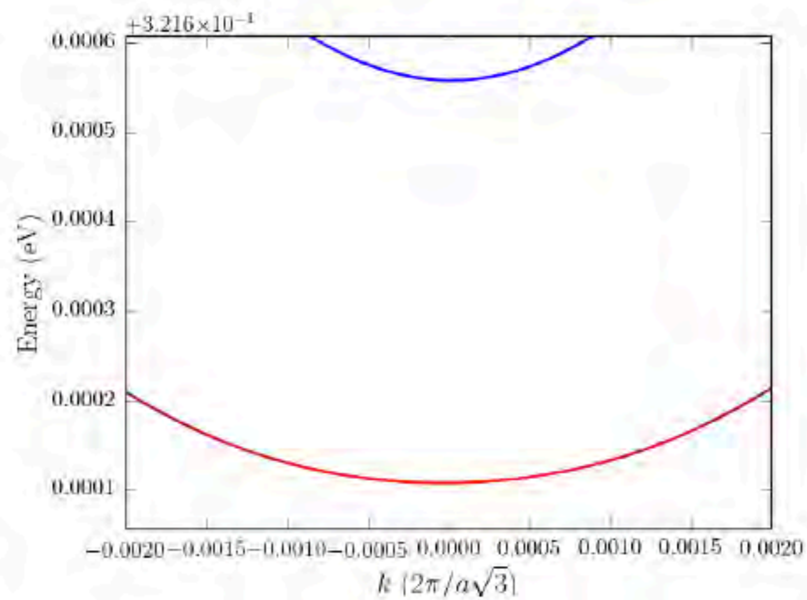


B_z = 1 T
E_x = 20 mV/nm

Rashba Hamiltonian:
$H_{SO} = \alpha\, \sigma_y\, E_x$

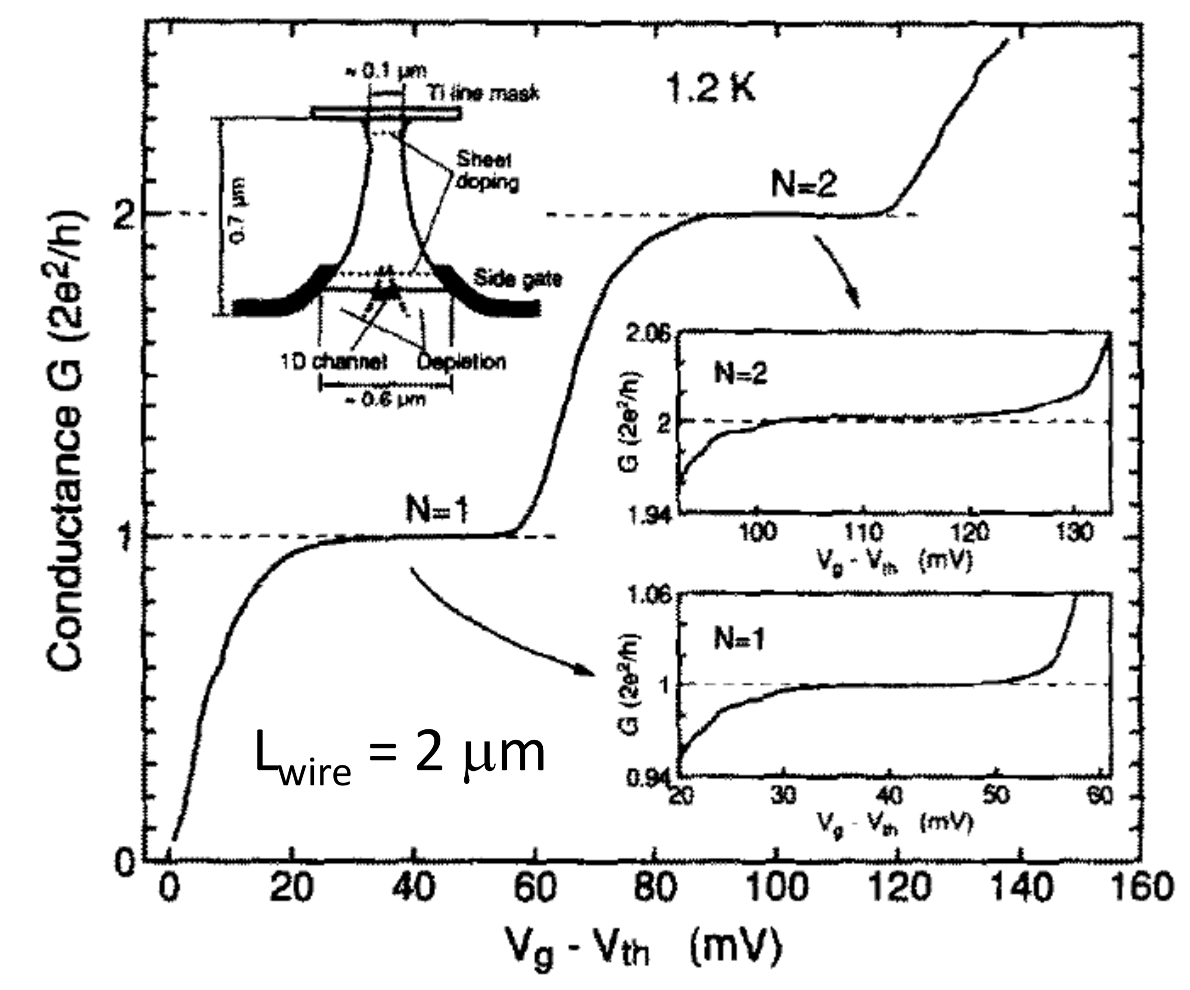


σ_y (red = +1 ; black = 0 ; blue = -1)

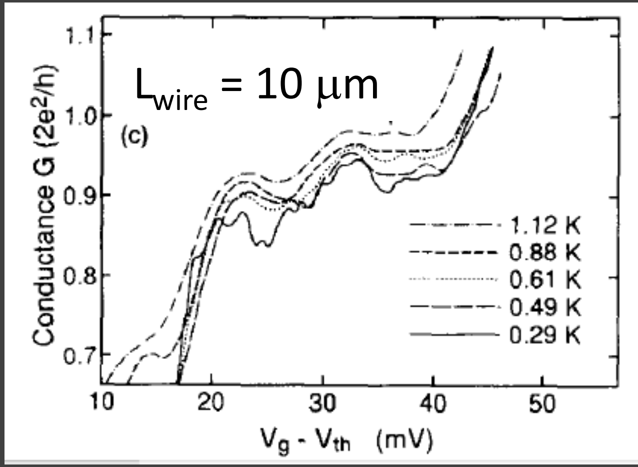


σ_z (red = +1 ; black = 0 ; blue = -1)

Best 1D conductors: GaAs/AlGaAs high-mobility heterostructures

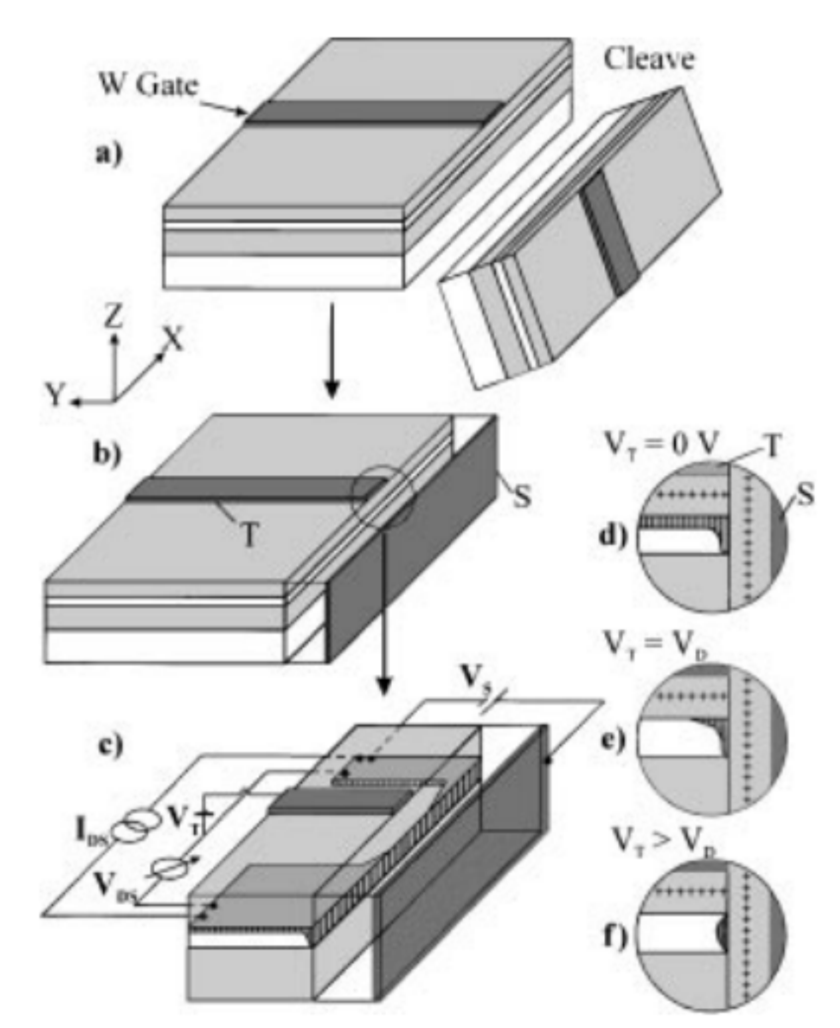


Very deep 2DEG!

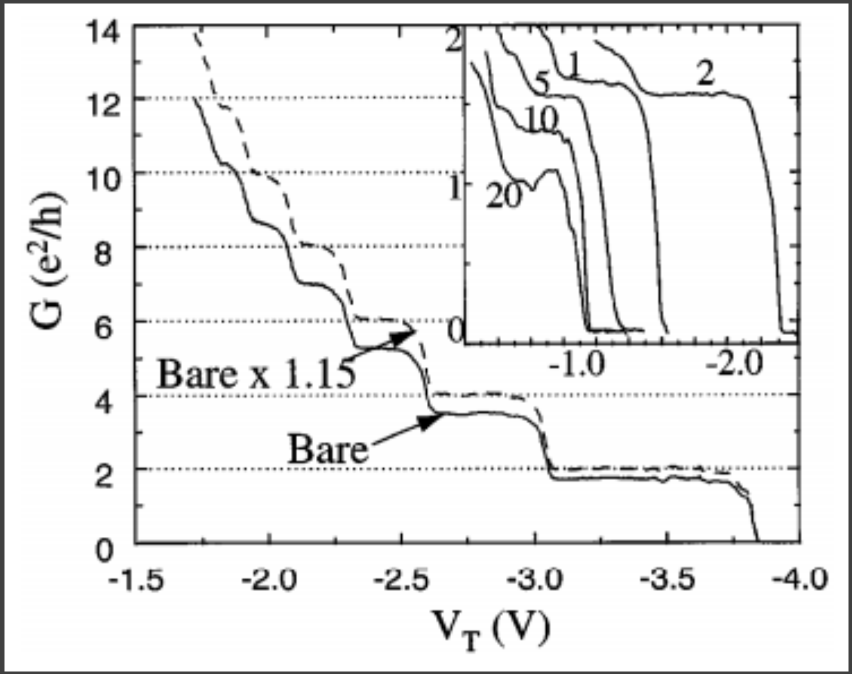


Tarucha et al., Solid State Comm. 94, 413 (1995)

Best 1D conductor: GaAs/AlGaAs high-mobility heterostructures



Very deep 2DEG!



Yacoby et al., PRL 77, 4612 (1996)

Superconducting proximity effect in InAs nanowires

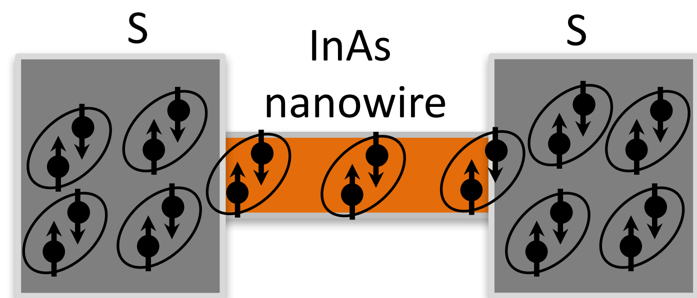
Science 309 272 (2005)

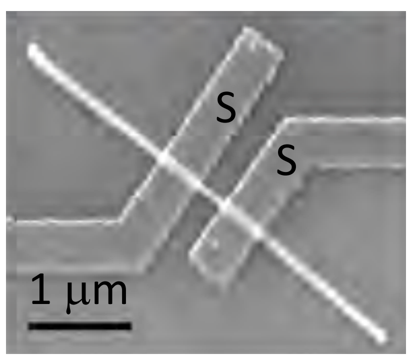
REPORTS

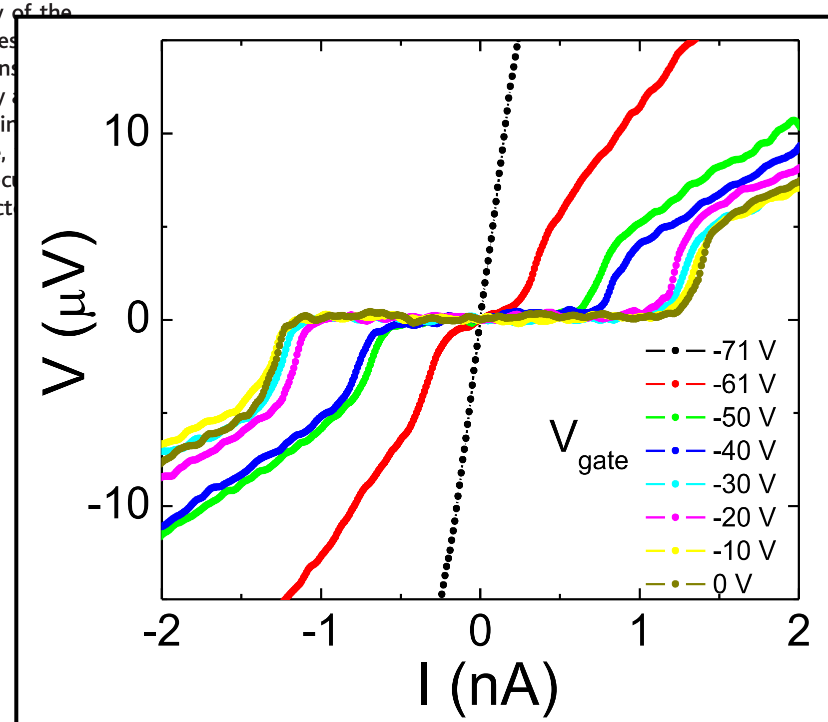
Tunable Supercurrent Through Semiconductor Nanowires

Yong-Joo Doh,[1*] Jorden A. van Dam,[1*] Aarnoud L. Roest,[1,2]
Erik P. A. M. Bakkers,[2] Leo P. Kouwenhoven,[1]
Silvano De Franceschi[1†]

Nanoscale superconductor/semiconductor hybrid devices are assembled from indium arsenide semiconductor nanowires individually contacted by aluminum-based superconductor electrodes. Below 1 kelvin, the high transparency of the contacts gives rise to proximity-induced superconductivity. The nanowires superconducting weak links operating as mesoscopic Josephson junctions electrically tunable coupling. The supercurrent can be switched on/off by voltage acting on the electron density in the nanowire. A variation in voltage induces universal fluctuations in the normal-state conductance, are clearly correlated to critical current fluctuations. The alternating-c Josephson effect gives rise to Shapiro steps in the voltage-current charact under microwave irradiation.







