Topological Superconductivity and Majorana Zero Modes in Superconductor-Semiconductor Hybrid Materials

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1) Topological superconductivity and Majorana zero modes in nanowires

2) Caution, skepticism, and what's going on

3) The pseudo-Zeeman route to topological superconductivity: super-semi-ferro

4) The vortex route to topological superconductivity: full-shell nanowires

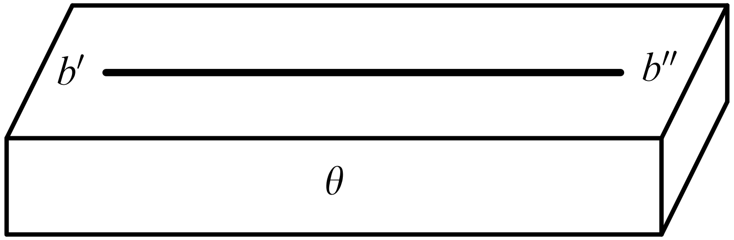
5) The planar Josephson junction route to topological superconductivity

Unpaired Majorana fermions in quantum wires

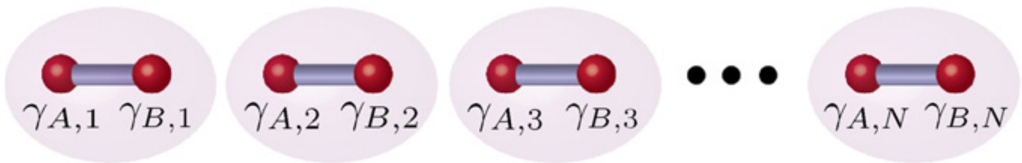
October, 2001 *Usp. Fiz. Nauk* (Suppl.) **171** (10)

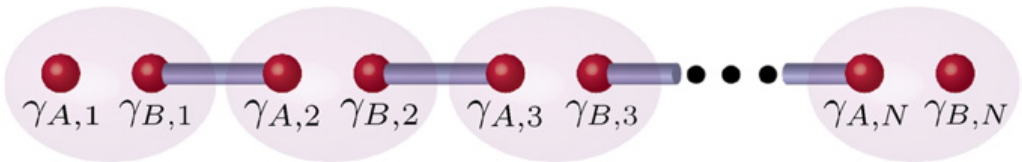
A Yu Kitaev

Abstract. Certain one-dimensional Fermi systems have an energy gap in the bulk spectrum while boundary states are described by one Majorana operator per boundary point. A finite system of length L possesses two ground states with an energy difference proportional to $\exp(-L/l_0)$ and different fermionic parities. Such systems can be used as qubits since they are intrinsically immune to decoherence. The property of a system to have boundary Majorana fermions is expressed as a condition on the bulk electron spectrum. The condition is satisfied in the presence of an arbitrary small energy gap induced by proximity of a three-dimensional p-wave superconductor, provided that the normal spectrum has an odd number of Fermi points in each half of the Brillouin zone (each spin component counts separately).



† It appears that only a triplet (p-wave) superconductivity in the three-dimensional substrate can effectively induce the desired pairing between electrons with the same spin direction — at least, this is true in the absence of spin-orbit interaction.





J. Alicea, *Rep. Prog. Phys.* **75**, 076501 (2012).

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

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

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Helical Liquids and Majorana Bound States in Quantum Wires

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[1]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, 76100, Israel*
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[3]*Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany*

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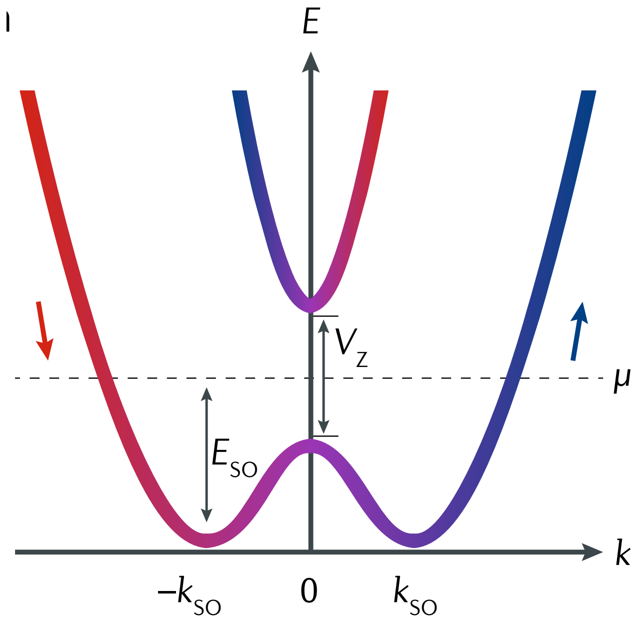
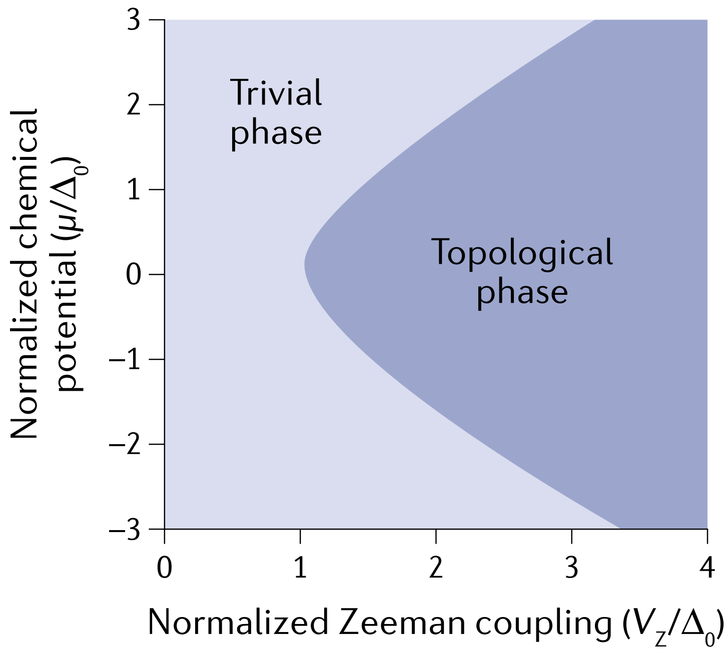
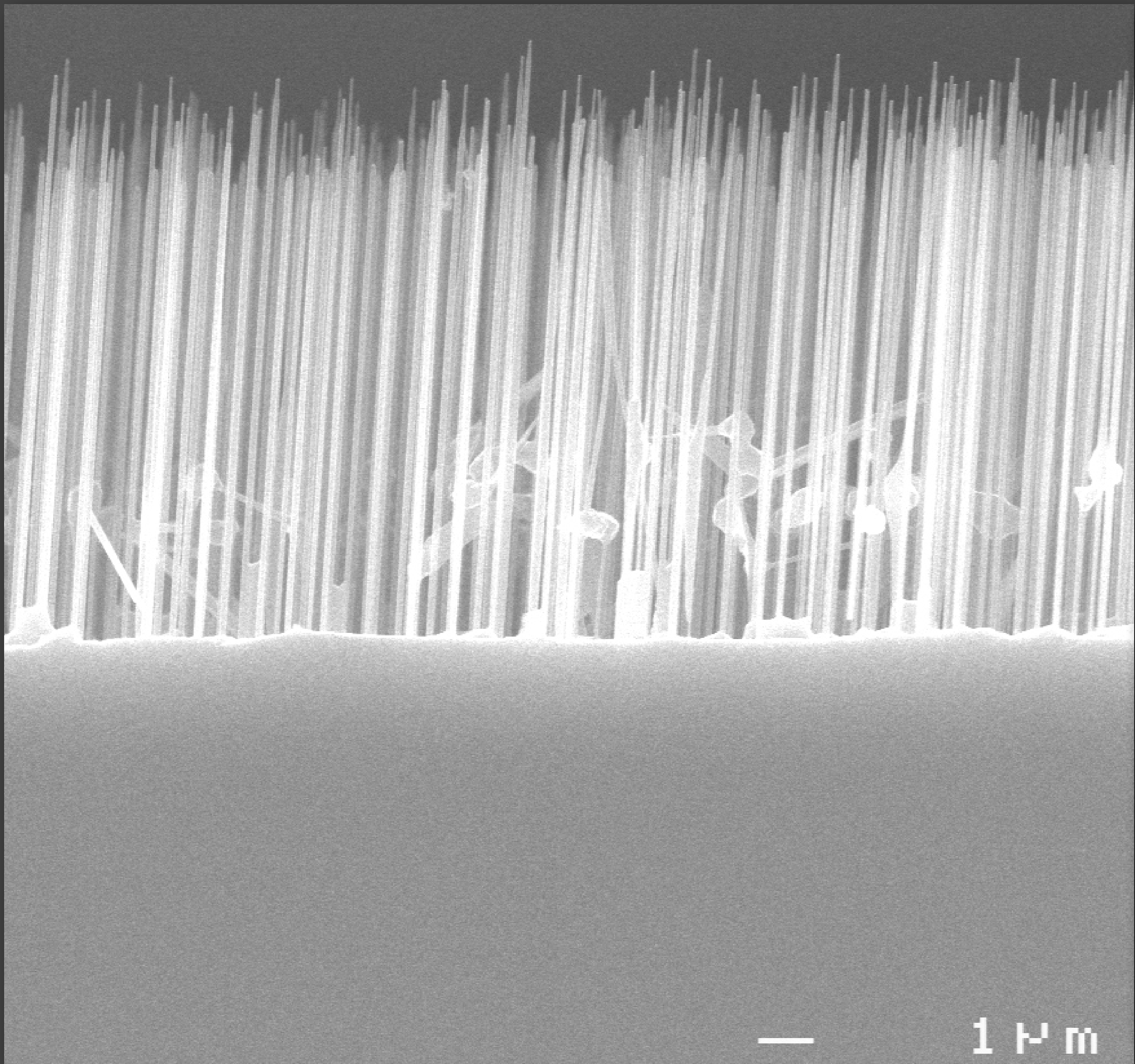
We show that the combination of spin-orbit coupling with a Zeeman field or strong interactions may lead to the formation of a helical electron liquid in single-channel quantum wires, with spin and velocity



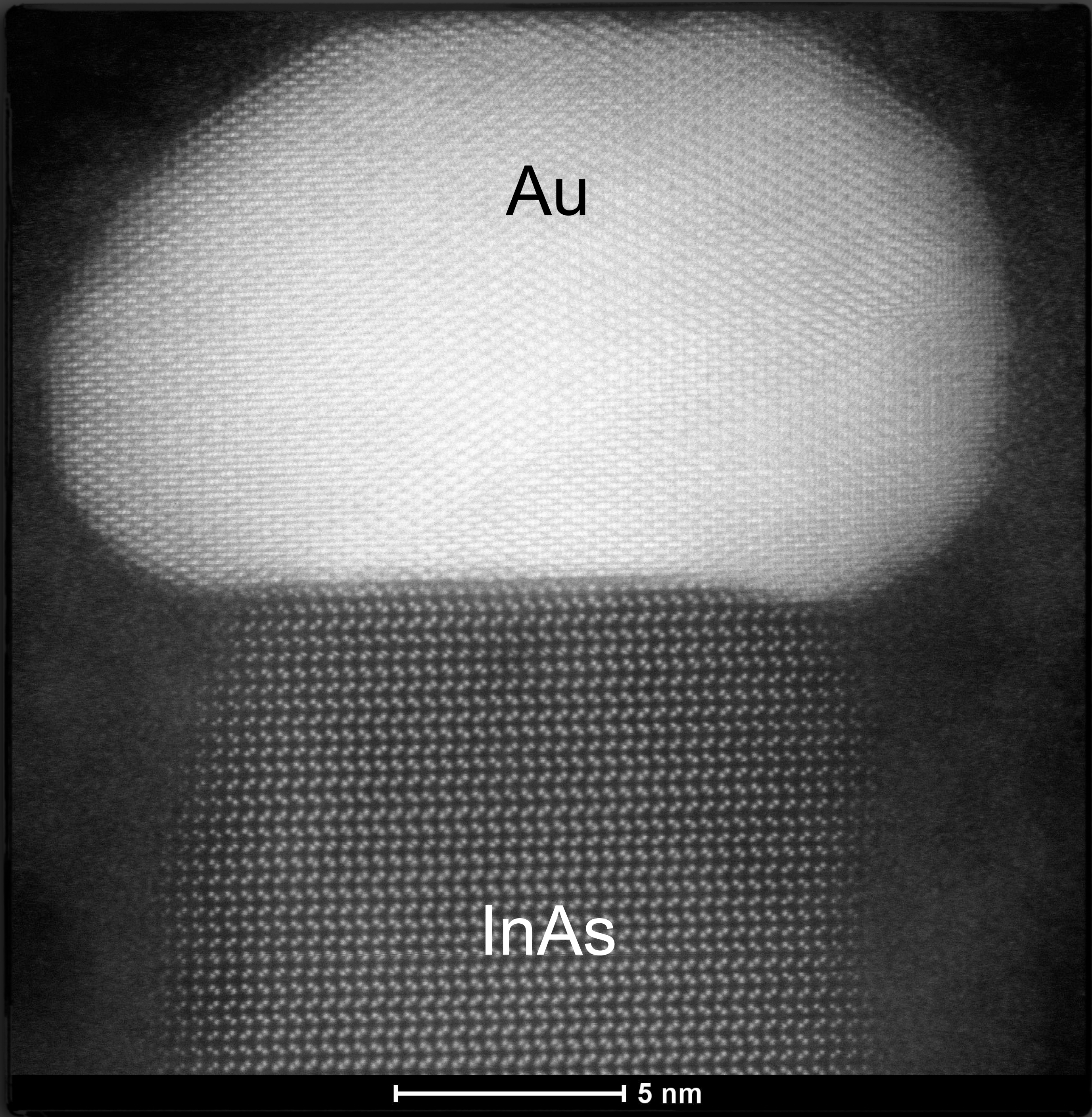


1D Semiconductors: InAs Nanowire



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

Growing Nanowires



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

Majorana fermions in semiconductor nanowires

Tudor D. Stanescu,[1] Roman M. Lutchyn,[2] and S. Das Sarma[3]
[1]*Department of Physics, West Virginia University, Morgantown, West Virginia 26506, USA*
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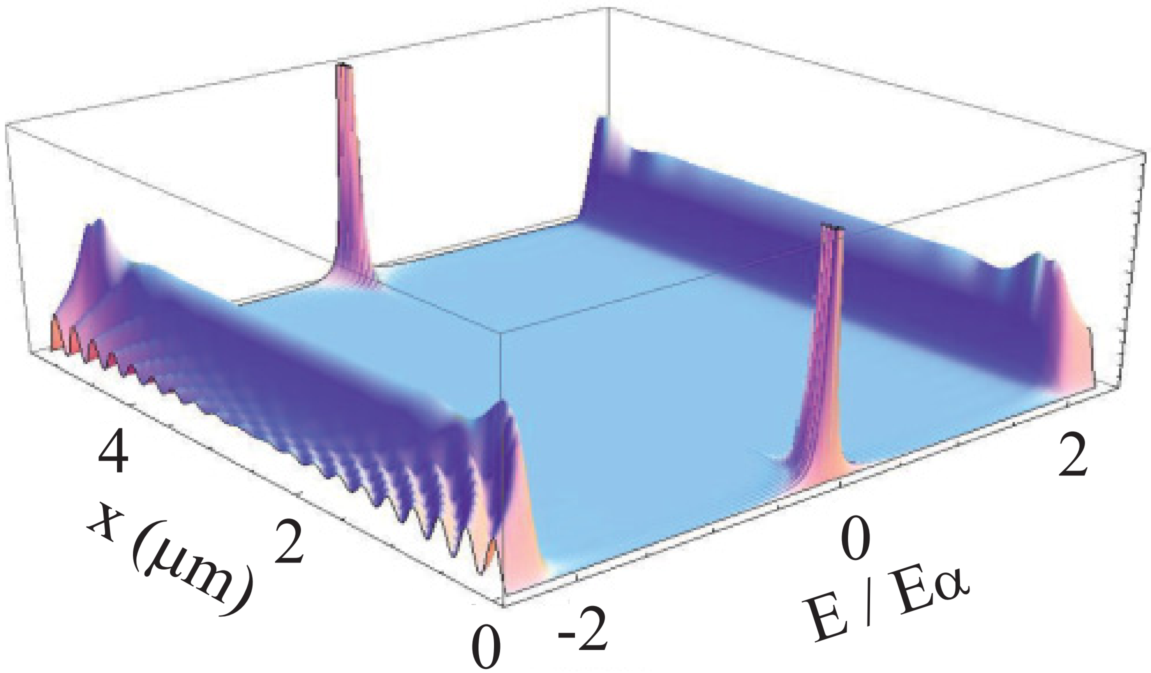
(Received 27 July 2011; revised manuscript received 27 September 2011; published 28 October 2011)

Zero-energy end states as signature of topological superconductor



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

Majorana fermions in semiconductor nanowires

Tudor D. Stanescu,[1] Roman M. Lutchyn,[2] and S. Das Sarma[3]
[1]*Department of Physics, West Virginia University, Morgantown, West Virginia 26506, USA*
[2]*Station Q, Microsoft Research, Santa Barbara, California 93106-6105, USA*
[3]*Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
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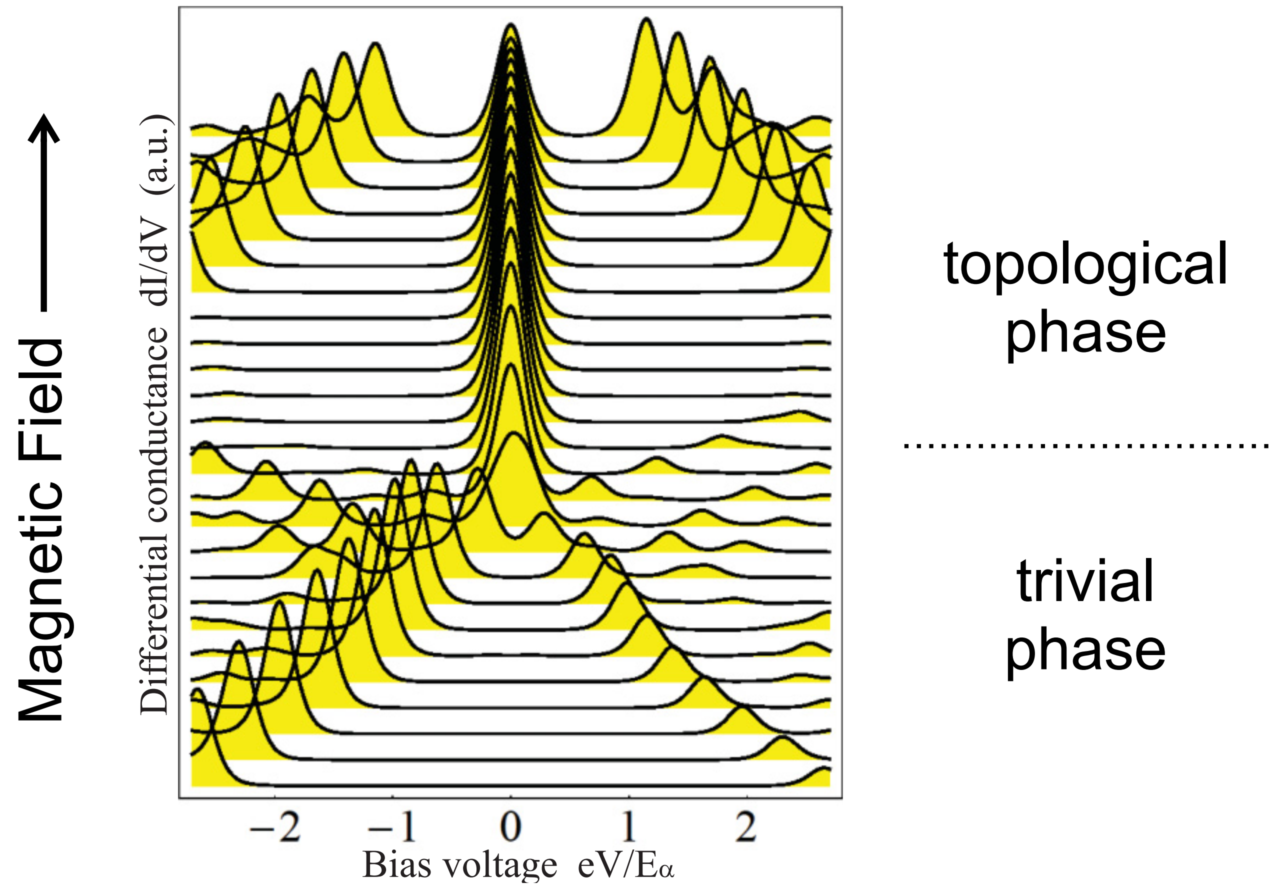
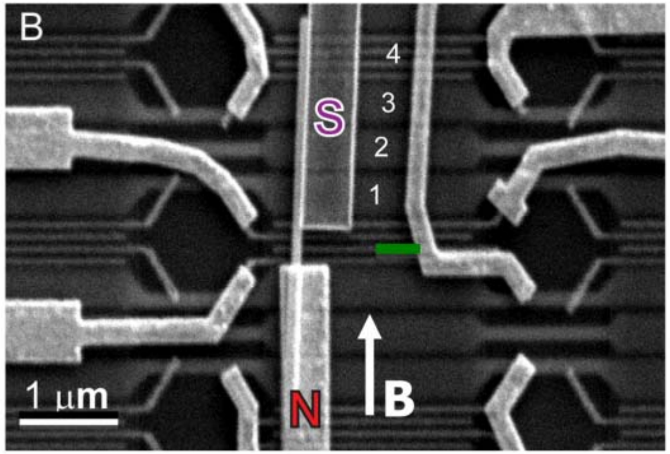
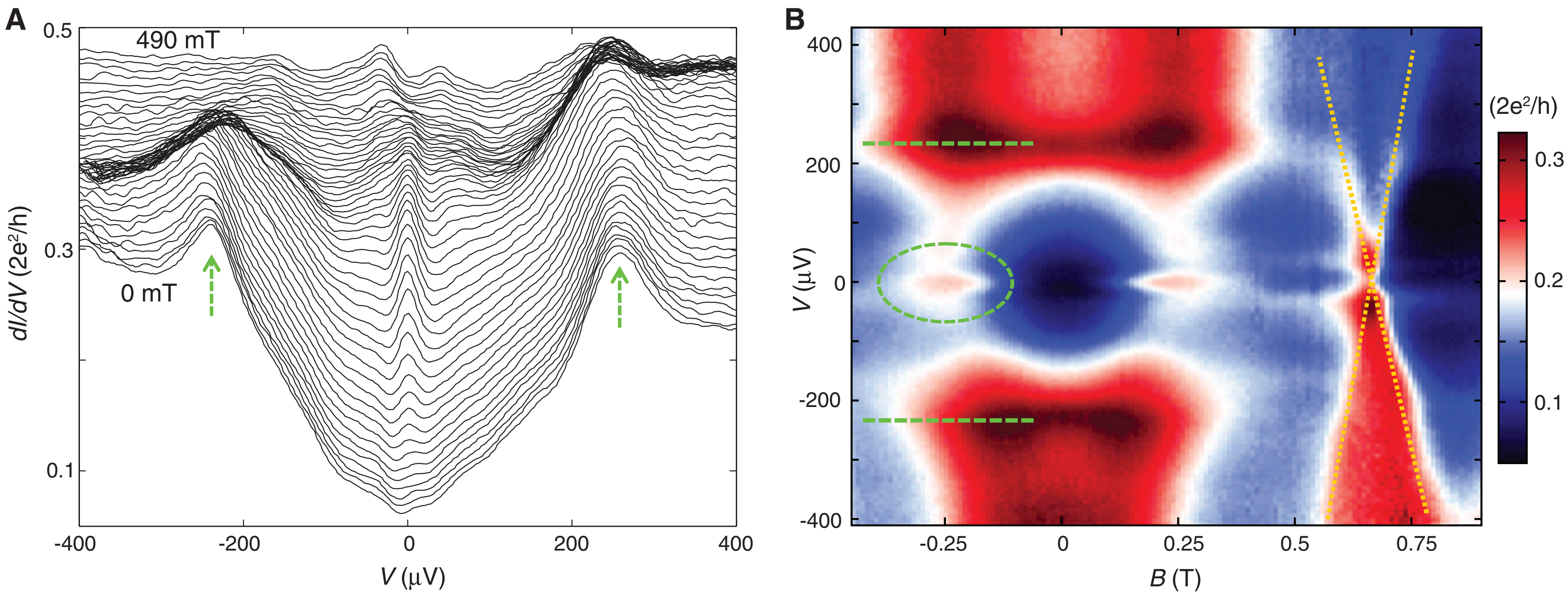


Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

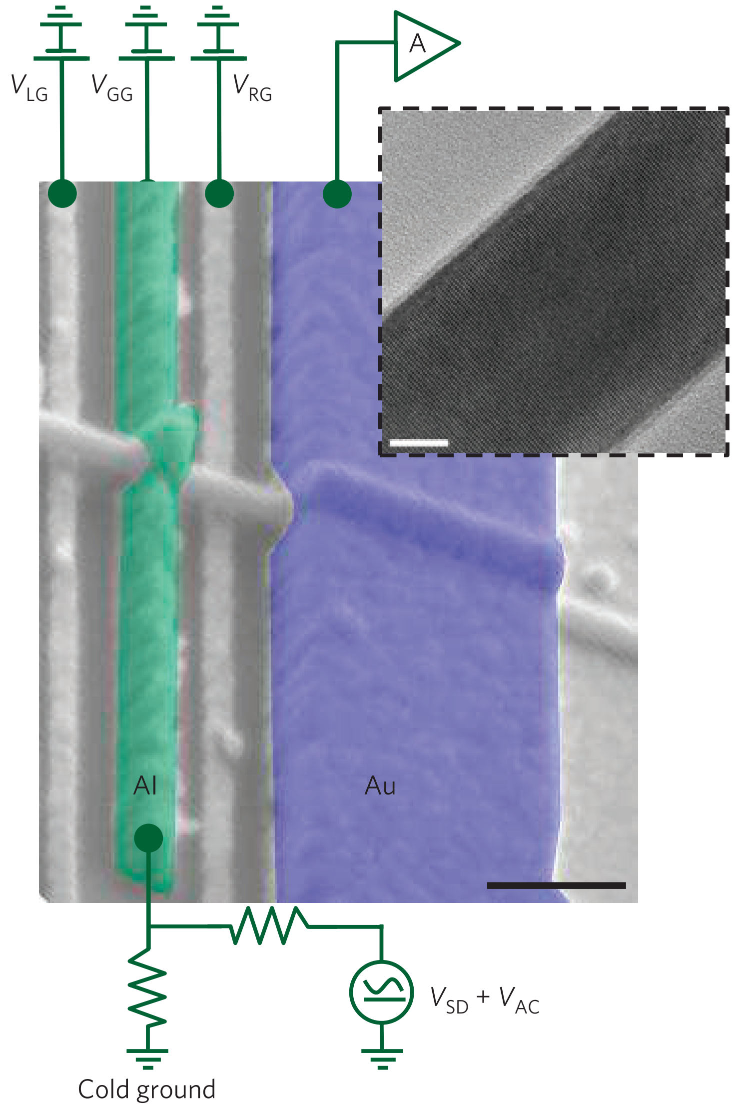
V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

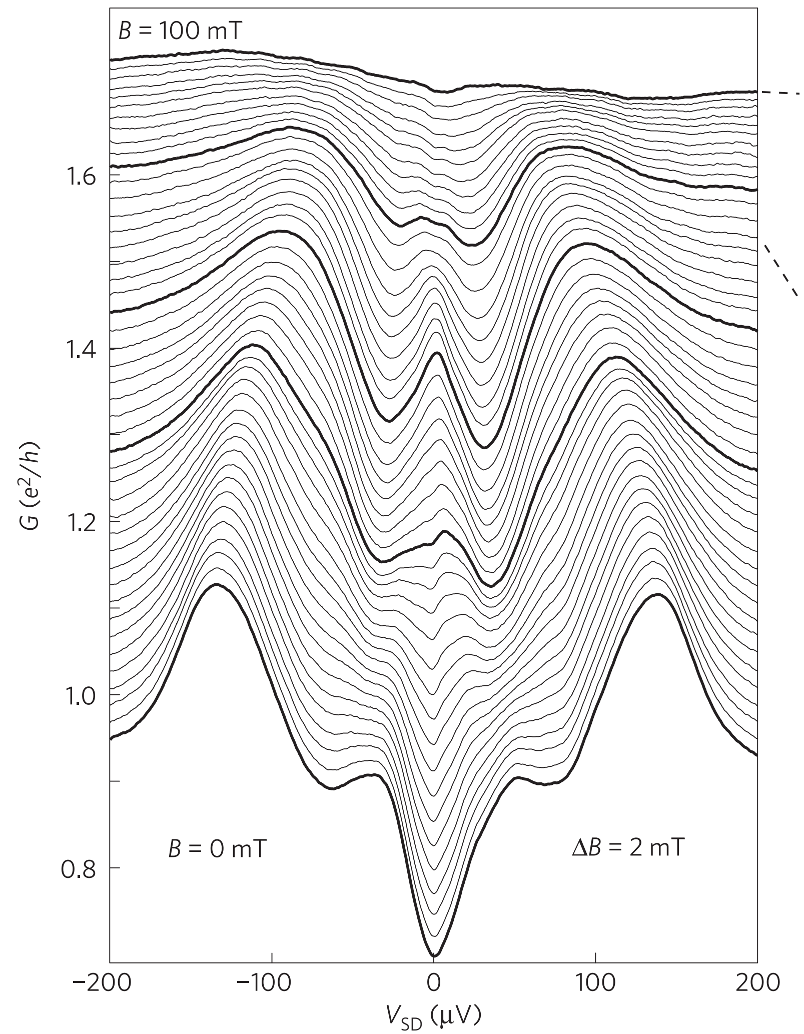




Zero-bias peaks and splitting in an Al–InAs nanowire topological superconductor as a signature of Majorana fermions

Anindya Das[†], Yuval Ronen[†], Yonatan Most, Yuval Oreg, Moty Heiblum* and Hadas Shtrikman



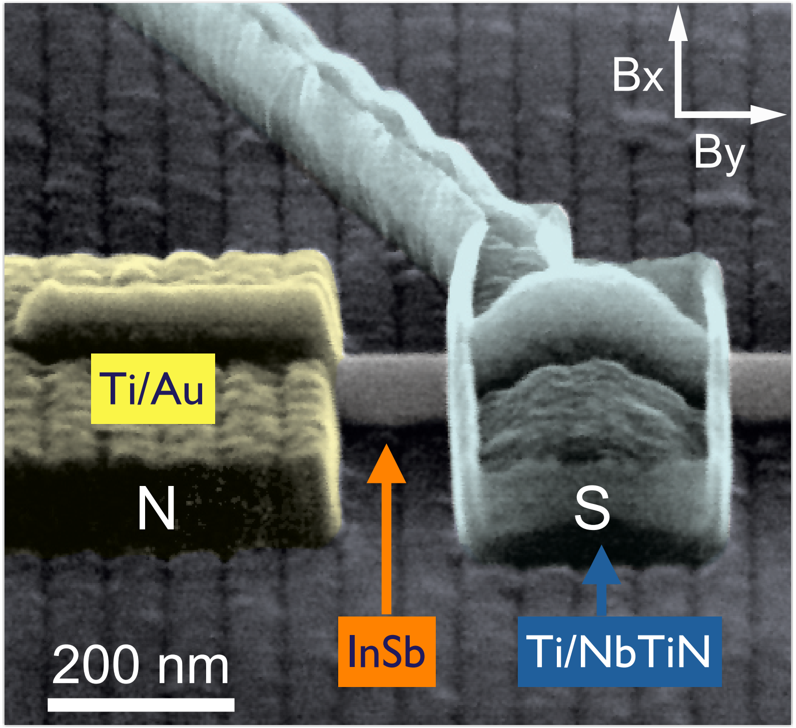


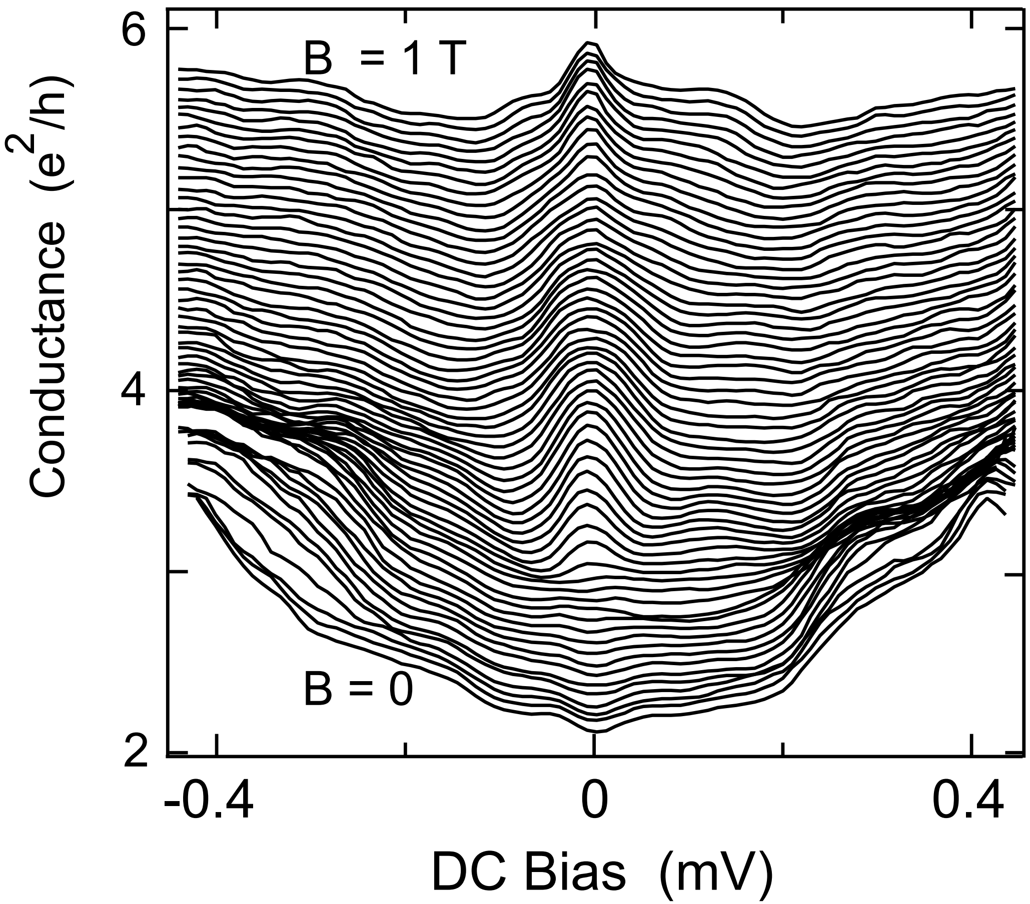
RAPID COMMUNICATIONS

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,*]

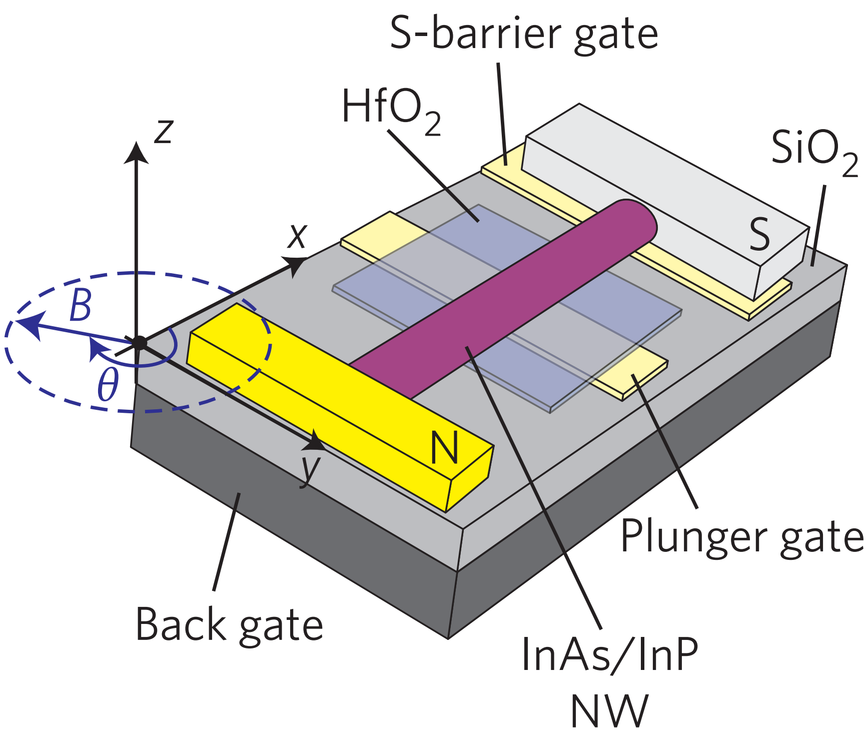


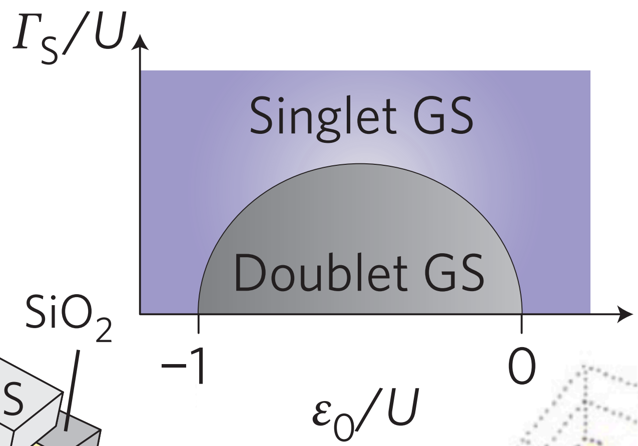


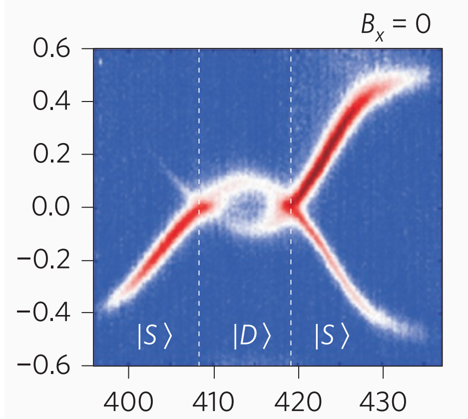
nature nanotechnology
ARTICLES
PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NNANO.2013.267

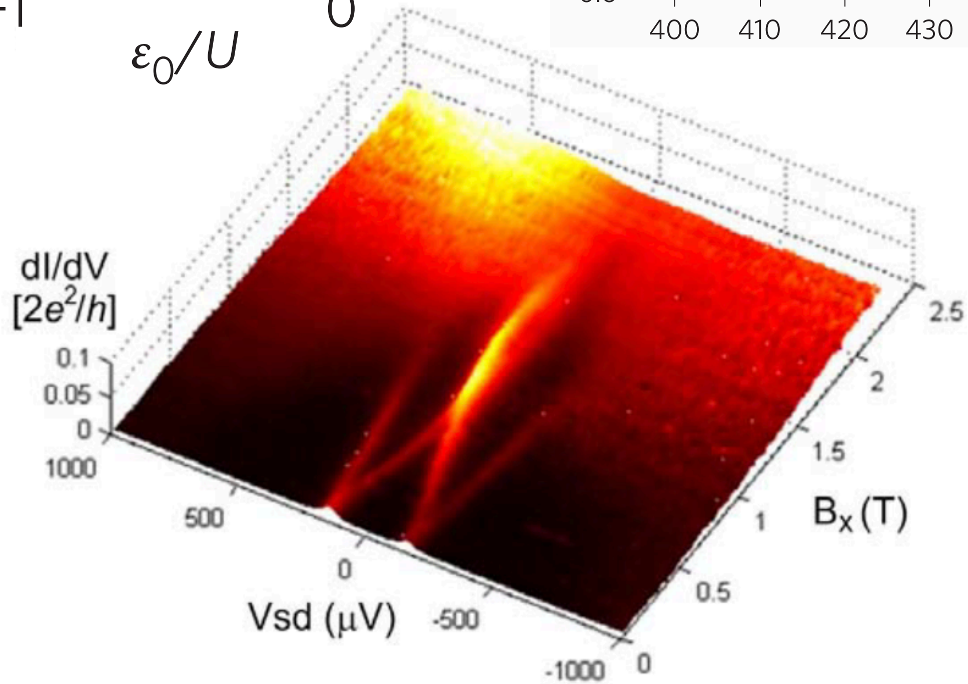
Spin-resolved Andreev levels and parity crossings in hybrid superconductor–semiconductor nanostructures

Eduardo J. H. Lee[1], Xiaocheng Jiang[2], Manuel Houzet[1], Ramón Aguado[3], Charles M. Lieber[2] and Silvano De Franceschi[1]*





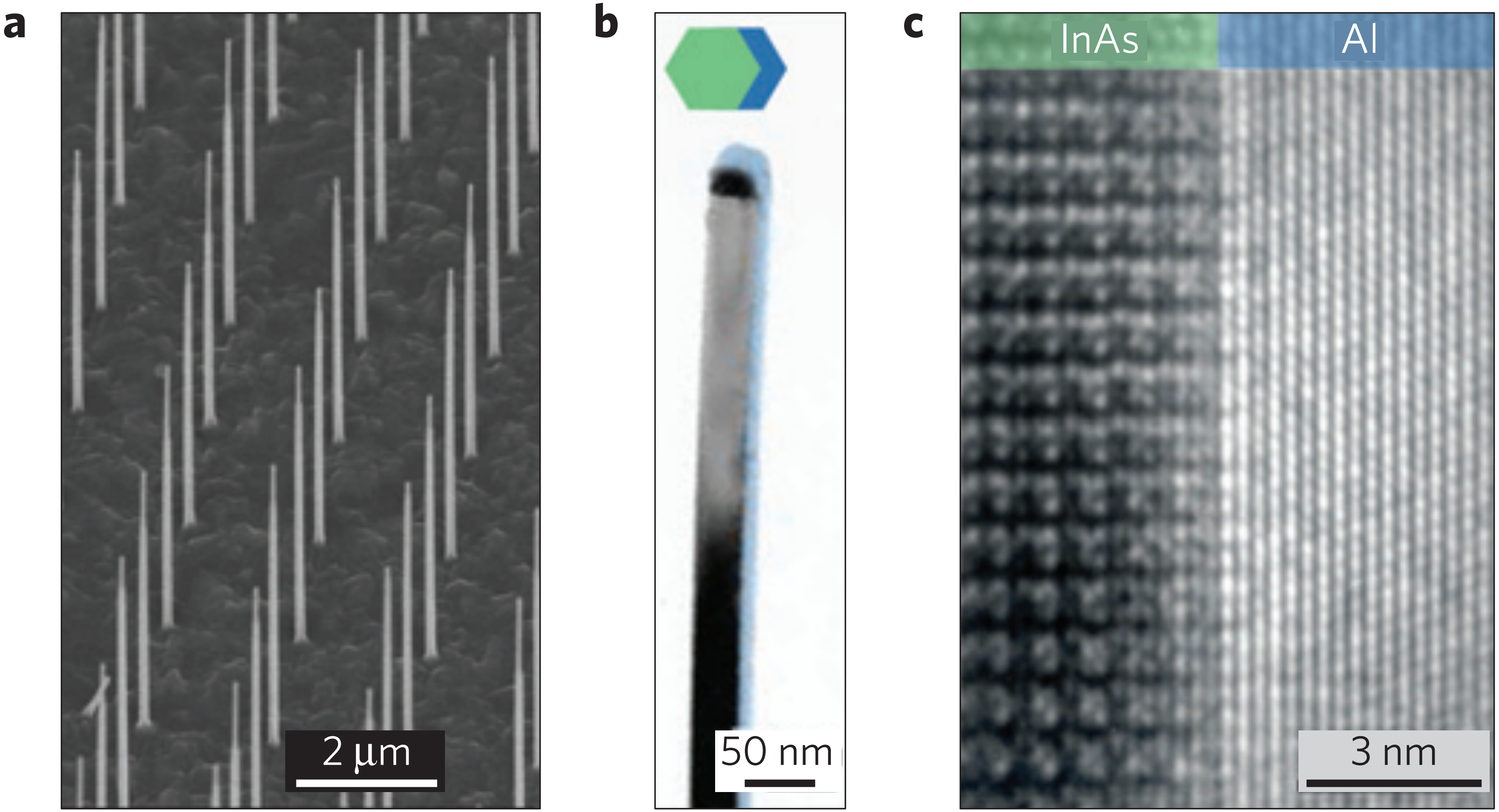




nature materials
ARTICLES
PUBLISHED ONLINE: 12 JANUARY 2015 | DOI: 10.1038/NMAT4176

Epitaxy of semiconductor–superconductor nanowires

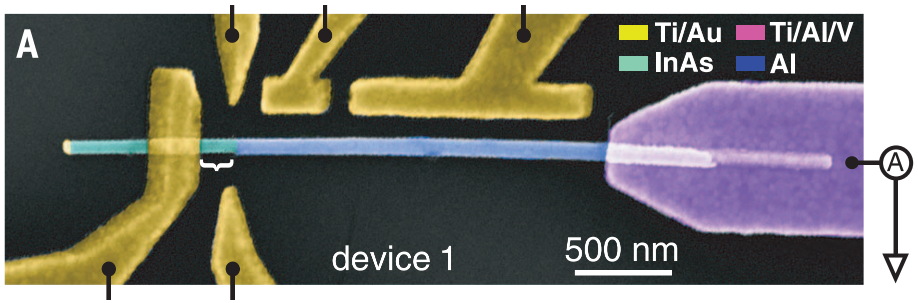
P. Krogstrup[1]*, N. L. B. Ziino[1], W. Chang[1], S. M. Albrecht[1], M. H. Madsen[1], E. Johnson[1,2], J. Nygård[1,3]*, C. M. Marcus[1] and T. S. Jespersen[1]*

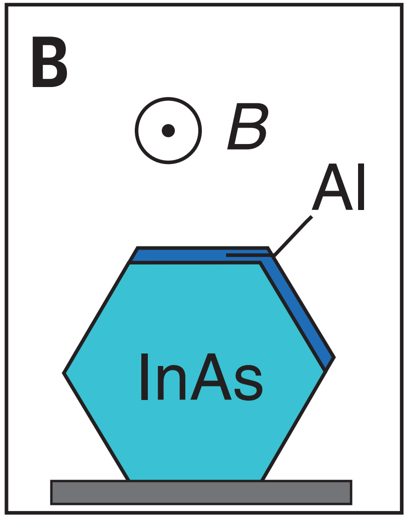


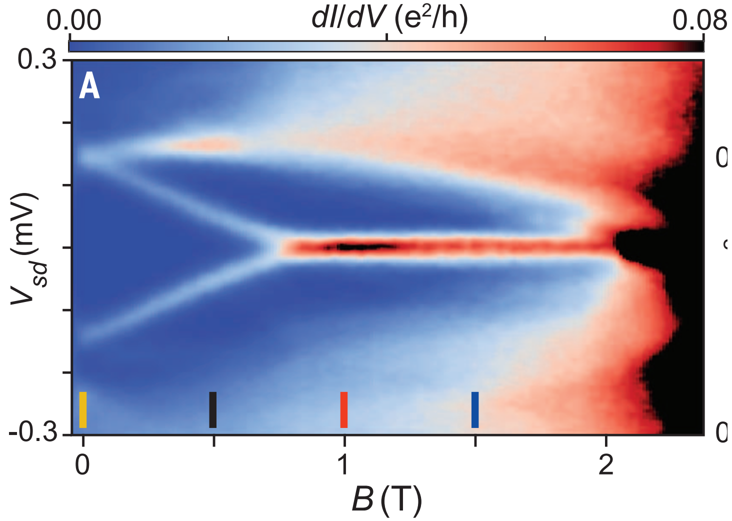
TOPOLOGICAL MATTER

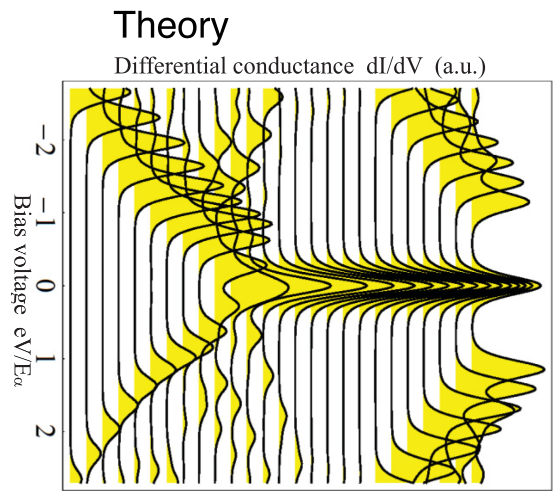
Majorana bound state in a coupled quantum-dot hybrid-nanowire system

M. T. Deng,[1,2] S. Vaitiekėnas,[1,3] E. B. Hansen,[1] J. Danon,[1,4] M. Leijnse,[1,5] K. Flensberg,[1] J. Nygård,[1] P. Krogstrup,[1] C. M. Marcus[1]*





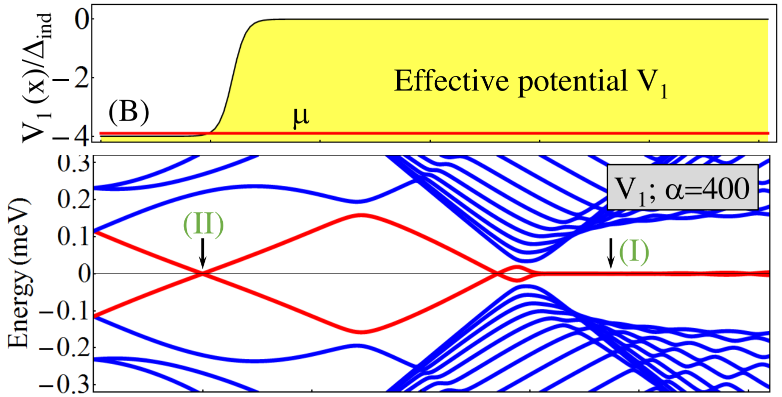


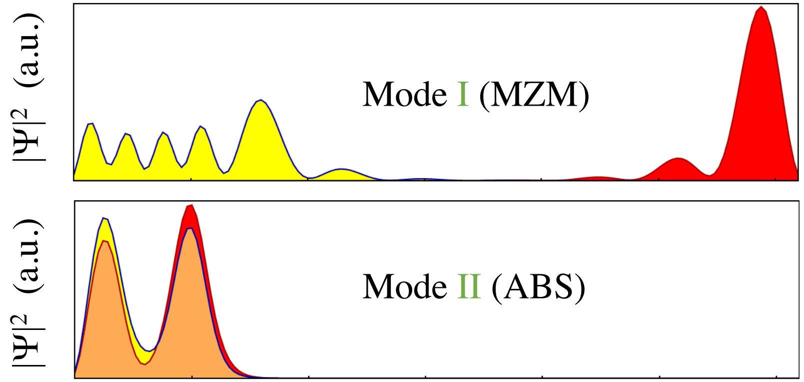


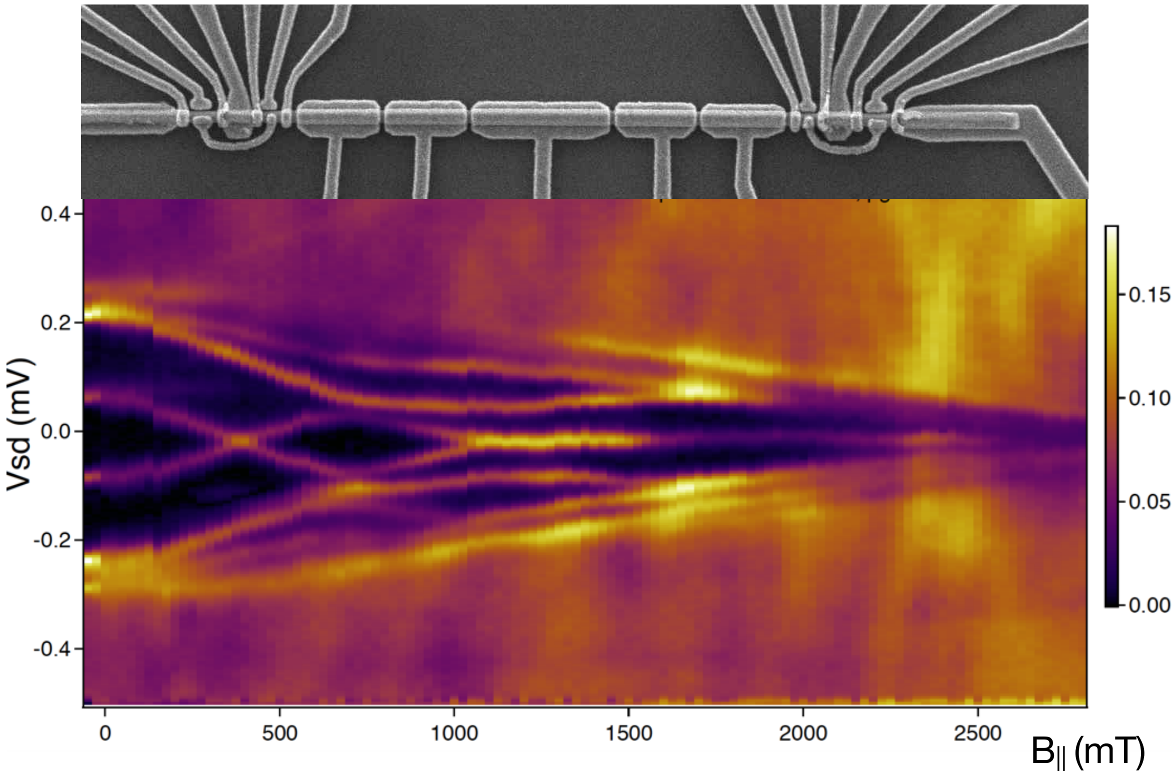
PHYSICAL REVIEW B **97**, 165302 (2018)

Two-terminal charge tunneling: Disentangling Majorana zero modes from partially separated Andreev bound states in semiconductor-superconductor heterostructures

Christopher Moore,[1] Tudor D. Stanescu,[2] and Sumanta Tewari[1]
[1]*Department of Physics and Astronomy, Clemson University, Clemson, South Carolina 29634, USA*
[2]*Department of Physics and Astronomy, West Virginia University, Morgantown, West Virginia 26506, USA*



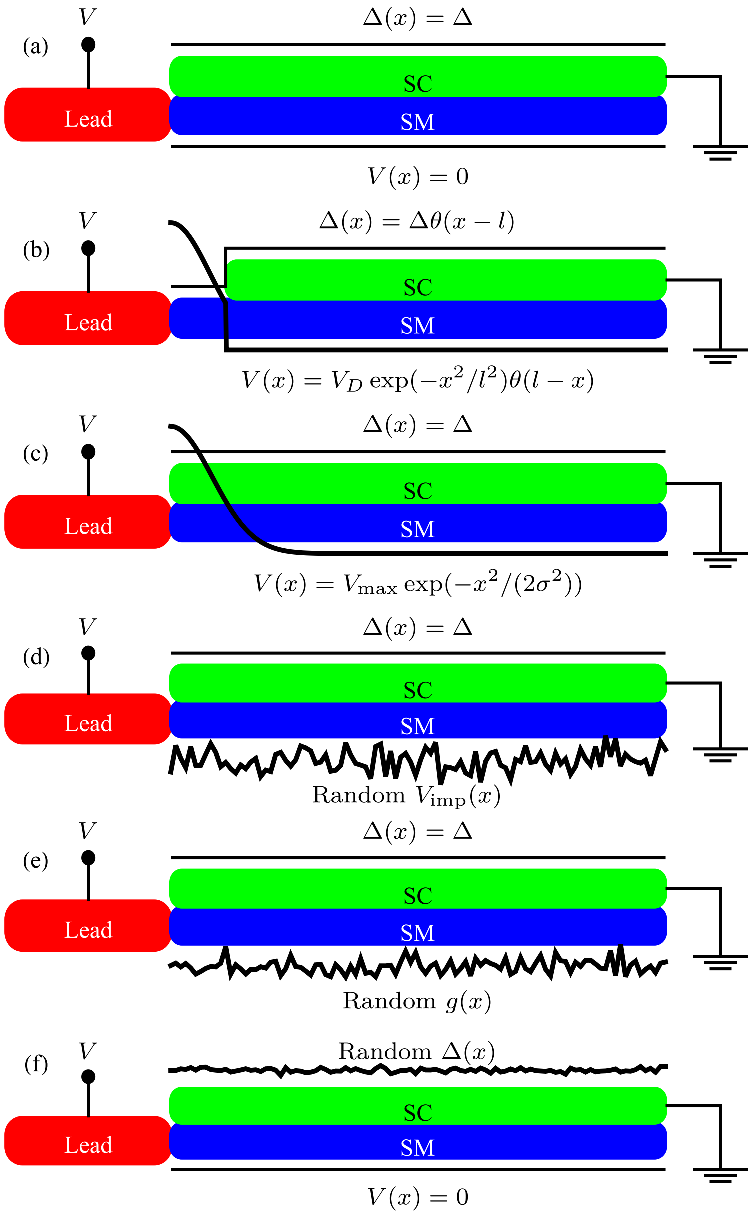




Experiment:
M.T. Deng, S. Vaitenekanas
Center for Quantum Devices
(unpublished)

Physical mechanisms for zero-bias conductance peaks in Majorana nanowires

Haining Pan and S. Das Sarma
Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA

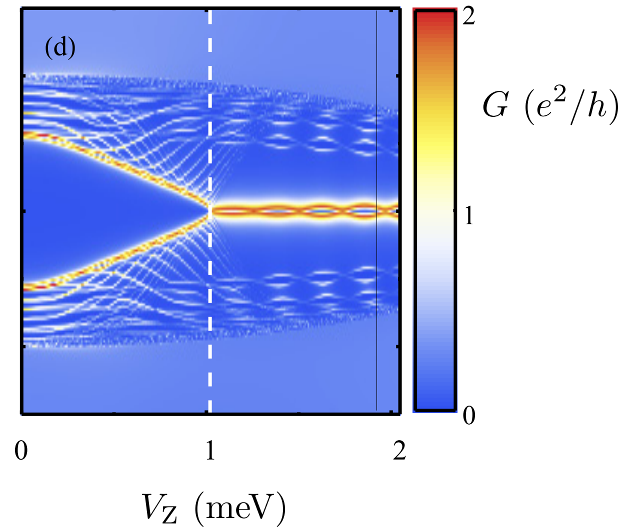


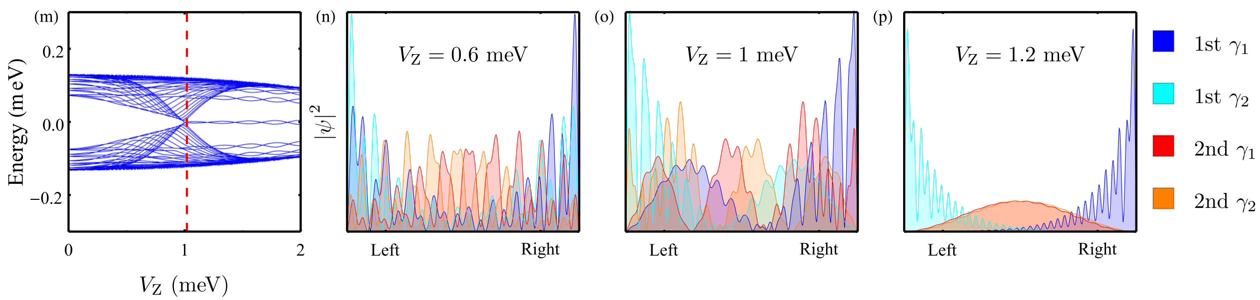
"good"

The general form of the Hamiltonian to describe a SC-SM hybrid nanowire is [5]

$$H_{\mathrm{tot}}=H_{\mathrm{SM}}+H_{\mathrm{Z}}+H_{\mathrm{V}}+H_{\mathrm{SC}}+H_{\text{SC-SM}}, \tag{1}$$

where H_{SM} is the Hamiltonian for SM component, H_{Z} describes the contribution from the applied magnetic field (entering as the Zeeman splitting energy), H_{V} contains various effects of disorder and gate potentials, H_{SC} quantifies the parent SC, and $H_{\text{SC-SM}}$ is the SC-SM coupling.

