Zero-Bias Features and the Identification of Majorana End States

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wires: Mingtang Deng (Lund)
Pierre Caroff (Lund)
Hongqi Xu (Lund)
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http://qdev.dk

New directions in the pursuit of Majorana fermions in solid state systems

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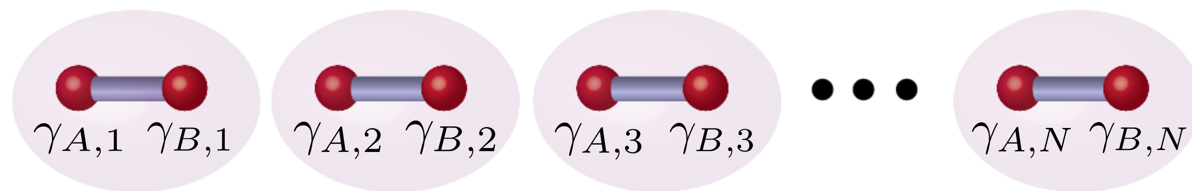
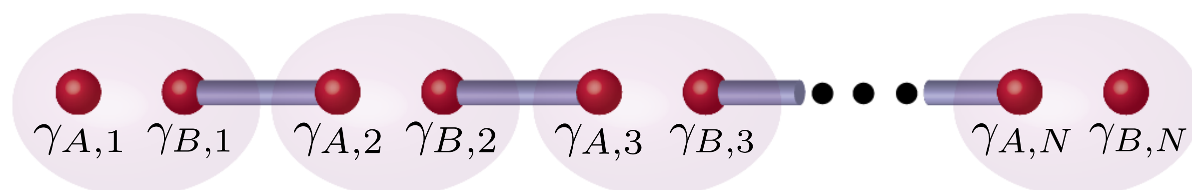
(Dated: February 8, 2012)





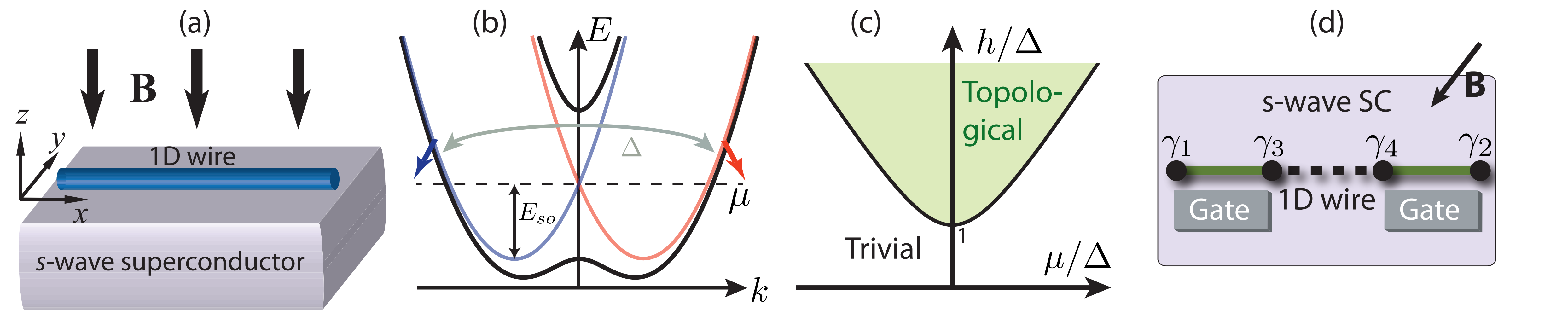
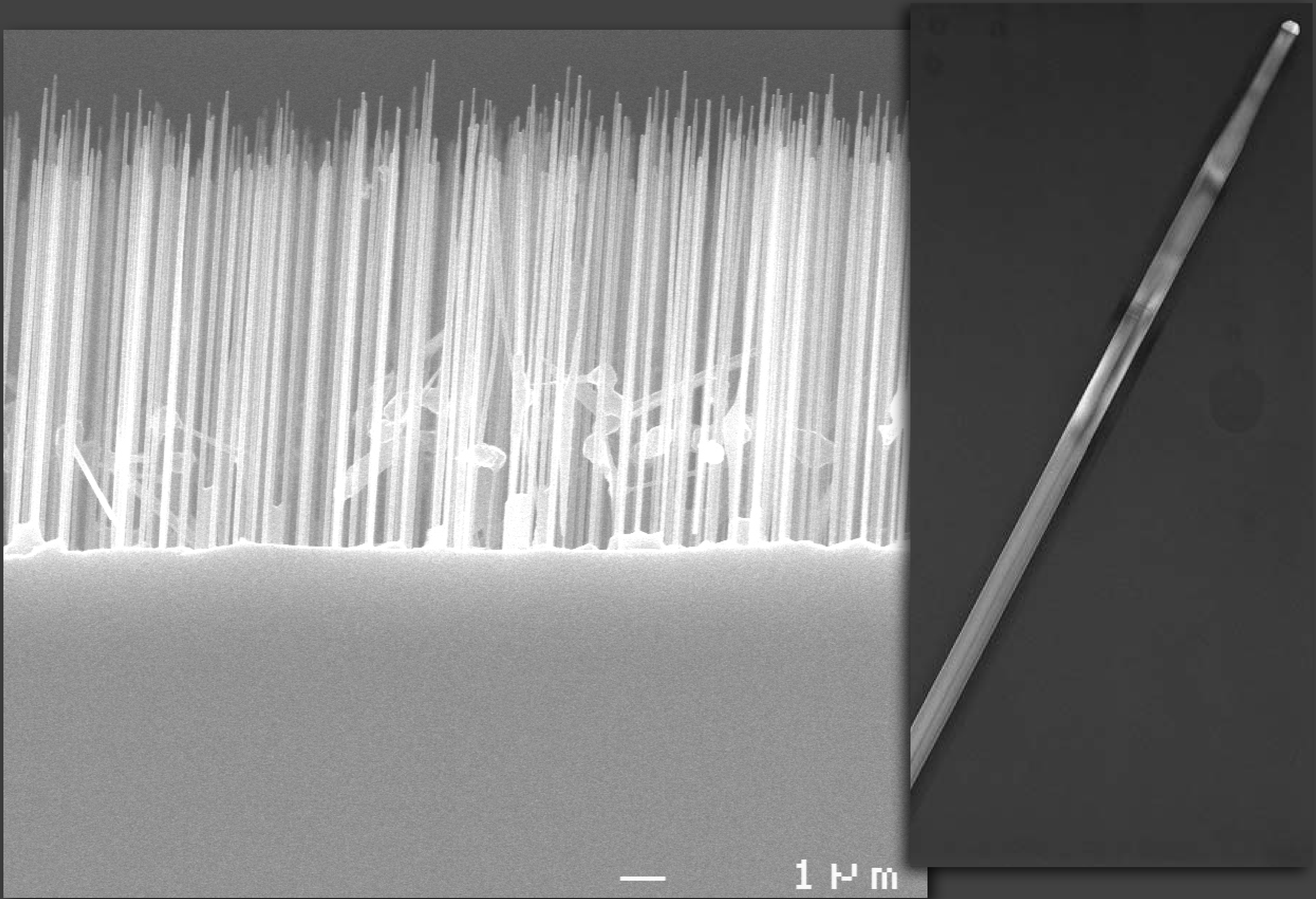


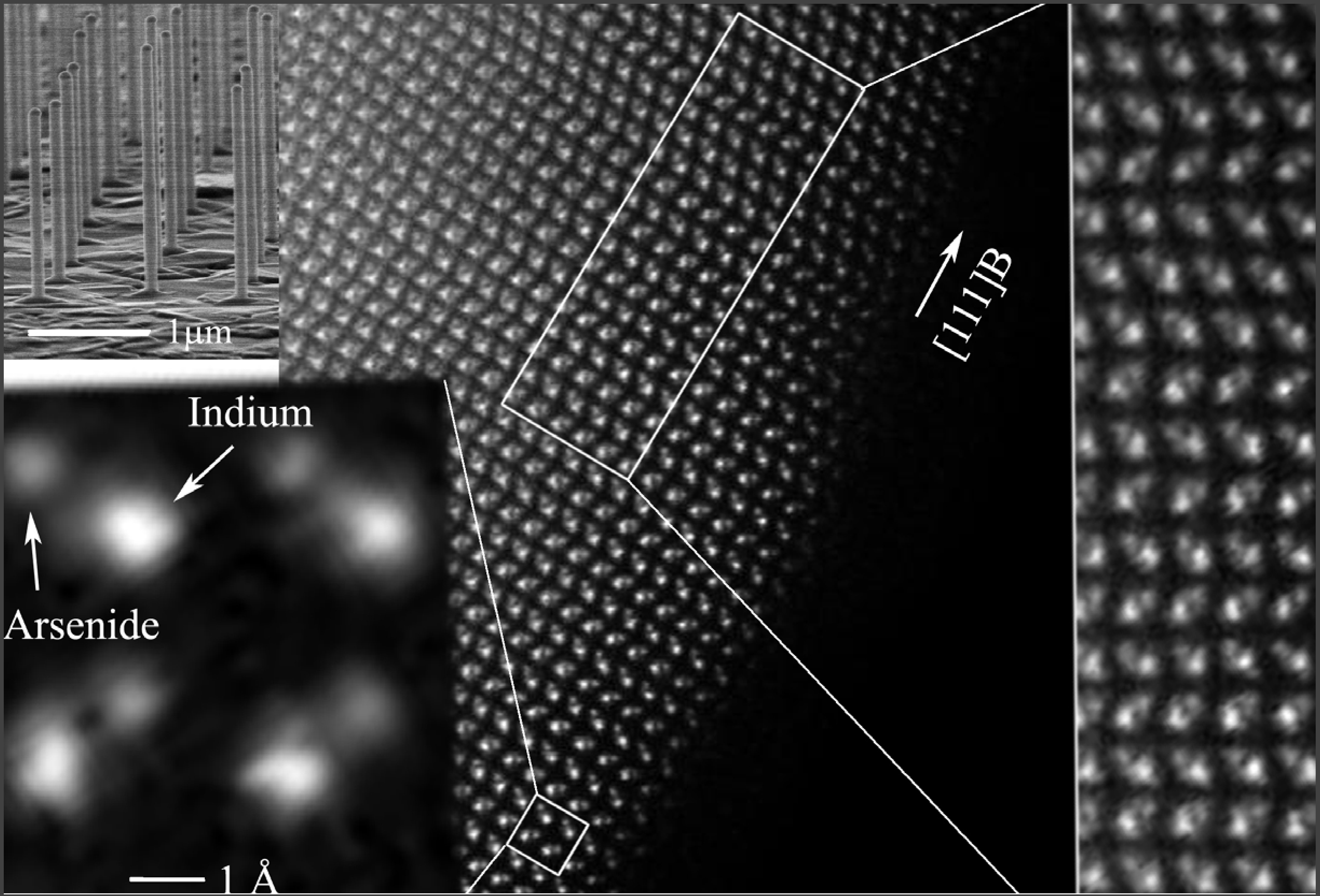
FIG. 6. (a) Basic architecture required to stabilize a topological superconducting state in a 1D spin-orbit-coupled wire. (b) Band structure for the wire when time-reversal symmetry is present (red and blue curves) and broken by a magnetic field (black curves). When the chemical potential lies within the field-induced gap at $k = 0$, the wire appears 'spinless'. Incorporating the pairing induced by the proximate superconductor leads to the phase diagram in (c). The endpoints of topological (green) segments of the wire host localized, zero-energy Majorana modes as shown in (d).

10 µm wires, pure wurzite structure



M.H. Madsen, P. Krogstrup, J. Nygård, Univ. of Copenhagen

Epitaxial growth of InAs nanowires

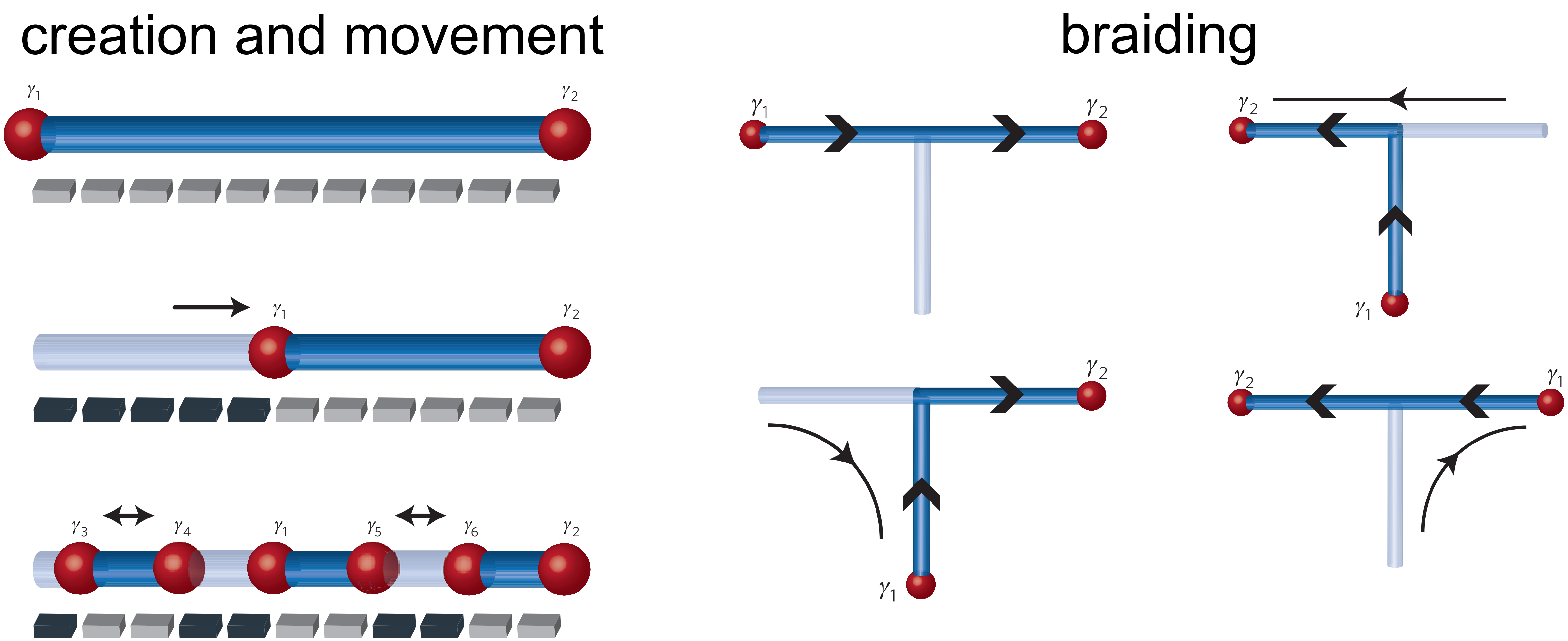


P. Krogstrup, J. Nygård, Univ. of Copenhagen

nature physics
ARTICLES
PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NPHYS1915

Non-Abelian statistics and topological quantum information processing in 1D wire networks

Jason Alicea[1]*, Yuval Oreg[2], Gil Refael[3], Felix von Oppen[4] and Matthew P. A. Fisher[3,5]



PHYSICAL REVIEW B **84**, 144522 (2011)

Majorana fermions in semiconductor nanowires

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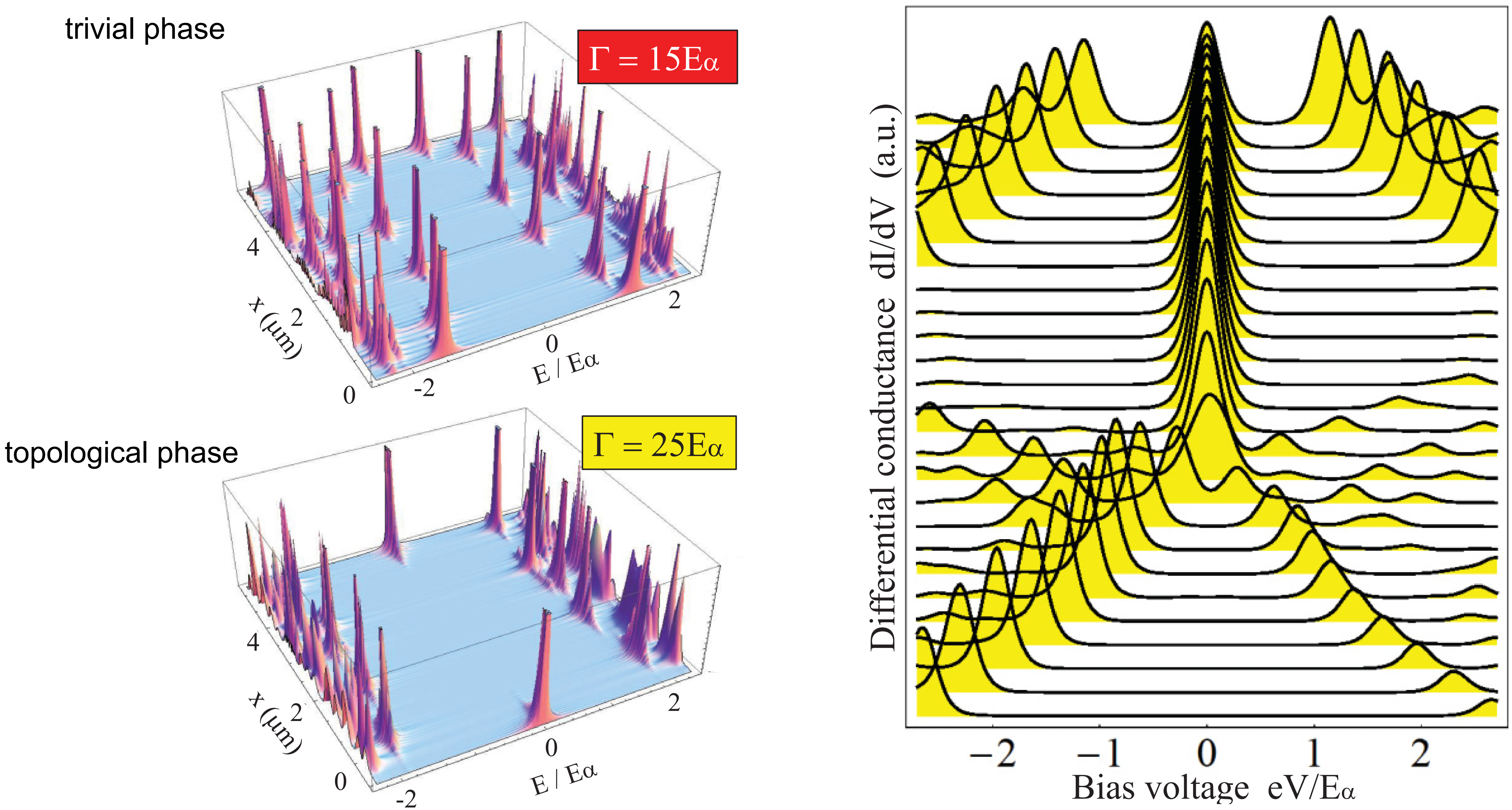
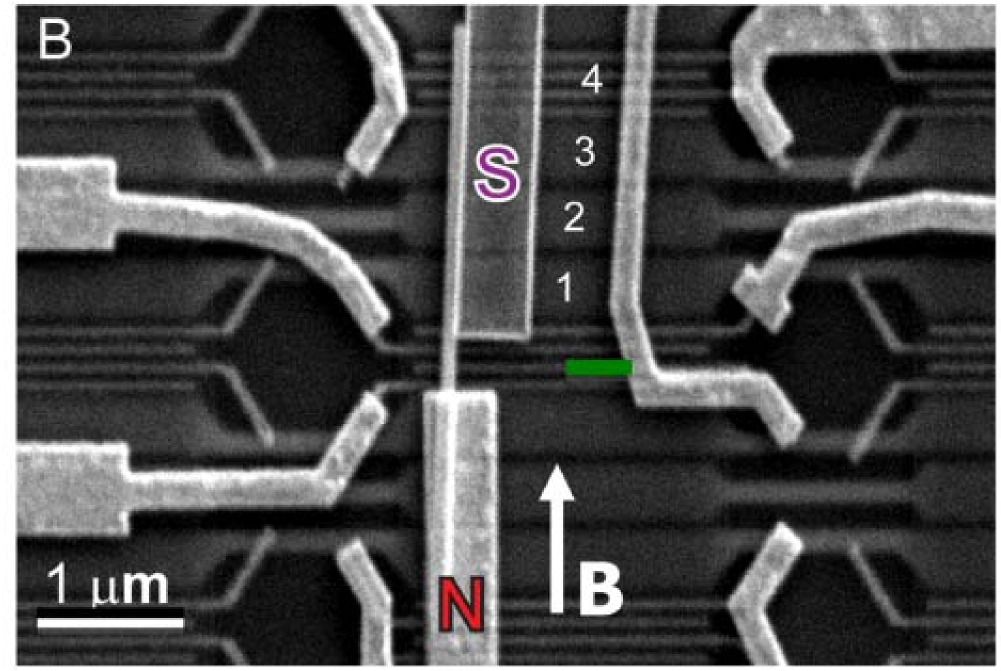
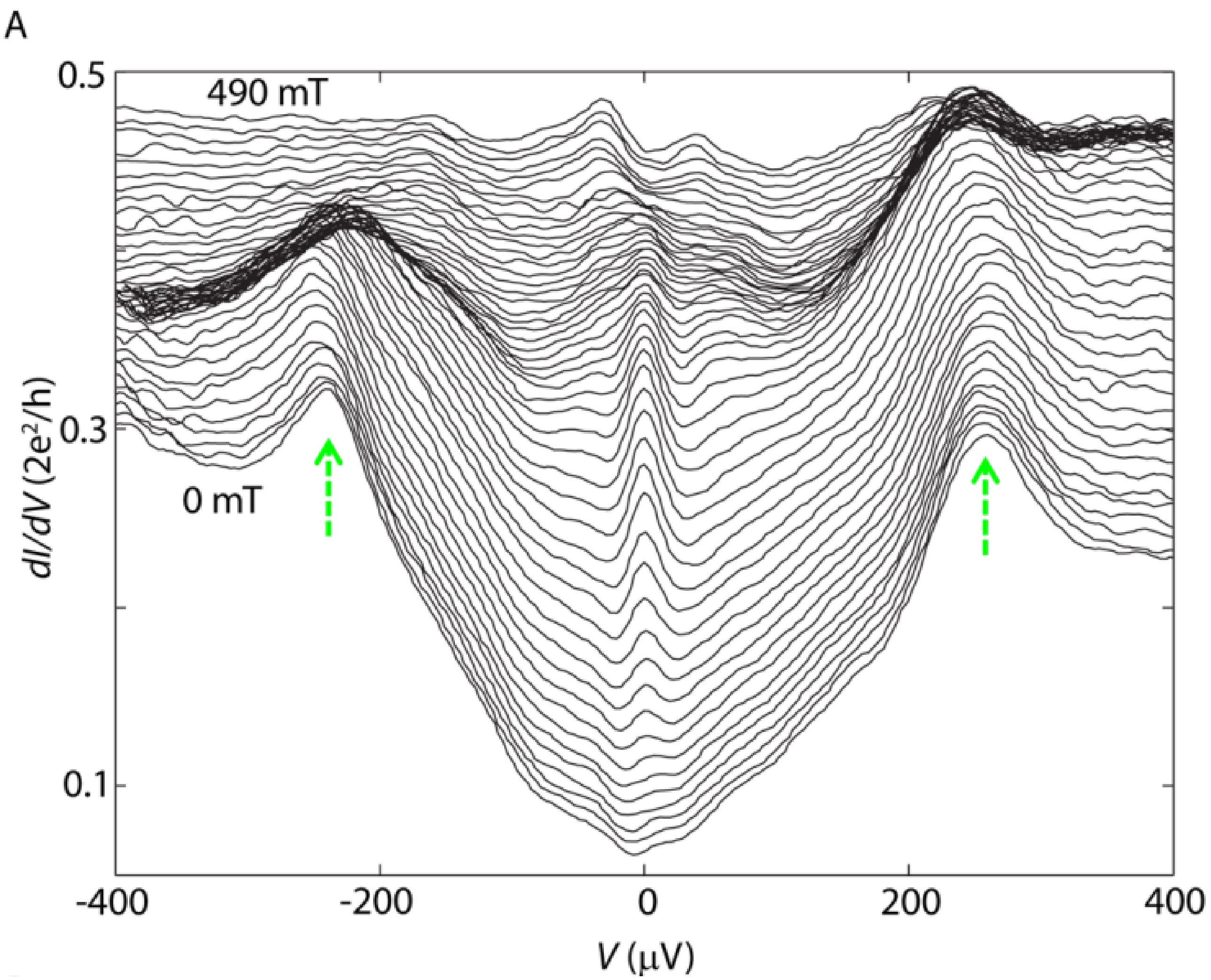
(Received 27 July 2011; revised manuscript received 27 September 2011; published 28 October 2011)

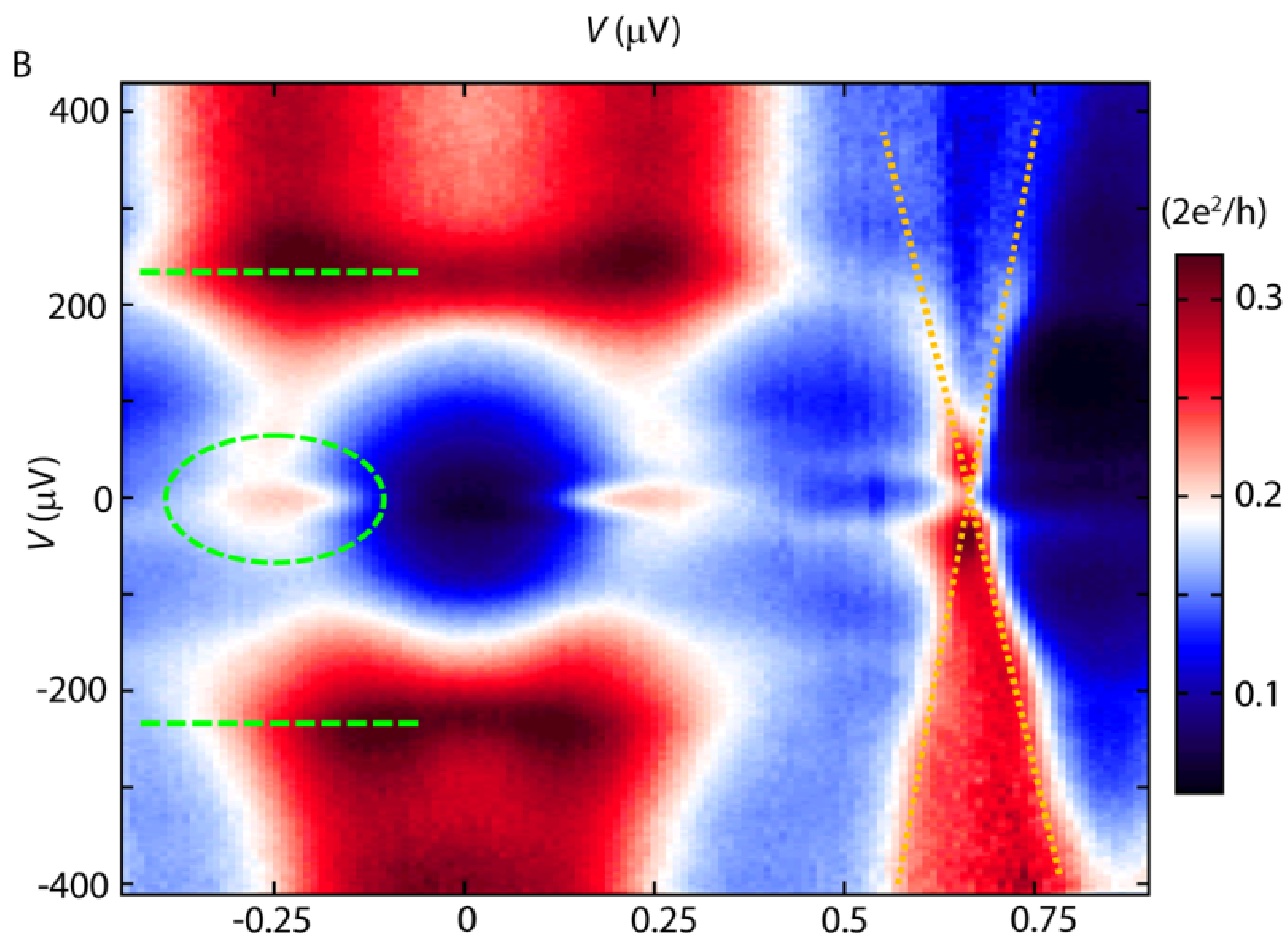


Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

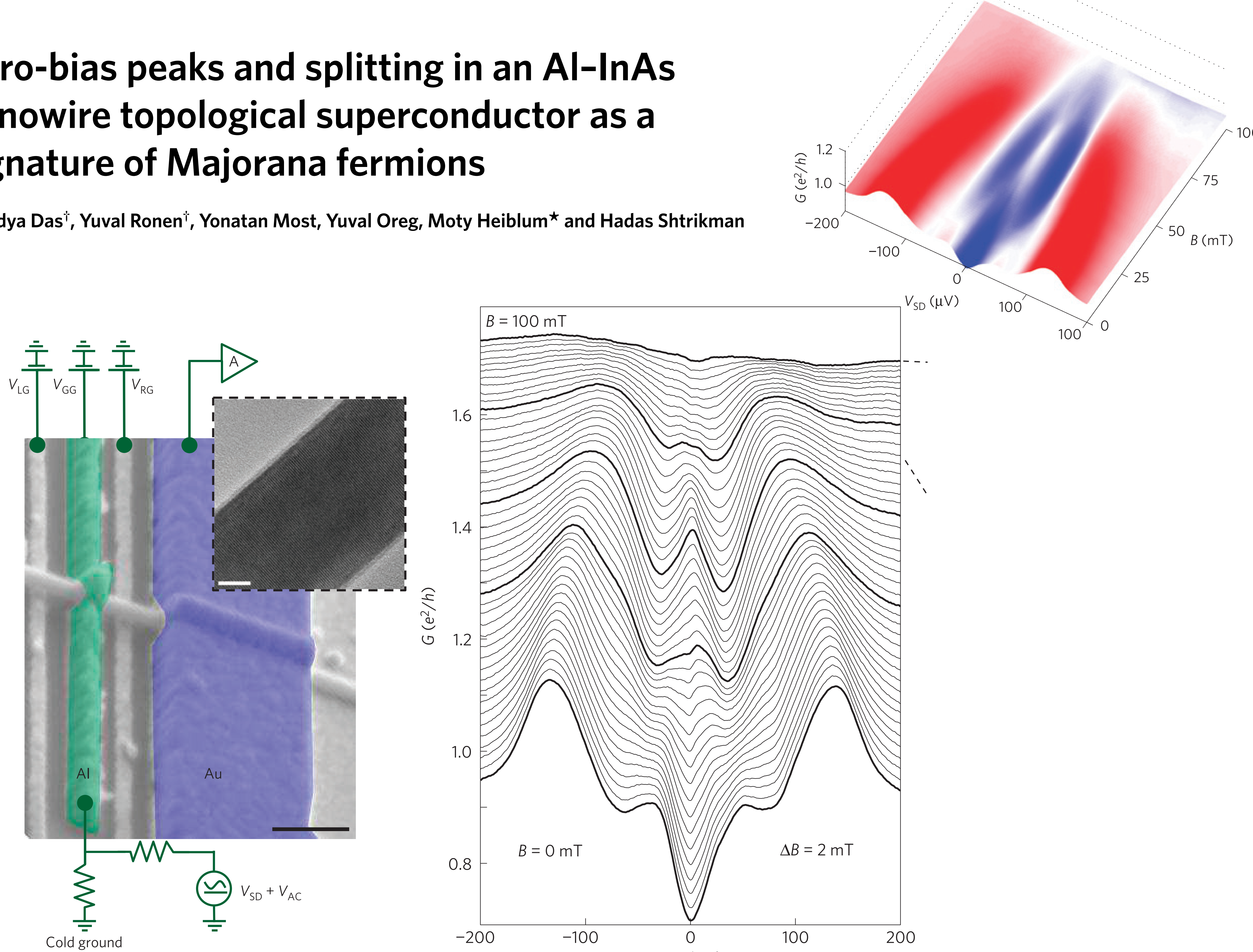






Zero-bias peaks and splitting in an Al–InAs nanowire topological superconductor as a signature of Majorana fermions

Anindya Das†, Yuval Ronen†, Yonatan Most, Yuval Oreg, Moty Heiblum★ and Hadas Shtrikman