Superconducting proximity effect in InAs nanowires

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Tunable Supercurrent Through Semiconductor Nanowires

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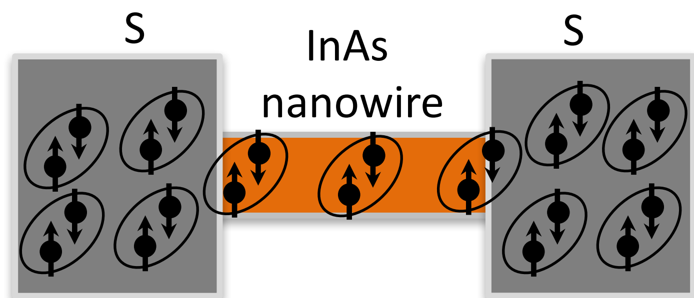
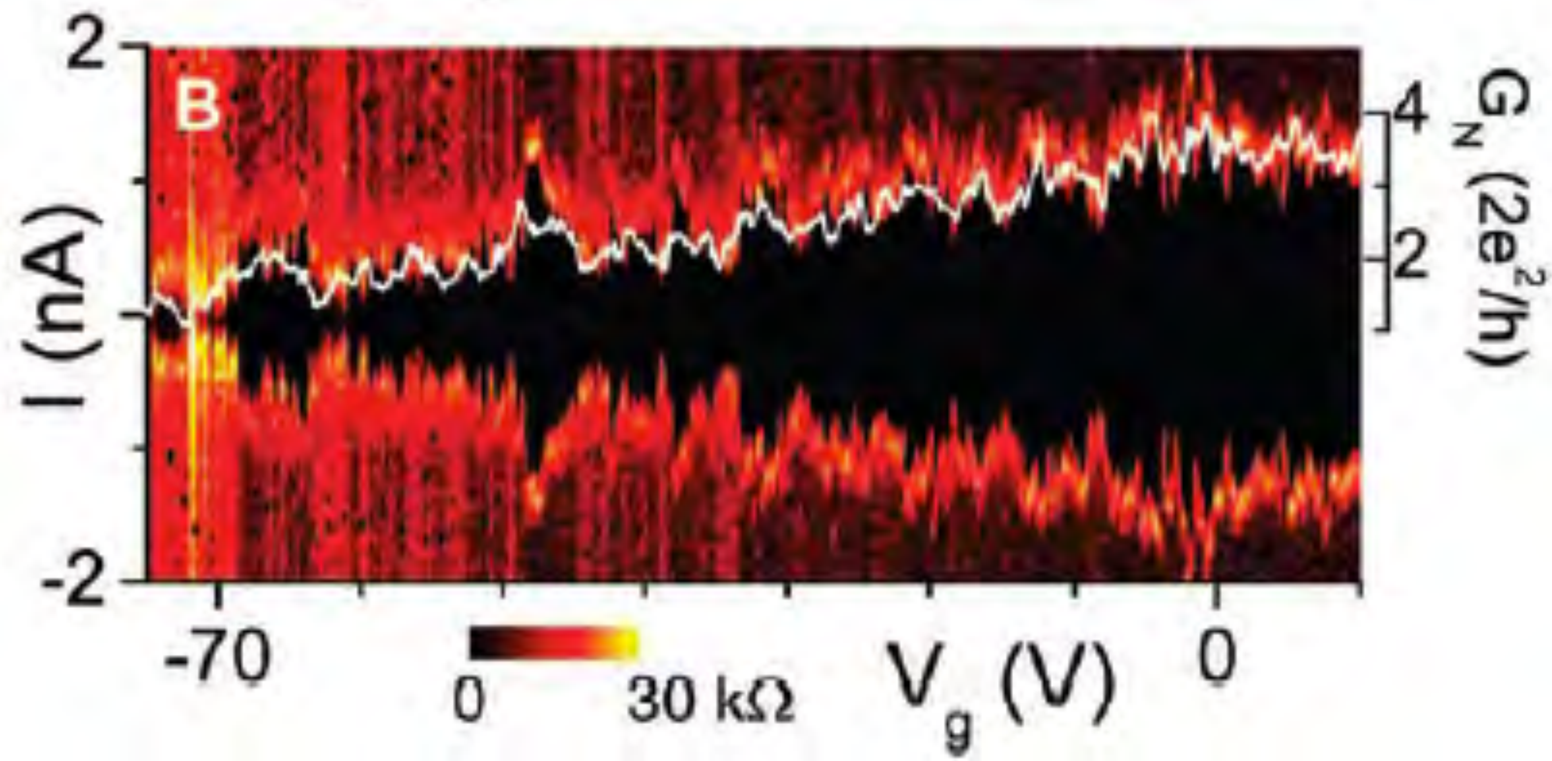
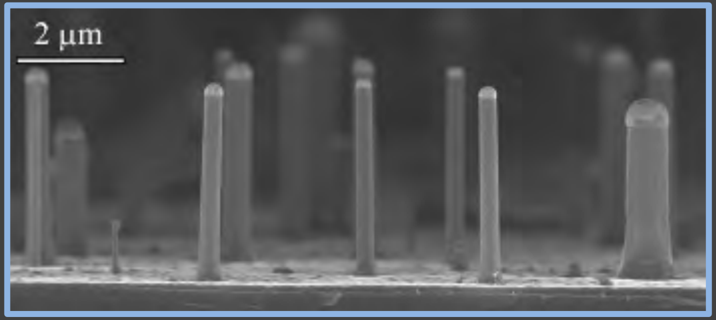
Nanoscale superconductor/semiconductor hybrid devices are assembled from



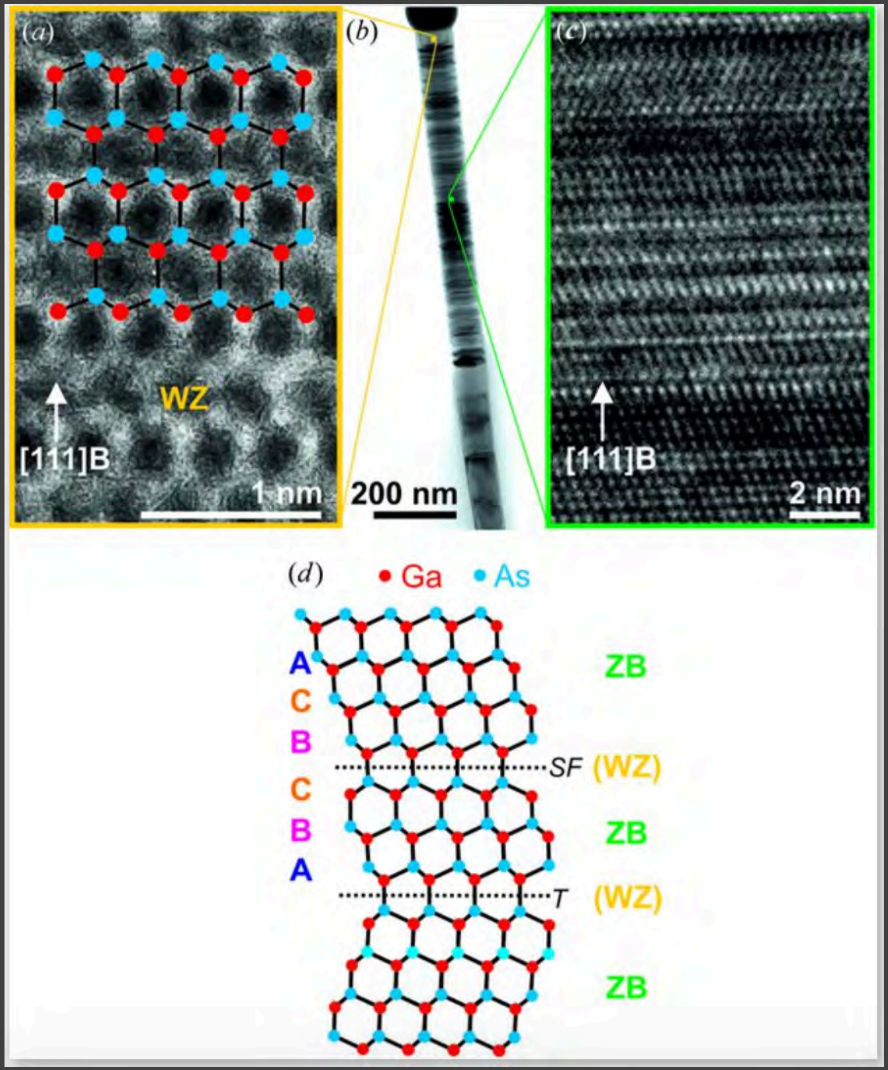


Outline

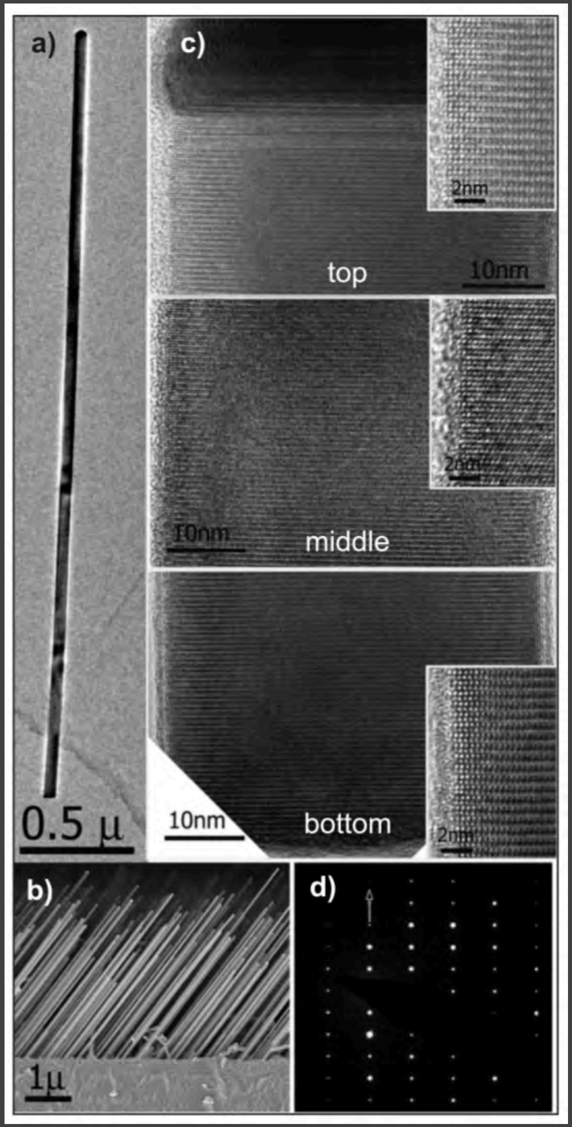


- 1D transport in bottom-up semiconductor nanowires
- Localization effects
- Superconducting proximity effect in a quasi-ballistic channel

Stacking faults in InAs nanowires



[from Bussone et al. J. Appl. Crystal (2013)]



[from Kretinin et al. Nano Lett. 2010]

Nanotechnology 26 (2015) 215202 (7pp) doi:10.1088/0957-4484/26/21/215202

Towards high mobility InSb nanowire devices

Önder Gül[1,4], David J van Woerkom[1,4], Ilse van Weperen[1,4], Diana Car[2], Sébastien R Plissard[1,2,3], Erik P A M Bakkers[1,2] and Leo P Kouwenhoven[1]

[1] QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands
[2] Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
[3] Present address: Laboratoire d'Analyse et d'Architecture des Systèmes, 7, avenue du Colonel Roche BP 54200 F-31031 Toulouse cedex 4, France

E-mail: o.gul@tudelft.nl

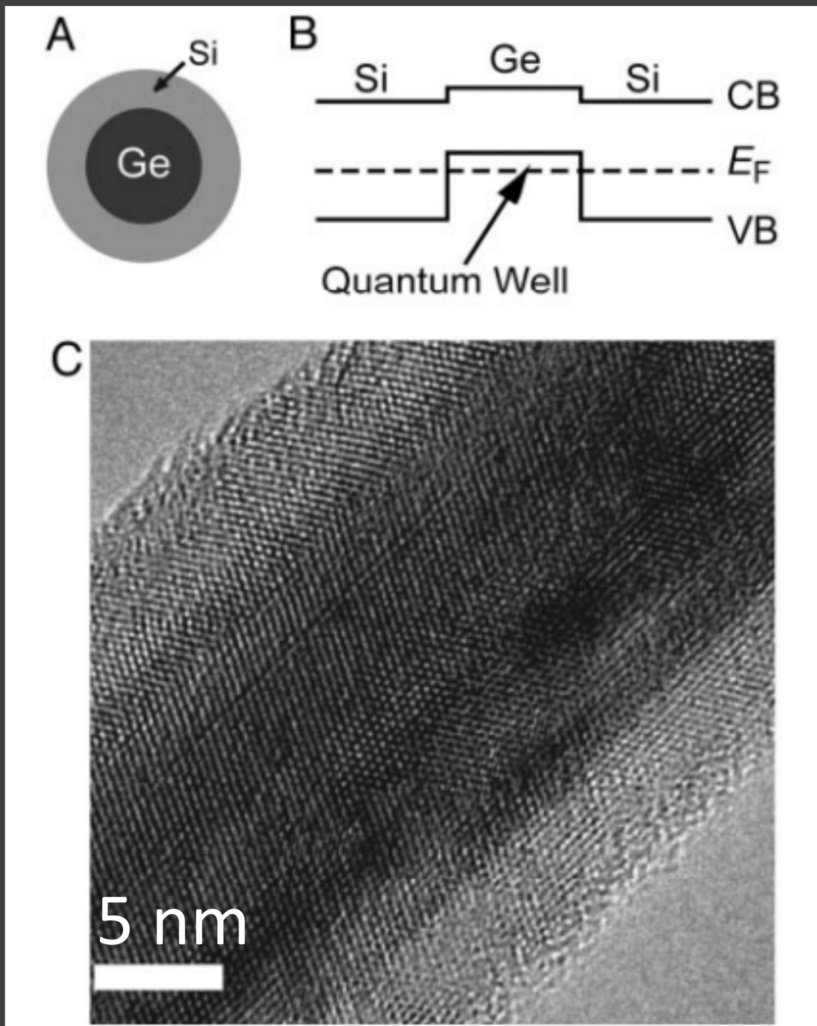
Received 26 November 2014, revised 25 March 2015
Accepted for publication 27 March 2015
Published 6 May 2015