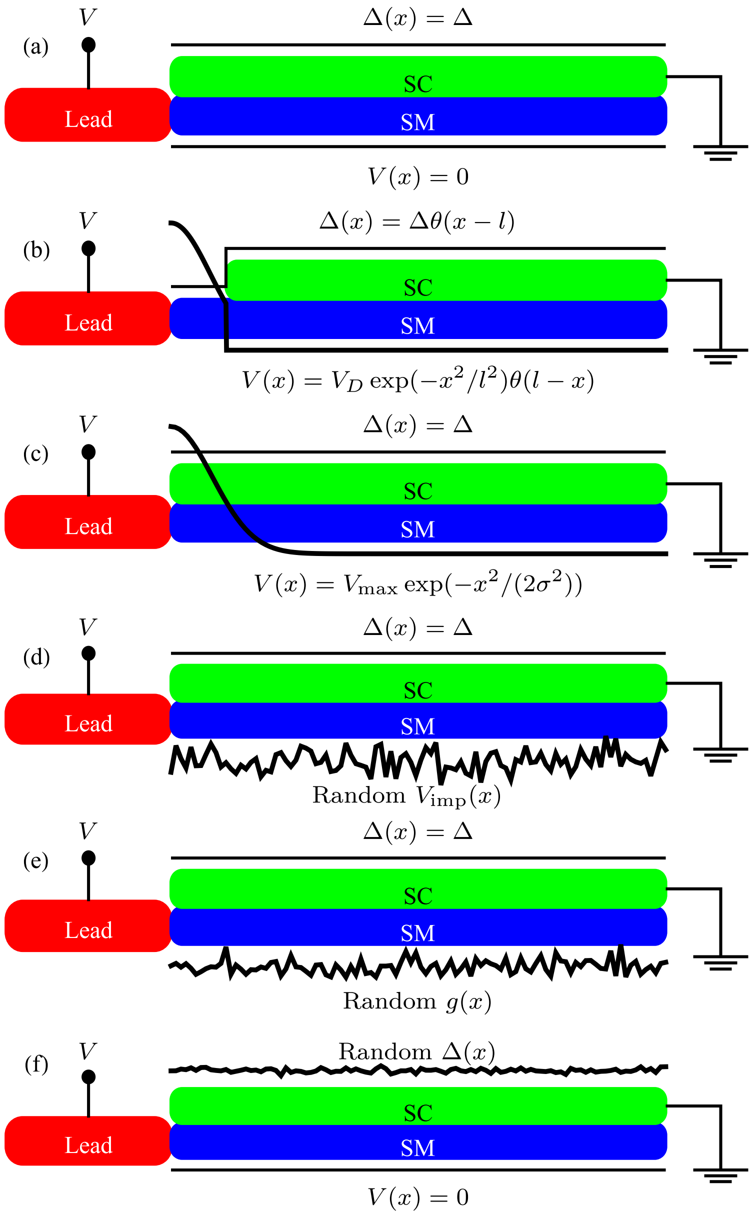




PHYSICAL REVIEW RESEARCH **2**, 013377 (2020)

Physical mechanisms for zero-bias conductance peaks in Majorana nanowires

Haining Pan and S. Das Sarma
Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA



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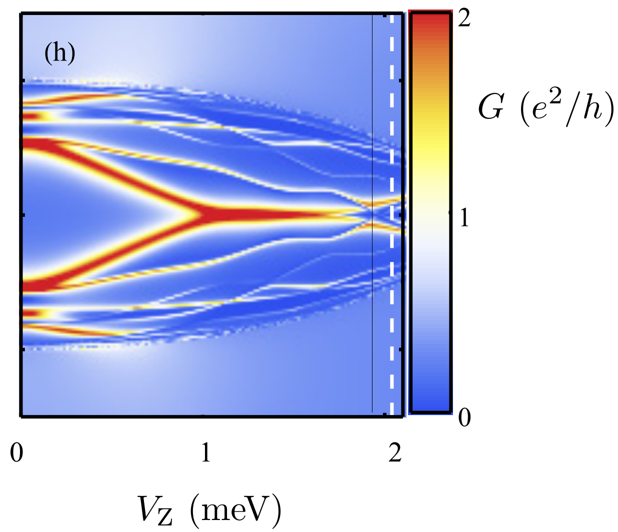
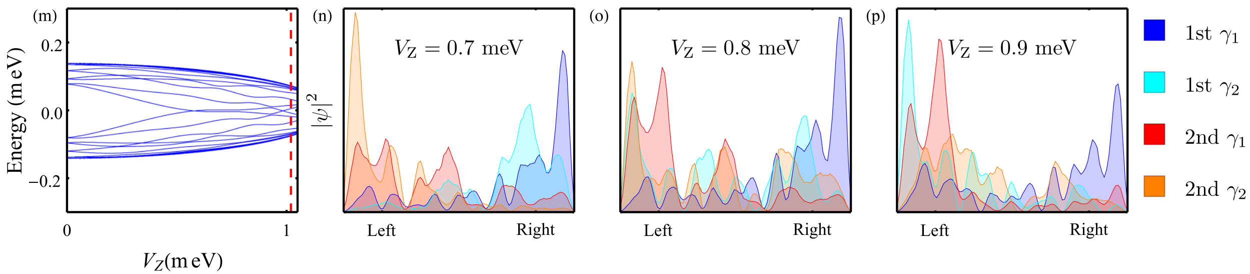
"ugly"





Physical mechanisms for zero-bias conductance peaks in Majorana nanowires

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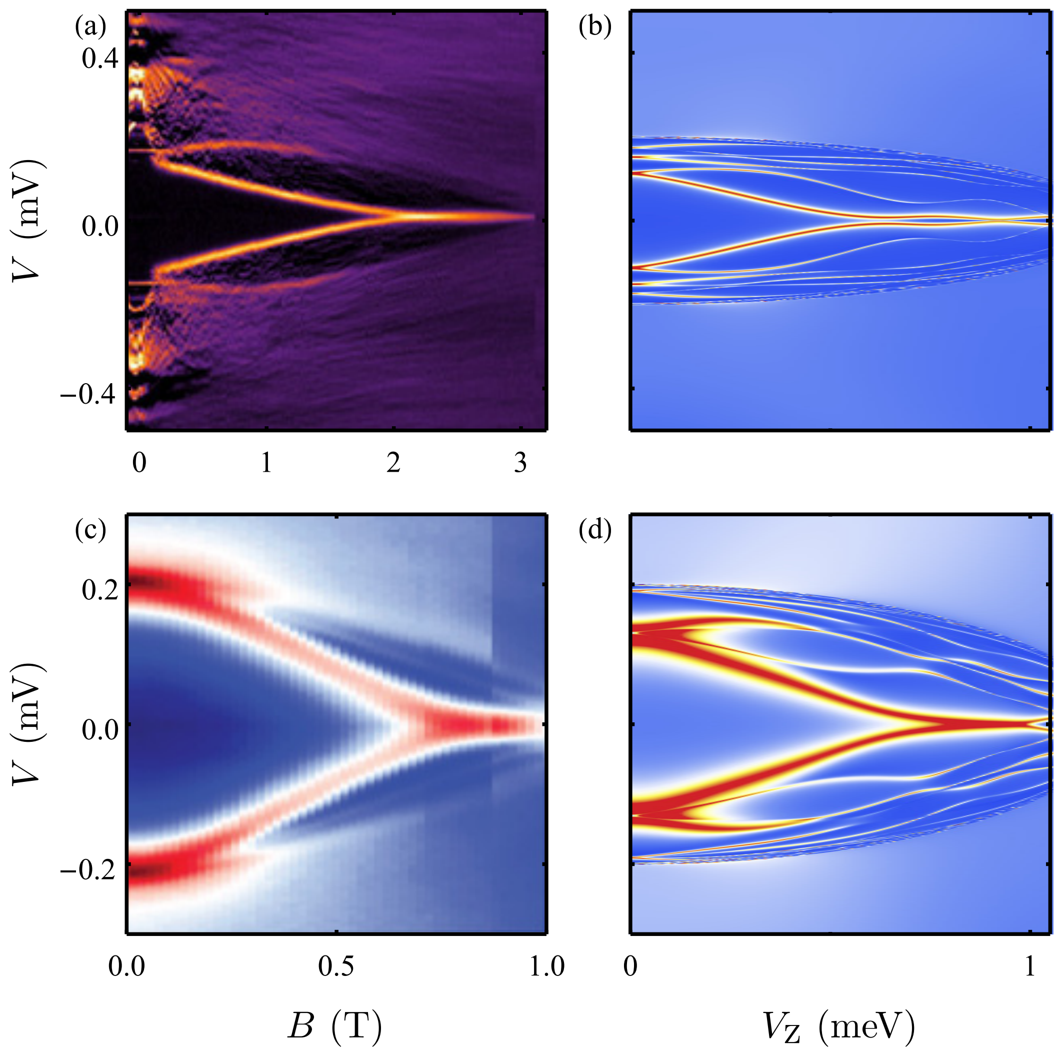

FIG. 7. (a) Tunneling conductance as a function of the magnetic field at a small transmission rate to the lead. The darker color indicates the smaller conductance. This experimental result is from Ref. [28]; (b) fine-tuning parameters to fit (a); The ZBCP is the ugly one with $\sigma_\mu = 1$ meV; (c) tunneling conductance as a function of the magnetic field. The redder color indicates the larger conductance. This experimental result is from Ref. [29]; (d) fine-tuning parameters to fit (d). The ZBCP is the ugly one with $\sigma_\mu = 1$ meV.

Single-Electron Charging of a Superconducting Island

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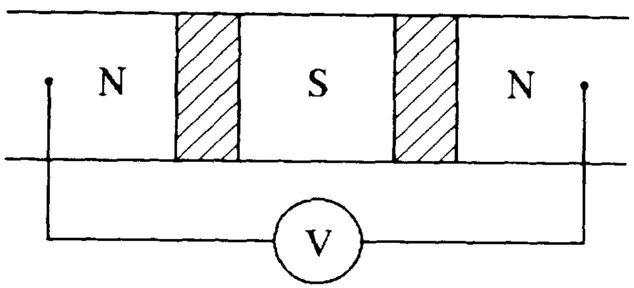
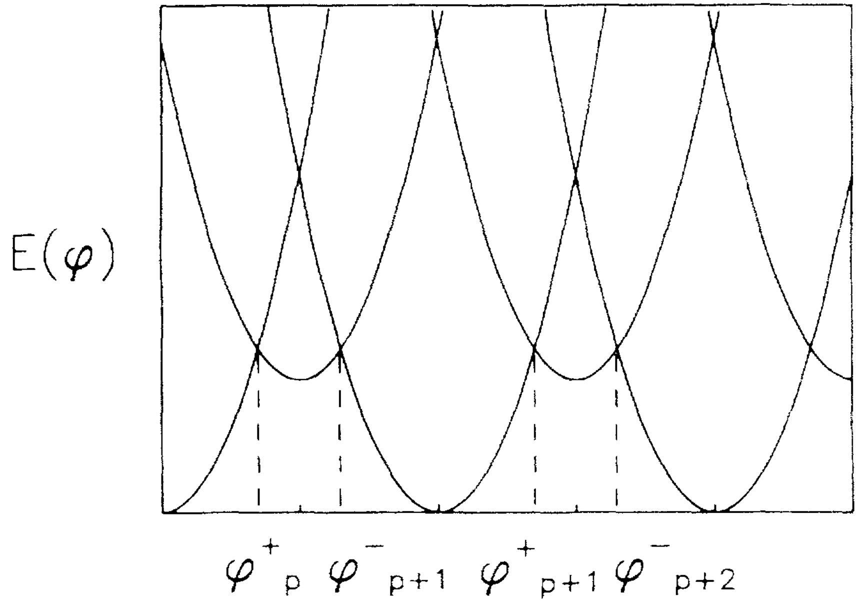
and Institute of Nuclear Physics, Moscow State University, Moscow 119899 GSP, Russia

(Received 3 March 1992)

We have calculated the quasiparticle current through a superconducting island in the Coulomb blockade regime. The current depends strongly on the parity of the total number of free electrons in the island. This dependence reflects the difference between ground-state properties of the superconductor with even and with odd number of electrons.

PACS numbers: 73.40.Gk, 72.10.Bg, 74.20.Fg

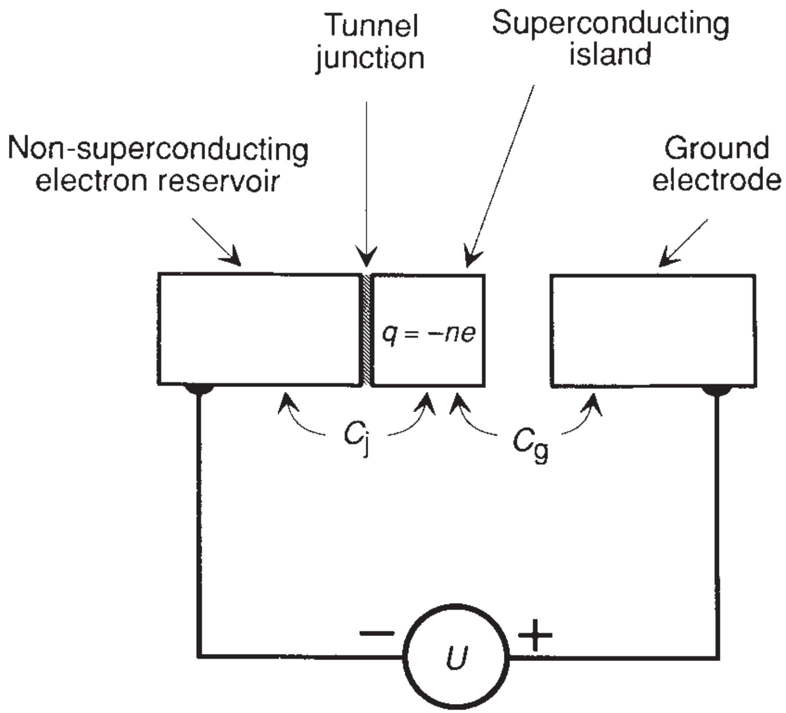


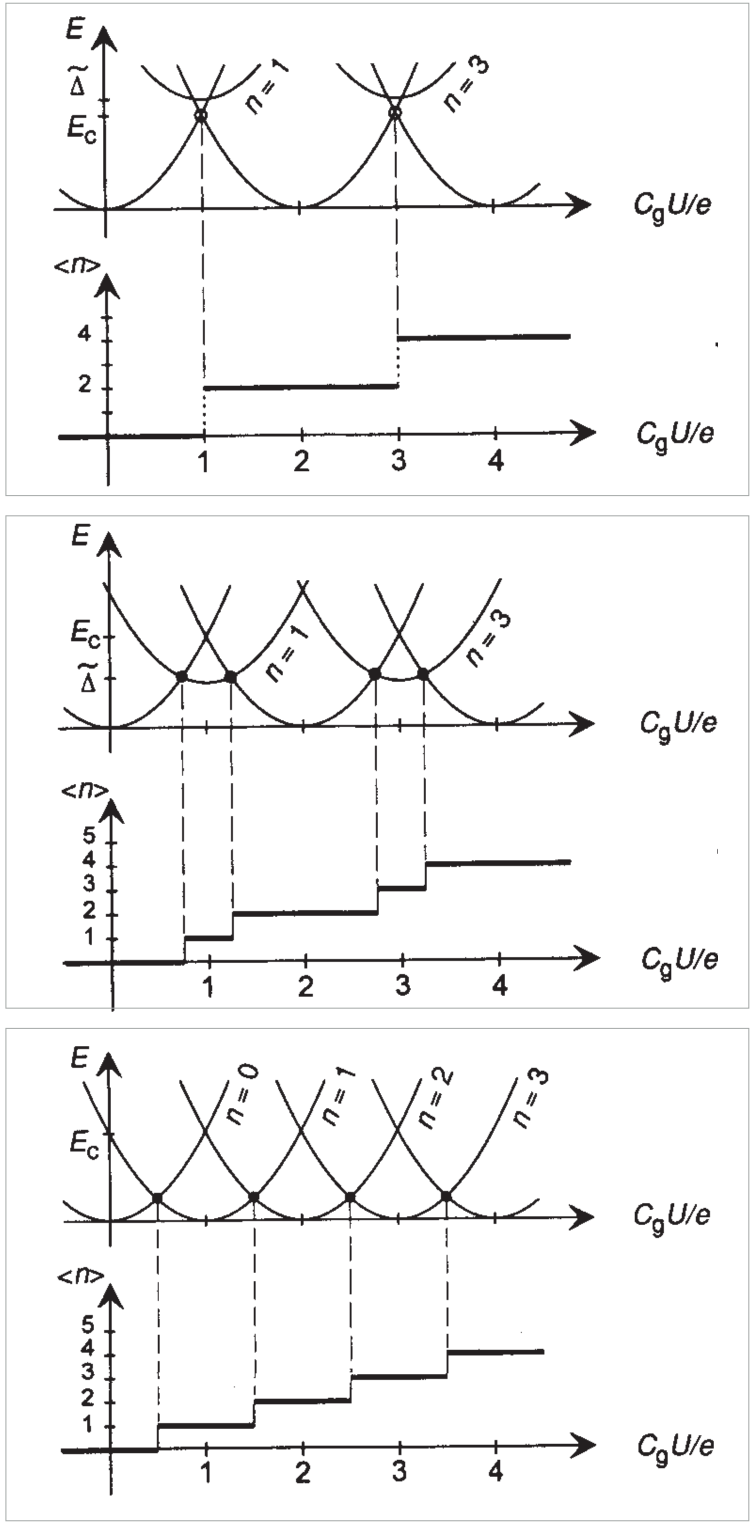


NATURE · VOL 365 · 30 SEPTEMBER 1993

Two-electron quantization of the charge on a superconductor

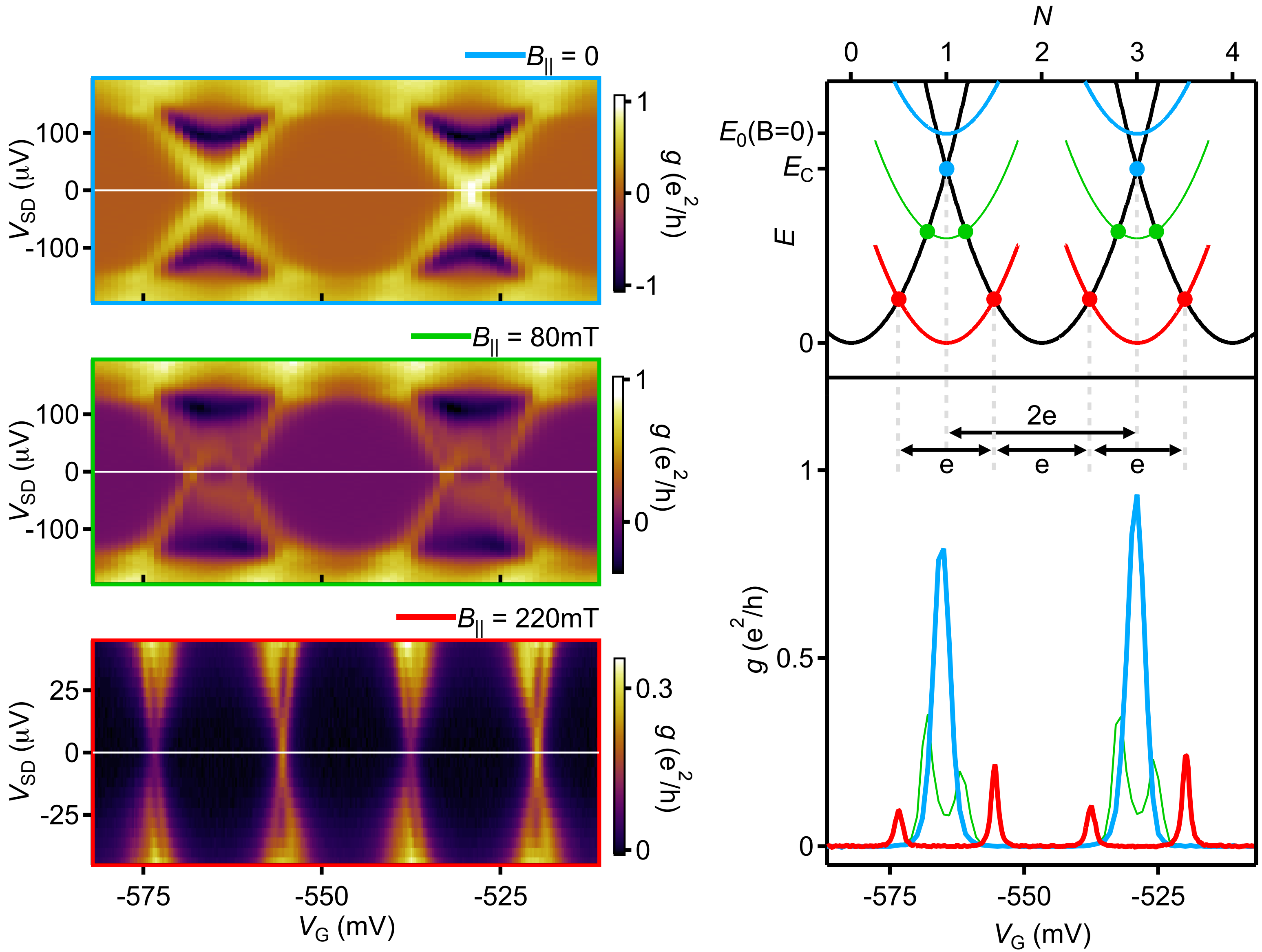
P. Lafarge, P. Joyez, D. Esteve, C. Urbina & M. H. Devoret





Exponential protection of zero modes in Majorana islands

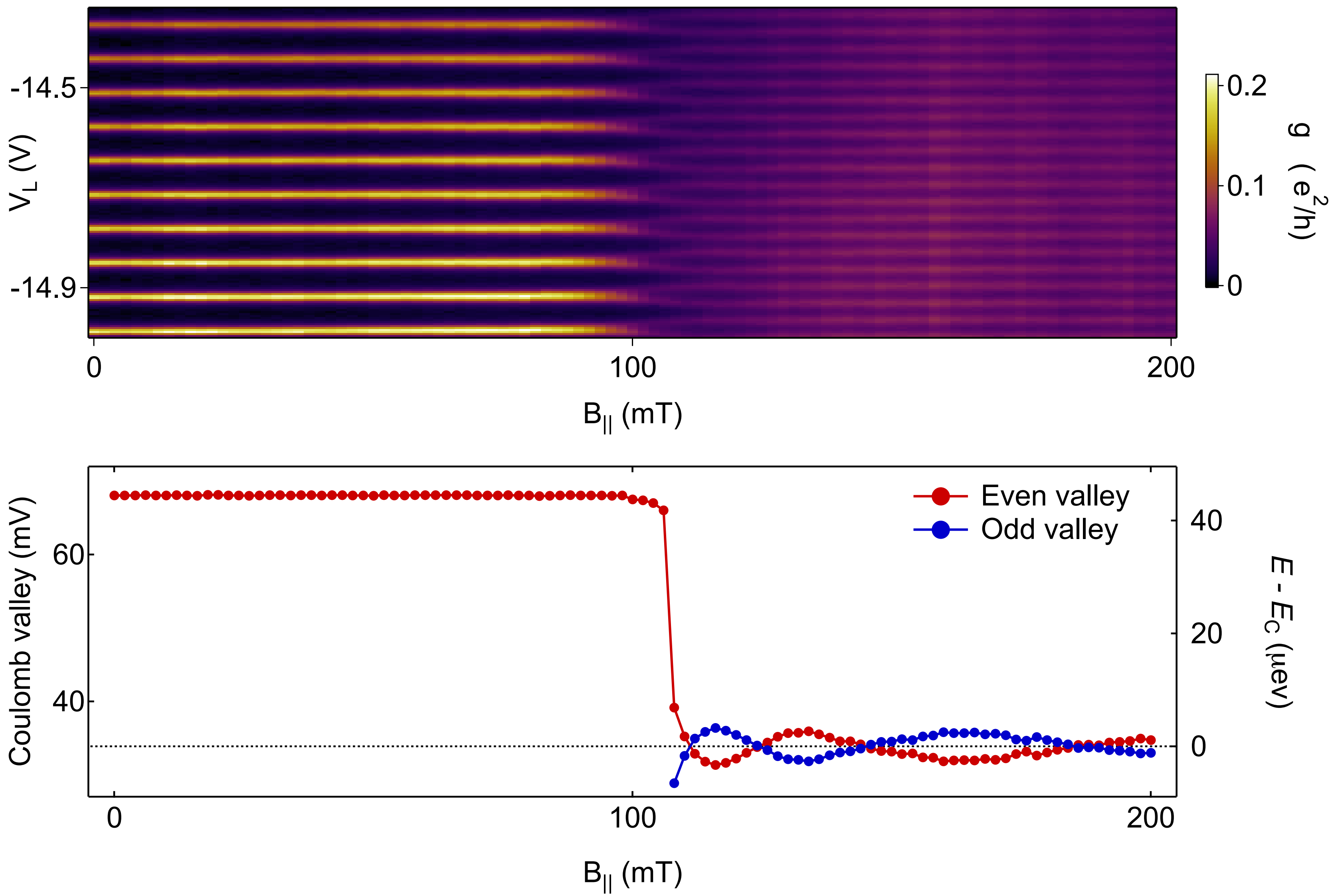
S. M. Albrecht[1]*, A. P. Higginbotham[1,2]*, M. Madsen[1], F. Kuemmeth[1], T. S. Jespersen[1], J. Nygård[1], P. Krogstrup[1] & C. M. Marcus[1]



206 | NATURE | VOL 531 | 10 MARCH 2016

Exponential protection of zero modes in Majorana islands

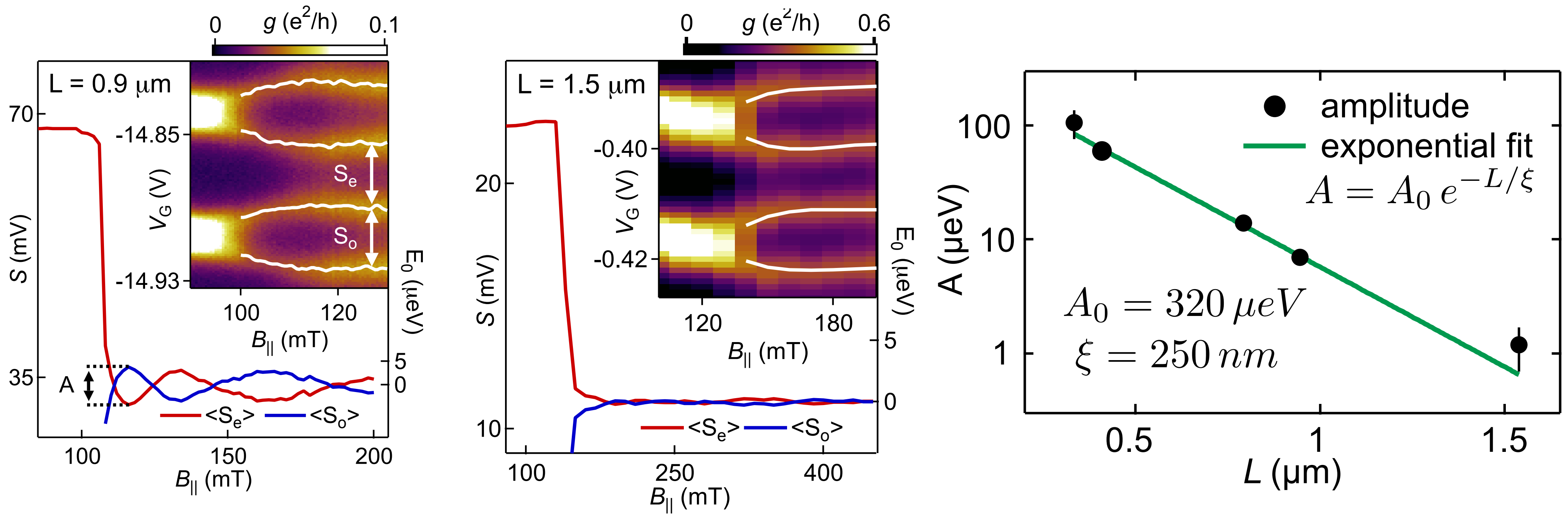
S. M. Albrecht[1]*, A. P. Higginbotham[1,2]*, M. Madsen[1], F. Kuemmeth[1], T. S. Jespersen[1], J. Nygård[1], P. Krogstrup[1] & C. M. Marcus[1]



206 | NATURE | VOL 531 | 10 MARCH 2016

Exponential protection of zero modes in Majorana islands

S. M. Albrecht[1]*, A. P. Higginbotham[1,2]*, M. Madsen[1], F. Kuemmeth[1], T. S. Jespersen[1], J. Nygård[1], P. Krogstrup[1] & C. M. Marcus[1]



Conclusions

- Exponential convergence to zero-energy mode with 1/4-micron characteristic length.
- Zero modes located at ends of wire.

PHYSICAL REVIEW B **93**, 235431 (2016)

Conductance of a proximitized nanowire in the Coulomb blockade regime

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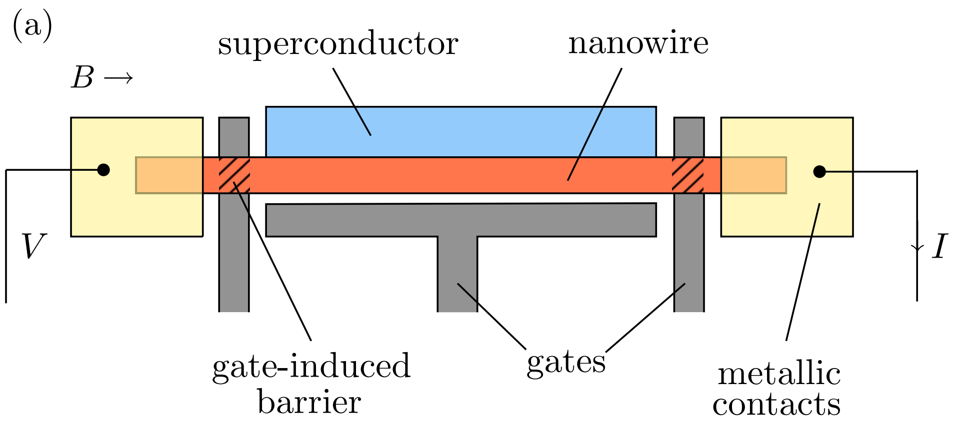
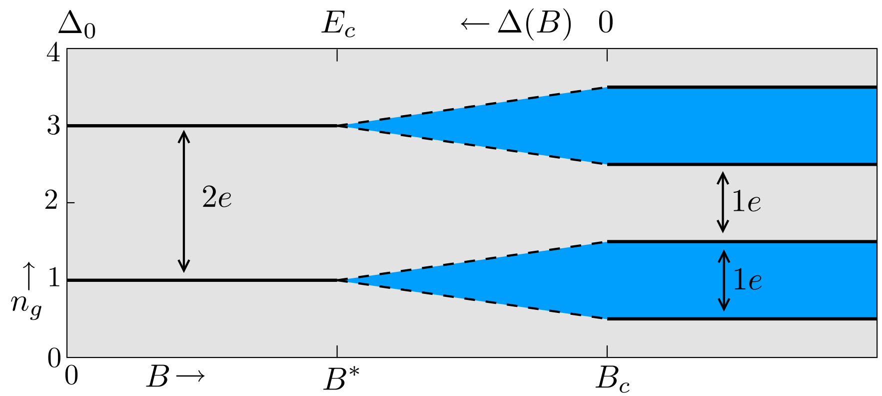
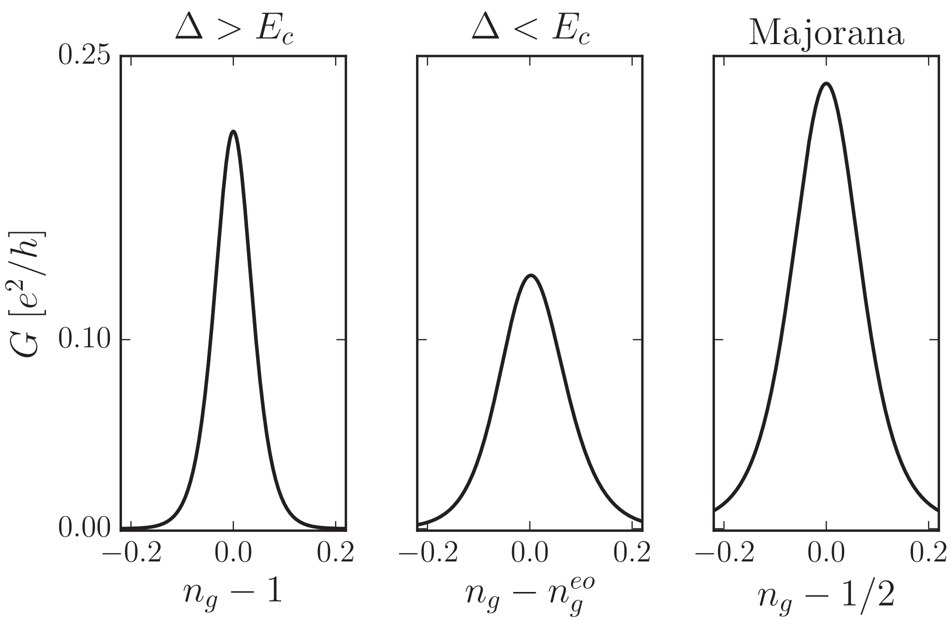
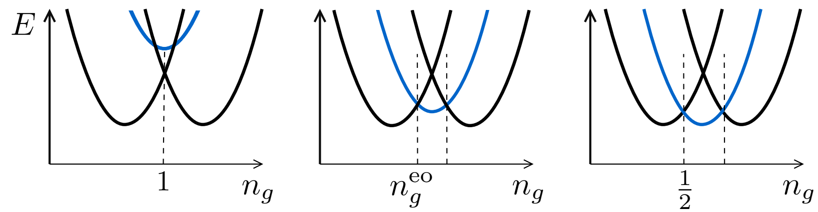
(Received 31 March 2016; published 20 June 2016)









Thus, we find that in the Majorana regime (c) the position of the Coulomb blockade peaks, even if those are thermally broadened, can be used as a sensitive probe of the ground-state degeneracy splitting due to a finite length of a nanowire. In this sense, our finding corroborates the conclusions of Ref. [44].

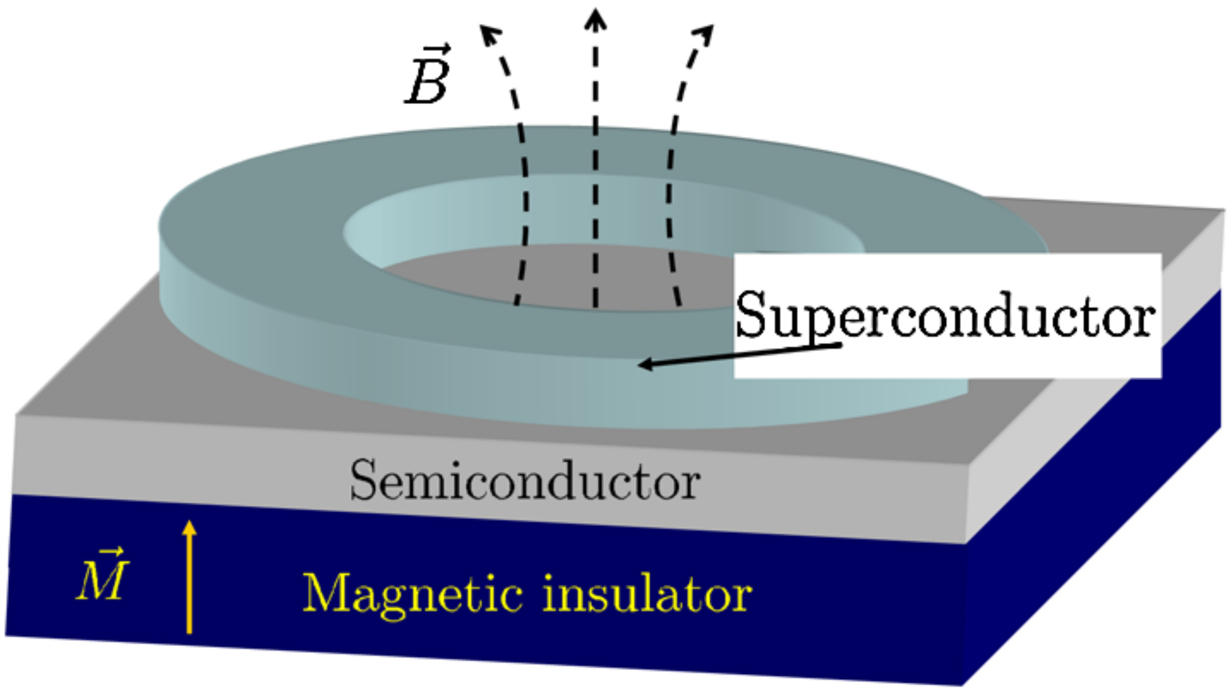
Generic New Platform for Topological Quantum Computation Using Semiconductor Heterostructures

Jay D. Sau,[1] Roman M. Lutchyn,[1] Sumanta Tewari,[1,2] and S. Das Sarma[1]

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

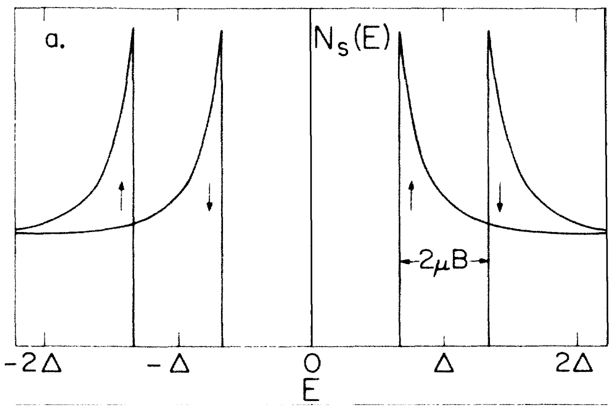
[2]*Department of Physics and Astronomy, Clemson University, Clemson, South Carolina 29634, USA*

(Received 17 July 2009; published 27 January 2010)



Spin-Polarized Electron Tunneling Study of an Artificially Layered Superconductor with Internal Magnetic Field: EuO-Al

P. M. Tedrow and J. E. Tkaczyk
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
and
A. Kumar
Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 3 February 1986)



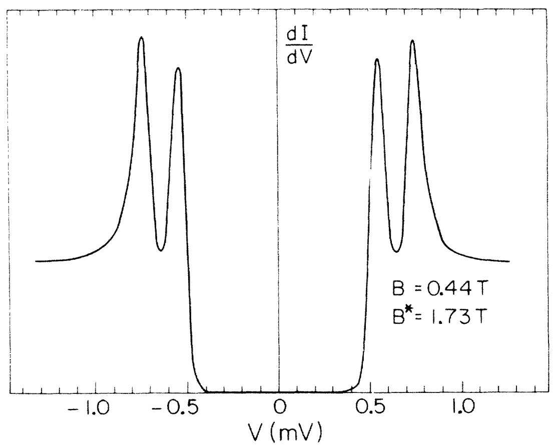


FIG. 2. Measured tunneling conductance vs voltage for an EuO-Al/Al_2O_3/Al junction with an applied field of 0.44 T and a voltage splitting equivalent to 1.73 T.

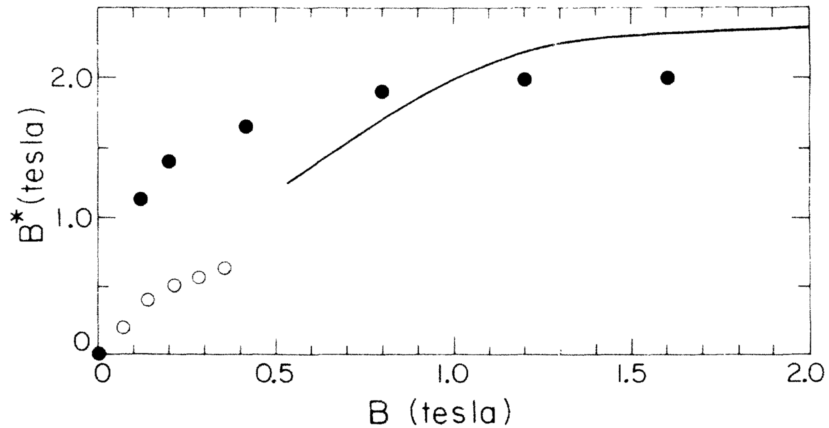


FIG. 3. Observed values of B^* vs applied field B for two EuO-Al films. The magnetization $\mu_0 M$ for EuO from Ref. 8 is shown by the solid line.

Thin-Film Superconductor in an Exchange Field

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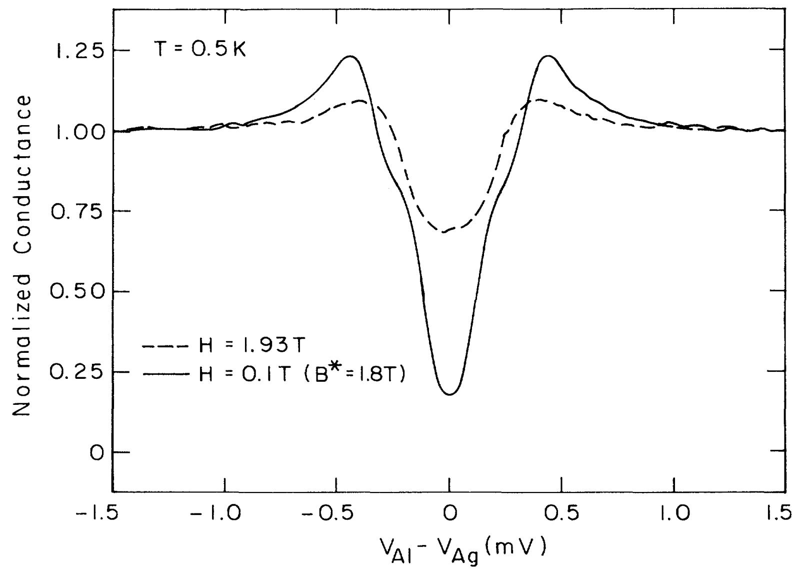
(Received 14 December 1990)

Using the technique of spin-polarized tunneling, we studied tunnel junctions with EuS/Al bilayer electrodes. We found a large effective internal field in the Al film, which gives rise to extra Zeeman splitting in the superconducting quasiparticle density of states and which is attributed to the exchange interaction between the Eu ions and the Al conduction electrons. This exchange field, acting only on the electron spins, is inversely proportional to the thickness of the Al, causes no observable orbital depairing in the Al, and leads to a first-order transition to the normal state.



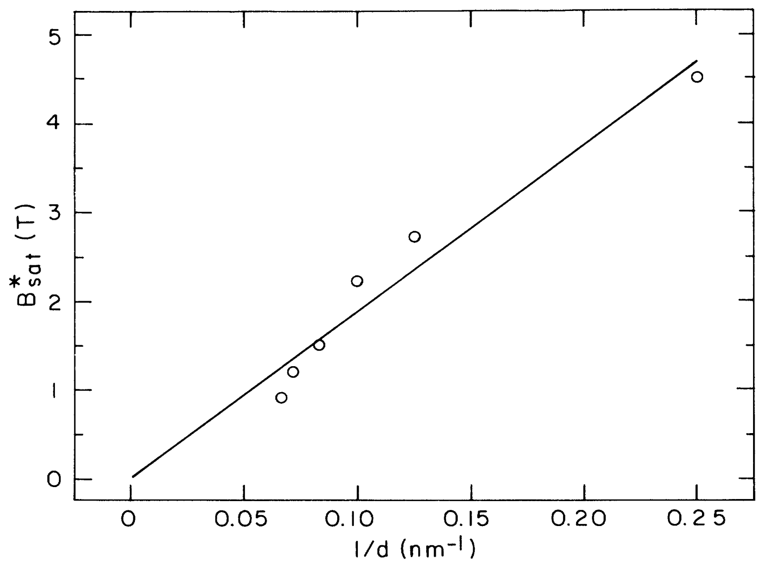


FIG. 4. The dependence of the saturation internal field on the Al film thickness.