NANO LETTERS

Anomalous Zero-Bias Conductance Peak in a Nb–InSb Nanowire–Nb Hybrid Device

M. T. Deng,[†] C. L. Yu,[†] G. Y. Huang,[†] M. Larsson,[†] P. Caroff,[‡] and H. Q. Xu[†,§,*]

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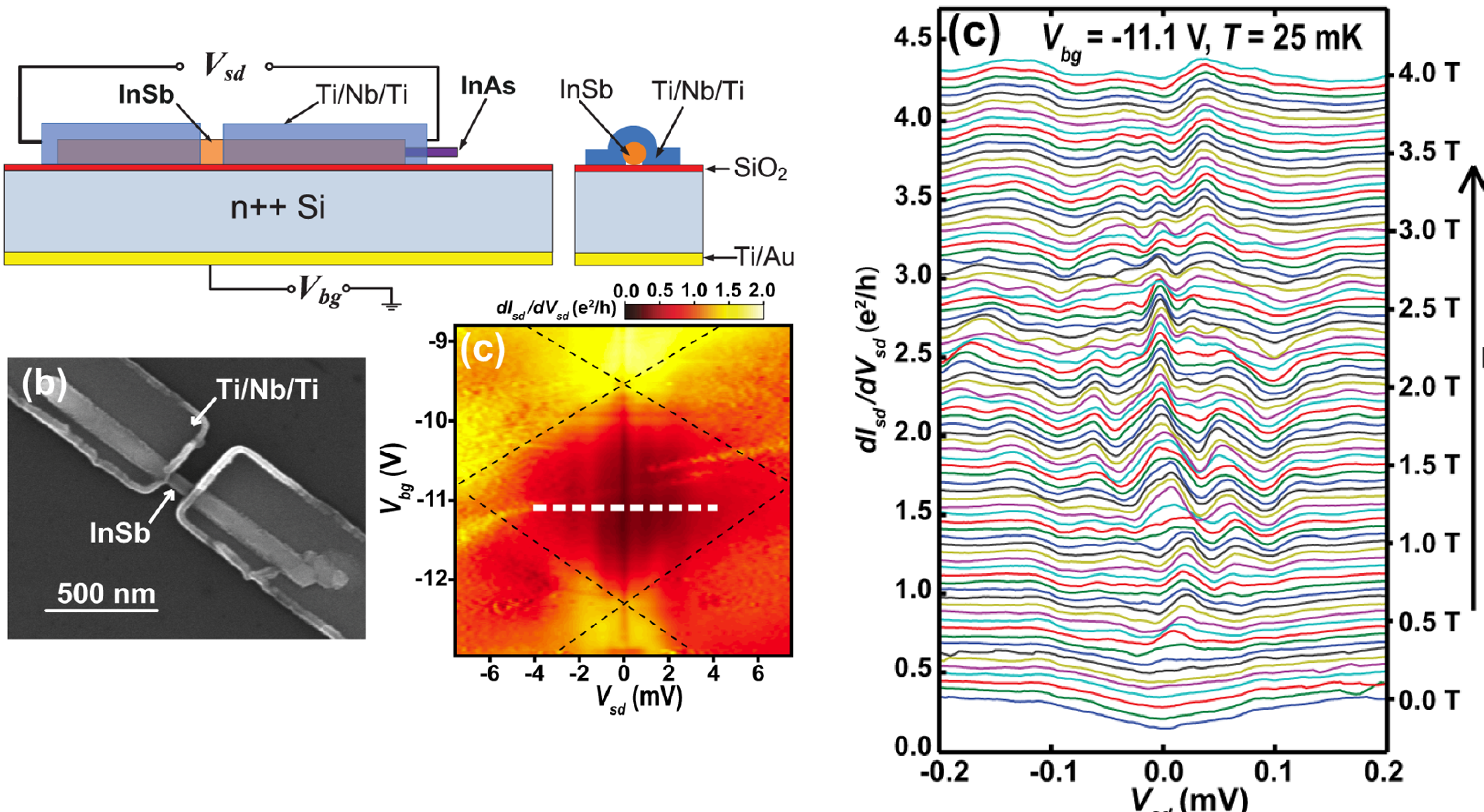

PHYSICAL REVIEW B **87**, 241401(R) (2013)

Superconductor-nanowire devices from tunneling to the multichannel regime: Zero-bias oscillations and magnetoconductance crossover

H. O. H. Churchill,[1,2] V. Fatemi,[2] K. Grove-Rasmussen,[3] M. T. Deng,[4] P. Caroff,[4] H. Q. Xu,[4,5] and C. M. Marcus[3,*]

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[2]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen Ø, Denmark*
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Device #1: one-sided (N-wire-S)

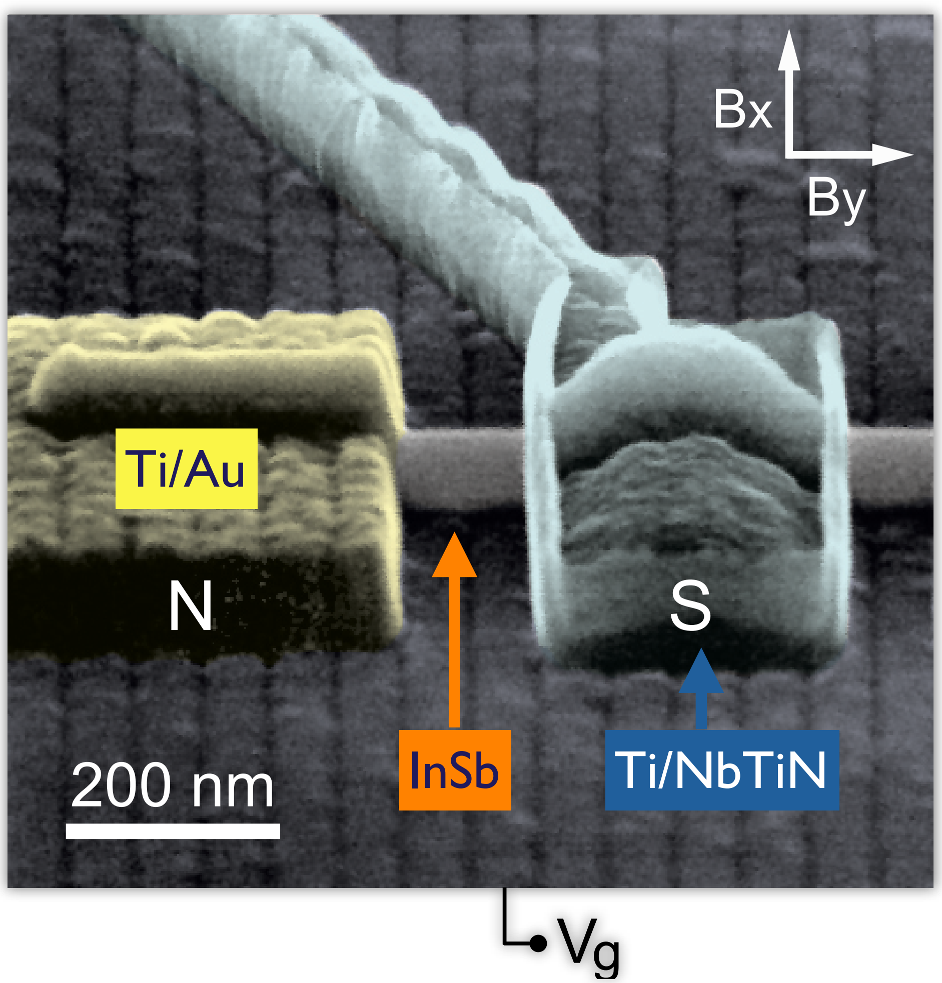
150 nm wide uncovered region

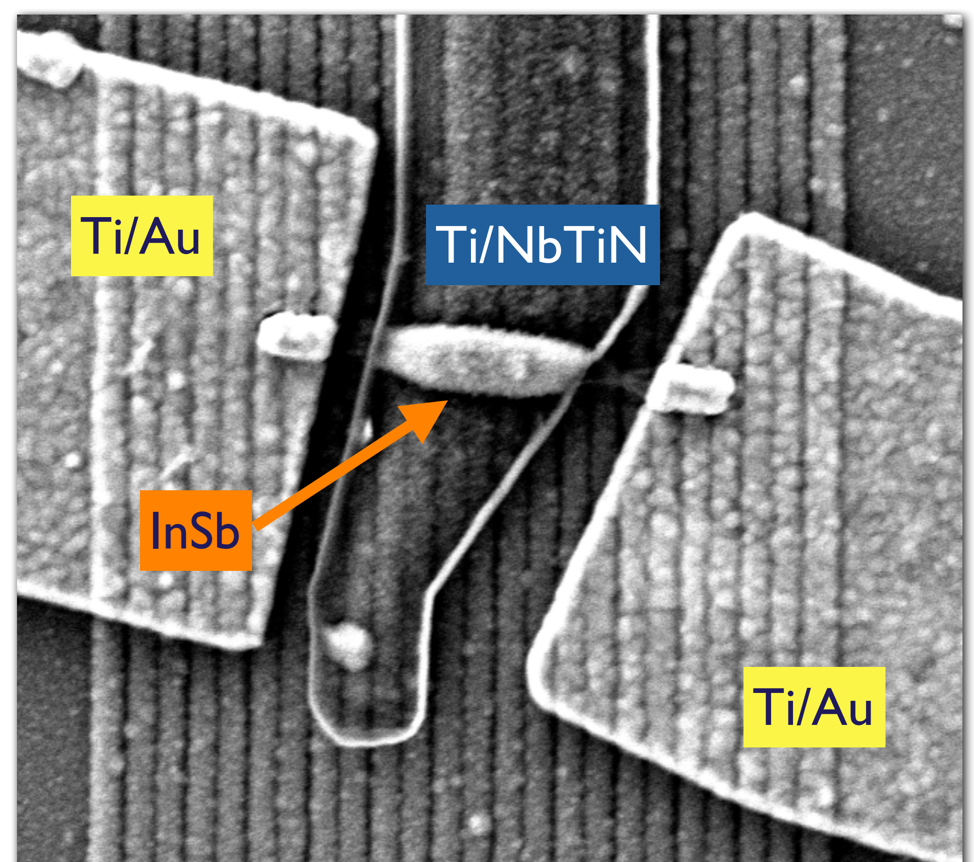
350 nm wide superconducting contact

Device #2: two-sided (N-wire-S-wire-N)

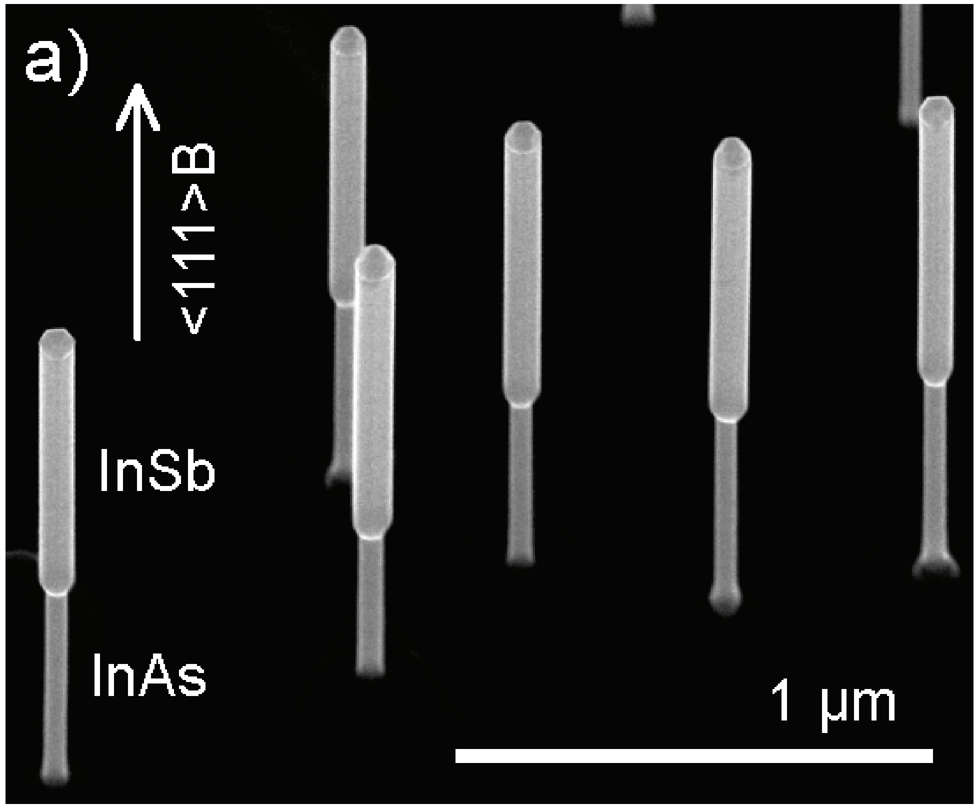
200 nm wide uncovered regions

250 nm wide superconducting contacts

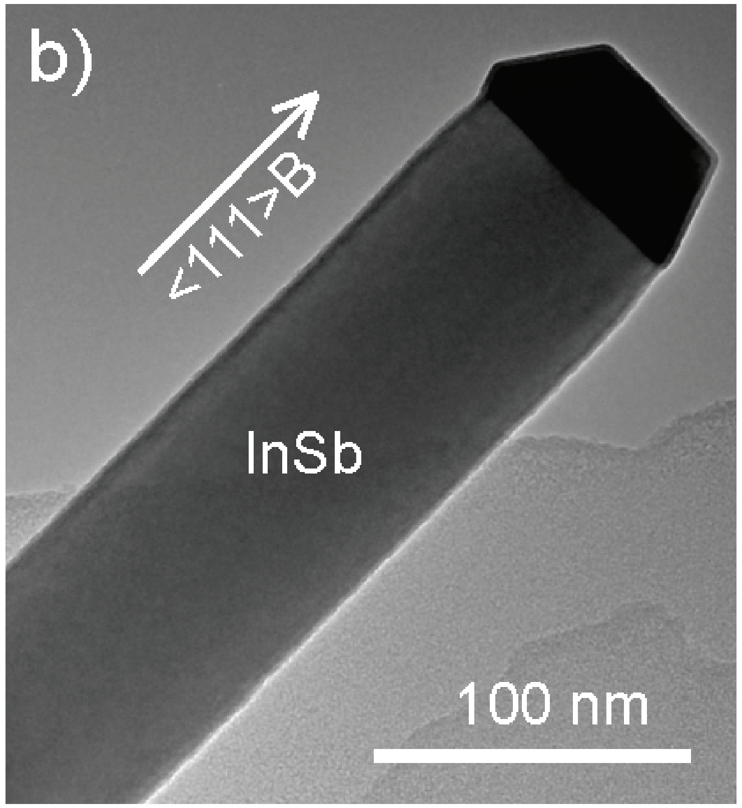




InSb nanowires

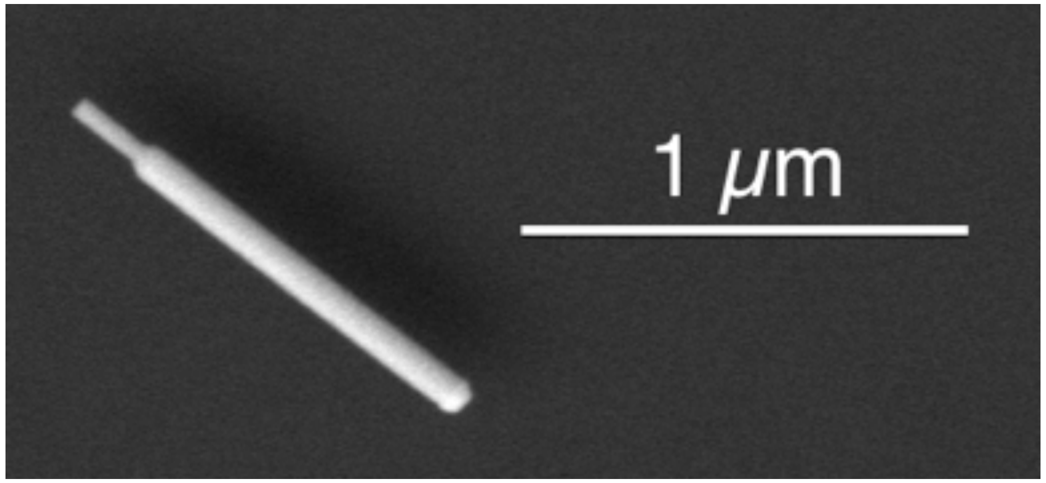


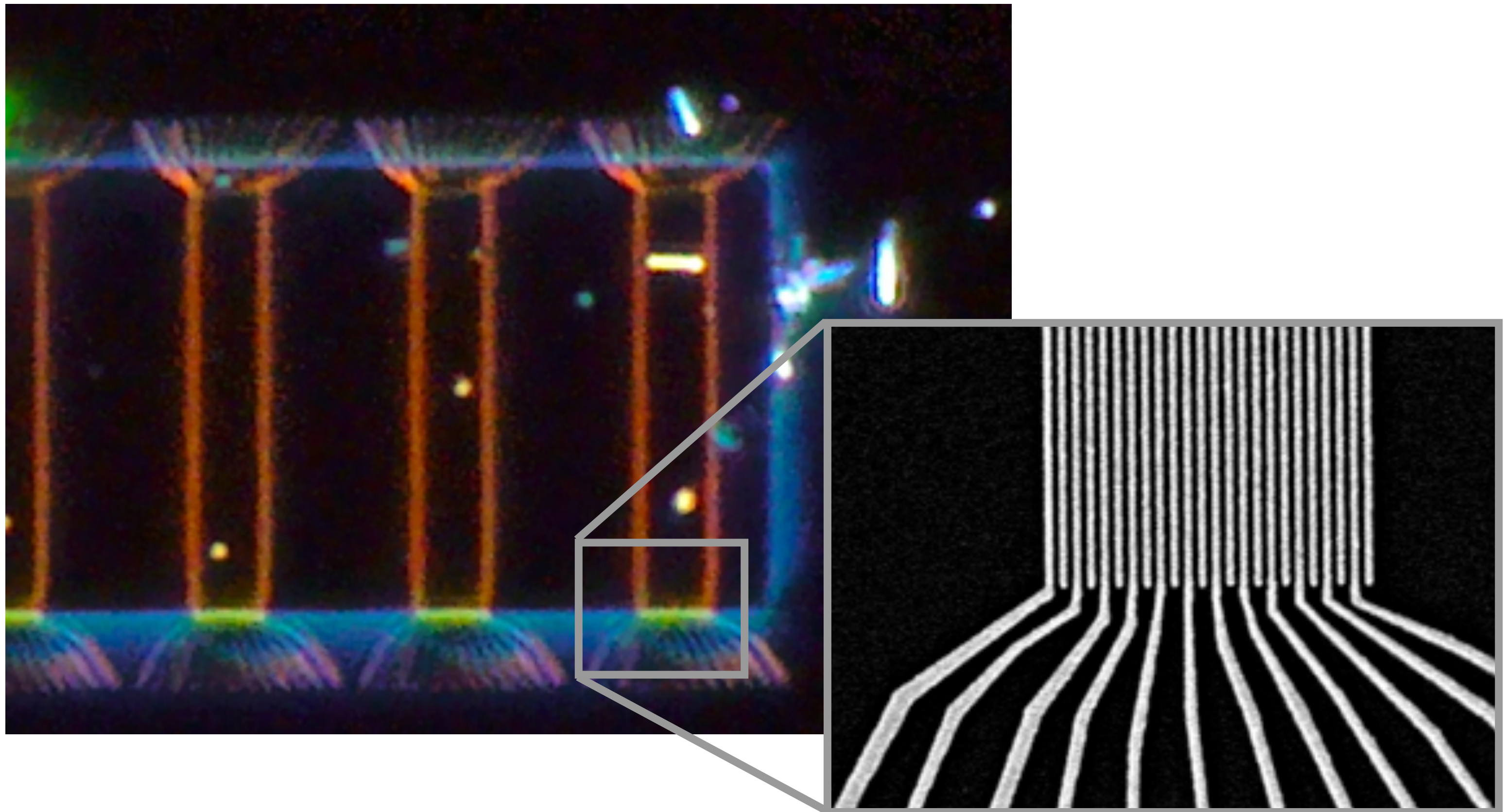
Nilsson *et al.* Nano Lett. (2009)



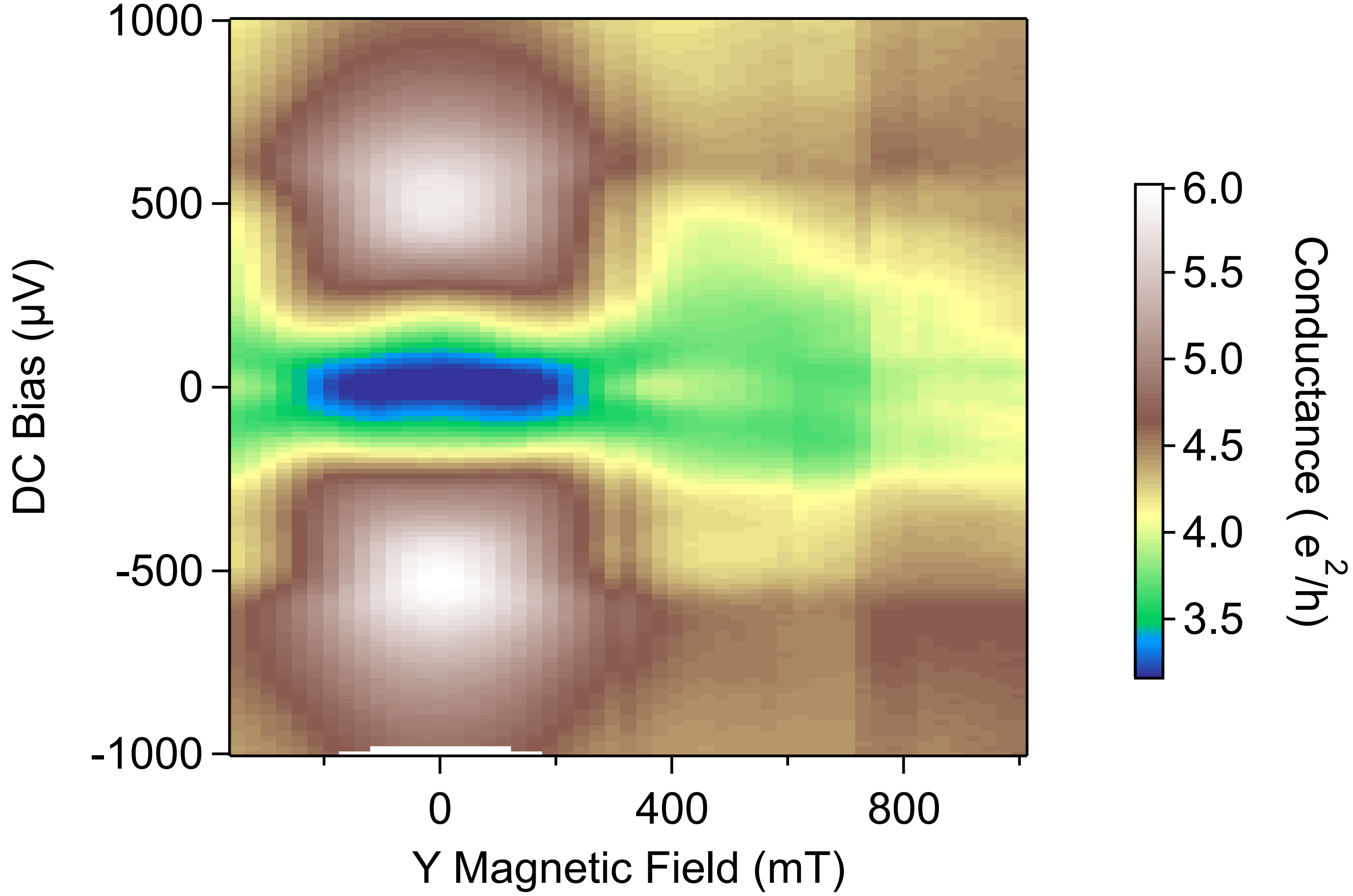
H. Xu, Lund

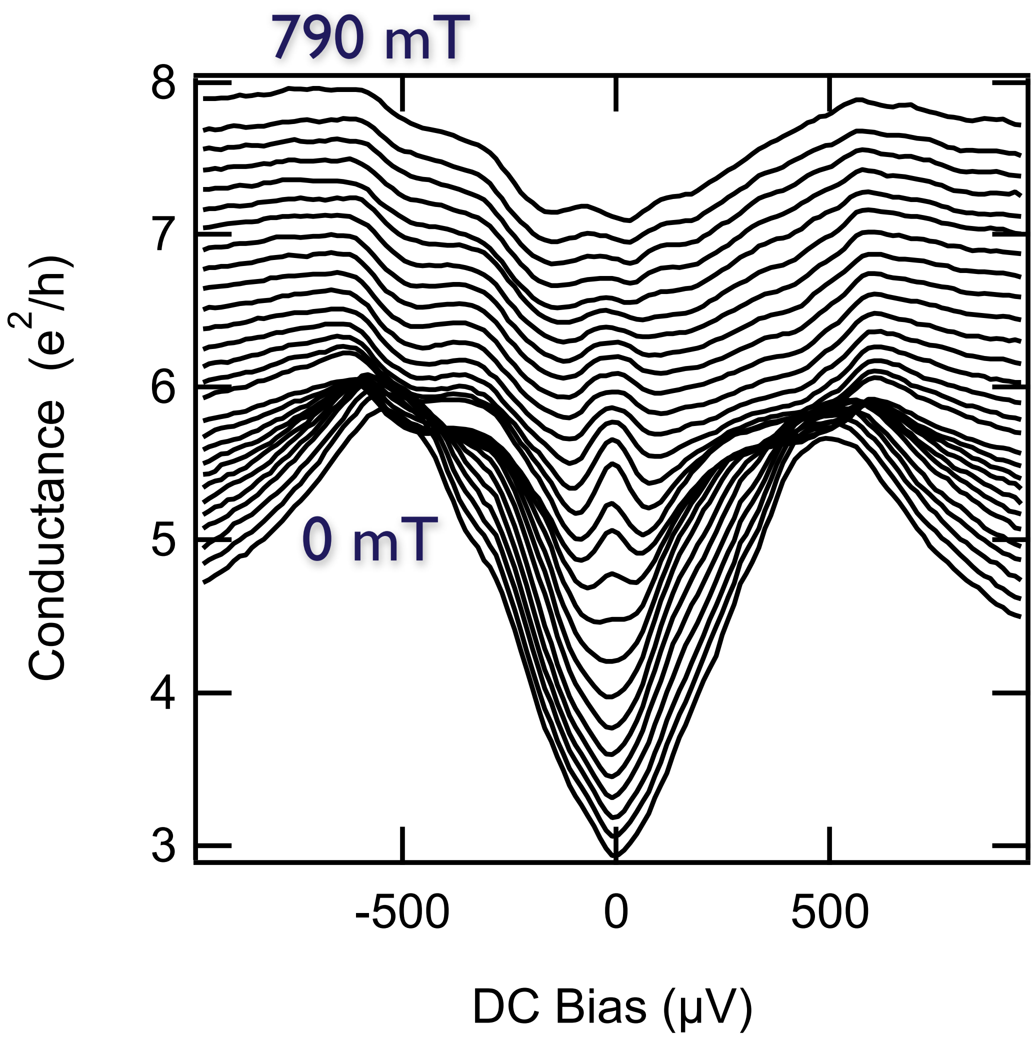
Wires deposited on bottom-gate substrates:

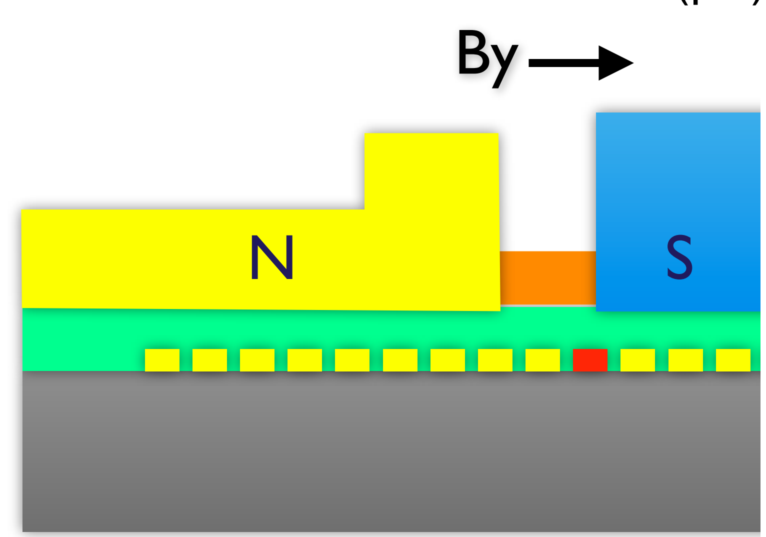


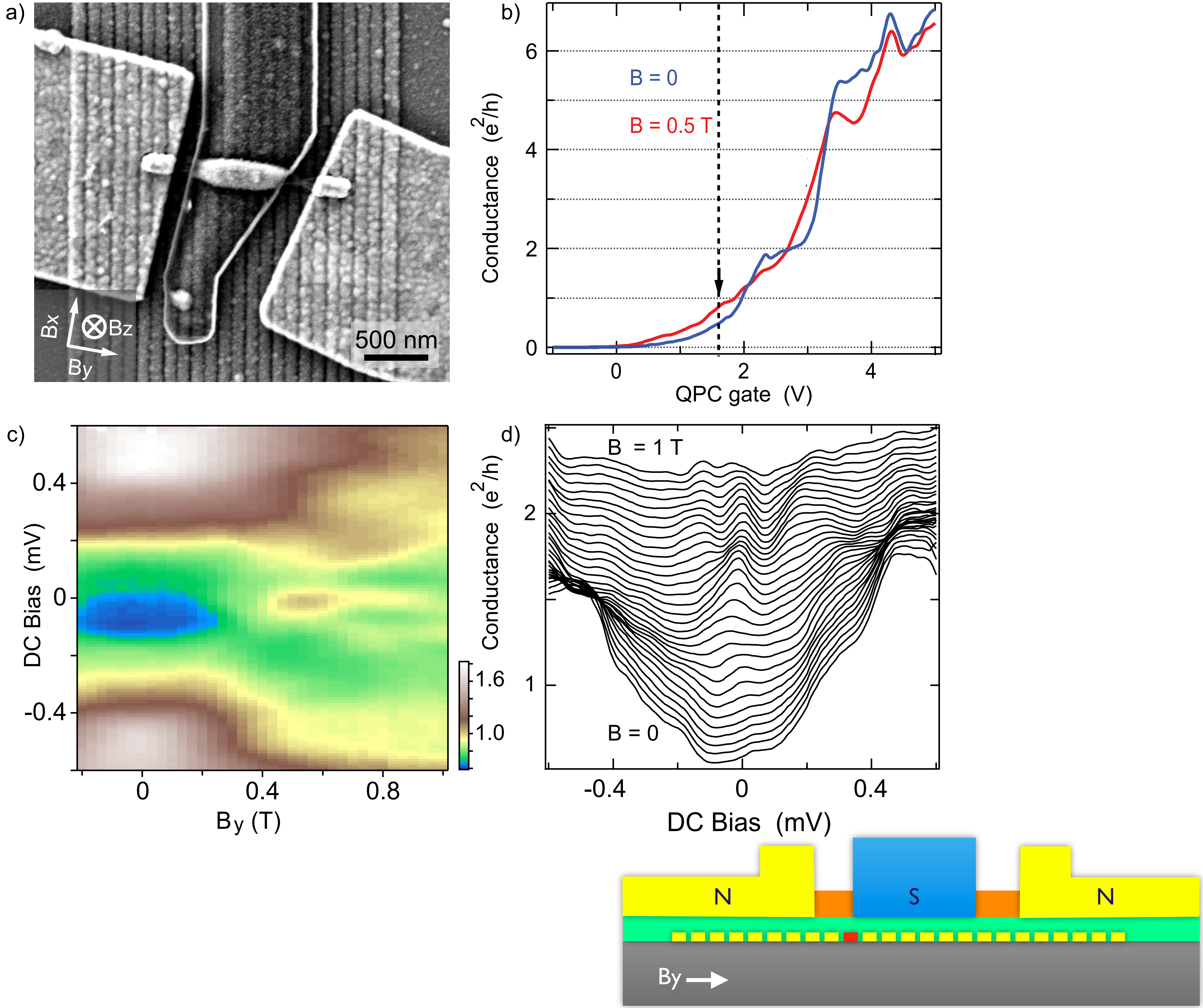


Important check:
Reproduce previously observed behavior

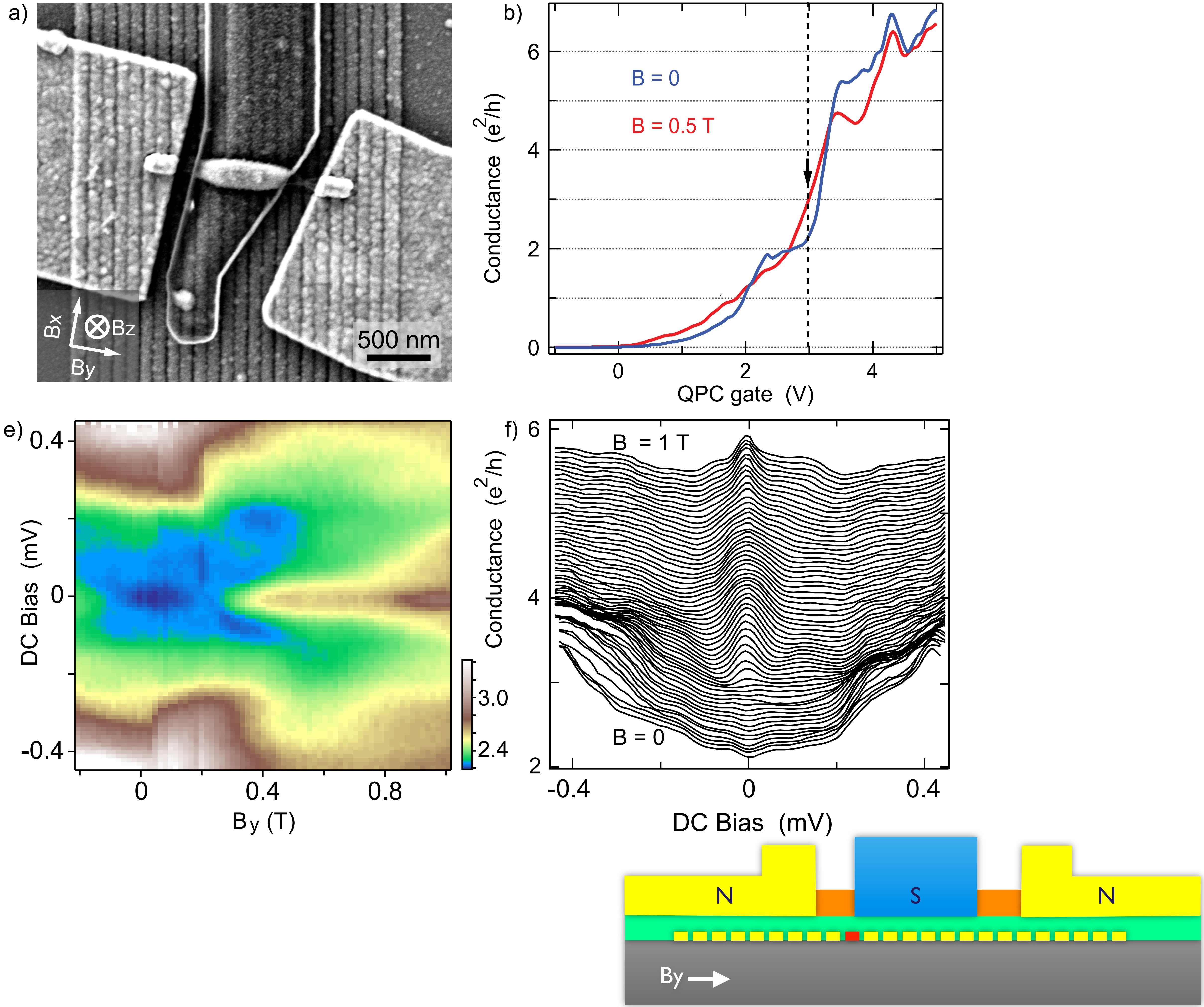








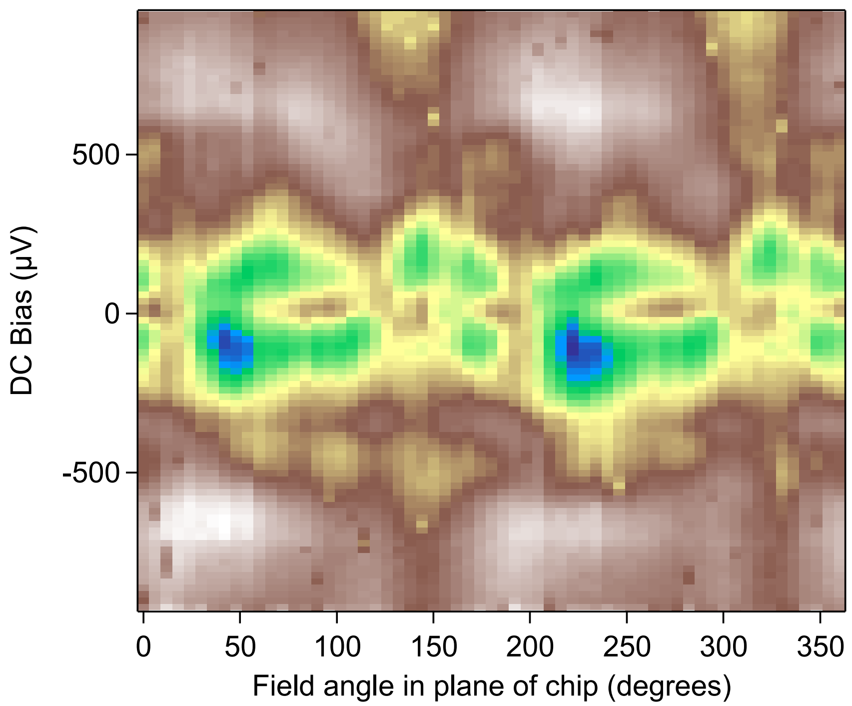
a)
Bx
⊗Bz
By
500 nm
b)
B = 0
B = 0.5 T
Conductance (e²/h)
QPC gate (V)
c)
DC Bias (mV)
By (T)
1.6
1.0
d)
B = 1 T
B = 0
Conductance (e²/h)
DC Bias (mV)
N
S
N
By