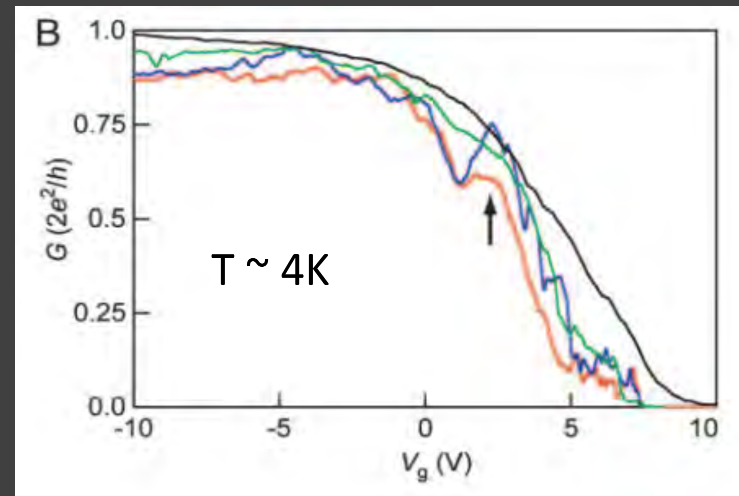
Abstract

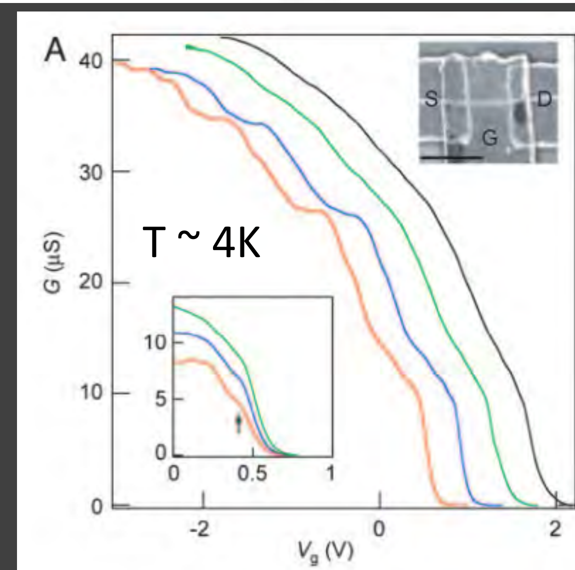
We study the low-temperature electron mobility of InSb nanowires. We extract the mobility at 4.2 K by means of field effect transport measurements using a model consisting of a nanowire-transistor with contact resistances. This model enables an accurate extraction of device parameters, thereby allowing for a systematic study of the nanowire mobility. We identify factors affecting the mobility, and after optimization obtain a field effect mobility of $\sim 2.5 \times 10^4$ $cm^2\,V^{-1}\,s^{-1}$. We further demonstrate the reproducibility of these mobility values which are among the highest reported for nanowires. Our investigations indicate that the mobility is currently limited by adsorption of molecules to the nanowire surface and/or the substrate.

Conductance quantization reported for Ge/Si core/shell nanowires

Lu et al. PNAS **102**, 10036 (2005)







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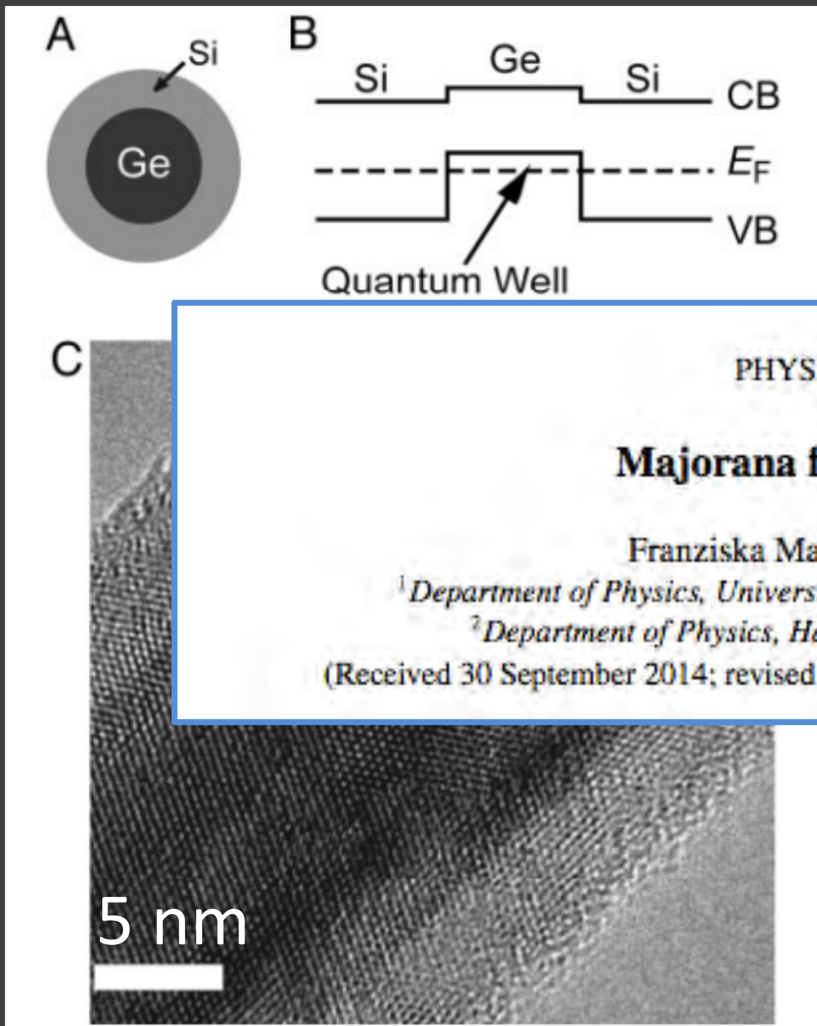
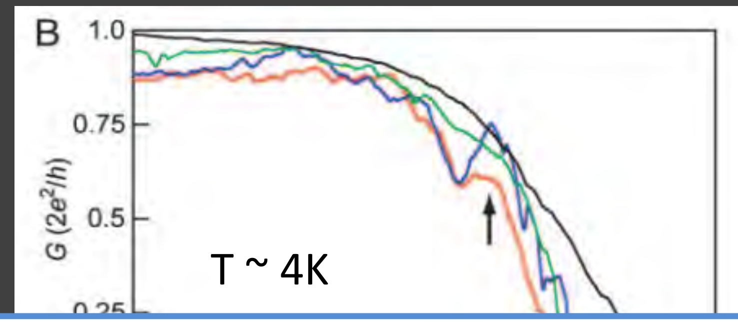
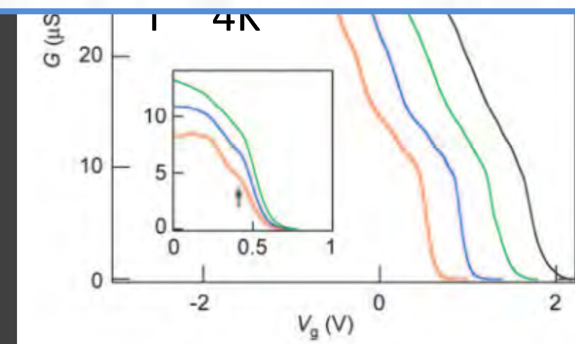




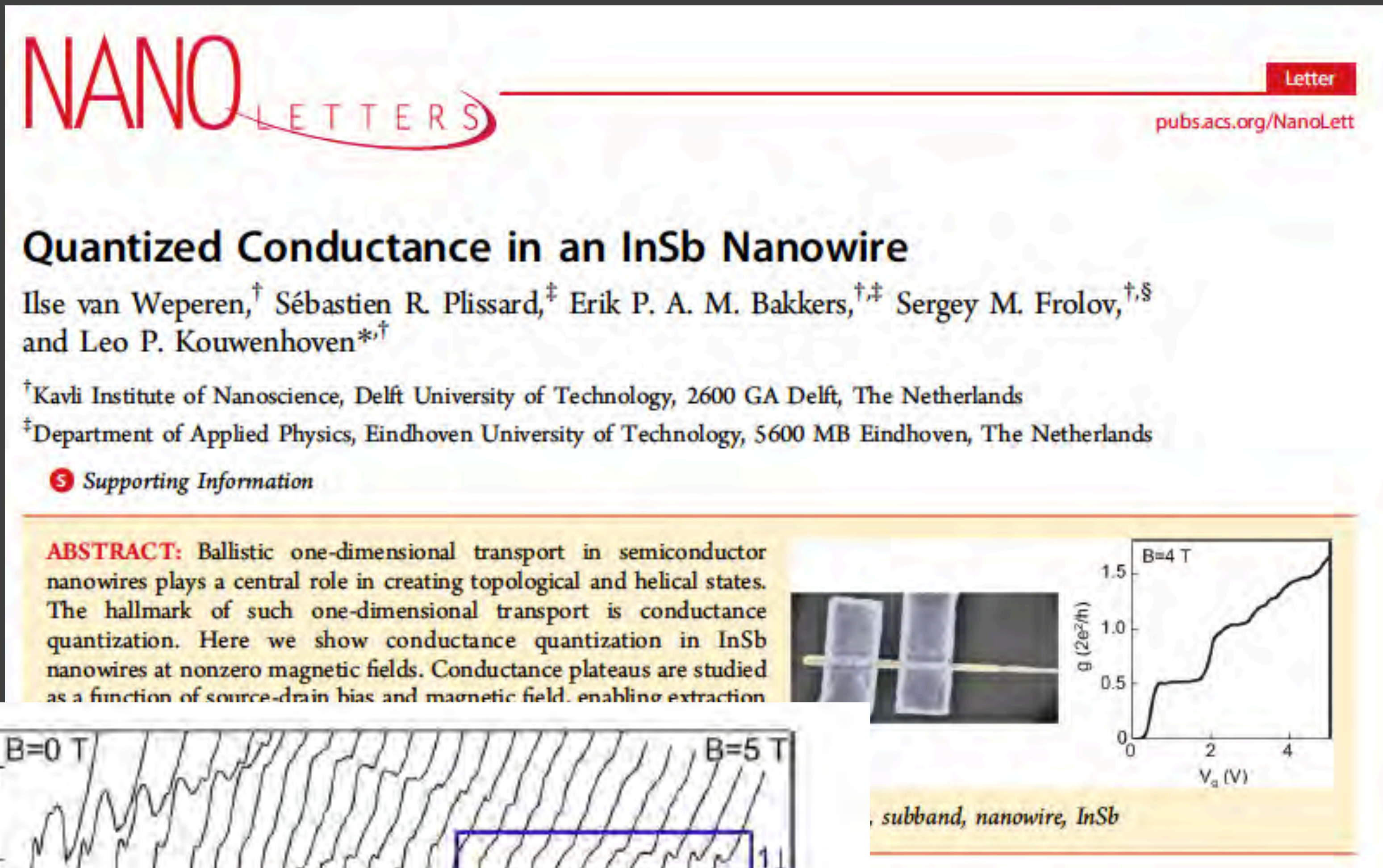
PHYSICAL REVIEW B **90**, 195421 (2014)

Majorana fermions in Ge/Si hole nanowires

Franziska Maier,[1] Jelena Klinovaja,[2] and Daniel Loss[1]
[1] *Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[2] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
(Received 30 September 2014; revised manuscript received 31 October 2014; published 17 November 2014)



One-dimensionality in InSb nanowires


NANO LETTERS
Letter
pubs.acs.org/NanoLett

Quantized Conductance in an InSb Nanowire

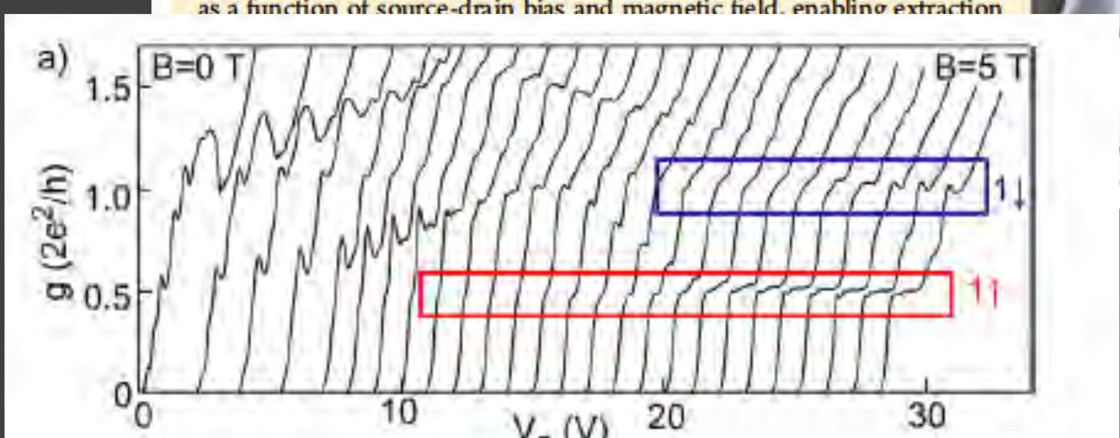
Ilse van Weperen,[†] Sébastien R. Plissard,[‡] Erik P. A. M. Bakkers,[†,‡] Sergey M. Frolov,[†,§] and Leo P. Kouwenhoven*[,†]

[†]Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands
[‡]Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

Supporting Information

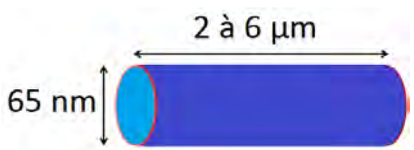
ABSTRACT: Ballistic one-dimensional transport in semiconductor nanowires plays a central role in creating topological and helical states. The hallmark of such one-dimensional transport is conductance quantization. Here we show conductance quantization in InSb nanowires at nonzero magnetic fields. Conductance plateaus are studied as a function of source-drain bias and magnetic field, enabling extraction