PHYSICAL REVIEW MATERIALS **1**, 054402 (2017)

Revealing the magnetic proximity effect in EuS/Al bilayers through superconducting tunneling spectroscopy

E. Strambini,[1,*] V. N. Golovach,[2,3,4] G. De Simoni,[1] J. S. Moodera,[5] F. S. Bergeret,[2,3,†] and F. Giazotto[1,‡]

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[2]*Centro de Fisica de Materiales (CFM-MPC), Centro Mixto CSIC-UPV/EHU, Manuel de Lardizabal 5, E-20018 San Sebastian, Spain*

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[5]*Department of Physics and Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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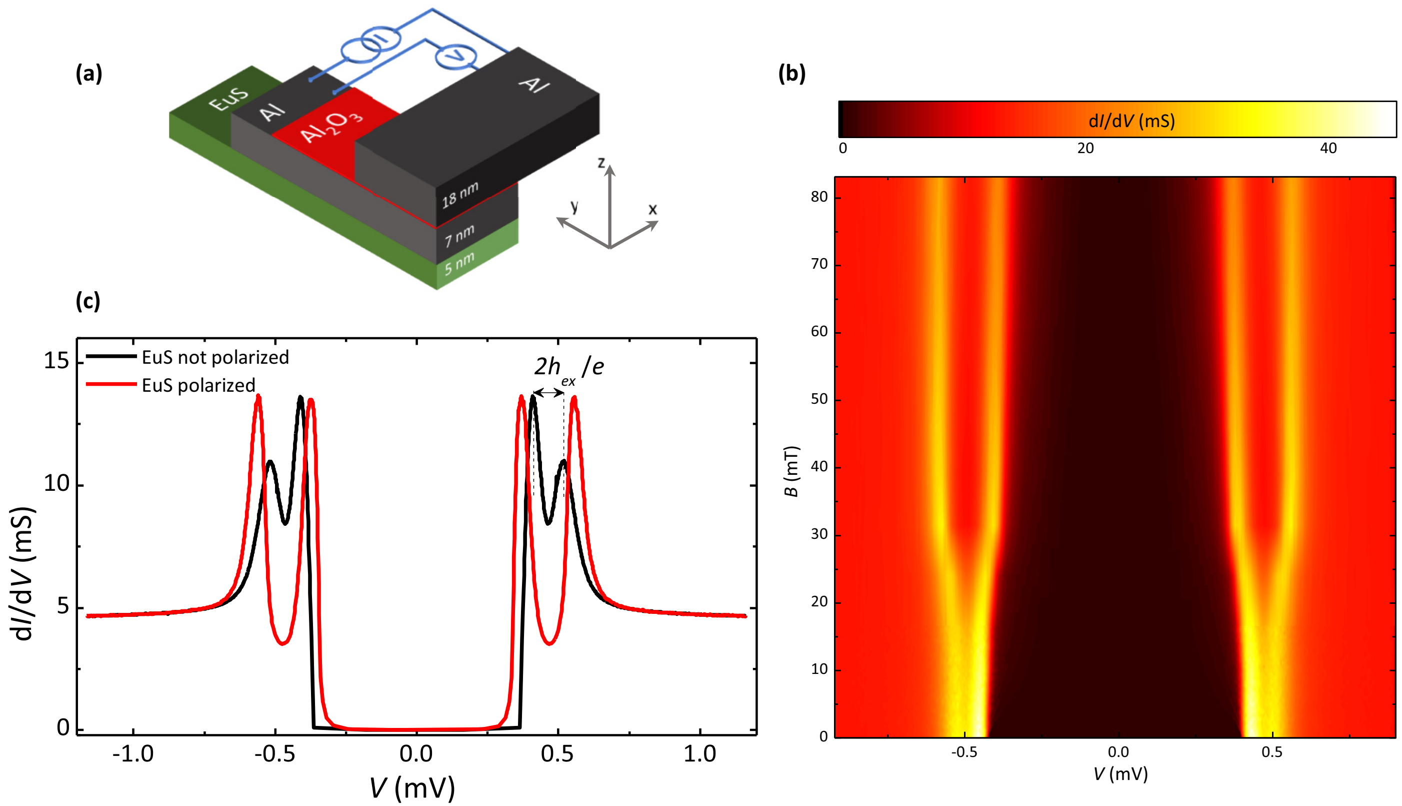
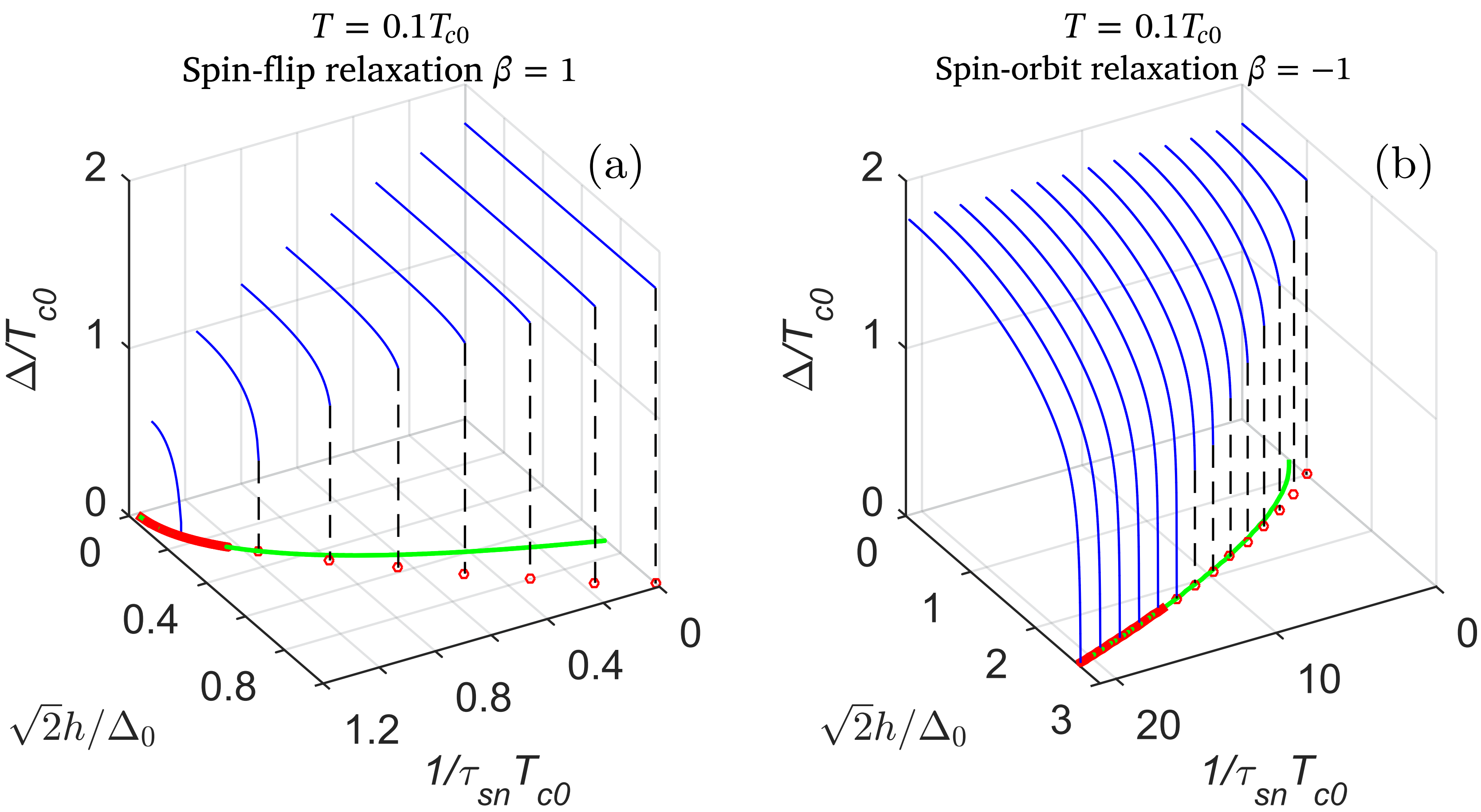


FIG. 1. Junction layout and tunneling spectroscopy of the first magnetization. (a) Sketch of the cross bar forming the EuS(5)/Al(7)/Al_2O_3/Al(18) vertical tunnel junction (the thickness is in nanometers). The area of the junction is a square of 290 × 290 μm^2. (b) Evolution of the differential conductance, obtained from the numerical derivative of the I-V curves, as a function of the voltage drop (V) and in-plane magnetic field (B) during the first magnetization of the EuS layer. (c) Comparison between the differential conductance of the tunnel junction measured at zero field before (black curve) and after (red curve) the magnetization of the EuS layer. All the measurements were taken at 25 mK.

Progress in Surface Science 94 (2019) 100540

Thermal, electric and spin transport in superconductor/ferromagnetic-insulator structures

Tero T. Heikkilä[a,*], Mikhail Silaev[a], Pauli Virtanen[a,b], F. Sebastian Bergeret[c,d,*]



$$\tau_{sn} = 1/(\tau_{sf}^{-1} + \tau_{so}^{-1})$$
$$\beta = (\tau_{\rm so} - \tau_{\rm sf})/(\tau_{\rm so} + \tau_{\rm sf})$$

Signature of a pair of Majorana zero modes in superconducting gold surface states

Sujit Manna[a,b,1], Peng Wei[c,1,2], Yingming Xie[d], Kam Tuen Law[d], Patrick A. Lee[a,2], and Jagadeesh S. Moodera[a,e,f,2]

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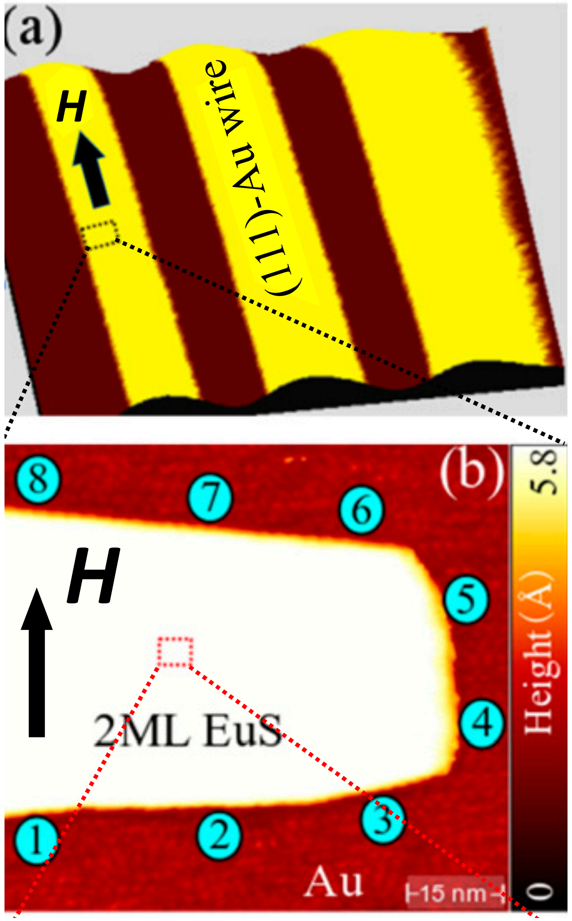
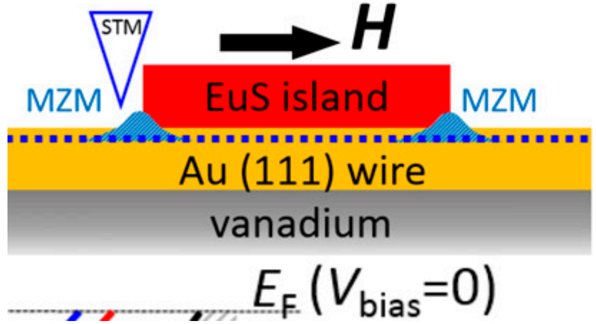
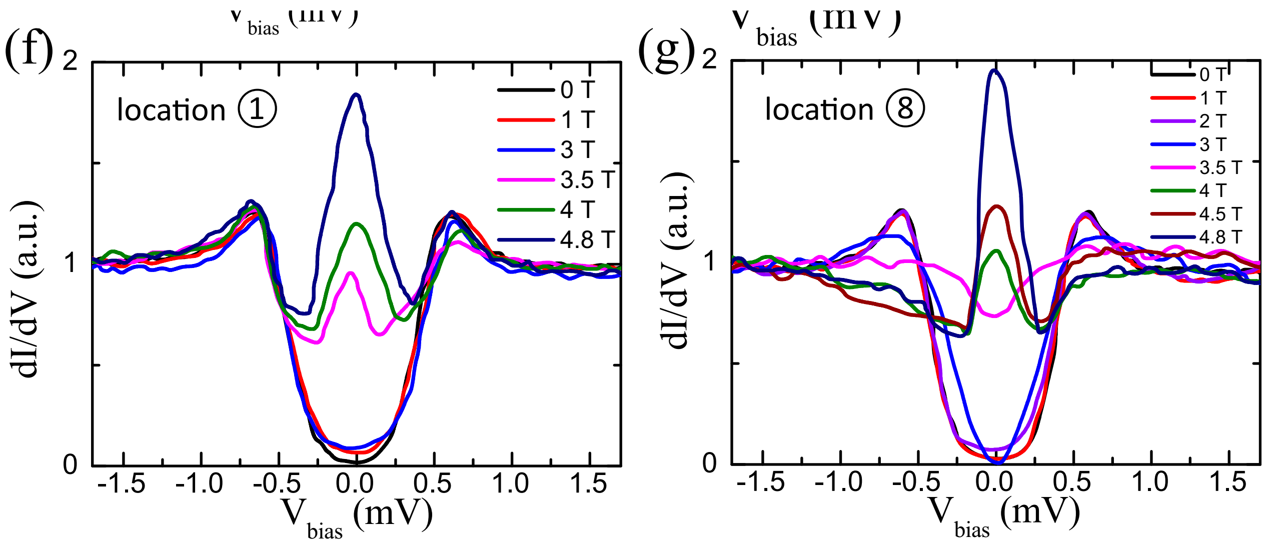


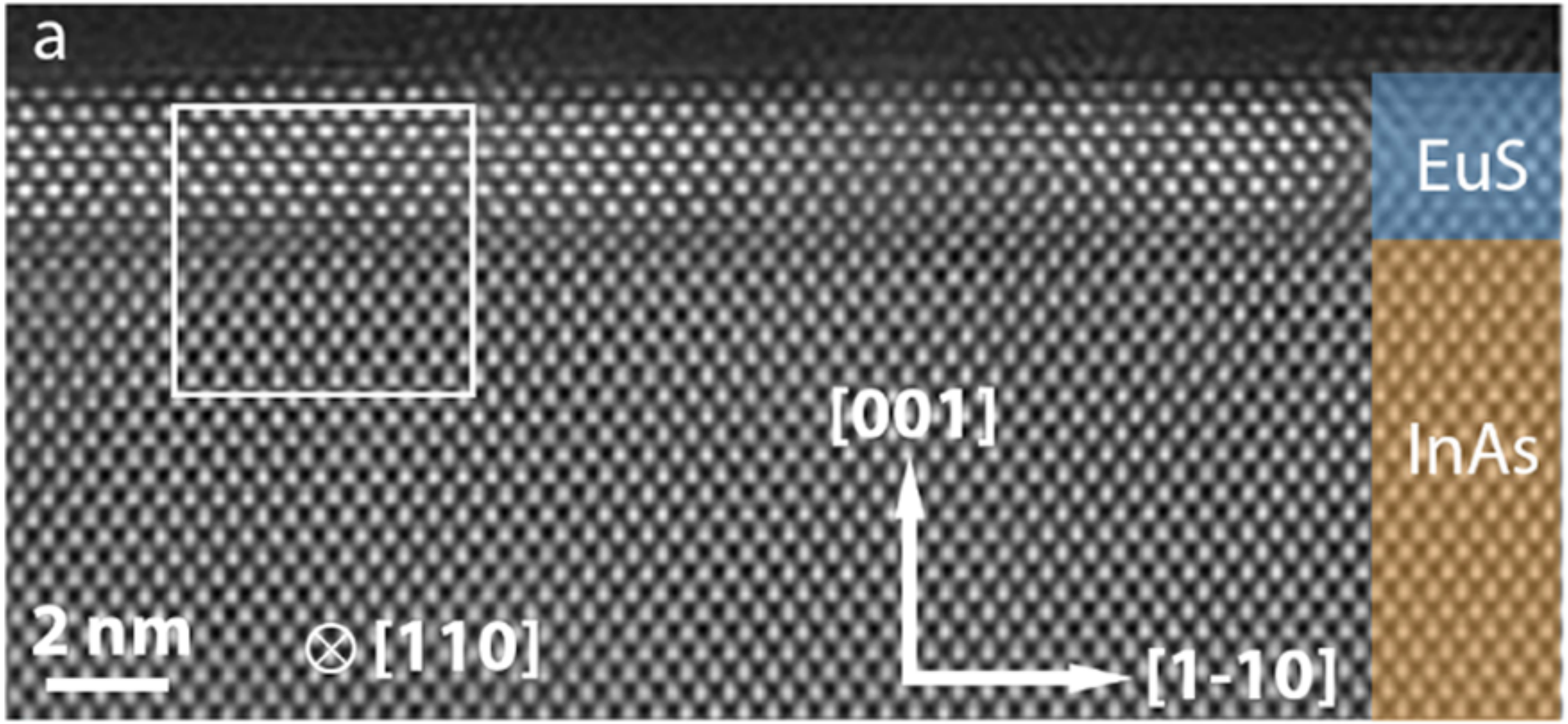




ACS APPLIED MATERIALS & INTERFACES

Coherent Epitaxial Semiconductor–Ferromagnetic Insulator InAs/EuS Interfaces: Band Alignment and Magnetic Structure

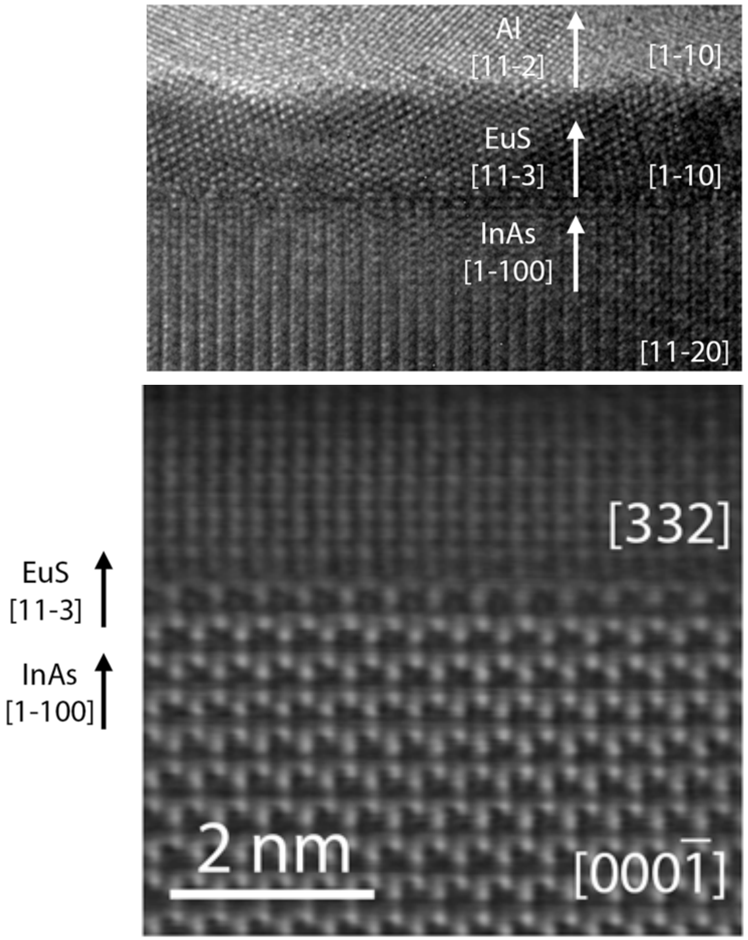
Yu Liu, Alessandra Luchini, Sara Martí-Sánchez, Christian Koch, Sergej Schuwalow, Sabbir A. Khan, Tomaš Stankevič, Sonia Francoual, Jose R. L. Mardegan, Jonas A. Krieger, Vladimir N. Strocov, Jochen Stahn, Carlos A. F. Vaz, Mahesh Ramakrishnan, Urs Staub, Kim Lefmann, Gabriel Aeppli, Jordi Arbiol, and Peter Krogstrup*

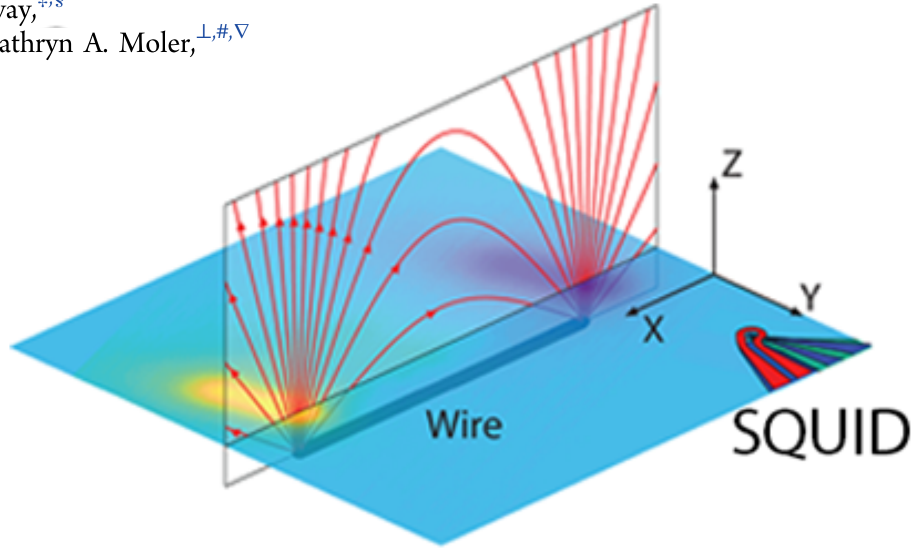


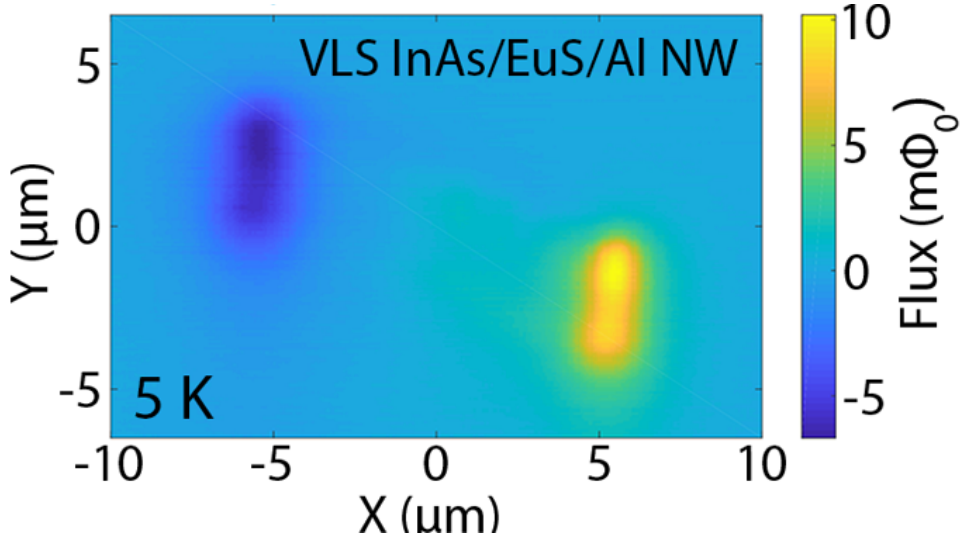
NANO LETTERS
Letter
Cite This: Nano Lett. 2020, 20, 456−462
pubs.acs.org/NanoLett

Semiconductor−Ferromagnetic Insulator−Superconductor Nanowires: Stray Field and Exchange Field

Yu Liu,[†,‡] Saulius Vaitiekėnas,[‡,§] Sara Martí-Sánchez,[∥] Christian Koch,[∥] Sean Hart,[⊥,#] Zheng Cui,[⊥,∇] Thomas Kanne,[‡] Sabbir A. Khan,[†,‡] Rawa Tanta,[†,‡] Shivendra Upadhyay,[‡,§] Martin Espiñeira Cachaza,[†,‡] Charles M. Marcus,[‡,§] Jordi Arbiol,[∥,○] Kathryn A. Moler,[⊥,#,∇] and Peter Krogstrup*[,†,‡]







NANO LETTERS
Letter
Cite This: Nano Lett. 2020, 20, 456–462
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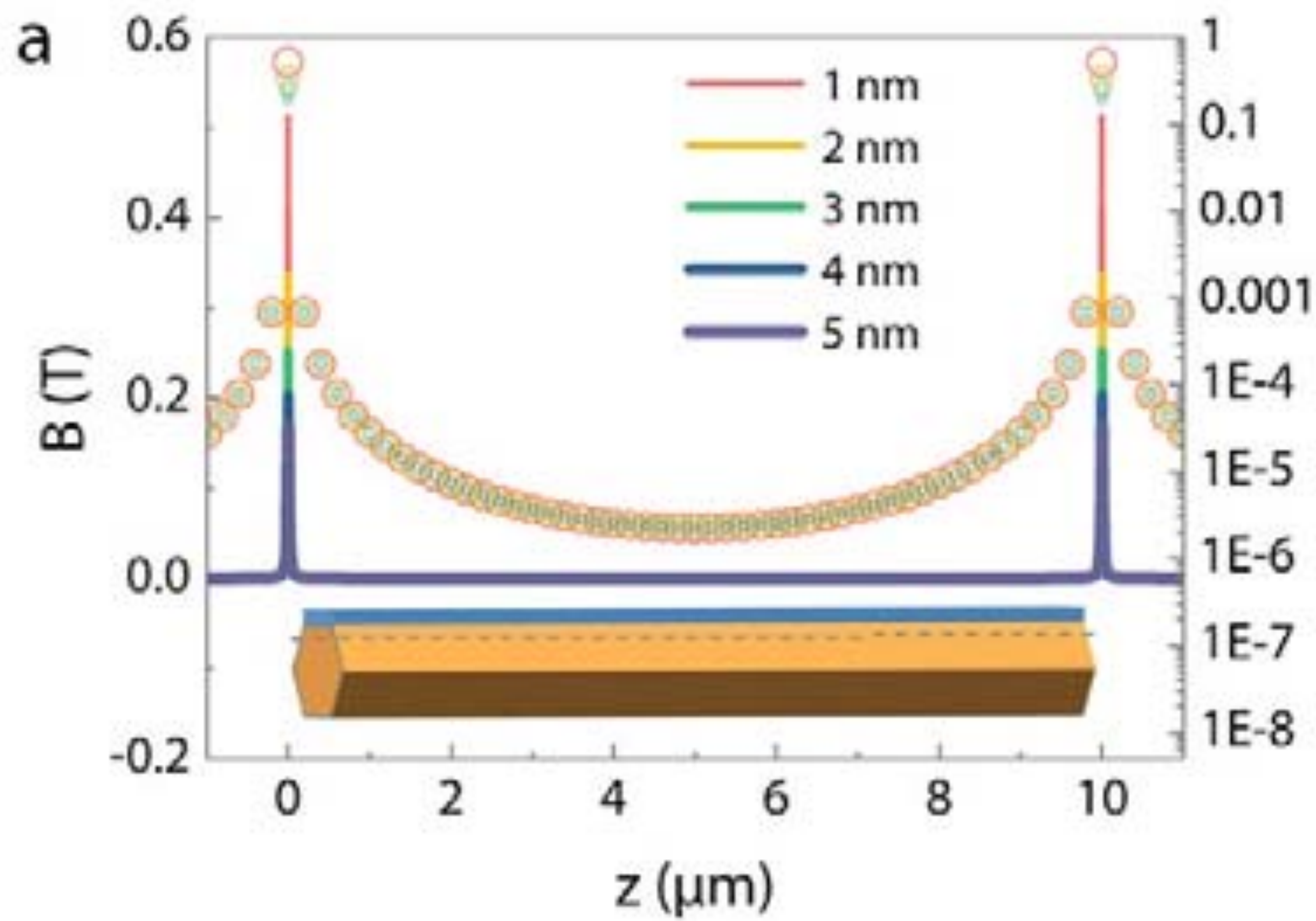
Semiconductor–Ferromagnetic Insulator–Superconductor Nanowires: Stray Field and Exchange Field

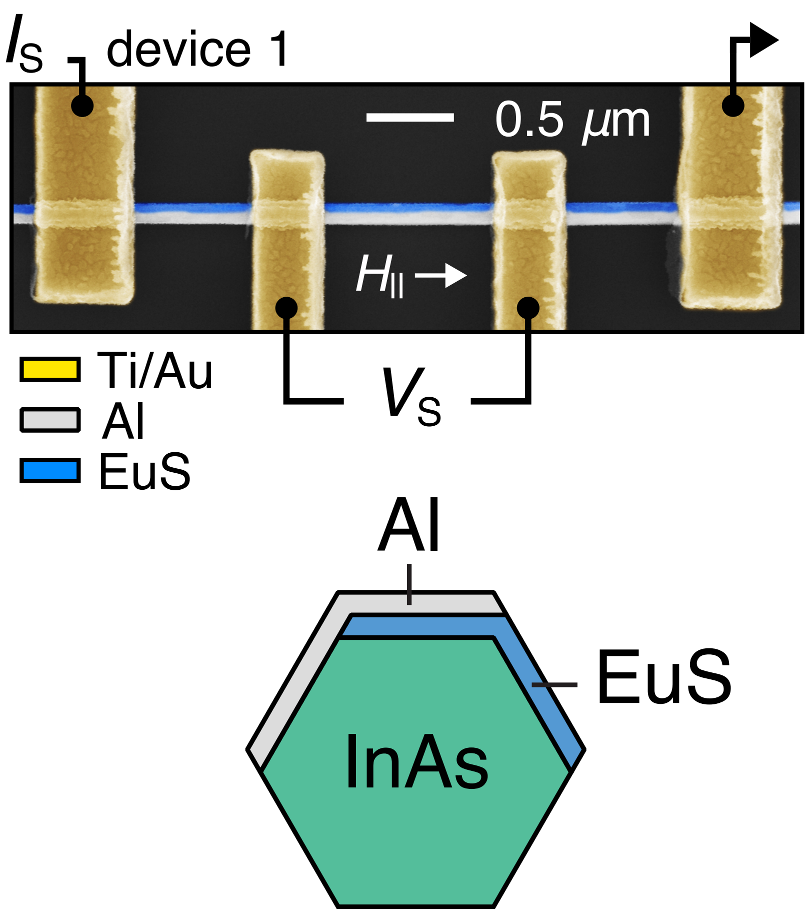
Yu Liu,[†,‡] Saulius Vaitiekėnas,[‡,§] Sara Martí-Sánchez,[∥] Christian Koch,[∥] Sean Hart,[⊥,#] Zheng Cui,[⊥,∇] Thomas Kanne,[‡] Sabbir A. Khan,[†,‡] Rawa Tanta,[†,‡] Shivendra Upadhyay,[‡,§] Martin Espiñeira Cachaza,[†,‡] Charles M. Marcus,[‡,§] Jordi Arbiol,[∥,○] Kathryn A. Moler,[⊥,#,∇] and Peter Krogstrup*[,†,‡]

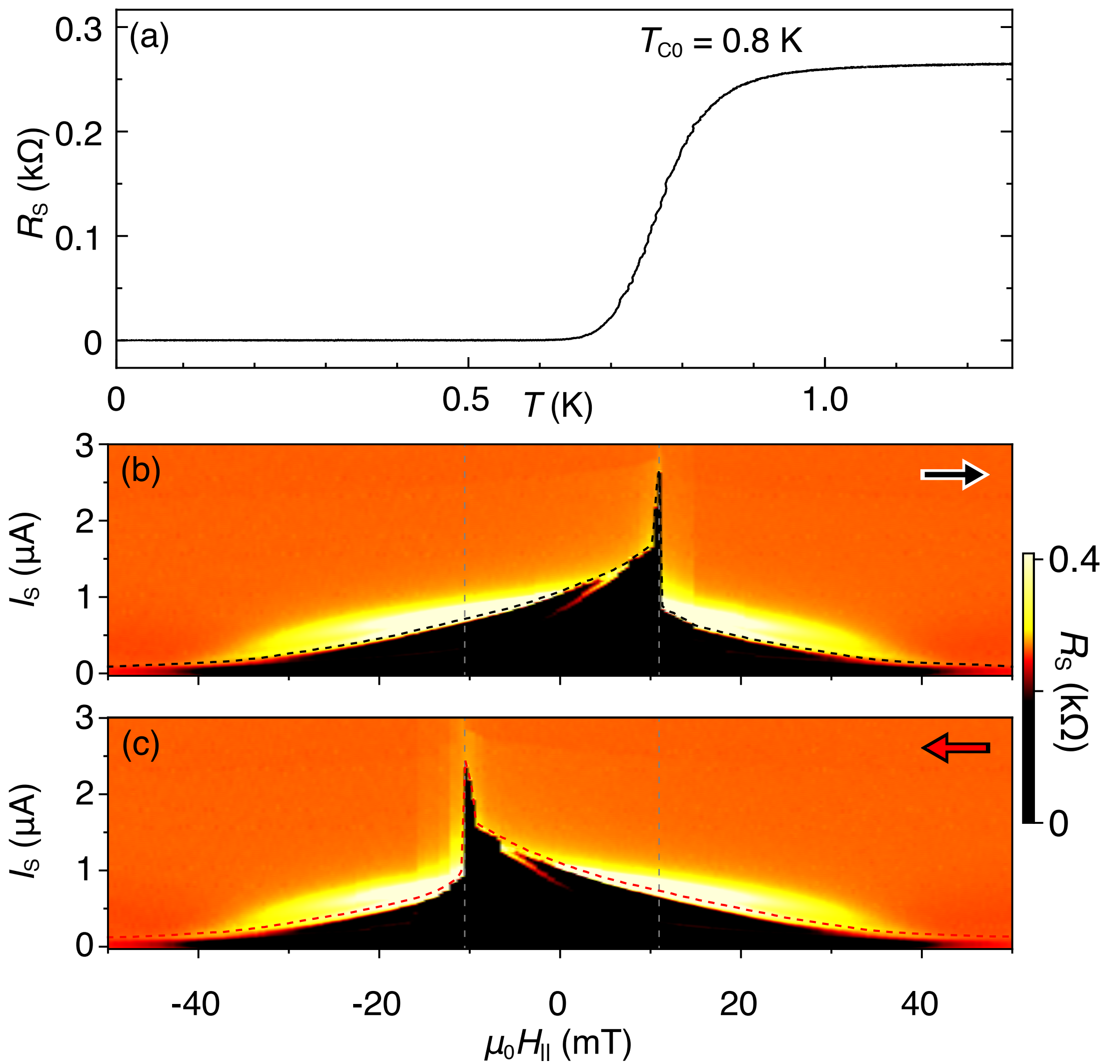


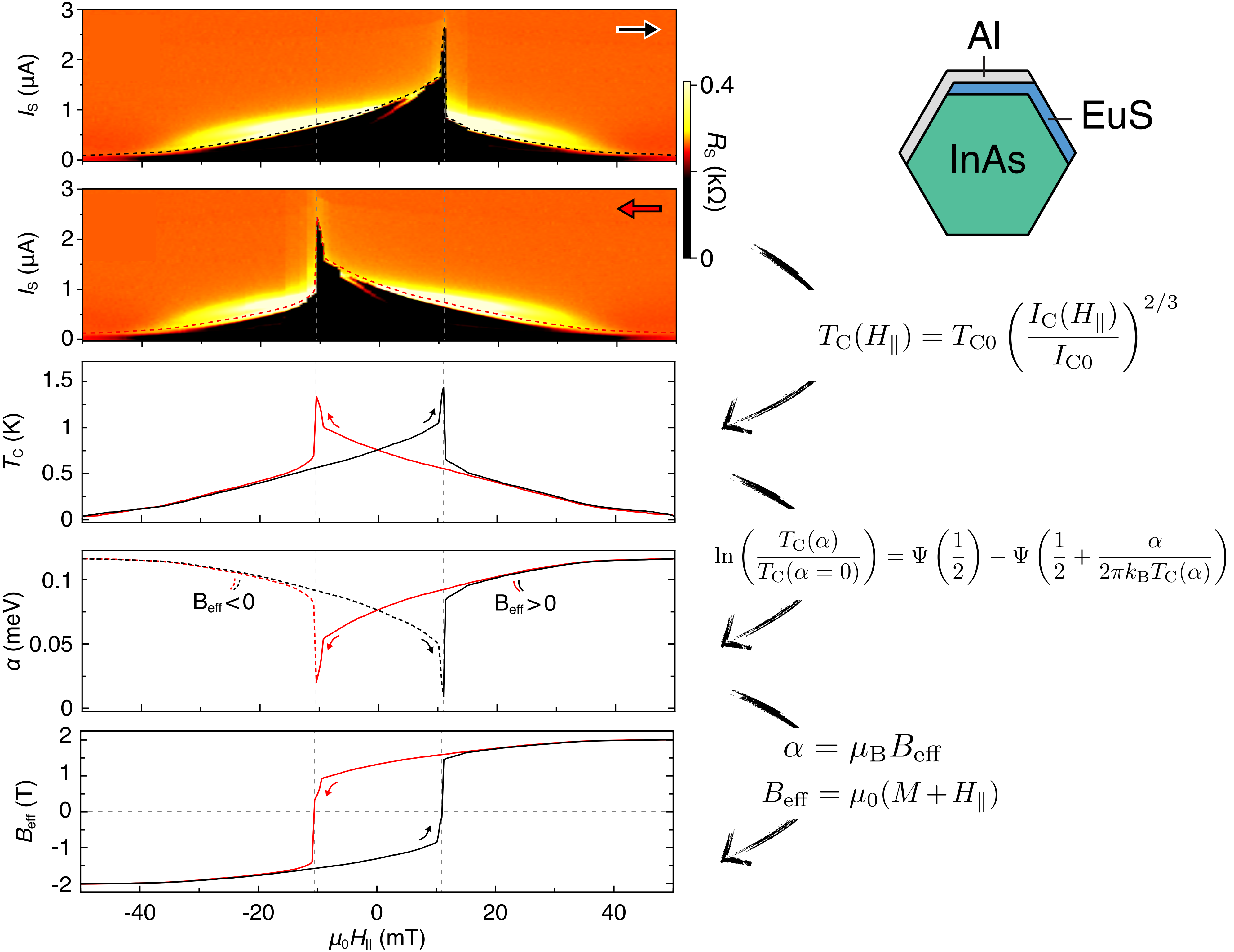
nature physics

Zero-bias peaks at zero magnetic field in ferromagnetic hybrid nanowires

S. Vaitiekėnas[1,2], Y. Liu[1,3], P. Krogstrup[1,3] and C. M. Marcus[1,2]✉





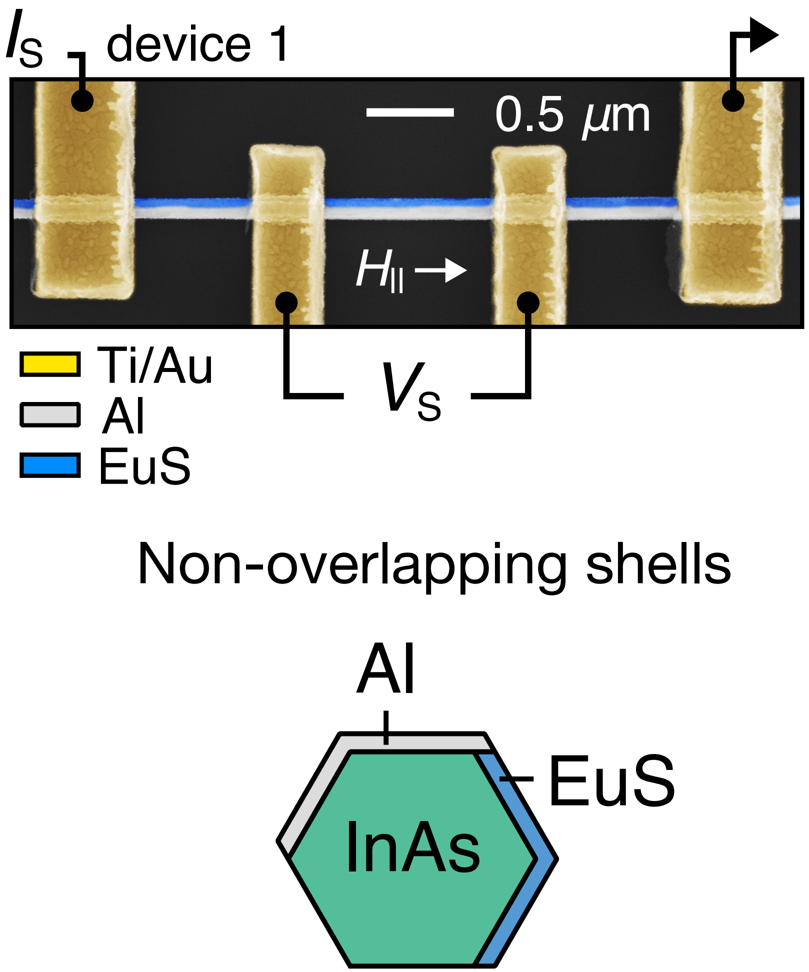


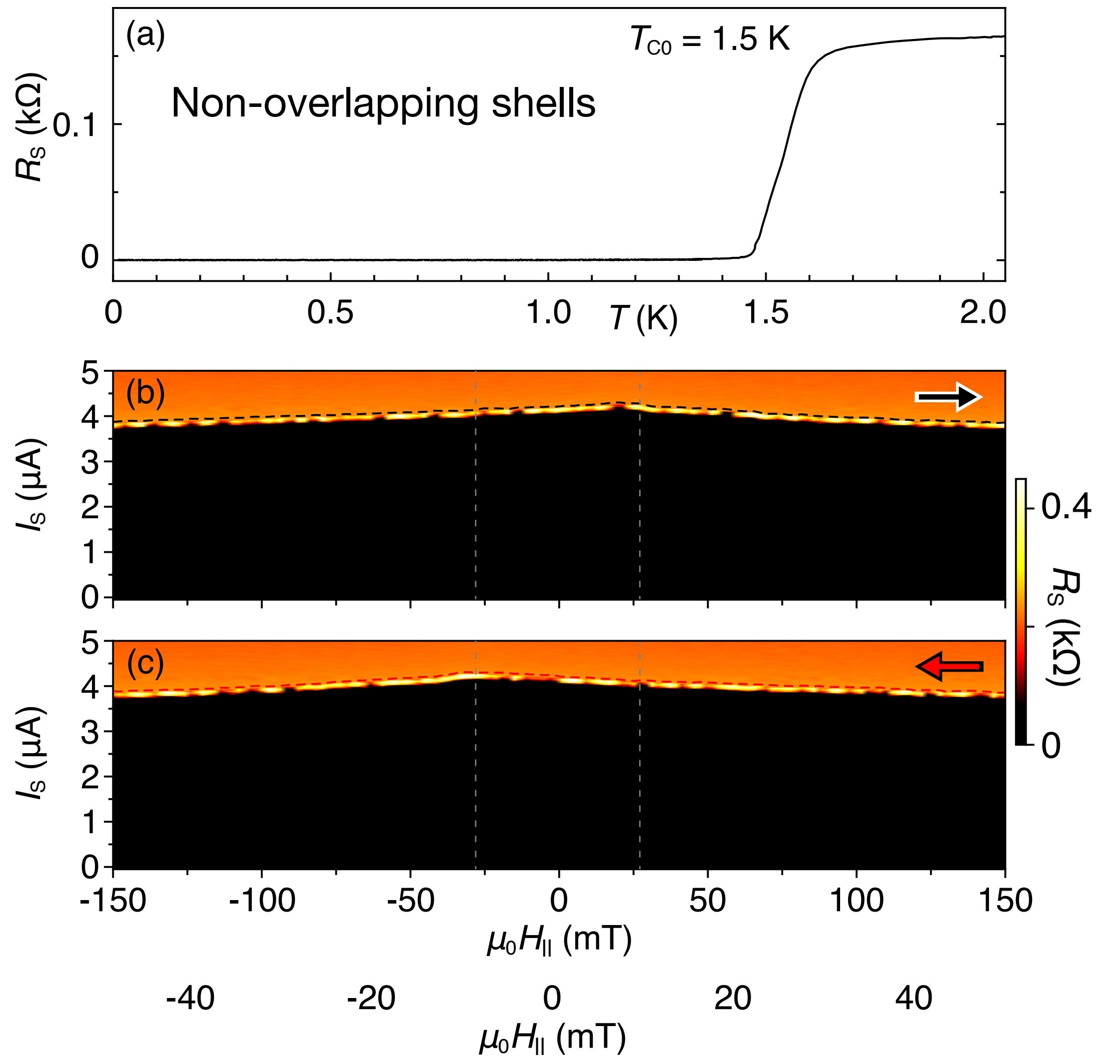
Al
EuS
InAs
I_S (μA)
R_S (kΩ)
0.4
0
T_C (K)
α (meV)
B_{eff} (T)
$B_{eff} < 0$
$B_{eff} > 0$
$\mu_0 H_{\parallel}$ (mT)
$$T_C(H_{\parallel}) = T_{C0}\left(\frac{I_C(H_{\parallel})}{I_{C0}}\right)^{2/3}$$
$$\ln\left(\frac{T_C(\alpha)}{T_C(\alpha=0)}\right) = \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2} + \frac{\alpha}{2\pi k_B T_C(\alpha)}\right)$$
$$\alpha = \mu_B B_{eff}$$
$$B_{eff} = \mu_0(M + H_{\parallel})$$

nature physics

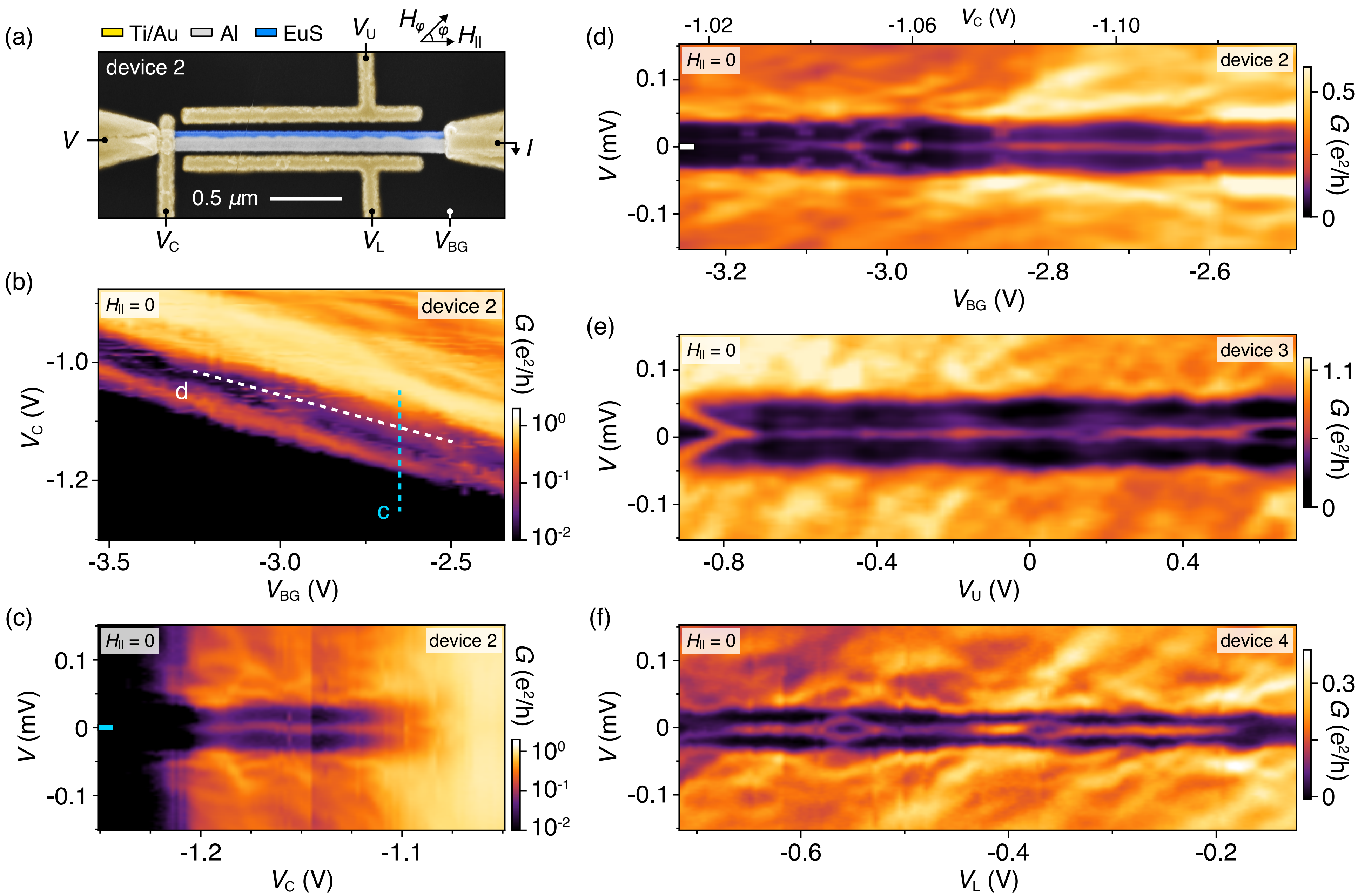
Zero-bias peaks at zero magnetic field in ferromagnetic hybrid nanowires

S. Vaitiekėnas[1,2], Y. Liu[1,3], P. Krogstrup[1,3] and C. M. Marcus[1,2]

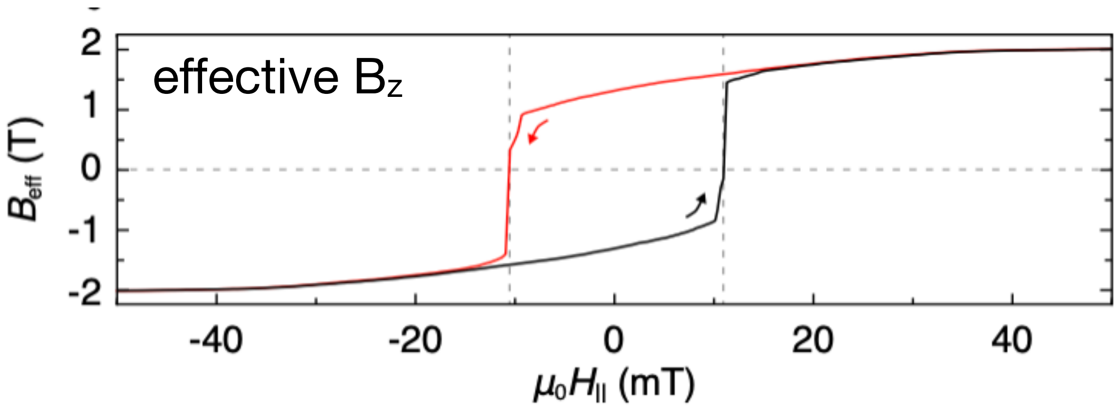


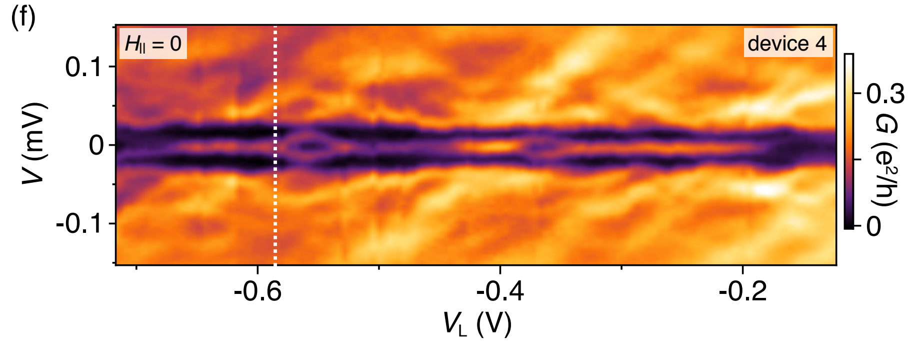


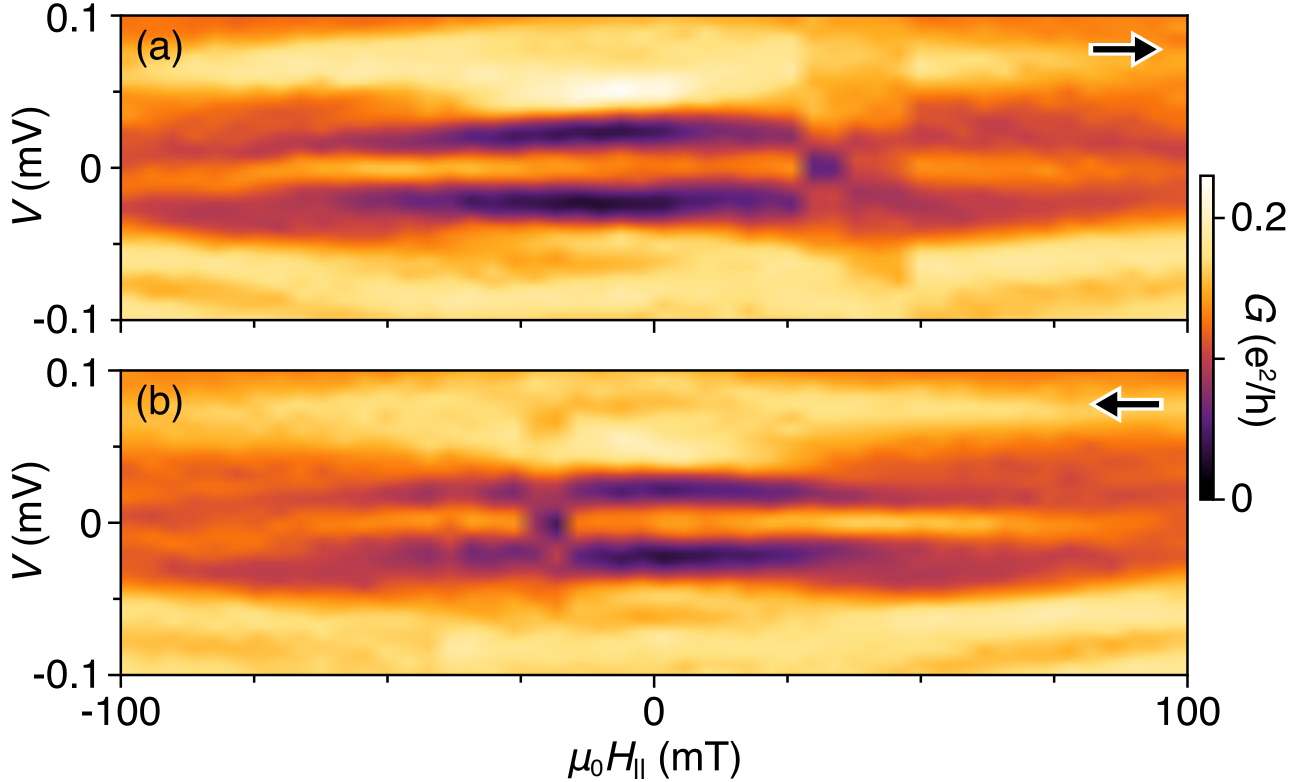
Zero-bias tunneling conductance peaks at zero applied magnetic field