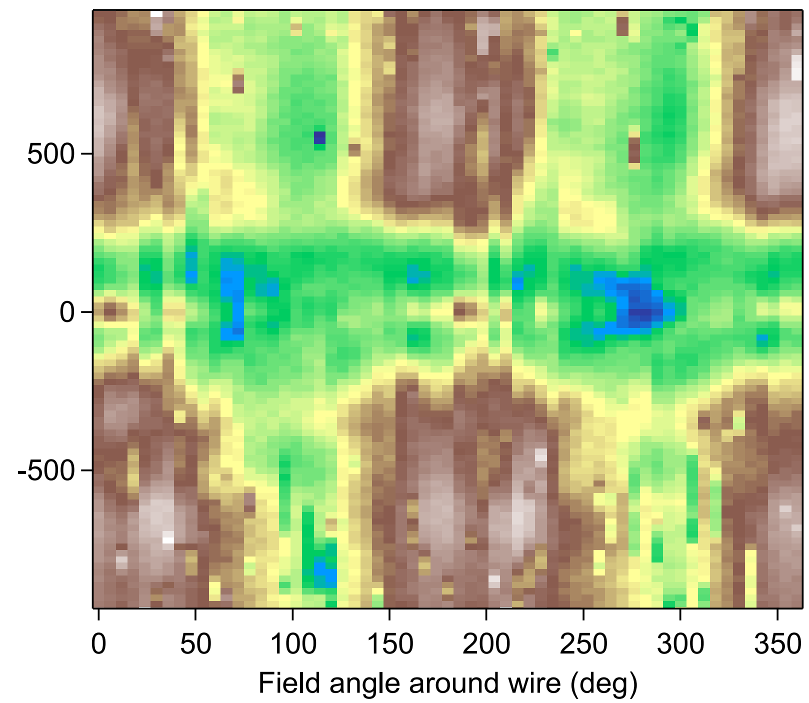


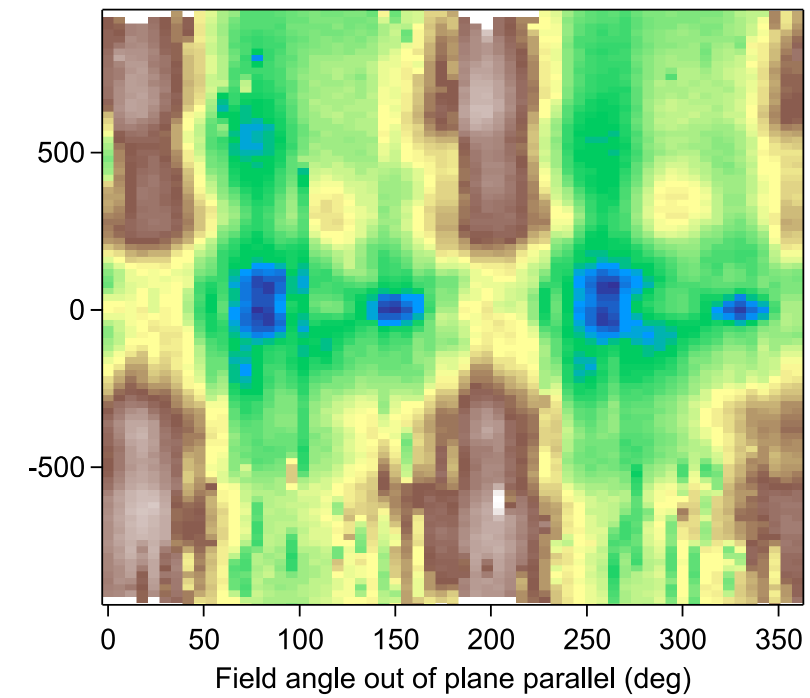
a)
Bx
Bz
By
500 nm
b)
B = 0
B = 0.5 T
Conductance (e^2/h)
QPC gate (V)
e)
DC Bias (mV)
By (T)
3.0
2.4
f)
B = 1 T
B = 0
Conductance (e^2/h)
DC Bias (mV)
N
S
N
By

QPC, vary field angle

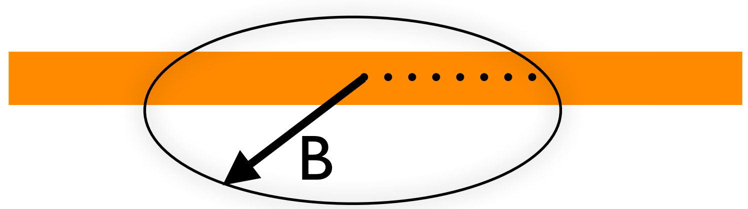
$|B| = 500$ mT

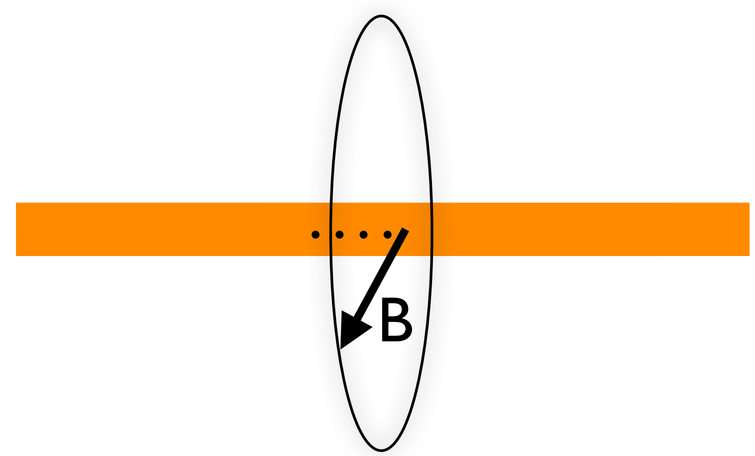


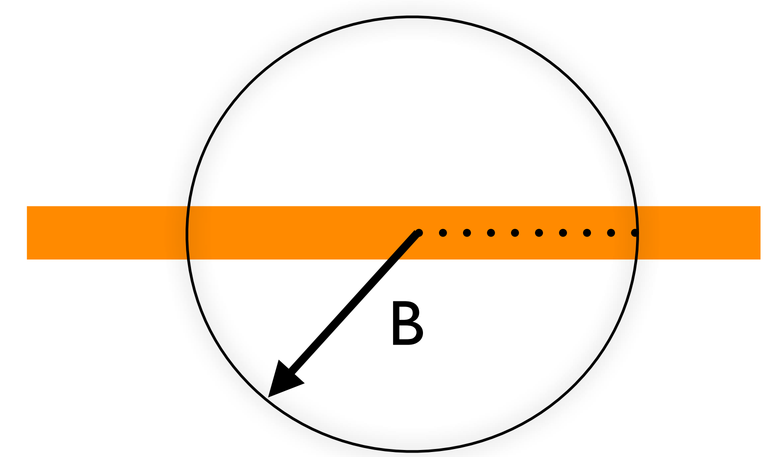




side view:



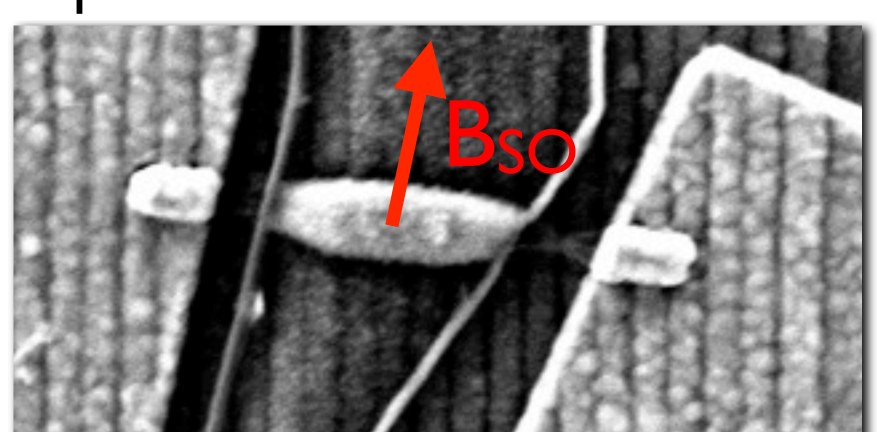




.... is 0 degrees

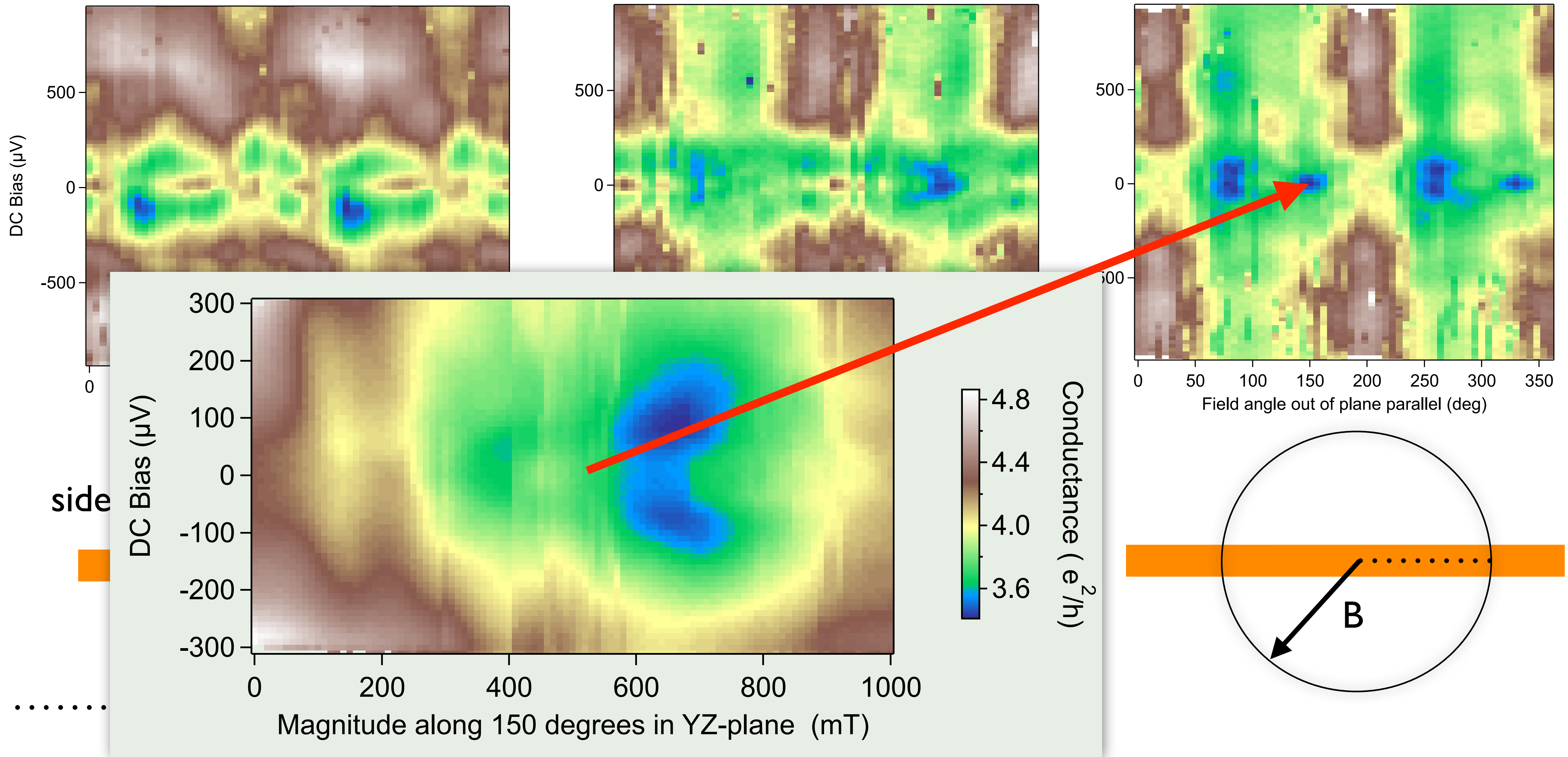
top view:

"expectation":

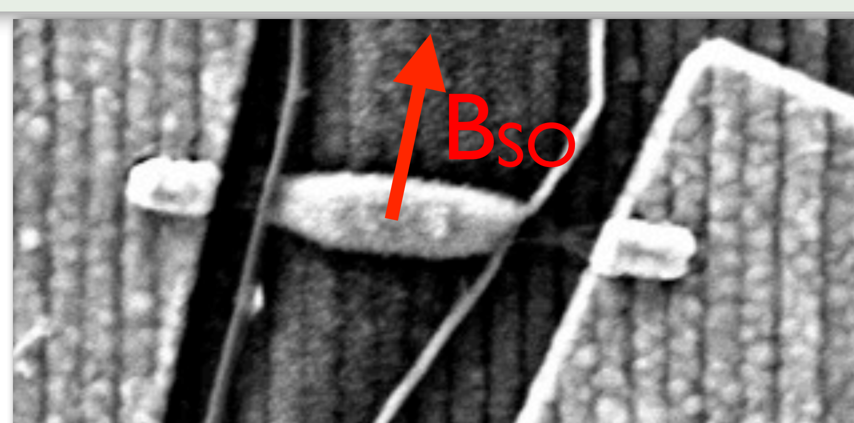


QPC, vary field angle

|B| = 500 mT



“expectation”:



PRL 109, 186802 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Zero-Bias Anomaly in a Nanowire Quantum Dot Coupled to Superconductors

Eduardo J. H. Lee,[1] Xiaocheng Jiang,[2] Ramón Aguado,[3] Georgios Katsaros,[1,*] Charles M. Lieber,[2] and Silvano De Franceschi[1,†]
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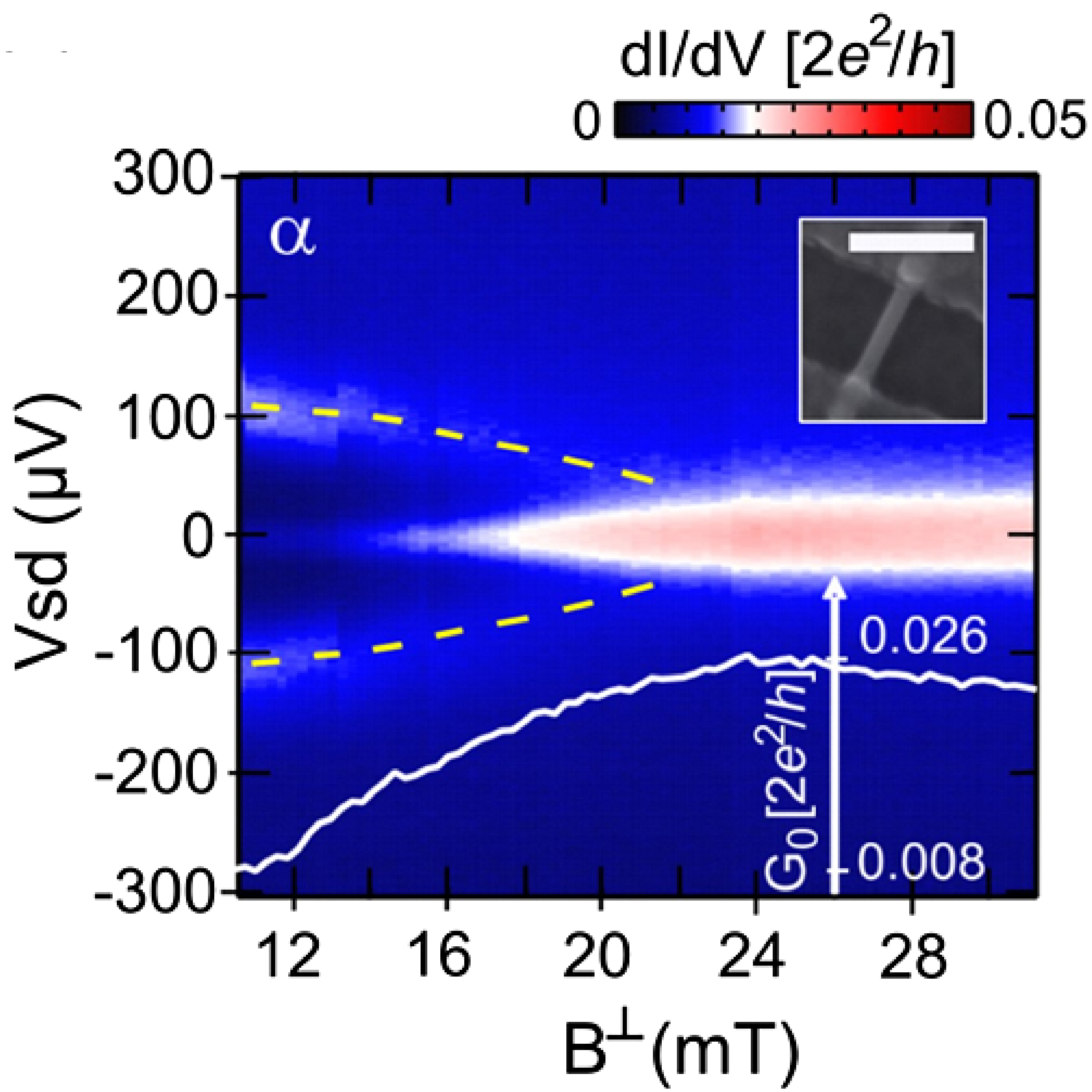
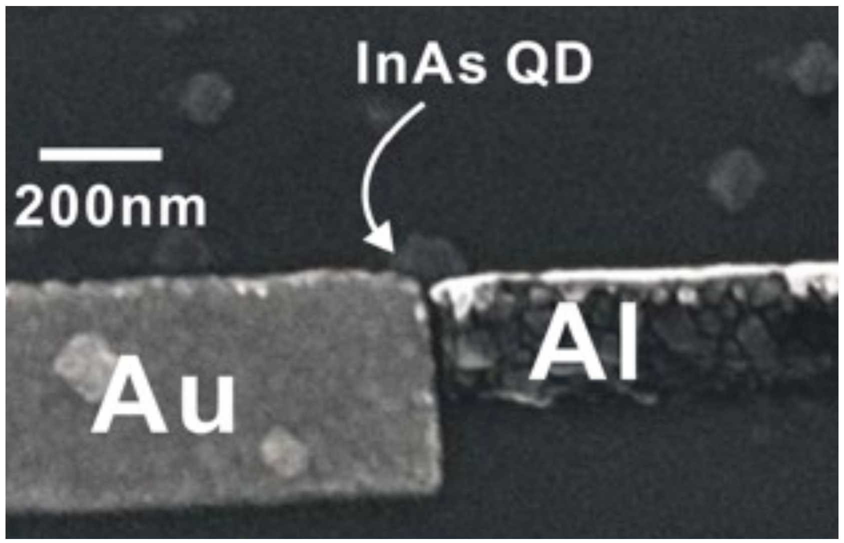
(Received 5 July 2012; published 31 October 2012)

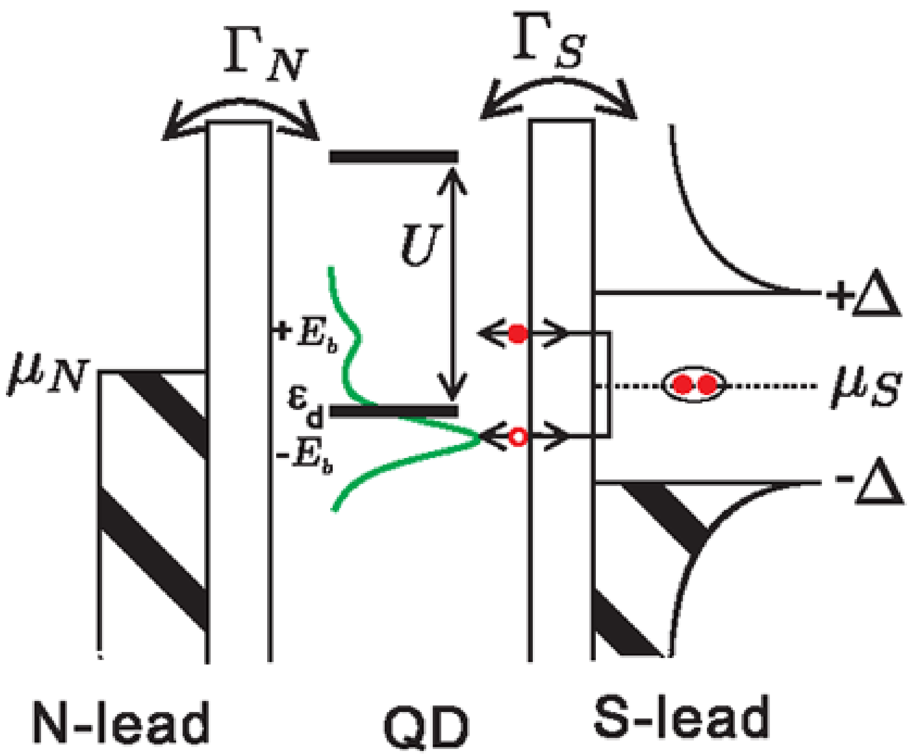


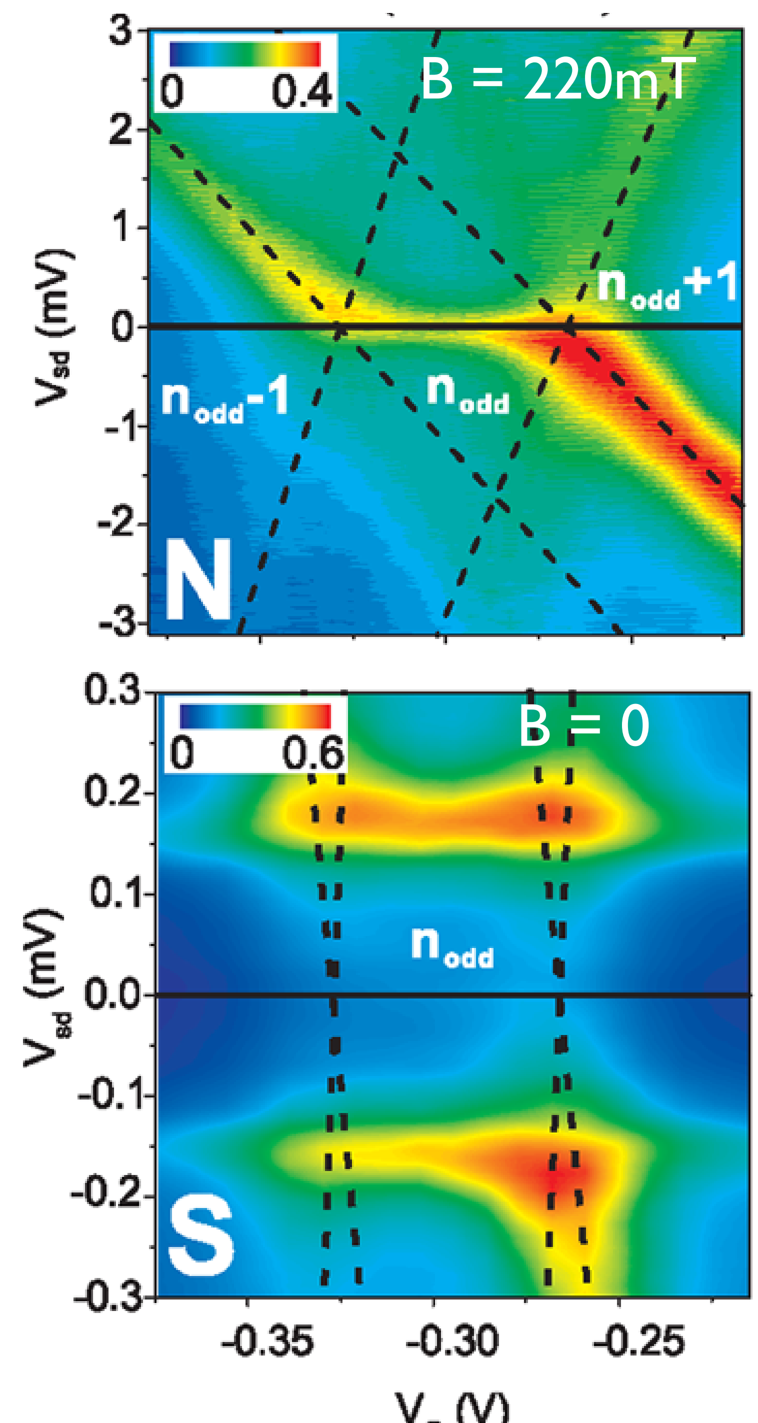
PRL 104, 076805 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

Tunneling Spectroscopy of Andreev Energy Levels in a Quantum Dot Coupled to a Superconductor

R. S. Deacon,[1,*] Y. Tanaka,[2] A. Oiwa,[1,3,4] R. Sakano,[1] K. Yoshida,[3] K. Shibata,[5] K. Hirakawa,[4,5,6] and S. Tarucha[1,3,6,7]







Tunneling Spectroscopy of Quasiparticle Bound States in a Spinful Josephson Junction

W. Chang,[1,2] V. E. Manucharyan,[3] T. S. Jespersen,[2] J. Nygård,[2] and C. M. Marcus[1,2]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
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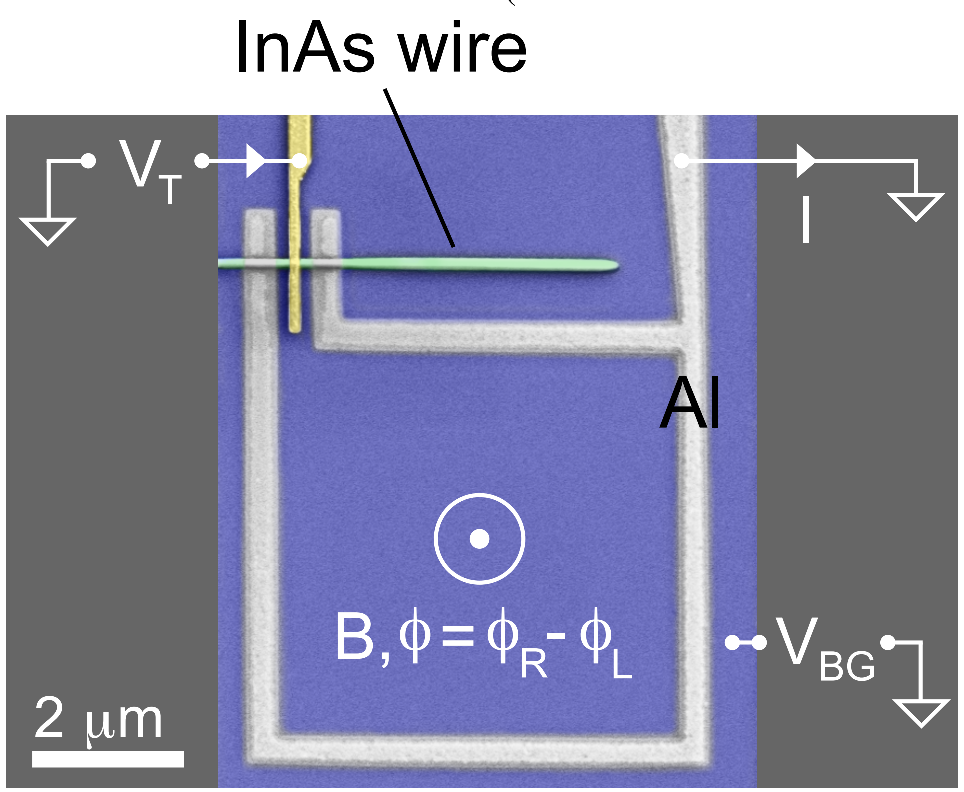
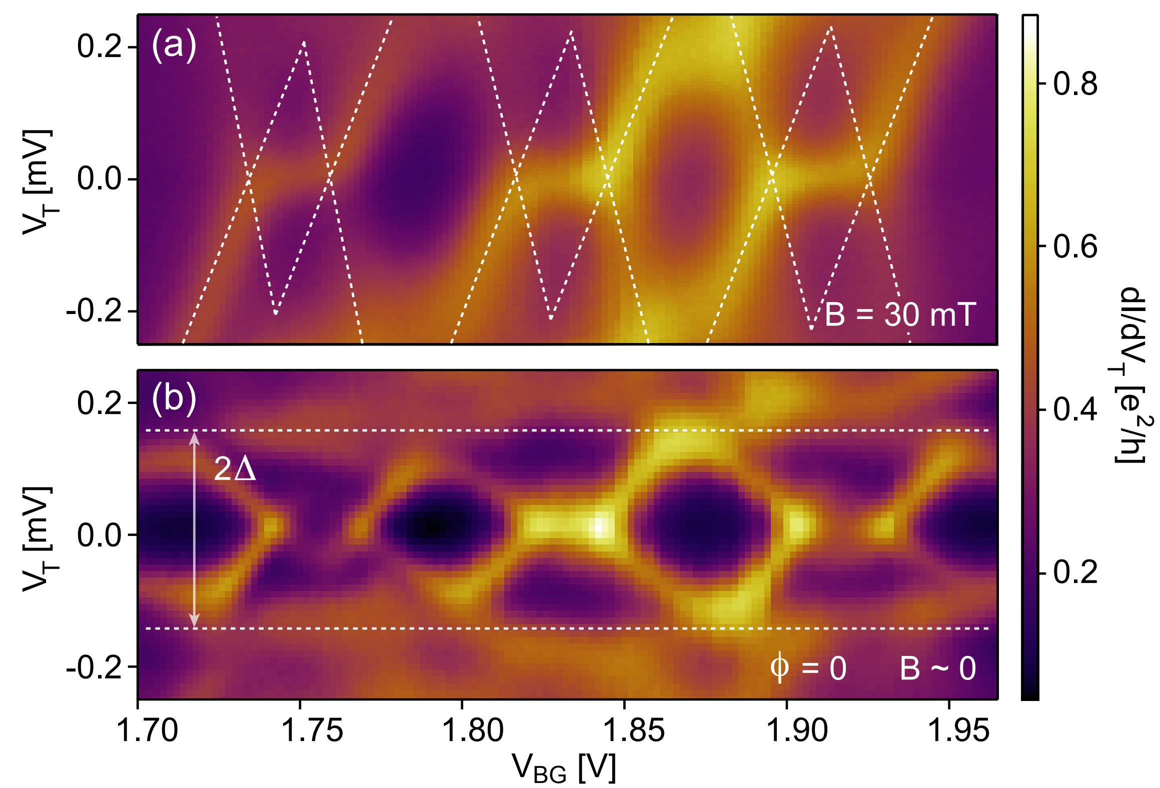
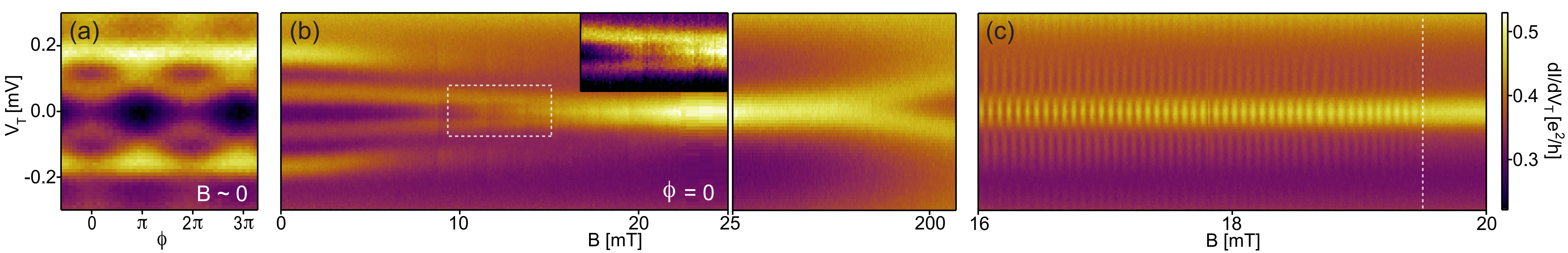
[3]*Society of Fellows, Harvard University, Cambridge, Massachusetts 02138, USA*
(Received 13 November 2012; published 23 May 2013)