, *subband, nanowire, InSb*

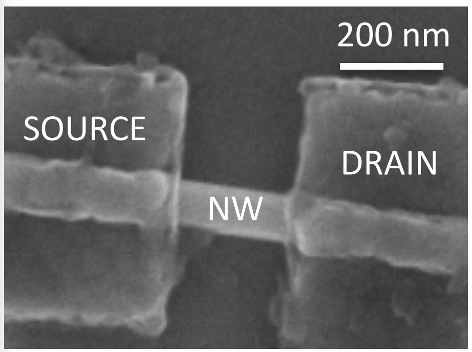


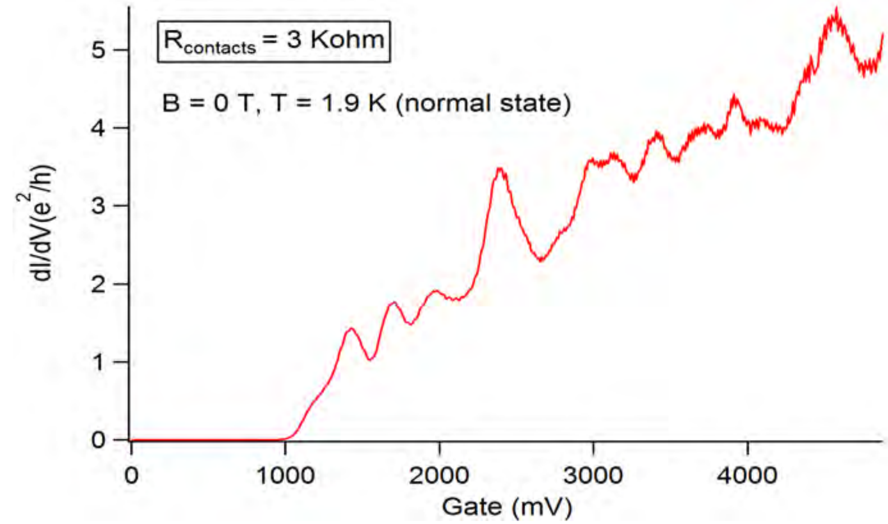
(2013)

Assessing 1D character of InAs nanowires

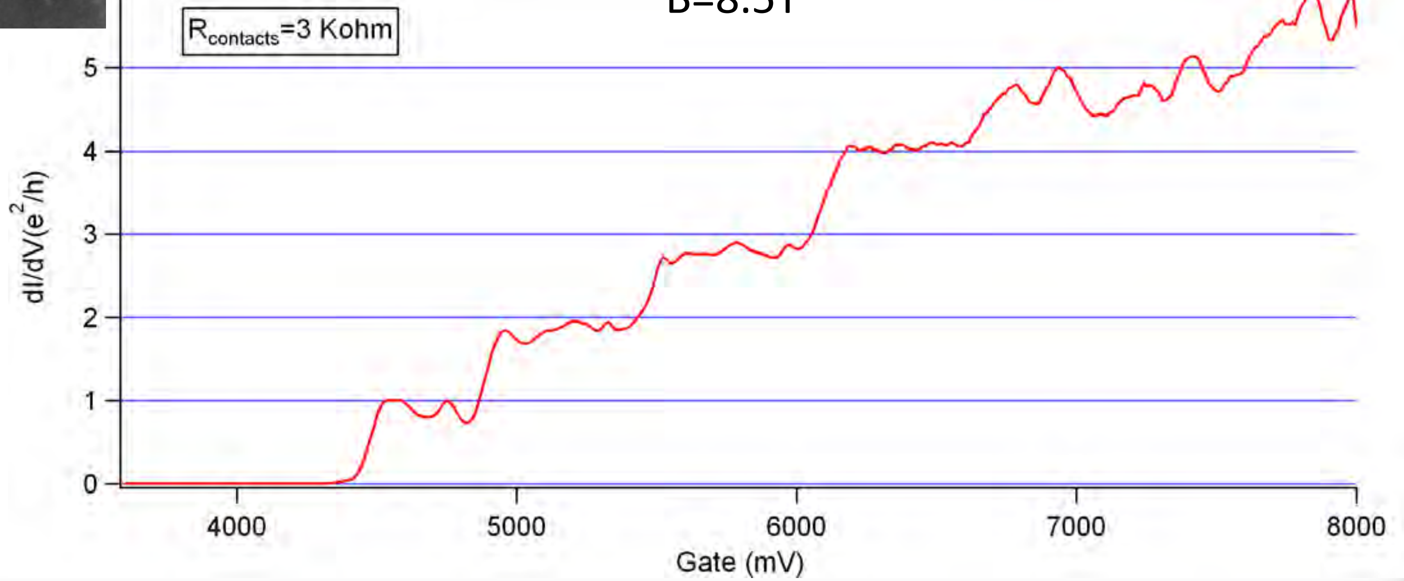


Material from Sorba's group (Pisa)



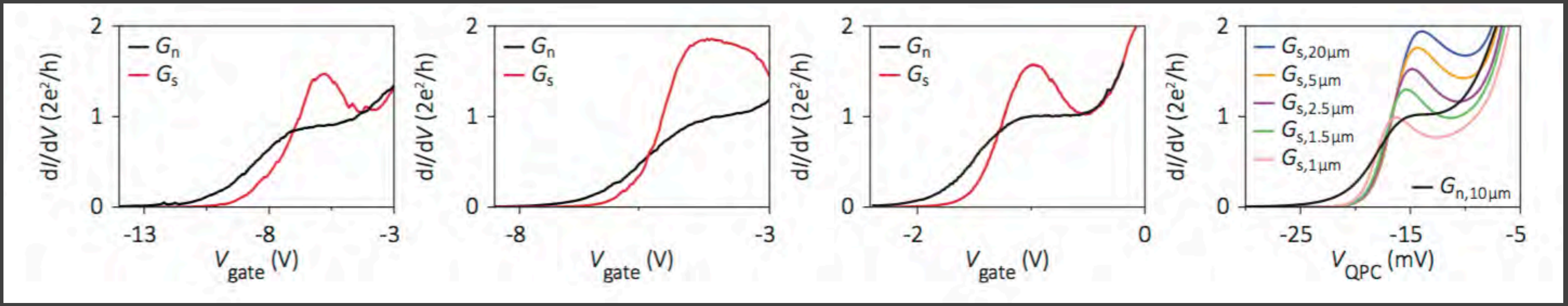


B=8.5T

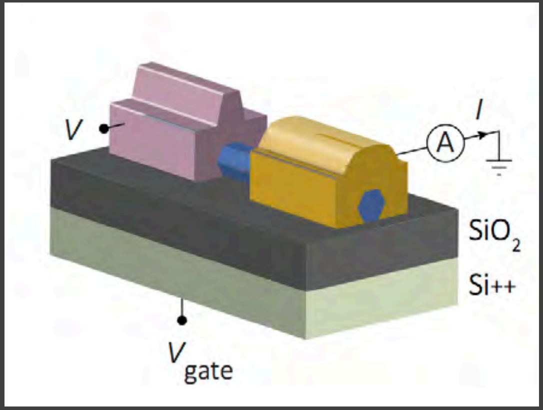


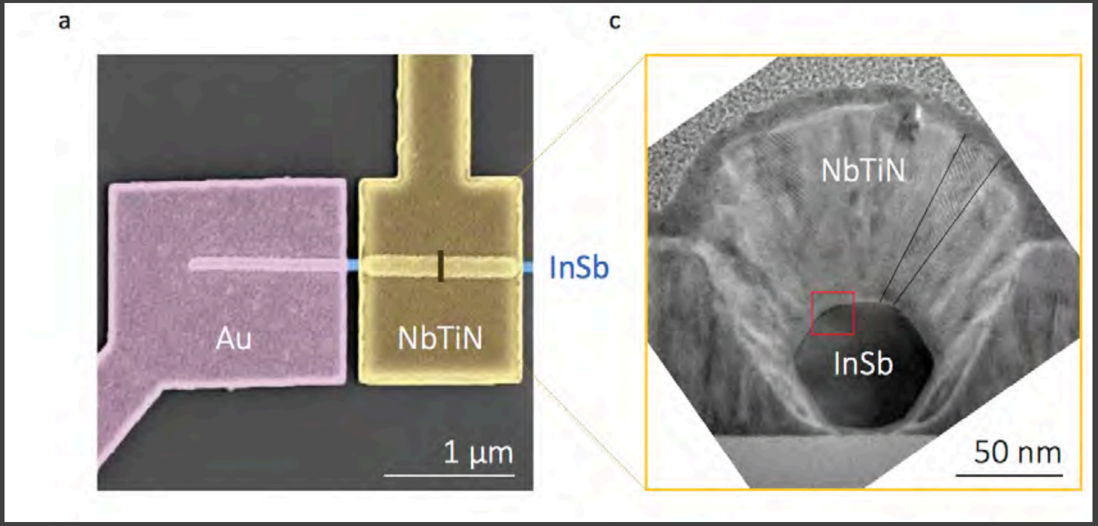
(unpublished)

One-dimensionality in InSb nanowires

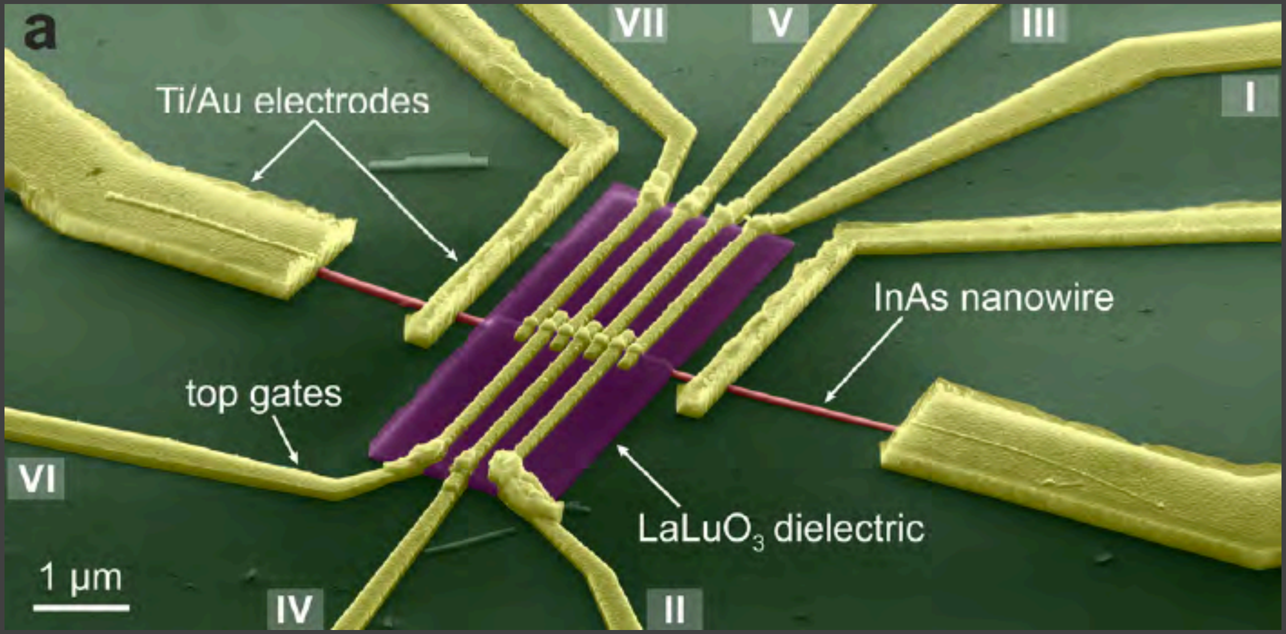


[reproduced from Zhang et al., arXiv:1603.04069]

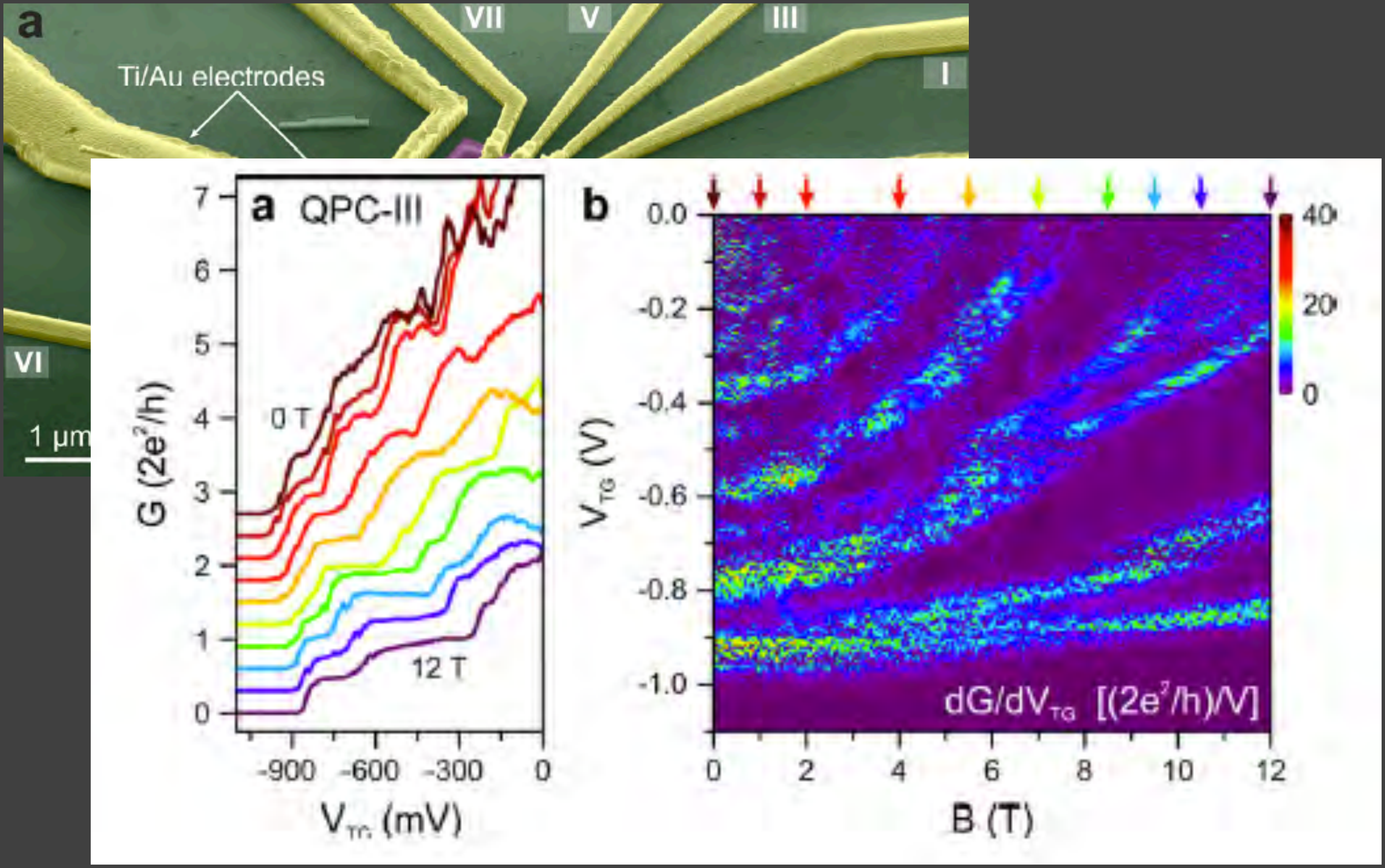




One-dimensionality in InAs nanowires (Heedt et al. Nano Lett. 2016)