Turning off the ferromagnetic pseudo-Zeeman field removes the zero-bias peak

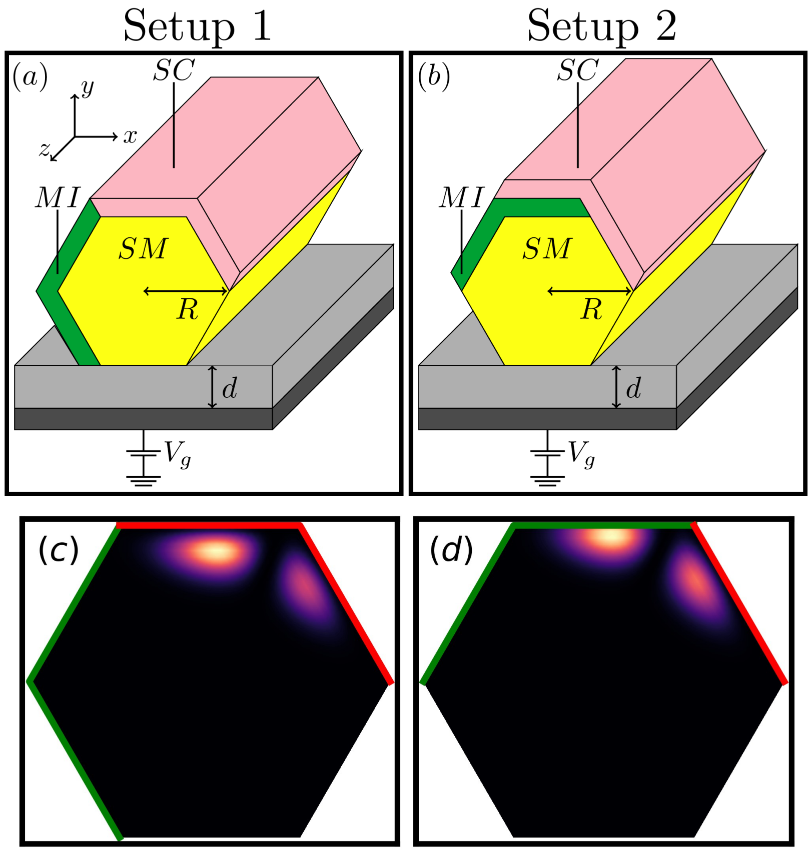


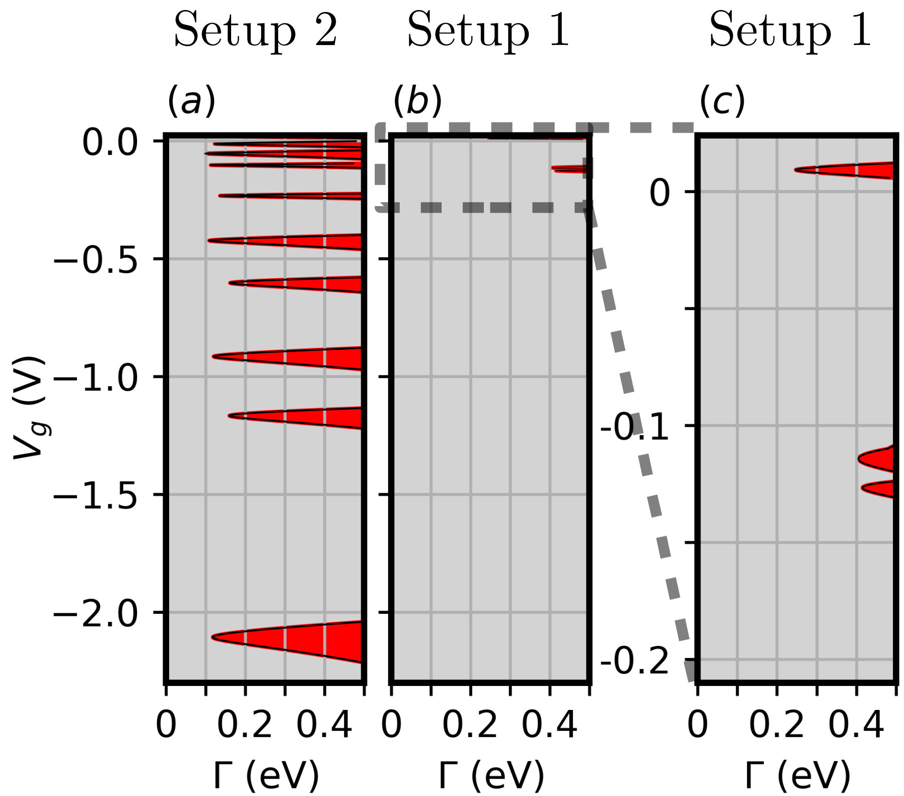




Electrostatic effects and topological superconductivity in semiconductor-superconductor-magnetic insulator hybrid wires

Benjamin D. Woods and Tudor D. Stanescu
Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA





Microscopic analysis of topological superconductivity in ferromagnetic hybrid nanowires

Samuel D. Escribano,[1] Elsa Prada,[2] Yuval Oreg,[3] and Alfredo Levy Yeyati[1]

[1] *Departamento de Física Teórica de la Materia Condensada C5, Condensed Matter Physics Center (IFIMAC) and Instituto Nicolás Cabrera, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

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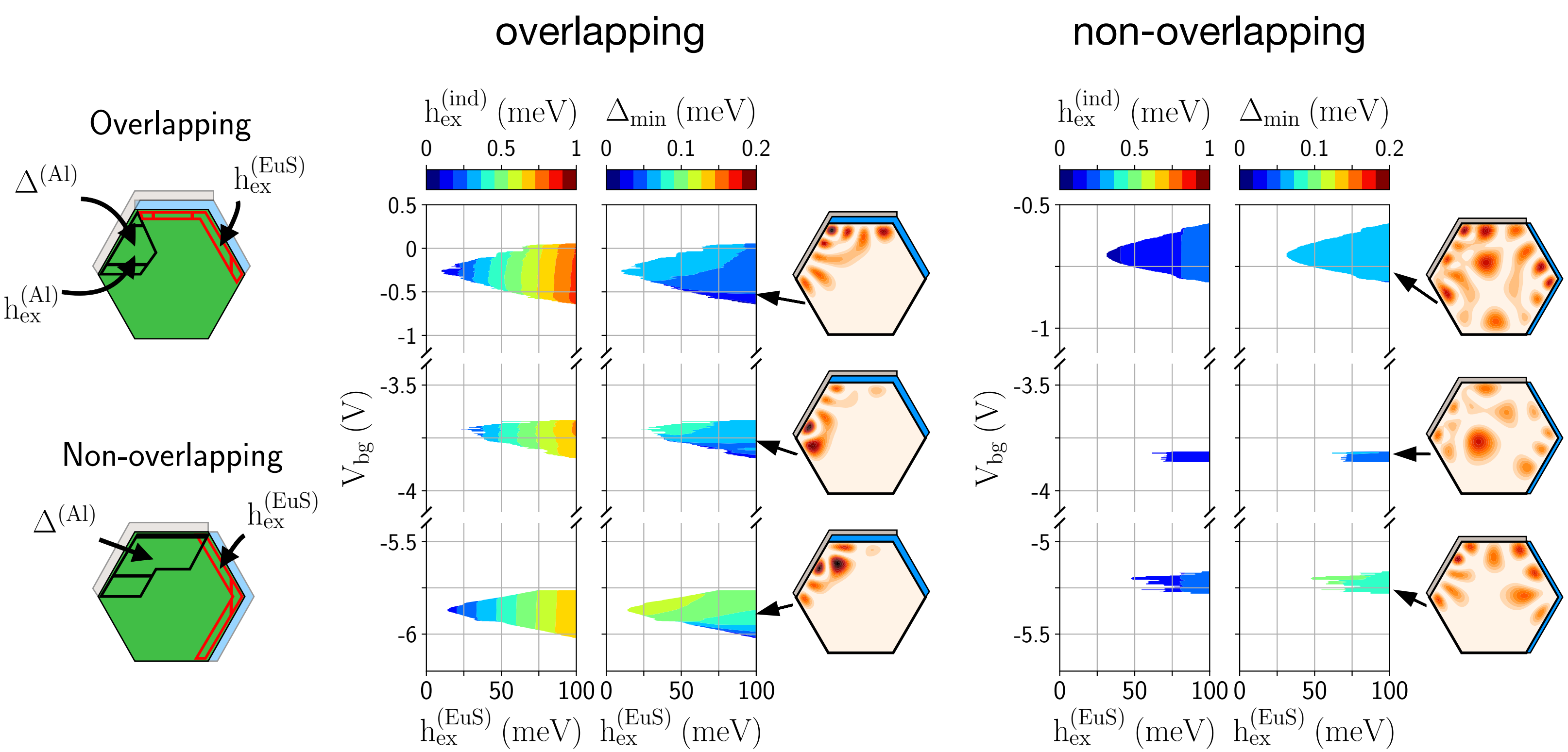
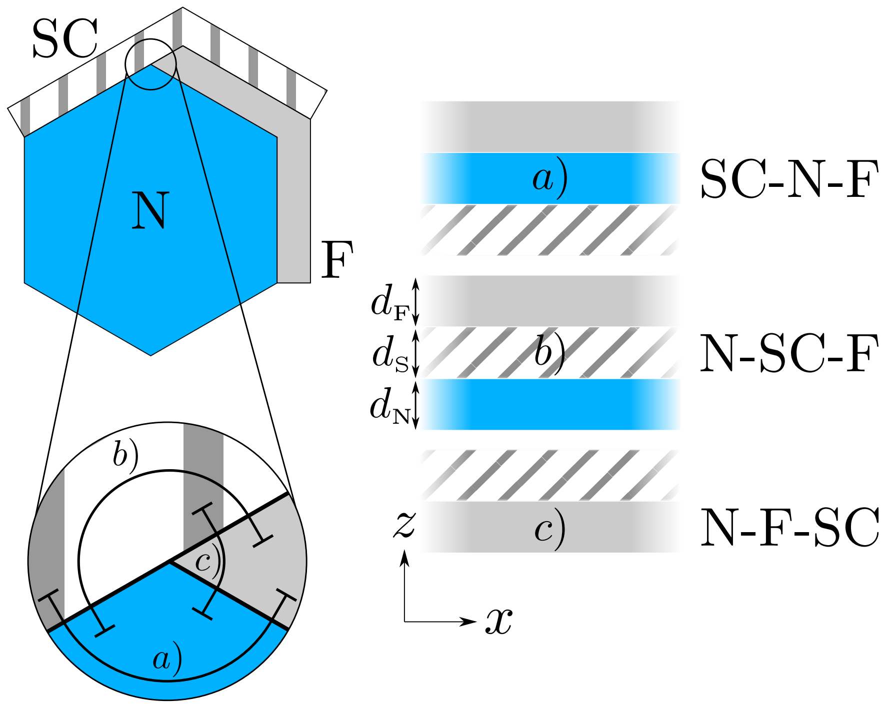


Topological superconductivity in tripartite superconductor-ferromagnet-semiconductor nanowires

Josias Langbehn, Sergio Acero González, Piet W. Brouwer, and Felix von Oppen
Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany

Motivated by recent experiments searching for Majorana zero modes in tripartite semiconductor nanowires with epitaxial superconductor and ferromagnetic-insulator layers, we explore the emergence of topological superconductivity in such devices for paradigmatic arrangements of the three constituents. Accounting for the competition between magnetism and superconductivity, we treat superconductivity self consistently and describe the electronic properties, including the superconducting and ferromagnetic proximity effects, within a direct wave-function approach. We conclude that the most viable mechanism for topological superconductivity relies on a superconductor-semiconductor-ferromagnet arrangement of the constituents, in which spin splitting and superconductivity are independently induced in the semiconductor by proximity and superconductivity is only weakly affected by the ferromagnetic insulator.

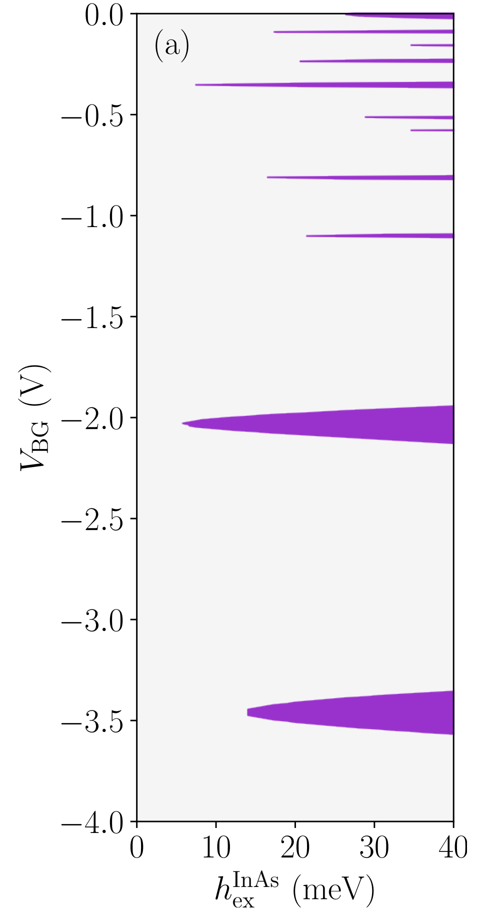


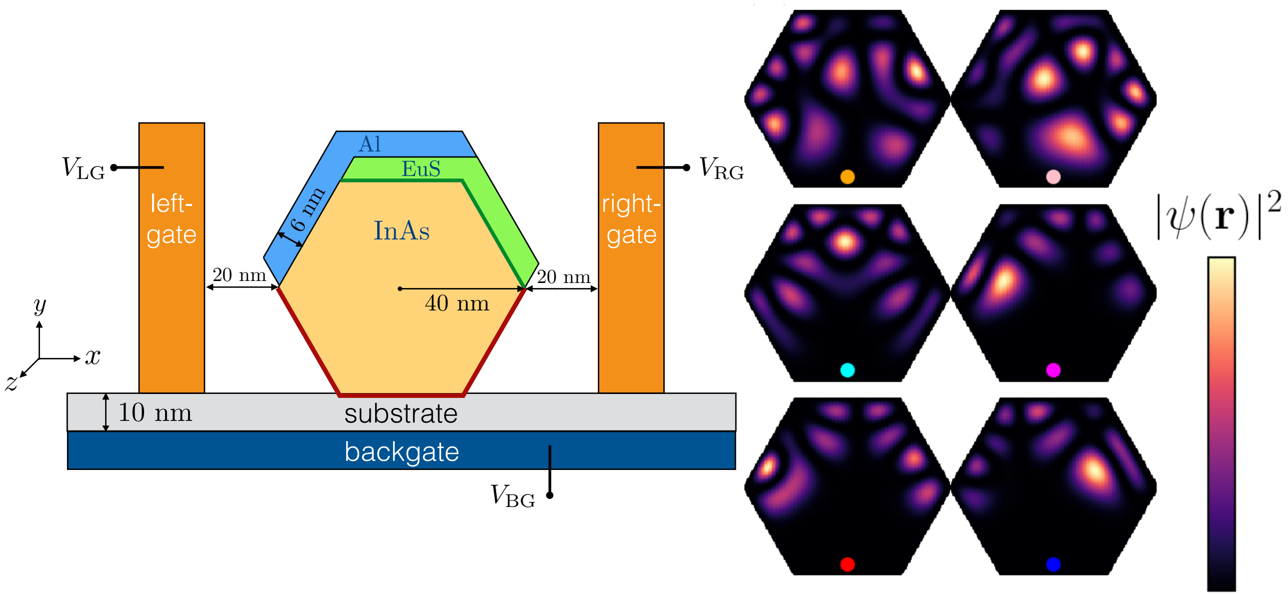
Electronic properties of InAs/EuS/Al hybrid nanowires

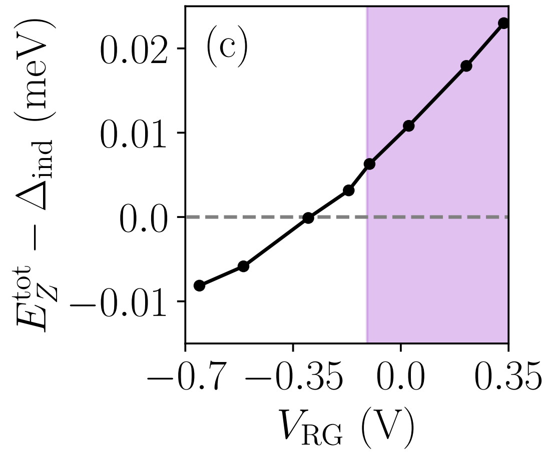
Chun-Xiao Liu,[1,2,*] Sergej Schuwalow,[3] Yu Liu,[3] Kostas Vilkelis,[1,2]
A. L. R. Manesco,[4,2] P. Krogstrup,[3] and Michael Wimmer[1,2]

[1] *Qutech, Delft University of Technology, Delft 2600 GA, The Netherlands.*
[2] *Kavli Institute of Nanoscience, Delft University of Technology, Delft 2600 GA, The Netherlands.*
[3] *Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen and Microsoft Quantum Materials Lab Copenhagen, Lyngby, Denmark.*
[4] *Computational Materials Science Group (ComputEEL), Escola de Engenharia de Lorena, Universidade de São Paulo (EEL-USP), Materials Engineering Department (Demar), Lorena – SP, Brazil*

We study the electronic properties of InAs/EuS/Al heterostructures as explored in a recent experiment [S. Vaitiekėnas *et al.*, Nat. Phys. (2020)], combining both spectroscopic results and microscopic device simulations. In particular, we use angle-resolved photoemission spectroscopy to investigate the band bending at the InAs/EuS interface. The resulting band offset value serves as an essential input to subsequent microscopic device simulations, allowing us to map the electronic wave function distribution. We conclude that the magnetic proximity effects at the Al/EuS as well as the InAs/EuS interfaces are both essential to achieve topological superconductivity at zero applied magnetic field. Mapping the topological phase diagram as a function of gate voltages and proximity-induced exchange couplings, we show that the ferromagnetic hybrid nanowire with overlapping Al and EuS layers can become a topological superconductor within realistic parameter regimes, and that the topological phase can be optimized by external gating. Our work highlights the need for a combined experimental and theoretical effort for faithful device simulations.







PHYSICAL REVIEW B **105**, L041304 (2022)

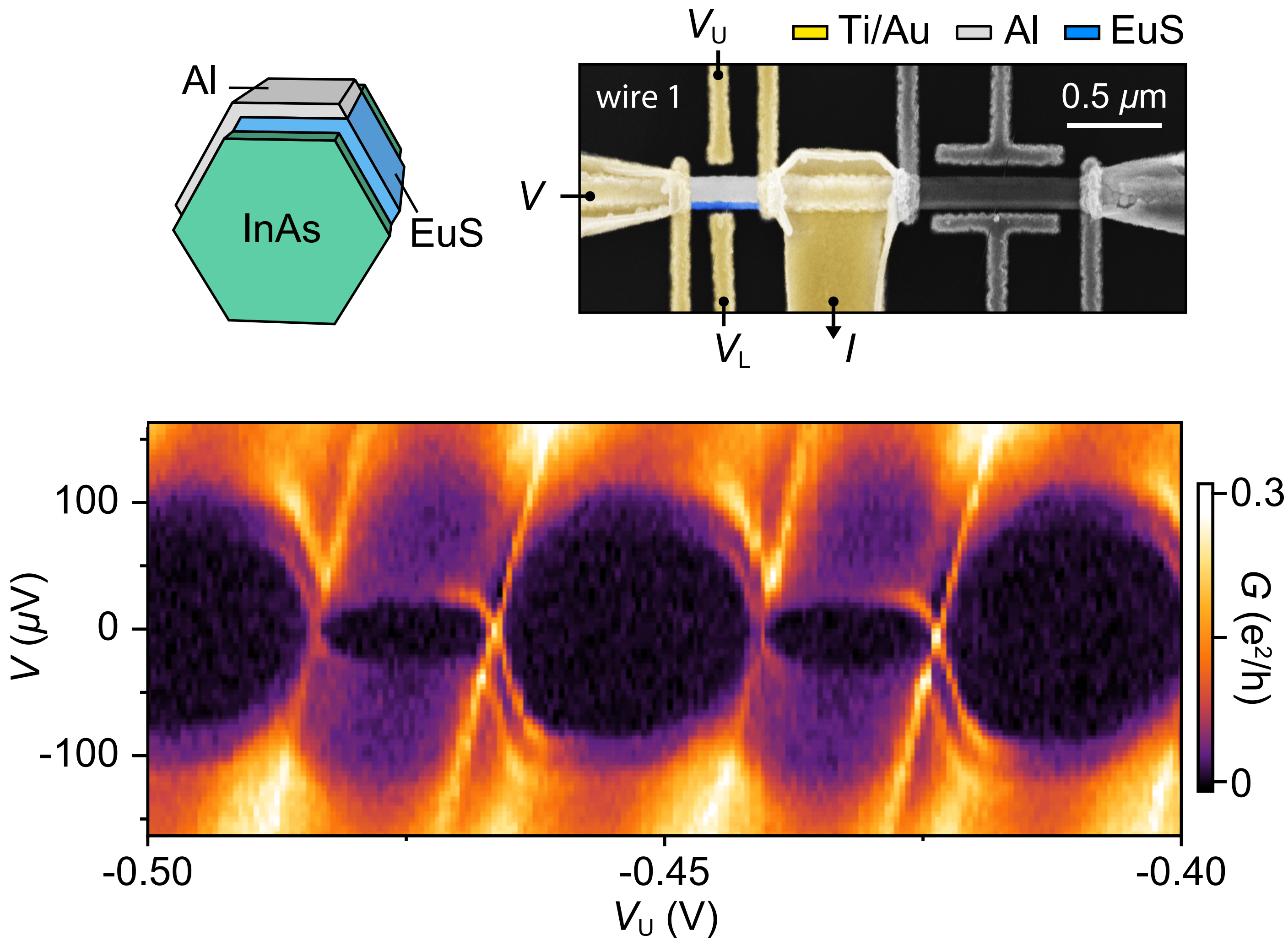
Letter

Evidence for spin-polarized bound states in semiconductor–superconductor–ferromagnetic-insulator islands

S. Vaitiekėnas,[1] R. Seoane Souto,[1,2] Y. Liu,[1] P. Krogstrup,[1] K. Flensberg,[1] M. Leijnse,[1,2] and C. M. Marcus[1]

[1]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*

[2]*Division of Solid State Physics and NanoLund, Lund University, 22100 Lund, Sweden*



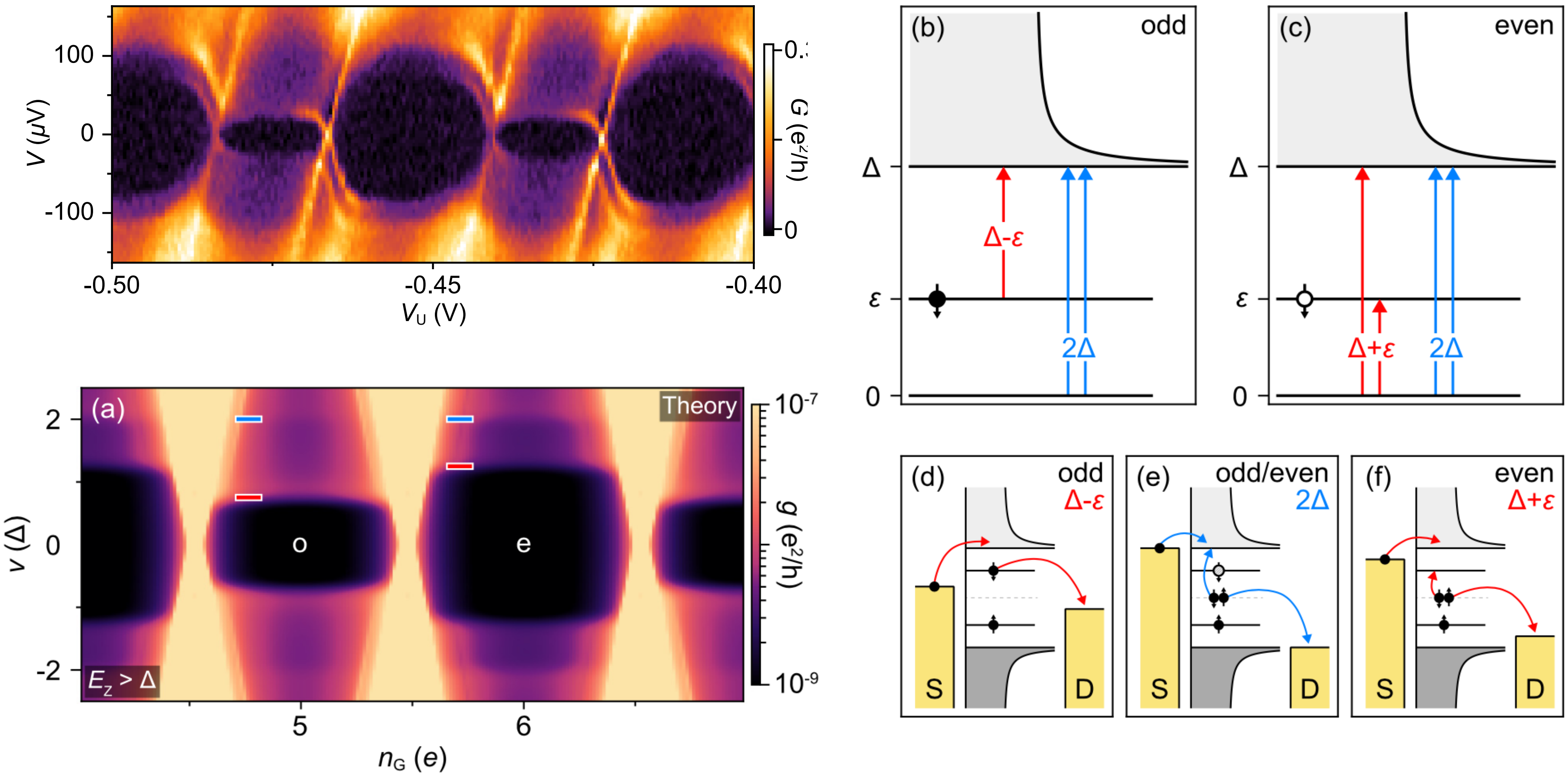
Letter

Evidence for spin-polarized bound states in semiconductor–superconductor–ferromagnetic-insulator islands

S. Vaitiekėnas,[1] R. Seoane Souto,[1,2] Y. Liu,[1] P. Krogstrup,[1] K. Flensberg,[1] M. Leijnse,[1,2] and C. M. Marcus[1]

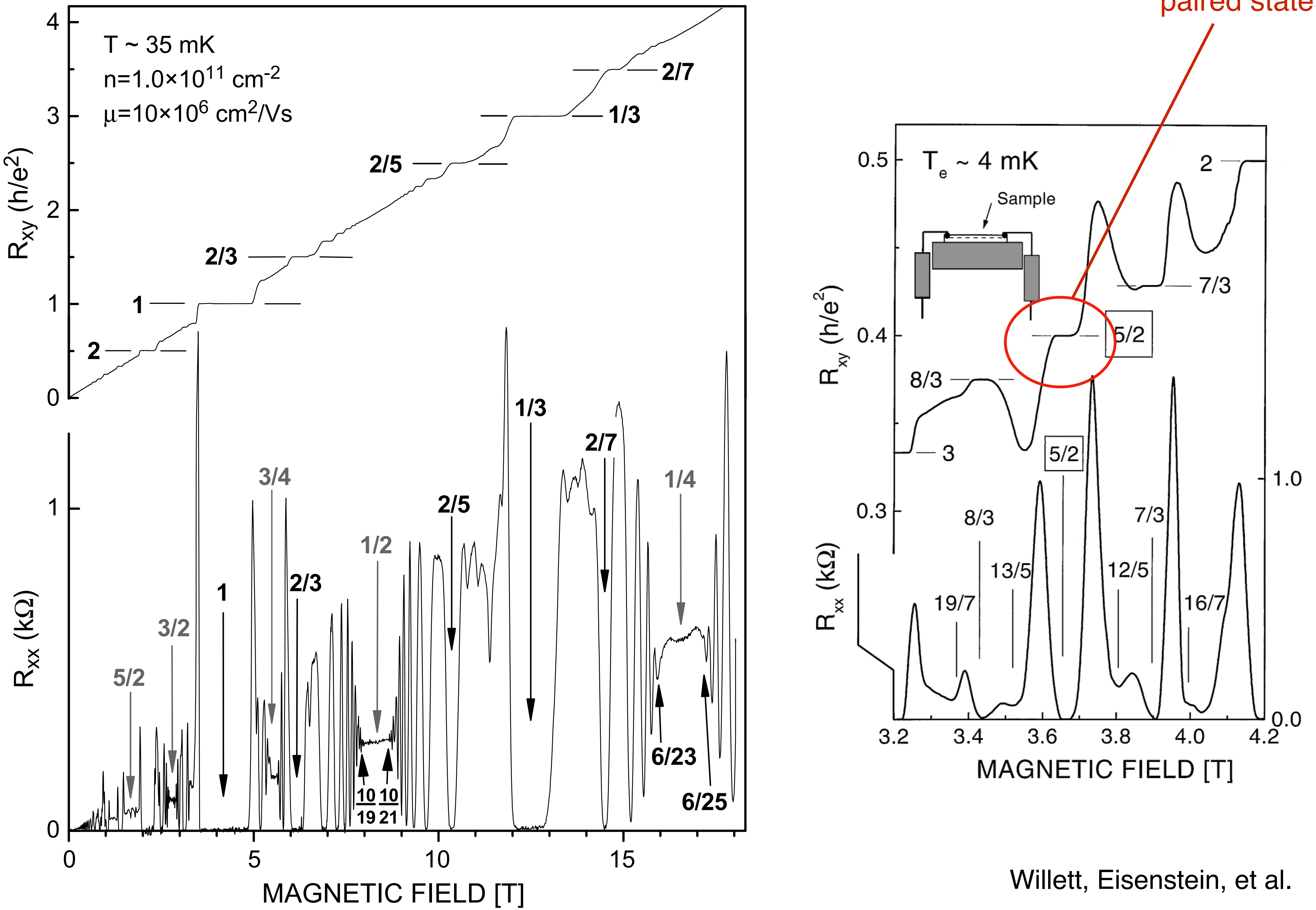
[1]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

[2]Division of Solid State Physics and NanoLund, Lund University, 22100 Lund, Sweden



Fractional Quantum Hall Effect

theory:
spinless
paired state



Willett, Eisenstein, et al.

PHYSICAL REVIEW B VOLUME 61, NUMBER 15 15 APRIL 2000-I

Paired states of fermions in two dimensions with breaking of parity and time-reversal symmetries and the fractional quantum Hall effect

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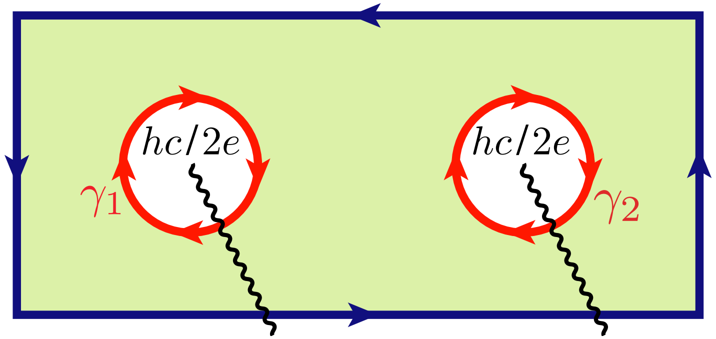
Departments of Physics and Applied Physics, Yale University, P.O. Box 208120, New Haven, Connecticut 06520-8120

(Received 30 June 1999)

To conclude, our main results are: (i) p-wave pairing in spinless or spin-polarized fermions in the weak-pairing phase leads to the properties also found in the FQHE in the MR states, and supports the ideas of nonabelian statistics as a robust property, at least in the case of a pure system. Such statistics will also occur for the vortices in such a p-wave state in general in charged superfluid



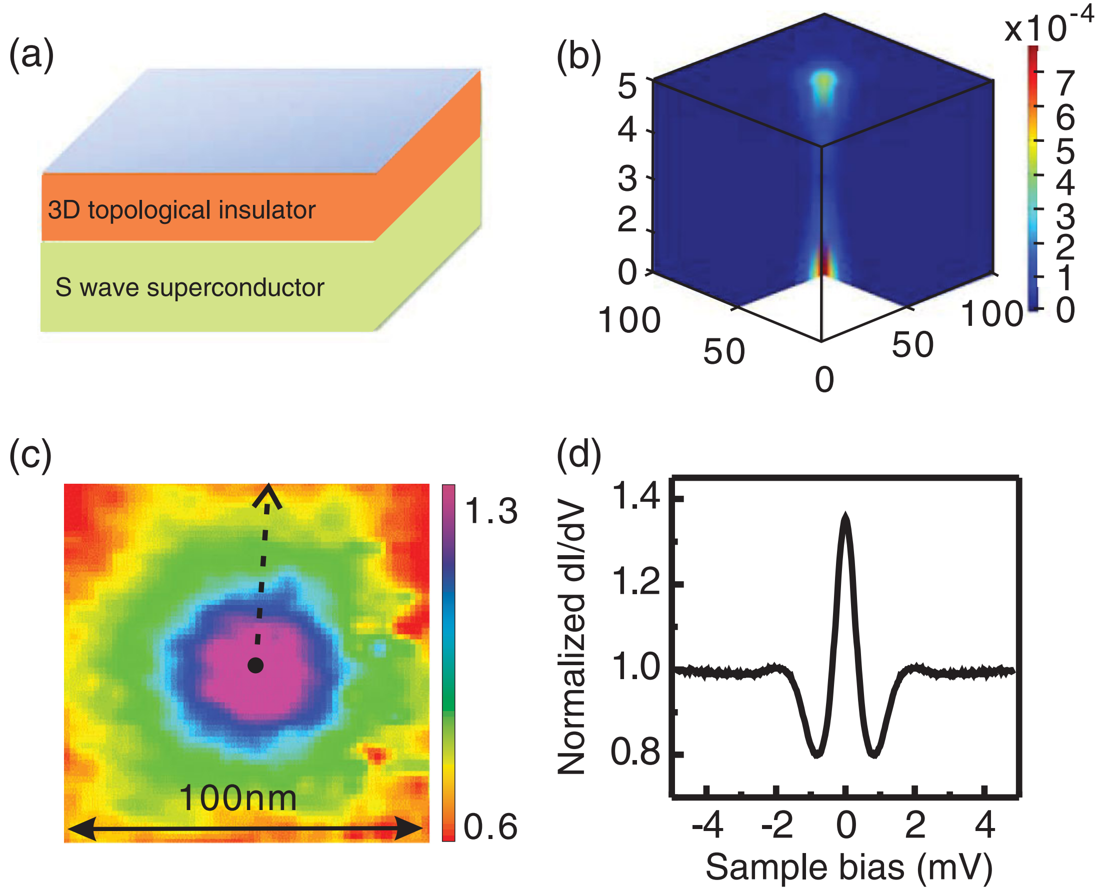
J. Alicea, *Rep. Prog. Phys.* **75**, 076501 (2012).

We note that a zero mode on a vortex in an A-phase p-wave paired state was first found in Ref. 68.

[68] N.B. Kopnin and M.M. Salomaa, Phys. Rev. B **44**, 9667 (1991)

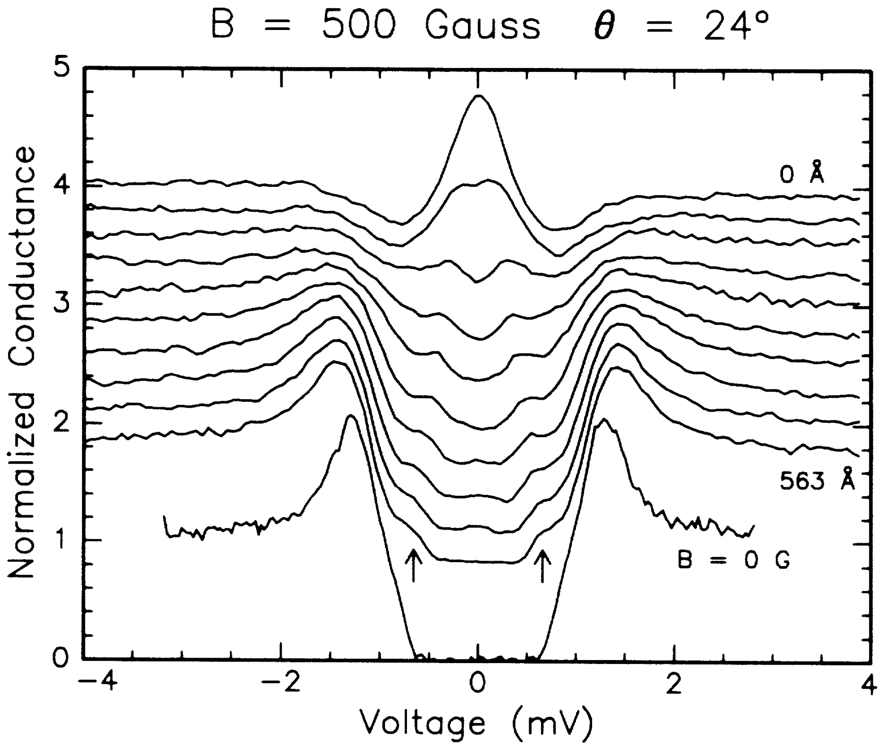
Experimental Detection of a Majorana Mode in the core of a Magnetic Vortex inside a Topological Insulator-Superconductor $Bi_2Te_3/NbSe_2$ Heterostructure

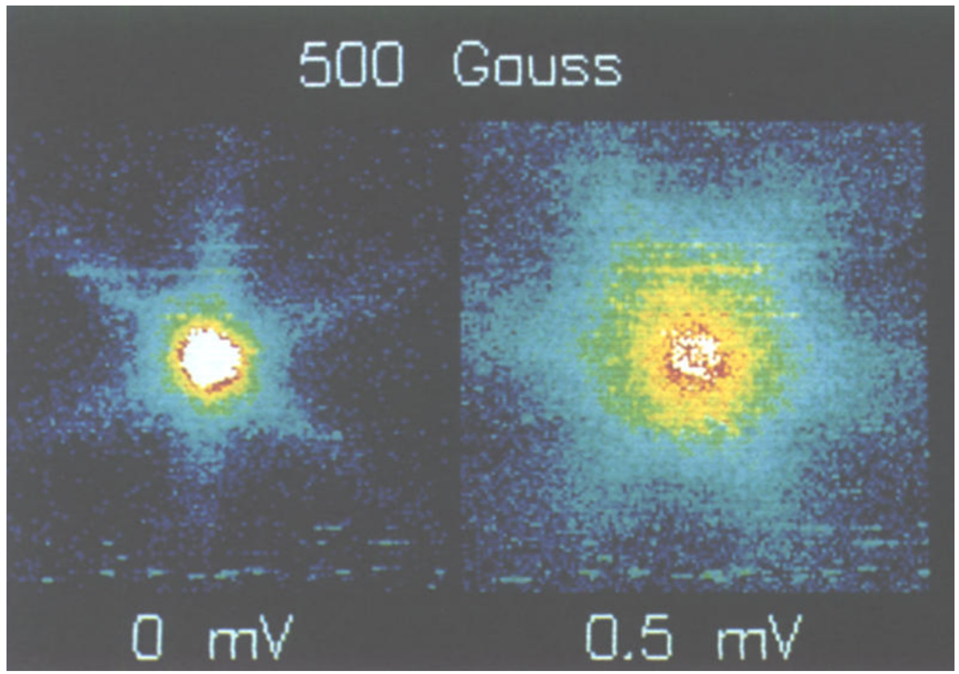
Jin-Peng Xu,[1] Mei-Xiao Wang,[1] Zhi Long Liu,[1] Jian-Feng Ge,[1] Xiaojun Yang,[2] Canhua Liu,[1,5,*] Zhu An Xu,[2,5] Dandan Guan,[1] Chun Lei Gao,[1] Dong Qian,[1] Ying Liu,[1,3,5] Qiang-Hua Wang,[4,5] Fu-Chun Zhang,[2,5] Qi-Kun Xue,[6] and Jin-Feng Jia[1,5,†]



Vortex-Core Structure Observed with a Scanning Tunneling Microscope

H. F. Hess, R. B. Robinson, and J. V. Waszczak
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 28 December 1989)





Selected for a Viewpoint in *Physics*
PRL **107,** 097001 (2011) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2011

Majorana Modes at the Ends of Superconductor Vortices in Doped Topological Insulators

Pavan Hosur,[1] Pouyan Ghaemi,[1,2] Roger S. K. Mong,[1] and Ashvin Vishwanath[1,2]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
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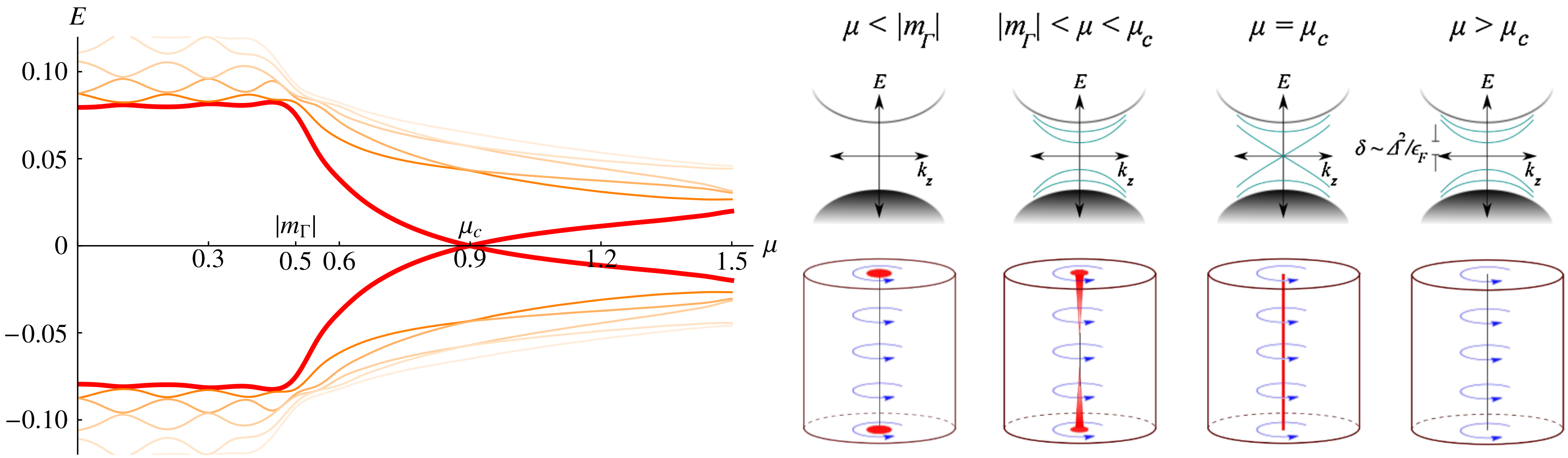
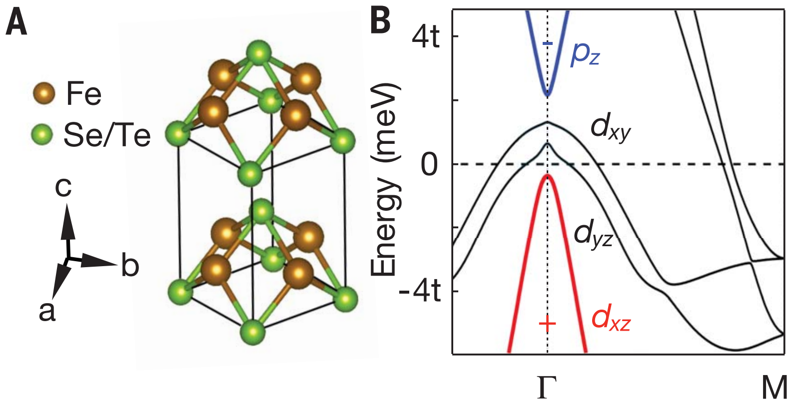
(Received 24 December 2010; published 22 August 2011)

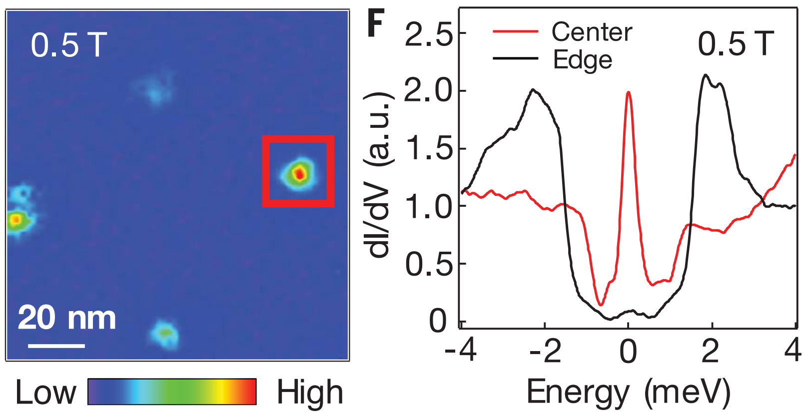


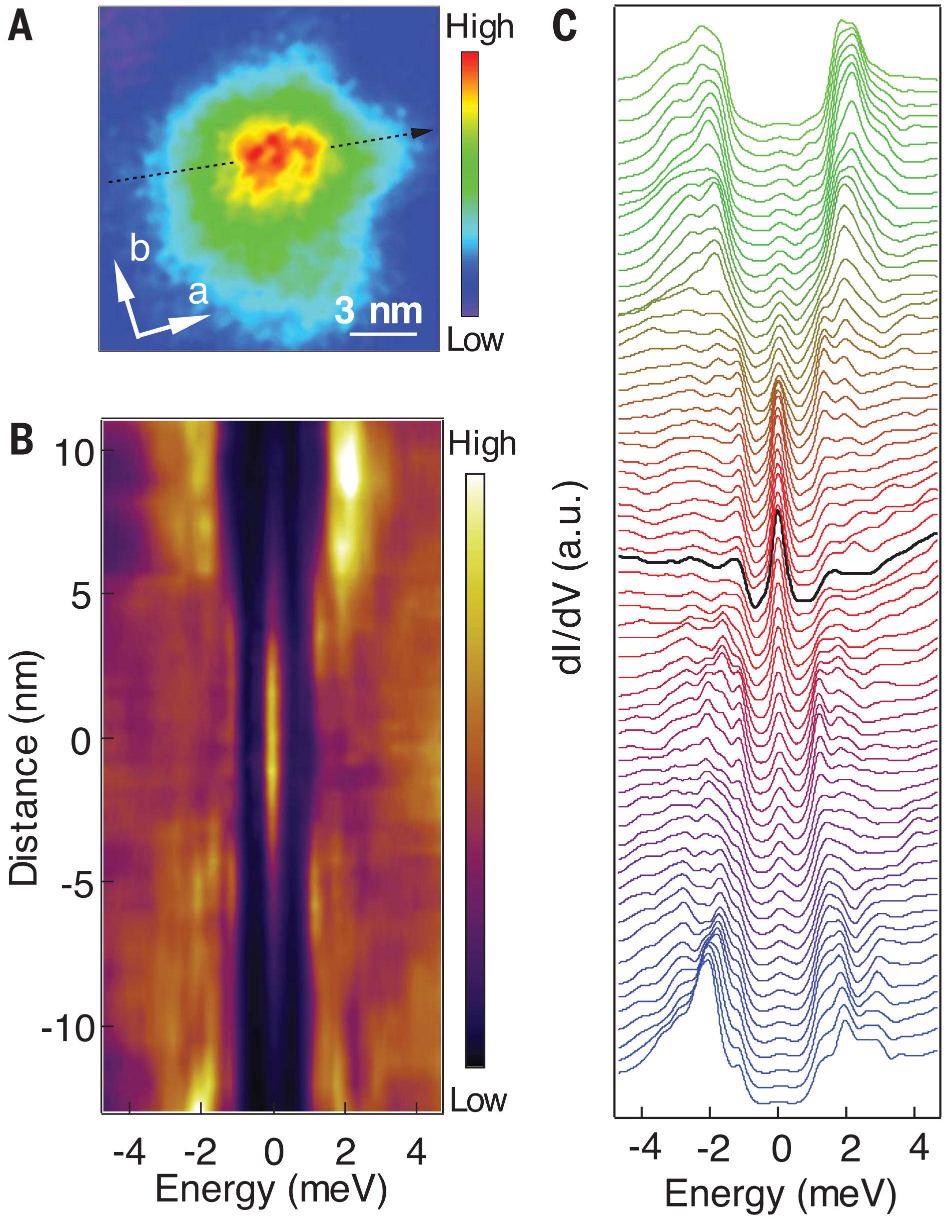
TOPOLOGICAL MATTER

Evidence for Majorana bound states in an iron-based superconductor

Dongfei Wang[1,2]*, Lingyuan Kong[1,2]*, Peng Fan[1,2]*, Hui Chen[1], Shiyu Zhu[1,2], Wenyao Liu[1,2], Lu Cao[1,2], Yujie Sun[1,3], Shixuan Du[1,3,4], John Schneeloch[5], Ruidan Zhong[5], Genda Gu[5], Liang Fu[6], Hong Ding[1,2,3,4]†, Hong-Jun Gao[1,2,3,4]†





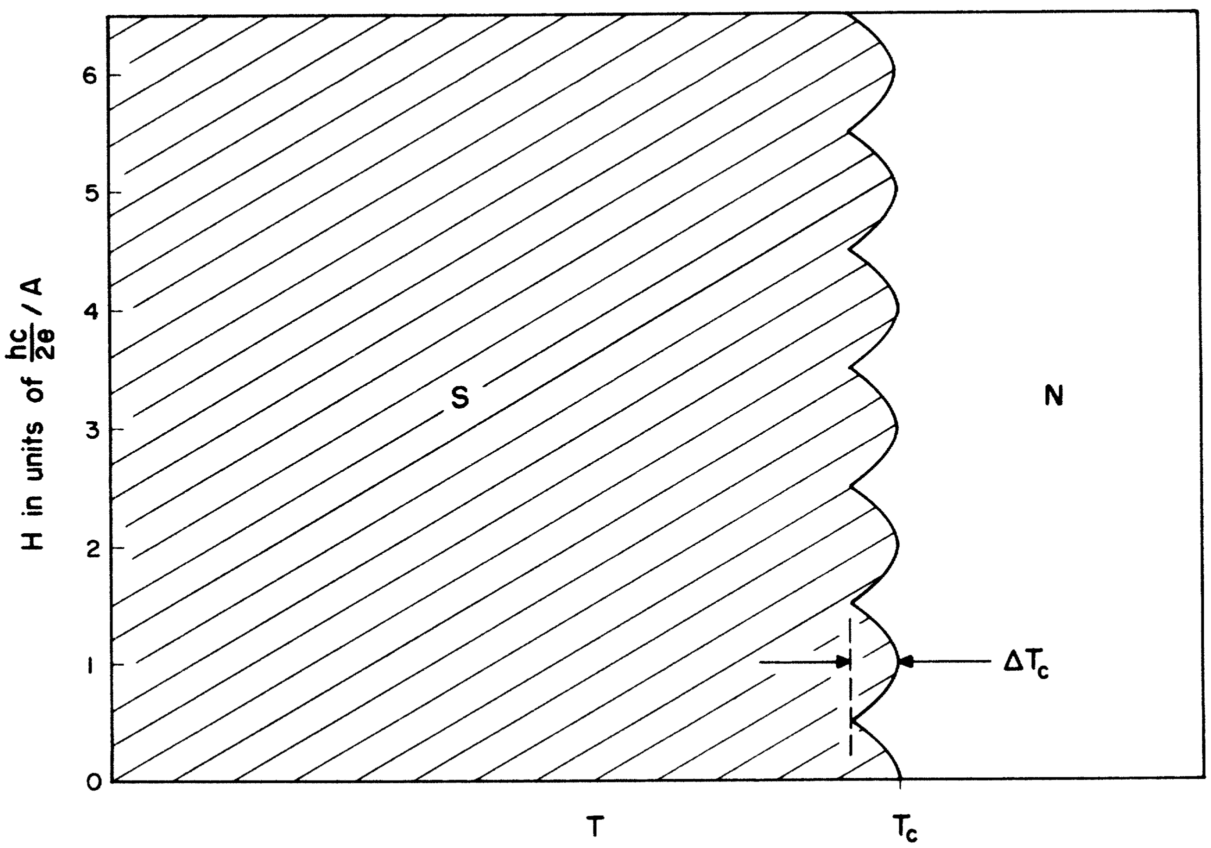


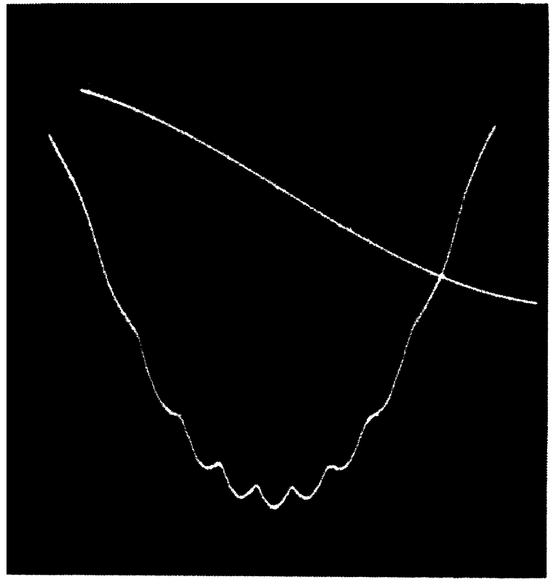
OBSERVATION OF QUANTUM PERIODICITY IN THE TRANSITION TEMPERATURE OF A SUPERCONDUCTING CYLINDER*

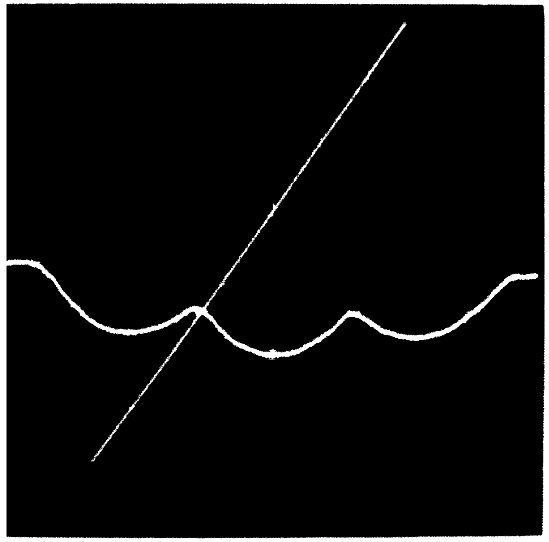
W. A. Little† and R. D. Parks‡

Department of Physics, Stanford University, Stanford, California

(Received May 10, 1962; revised manuscript received June 15, 1962)



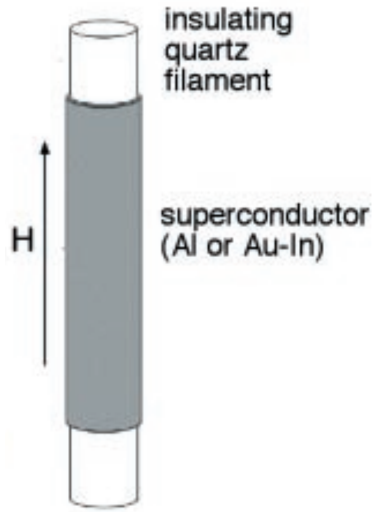


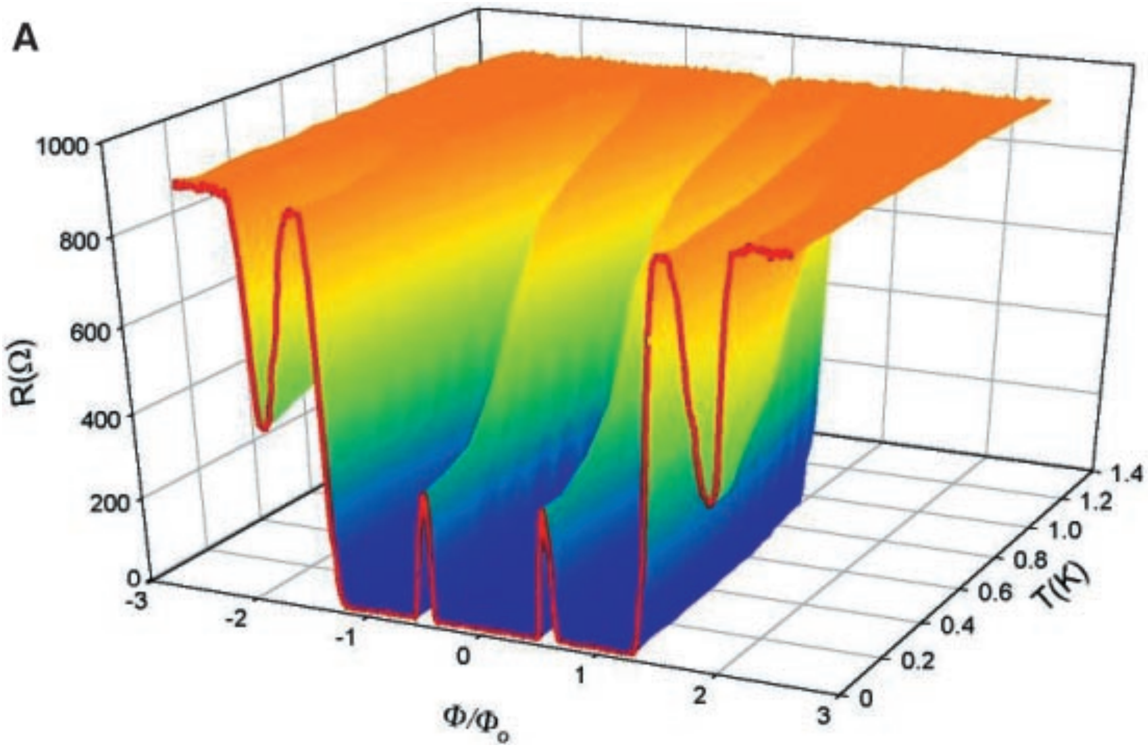


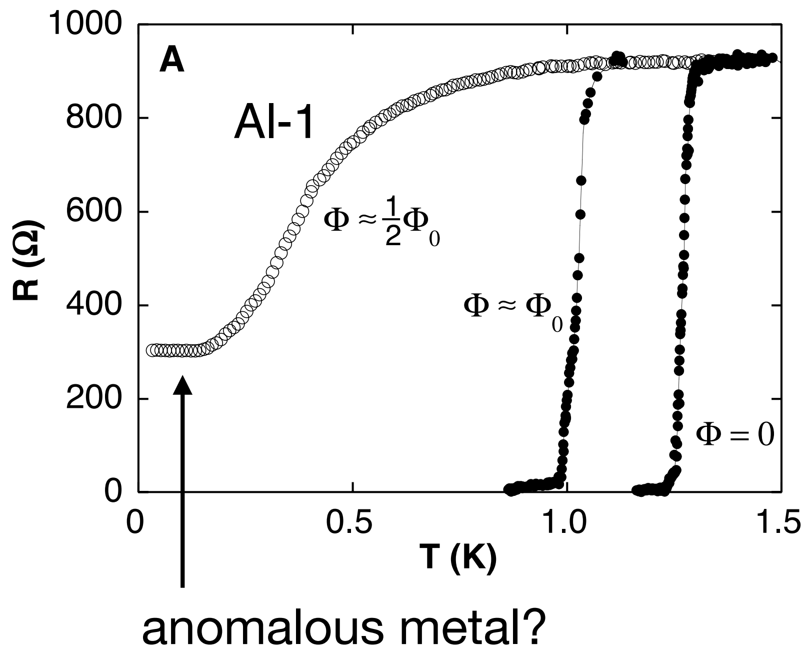
Destruction of the Global Phase Coherence in Ultrathin, Doubly Connected Superconducting Cylinders

Y. Liu,* Yu. Zadorozhny, M. M. Rosario, B. Y. Rock, P. T. Carrigan, H. Wang

In doubly connected superconductors, such as hollow cylinders, the fluxoid is known to be quantized, allowing the superfluid velocity to be controlled by an applied magnetic flux and the sample size. The sample-size–induced increase in superfluid velocity has been predicted to lead to the destruction of superconductivity around half-integer flux quanta. We report transport measurements in ultrathin Al and $Au_{0.7}In_{0.3}$ cylinders verifying the presence of this destructive regime characterized by the loss of the global phase coherence and reveal a phase diagram featuring disconnected phase coherent regions, as opposed to the single region seen in larger superconducting cylinders studied previously.