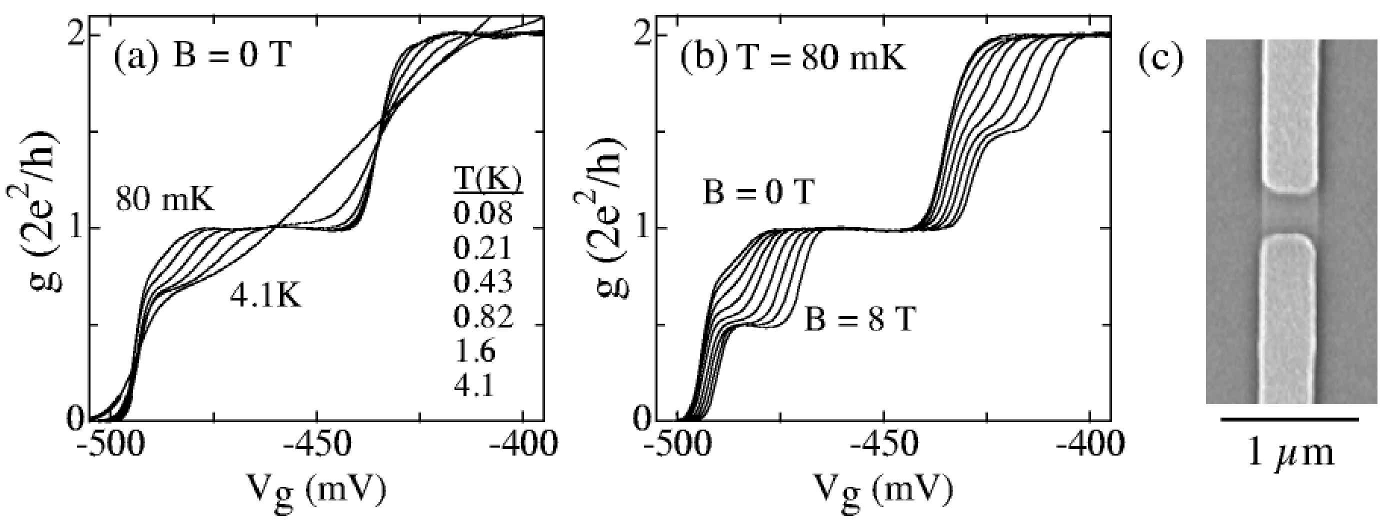


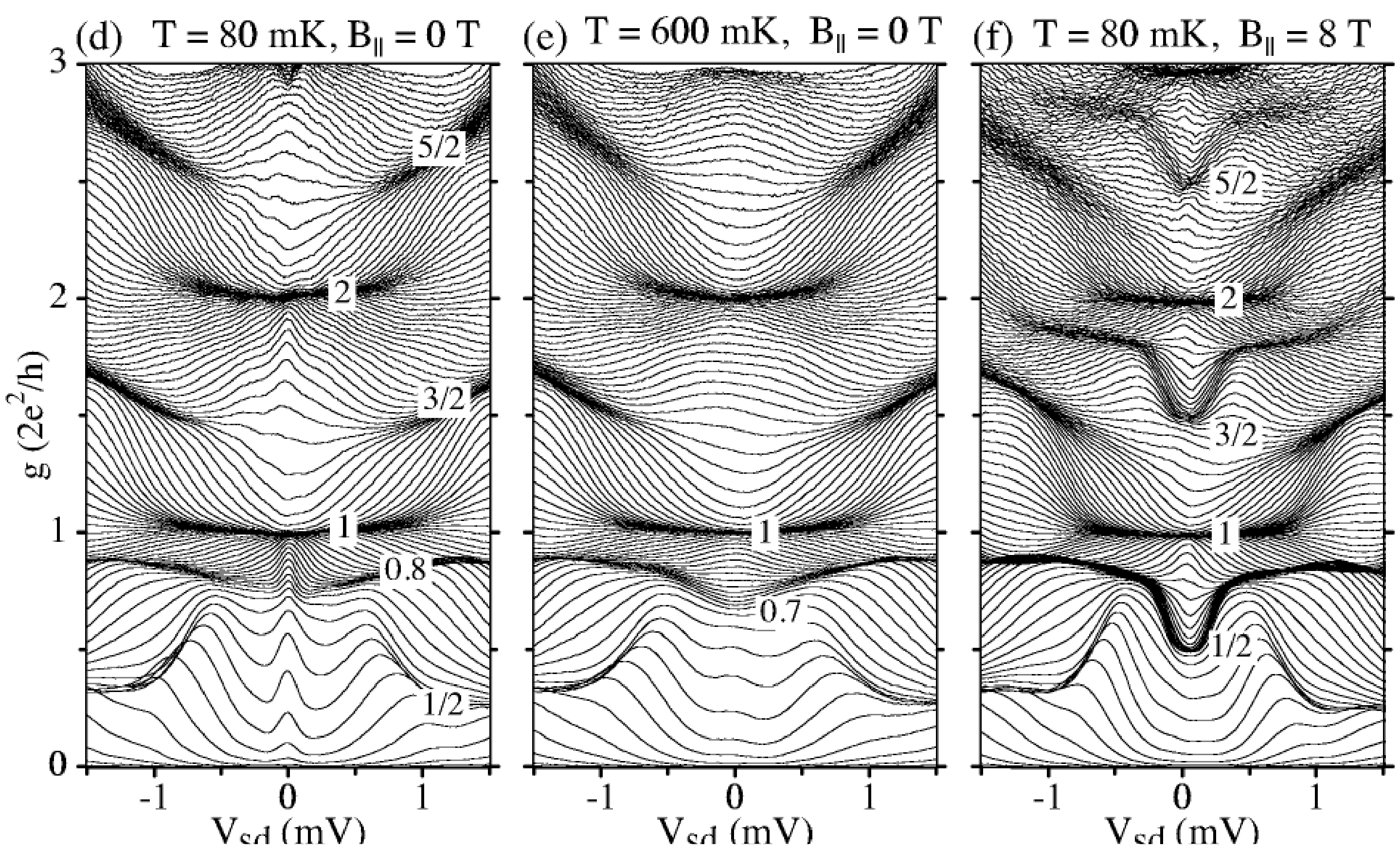


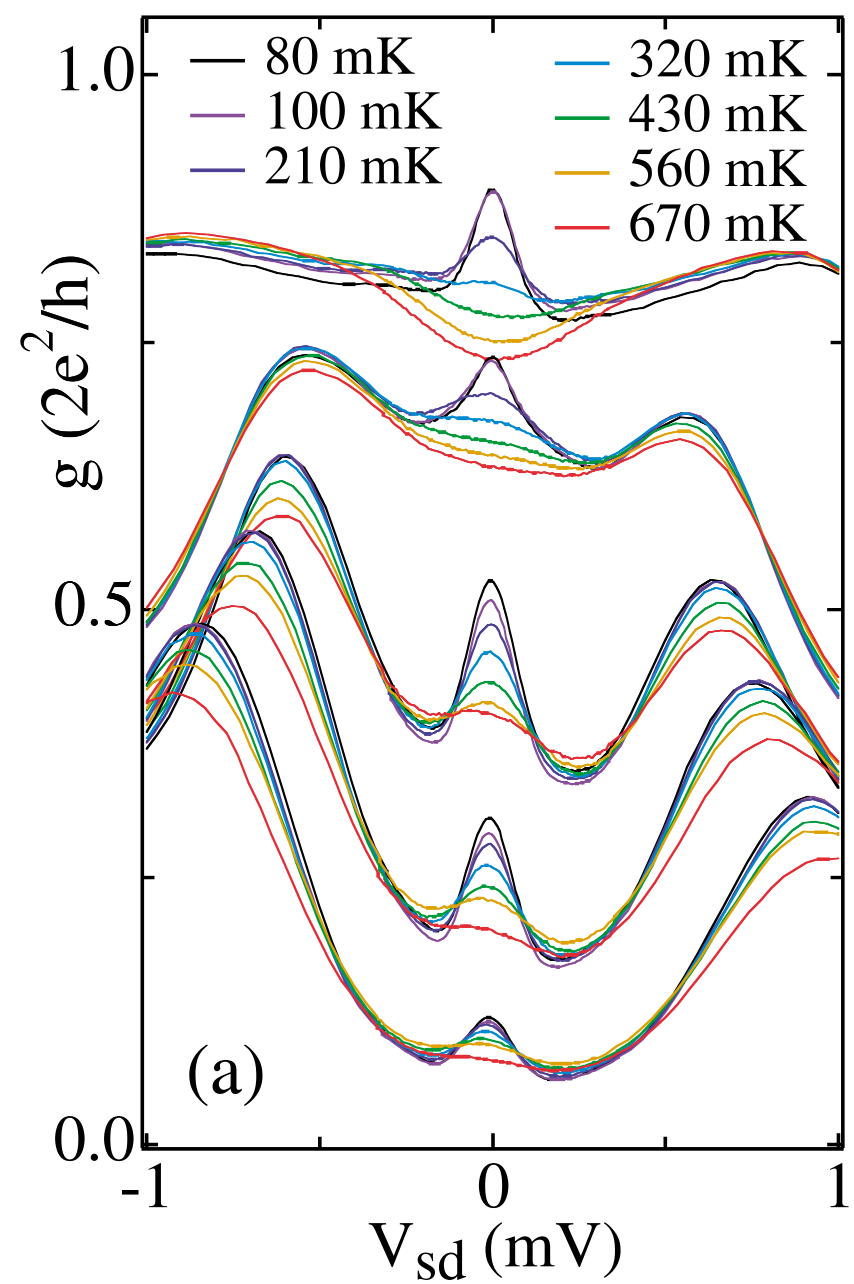


Low-Temperature Fate of the 0.7 Structure in a Point Contact: A Kondo-like Correlated State in an Open System

S. M. Cronenwett,[1,2] H. J. Lynch,[1] D. Goldhaber-Gordon,[1,2] L. P. Kouwenhoven,[1,3] C. M. Marcus,[1] K. Hirose,[4] N. S. Wingreen,[5] and V. Umansky[6]







PHYSICAL REVIEW B **82**, 045313 (2010)

Zero-bias anomaly of quantum point contacts in the low-conductance limit

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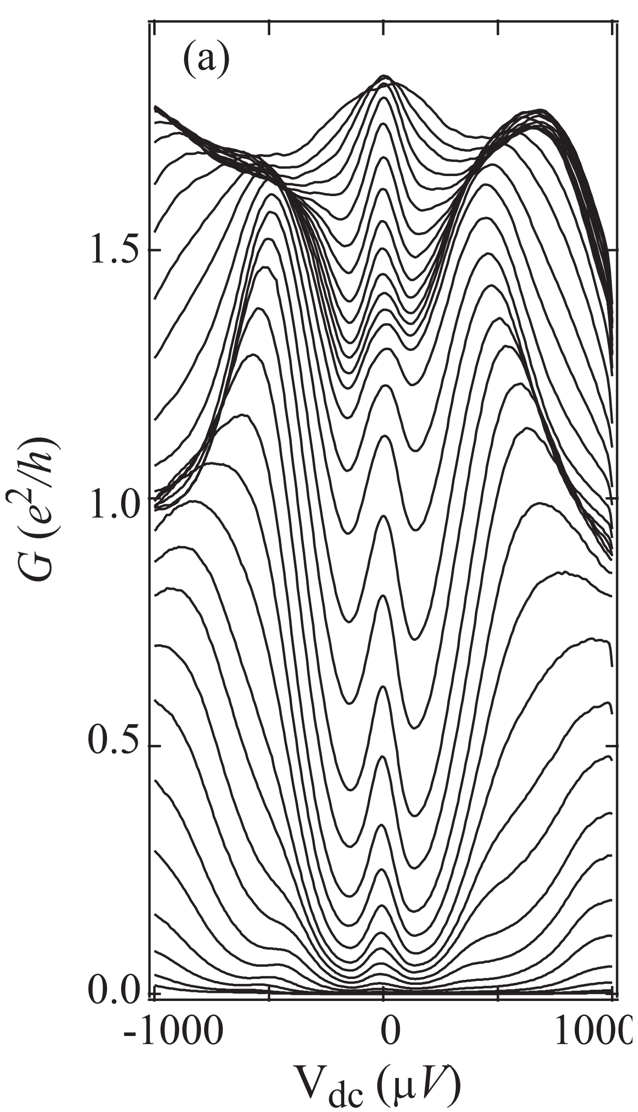
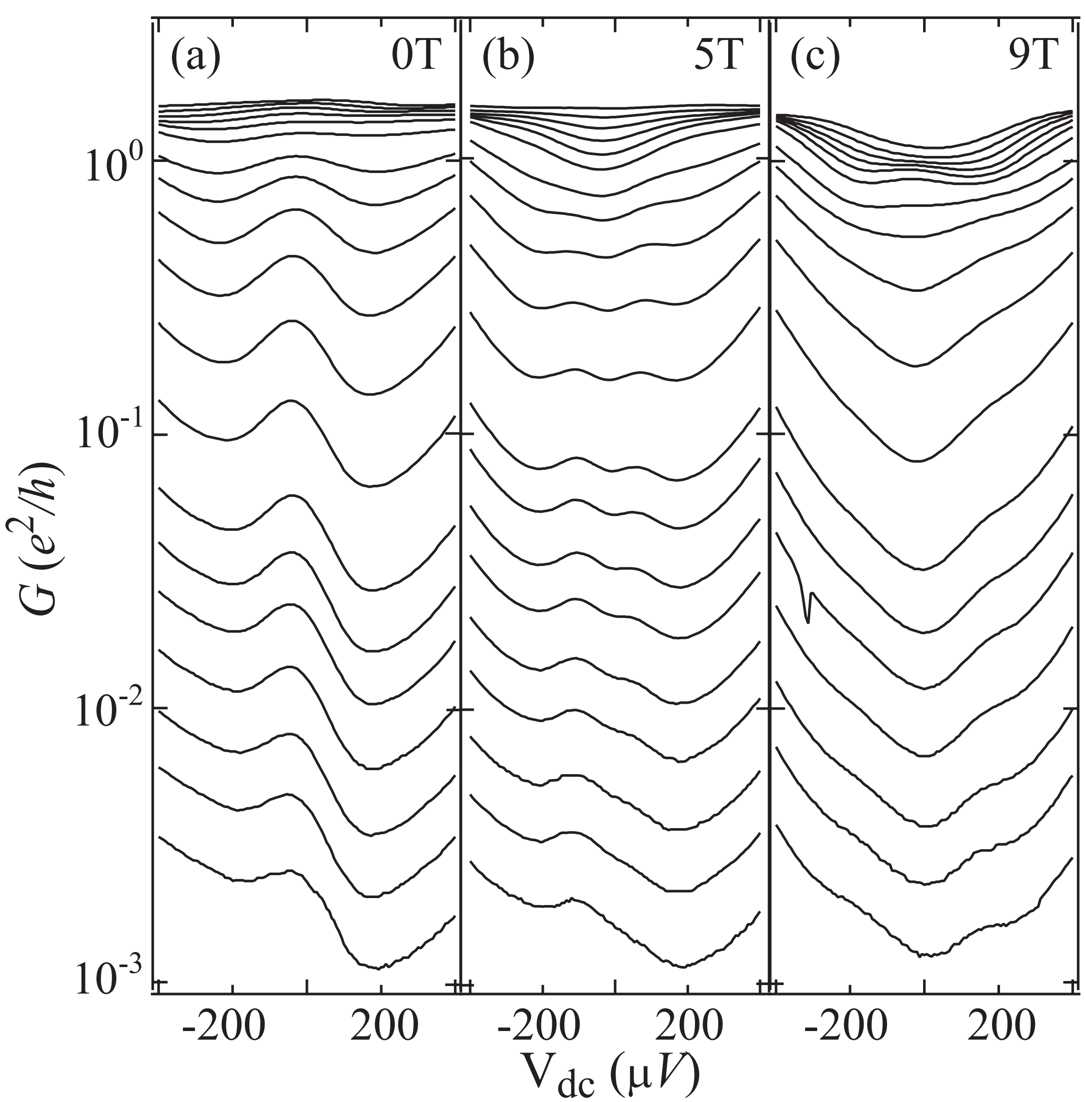
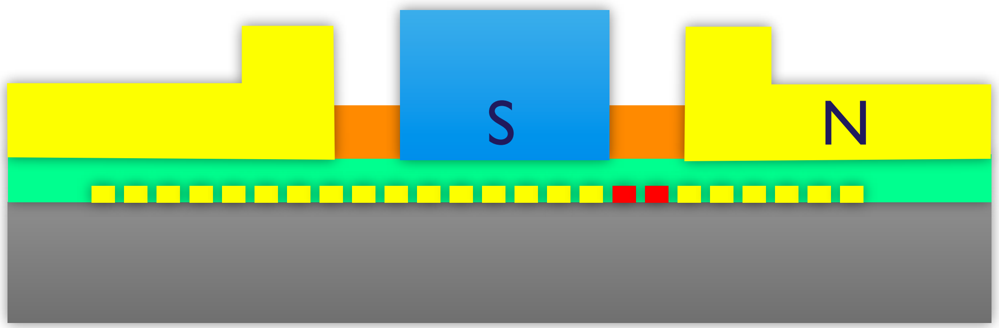
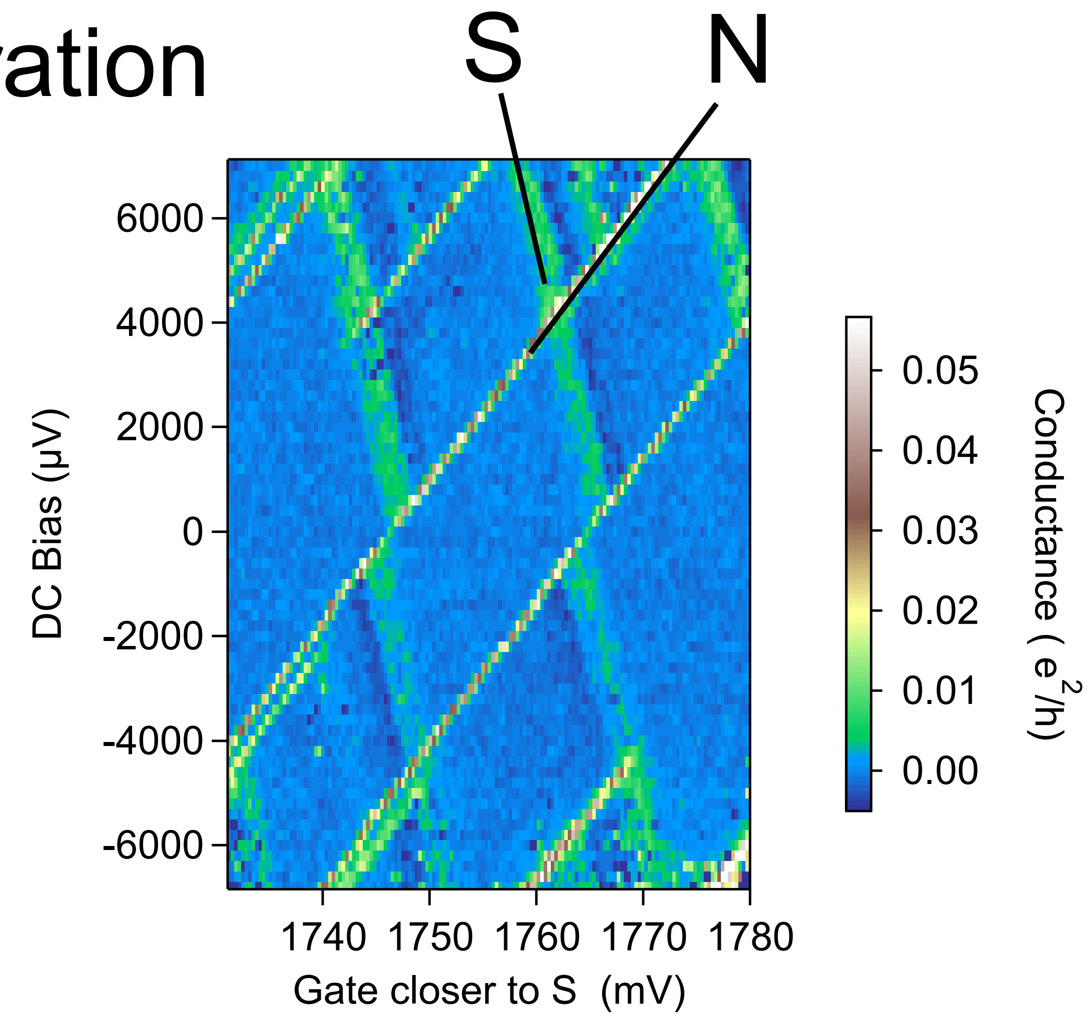
(Received 20 May 2010; published 23 July 2010)