One-dimensionality in InAs nanowires (Heedt et al. Nano Lett. 2016)



APPLIED PHYSICS LETTERS **110**, 083105 (2017)

Ballistic one-dimensional transport in InAs nanowires monolithically integrated on silicon

J. Gooth,[1,a),b)] V. Schaller,[1,a)] S. Wirths,[1] H. Schmid,[1] M. Borg,[1] N. Bologna,[1,2] S. Karg,[1] and H. Riel[1,b)]

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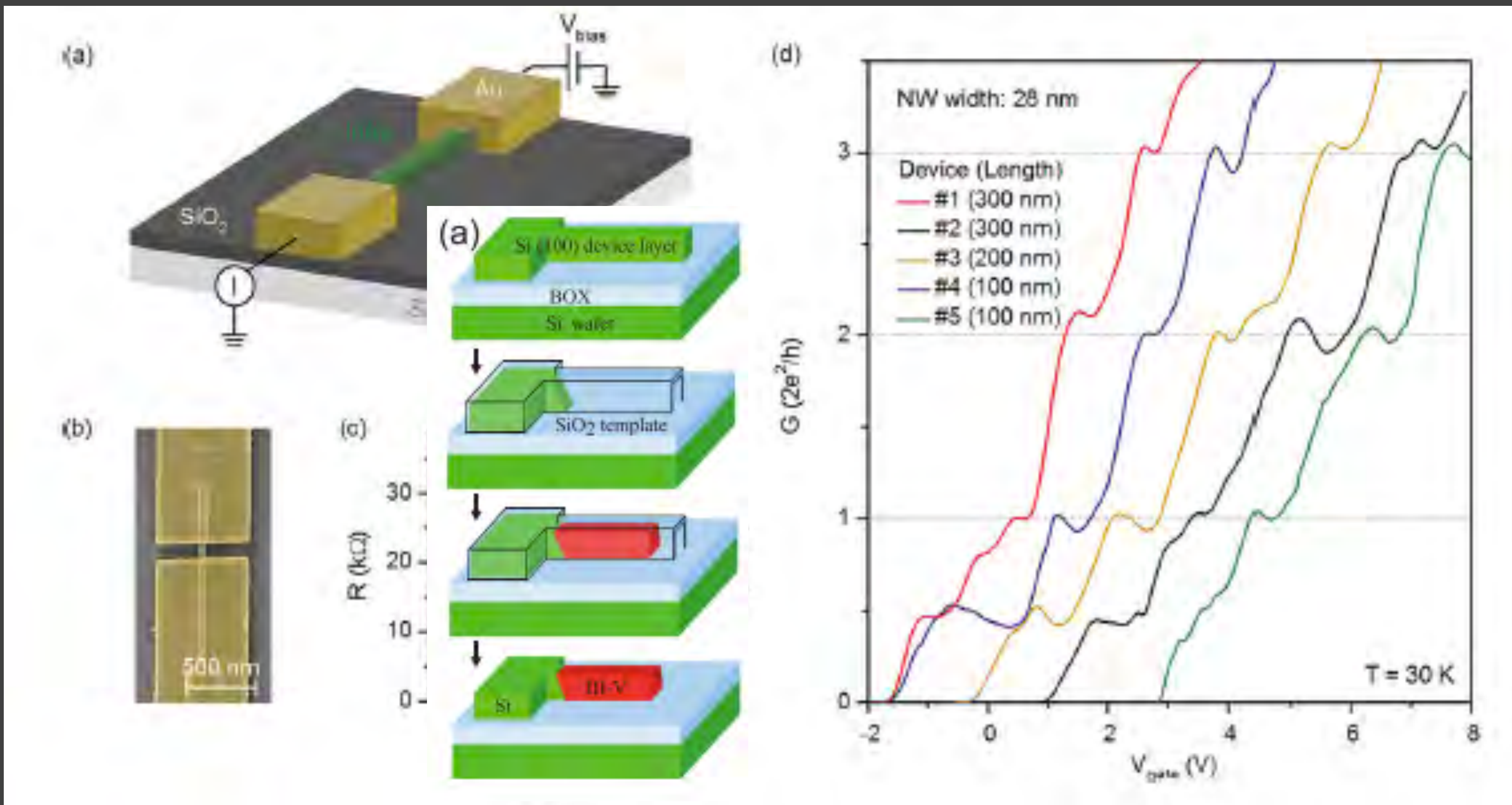
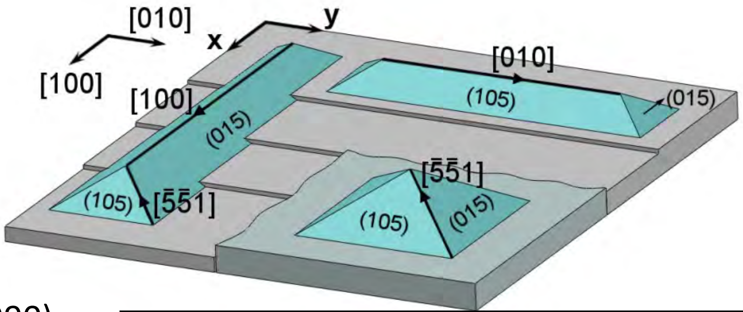
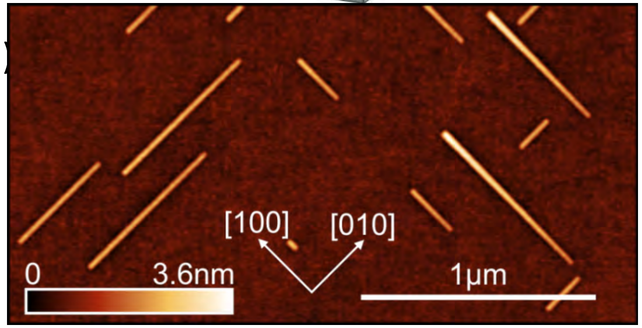
[2]*Electron Microscopy Center, EMPA, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland*



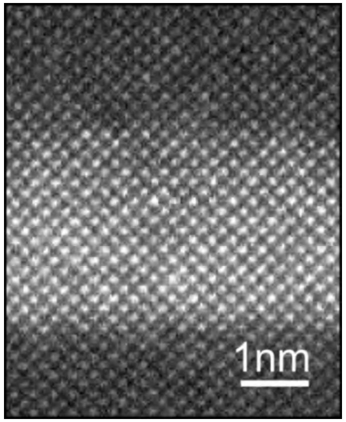
Ge-based hut nanowires

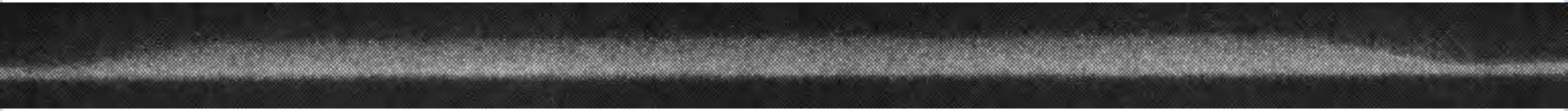


- Stranski-Krastanow growth
- Elongated Ge hut clusters { Mo et al. PRL **65**, 1020 (1990), Zhang et al. PRL**109**,085502(2012)
- Oriented along [100] and [010] on Si(001)
- Triangular cross section
- L x H x W ≈ 1000 nm x 2 nm x 20 nm



Watzinger et al., APL Materials (2014)

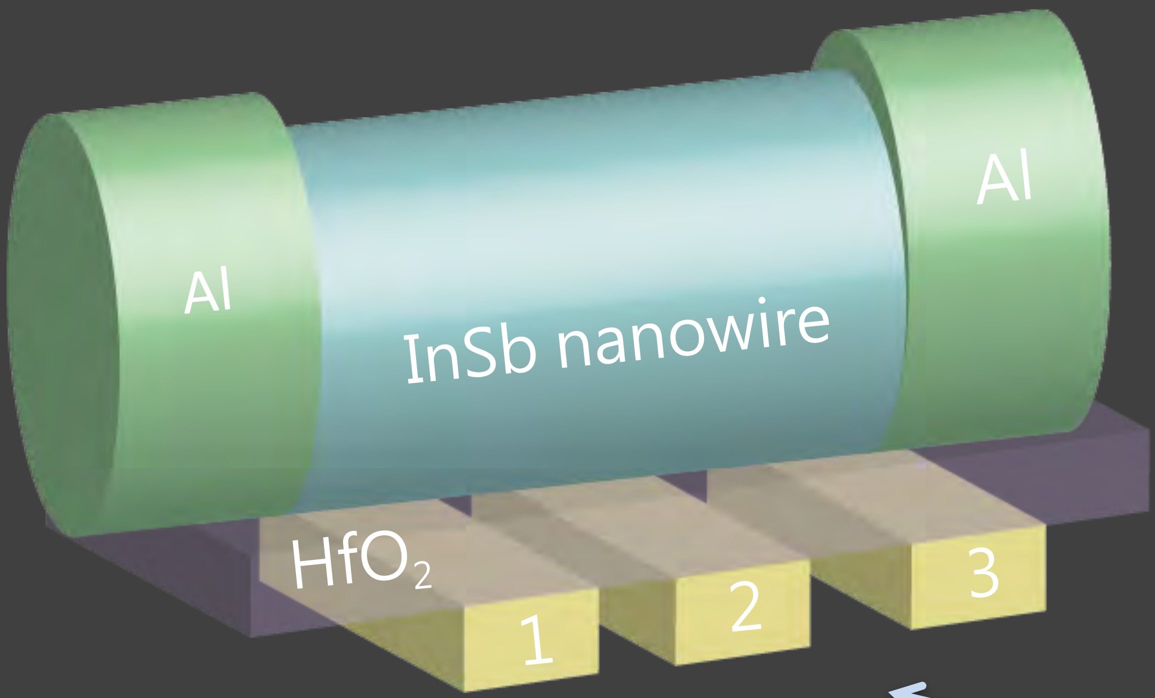




STEM: A. Fuhrer and M. Rossell, IBM Research Zürich

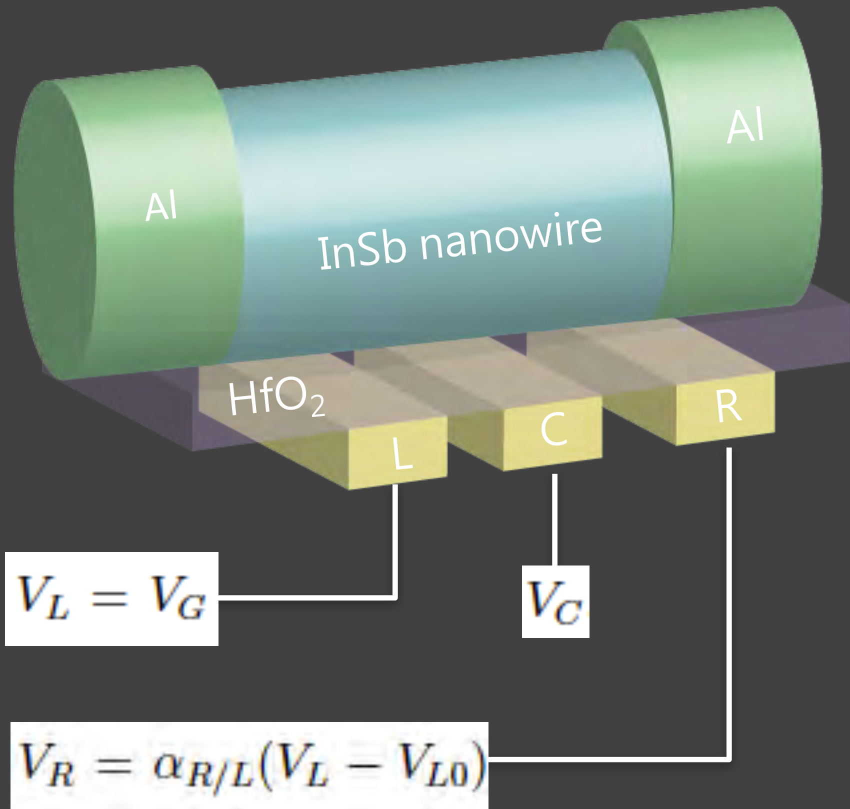
Device description

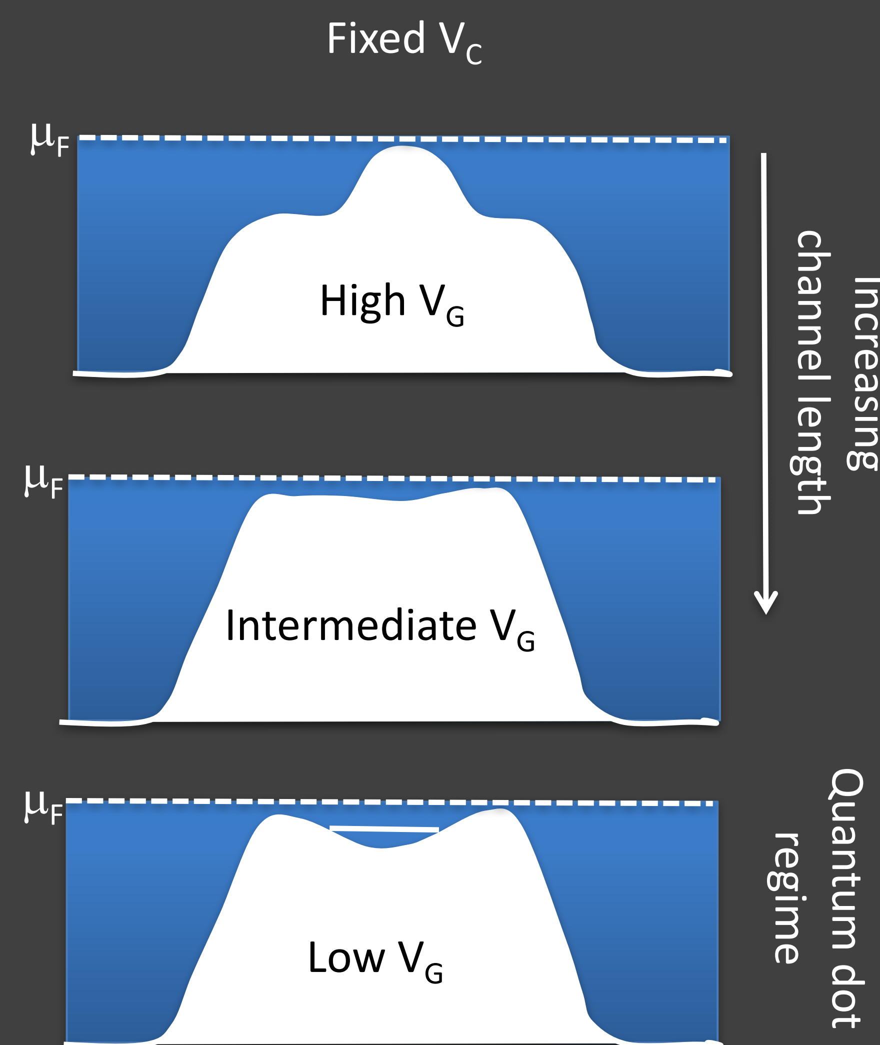
MOVPE-grown InSb NWs from Bakkers's group (Eindhoven)