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]

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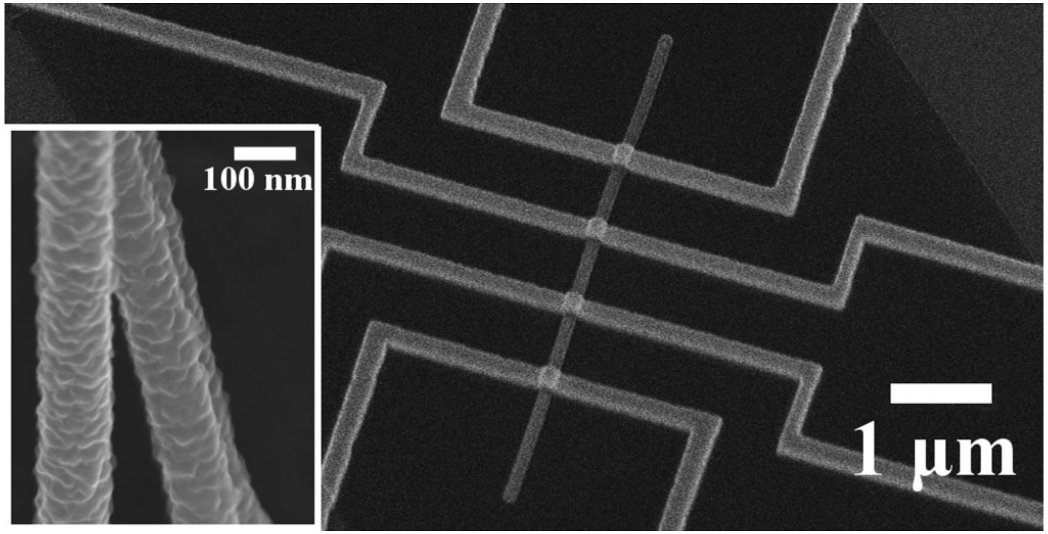
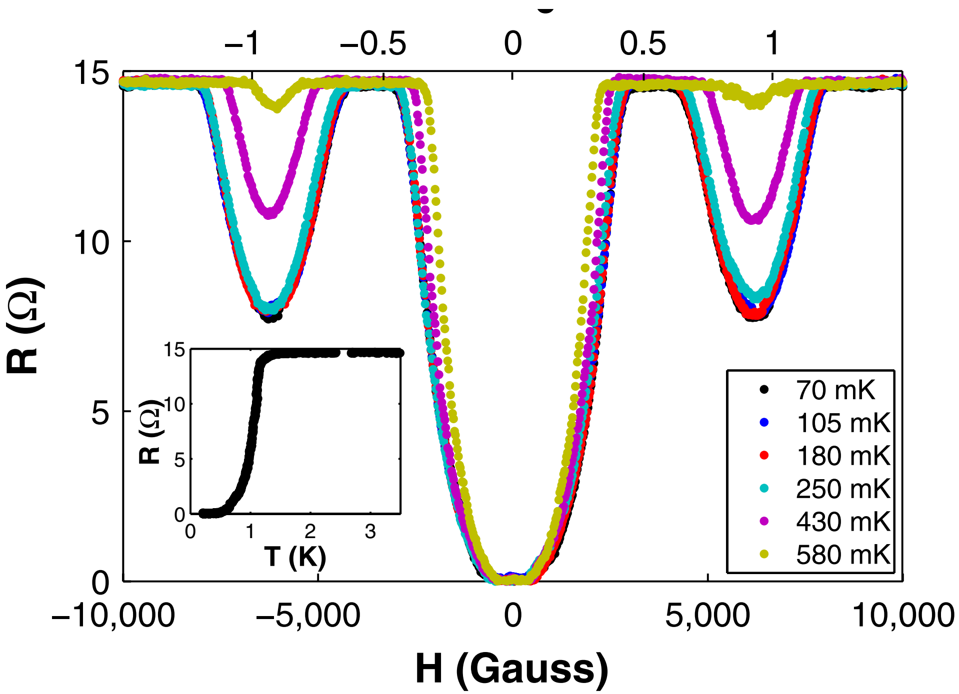
(Received 24 January 2011; published 11 July 2011)

When odd multiples of half flux quanta thread a cylindrical superconducting shell with a diameter d shorter than the zero temperature coherence length $\xi(0)$, superconductivity is predicted to be destroyed. We show here that as d is reduced in comparison to $\xi(0)$ the resistance attains the normal state value, which seems to be temperature independent in the vicinity of half flux quanta. The data are in agreement with recent theoretical results.

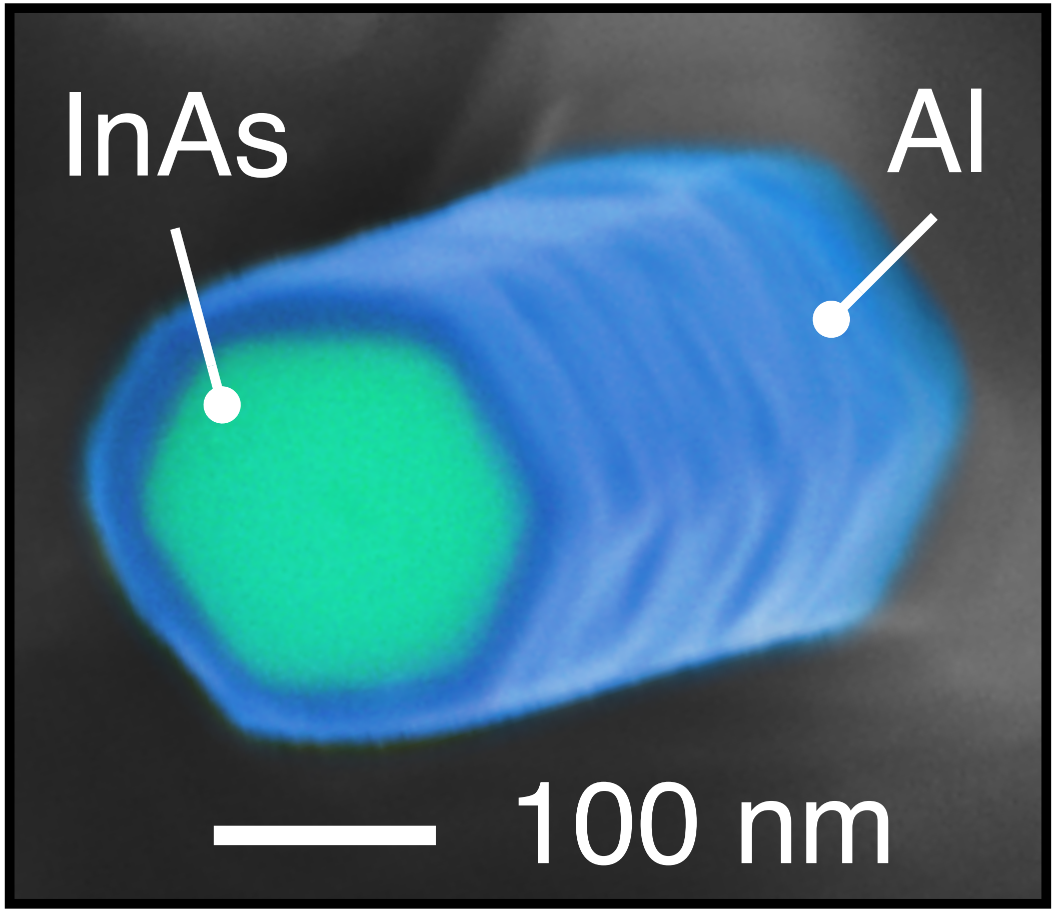




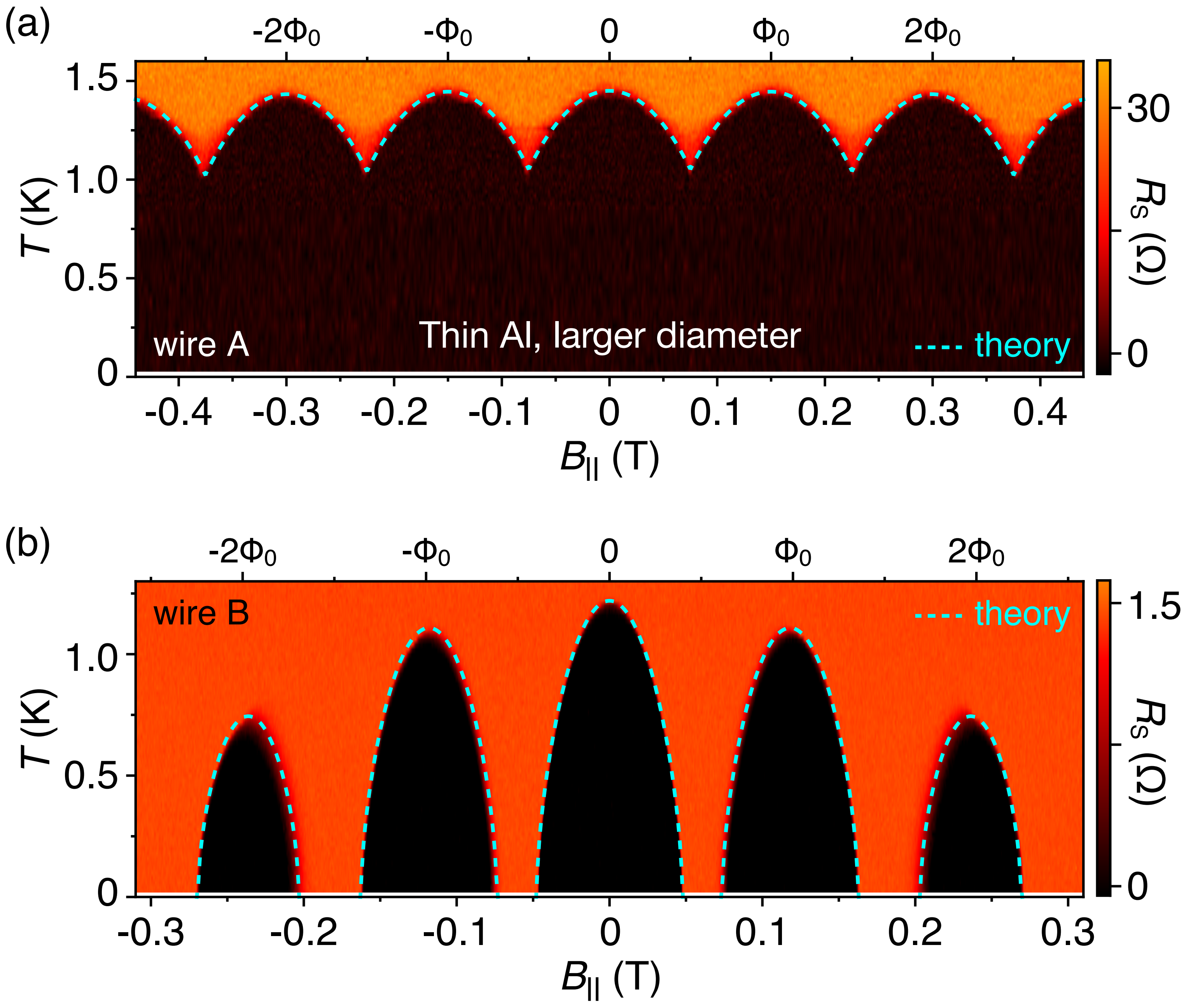
TOPOLOGICAL MATTER

Flux-induced topological superconductivity in full-shell nanowires

S. Vaitiekėnas, G. W. Winkler, B. van Heck, T. Karzig, M.-T. Deng, K. Flensberg, L. I. Glazman, C. Nayak, P. Krogstrup, R. M. Lutchyn*, C. M. Marcus*



From Little-Parks to Destructive Regime



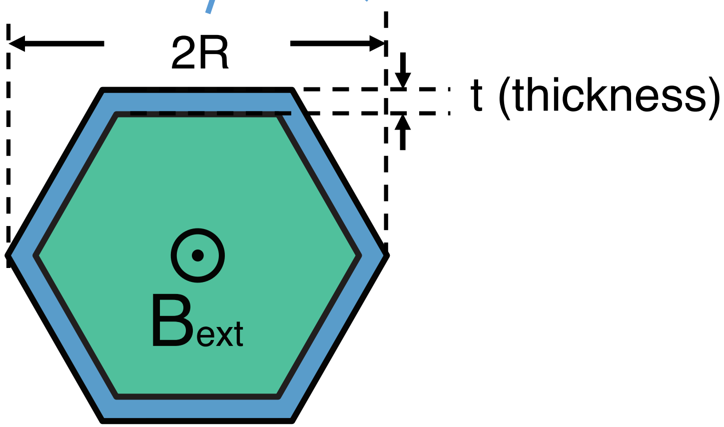
Mean-field theory of the destructive regime

A. A. Abrikosov and L. P. Gor'kov, Sov. Phys. JETP **12**, 1243 (1961).

$$\ln\left(\frac{T_C(n,\phi)}{T_C(0,0)}\right) = \psi\left(\frac{1}{2}\right) - \psi\left(\frac{1}{2} + \frac{\alpha(n,\phi)}{2\pi T_C(n,\phi)}\right)$$

- Cooper-pair breaking parameter:

$$\alpha(n,\phi) = \frac{\xi(0)^2}{\boxed{\pi R^2}} T_C(0,0)\left[4\left(n - \frac{\boxed{\phi}}{\phi_0}\right)^2 + \boxed{\frac{t^2}{R^2}}\left(\frac{\phi^2}{\phi_0^2} + \frac{n^2}{3}\right)\right]$$



- Dirty-limit coherence length

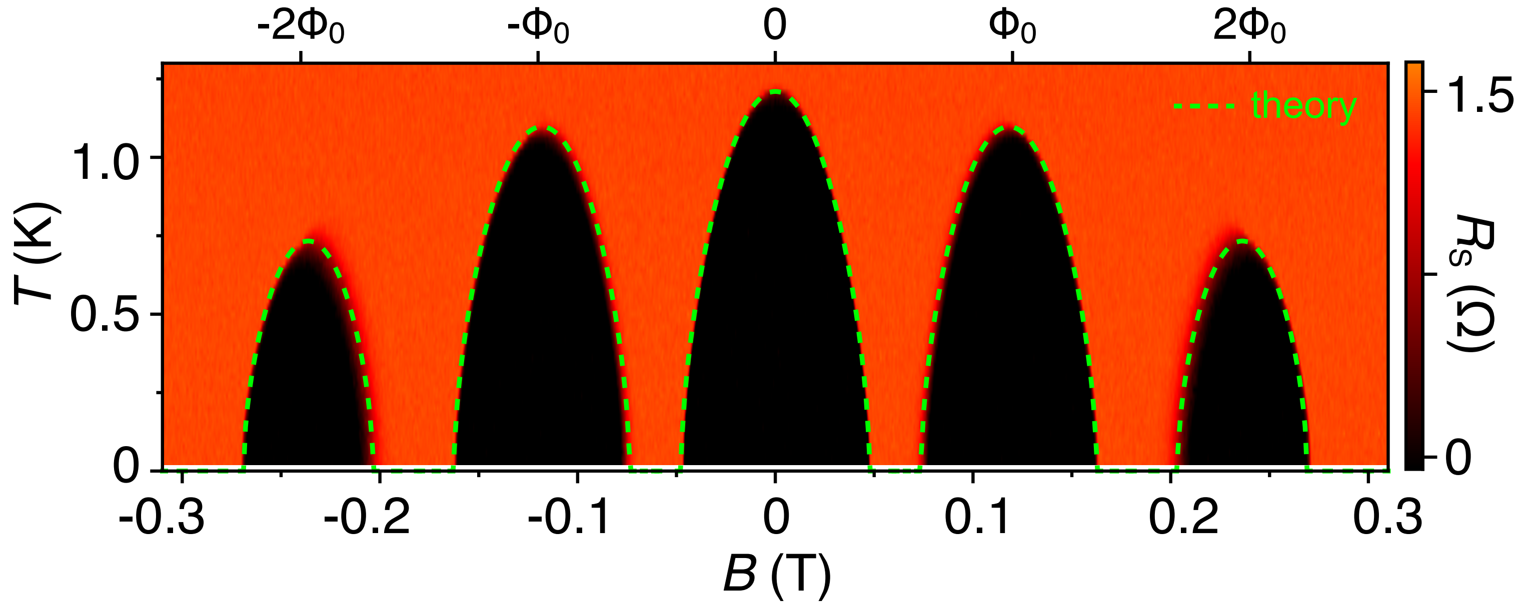
$$\xi(0) = \sqrt{\pi\hbar v_F \ell / 24 k_B T_C} \sim 180\ nm$$

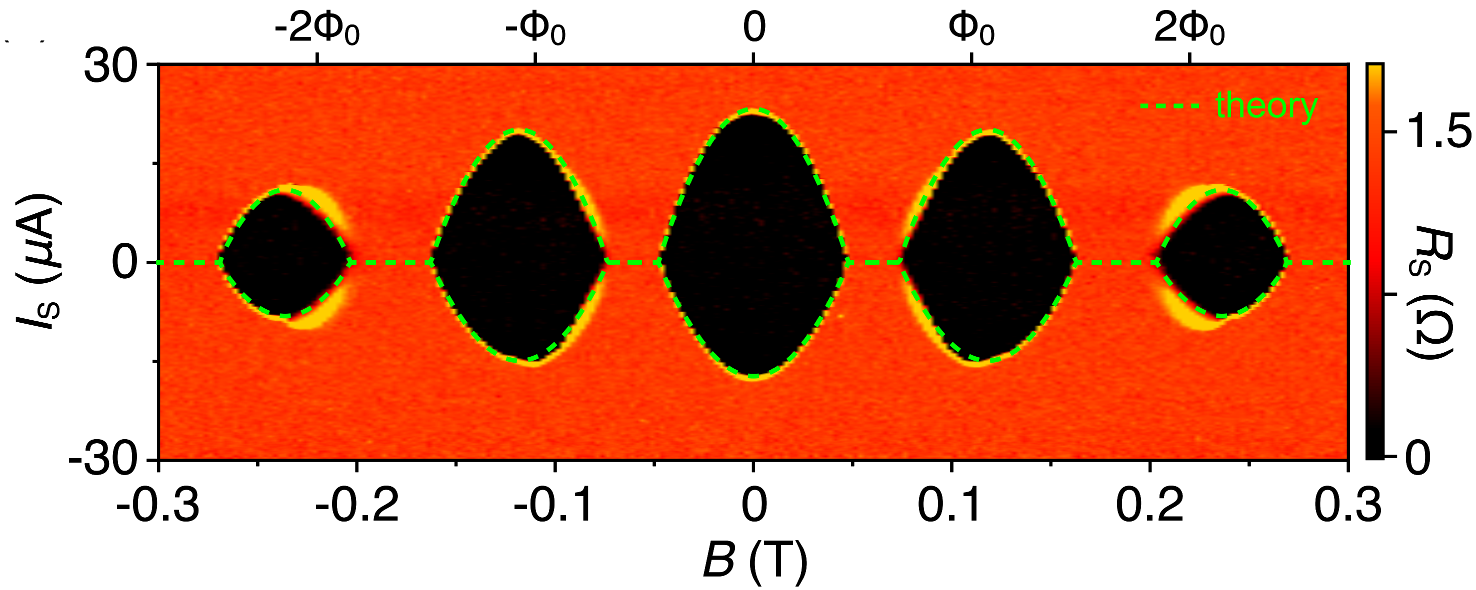
$R_S^{(N)}$

$$I_C(B) = I_C(0)\left(\frac{T_C(B)}{T_C(0)}\right)^{3/2}$$

Bardeen, RMP 1962

Compare experiment in the destructive regime

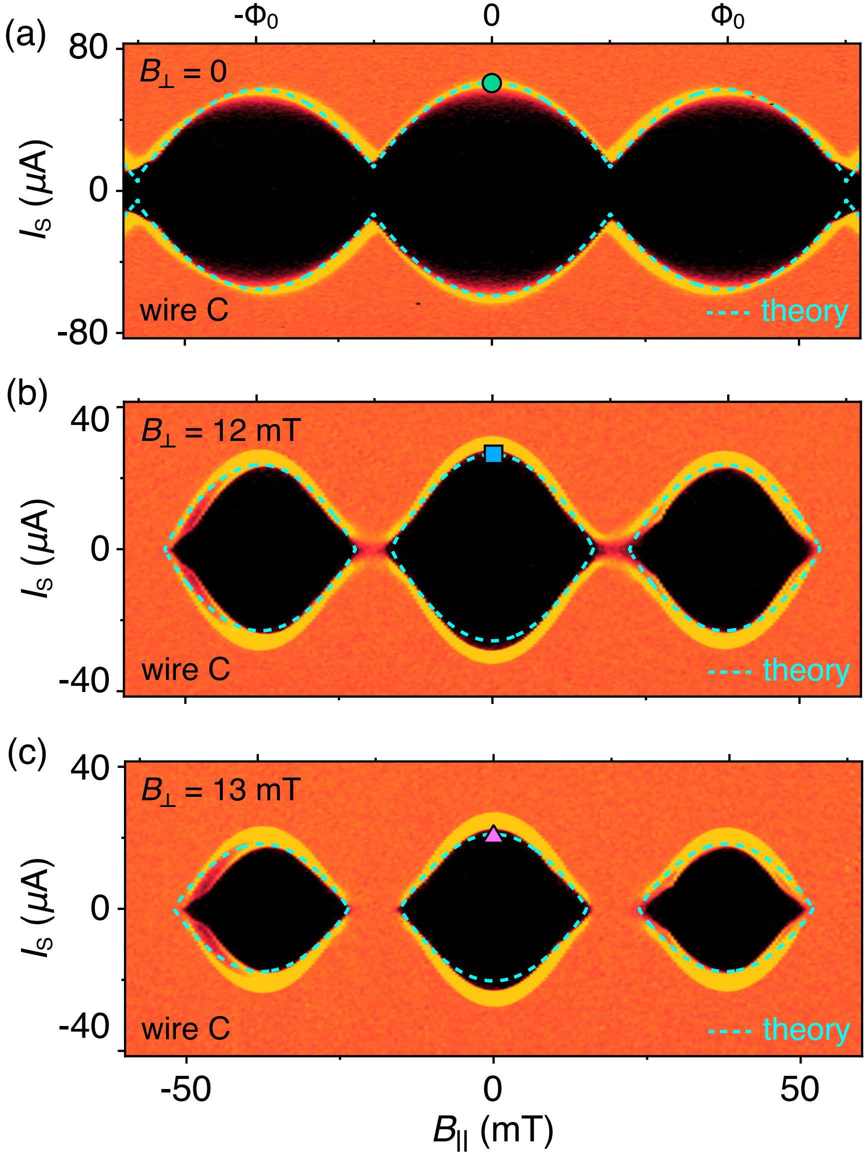


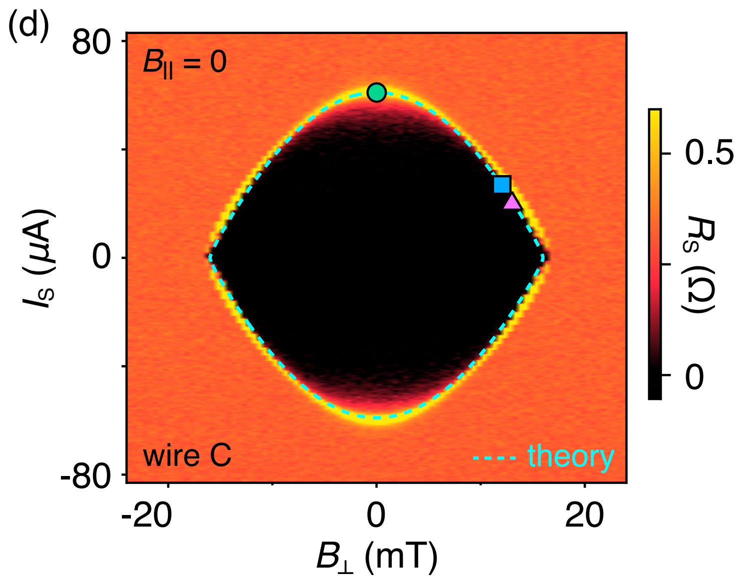


Rapid Communications

Anomalous metallic phase in tunable destructive superconductors

S. Vaitiekėnas, P. Krogstrup, and C. M. Marcus
Center for Quantum Devices and Microsoft Quantum Lab–Copenhagen, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark



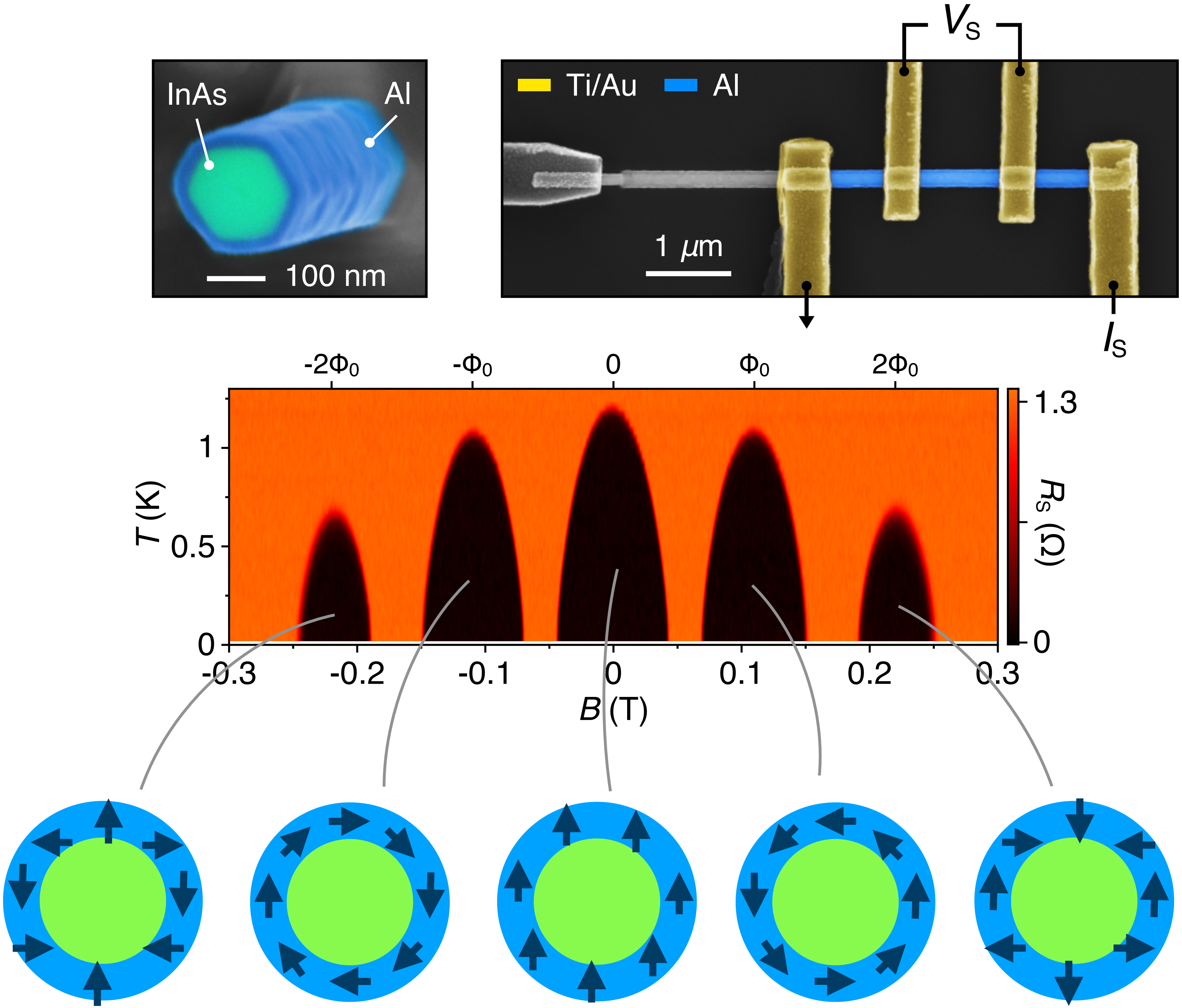


$$\ln\left(\frac{T_C(\alpha)}{T_{C0}}\right) = \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2} + \frac{\alpha}{2\pi T_C(\alpha)}\right)$$

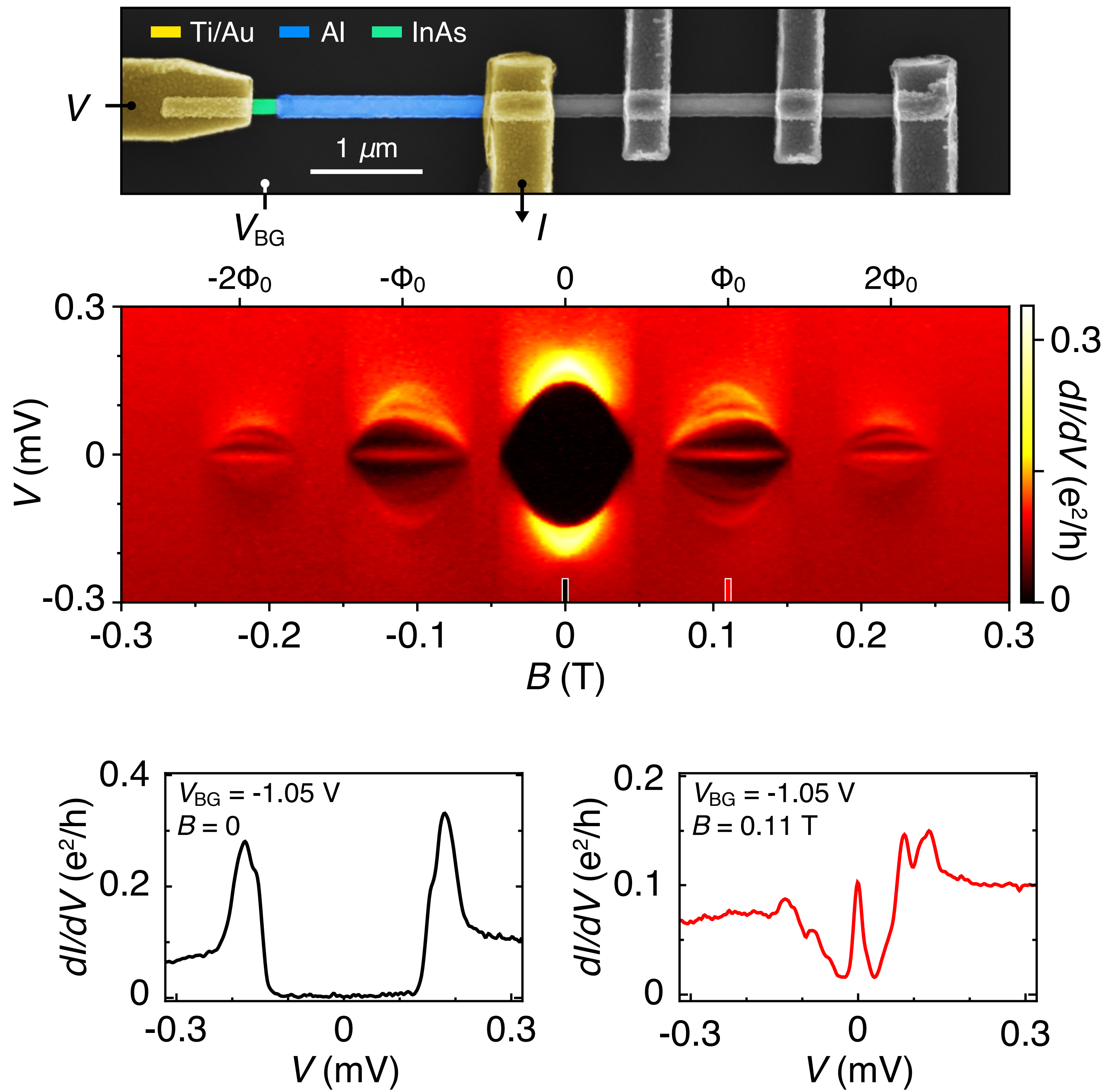
pair-breaking term

$$\alpha_\parallel = \frac{4\,\xi_S{}^2 T_{C0}}{A_F}\left[\left(n - \frac{\Phi}{\Phi_0}\right)^2 + \frac{t_S{}^2}{d_F{}^2}\left(\frac{\Phi^2}{\Phi_0{}^2} + \frac{n^2}{3}\right)\right]$$

$$\alpha_\perp = \frac{4\,\xi_S{}^2 T_{C0}}{A}\frac{\Phi_\perp{}^2}{\Phi_0{}^2} \qquad \alpha = \alpha_\parallel + \alpha_\perp$$

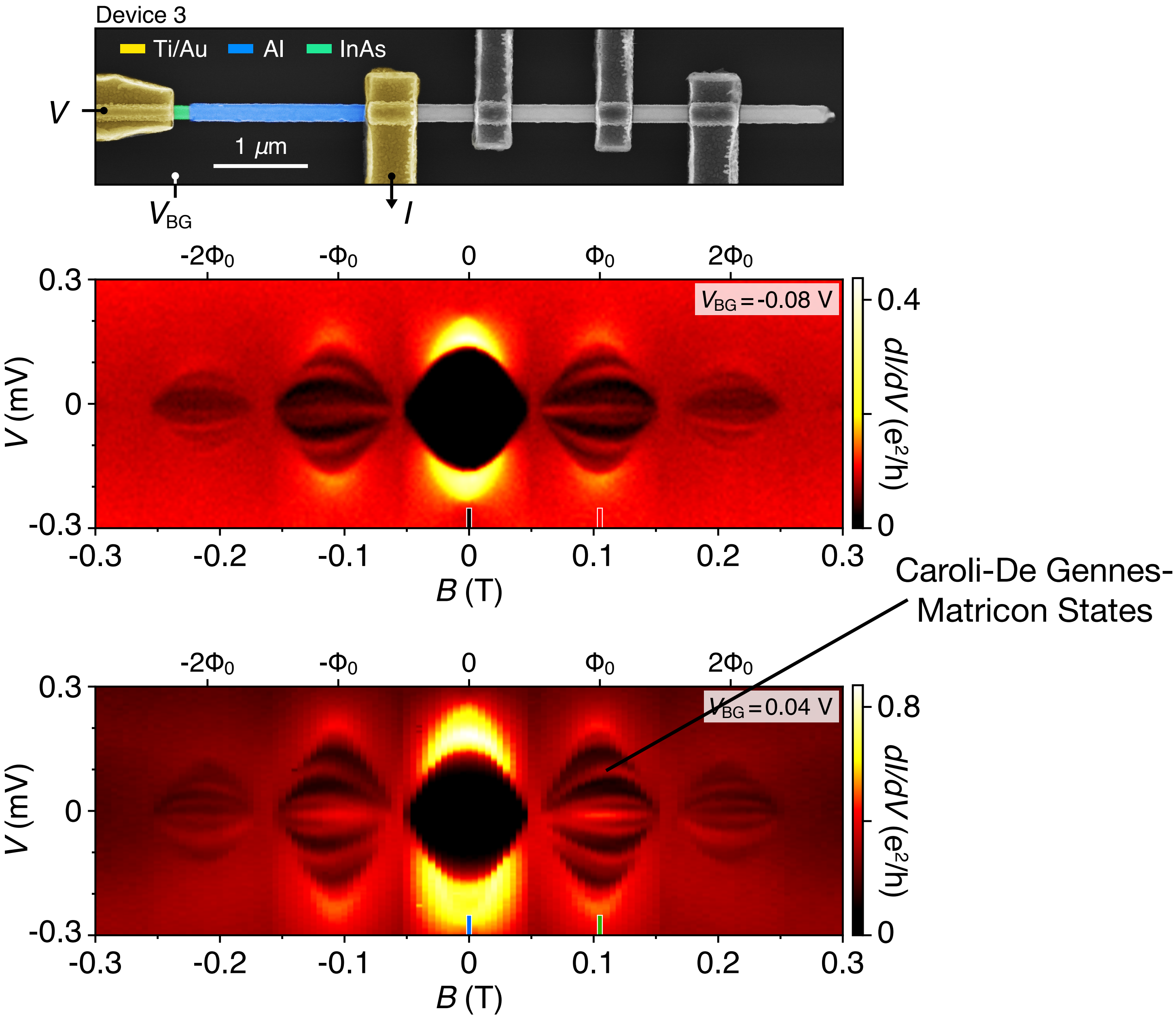

InAs
Al
100 nm
Ti/Au
Al
1 μm
V_S
I_S
$-2\Phi_0$
$-\Phi_0$
0
Φ_0
$2\Phi_0$
T (K)
B (T)
R_S (Ω)
1.3
0
-0.3
-0.2
-0.1
0.1
0.2
0.3
0.5
1

Spectroscopy of InAs nanowire with fluxoid-quantized boundary

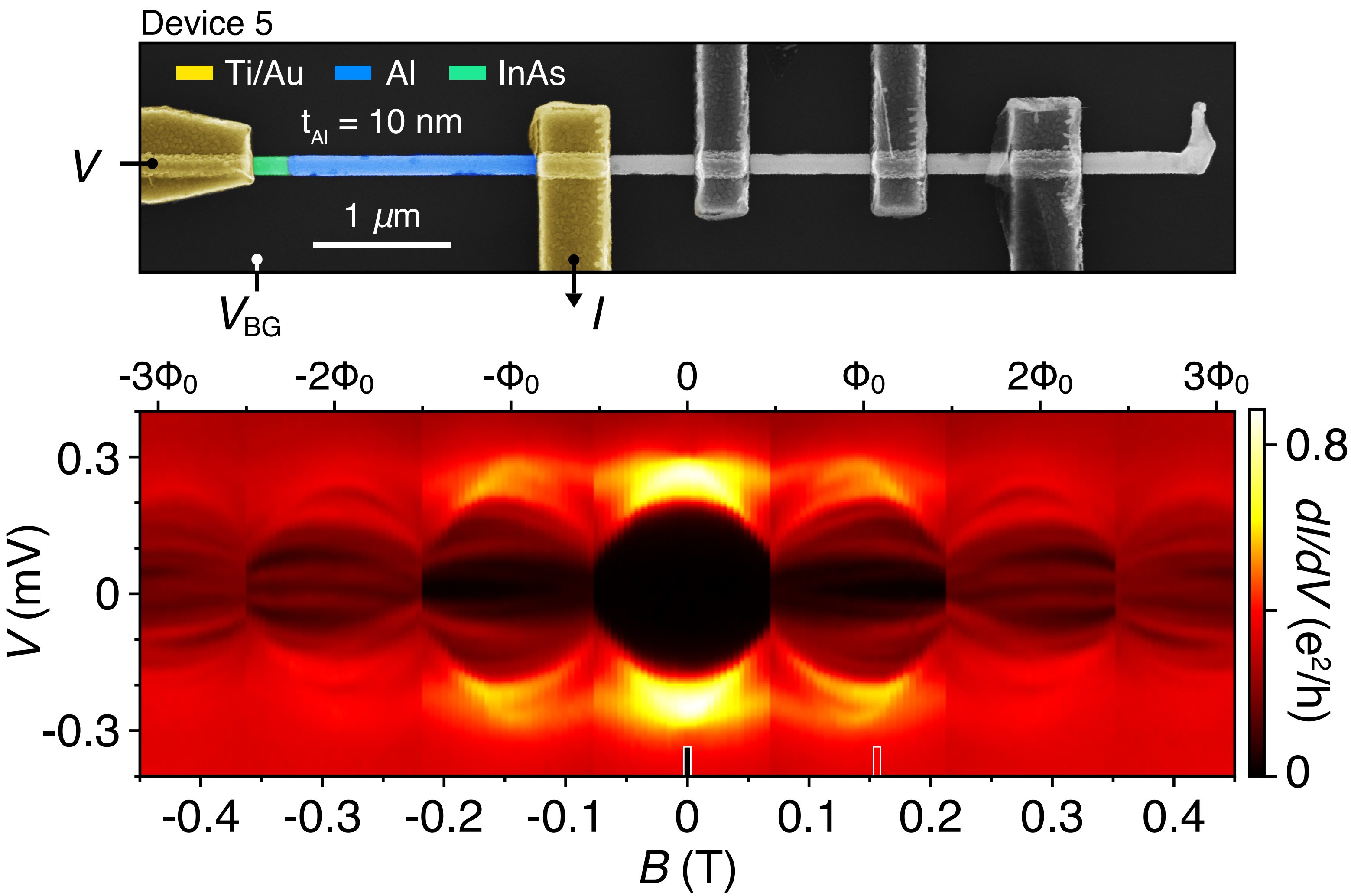


Spectroscopy of InAs nanowire with fluxoid-quantized boundary

Different device



Non-Topological Nanowires (larger diameter)

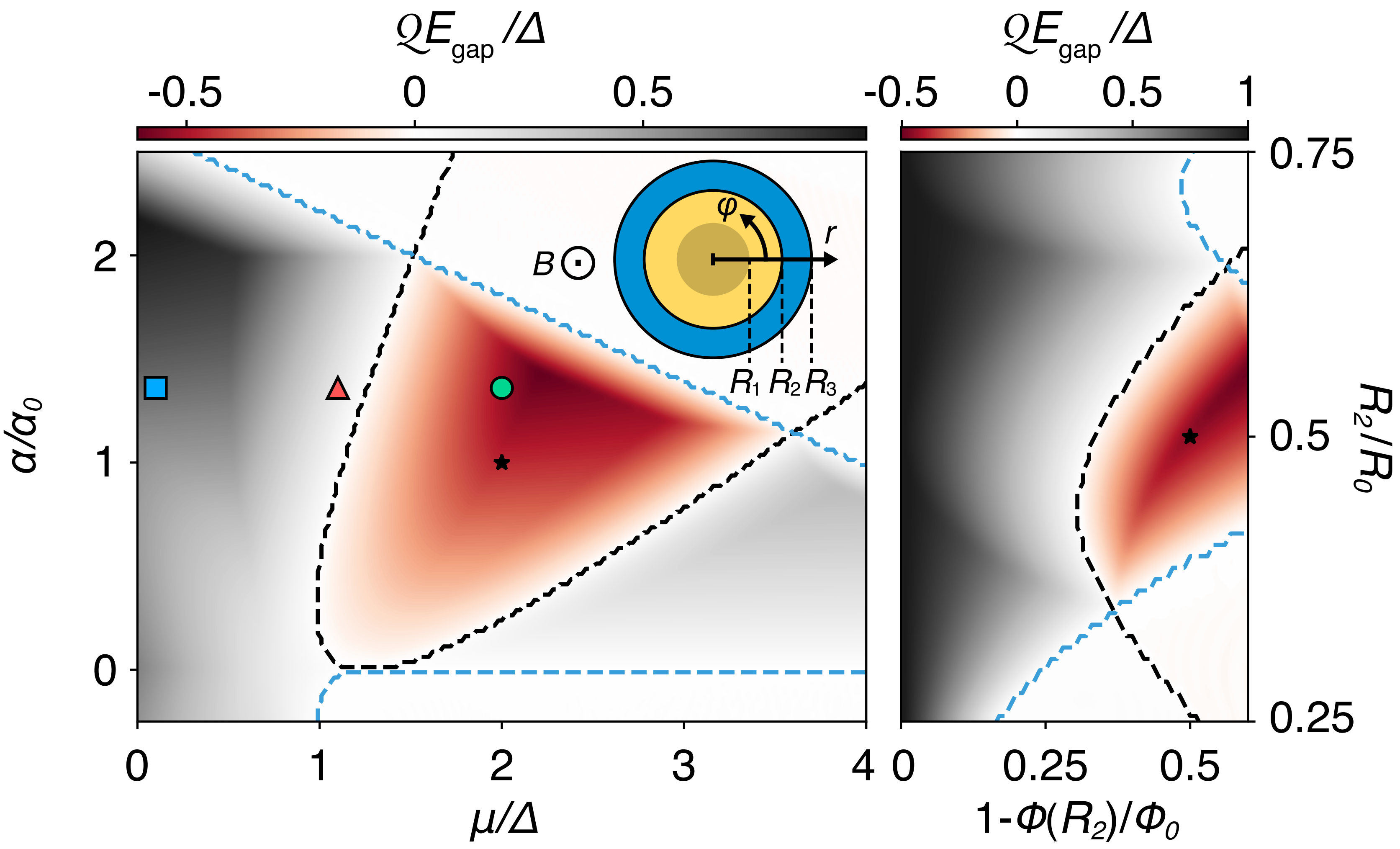


TOPOLOGICAL MATTER

Flux-induced topological superconductivity in full-shell nanowires

S. Vaitiekėnas, G. W. Winkler, B. van Heck, T. Karzig, M.-T. Deng, K. Flensberg, L. I. Glazman, C. Nayak, P. Krogstrup, R. M. Lutchyn*, C. M. Marcus*

Theory of the topological phase



TOPOLOGICAL MATTER

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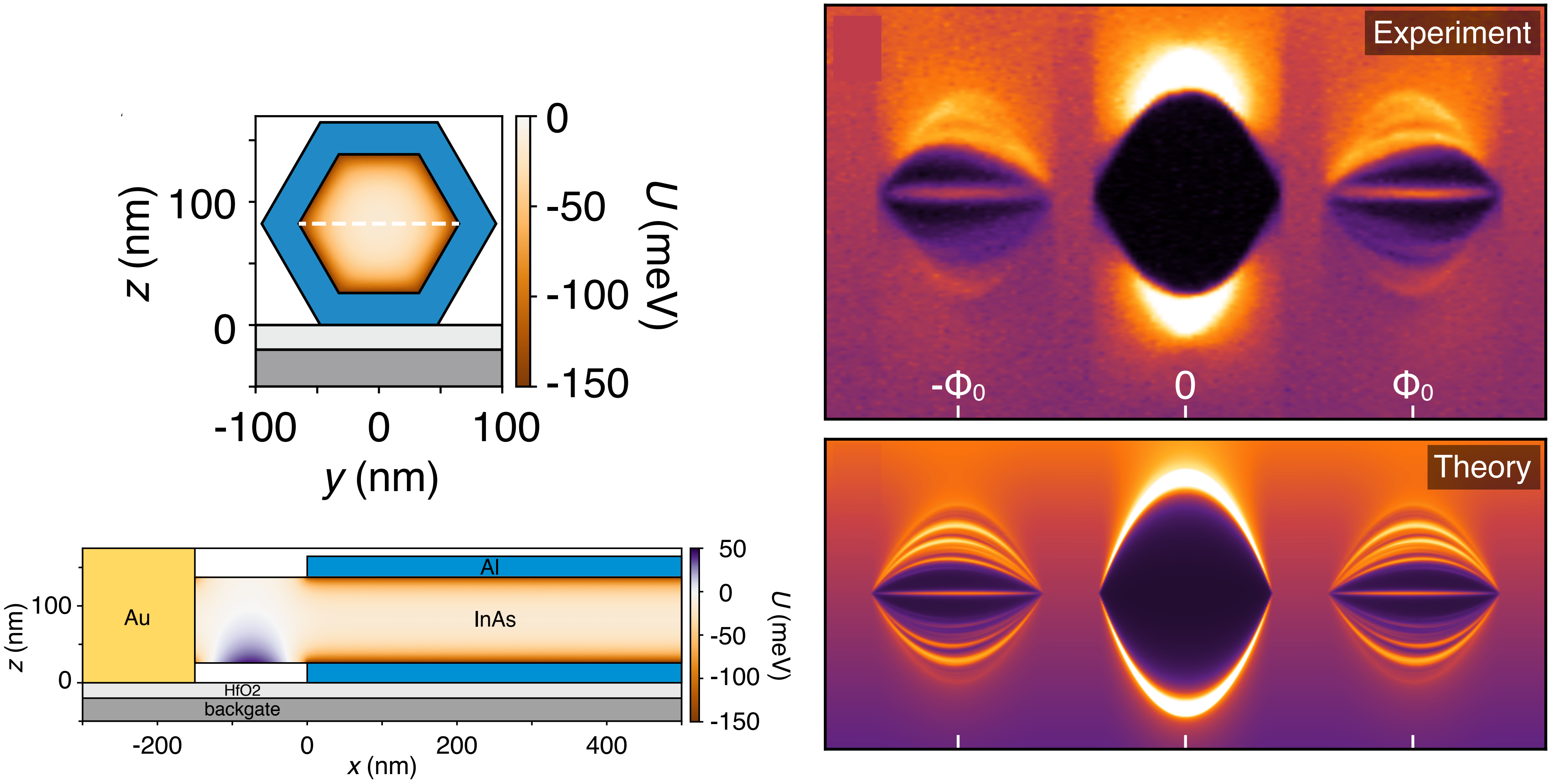
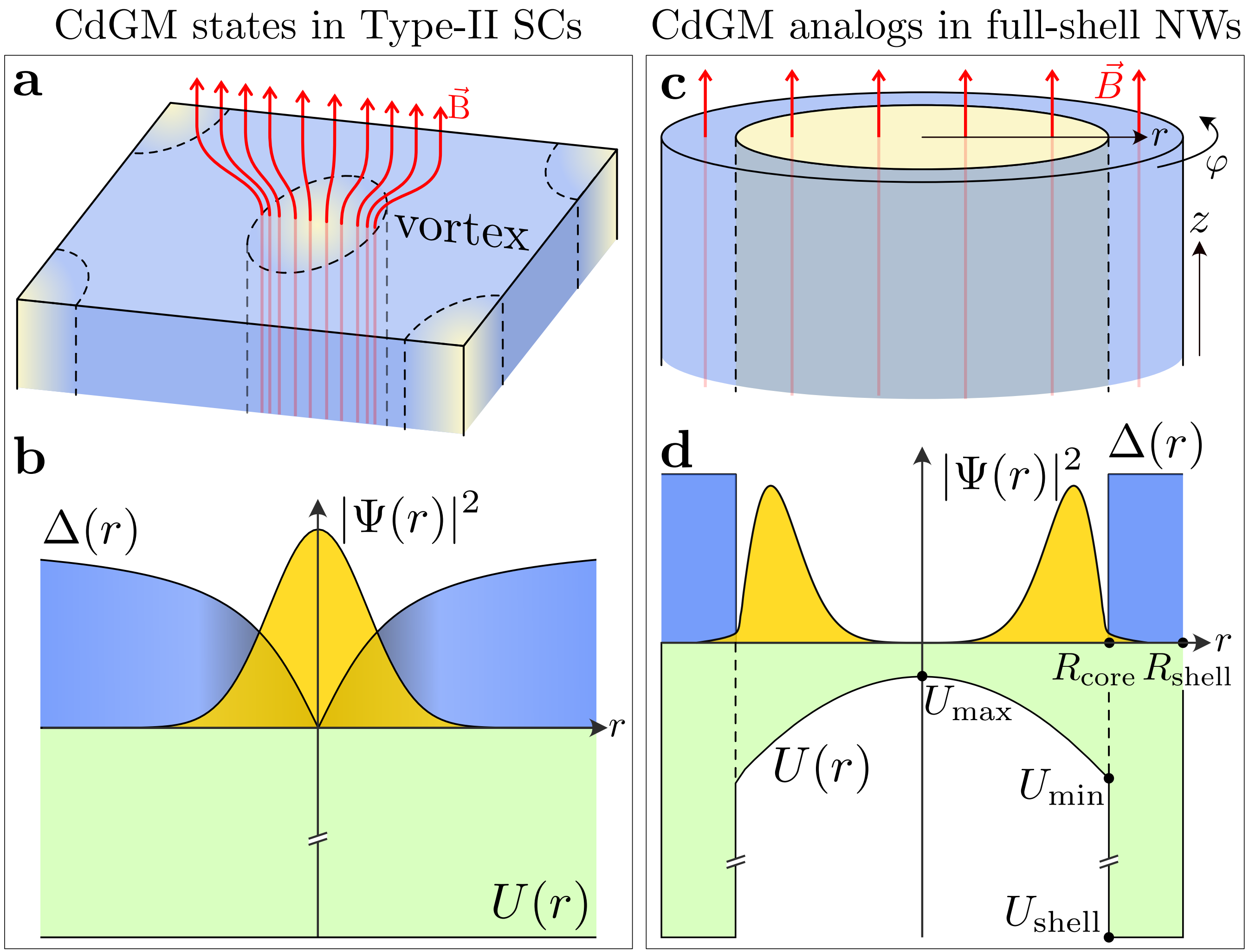