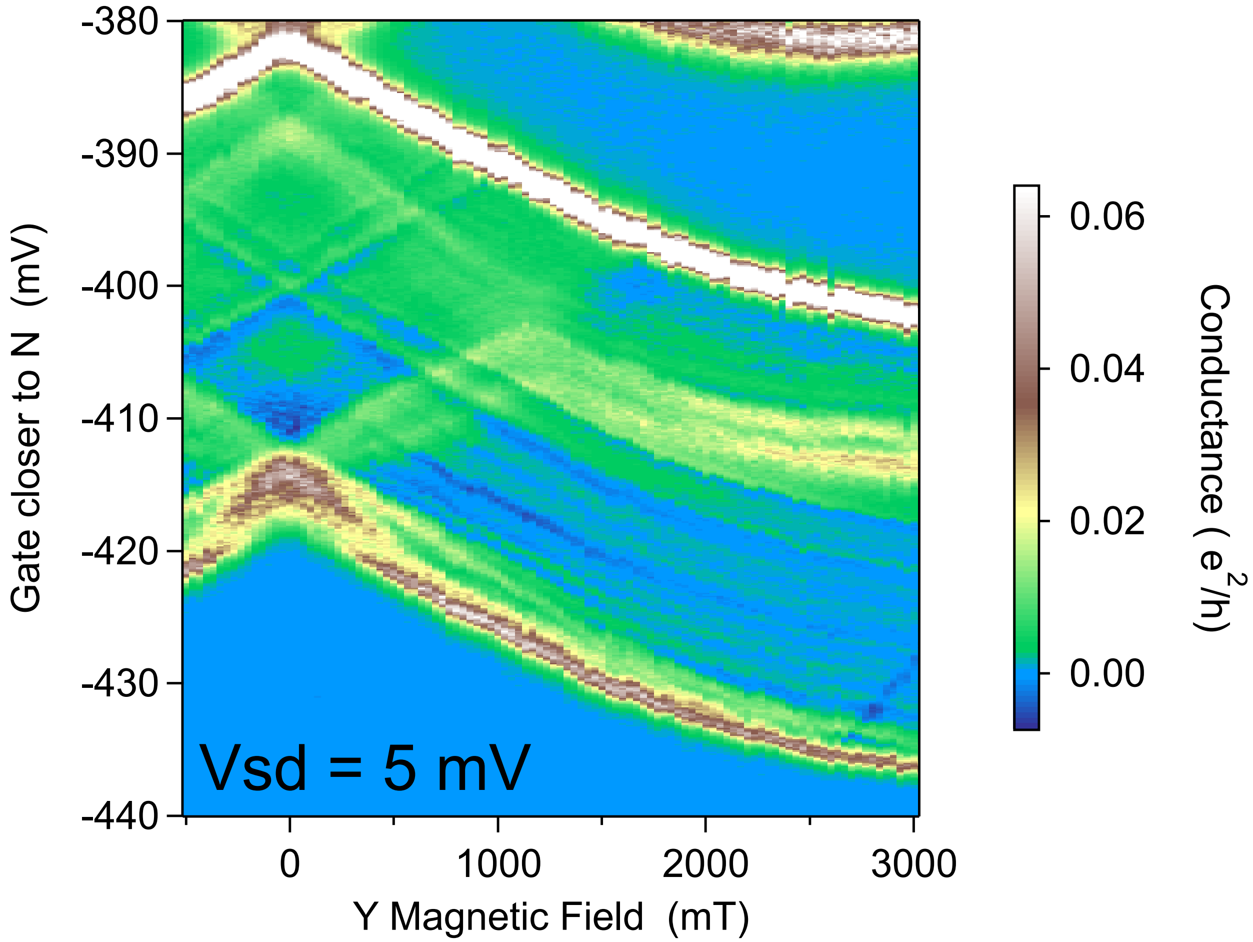


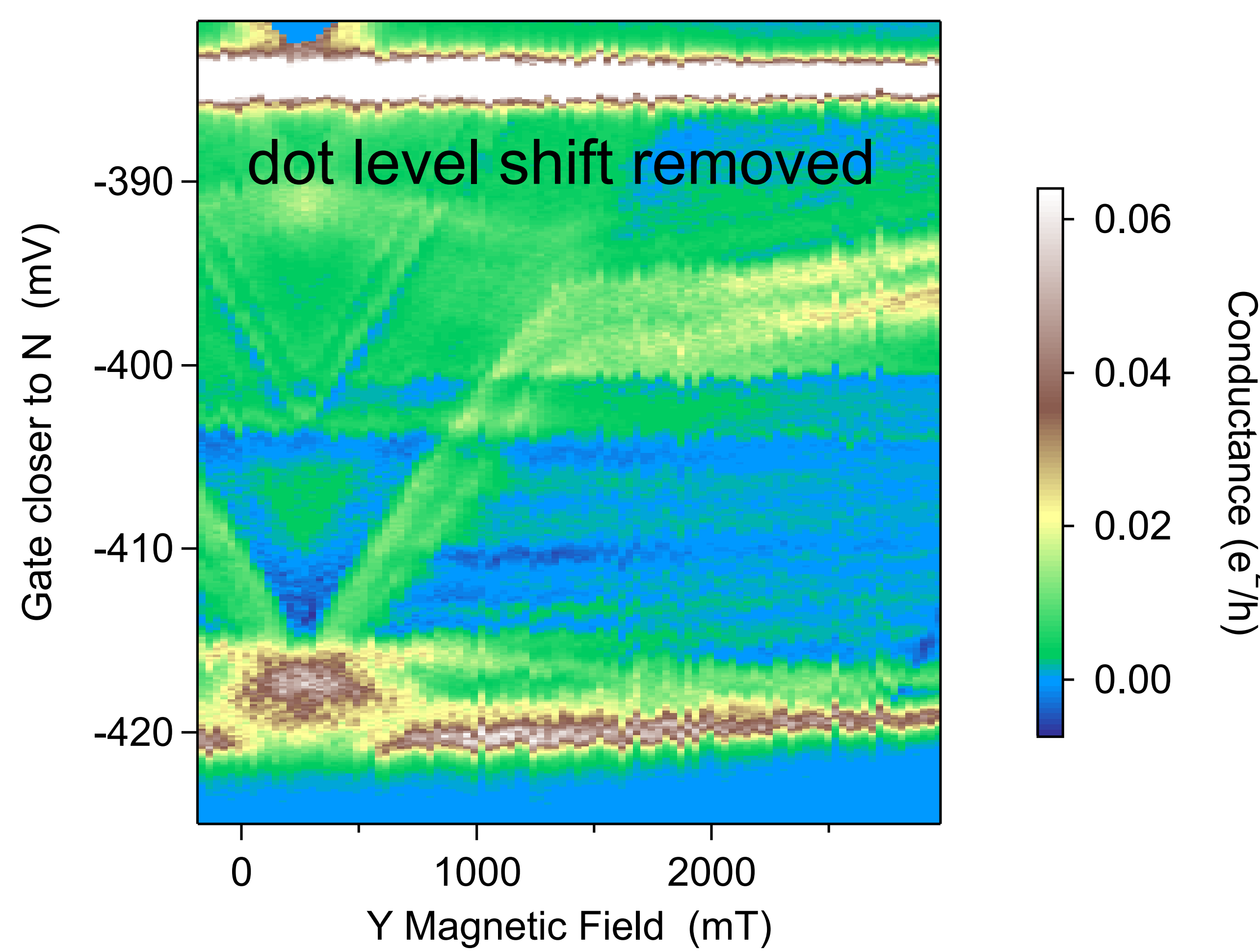


N-dot-S configuration

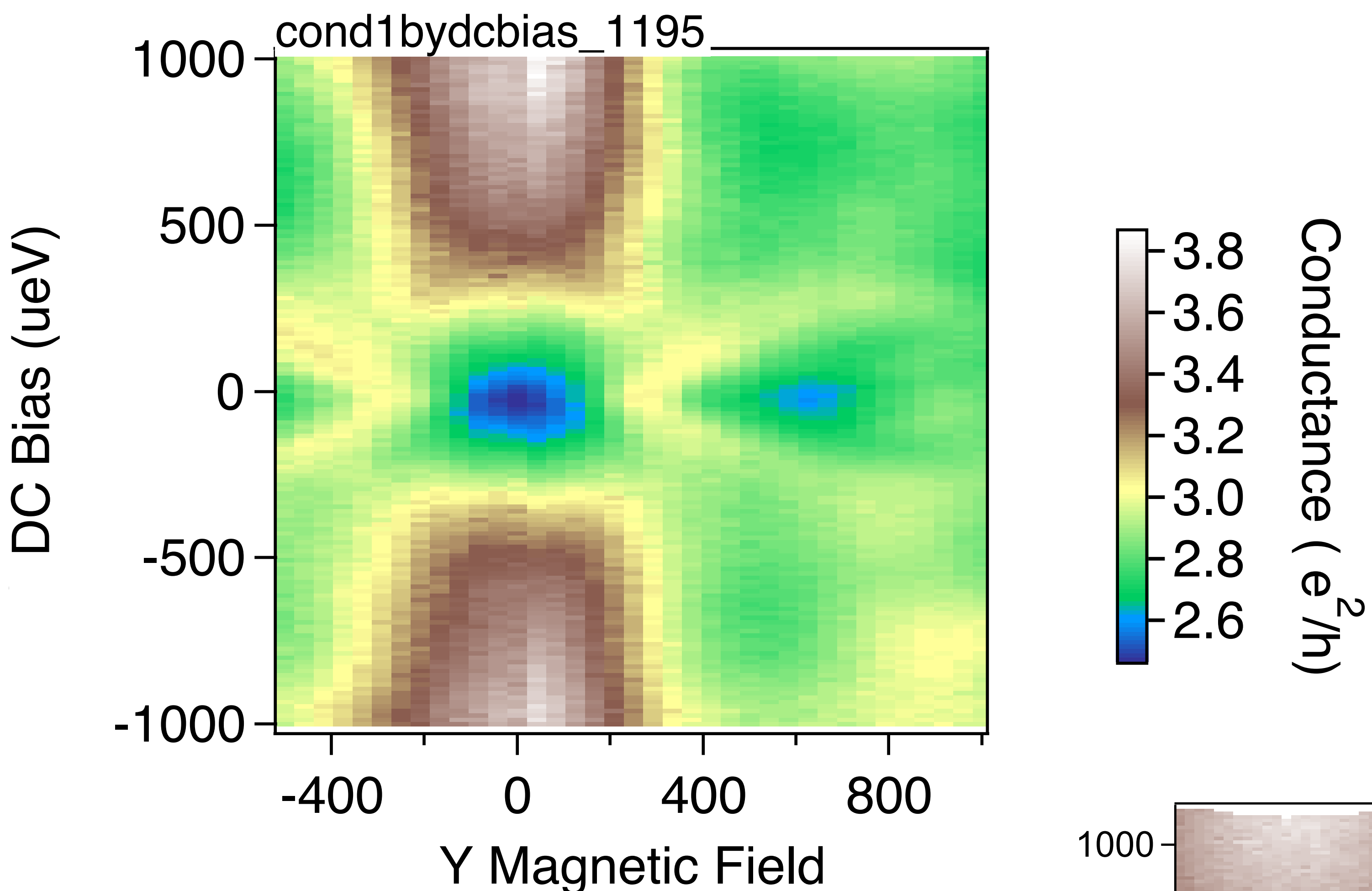


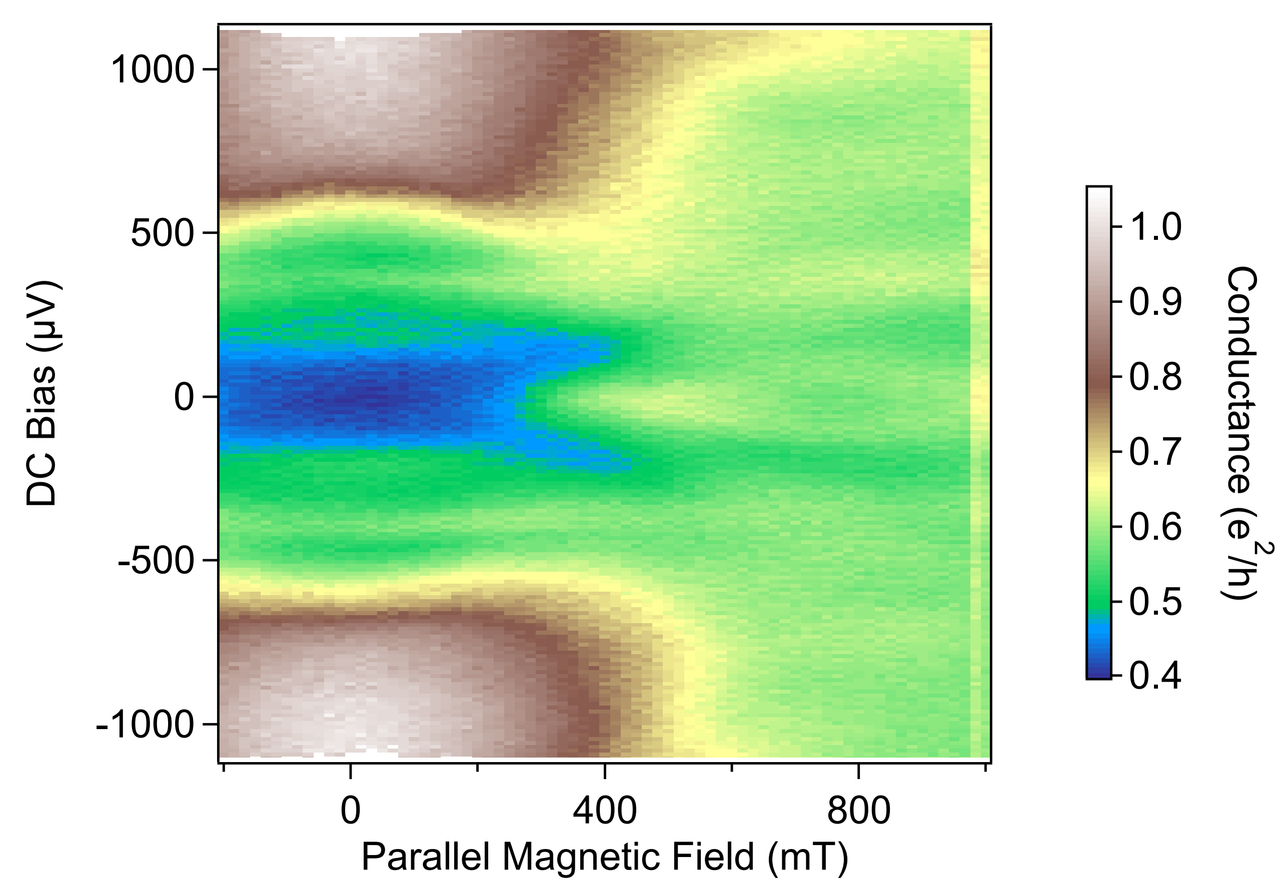






Splitting of ZBPs



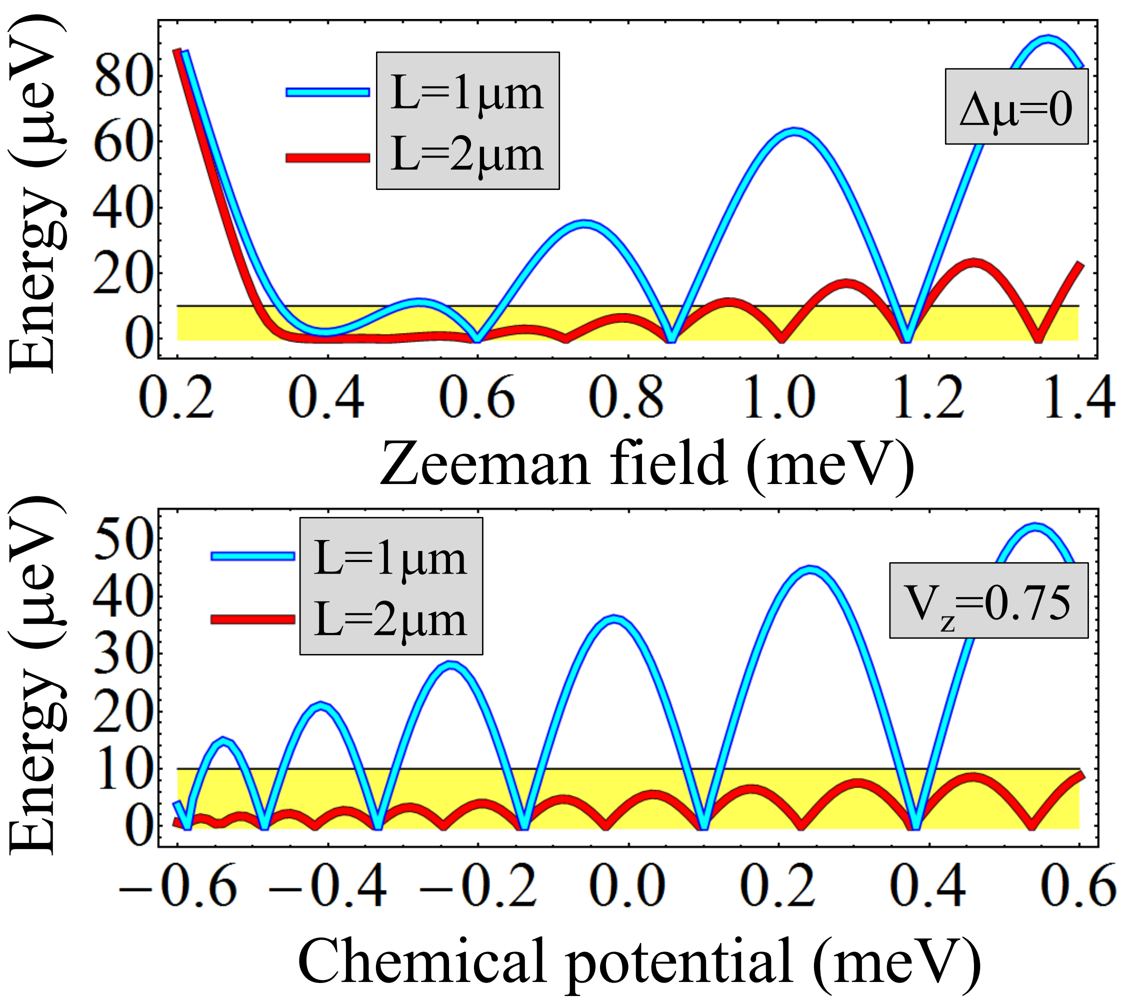


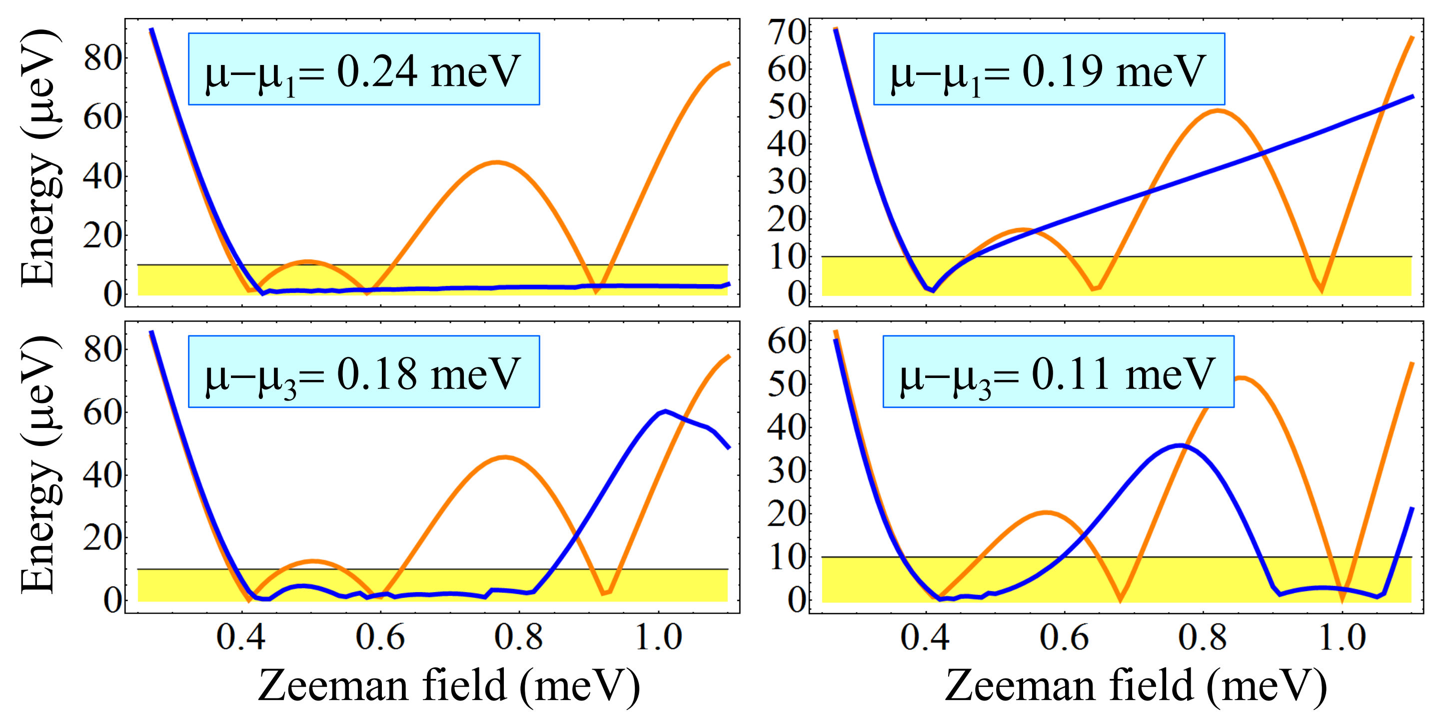
RAPID COMMUNICATIONS

PHYSICAL REVIEW B **86**, 220506(R) (2012)

Splitting of the zero-bias conductance peak as smoking gun evidence for the existence of the Majorana mode in a superconductor-semiconductor nanowire

S. Das Sarma,[1] Jay D. Sau,[2] and Tudor D. Stanescu[3]





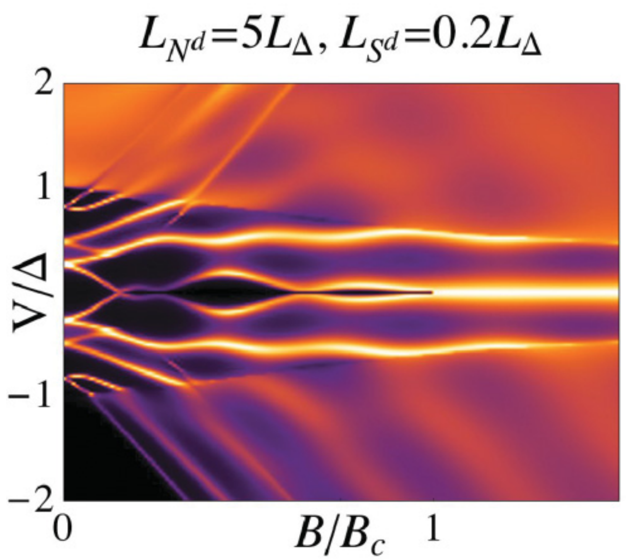
Discuss: constant chemical potential versus constant density models

Oscillations in finite length wires

PHYSICAL REVIEW B **86**, 180503(R) (2012)

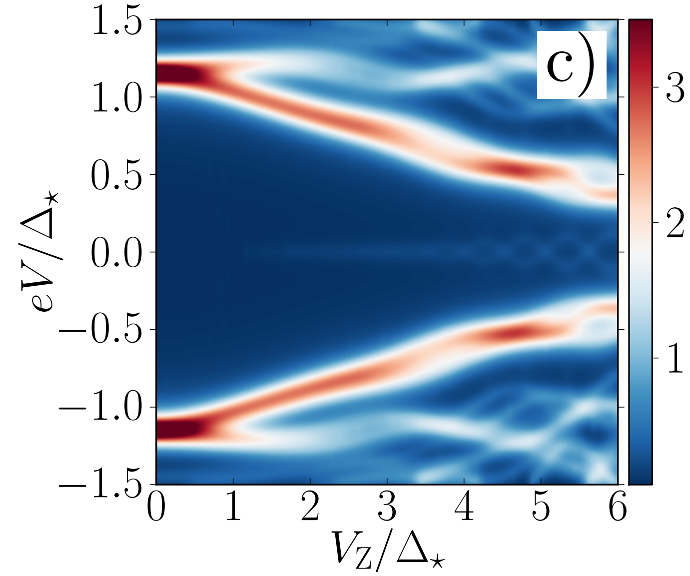
Transport spectroscopy of *NS* nanowire junctions with Majorana fermions

Elsa Prada,[1] Pablo San-Jose,[2] and Ramón Aguado[1]



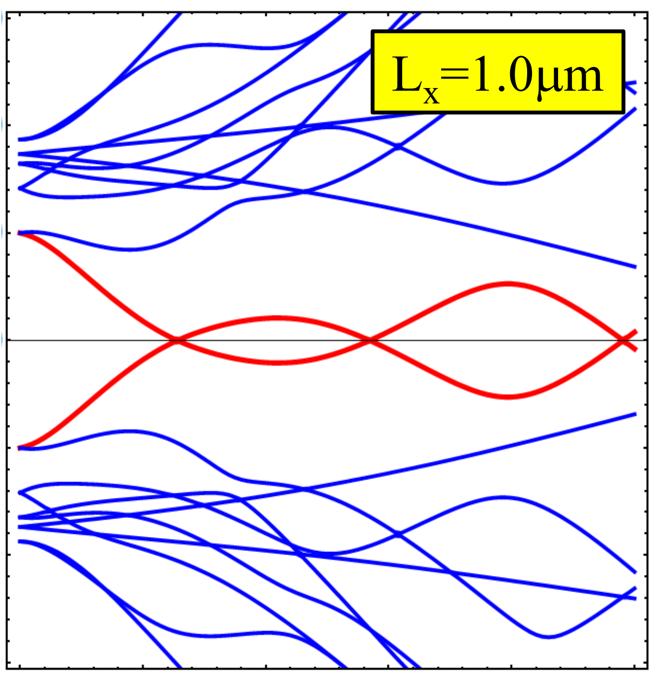
Realistic transport modeling for a superconducting nanowire with Majorana fermions

Diego Rainis, Luka Trifunovic, Jelena Klinovaja, and Daniel Loss
Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
(Dated: July 26, 2012)



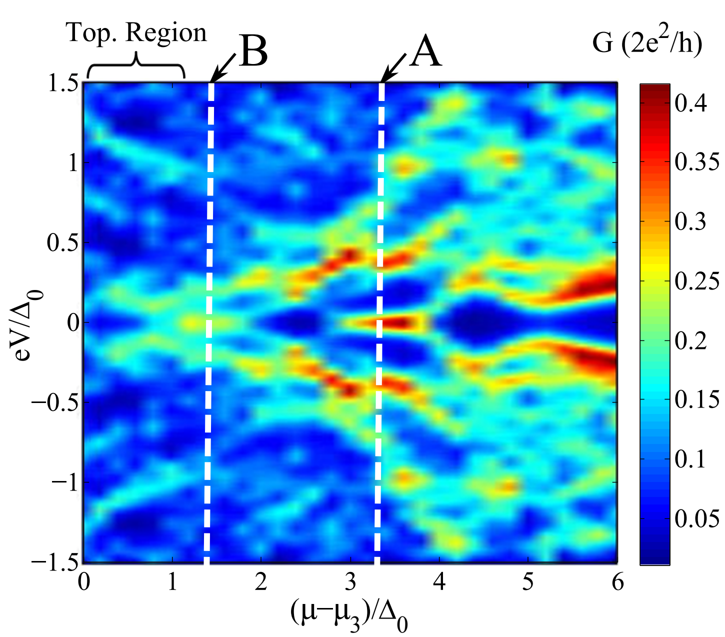
Magnetic field tuned dimensional crossover in spin-orbit coupled semiconductor nanowires with induced superconducting pairing

Tudor D. Stanescu,[1] Roman M. Lutchyn,[2] and S. Das Sarma[3]



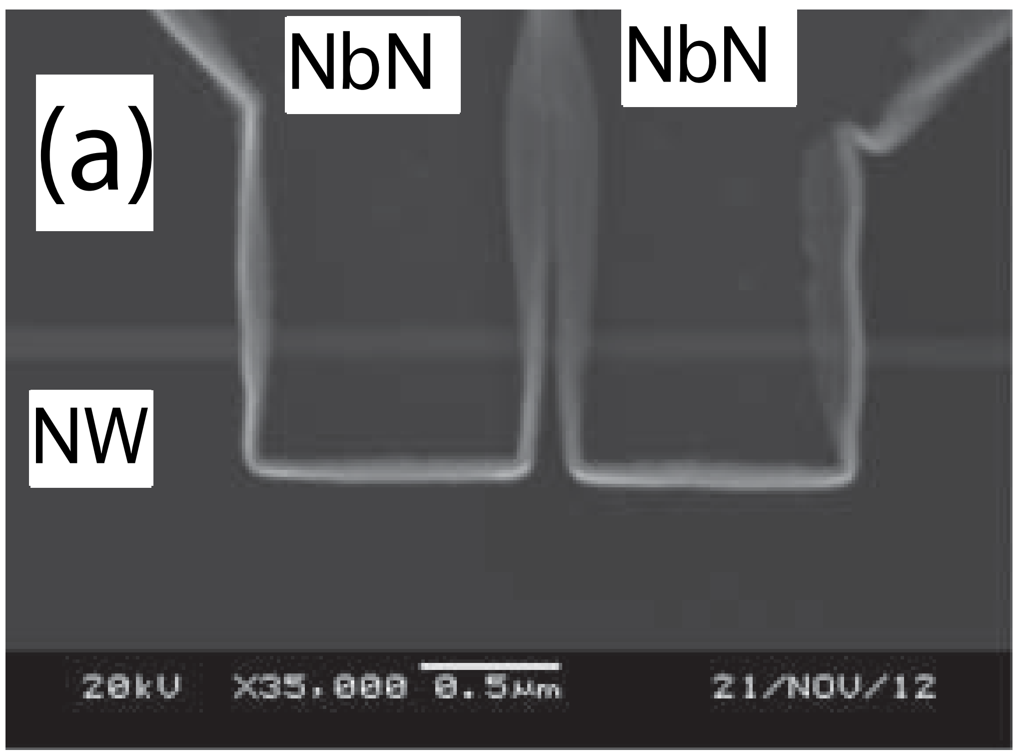
Zero-bias peaks in spin-orbit coupled superconducting wires with and without Majorana end-states

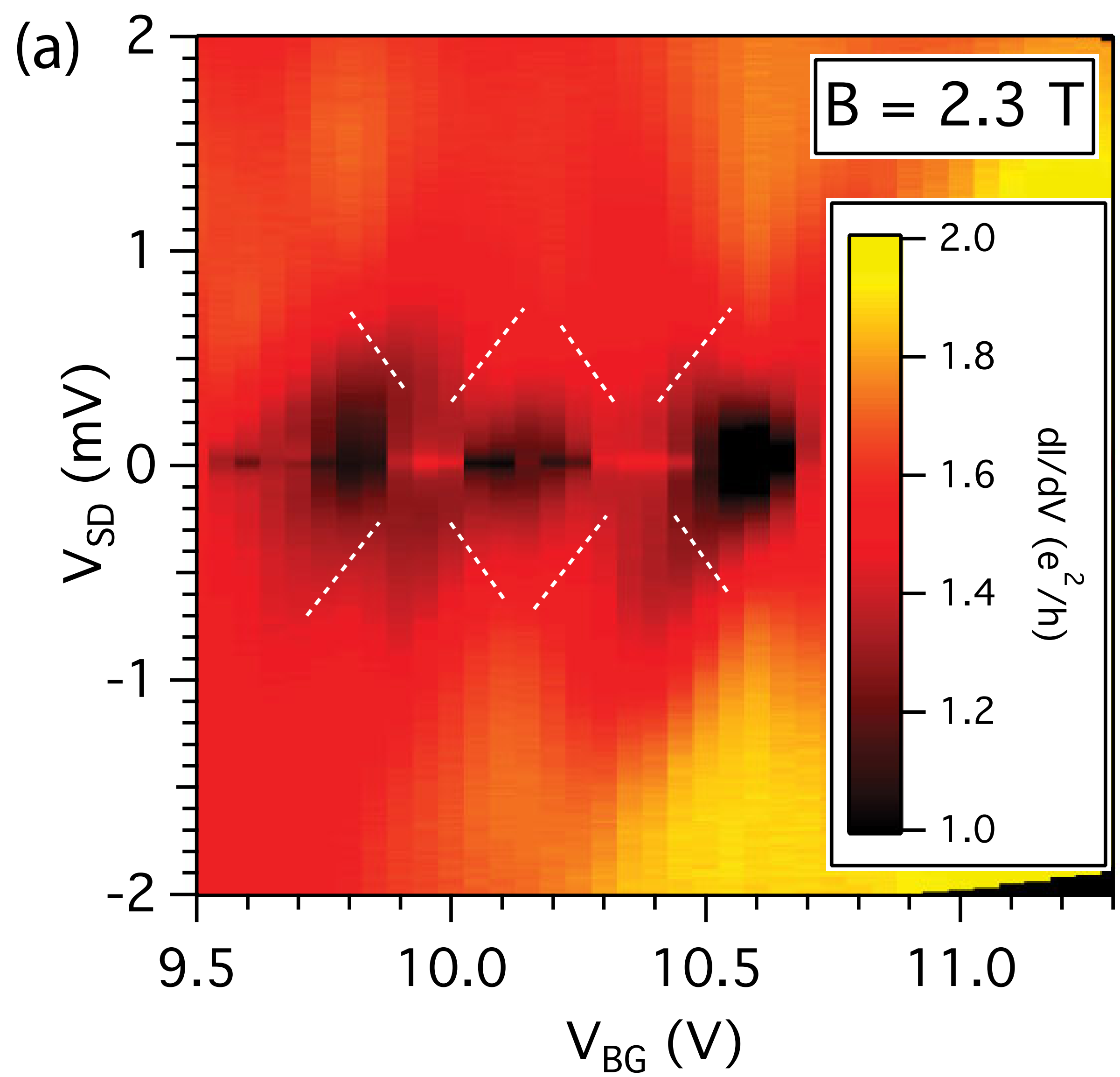
Jie Liu[1,*], Andrew C. Potter[2,*], K.T. Law[1], and Patrick A. Lee[2]
[1] *Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China and*
[2] *Massachusetts Institute of Technology 77 Massachusetts Ave. Cambridge, MA 02139*



Anomalous Modulation of a Zero-Bias Peak in a Hybrid Nanowire-Superconductor Device

A. D. K. Finck,[1] D. J. Van Harlingen,[1] P. K. Mohseni,[2] K. Jung,[2] and X. Li[2]
[1]*Department of Physics and Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[2]*Department of Electrical and Computer Engineering, Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
(Received 23 December 2012; published 21 March 2013)





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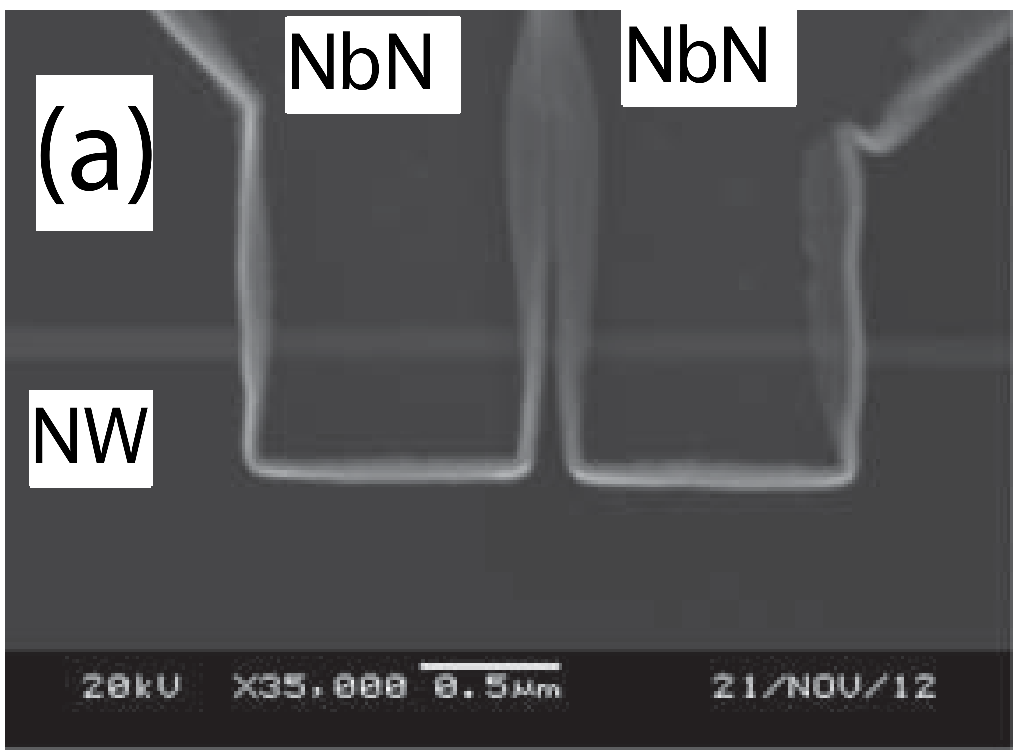

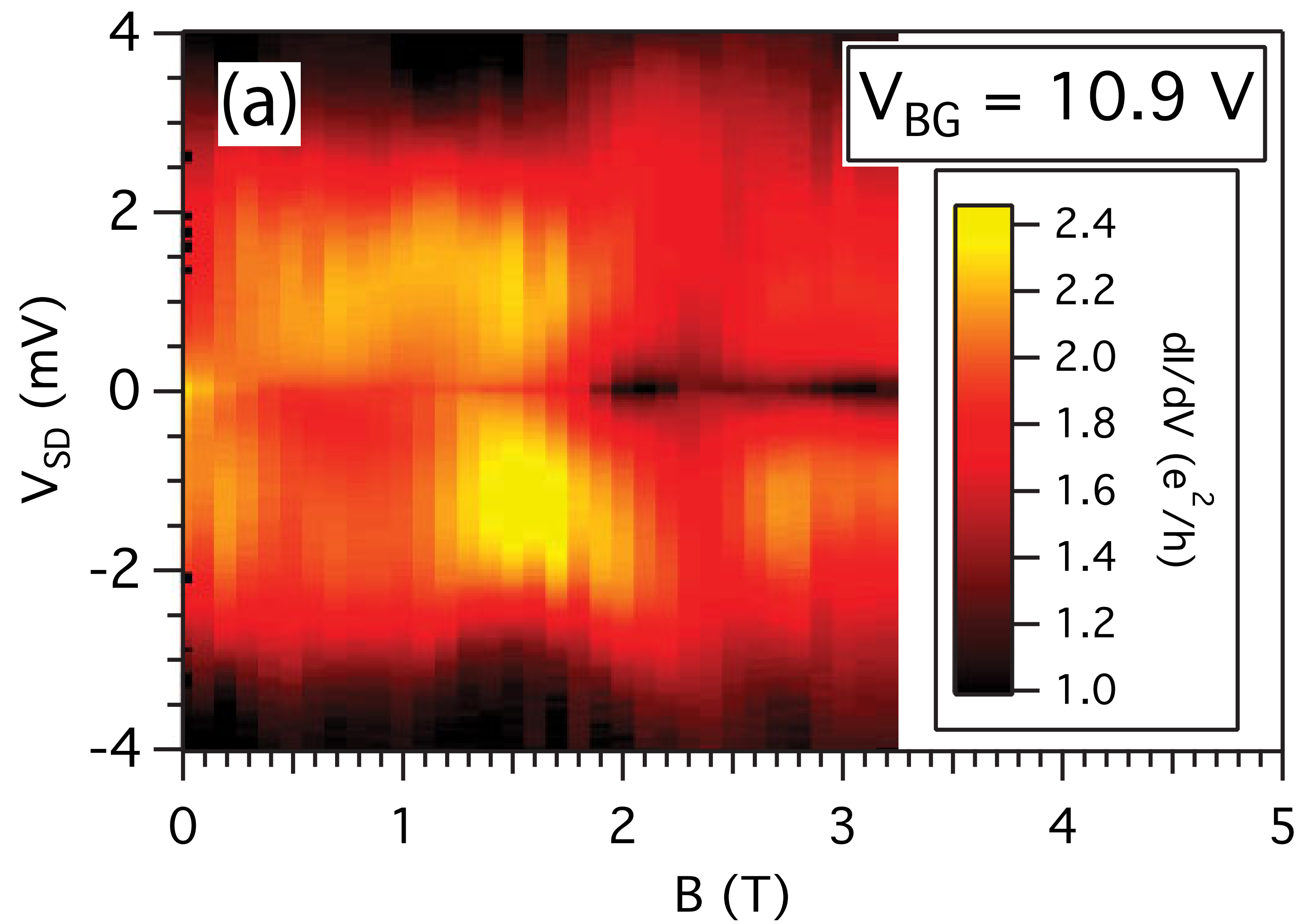

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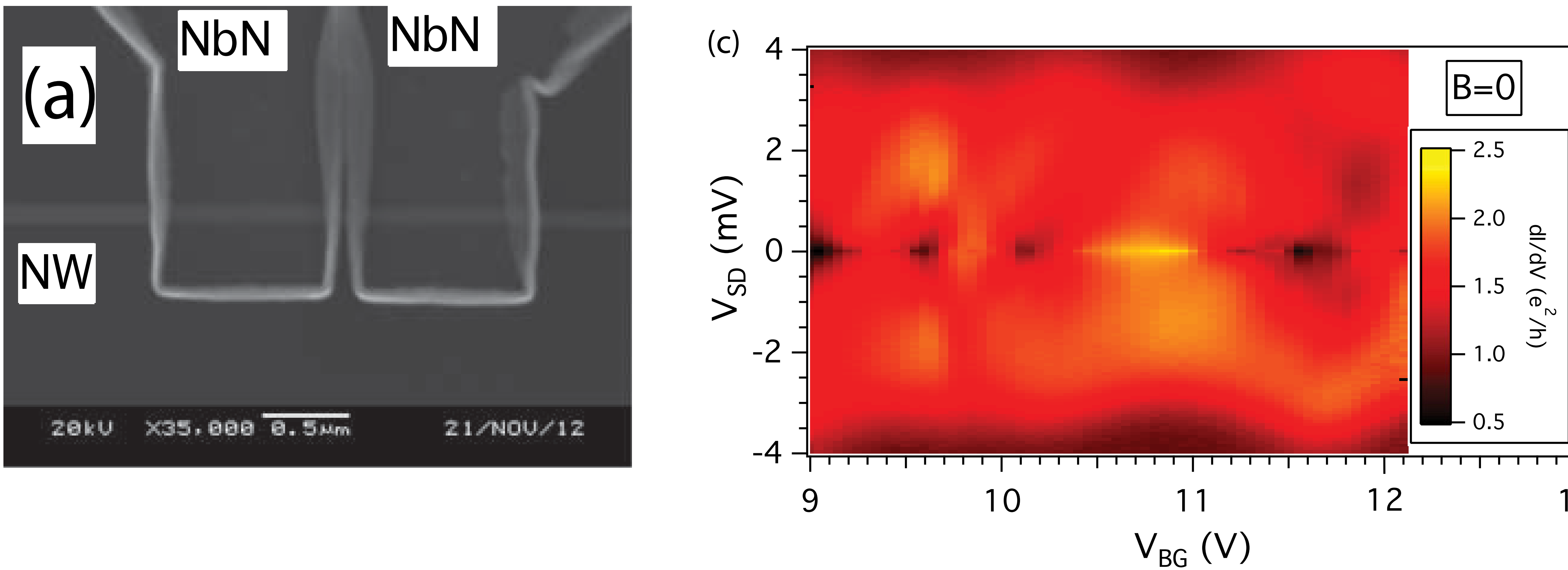
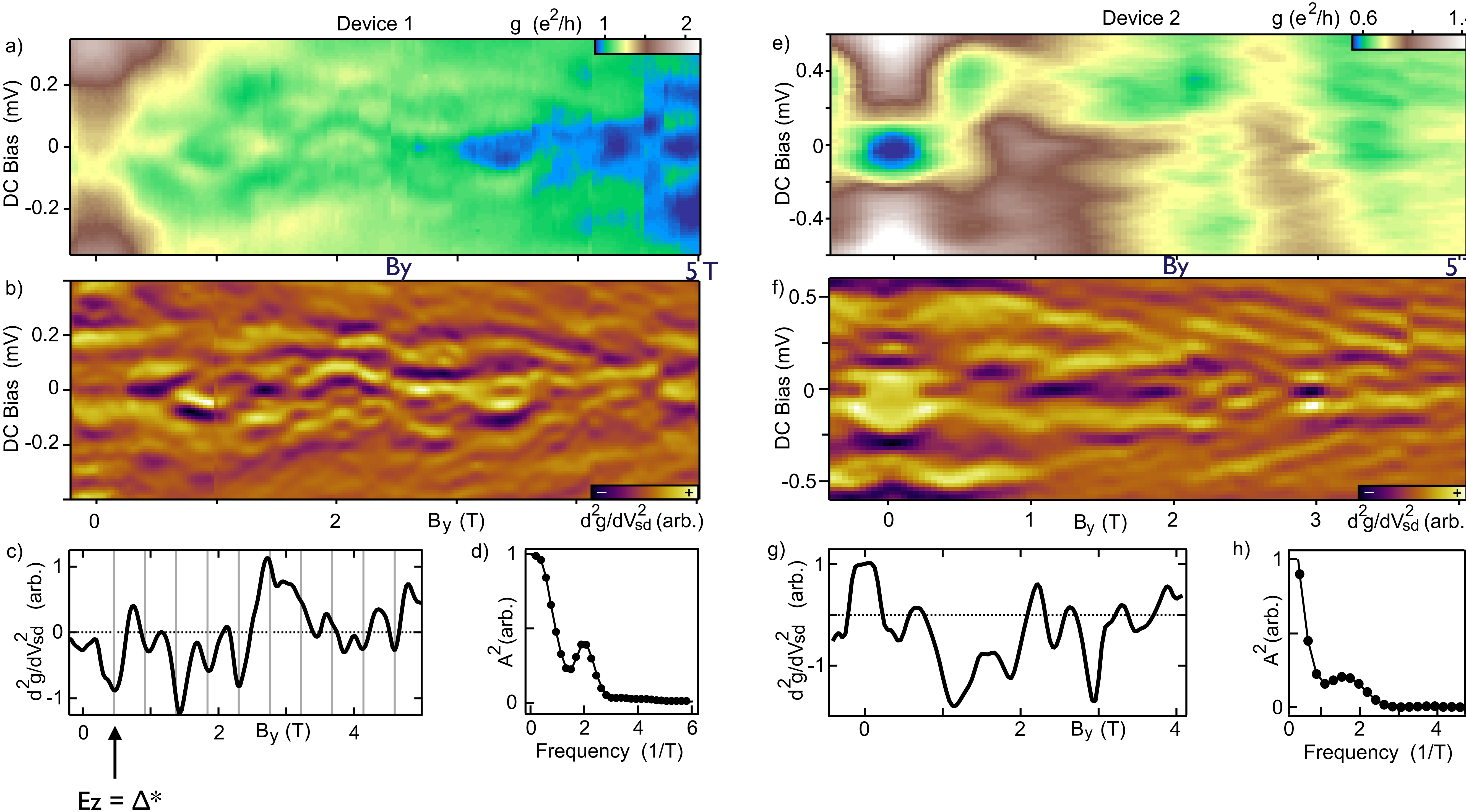