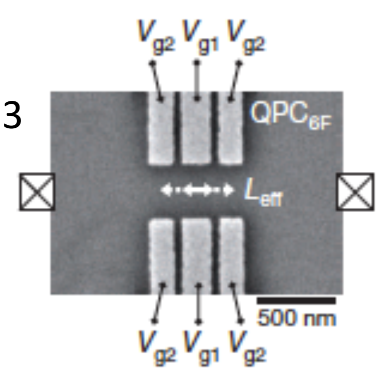
Bottom finger gates

Underlying idea

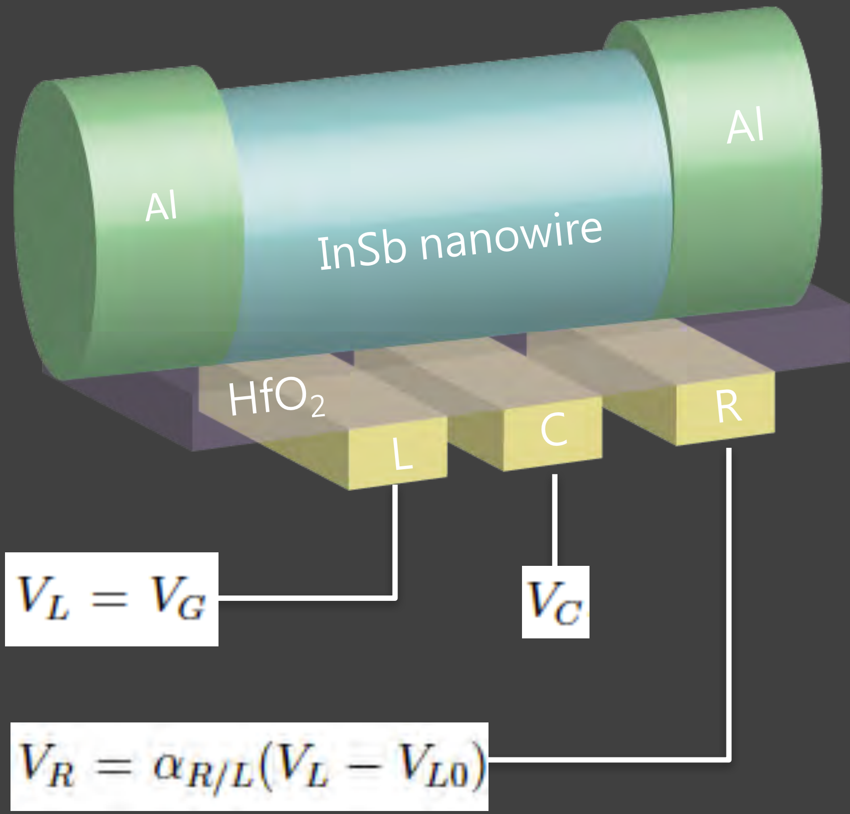


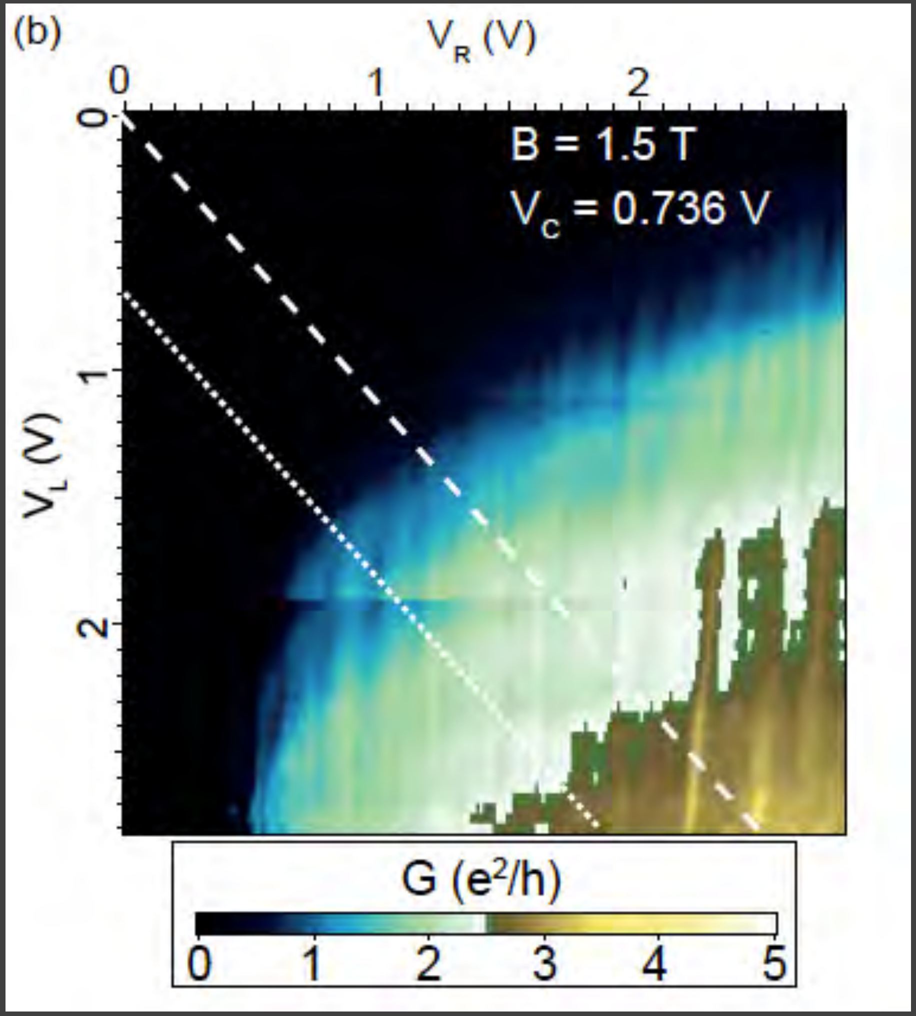


Same idea in
Iqbal et al Nature 2013

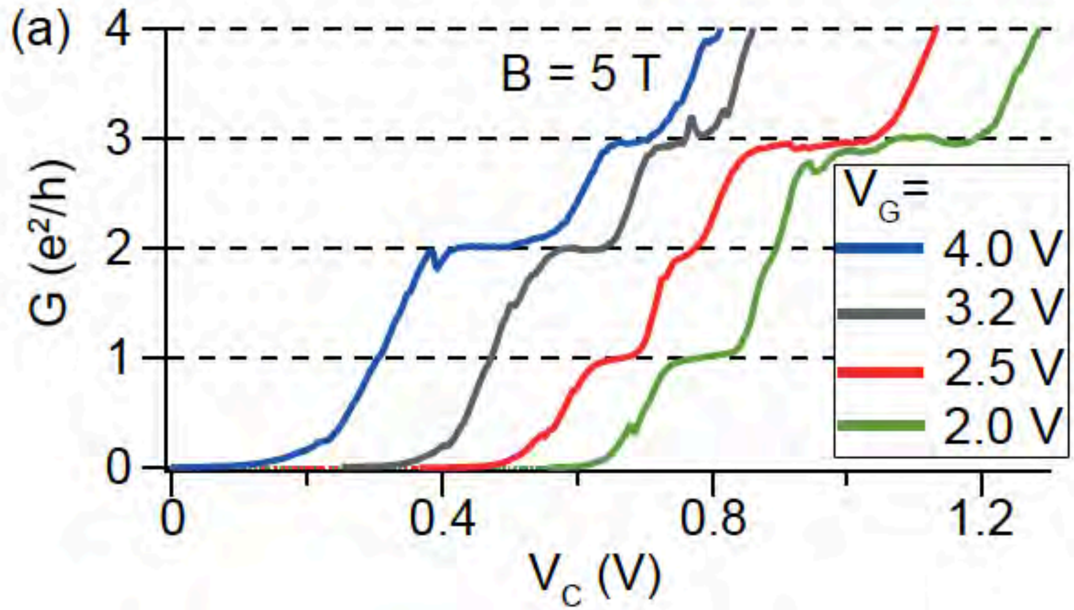


Gate sweeping configuration

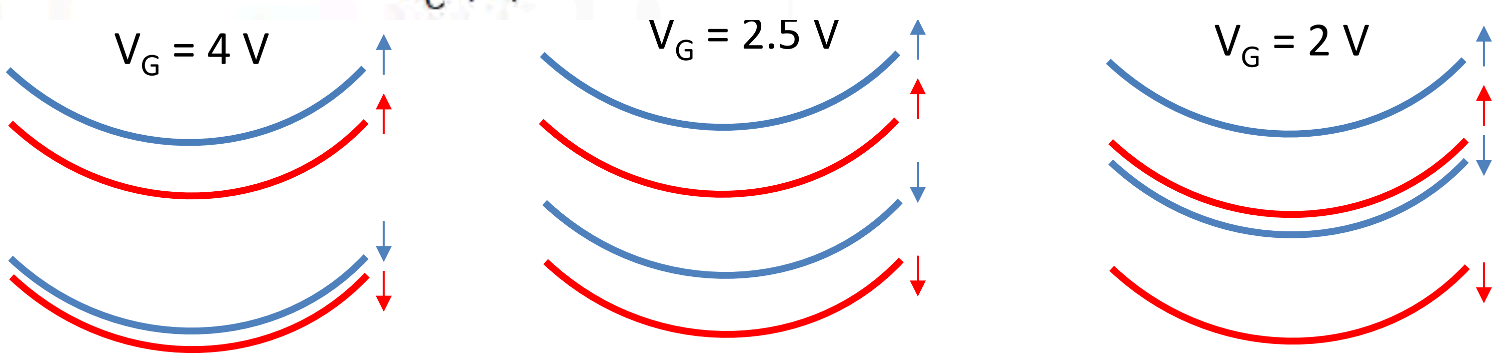




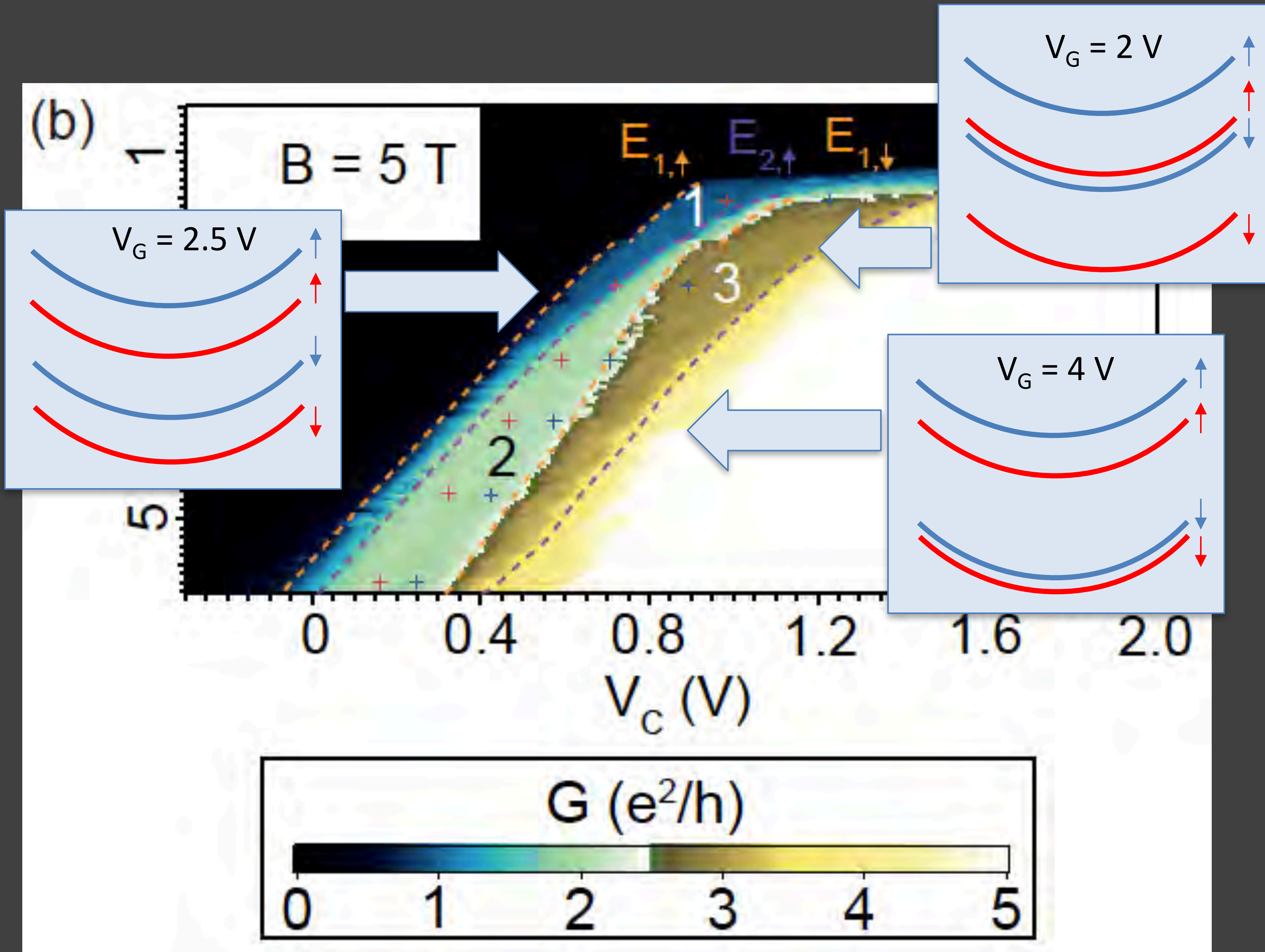
InSb nanowire with Al contacts: Electrical tuning of subband degeneracy