Theory of Caroli-de Gennes-Matricon analogs in full-shell nanowires

Pablo San-Jose,[1] Carlos Payá,[1] C. M. Marcus,[2] S. Vaitiekėnas,[2] and Elsa Prada[1]

[1] *Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Científicas (ICMM-CSIC), Madrid, Spain*
[2] *Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*

(Dated: July 18, 2022)



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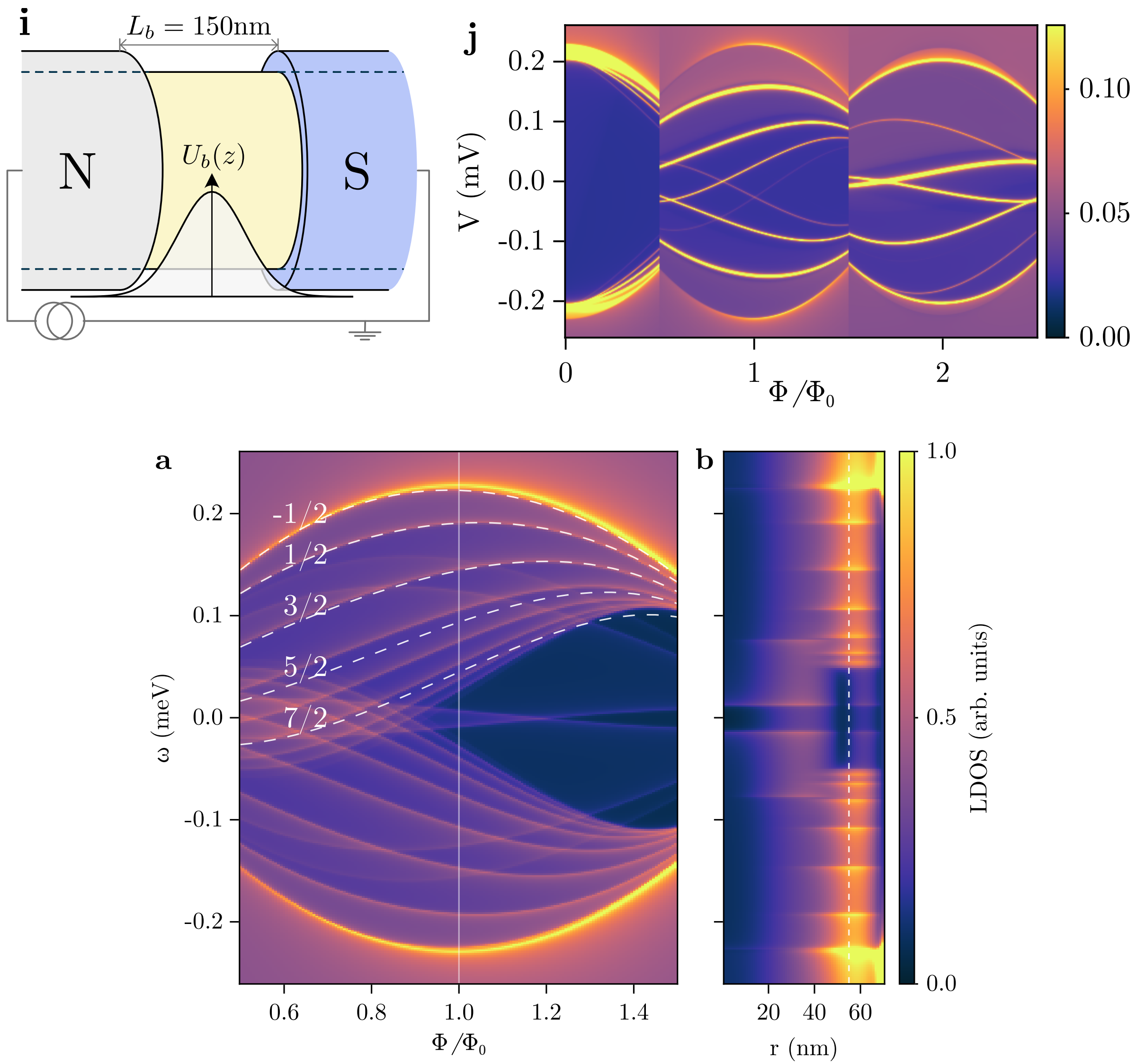
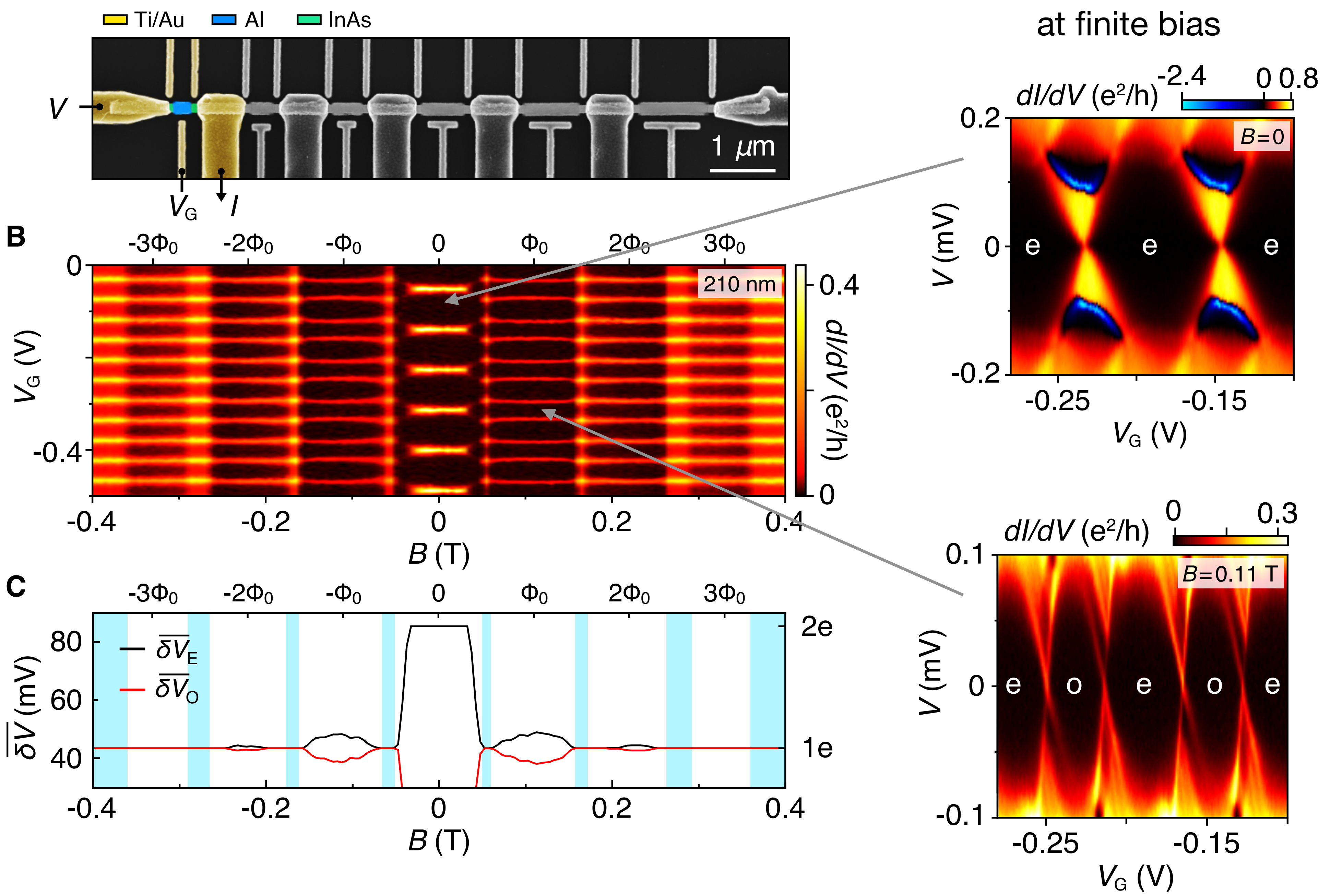
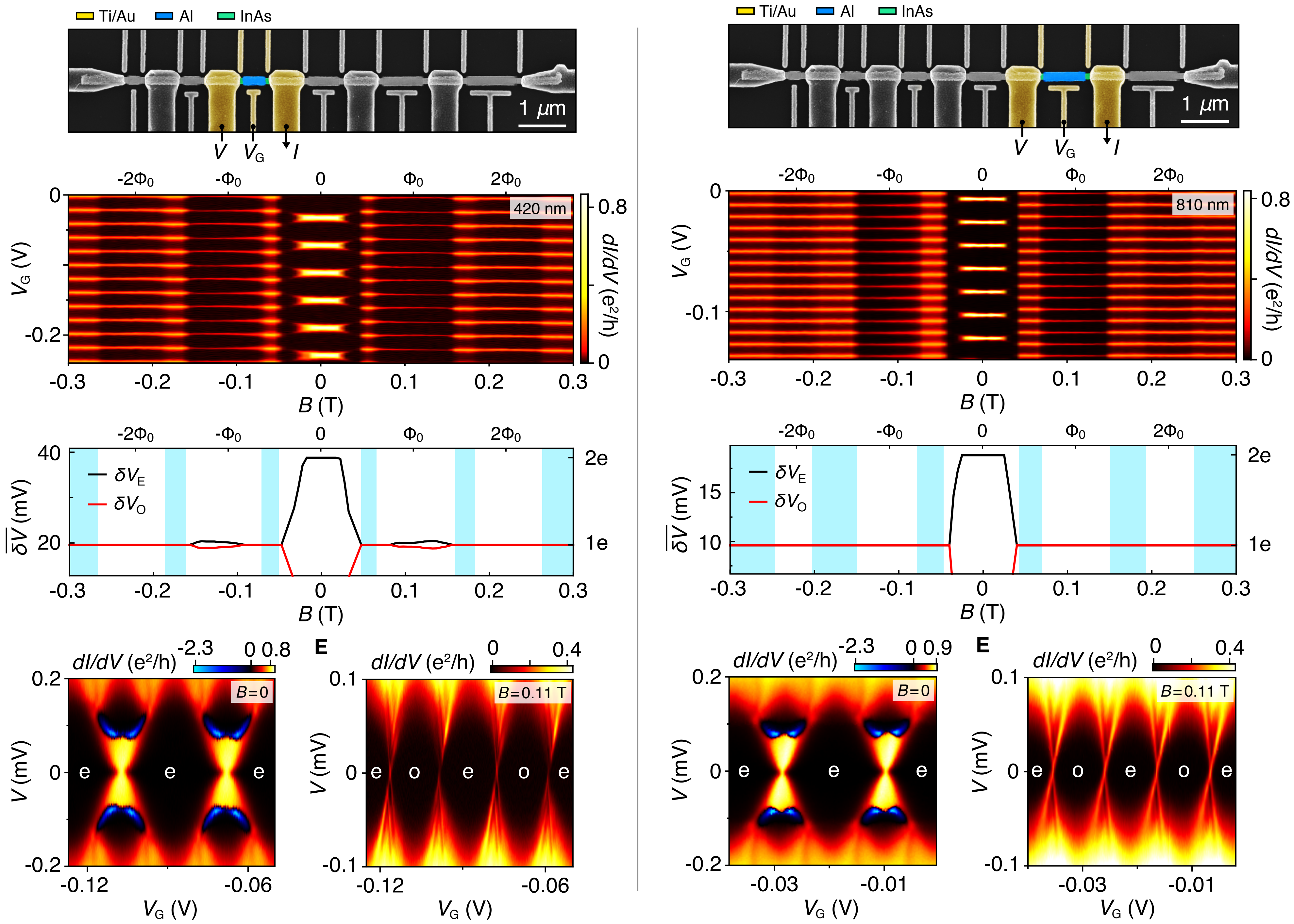


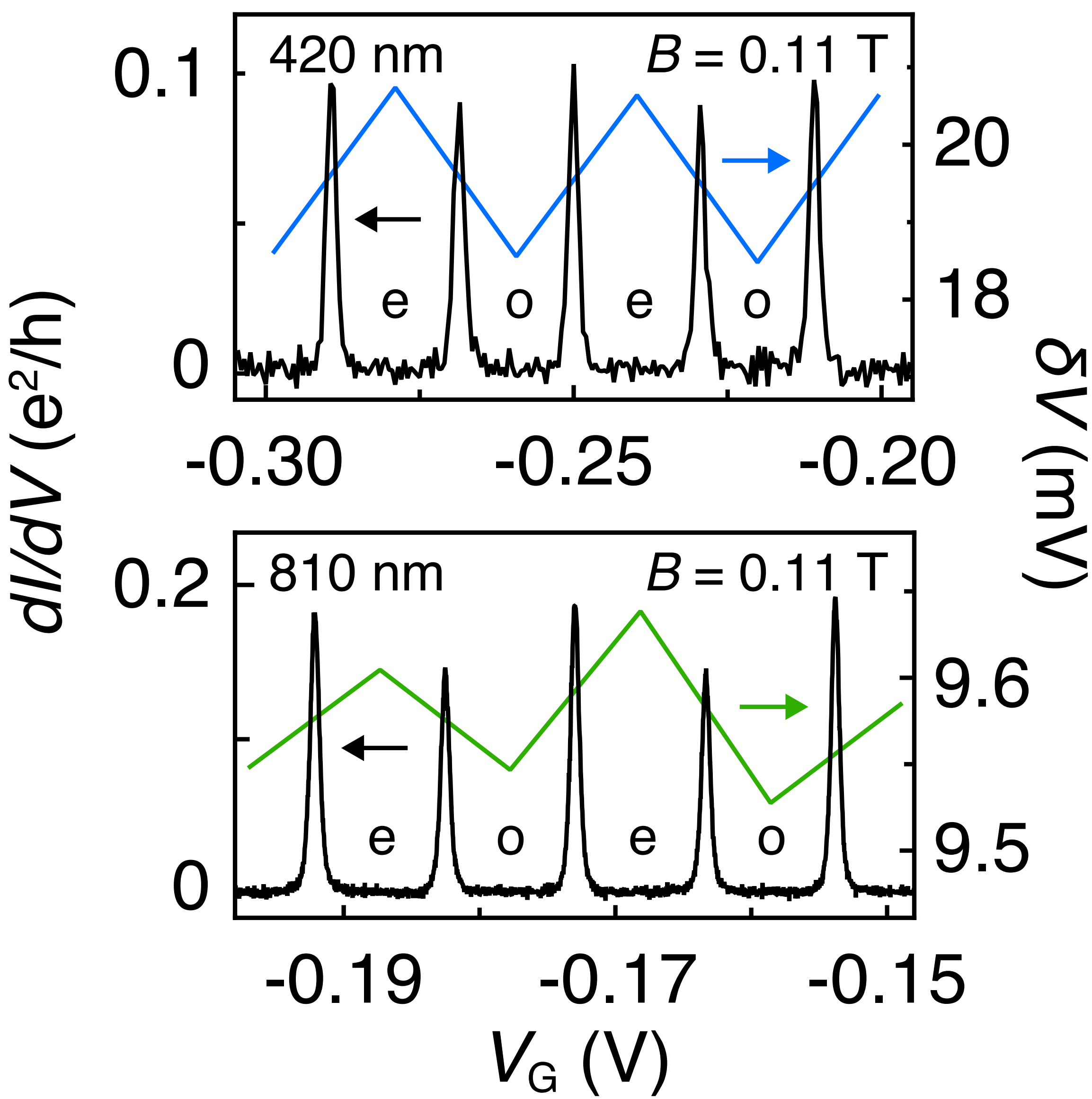
Length dependence of zero-bias splitting in Coulomb Islands



Length dependence of zero-bias splitting in Coulomb Islands



Length dependence of zero-bias splitting in Coulomb Islands

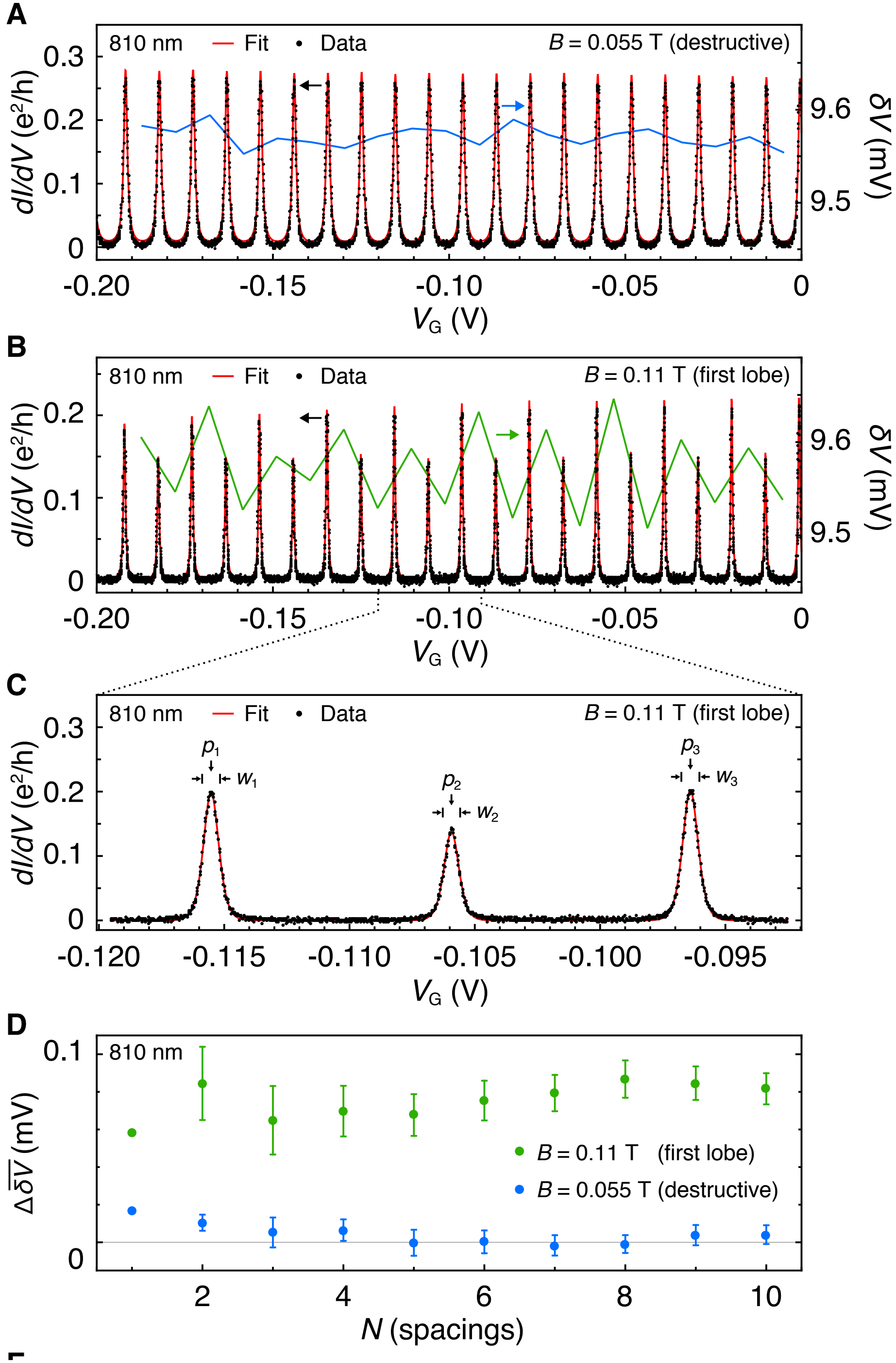


Longer segments have very small even odd spacing

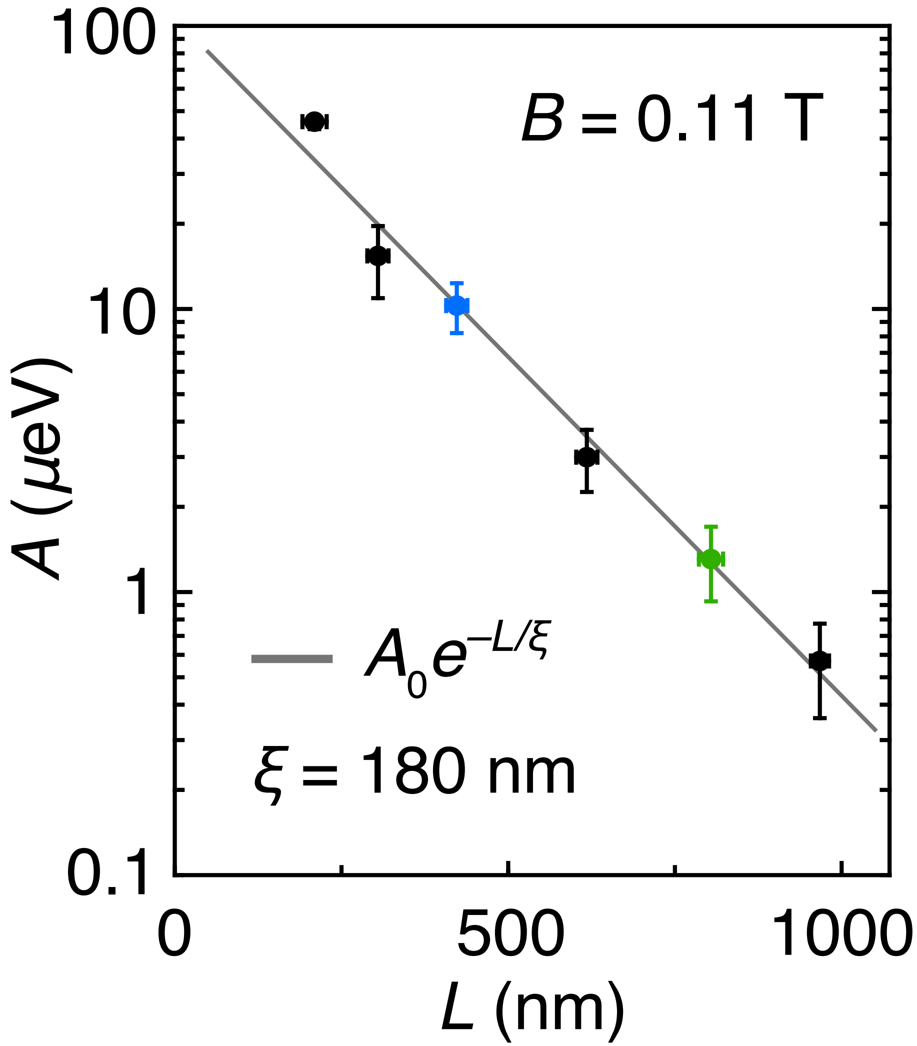
Length dependence of zero-bias splitting in Coulomb Islands

Destructive Regime (control)

First Lobe

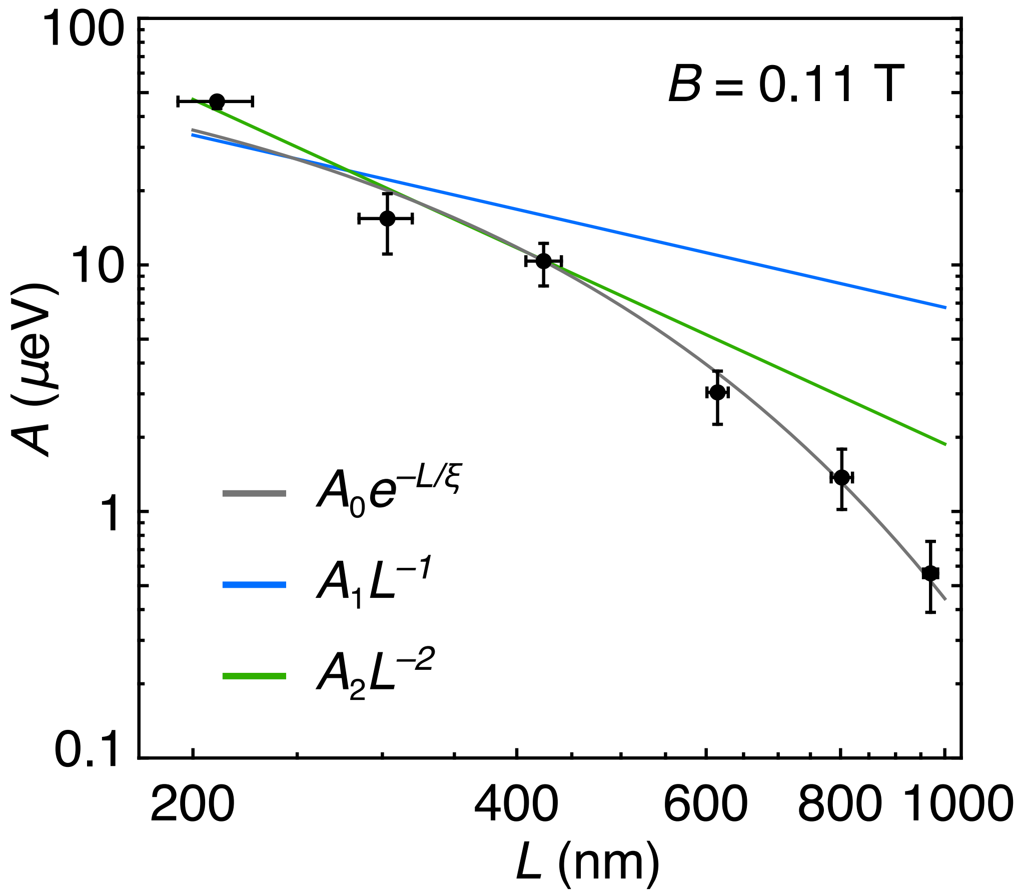


Length dependence of zero-bias splitting in Coulomb Islands



Length dependence of zero-bias splitting in Coulomb Islands

Comparing exponential and power-law splitting



Supercurrent Detection of Topologically Trivial Zero-Energy States in Nanowire Junctions

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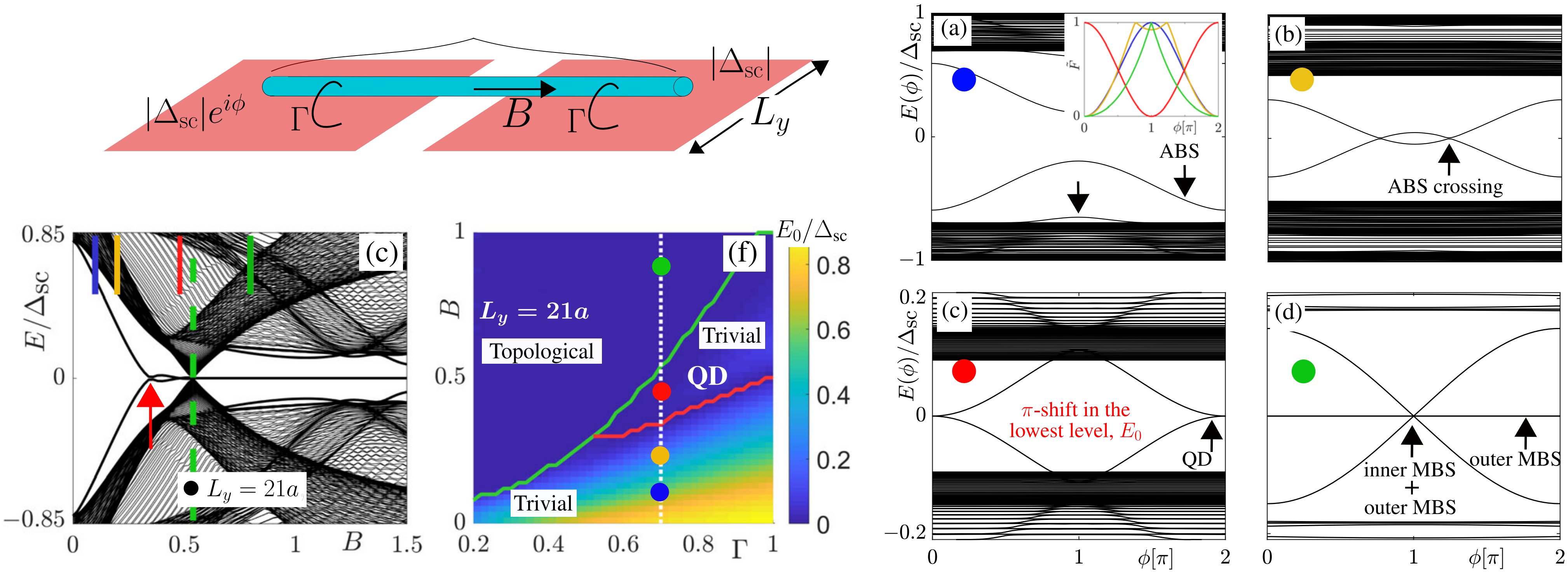
Department of Physics and Astronomy, Uppsala University, Box 516, S-751 20 Uppsala, Sweden

(Received 8 April 2019; published 12 September 2019)

We report the emergence of zero-energy states in the trivial phase of a short nanowire junction with a strong spin-orbit coupling and magnetic field, formed by strong coupling between the nanowire and two superconductors. The zero-energy states appear in the junction when the superconductors induce a large energy shift in the nanowire, such that the junction naturally forms a quantum dot, a process that is highly tunable by the superconductor width. Most importantly, we demonstrate that the zero-energy states produce a π shift in the phase-biased supercurrent, which can be used as a simple tool for their unambiguous detection, ruling out any Majorana-like interpretation.

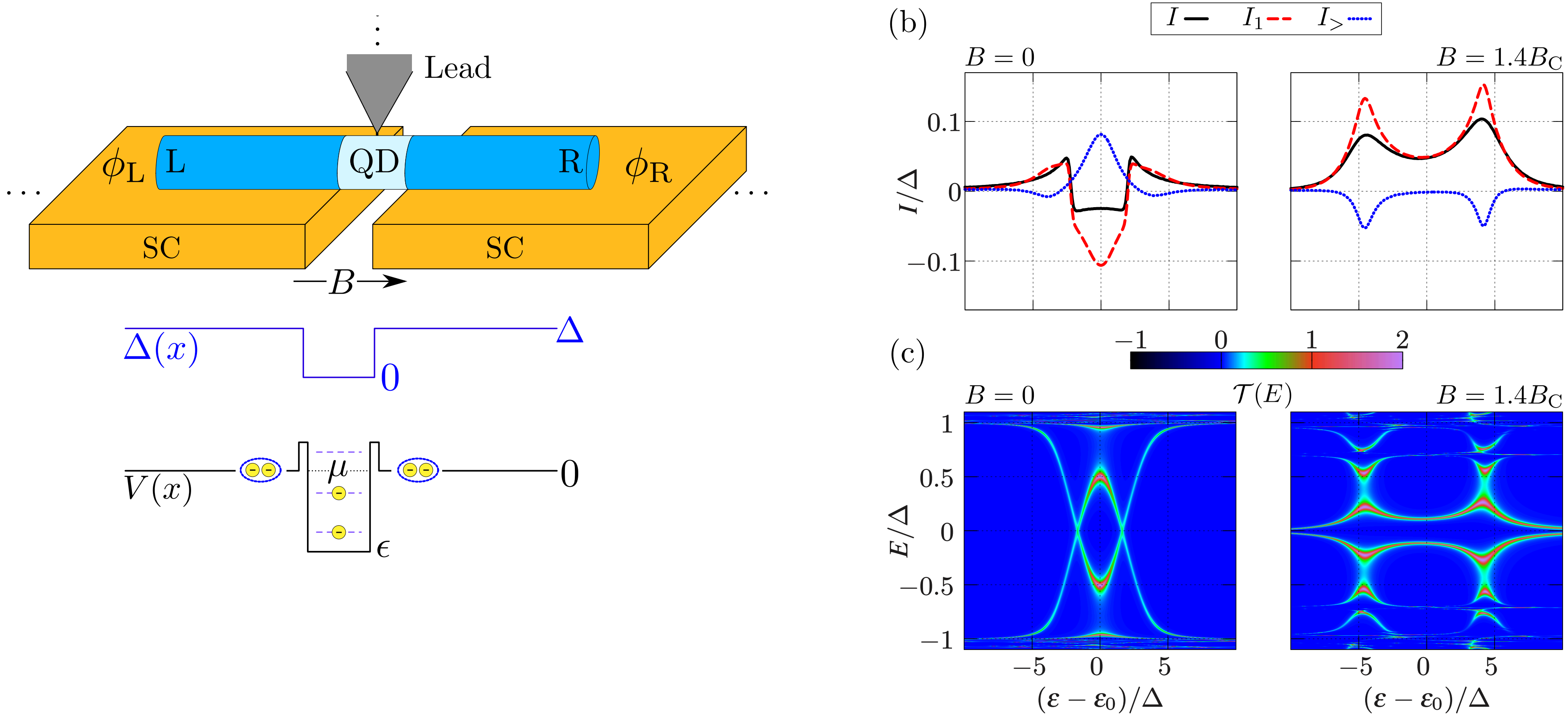


Absence of supercurrent sign reversal in a topological junction with a quantum dot

J. Schulenborg and K. Flensberg
Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

(Received 15 October 2019; revised manuscript received 6 January 2020; published 28 January 2020)

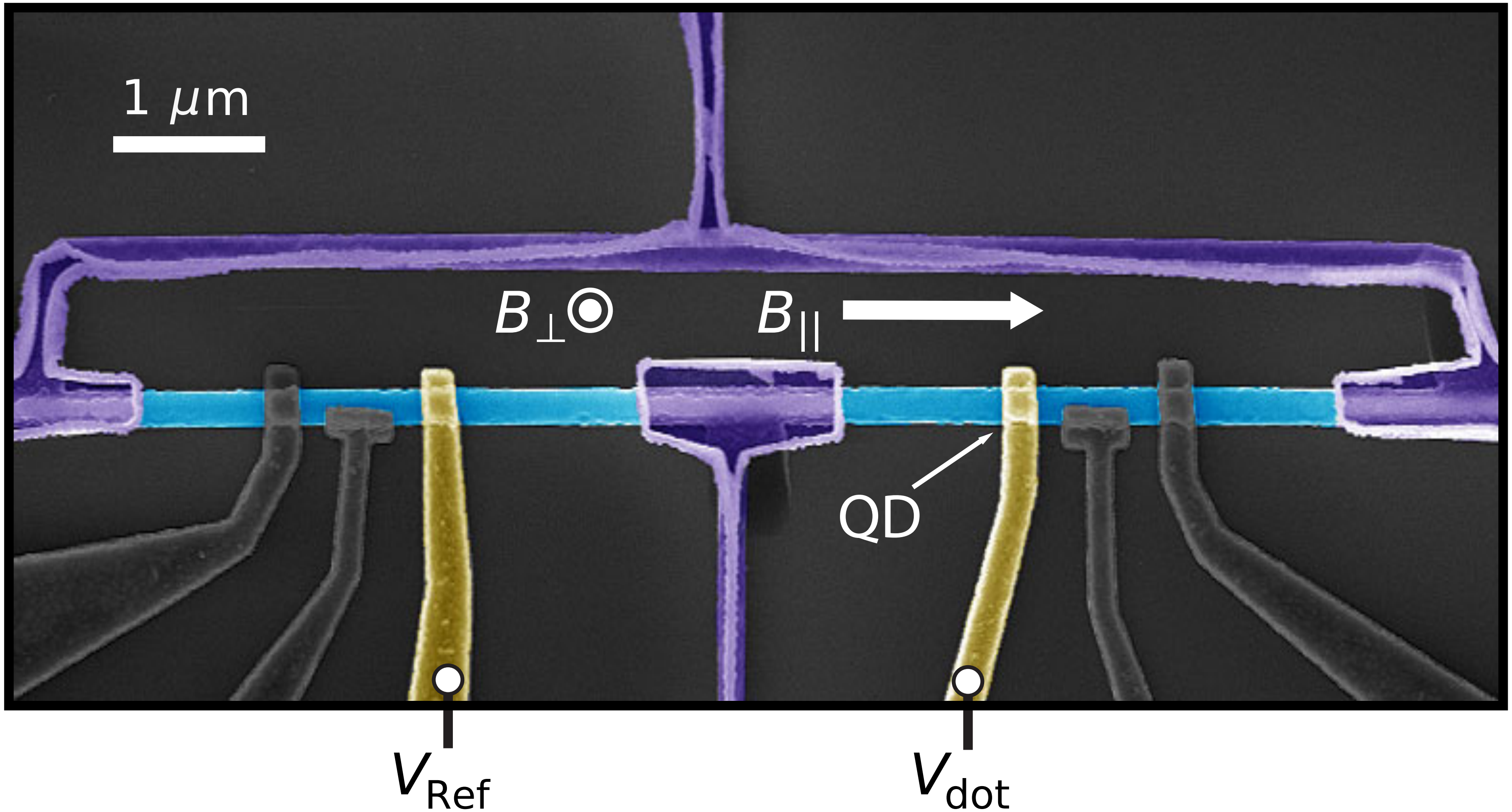
Experimental techniques to verify Majoranas are of current interest. A prominent test is the effect of Majoranas on the Josephson current between two wires linked via a normal junction. Here, we study the case of a quantum dot connecting the two superconductors and the sign of the supercurrent in the trivial and topological regimes under grand-canonical equilibrium conditions, explicitly allowing for parity changes due to, e.g., quasiparticle poisoning. We find that the well-known supercurrent reversal for odd occupancy of the quantum dot (π junction) in the trivial case does not occur in the presence of Majoranas in the wires. However, we also find this to be a mere consequence of Majoranas being zero energy states. Therefore, the lack of supercurrent sign reversal can also be caused by trivial bound states and is thus not a discriminating signature of Majoranas.



Quantum Dot Parity Effects in Trivial and Topological Josephson Junctions

D. Razmadze,[1,2] E. C. T. O'Farrell,[1,2] P. Krogstrup,[1,3] and C. M. Marcus[1,2]
[1]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*
[2]*Microsoft Quantum Lab–Copenhagen, 2100 Copenhagen, Denmark*
[3]*Microsoft Quantum Materials Lab–Copenhagen, 2800 Kongens Lyngby, Denmark*

(Received 24 May 2020; accepted 10 August 2020; published 8 September 2020)



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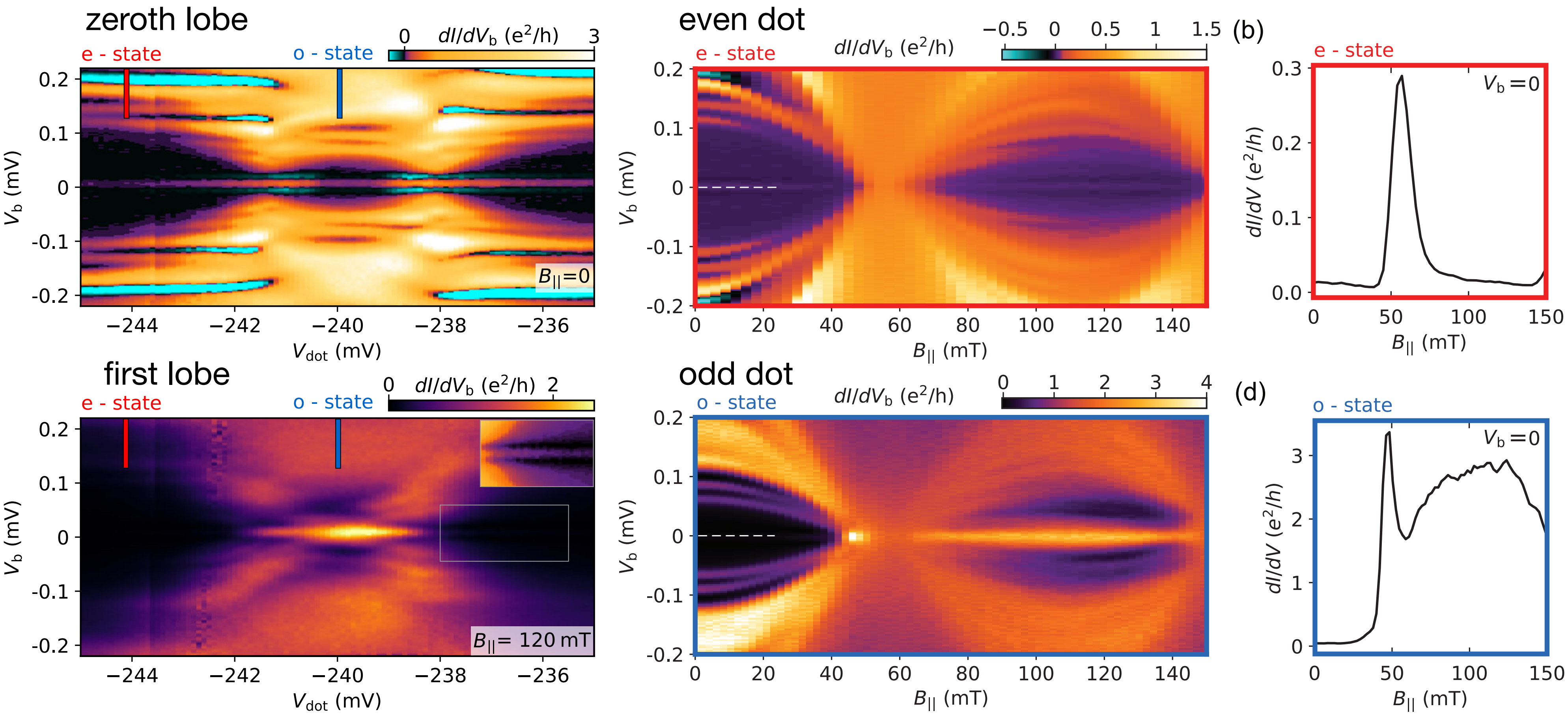

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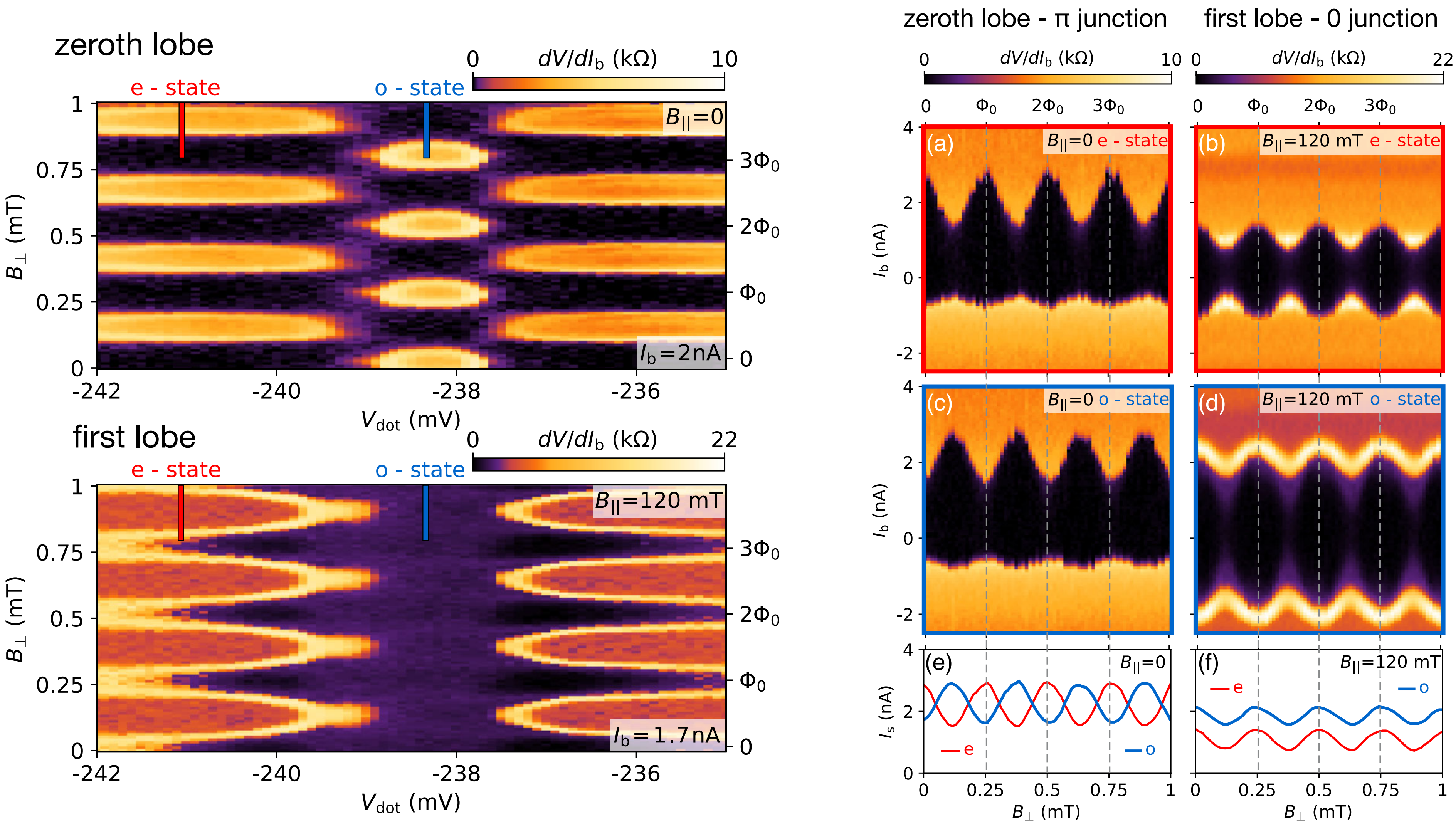
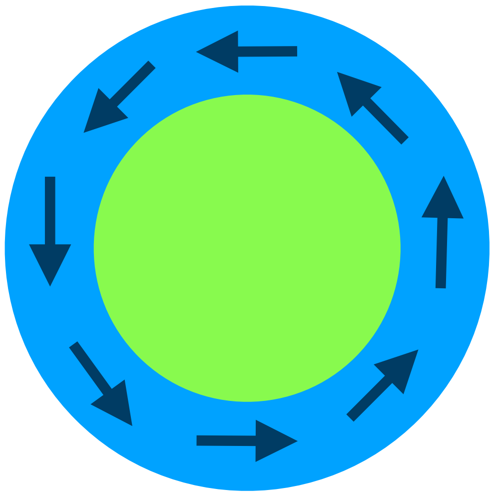
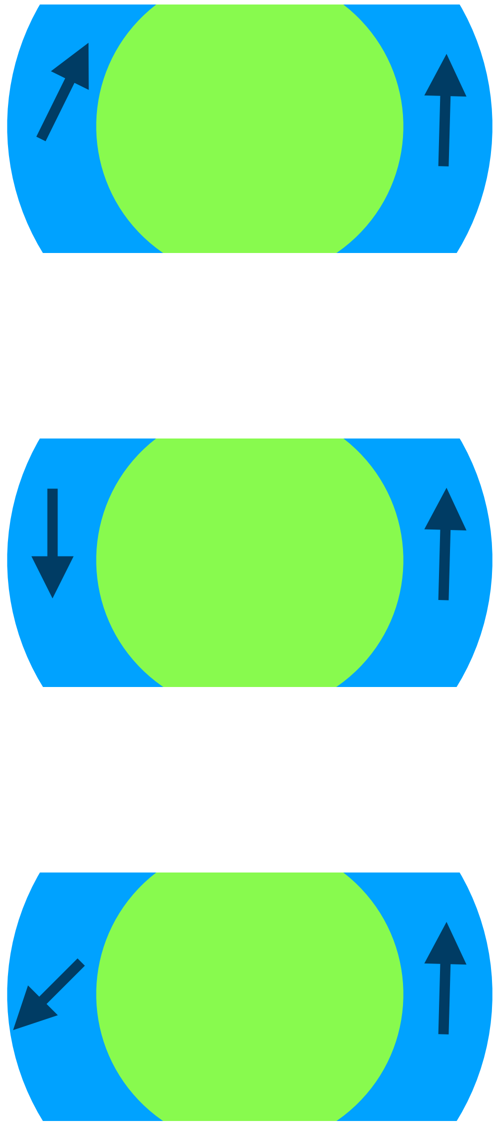


Frustrated proximity effect needn't be topological (quantized)



topologically locked
boundary condition
(fluxoid quantization)



unlocked phase difference

PHYSICAL REVIEW B VOLUME 55, NUMBER 2 1 JANUARY 1997-II

Nonstandard symmetry classes in mesoscopic normal-superconducting hybrid structures

Alexander Altland and Martin R. Zirnbauer
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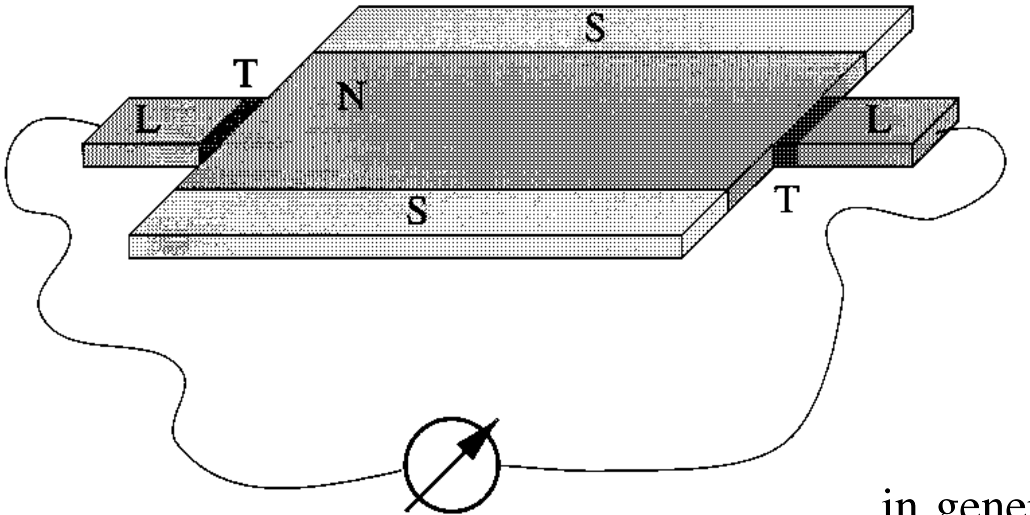
(Received 4 March 1996)



in general, an excitation gap opens up and we arrive at the ''boring'' situation where the vicinity of the chemical potential is devoid of single-particle states. However, by tuning the phase difference of the order parameters of the two superconducting regions to the special value π, we can make the gap close. More generally, we expect quasiparticle excitations to exist right at the chemical potential whenever the phase shift incurred during Andreev reflection vanishes on average over the NS-interfacial region.

Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

Liang Fu and C. L. Kane

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

(Received 11 July 2007; published 6 March 2008)

We study the proximity effect between an s-wave superconductor and the surface states of a strong topological insulator. The resulting two-dimensional state resembles a spinless $p_x + ip_y$ superconductor, but does not break time reversal symmetry. This state supports Majorana bound states at vortices. We show that linear junctions between superconductors mediated by the topological insulator form a nonchiral one-dimensional wire for Majorana fermions, and that circuits formed from these junctions provide a method for creating, manipulating, and fusing Majorana bound states.