Oscillations



Realistic transport modeling for a superconducting nanowire with Majorana fermions

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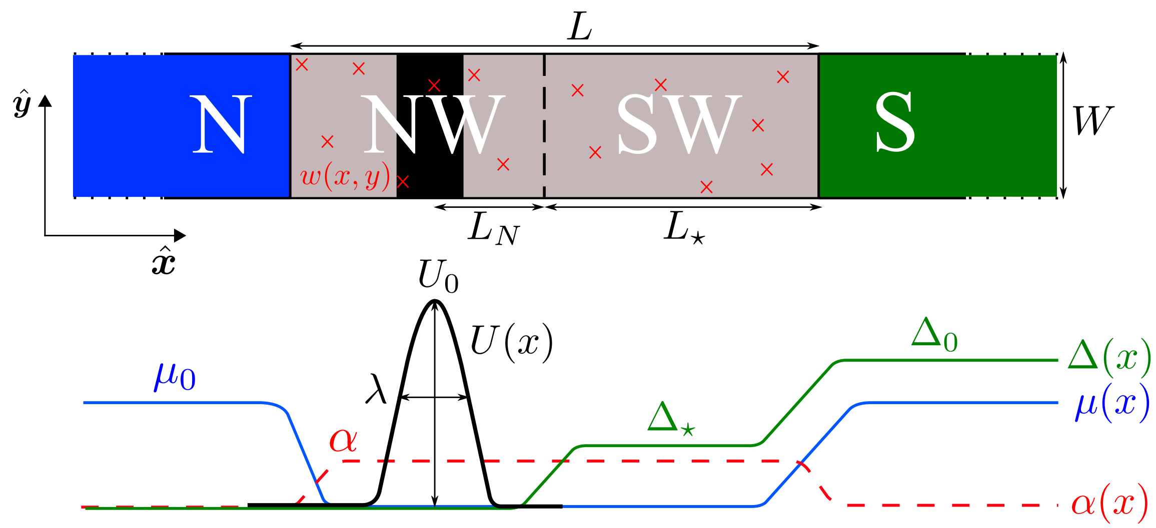

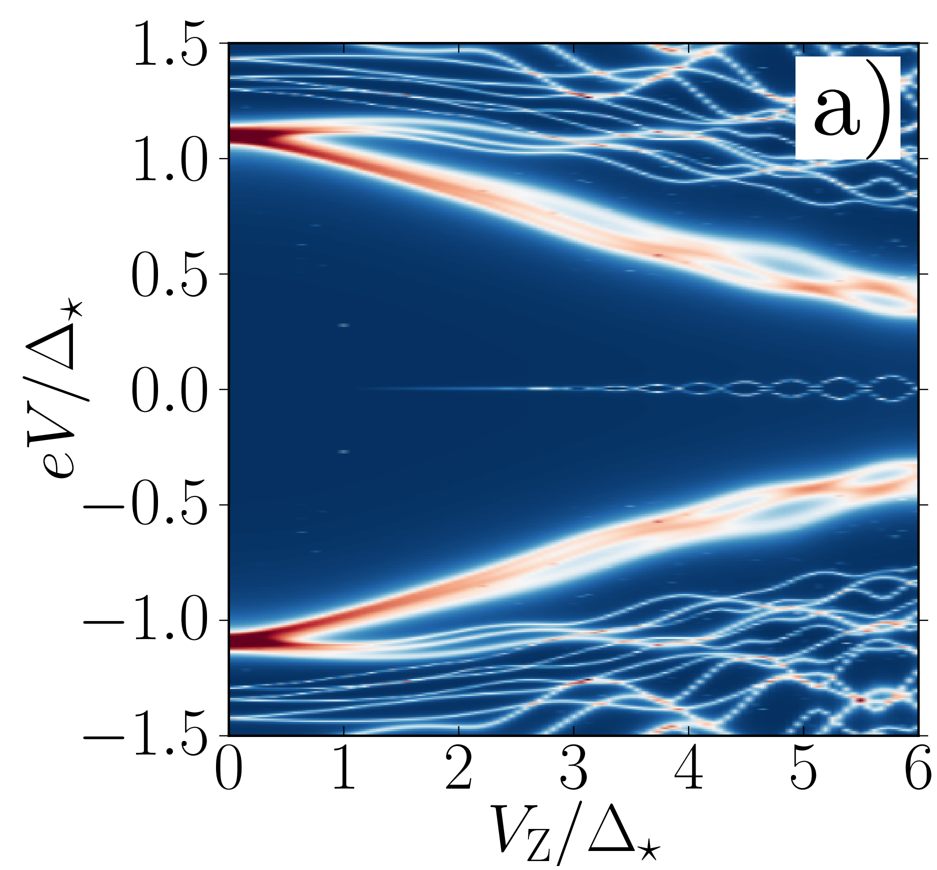

peak spacing

$$\delta(V_Z/\Delta_\star) = \frac{\pi\hbar}{L_\star\Delta_\star}\sqrt{\frac{2V_Z}{m}} = \frac{\pi a}{L_\star}\frac{\sqrt{tV_Z}}{\Delta_\star}$$

peak index

$B(n) \sim n^2$

Superconductor-Nanowire Devices from Tunneling to the Multichannel Regime: Zero-Bias Oscillations and Magnetoconductance Crossover

H. O. H. Churchill,[1,2] V. Fatemi,[2] K. Grove-Rasmussen,[3] M. T. Deng,[4] P. Caroff,[4] H. Q. Xu,[4,5] and C. M. Marcus[3,*]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
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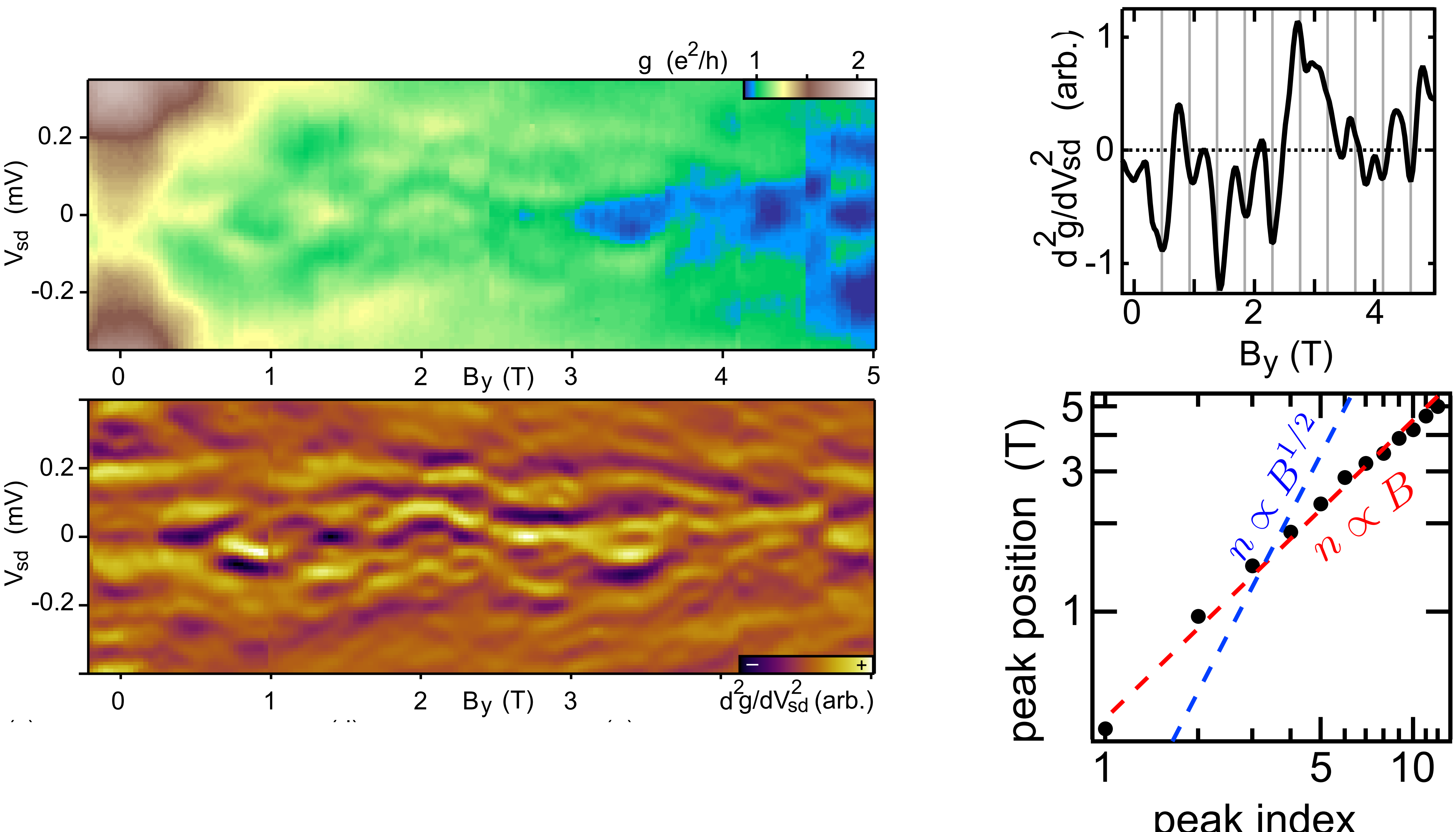
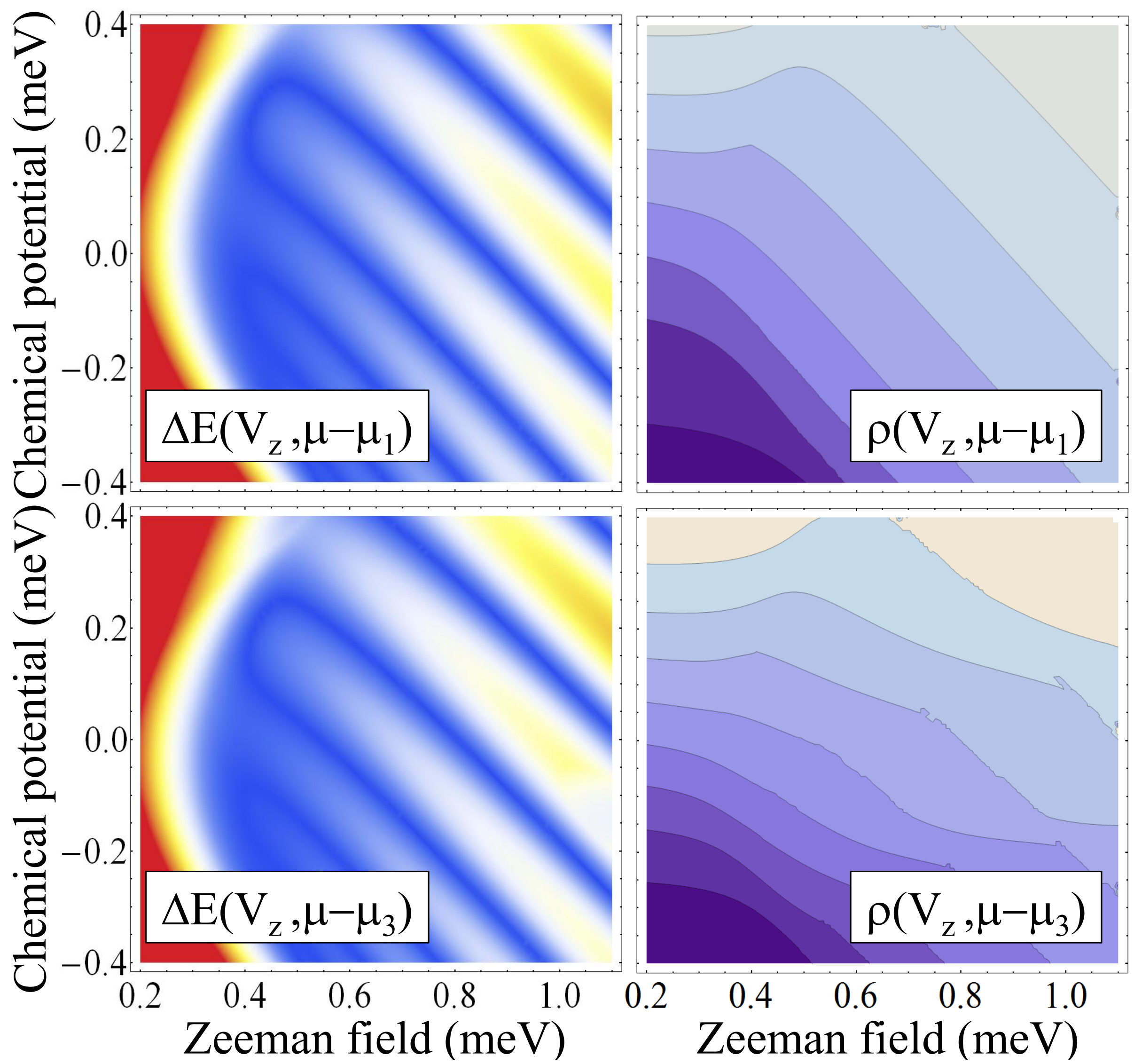
[5]*Department of Electronics and Key Laboratory for the Physics and Chemistry of Nanodevices, Peking University, Beijing 100871, China*



PHYSICAL REVIEW B **86**, 220506(R) (2012)

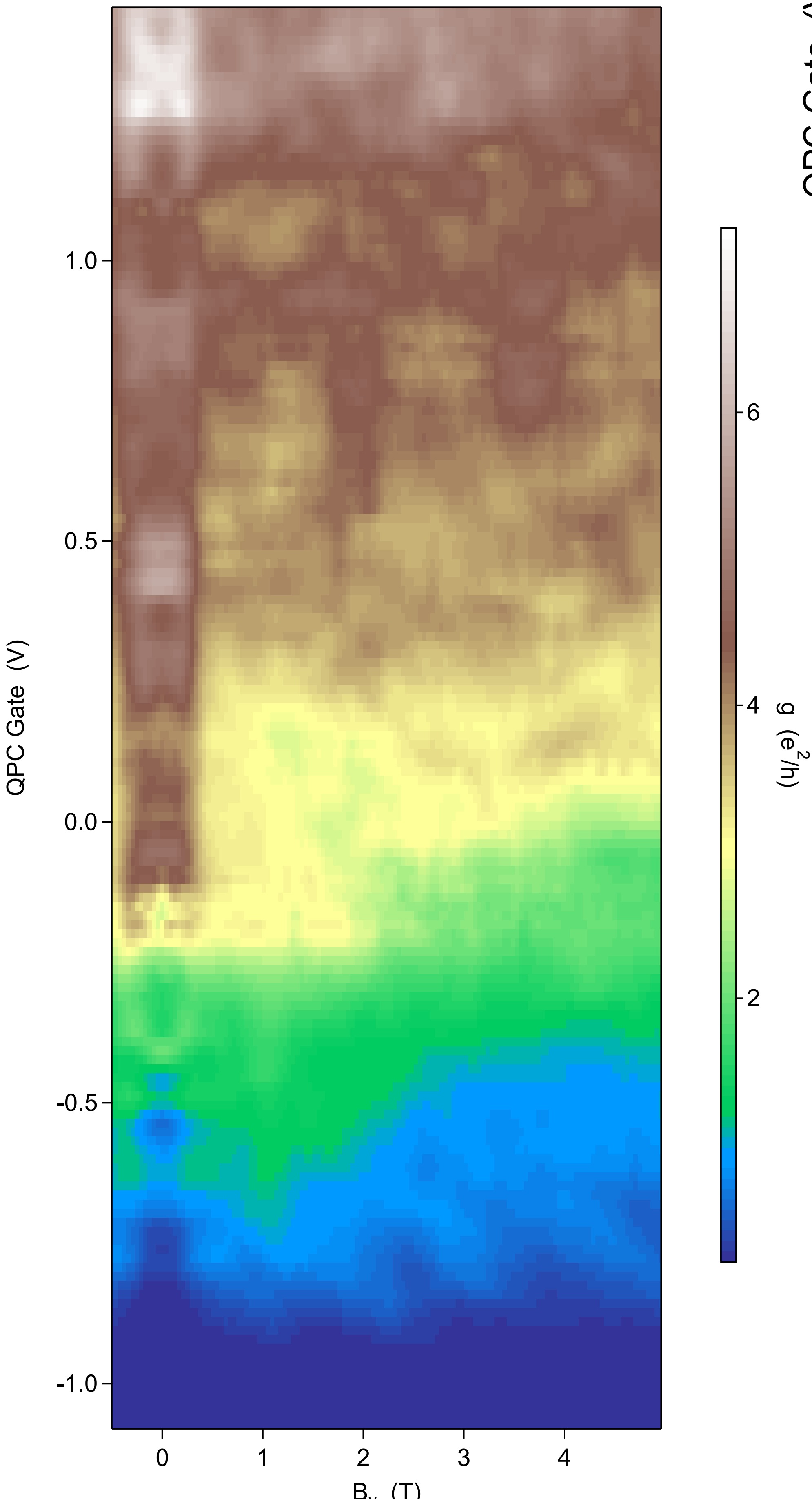
Splitting of the zero-bias conductance peak as smoking gun evidence for the existence of the Majorana mode in a superconductor-semiconductor nanowire

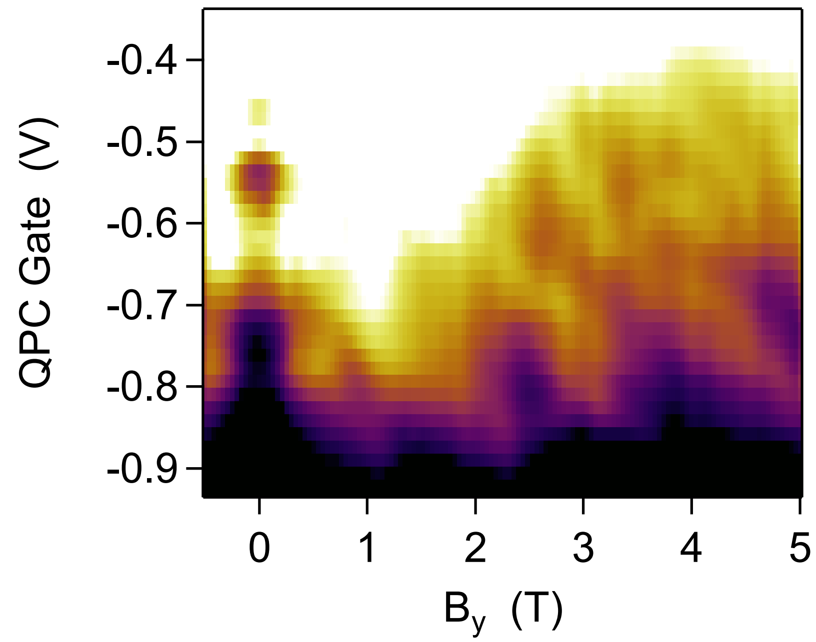
S. Das Sarma,[1] Jay D. Sau,[2] and Tudor D. Stanescu[3]

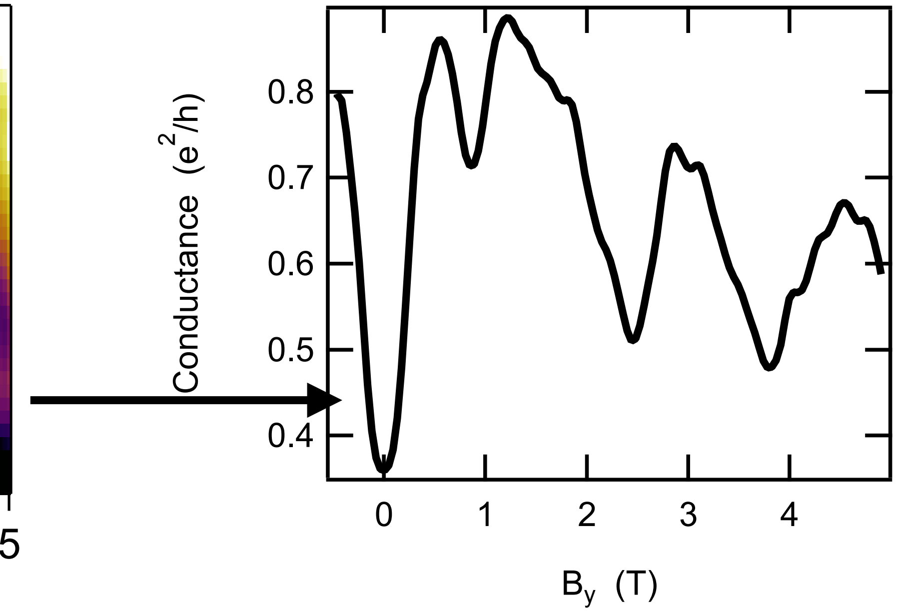


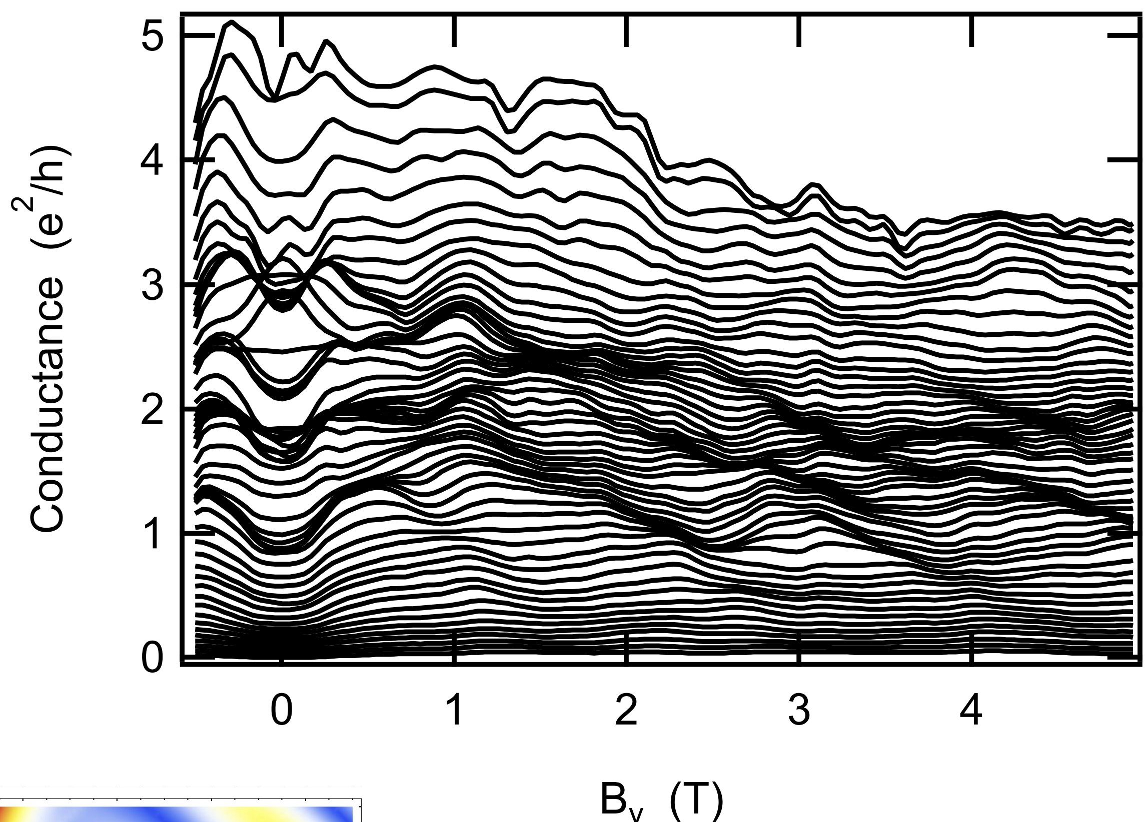
arXiv:1211.0539 (2012)

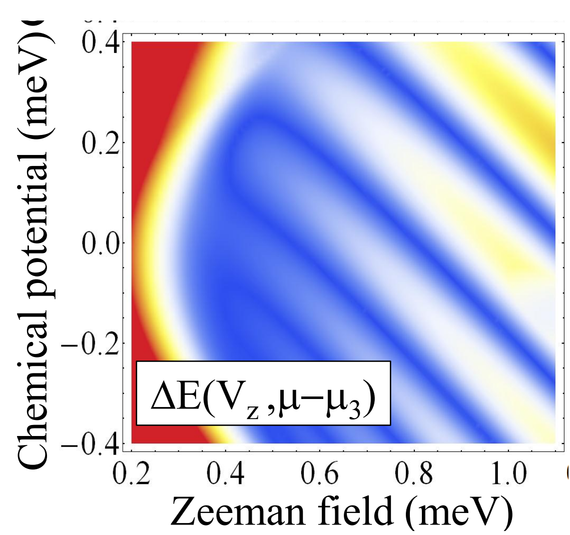
Oscillations











Das Sarma *et al.*

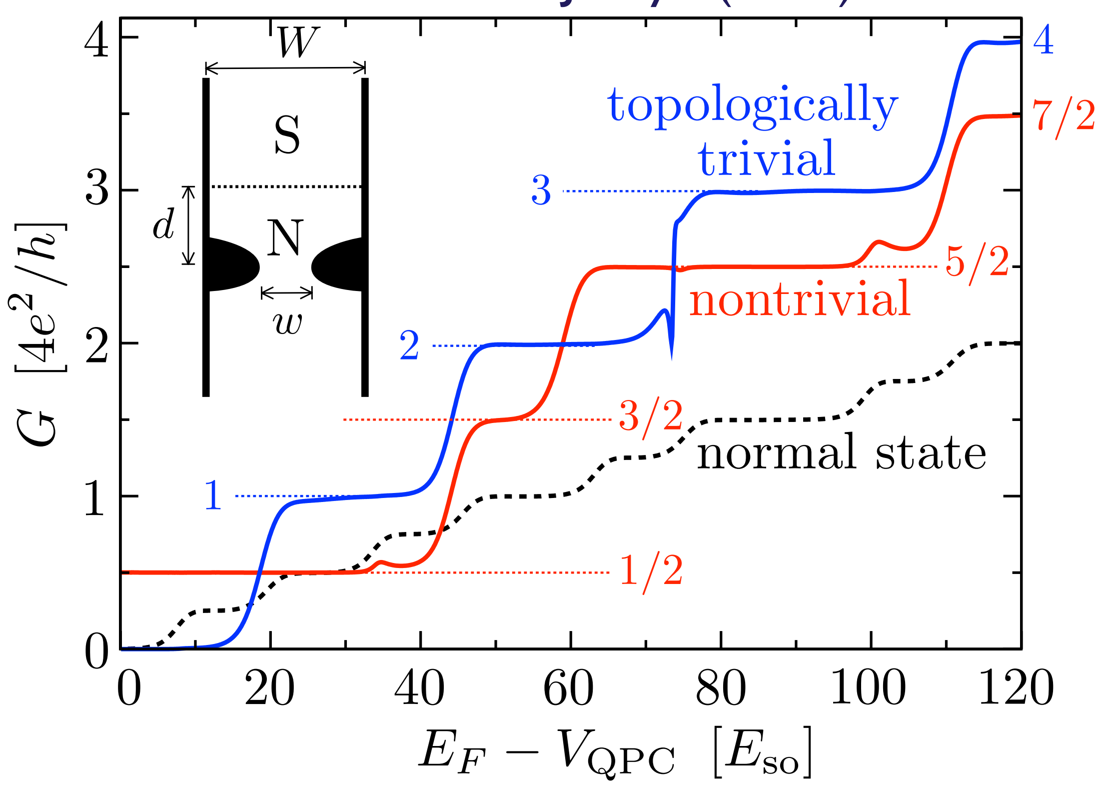
arXiv:1211.0539

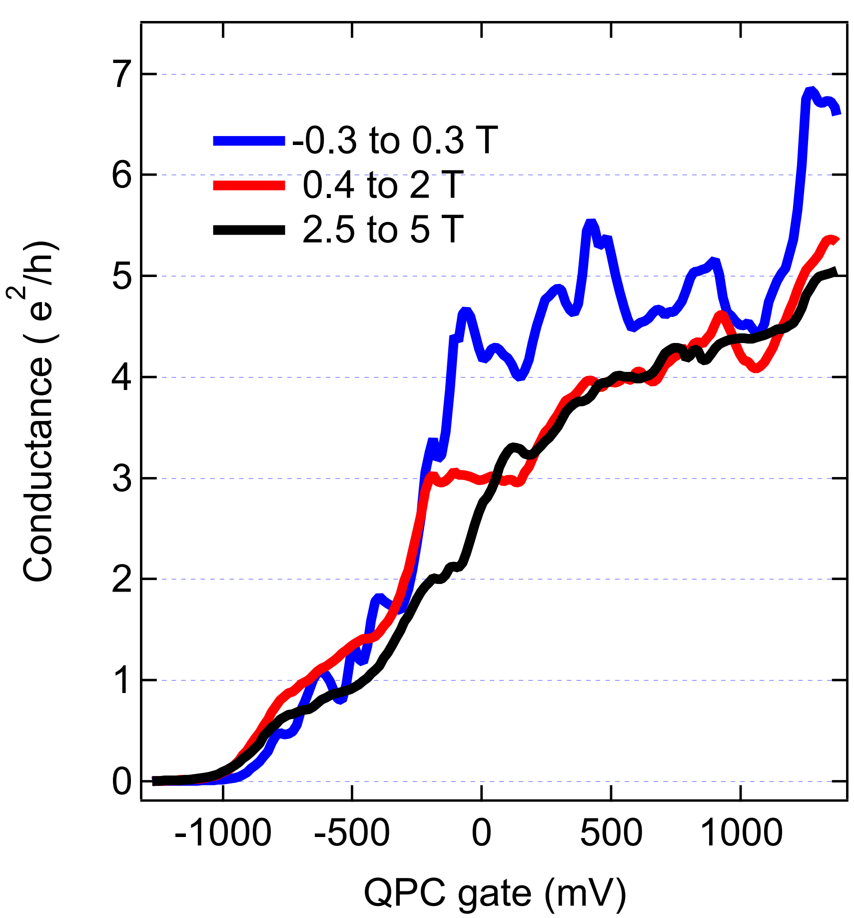
constant chemical potential

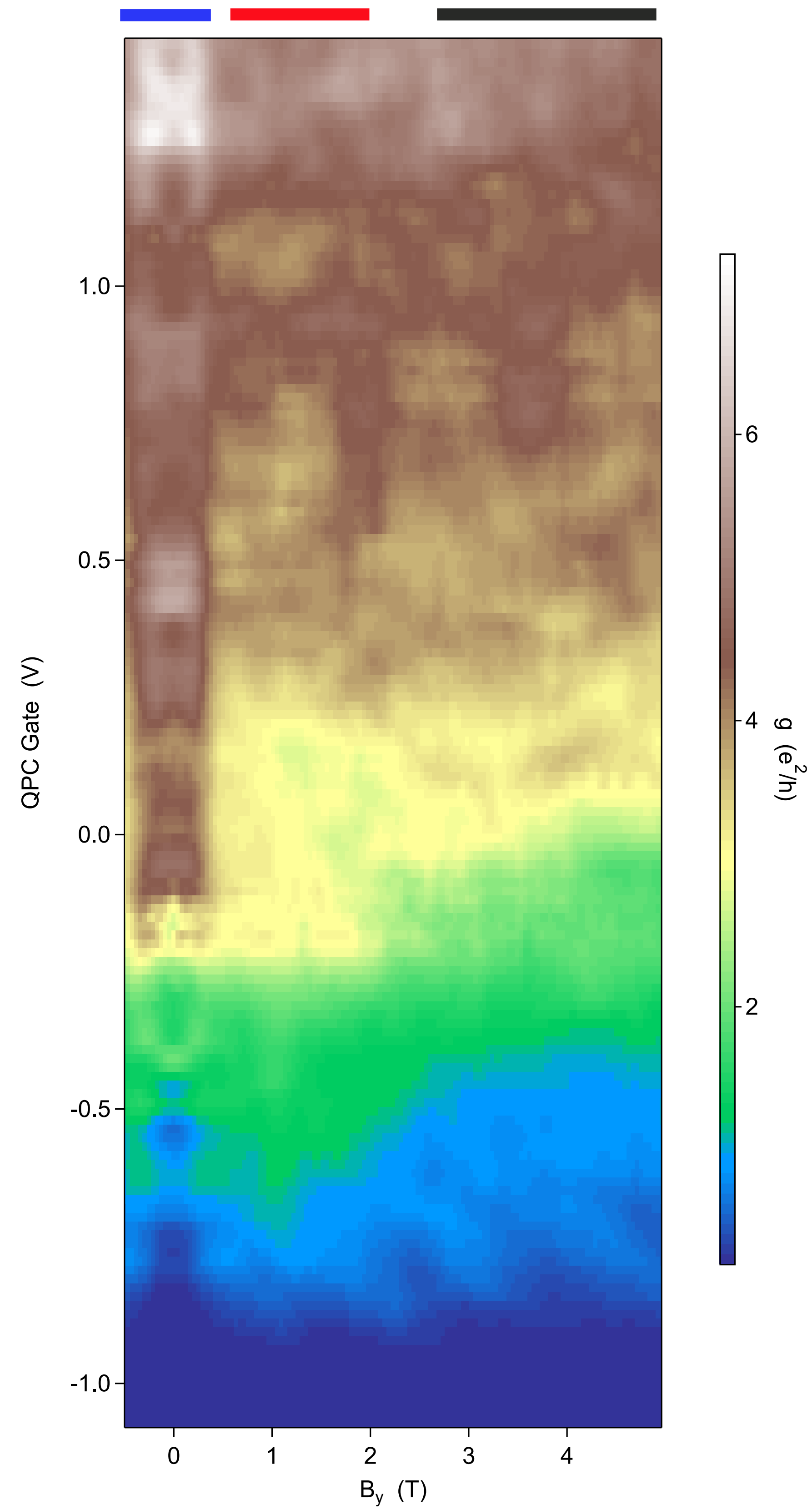
or constant density?