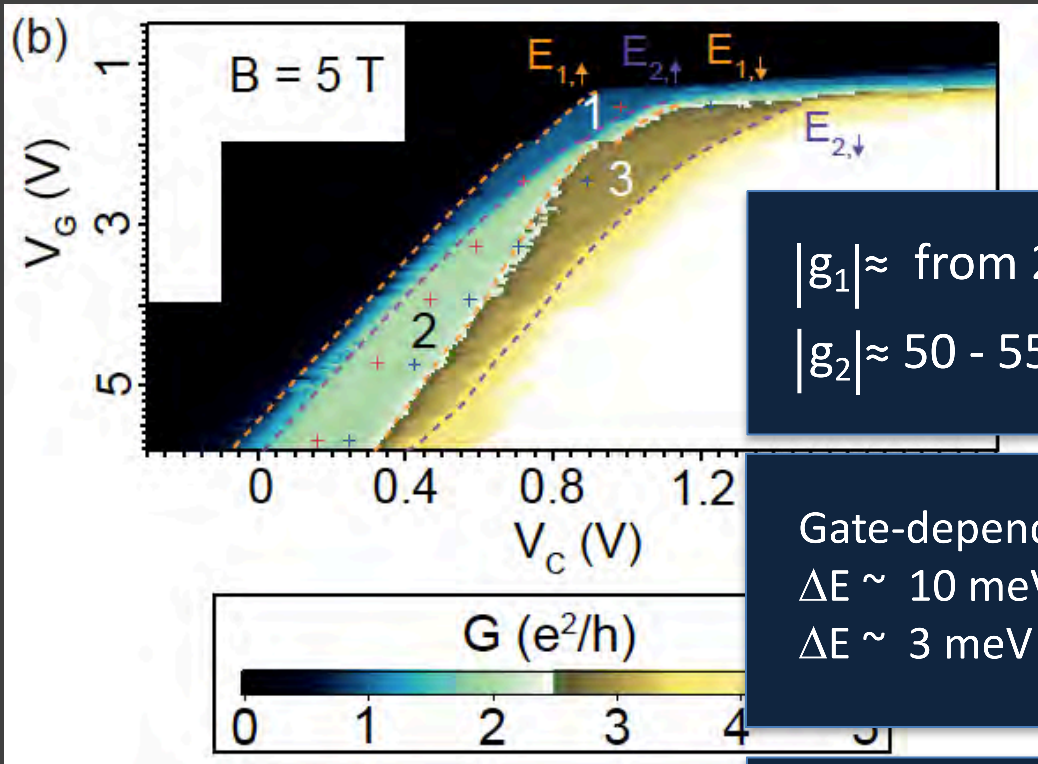
Note:
for g = -50 (bulk InSb)
$g\mu_B B$ = 2.85 meV @ B=1 T



Tuning comes from
Orbital & Spin effect



(b)
B = 5 T
$E_{1,\uparrow}$
$E_{2,\uparrow}$
$E_{1,\downarrow}$
1
2
3
5
0
0.4
0.8
1.2
1.6
2.0
V_C (V)
G (e^2/h)
0
1
2
3
4
5
V_G = 2.5 V
V_G = 2 V
V_G = 4 V



Main conclusions:

$|g_1| \approx$ from 28 to 55 => strong gate dependence

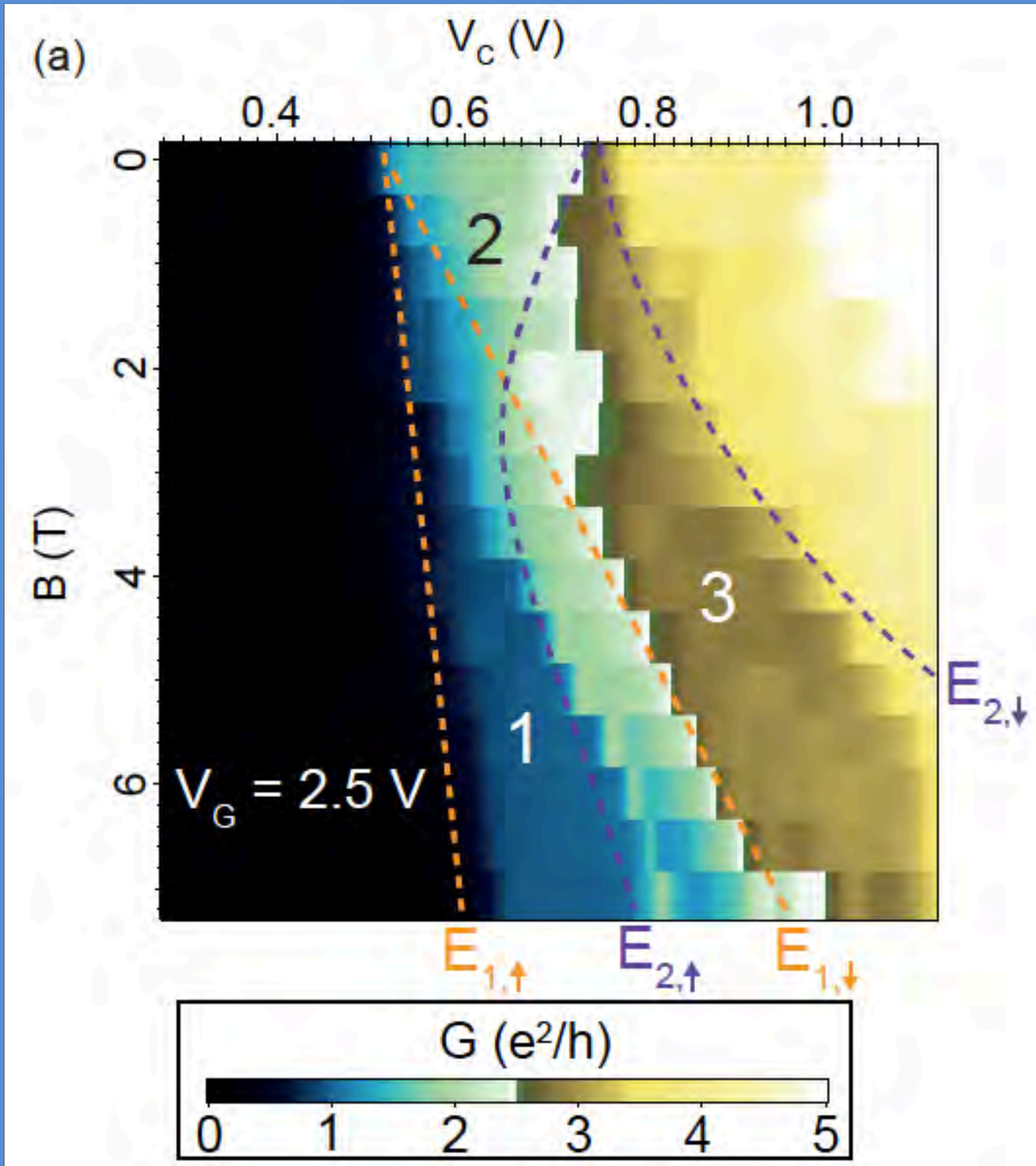
$|g_2| \approx$ 50 - 55

Gate-dependent subband spacing:
ΔE ~ 10 meV @ V_G= 1.5 V
ΔE ~ 3 meV @ V_G= 5.5 V

Recovery of subband degeneracy at high B

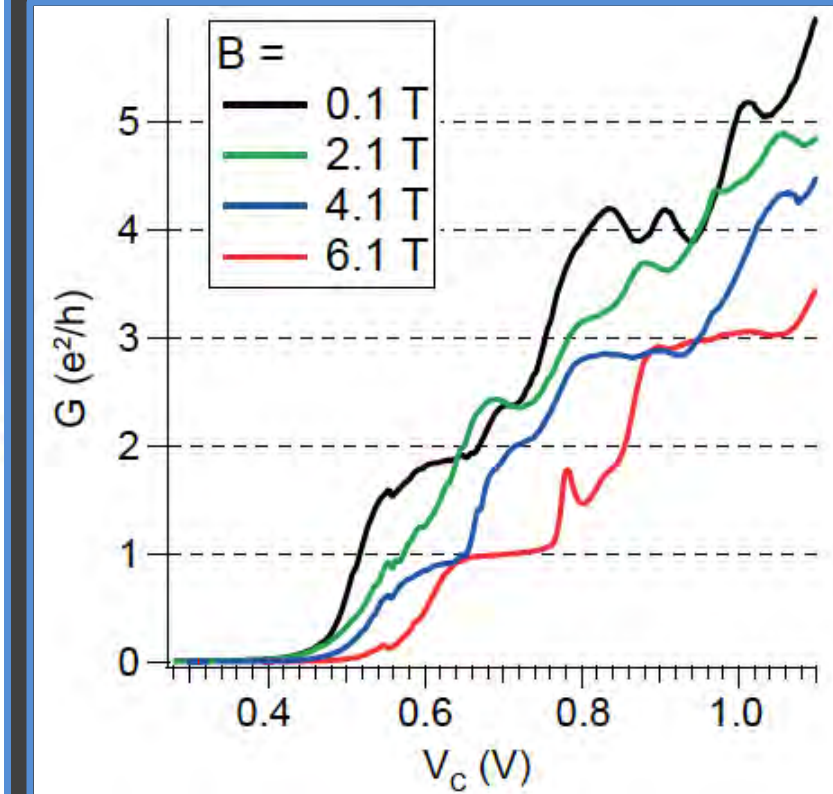
Degeneracy is robust in field (sticking effect)

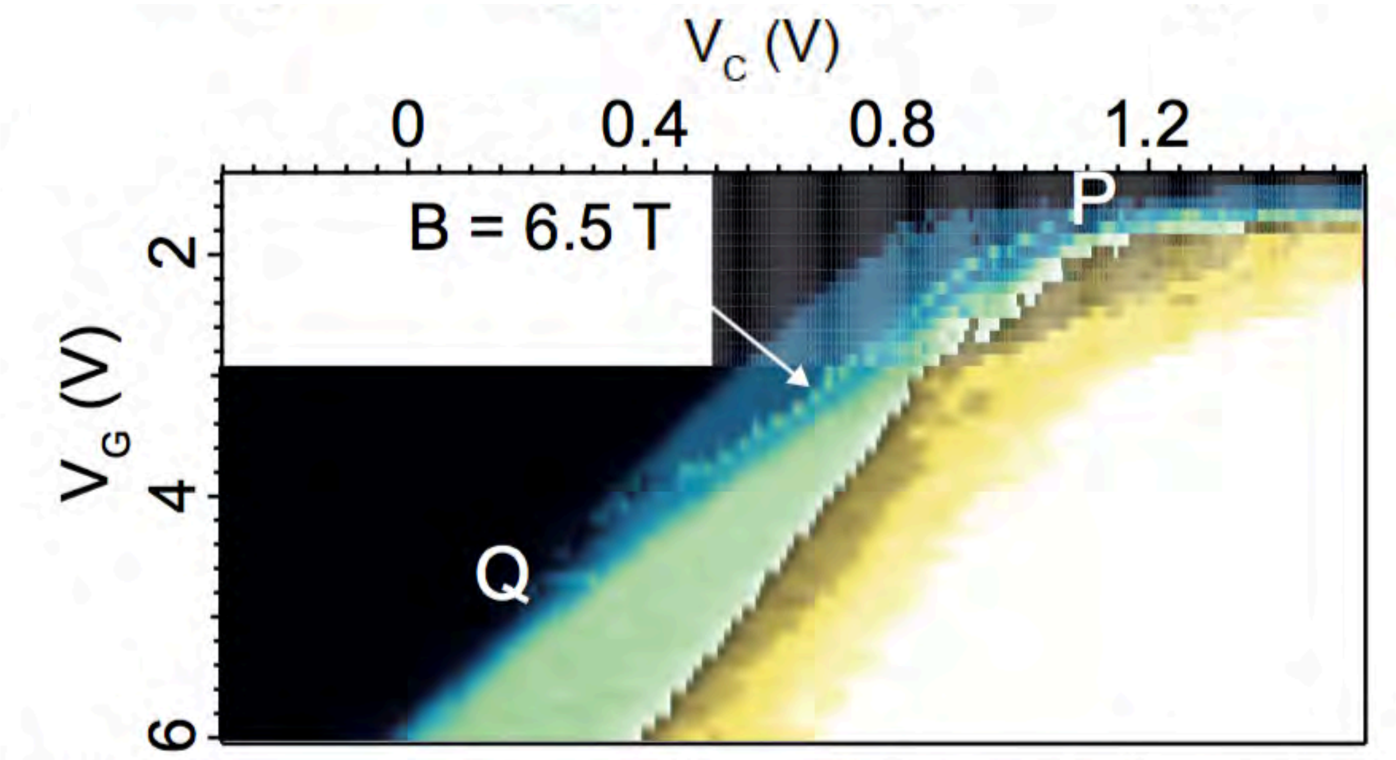
[Estrada Saldaña et al. (next week in cond-mat)]