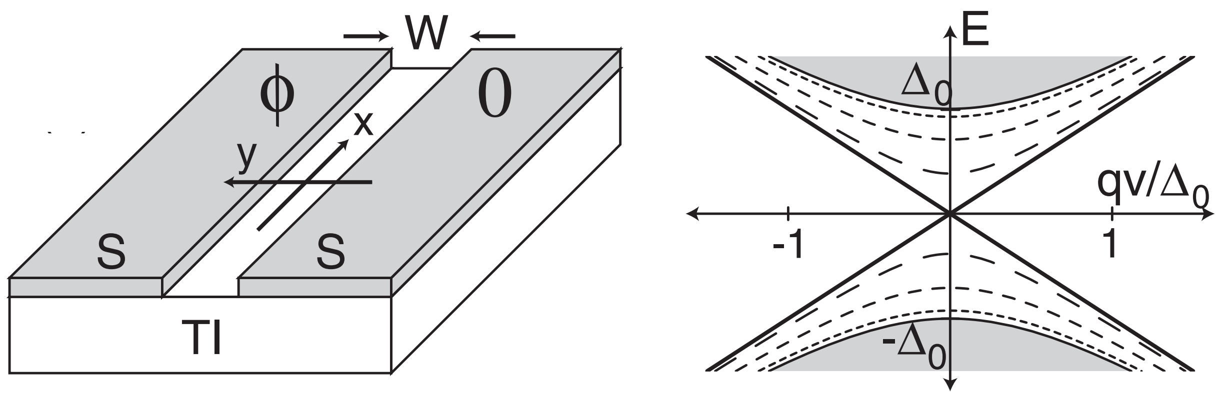
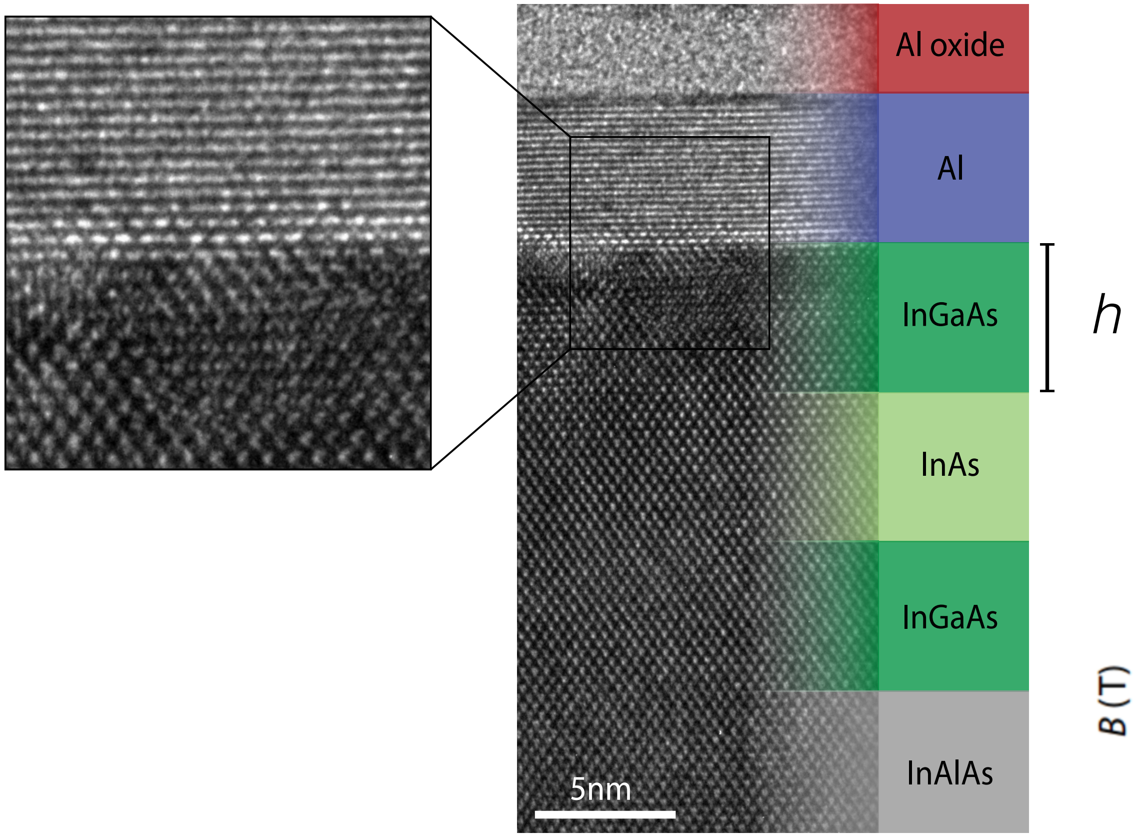


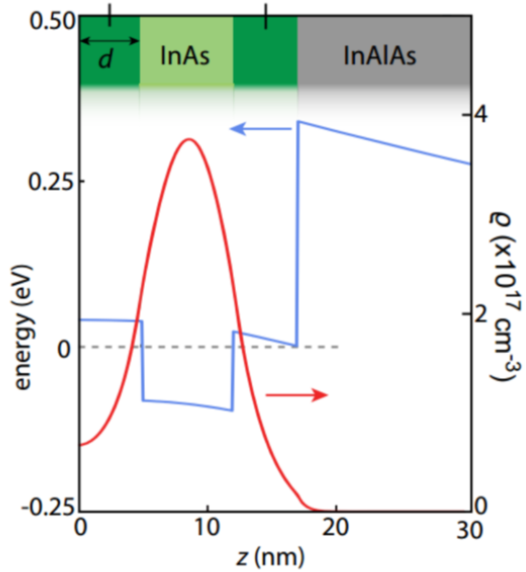
FIG. 1. (a) A STIS line junction. (b) Spectrum of a line junction for $W = \mu = 0$ as a function of momentum for various ϕ. The solid line shows the Andreev bound states for $\phi = \pi$. The dashed lines are for $\phi = 3\pi/4$, $\pi/2$, and $\pi/4$. The bound states for $\phi = 0$ merge with the continuum, indicated by the shaded region.

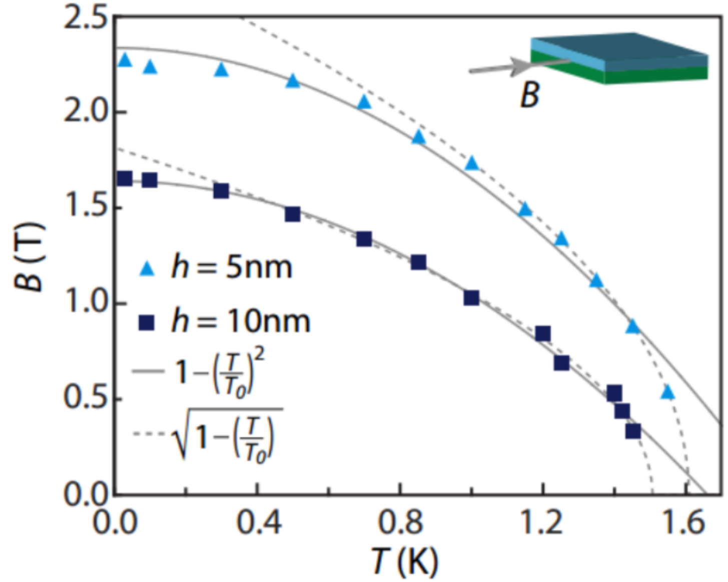
PHYSICAL REVIEW B **93**, 155402 (2016)

Two-dimensional epitaxial superconductor-semiconductor heterostructures: A platform for topological superconducting networks

J. Shabani,[1,2] M. Kjaergaard,[3] H. J. Suominen,[3] Younghyun Kim,[4] F. Nichele,[3] K. Pakrouski,[5] T. Stankevic,[3] R. M. Lutchyn,[6] P. Krogstrup,[3] R. Feidenhans'l,[3] S. Kraemer,[7] C. Nayak,[4,6] M. Troyer,[5] C. M. Marcus,[3] and C. J. Palmstrøm[1,7,8]







Two-Dimensional Platform for Networks of Majorana Bound States

Michael Hell,[1,2] Martin Leijnse,[1,2] and Karsten Flensberg[1]
[1]*Center for Quantum Devices and Station Q Copenhagen, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark*
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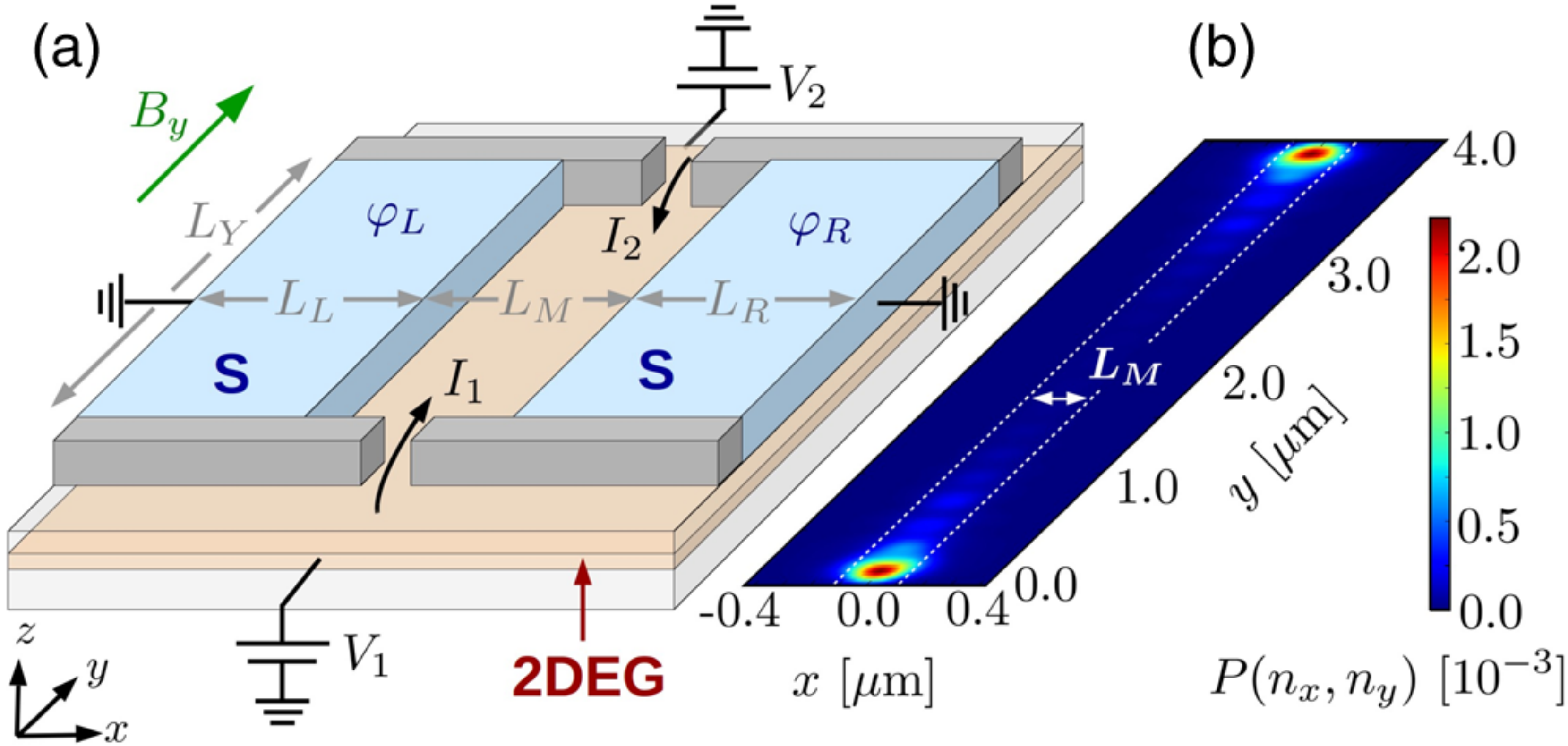
(Received 5 September 2016; published 10 March 2017)



PHYSICAL REVIEW X **7,** 021032 (2017)

Topological Superconductivity in a Planar Josephson Junction

Falko Pientka,[1] Anna Keselman,[2] Erez Berg,[2] Amir Yacoby,[1] Ady Stern,[2] and Bertrand I. Halperin[1]
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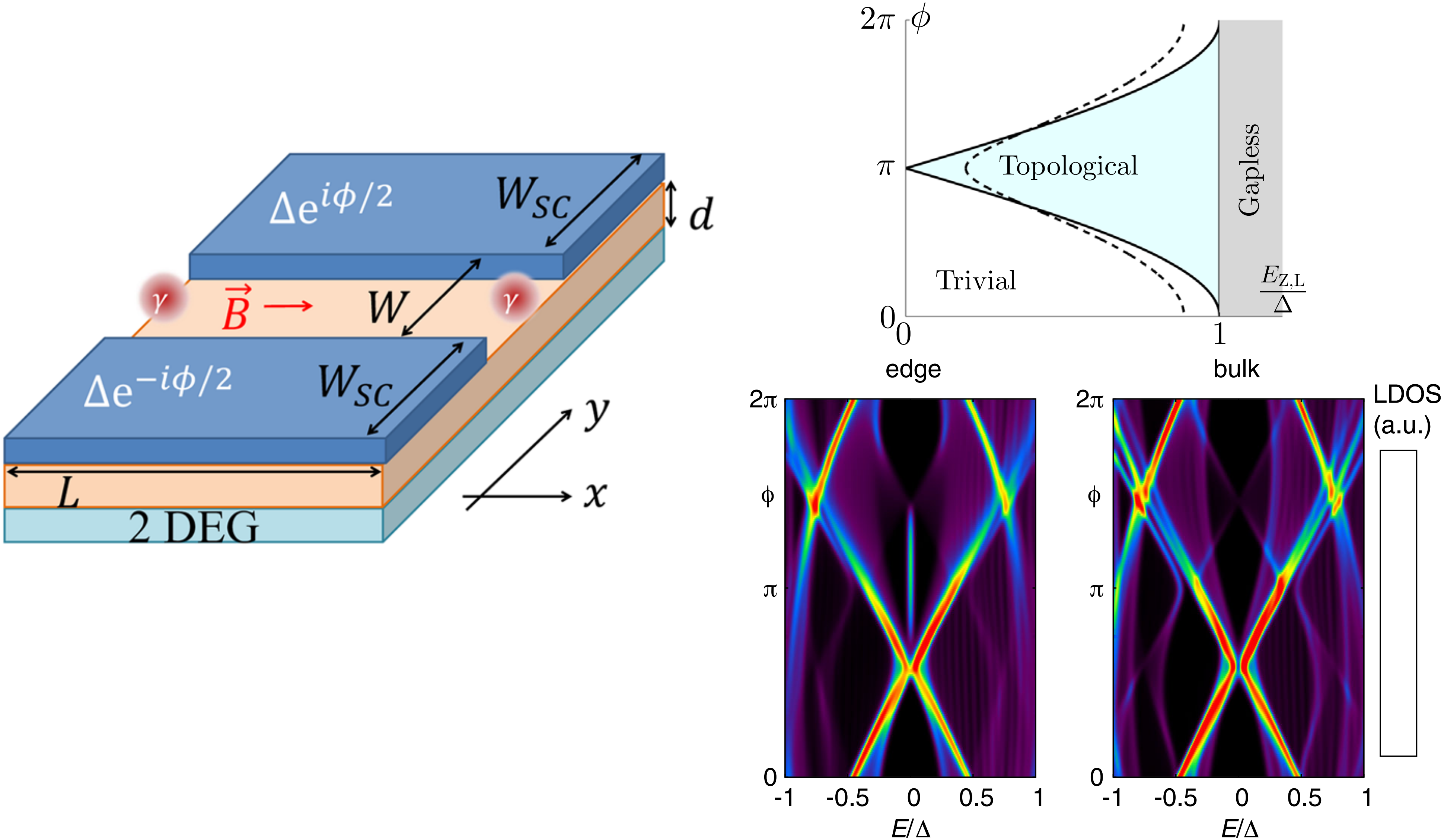
[2]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel 76100*
(Received 13 October 2016; revised manuscript received 17 January 2017; published 30 May 2017)



Benefits of Weak Disorder in One-Dimensional Topological Superconductors

Arbel Haim[1] and Ady Stern[2]
[1]*Walter Burke Institute for Theoretical Physics and the Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 7610001, Israel*

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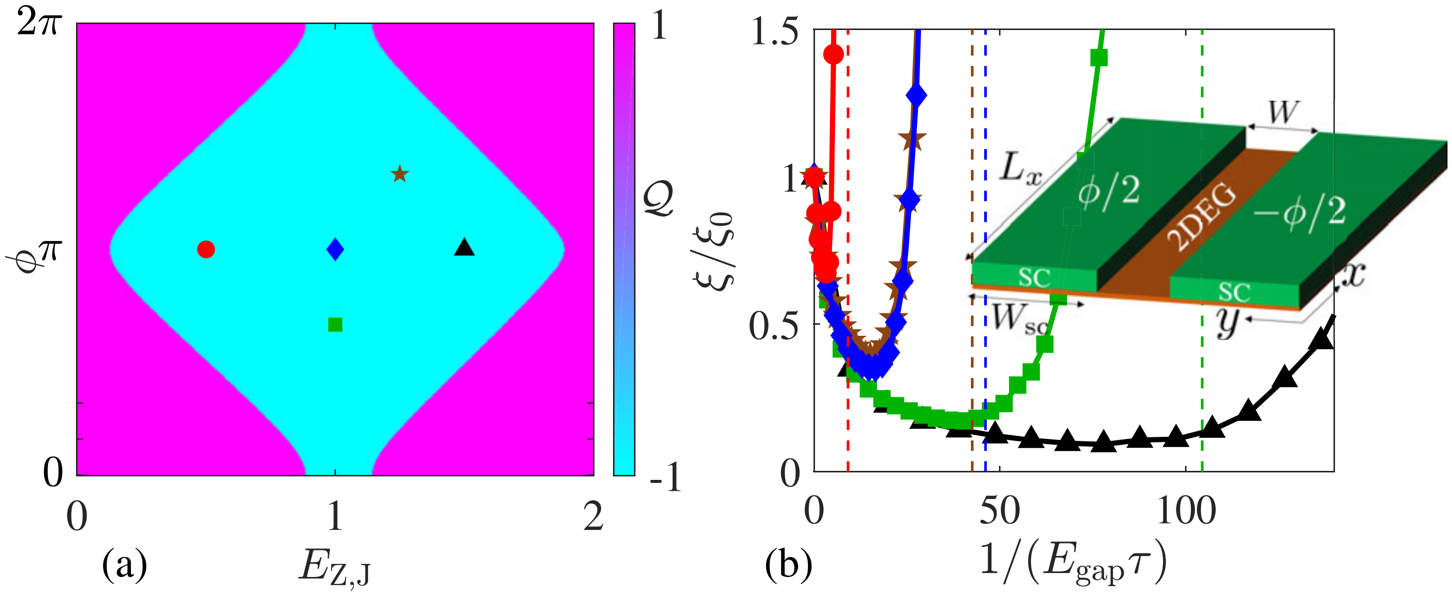
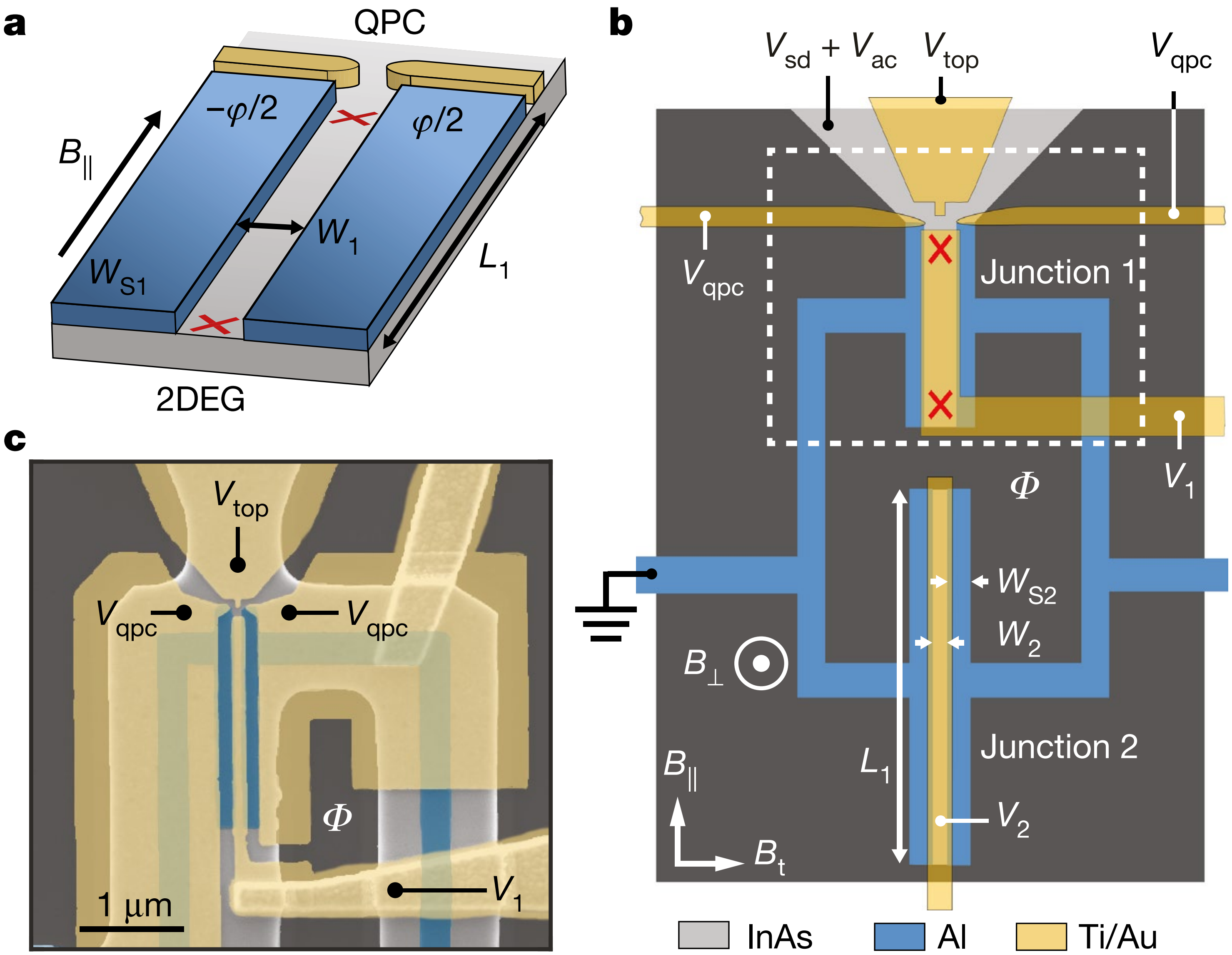
Majorana bound states are zero-energy modes localized at the ends of a one-dimensional (1D) topological superconductor. Introducing disorder usually increases the Majorana localization length, until eventually inducing a topological phase transition to a trivial phase. In this Letter, we show that in some cases weak disorder causes the Majorana localization length to *decrease*, making the topological phase more robust. Increasing the disorder further eventually leads to a change of trend and to a phase transition to a trivial phase. Interestingly, the transition occurs at $\xi_0 \gg l$, where l is the disorder mean free path, and ξ_0 is the localization length in the clean limit. Our results are particularly relevant to 1D topological superconductors formed in planar Josephson junctions.



Evidence of topological superconductivity in planar Josephson junctions

RESEARCH LETTER

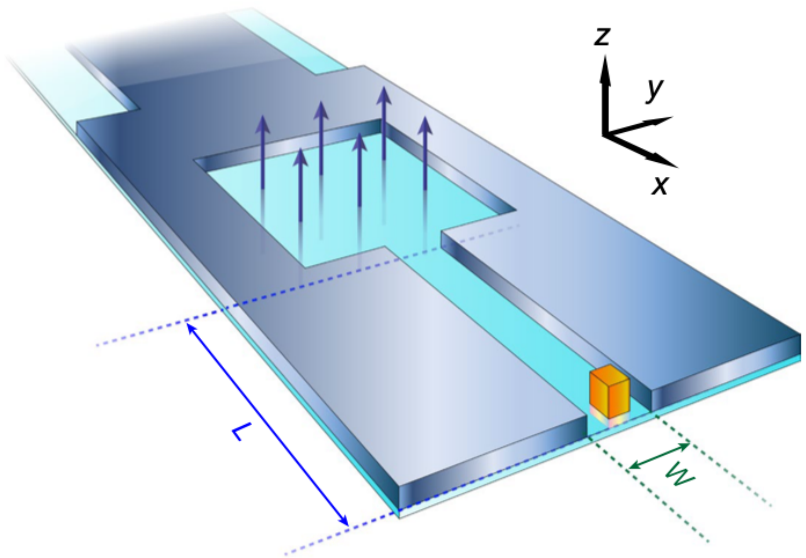
Antonio Fornieri[1,10], Alexander M. Whiticar[1,10], F. Setiawan[2], Elías Portolés Marín[1], Asbjørn C. C. Drachmann[1], Anna Keselman[3], Sergei Gronin[4,5], Candice Thomas[4,5], Tian Wang[4,5], Ray Kallaher[4,5], Geoffrey C. Gardner[4,5], Erez Berg[2,6], Michael J. Manfra[4,5,7,8], Ady Stern[6], Charles M. Marcus[1]* & Fabrizio Nichele[1,9]*

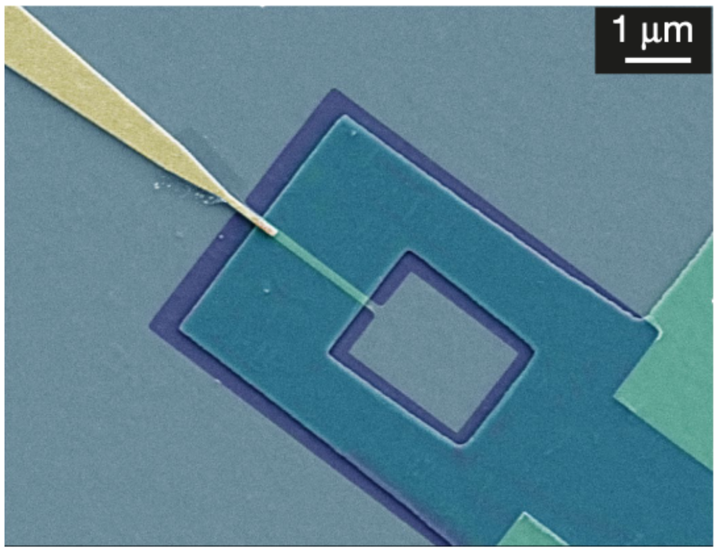


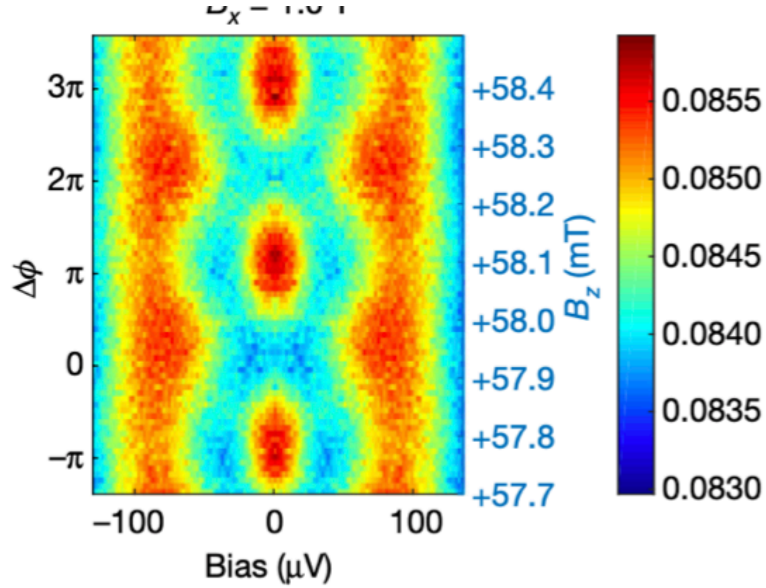
Topological superconductivity in a phase-controlled Josephson junction

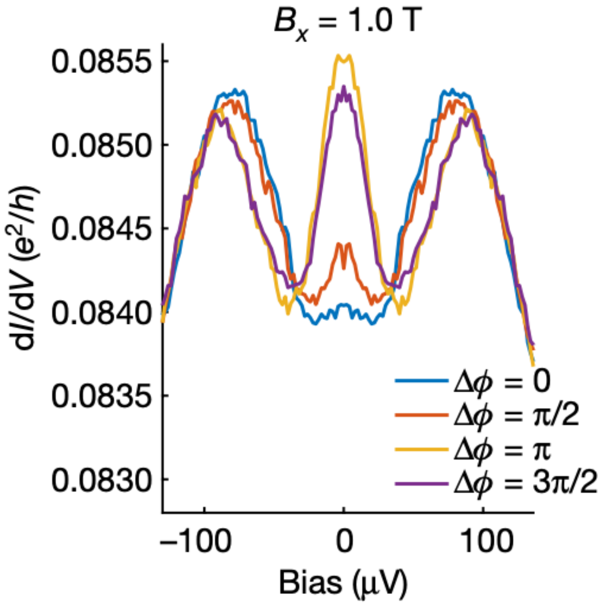
RESEARCH LETTER

Hechen Ren[1,2], Falko Pientka[1,3], Sean Hart[1,4], Andrew T. Pierce[1], Michael Kosowsky[1], Lukas Lunczer[5], Raimund Schlereth[5], Benedikt Scharf[6], Ewelina M. Hankiewicz[6], Laurens W. Molenkamp[5], Bertrand I. Halperin[1] & Amir Yacoby[1]*









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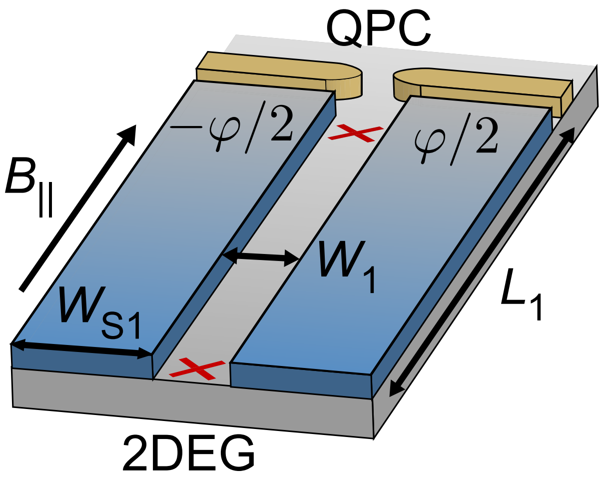

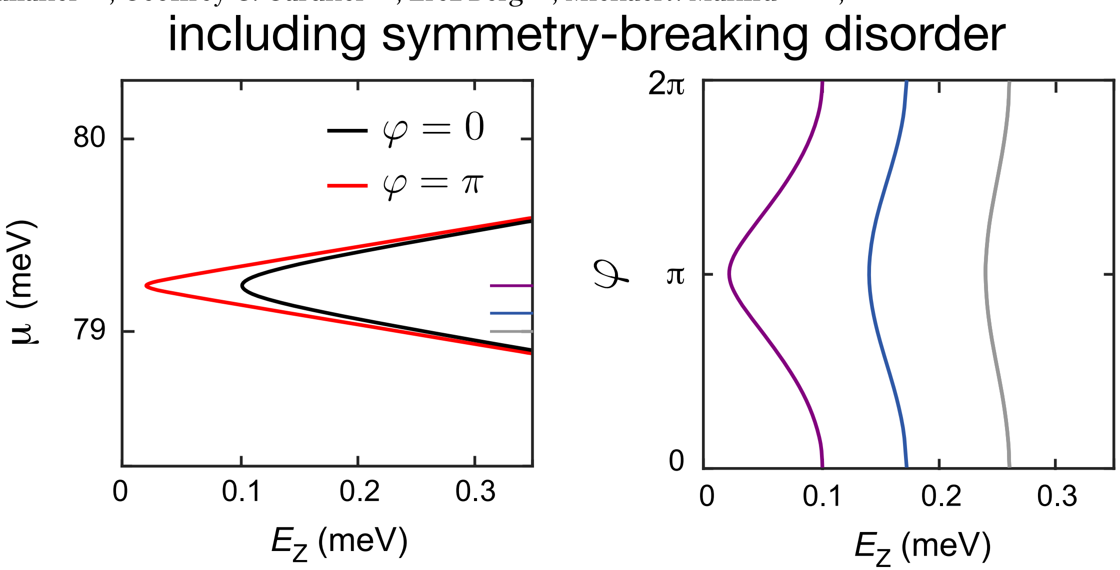

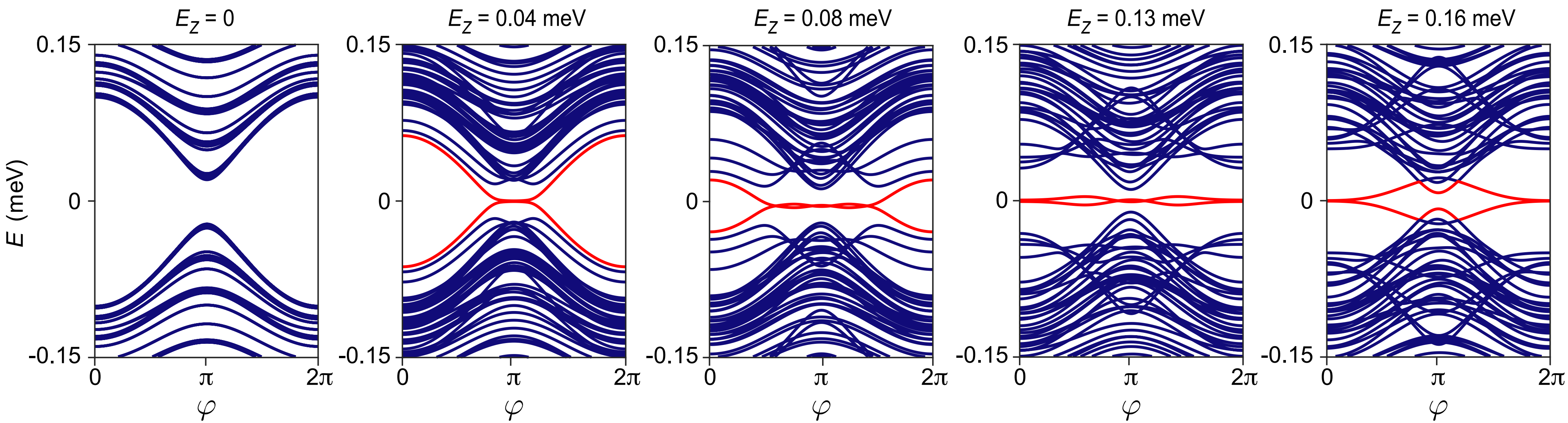

RESEARCH LETTER

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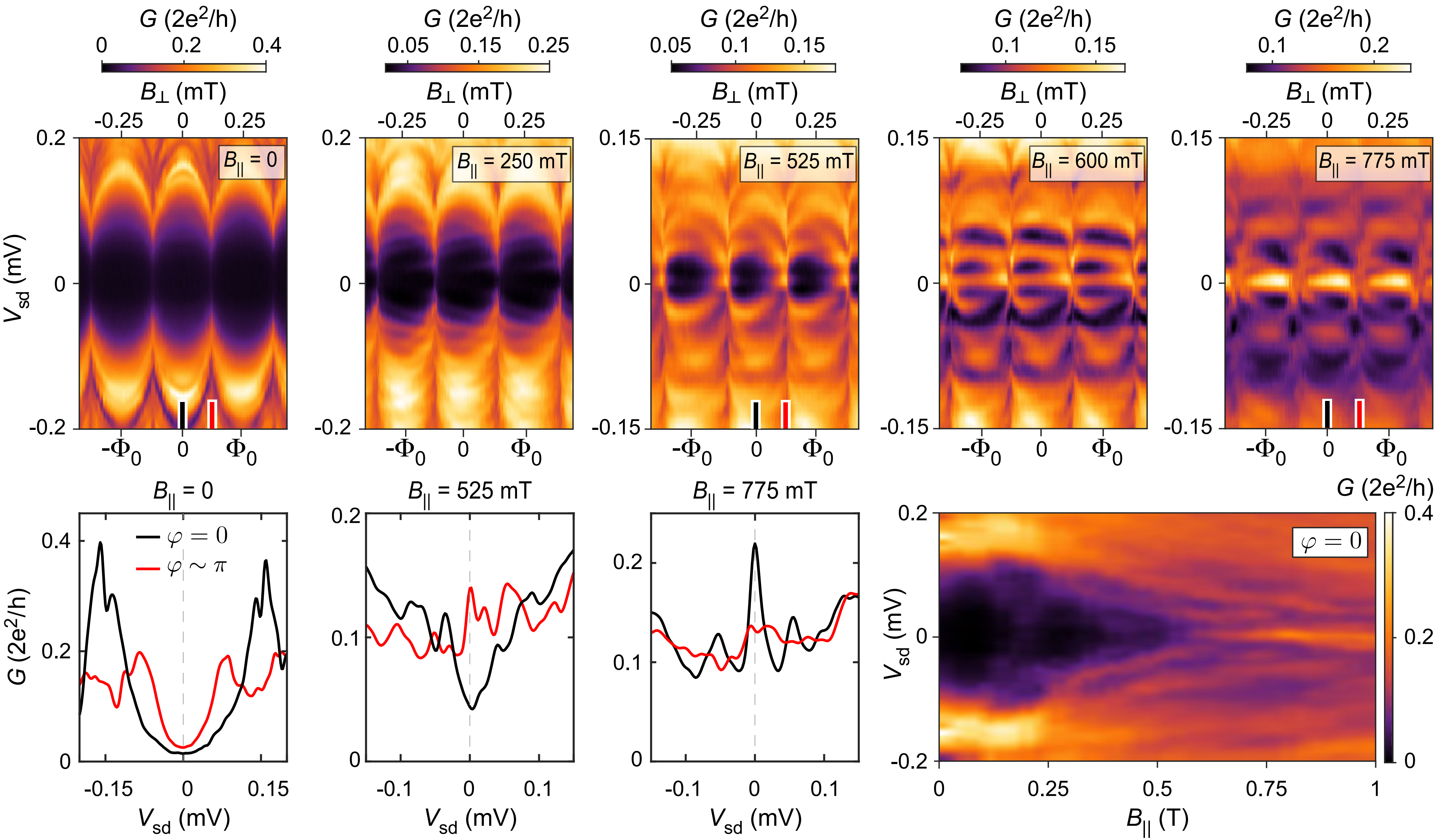

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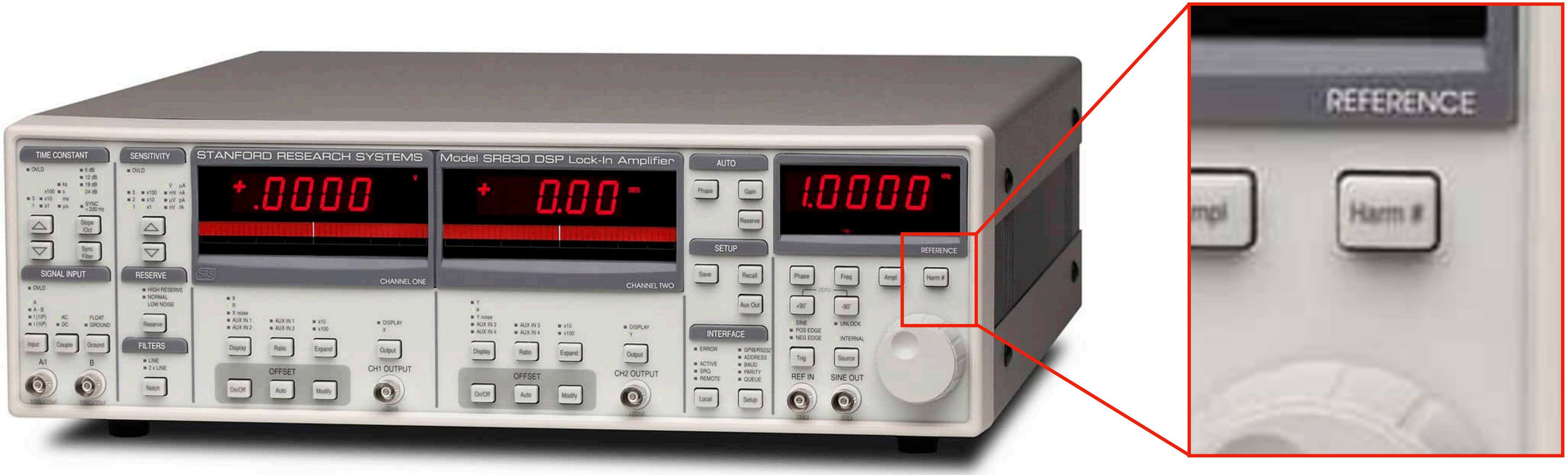
Phase diagram and Majorana hunting



"The Majorana Button"
- J. Eisenstein

$$I(t) \simeq I(V_{\rm sd}) + \frac{\partial I}{\partial V}\bigg|_{V_{\rm sd}} V_{\rm ac}\sin(\omega t) + \frac{1}{2}\frac{\partial^2 I}{\partial V^2}\bigg|_{V_{\rm sd}} \times [V_{\rm ac}\sin(\omega t)]^2 + \frac{1}{6}\frac{\partial^3 I}{\partial V^3}\bigg|_{V_{\rm sd}} [V_{\rm ac}\sin(\omega t)]^3.$$

$$I_{3\omega}(V_{\rm sd}) = -\frac{1}{24}\frac{\partial^3 I}{\partial V^3}\bigg|_{V_{\rm sd}} V_{\rm ac}^3 \propto -\frac{\partial^2 G}{\partial V^2}\bigg|_{V_{\rm sd}}$$

Evidence of topological superconductivity in planar Josephson junctions

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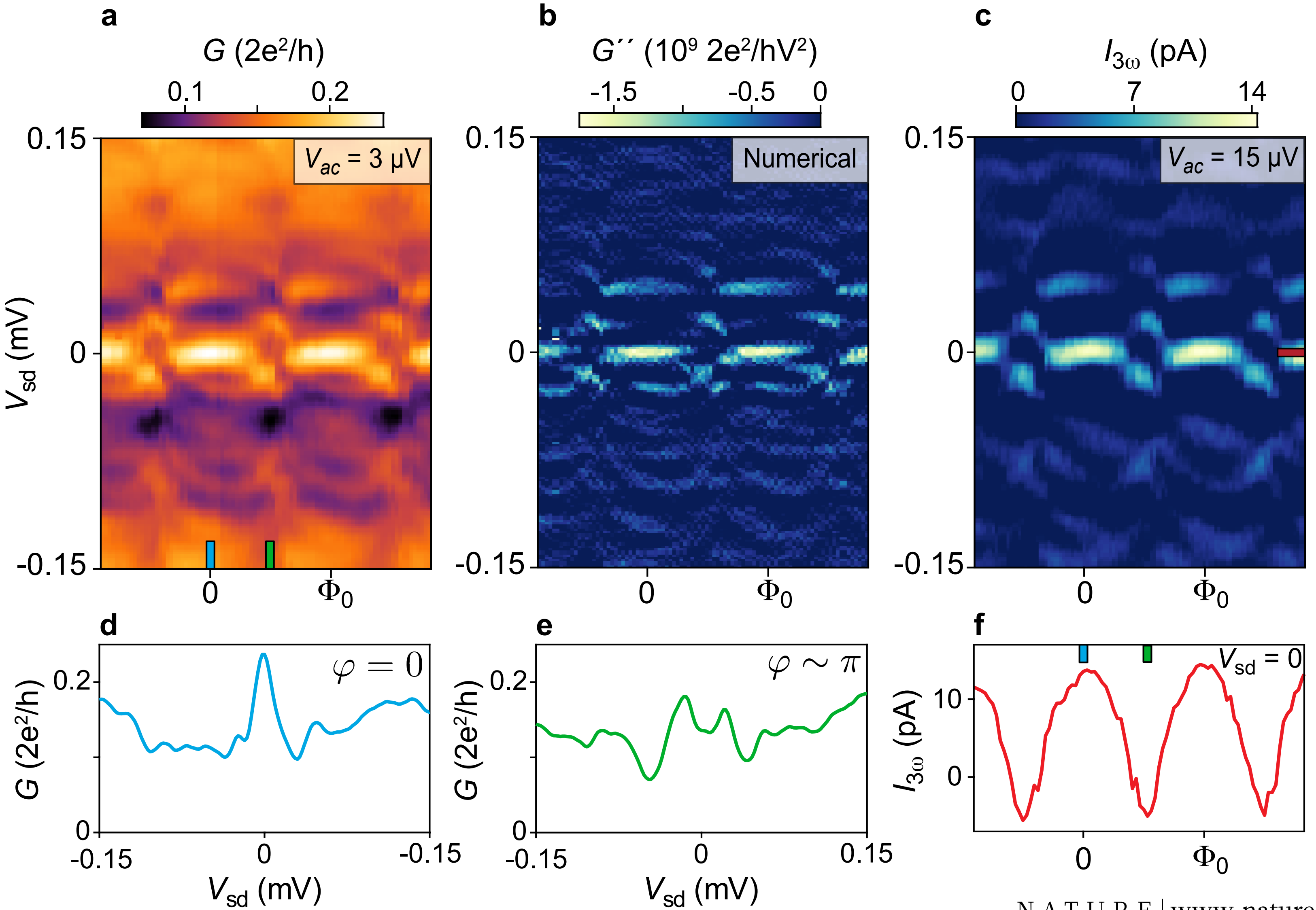

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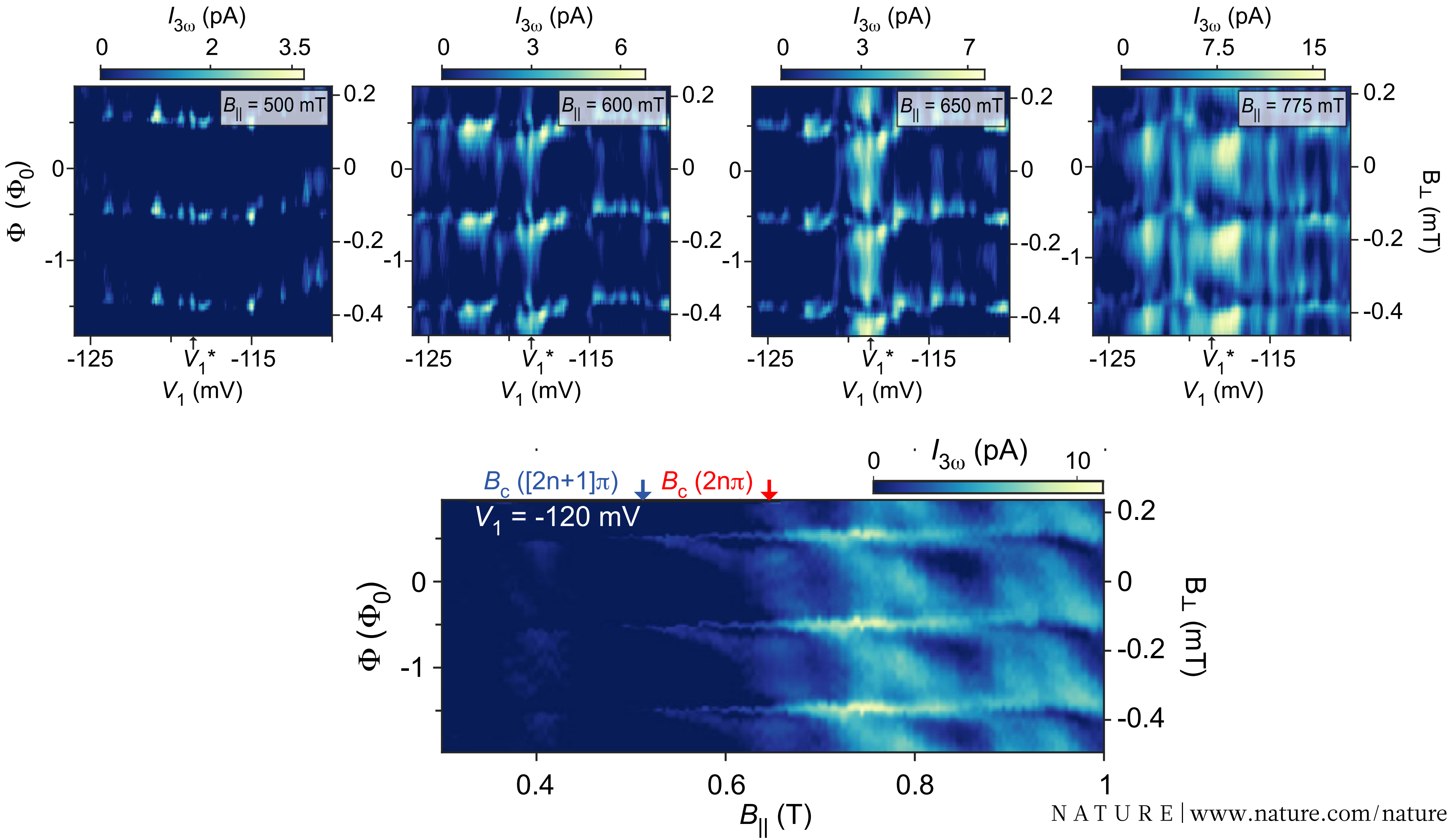


PHYSICAL REVIEW B **99**, 220506(R) (2019)

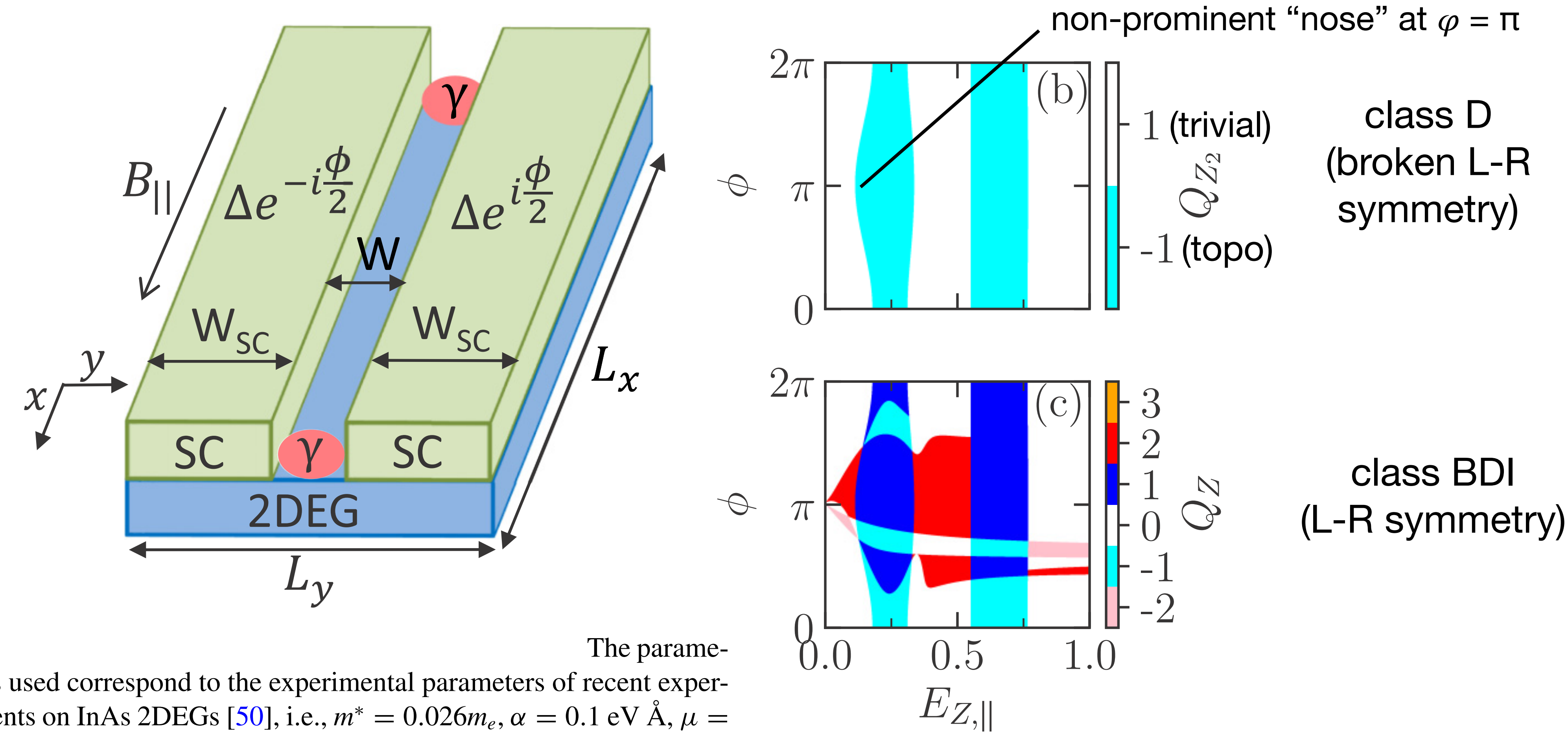
Rapid Communications

Topological superconductivity in planar Josephson junctions: Narrowing down to the nanowire limit

F. Setiawan,[1,*] Ady Stern,[2] and Erez Berg[1,2]

[1]*The James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*

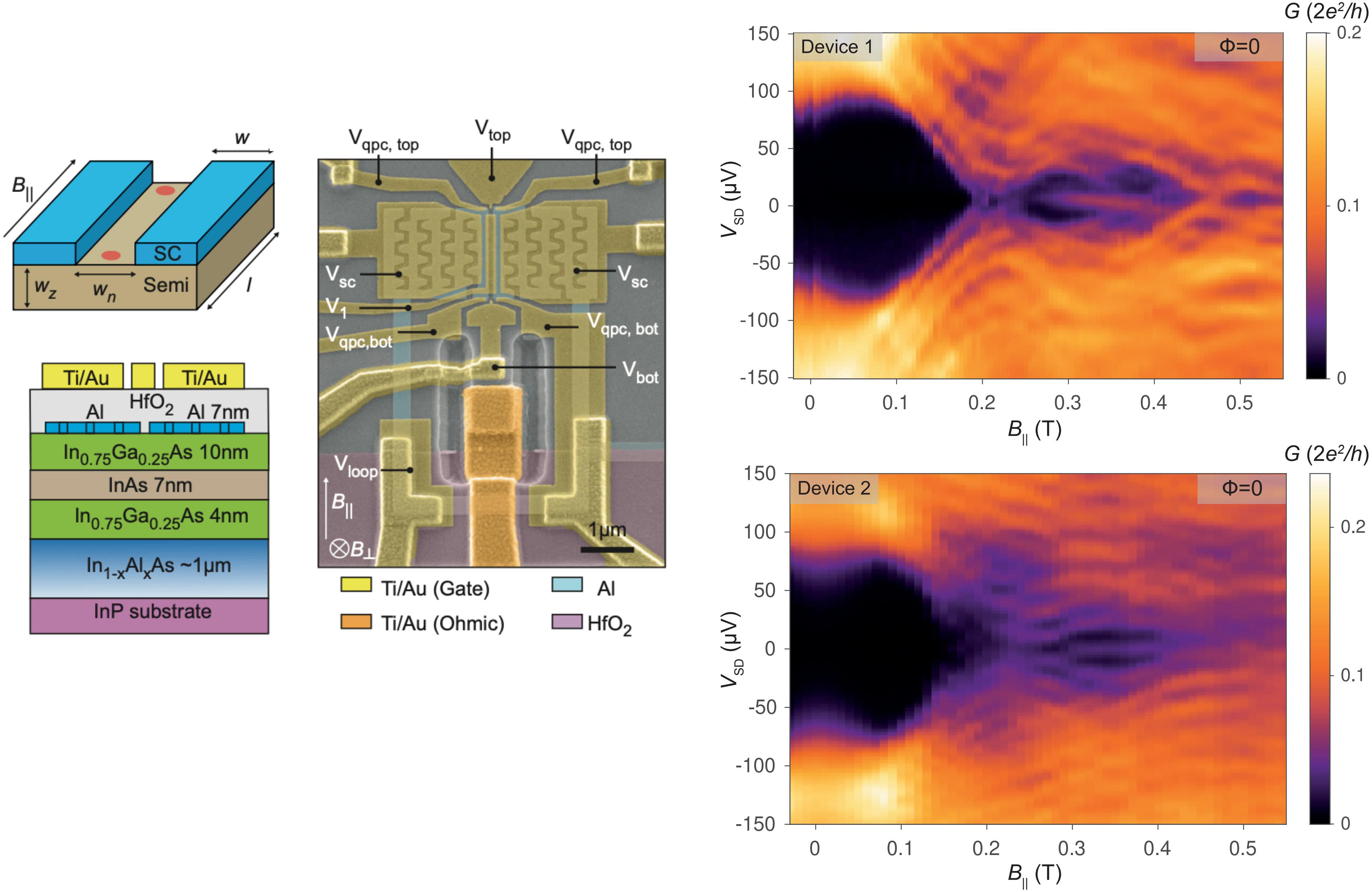
[2]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*



The parameters used correspond to the experimental parameters of recent experiments on InAs 2DEGs [50], i.e., $m^* = 0.026m_e$, $\alpha = 0.1$ eV Å, $\mu = 0.6$ meV, $\Delta = 0.15$ meV [$\xi = \hbar v_F/(\pi\Delta) = 126$ nm], $W = 80$ nm, and $W_{SC} = 160$ nm.