QPC, field dependence of plateaus

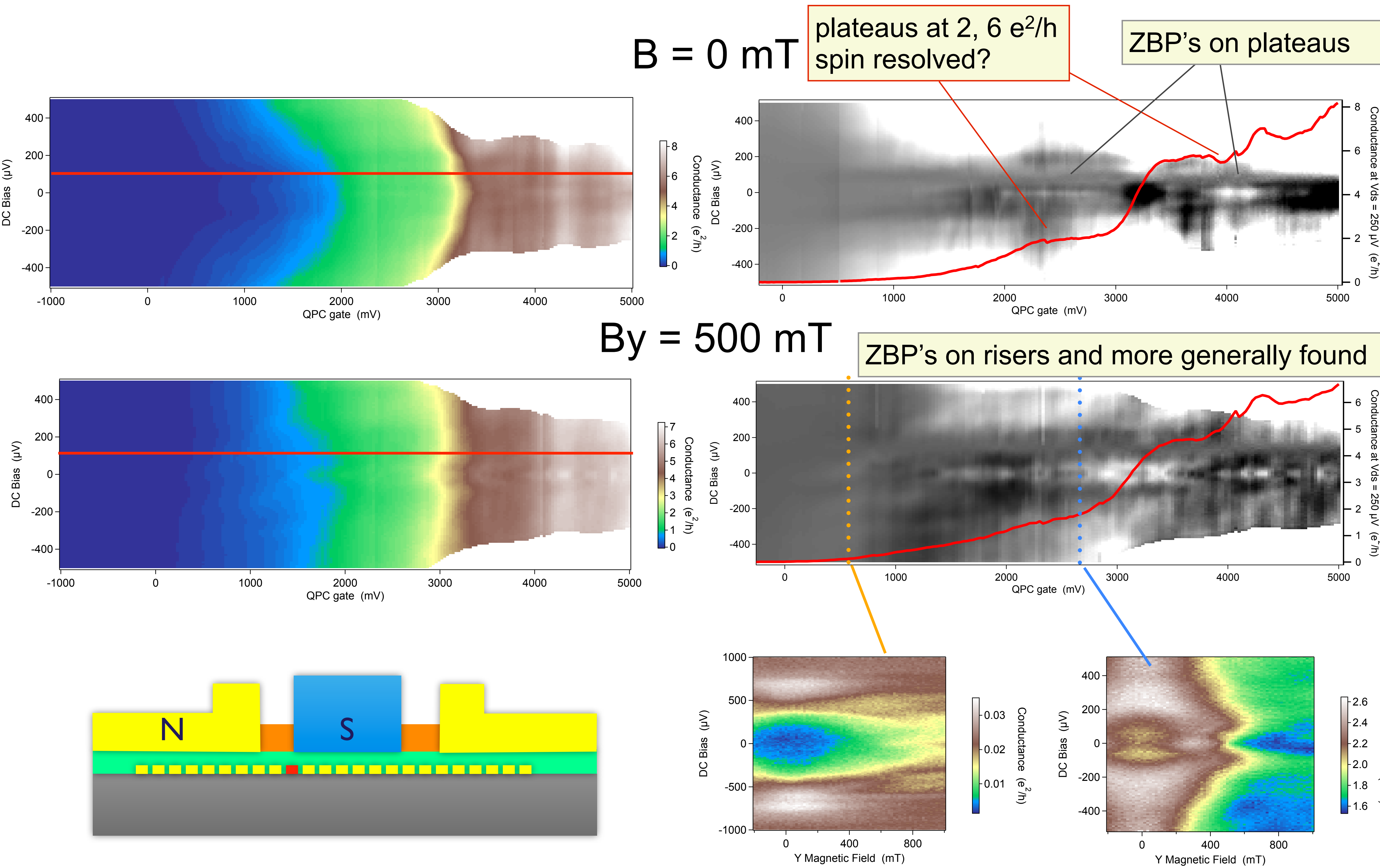
Wimmer *et al.* New J. Phys. (2011)







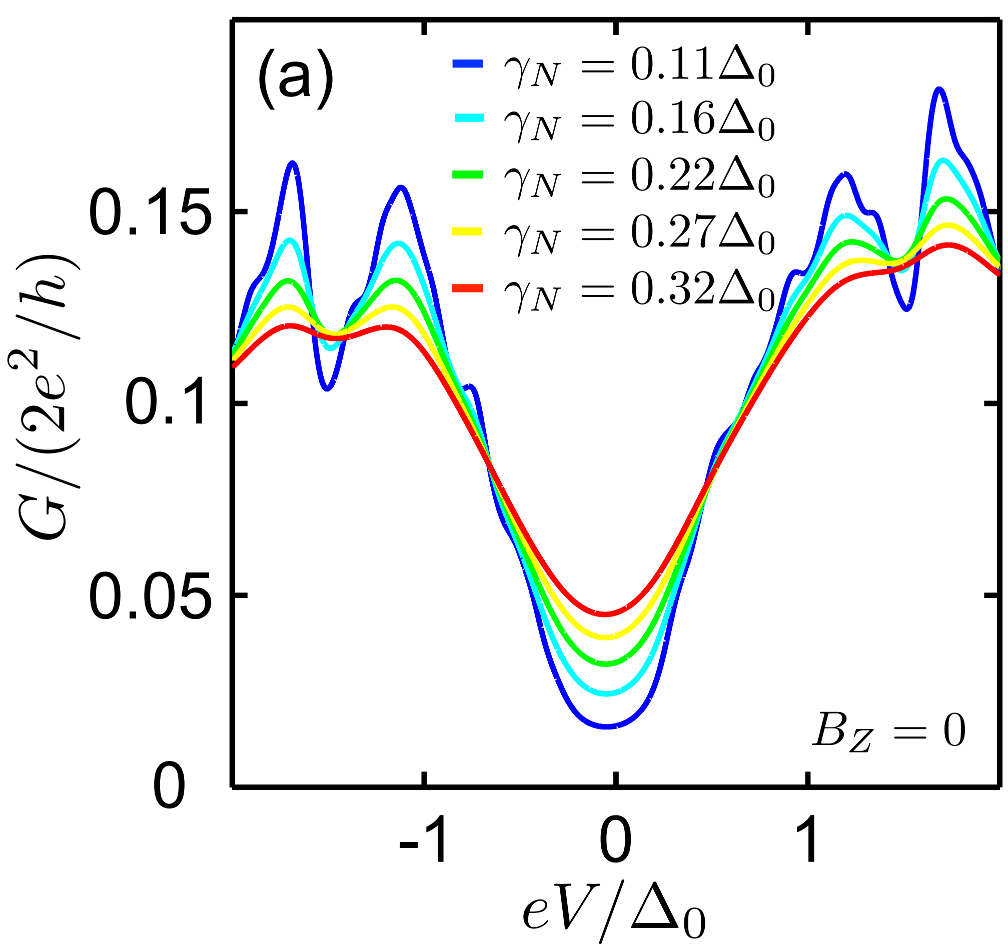
QPC configuration zero-field ZBP versus finite-field ZBP



The soft superconducting gap in semiconductor Majorana nanowires

So Takei, Benjamin M. Fregoso, Hoi-Yin Hui, Alejandro M. Lobos, and S. Das Sarma
Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics,
University of Maryland, College Park, Maryland 20742-4111, USA.
(Dated: May 15, 2013)

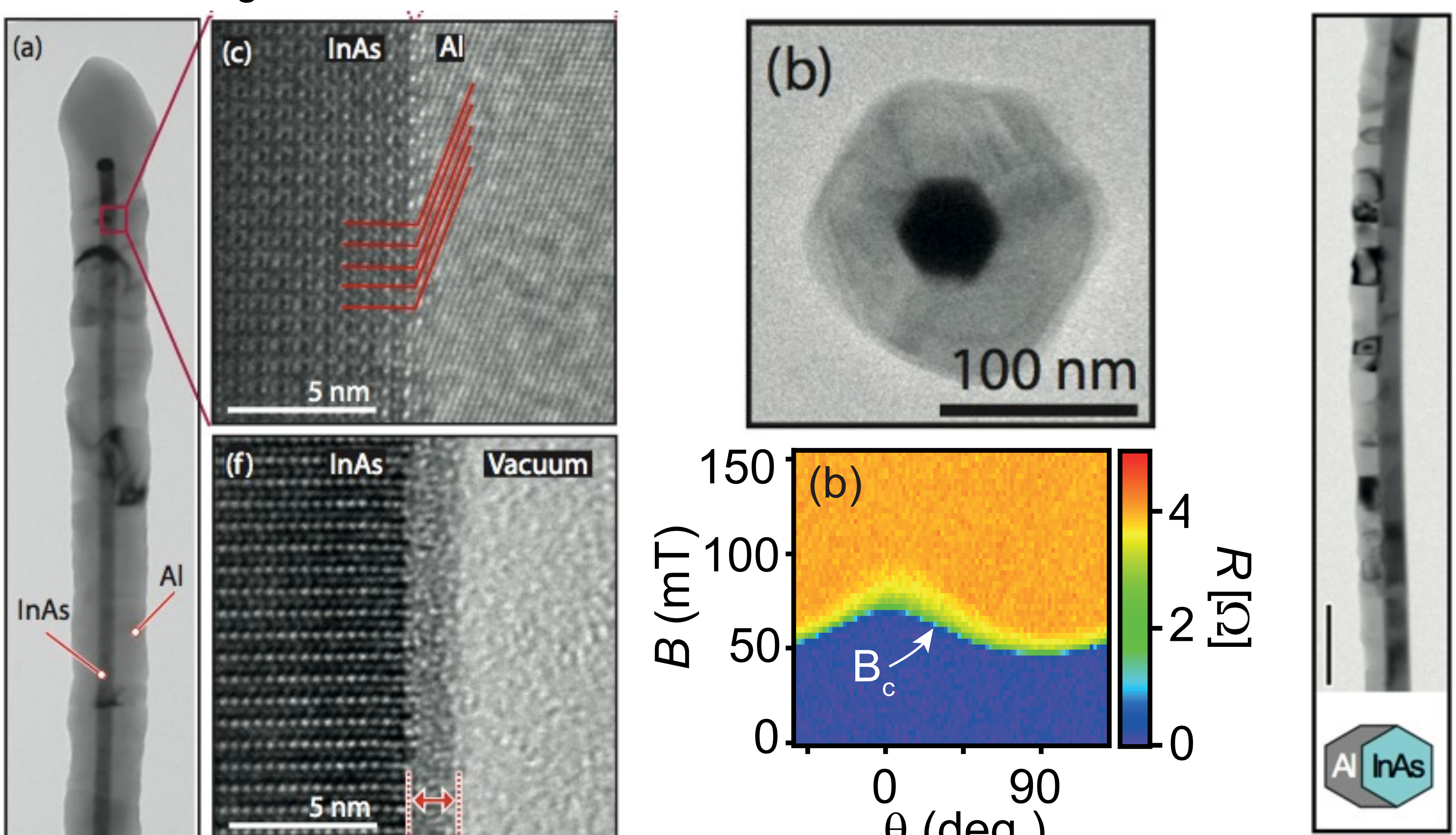
We theoretically consider the ubiquitous soft gap measured in the tunneling conductance of semiconductor-superconductor hybrid structures, in which recently observed signatures of elusive Majorana bound states have created much excitement. We systematically study the effects of magnetic and non-magnetic disorder, temperature, dissipative Cooper pair breaking, and interface inhomogeneity, which could lead to a soft gap. We find that interface inhomogeneity with moderate dissipation is the only viable mechanism that is consistent with the experimental observations. Our work indicates that improving the quality of the superconductor-semiconductor interface should result in a harder induced gap.



Epitaxial Aluminum contacts to InAs nanowires

N. L. B. Ziino[1], P. Krogstrup[1], M. H. Madsen[1], E. Johnson[1,2], J. Wagner[3], C. M. Marcus[1], J. Nygård[1], T. S. Jespersen[1]*
[1] Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark
[2] Department of Materials Research, Ris National Laboratory, Technical University of Denmark, DK-4000 Roskilde, Denmark
[3] Center for Electron Nanoscopy, Technical University of Denmark, Denmark,

Thick coating



JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 1 JANUARY 1971

Properties of Very Thin Aluminum Films

R. MESERVEY AND P. M. TEDROW

Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

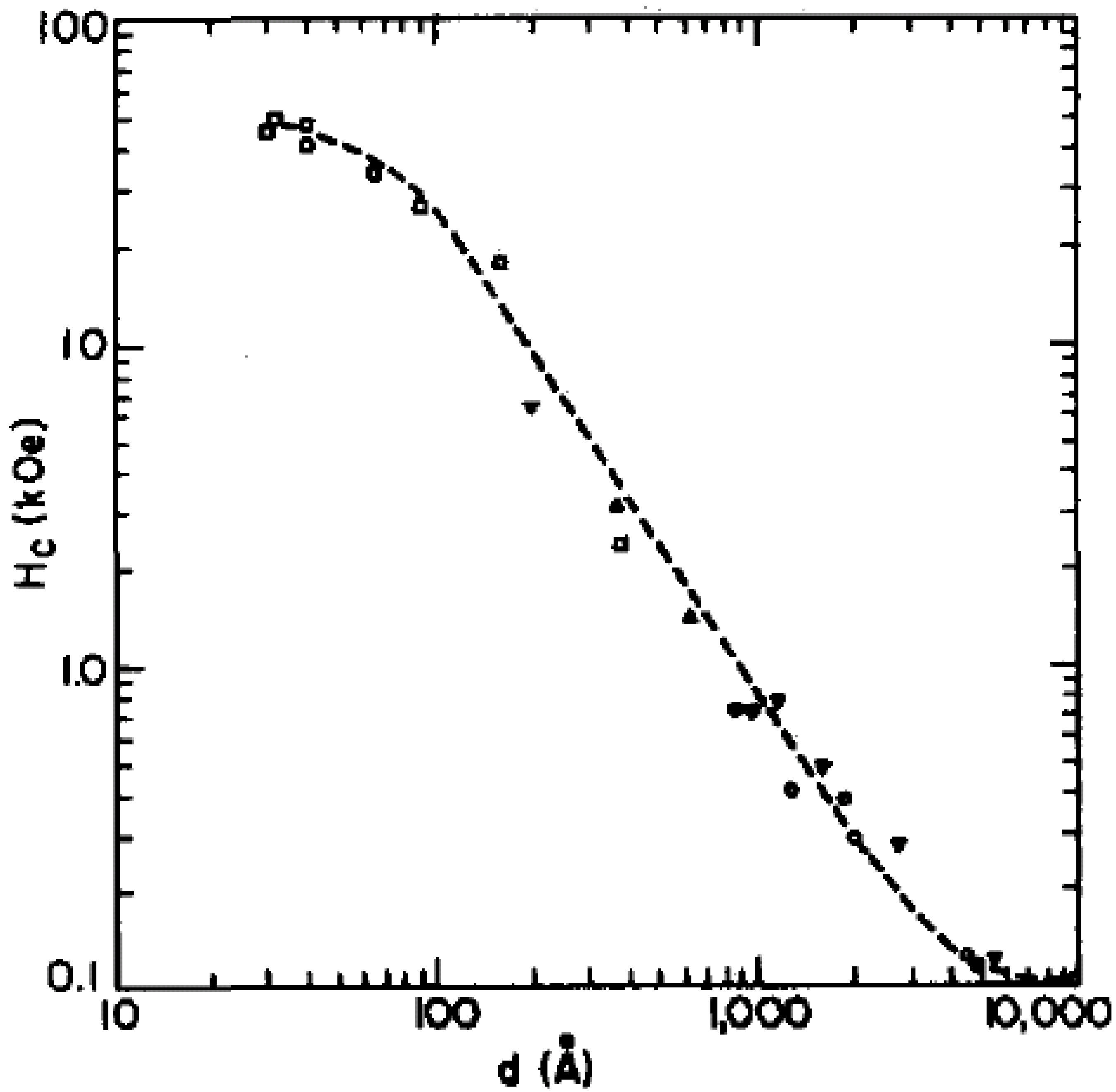
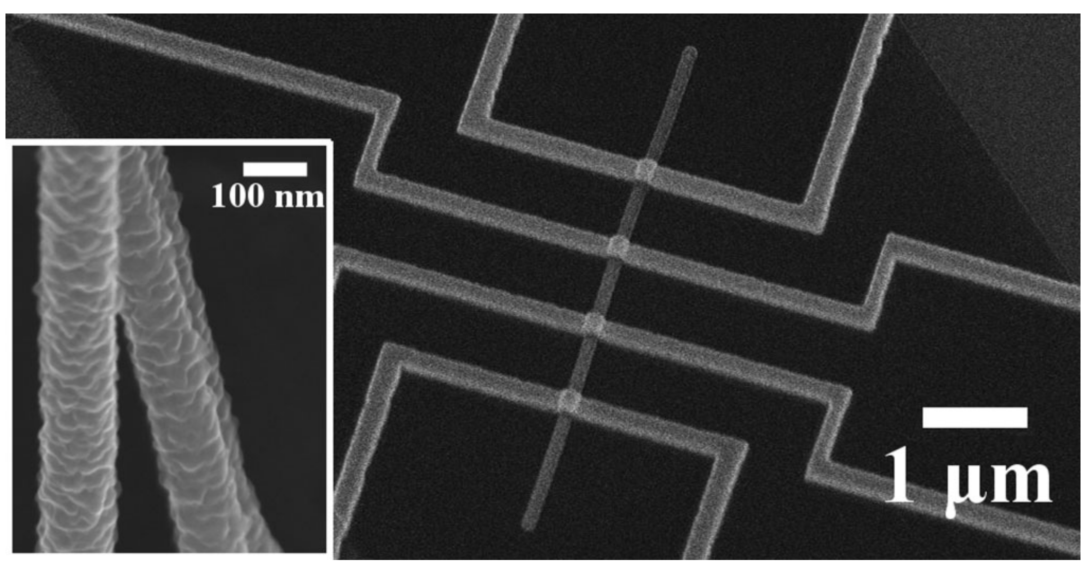


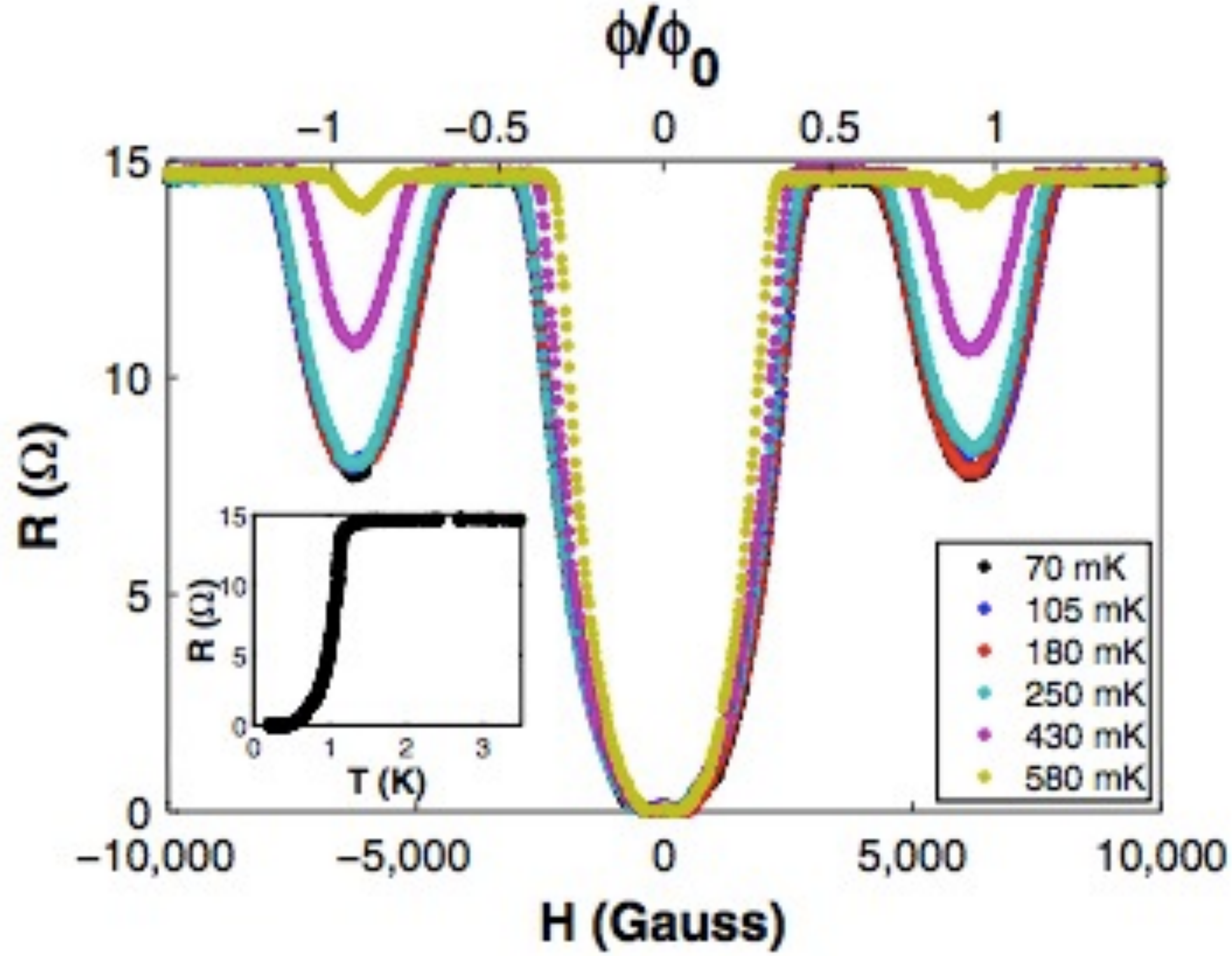
FIG. 4. Critical magnetic field H_c as a function of d. The dashed line has a slope of $-3/2$ in the region from 2000 to 200 Å. □—present work; △—Ref. 7; ▽—Ref. 5; ○—Ref. 4.

Magnetoresistance Oscillations of Superconducting Al-Film Cylinders Covering InAs Nanowires below the Quantum Critical Point

I. Sternfeld,[1,*] E. Levy,[1] M. Eshkol,[1] A. Tsukernik,[2] M. Karpovski,[1] Hadas Shtrikman,[3] A. Kretinin,[3] and A. Palevski[1]

[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*The Center for Nanoscience and Nanotechnology, Tel Aviv University, Tel Aviv 69978, Israel*
[3]*Department of Condensed Matter Physics, The Weizmann Institute of Scienece, Rehovot 76100, Israel*





Epitaxial Aluminum contacts to InAs nanowires

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C. M. Marcus[1], J. Nygård[1], T. S. Jespersen[1]*
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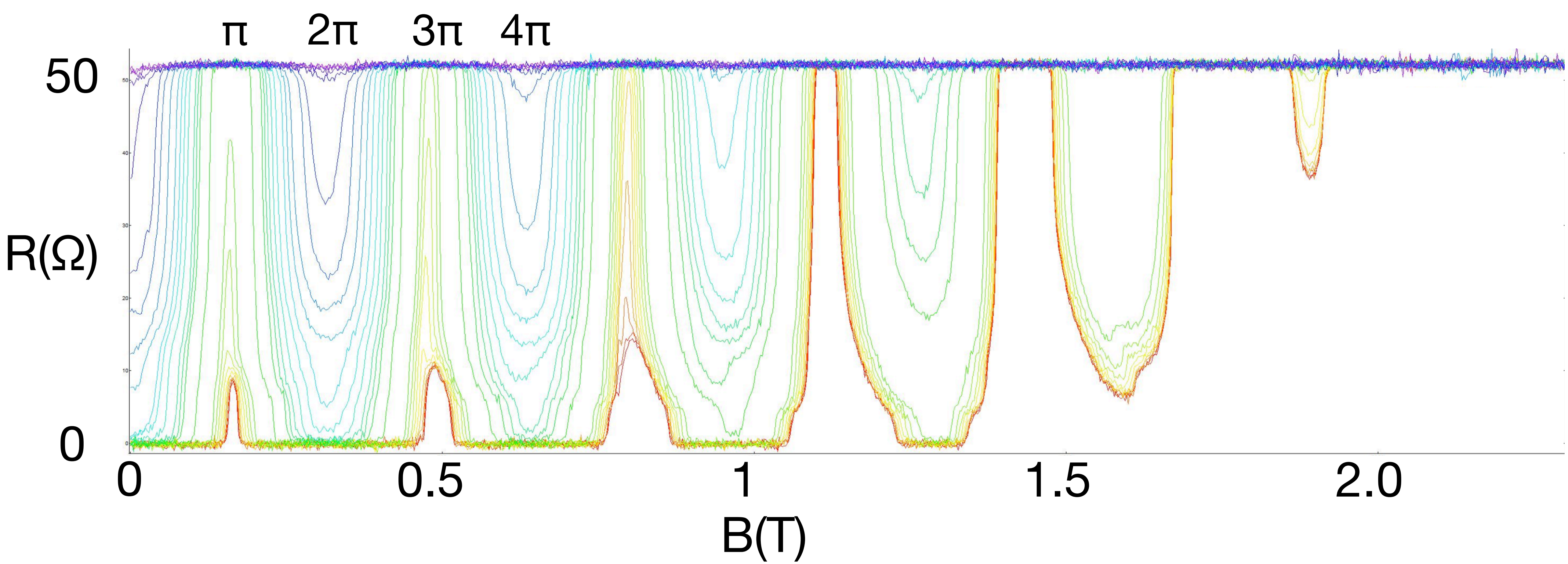
[2] Department of Materials Research, Ris National Laboratory,
Technical University of Denmark, DK-4000 Roskilde, Denmark
[3] Center for Electron Nanoscopy, Technical University of Denmark, Denmark,

Thin (30nm) coating



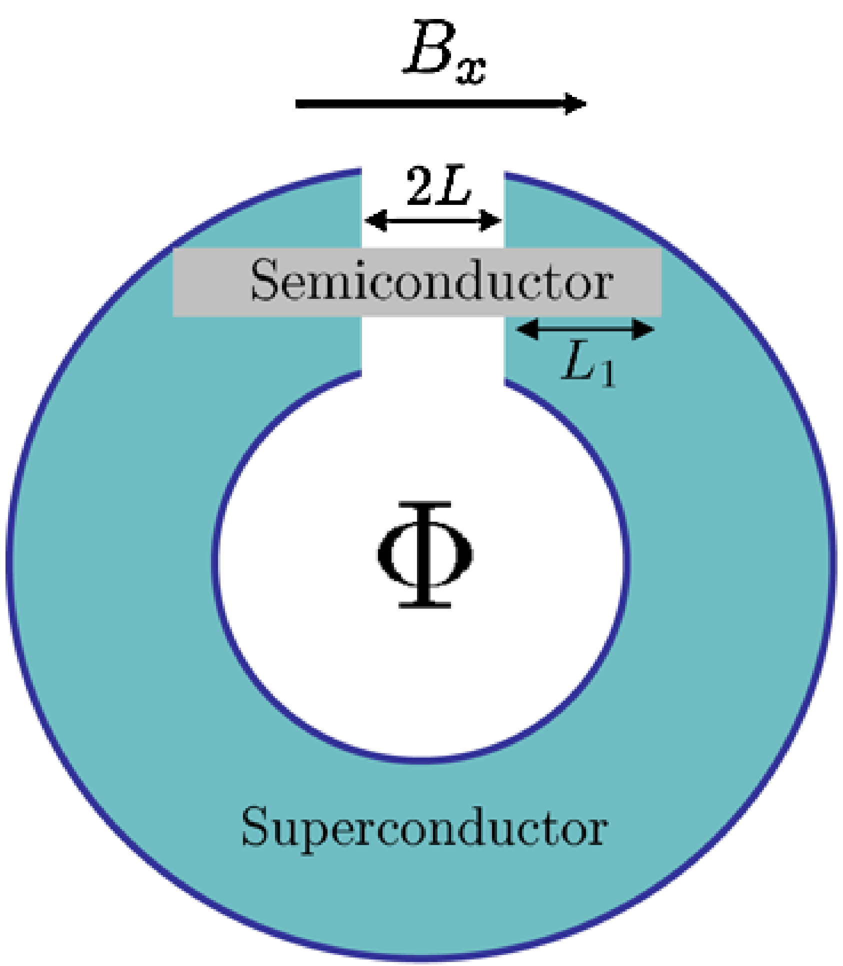
PRL **105,** 077001 (2010) PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2010

Majorana Fermions and a Topological Phase Transition in Semiconductor-Superconductor Heterostructures

Roman M. Lutchyn, Jay D. Sau, and S. Das Sarma

Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA

(Received 24 February 2010; published 13 August 2010)