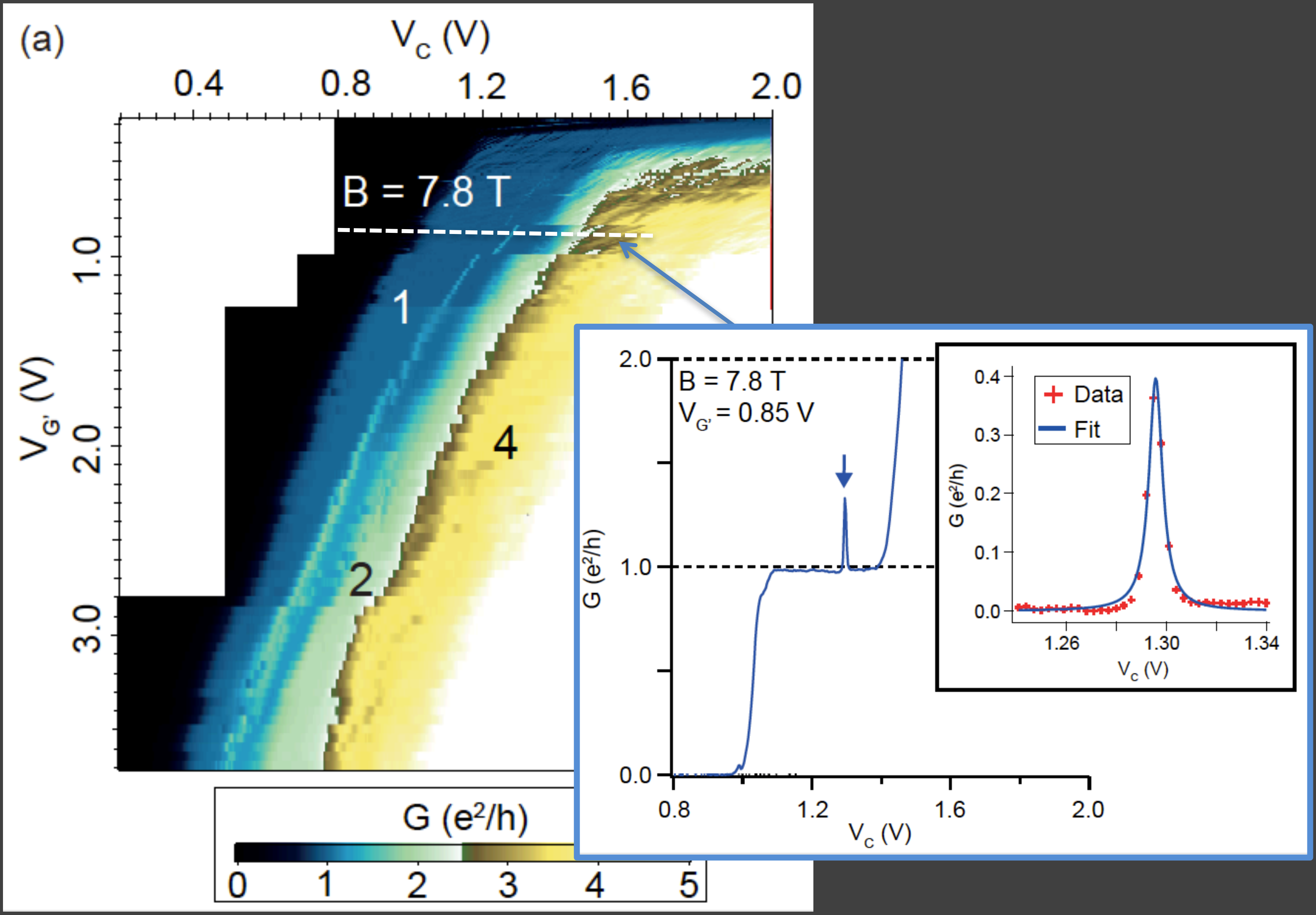
$|g_1| \approx 30$; $|g_2| \approx 50$

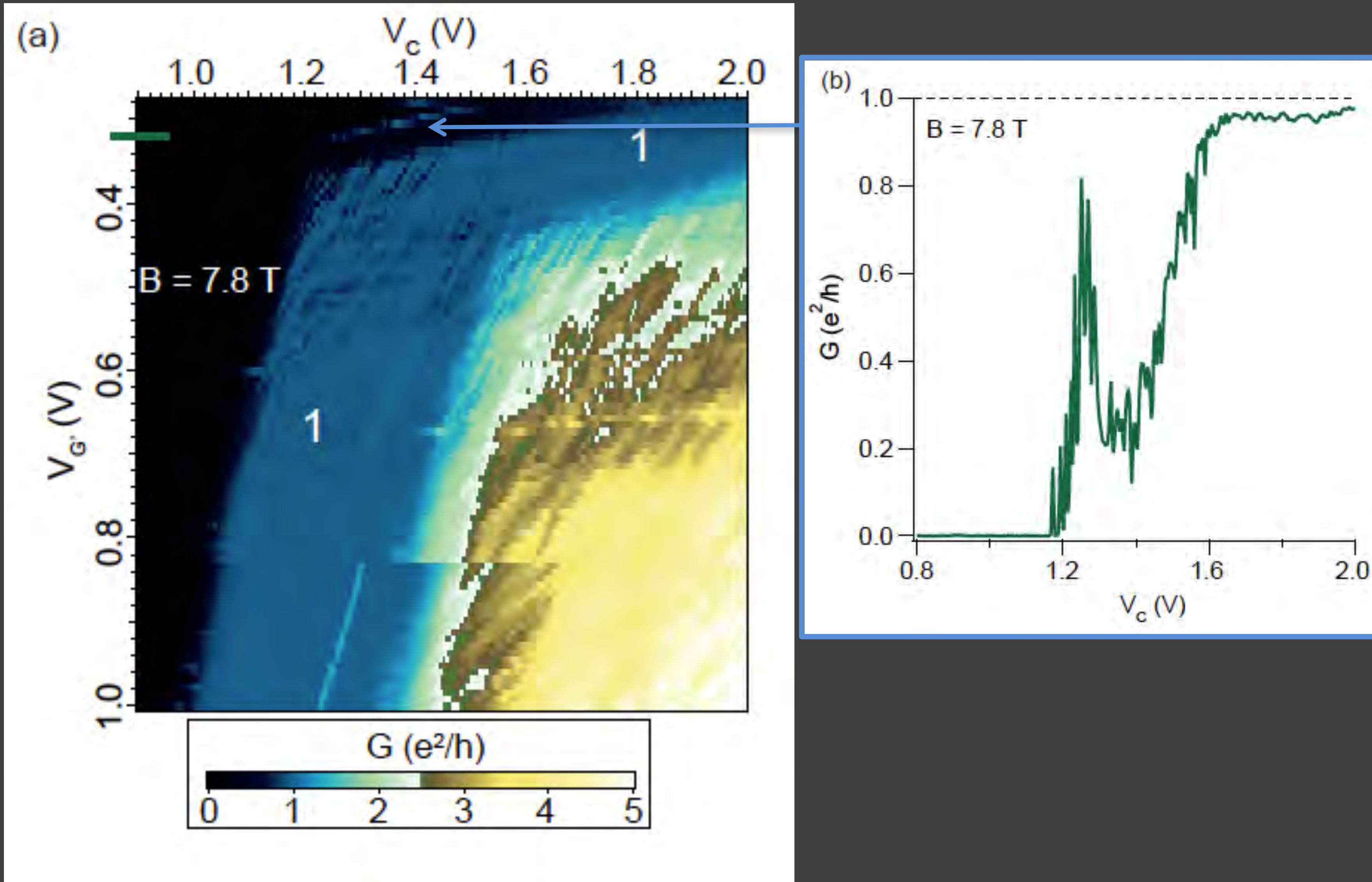
\+ adjustable orbital shift



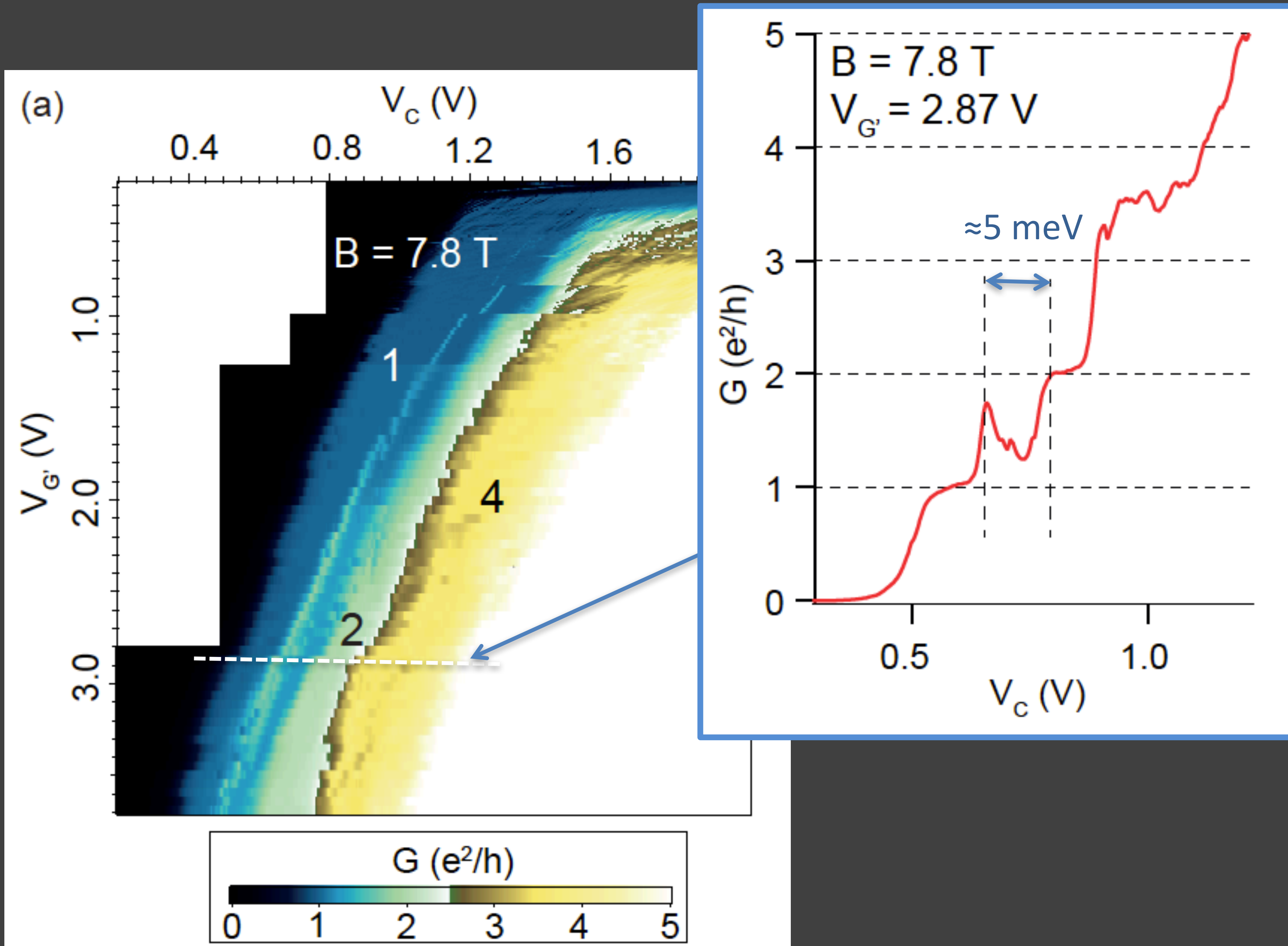


V_C (V)
0
0.4
0.8
1.2
B = 6.5 T
P
Q
V_G (V)
2
4
6

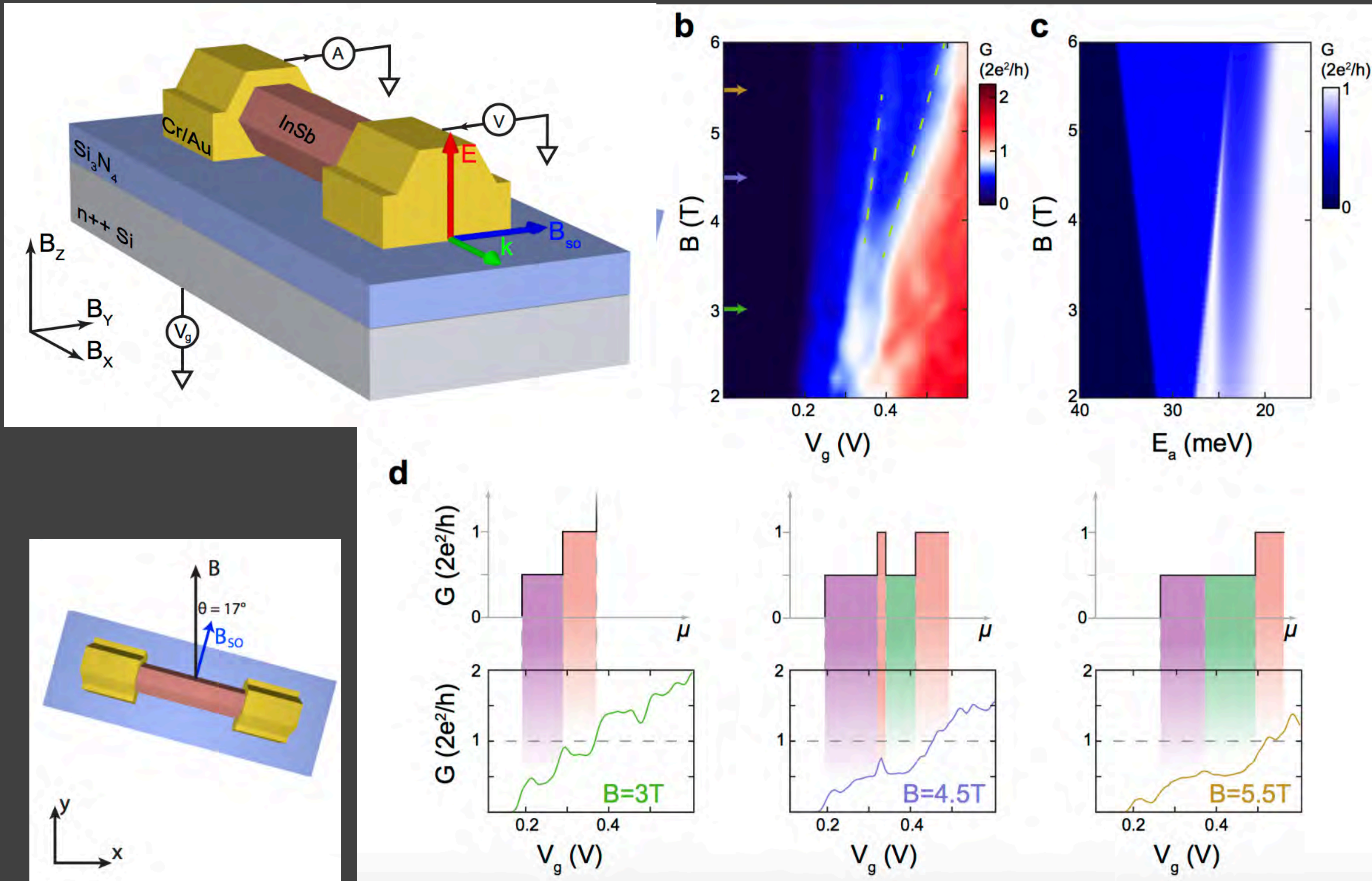

(a)
V_c (V)
0.4
0.8
1.2
1.6
2.0
$V_{G'}$ (V)
1.0
2.0
3.0
B = 7.8 T
1
2
4
G (e^2/h)
0
1
2
3
4
5
B = 7.8 T
$V_{G'}$ = 0.85 V
G (e^2/h)
2.0
1.0
0.0
0.8
1.2
1.6
2.0
V_c (V)
Data
Fit
G (e^2/h)
0.4
0.3
0.2
0.1
0.0
1.26
1.30
1.34
V_c (V)



(a)
V_c (V)
1.0 1.2 1.4 1.6 1.8 2.0
$V_{G'}$ (V)
0.4 0.6 0.8 1.0
B = 7.8 T
1
1
G (e²/h)
0 1 2 3 4 5
(b)
B = 7.8 T
G (e²/h)
1.0 0.8 0.6 0.4 0.2 0.0
0.8 1.2 1.6 2.0
V_c (V)



(a)
V_C (V)
0.4
0.8
1.2
1.6
V_G' (V)
1.0
2.0
3.0
B = 7.8 T
1
2
4
G (e²/h)
0
1
2
3
4
5
B = 7.8 T
V_G' = 2.87 V
≈5 meV
G (e²/h)
0
1
2
3
4
5
0.5
1.0
V_C (V)



[reproduced from Kammhuber et al., arXiv:1701.06878]