Signatures of a topological phase transition in a planar Josephson junction

A. Banerjee,[1] O. Lesser,[2] M. A. Rahman,[1] H.-R. Wang,[2,3] M.-R. Li,[2,3]
A. Kringhøj,[1] A. M. Whiticar,[1] A. C. C. Drachmann,[1] C. Thomas,[4,5] T. Wang,[4,5]
M. J. Manfra,[4,5,6,7] E. Berg,[2] Y. Oreg,[2] Ady Stern,[2] and C. M. Marcus[1]



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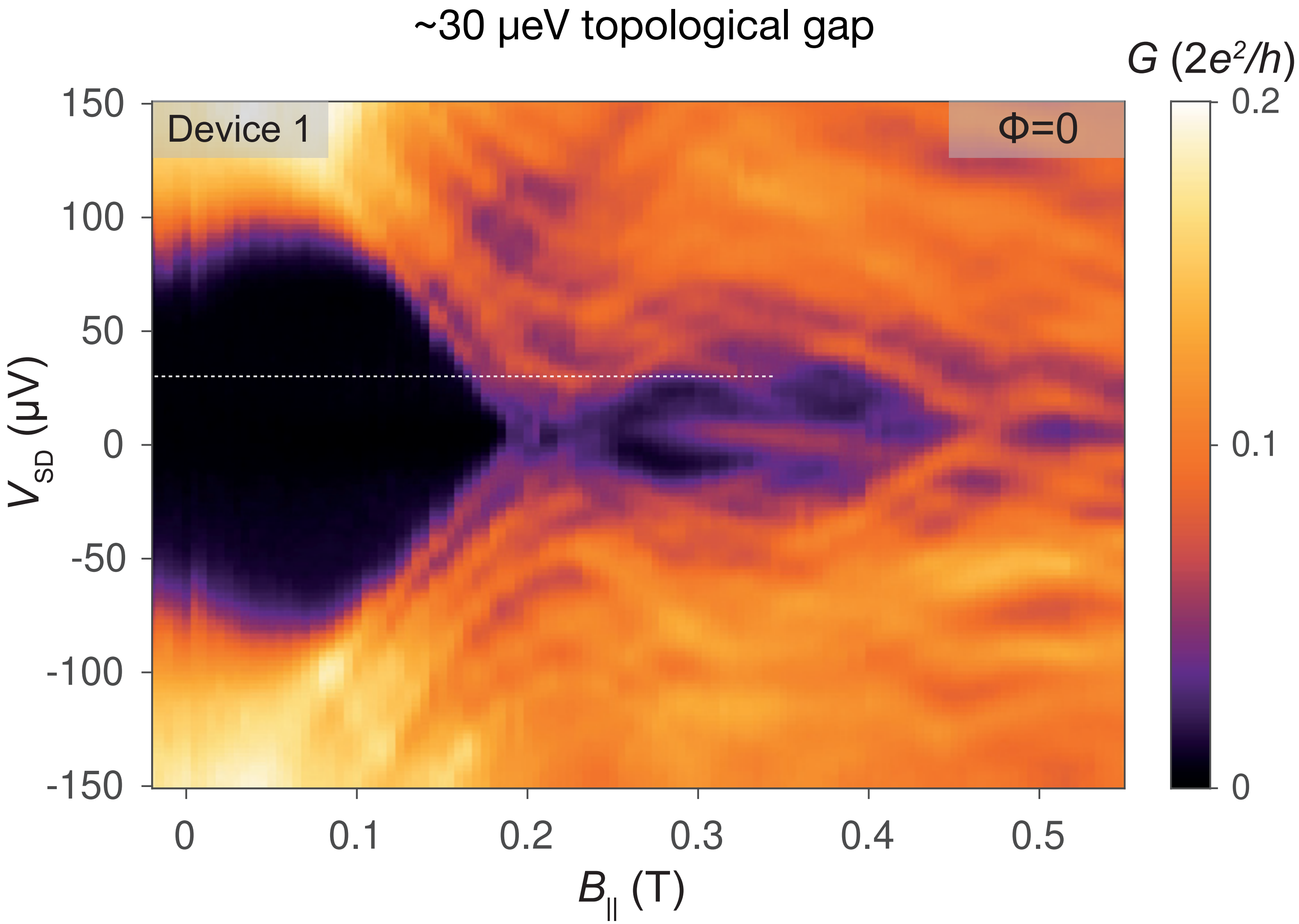

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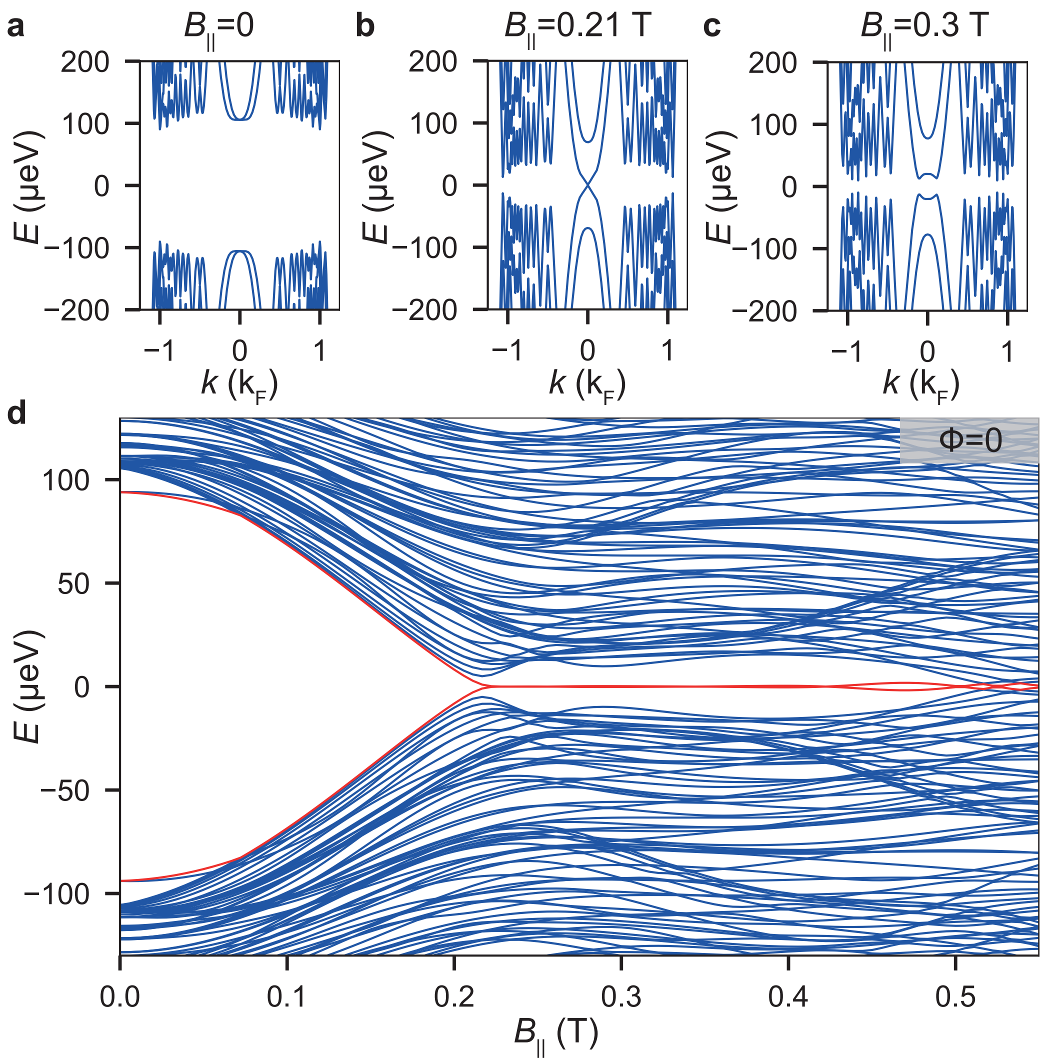
M. J. Manfra,[4,5,6,7] E. Berg,[2] Y. Oreg,[2] Ady Stern,[2] and C. M. Marcus[1]

Topological transition (theory)



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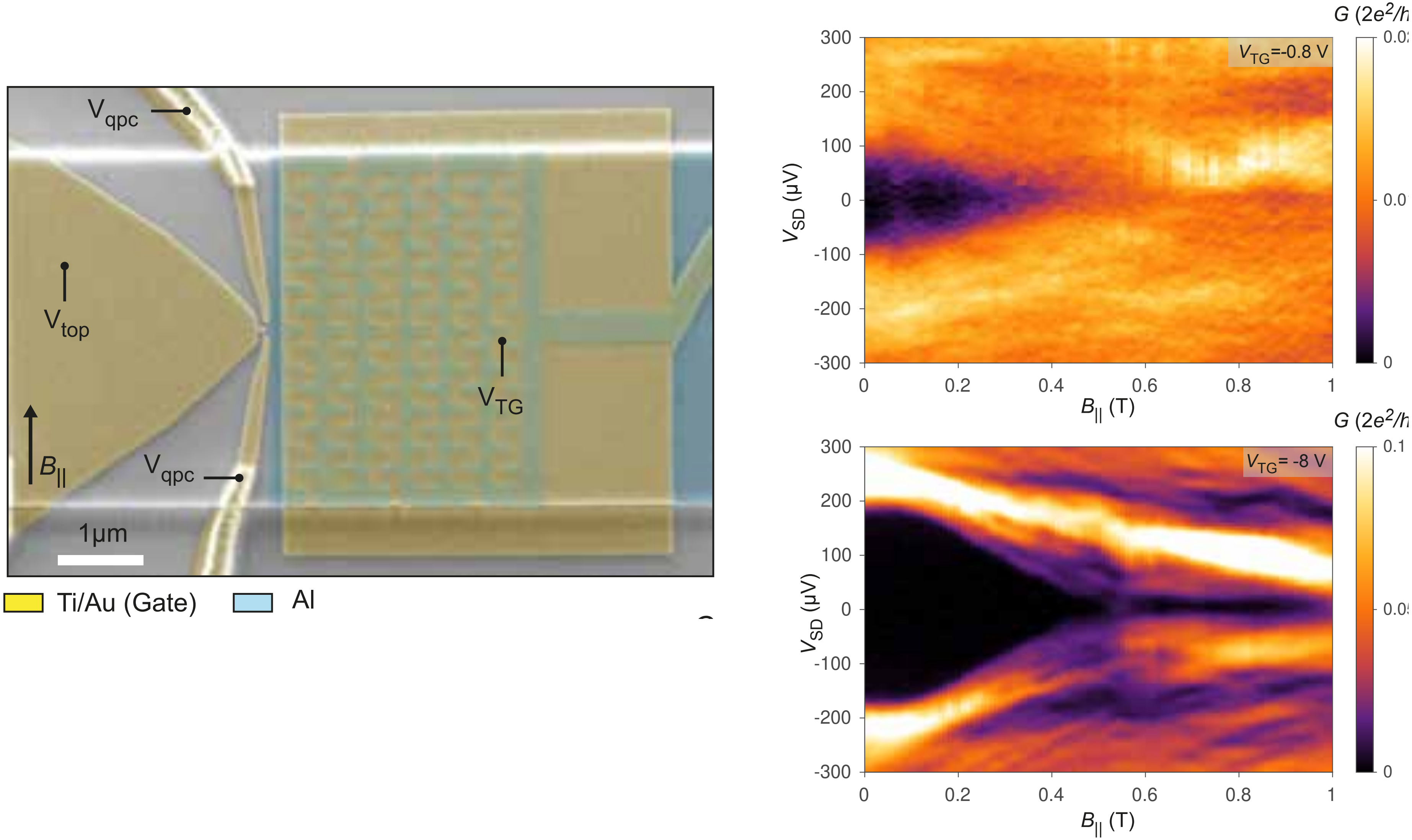
M. J. Manfra,[4,5,6,7] E. Berg,[2] Y. Oreg,[2] Ady Stern,[2] and C. M. Marcus[1]

The perforated wide leads



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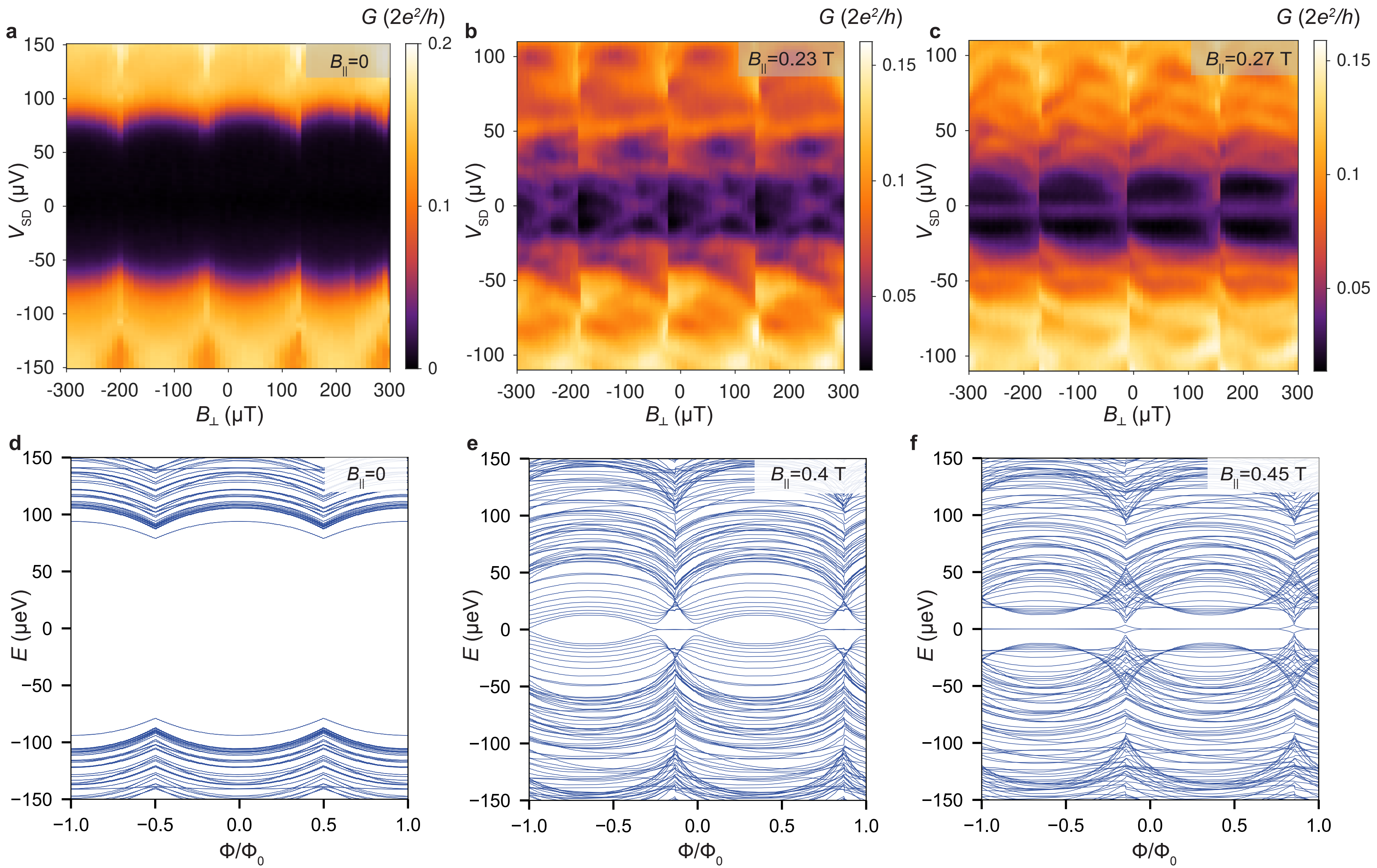
Phase dependence (experiment and theory)



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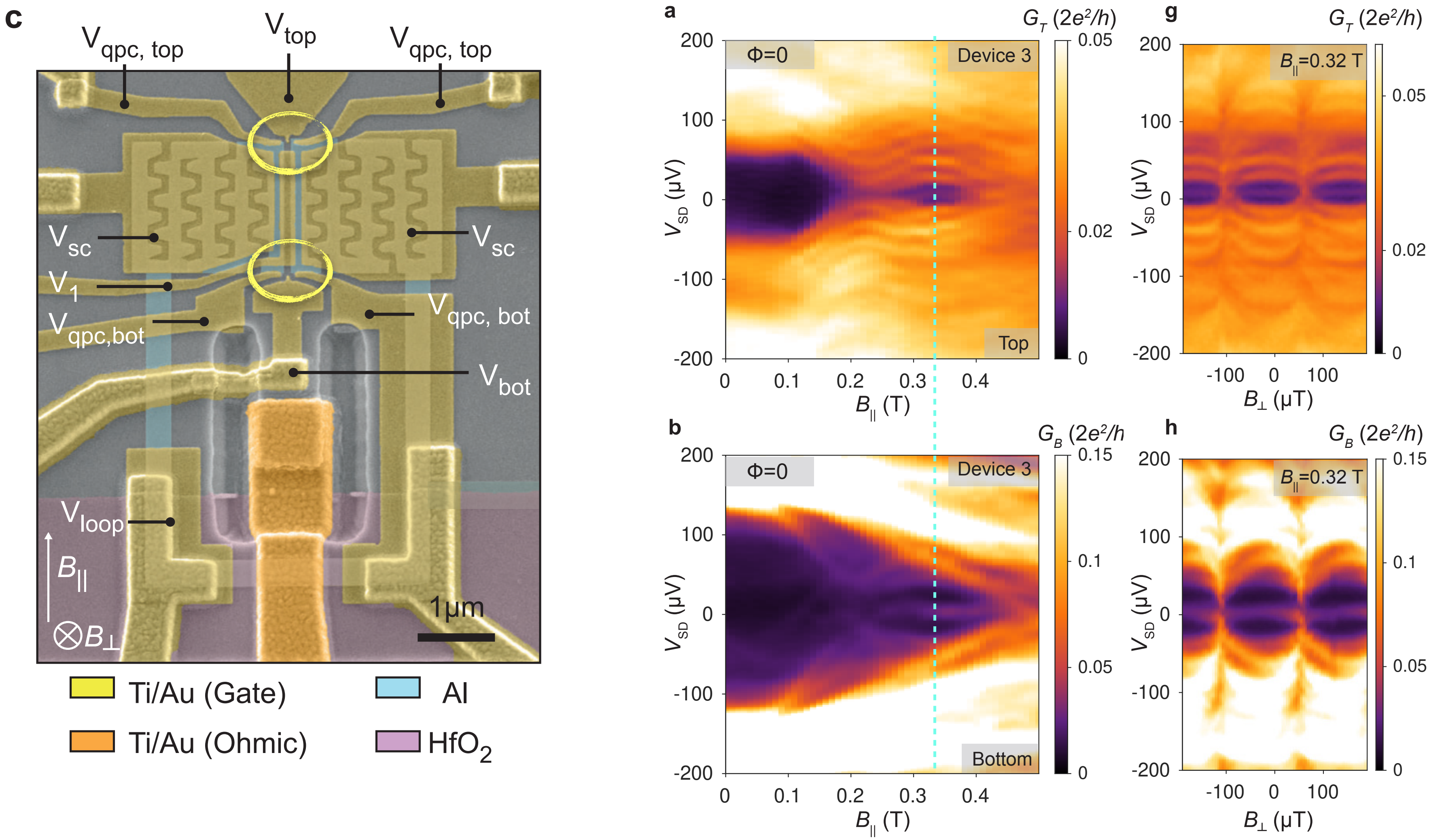
Simultaneous zero-bias peaks at both ends of the device (not always).



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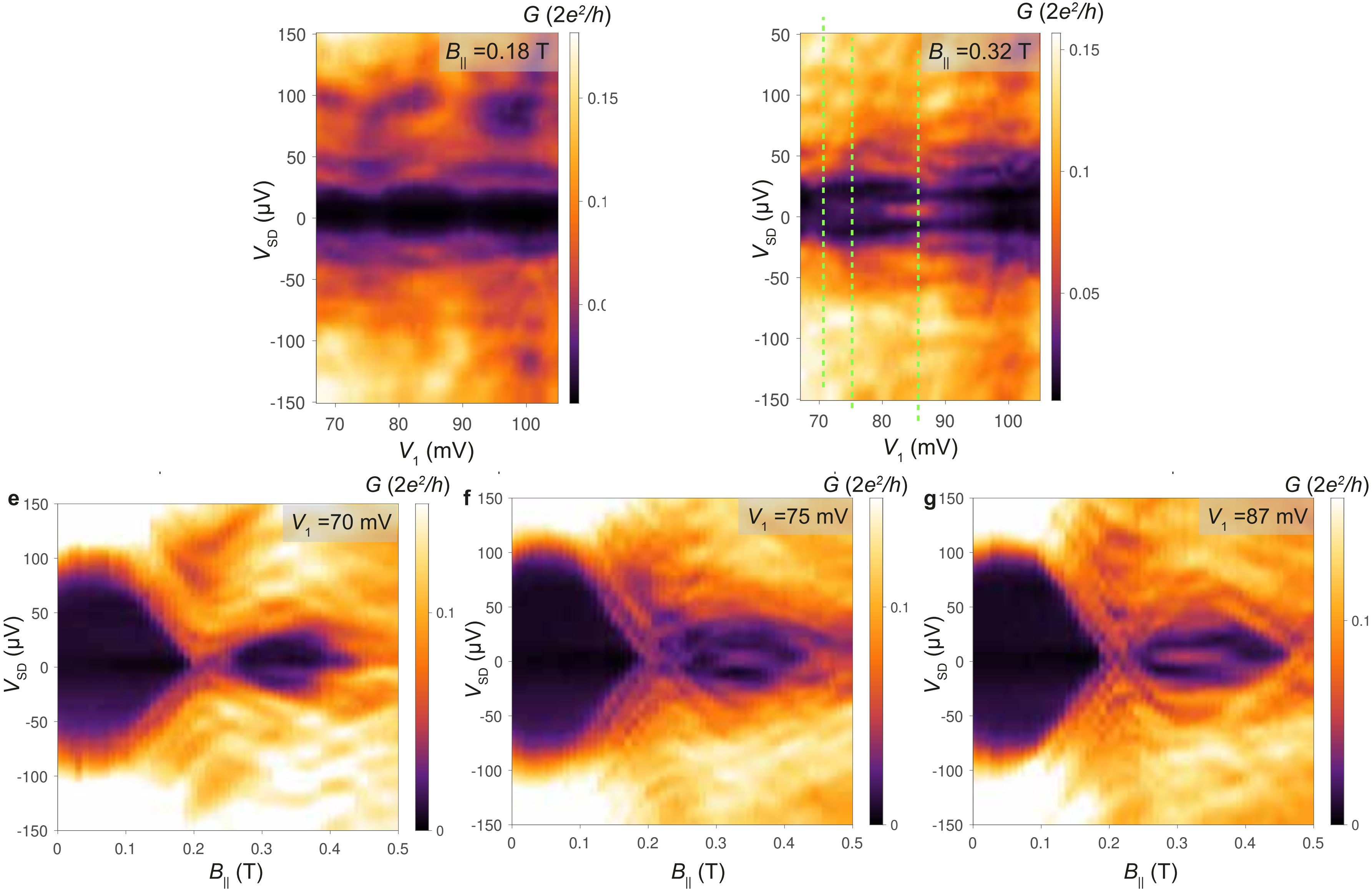
M. J. Manfra,[4,5,6,7] E. Berg,[2] Y. Oreg,[2] Ady Stern,[2] and C. M. Marcus[1]

Persistence of topological regions



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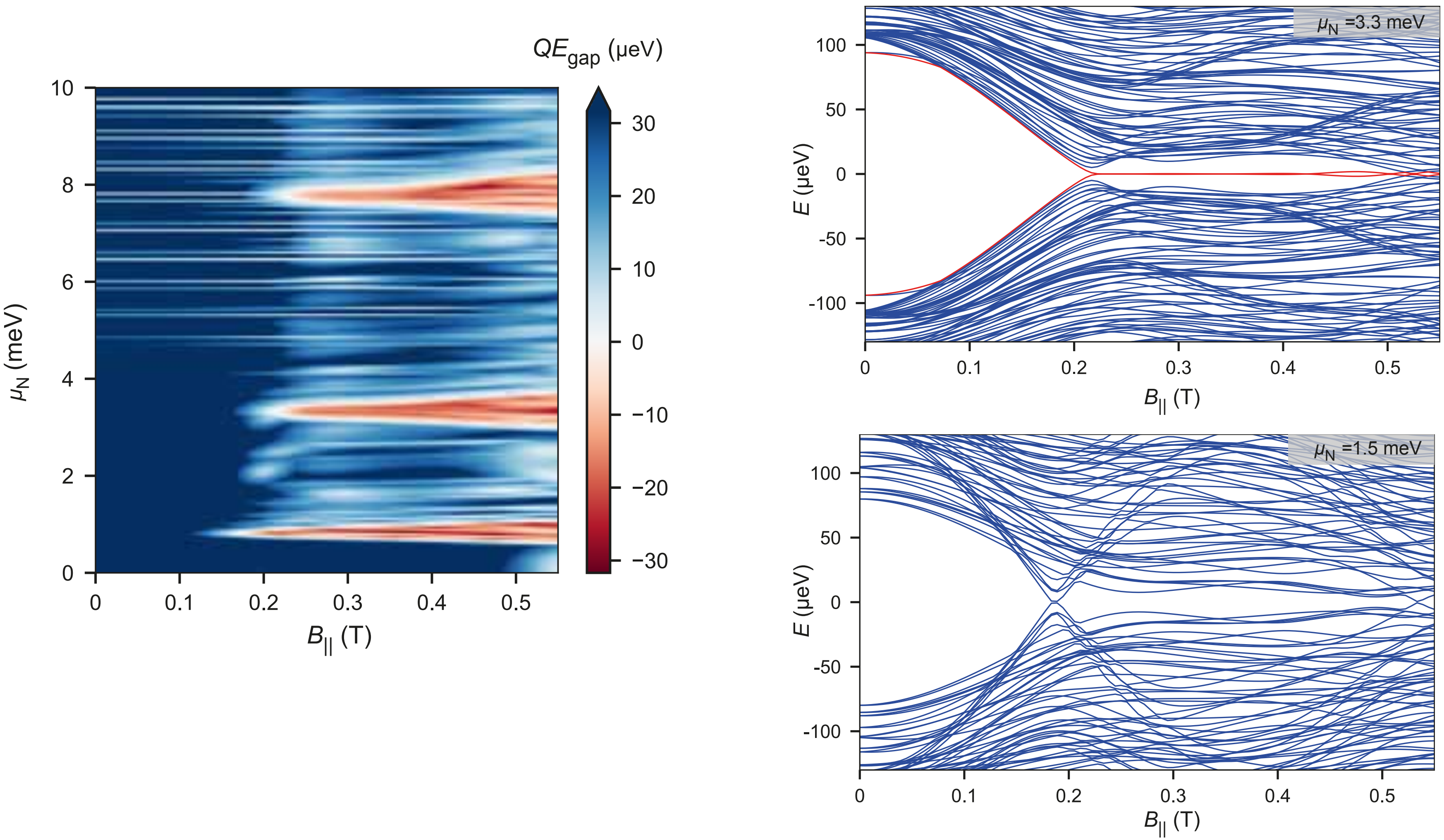
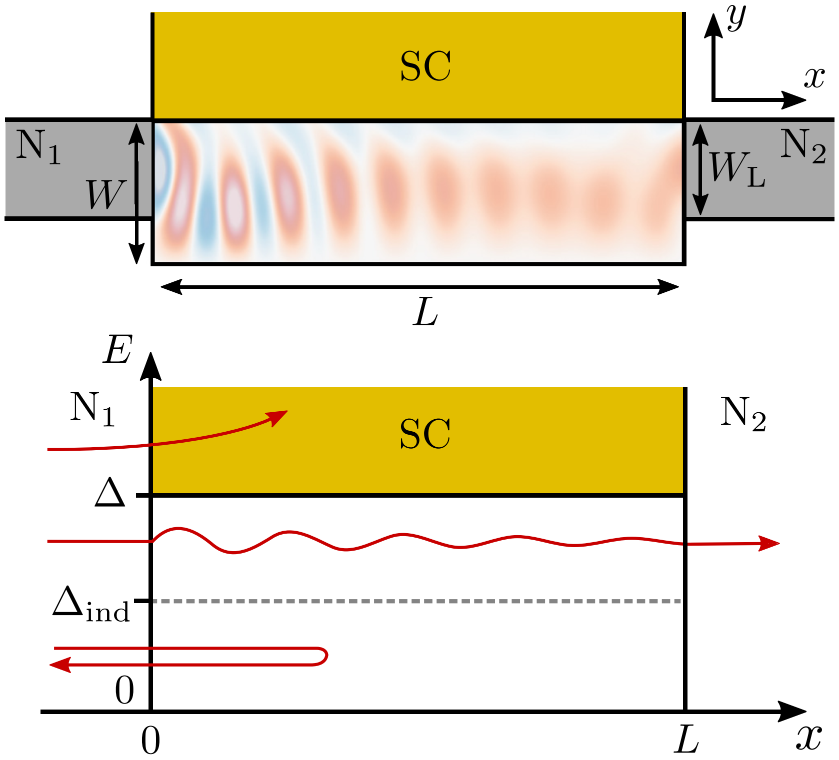
M. J. Manfra,[4,5,6,7] E. Berg,[2] Y. Oreg,[2] Ady Stern,[2] and C. M. Marcus[1]

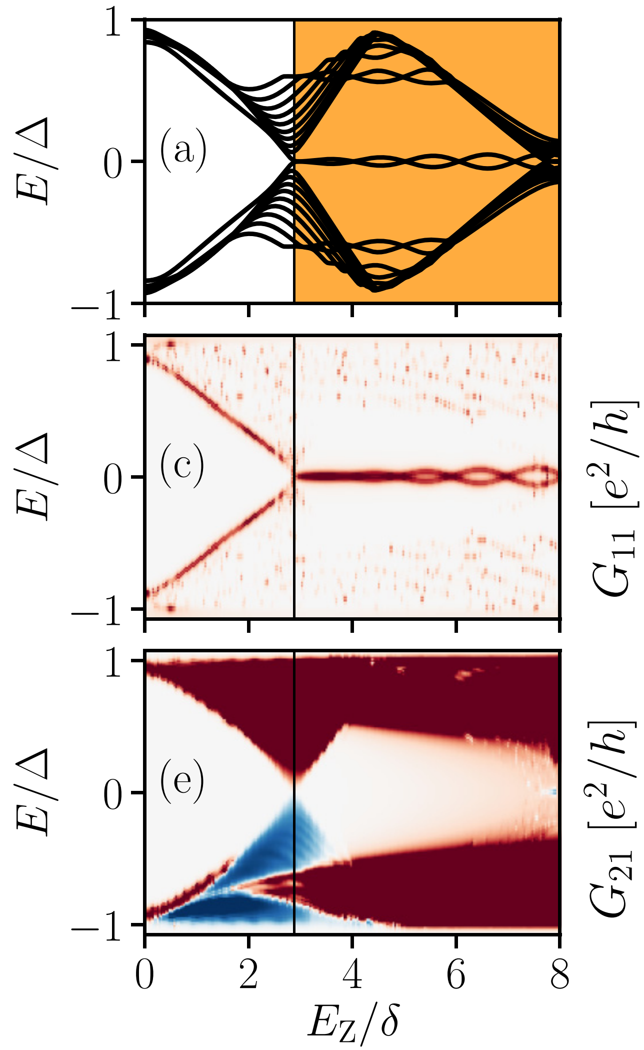
Prevalence of topological regions (theory)



Andreev rectifier: A nonlocal conductance signature of topological phase transitions

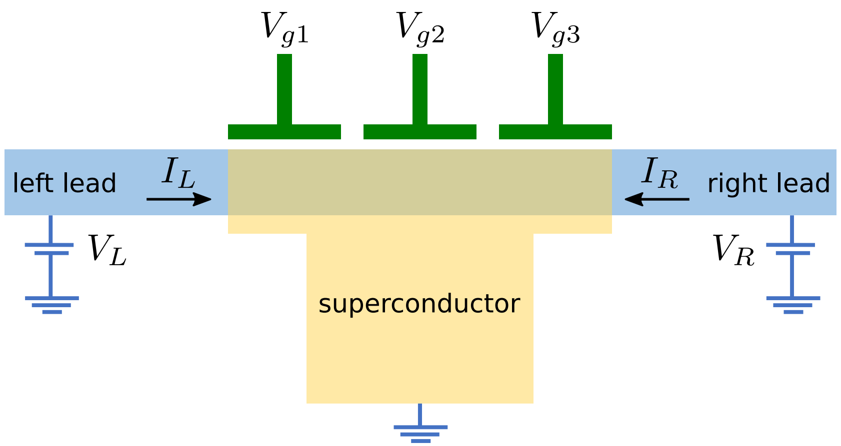
T. Ö. Rosdahl,[1,*] A. Vuik,[1,†] M. Kjaergaard,[2,3] and A. R. Akhmerov[1]

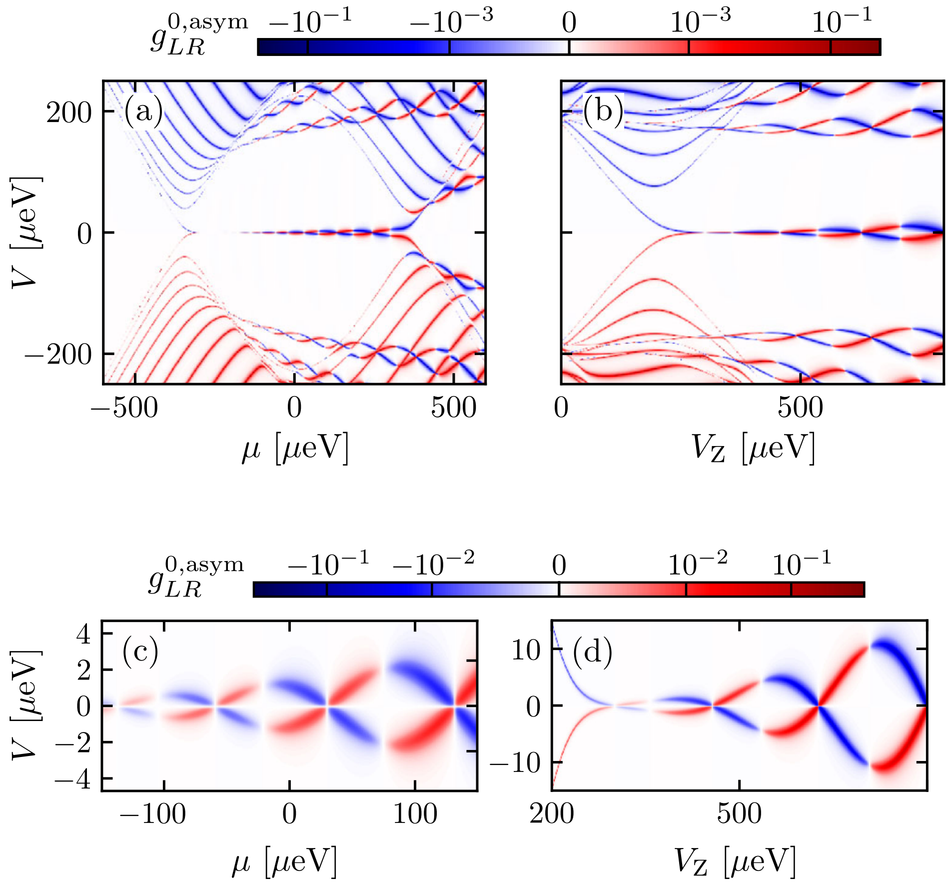




Nonlocal Conductance Spectroscopy of Andreev Bound States: Symmetry Relations and BCS Charges

Jeroen Danon,[1] Anna Birk Hellenes,[2] Esben Bork Hansen,[2] Lucas Casparis,[2,3]
Andrew P. Higginbotham,[2,3] and Karsten Flensberg[2]

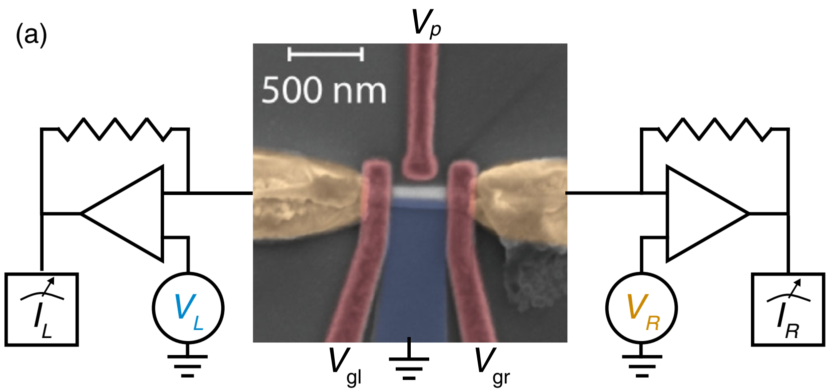


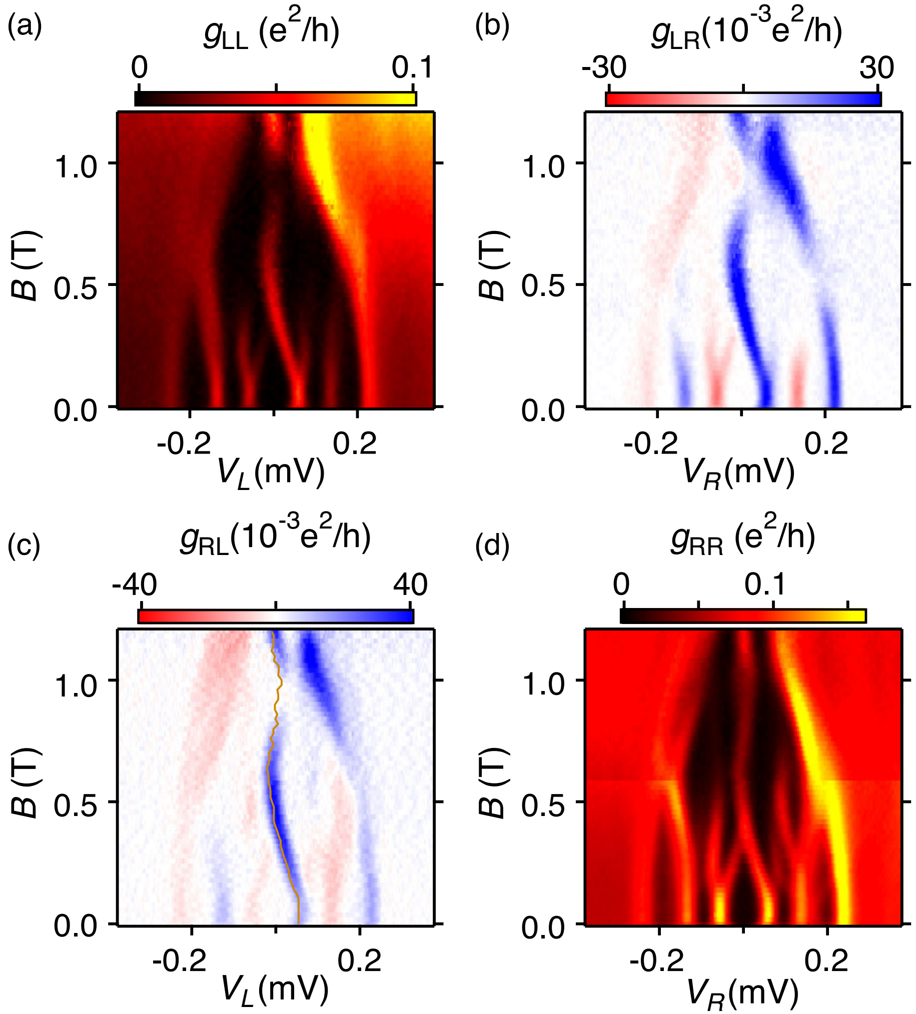


$$G_{\alpha\beta} = \frac{dI_\alpha}{dV_\beta}$$

Conductance-Matrix Symmetries of a Three-Terminal Hybrid Device

G. C. Ménard,[1,2] G. L. R. Anselmetti,[1,2] E. A. Martinez,[1,2] D. Puglia,[1,2] F. K. Malinowski,[1,2] J. S. Lee,[3] S. Choi,[4] M. Pendharkar,[4] C. J. Palmstrøm,[3,4,5] K. Flensberg,[1] C. M. Marcus,[1,2] L. Casparis,[1,2,*] and A. P. Higginbotham[1,2,†]





Local and Nonlocal Transport Spectroscopy in Planar Josephson Junctions

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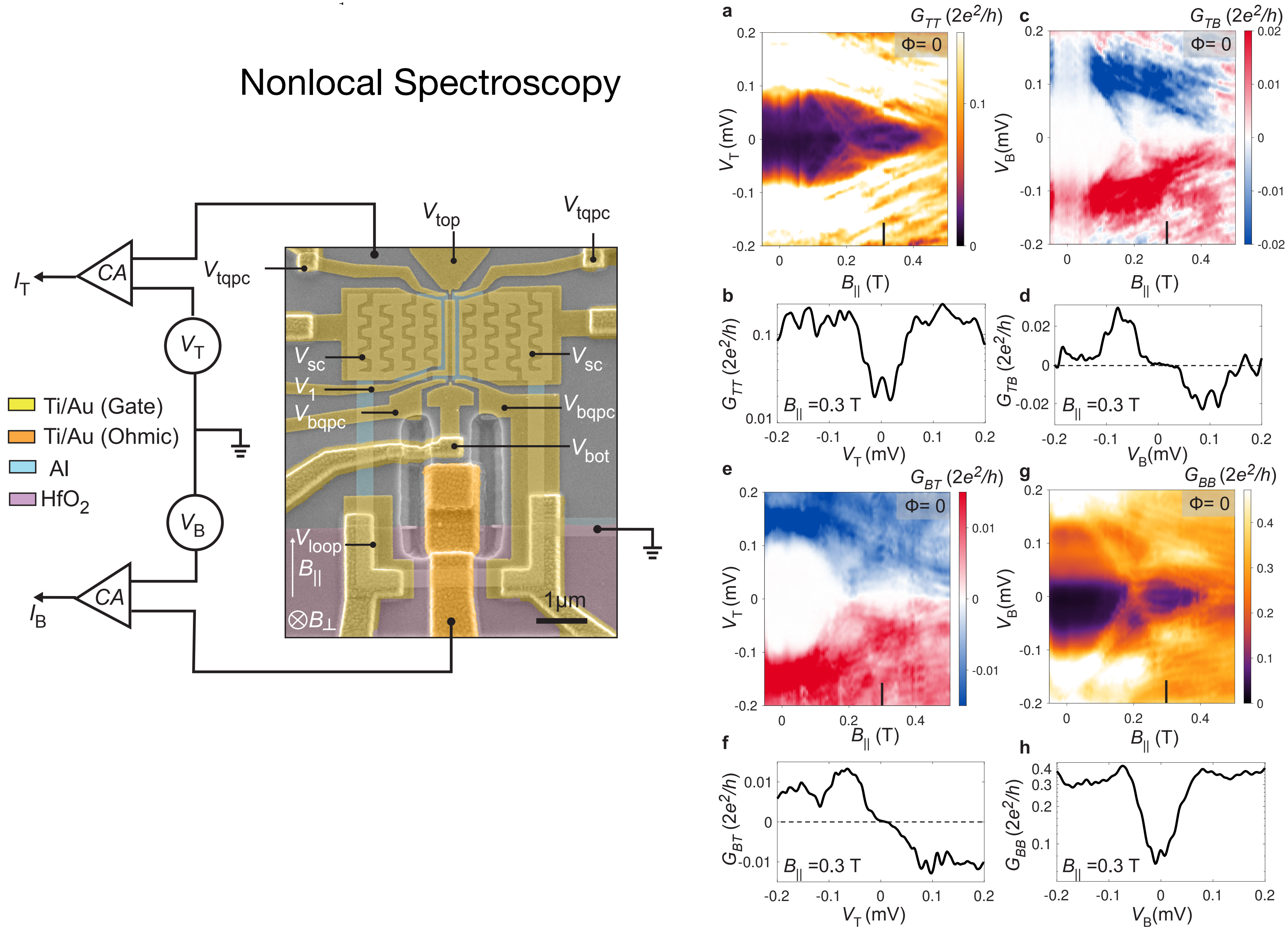

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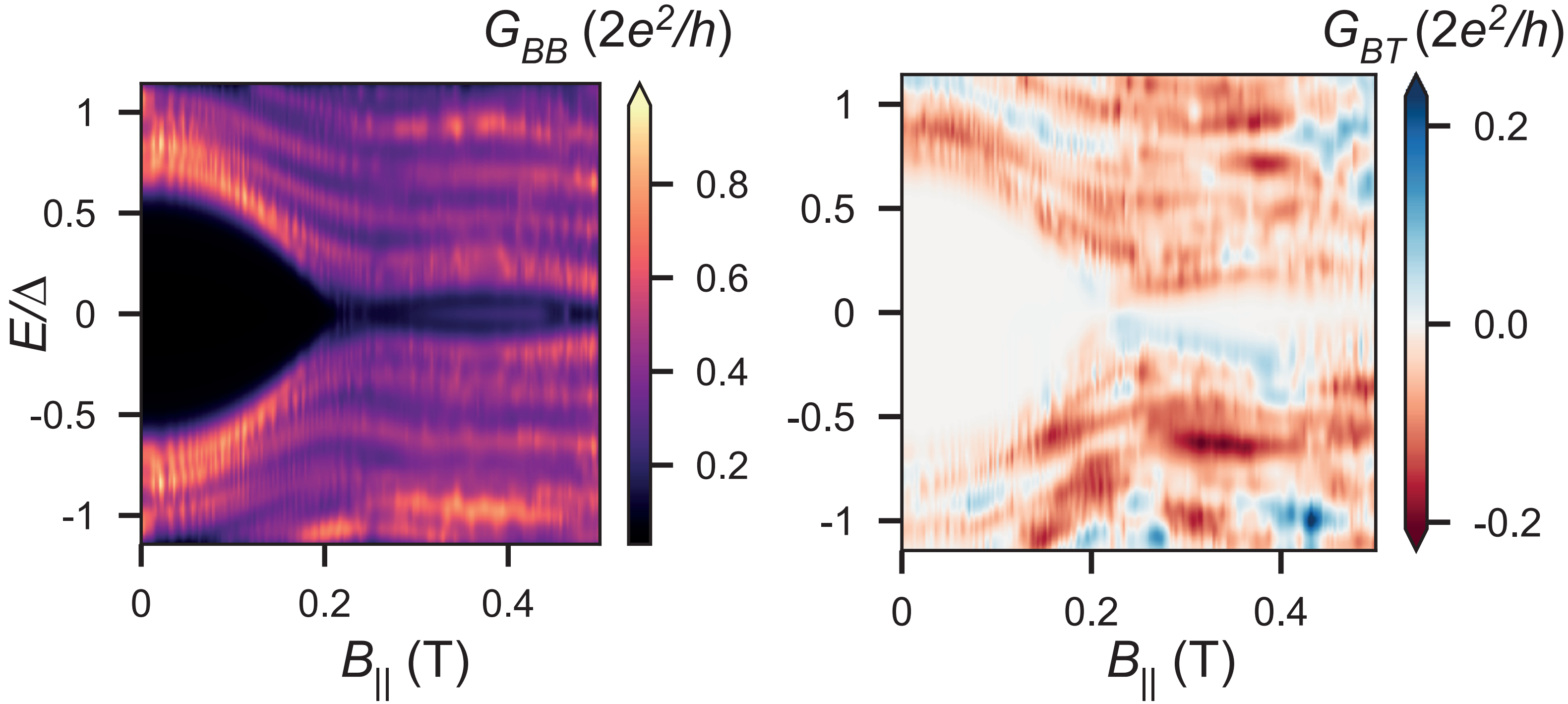

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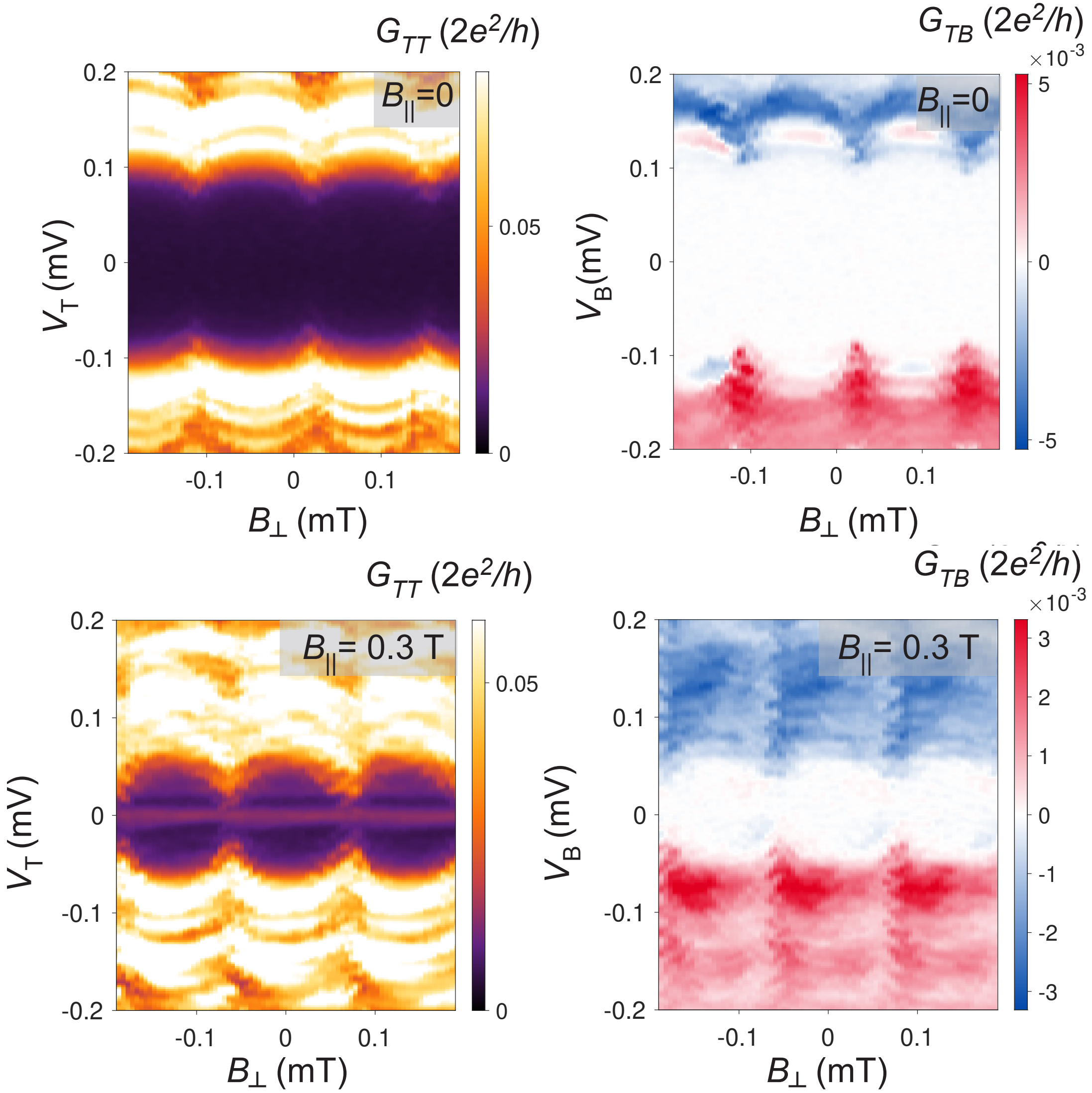

Fractional Josephson Vortices and Braiding of Majorana Zero Modes in Planar Superconductor-Semiconductor Heterostructures

Ady Stern[1] and Erez Berg[1,2]

[1]*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel 76100*

[2]*Department of Physics and the James Frank Institute, University of Chicago, Chicago, Illinois 60637, USA*