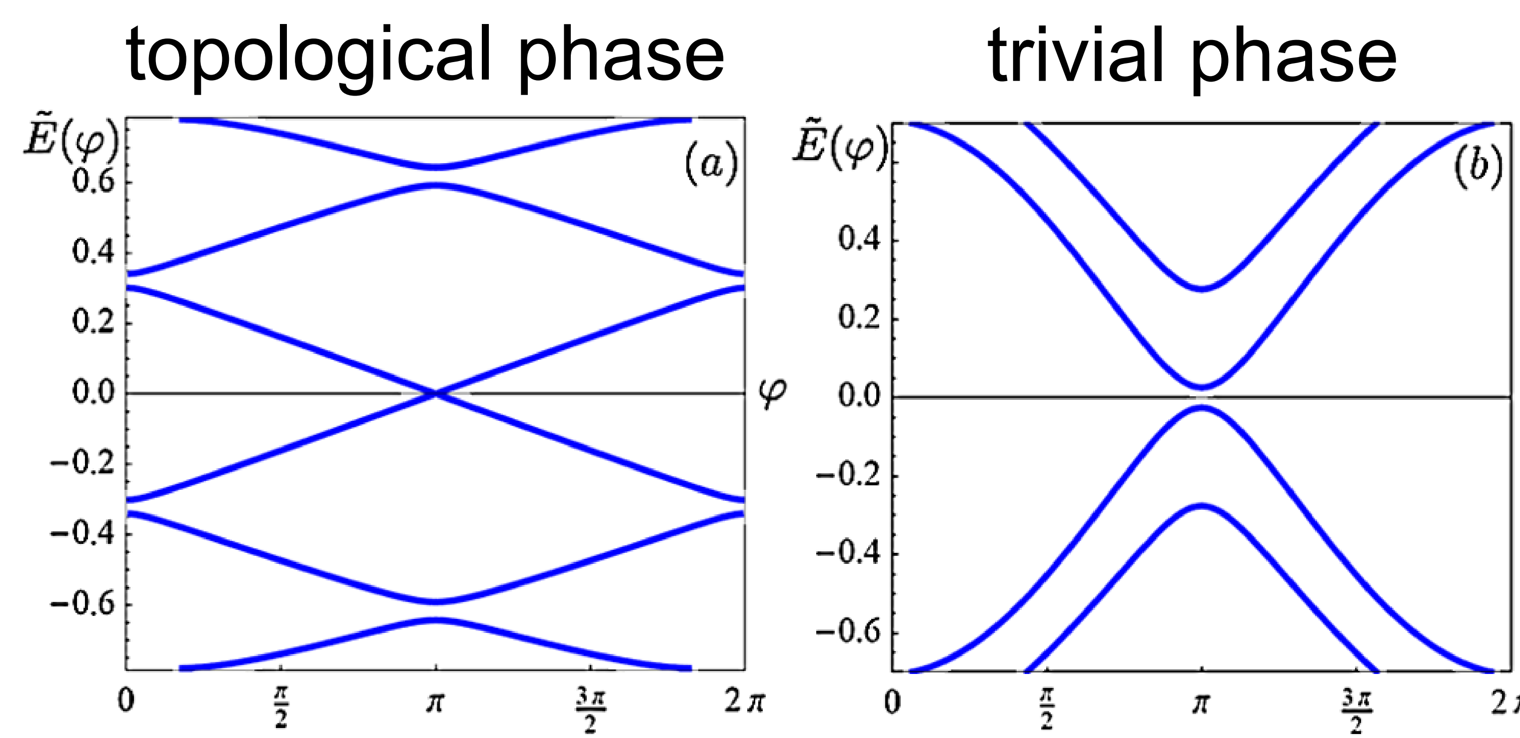
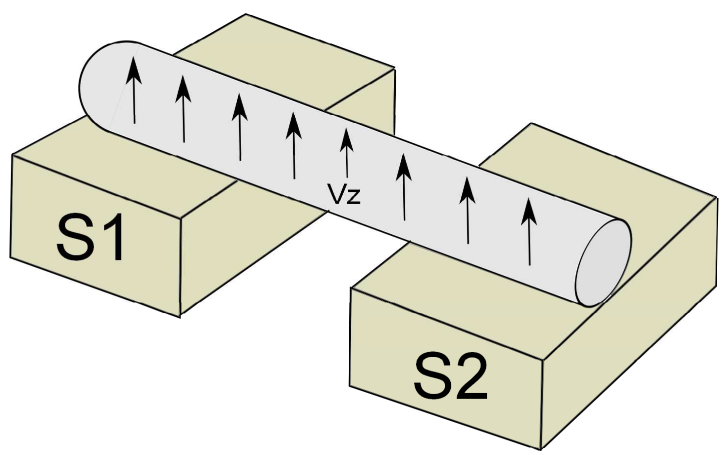
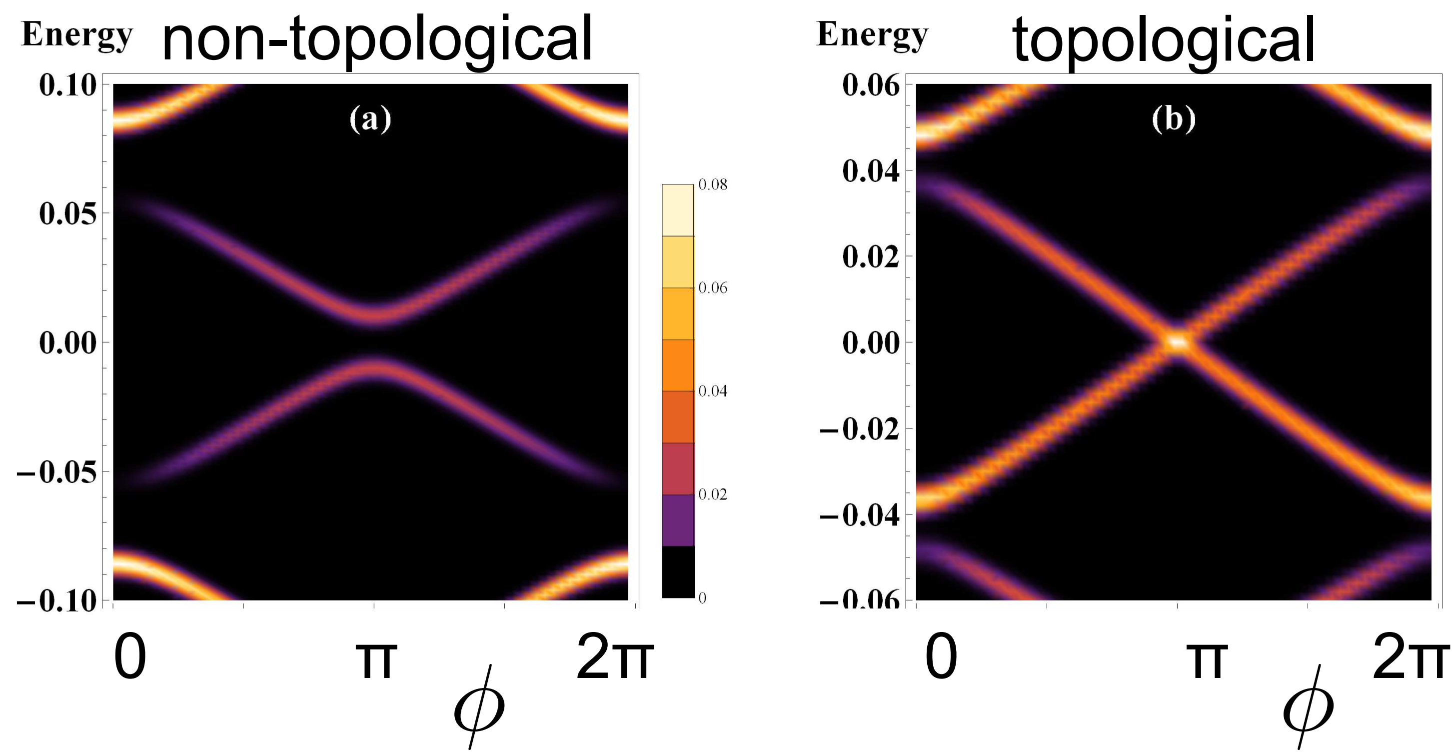


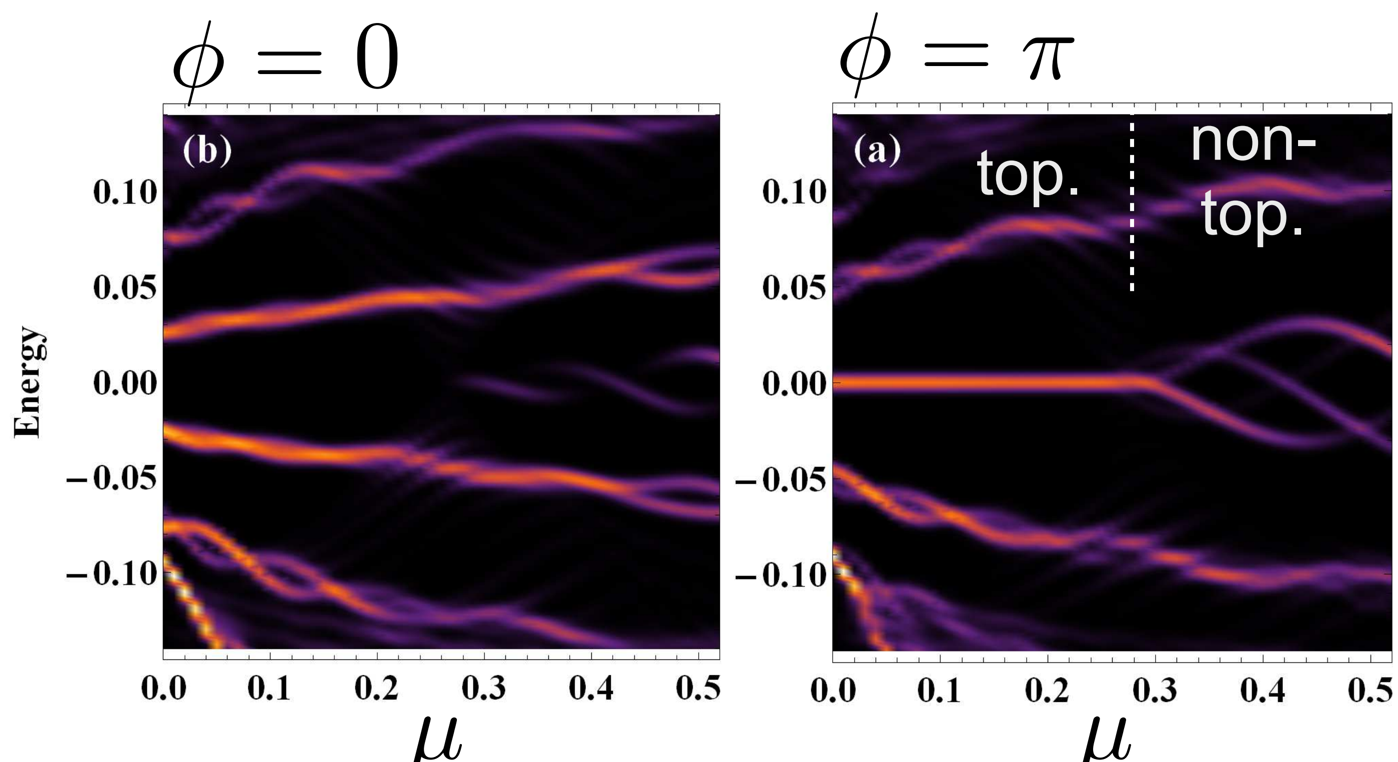
FIG. 3 (color online). (a) Andreev spectrum for a finite-size junction $\tilde{L} = 3$ in a TP nontrivial phase. Here $\tilde{\mu} = 0$, $\tilde{\Delta} = 1$, $\tilde{V}_x = 2$, and $U_0/\alpha = 1$. (b) Andreev spectrum in TP trivial phase for $\tilde{\mu} = 5$, $\tilde{\Delta} = 1$, $\tilde{V}_x = 2$, $\tilde{L} \ll 1$, and $U_0/\alpha = 1$.

Mutation of Andreev into Majorana bound states in long NS and SNS junctions

D. Chevallier,[1] D. Sticlet,[1] P. Simon,[1] and C. Bena[1,2,*]
[1] *Laboratoire de Physique des Solides, CNRS UMR-8502, Université Paris Sud, 91405 Orsay Cedex, France*
[2] *Institute de Physique Théorique, CEA/Saclay, Orme des Merisiers, 91190 Gif-sur-Yvette Cedex, France*
(Dated: March 14, 2012)



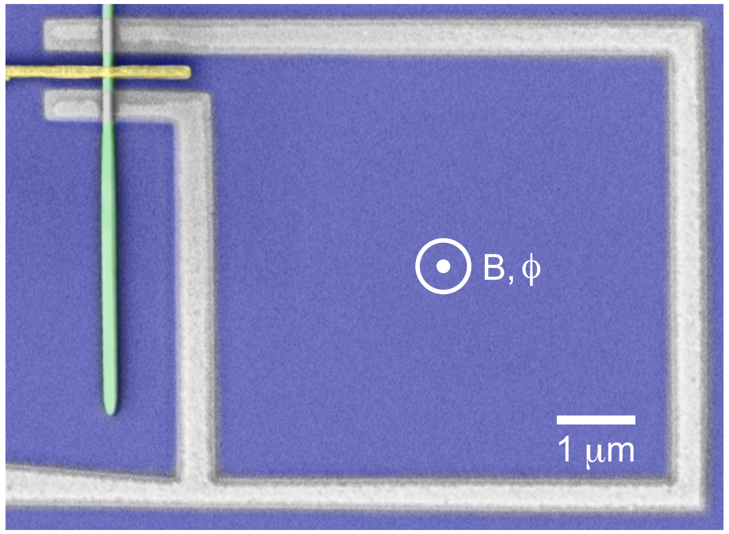


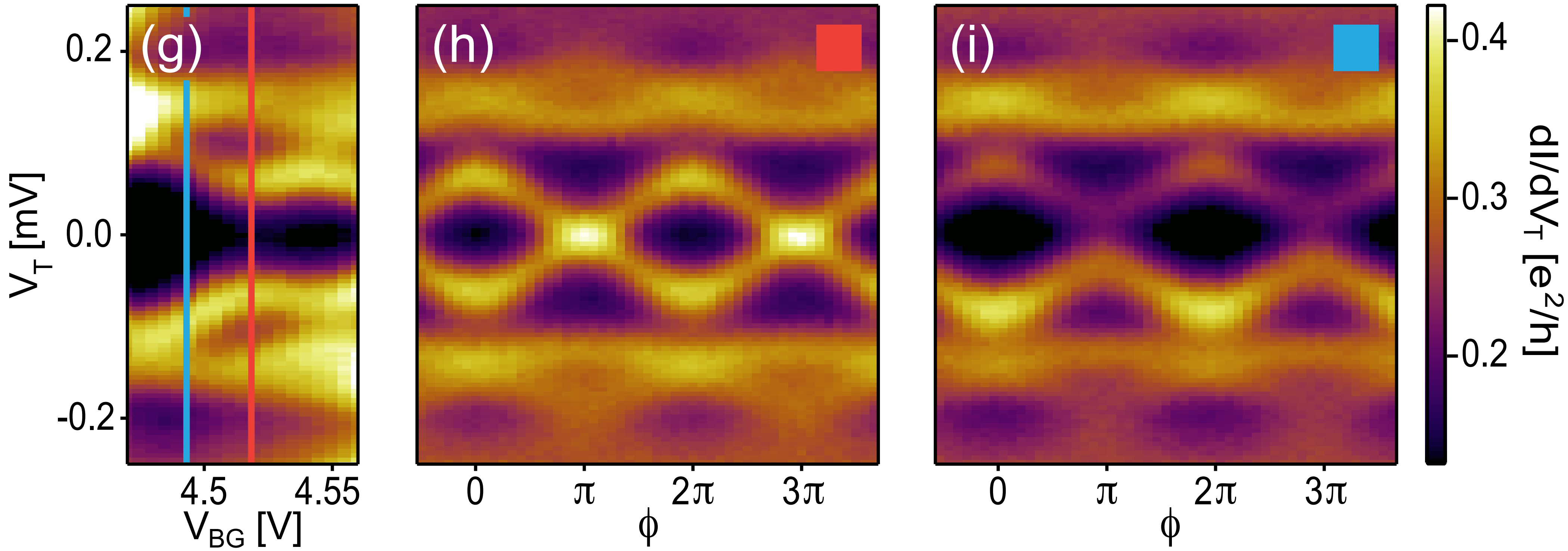


"We claim that the detection of a zero-energy peak at $\phi = \pi$ in the spectrum of the normal long link would constitute a direct measurement of the Majorana states..."

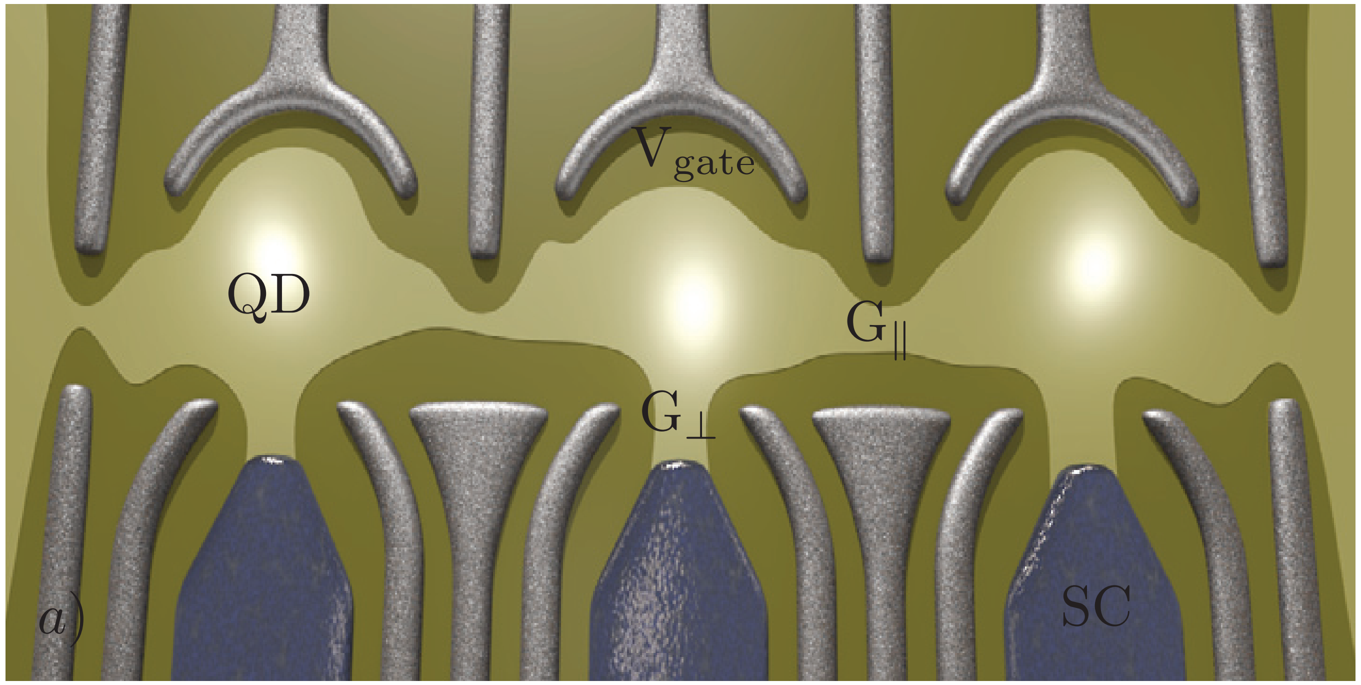
Tunneling Spectroscopy of Quasiparticle Bound States in a Spinful Josephson Junction

W. Chang,[1,2] V. E. Manucharyan,[3] T. S. Jespersen,[2] J. Nygård,[2] and C. M. Marcus[1,2]
[1]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen Ø, Denmark
[3]Society of Fellows, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 13 November 2012; published 23 May 2013)

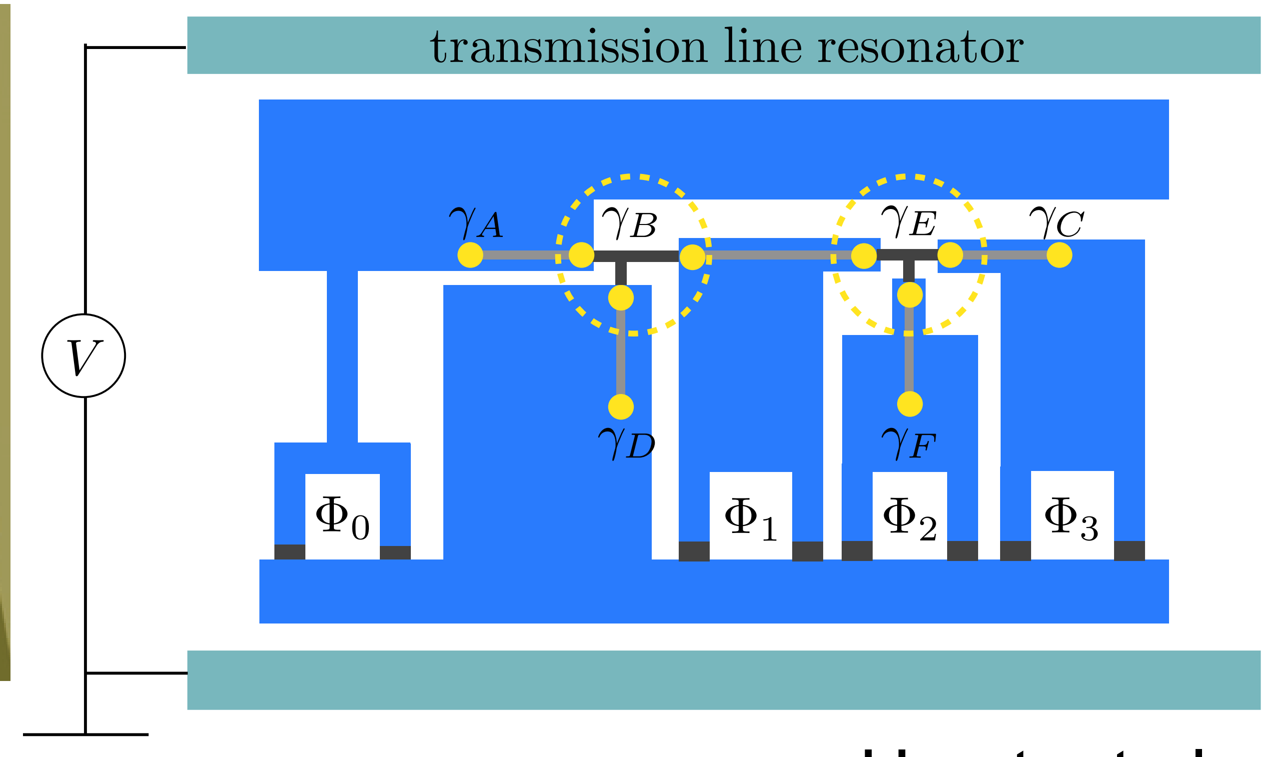




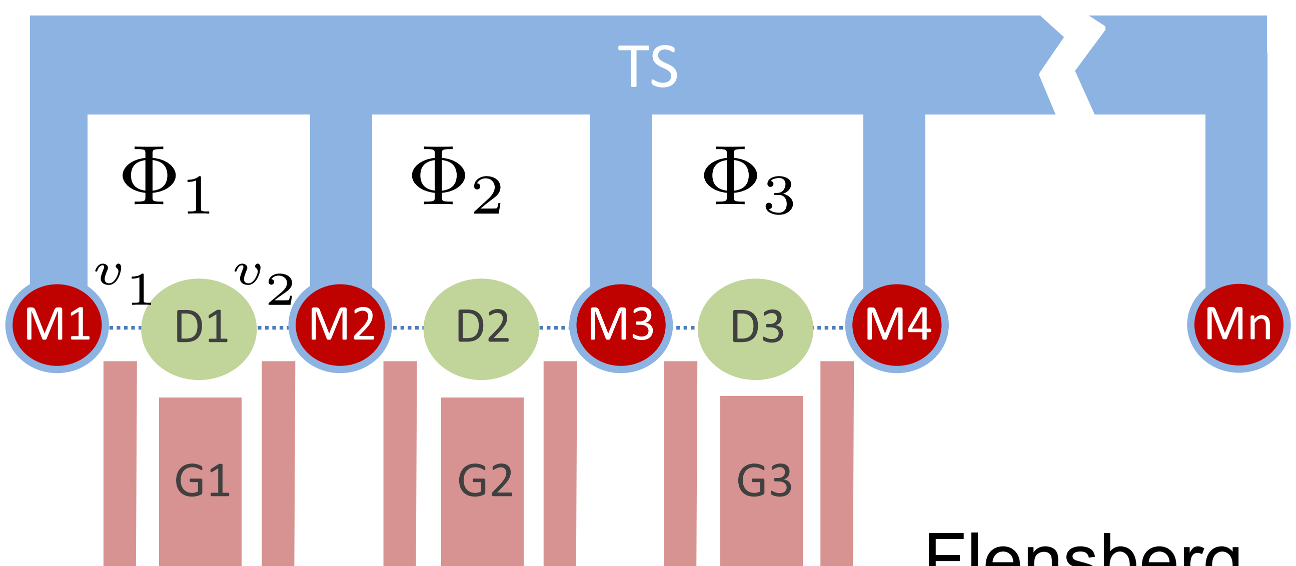
Approaches benefitting from 2D top-down fabrication



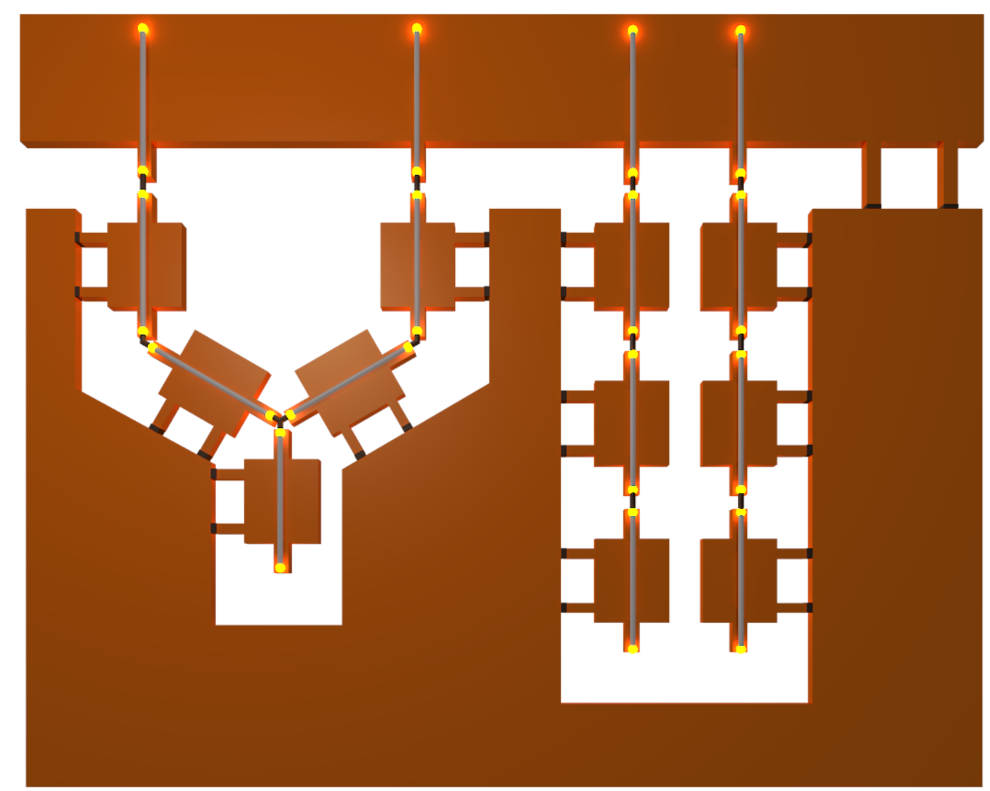
Fulga, et al.



Hyart, et al.

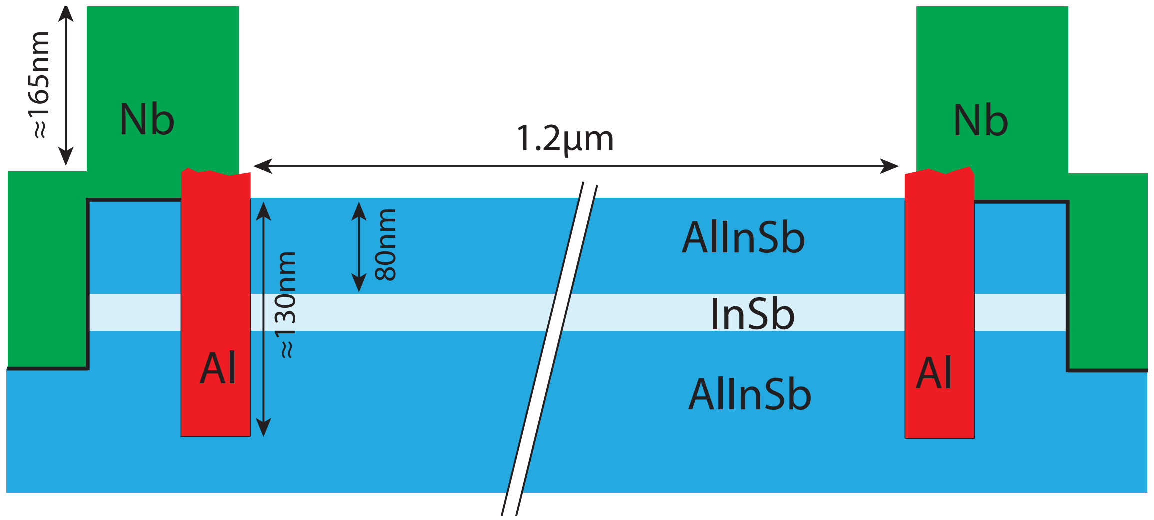


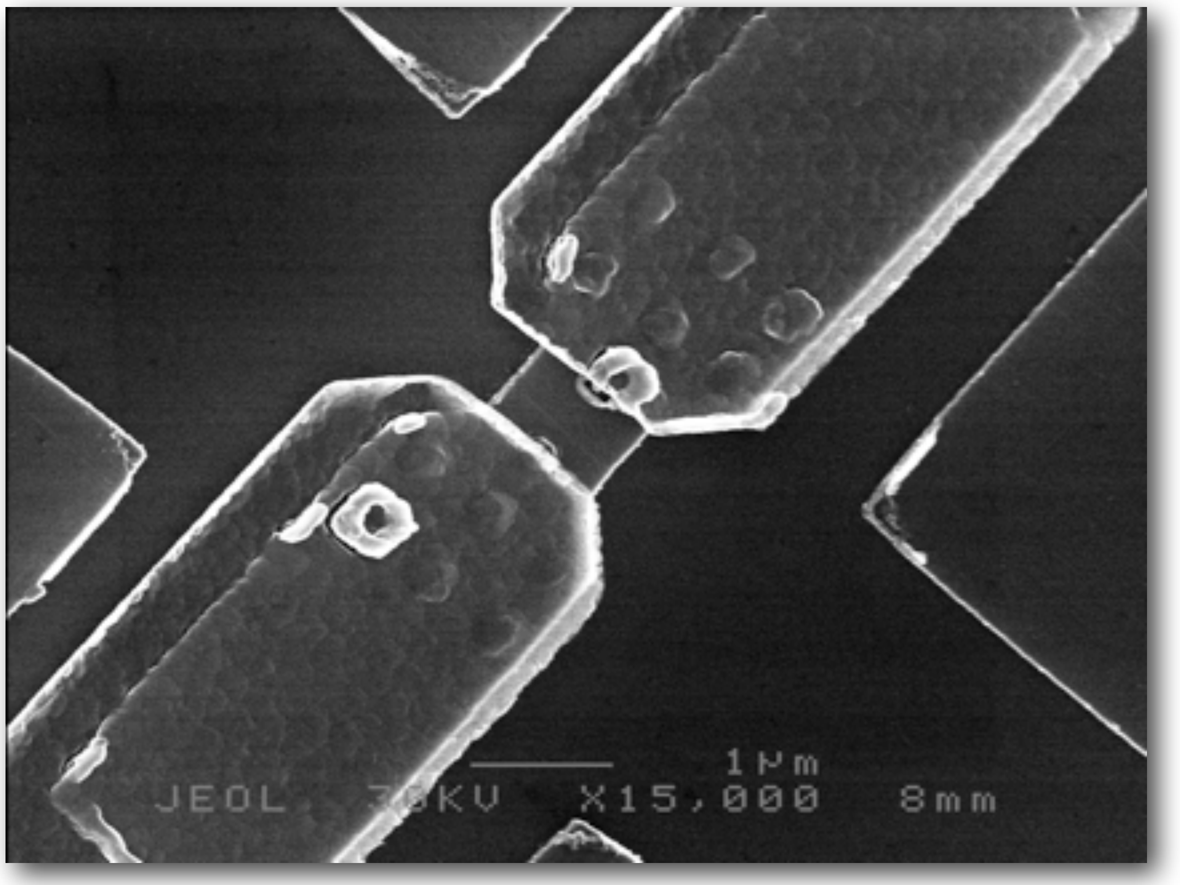
Flensberg

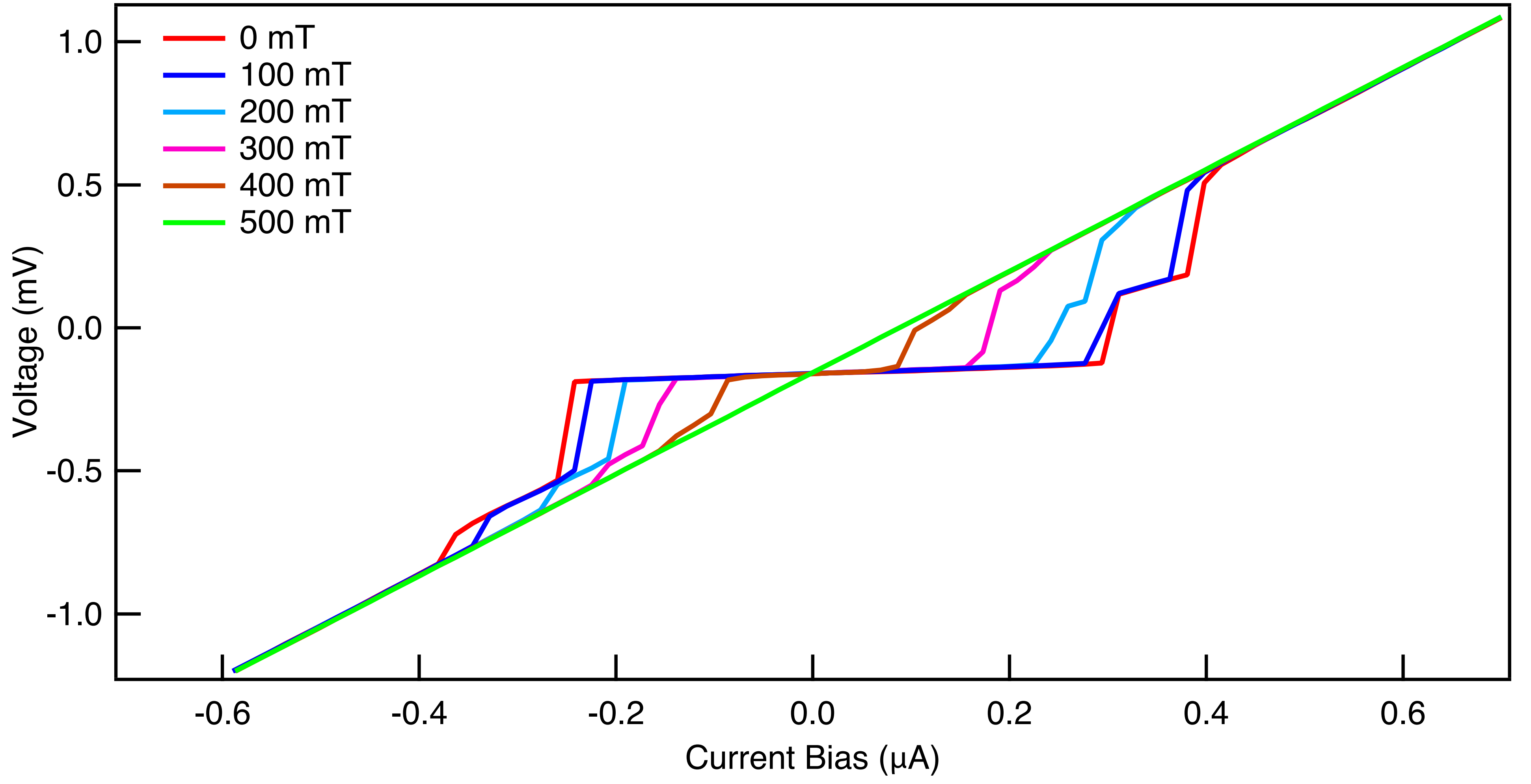


van Heck, et al.

Proximity effect in InSb quantum well





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