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Société Française de Physique

Spin-polarized Majorana zero modes in penta-silicene nanoribbons

Guy Le Lay
Aix-Marseille University, CNRS-PIIM, France

R. C. Bento Ribeiro and Mucio A. Continentino, **M. S. Figueira**
Rio de Janeiro, Brazil
J. H. Correa
Lima, Peru
L. S. Ricco, I. A. Shelykh
Reykjavik, Iceland
A. C. Seridonio
Ilha Solteira, Brazil
M. Minissale and G. Le Lay
Marseille, France

Majorana quasiparticles in condensed matter

Ramon Aguado, Rivista Del Nuovo Cimento 40, 523 (2017)

Fig. 1. – Top: Portrait of Ettore Majorana (Copyright E. Recami and Maria Majorana, courtesy AIP Emilio Segre Visual Archives, E. Recami and Fabio Majorana Collection). Bottom: On the day of his disappearance, March 25 1938, Majorana sent a letter to Antonio Carrelli, Director of the Naples Physics Institute: *Dear Carrelli, I made a decision that has become unavoidable. There isn't a bit of selfishness in it, but I realize what trouble my sudden disappearance will cause you and the students. For this as well, I beg your forgiveness, but especially for betraying the trust, the sincere friendship and the sympathy you gave me over the past months. I ask you to remember me to all those I learned to know and appreciate in your Institute, especially Sciuti: I will keep a fond memory of them all at least until 11 pm tonight, possibly later too. E. Majorana.* The next day, Carelli received a telegram and a second letter (in the image) from Palermo: *Dear Carrelli, I hope you got my telegram and my letter at the same time. The sea rejected me and I'll be back tomorrow at the Hotel Bologna traveling perhaps with this letter. However, I have the intention of giving up teaching. Don't think I'm like an Ibsen heroine, because the case is different. I'm at your disposal for further details. E. Majorana.* He apparently bought a ticket from Palermo to Naples and was never seen again [7, 8].

SM/SC hybrids for topological superconductivity

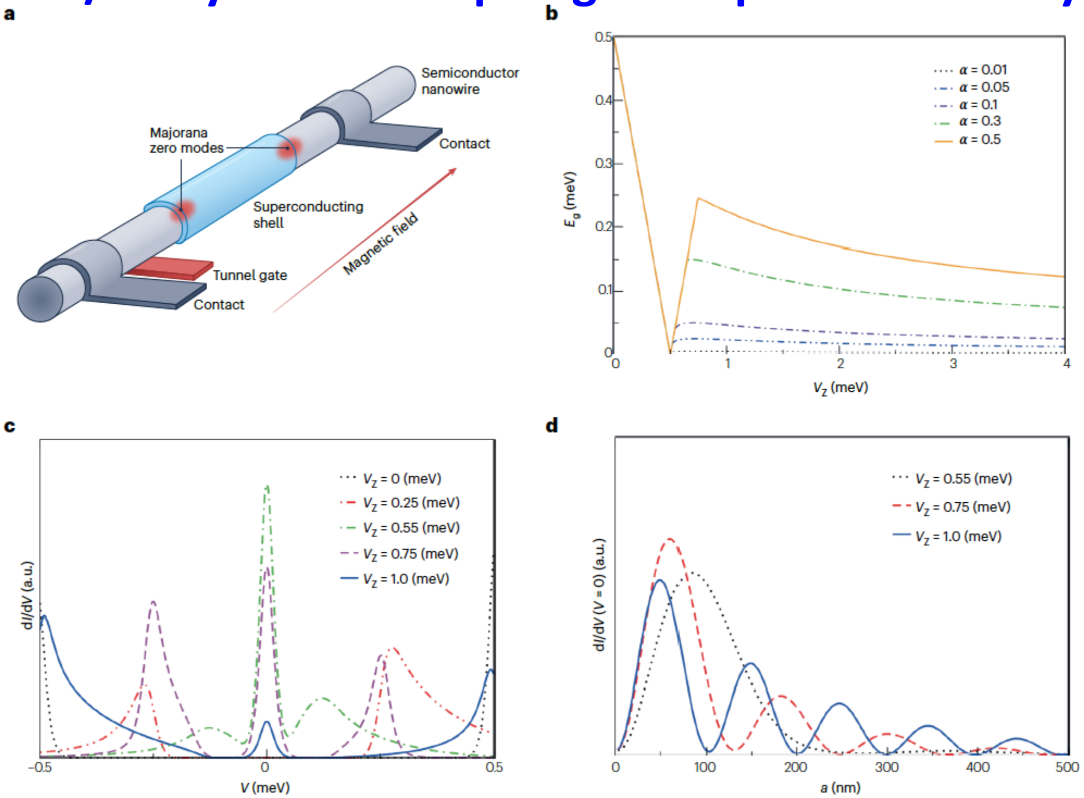


Fig. 1 | **Theoretical predictions for experimental signatures of MZMs.**

a, Sketch of a typical SM/SC nanowire. Electrical current enters and leaves via the two metallic contacts, and the tunnel gate regulates its flow into the region under the superconducting shell, allowing for spectroscopic measurements. The in-plane magnetic field (red arrow) provides the Zeeman splitting V_Z and can drive the topological phase transition. There are more gates (not shown) in the experimental set up controlling the chemical potential in the SM wire.

b, The calculated induced gap closing and reopening as a function of V_Z. The topological quantum phase transition occurs when the induced gap closes at the critical value (TQPT) when $V_Z = Vc = 0.5$ meV.

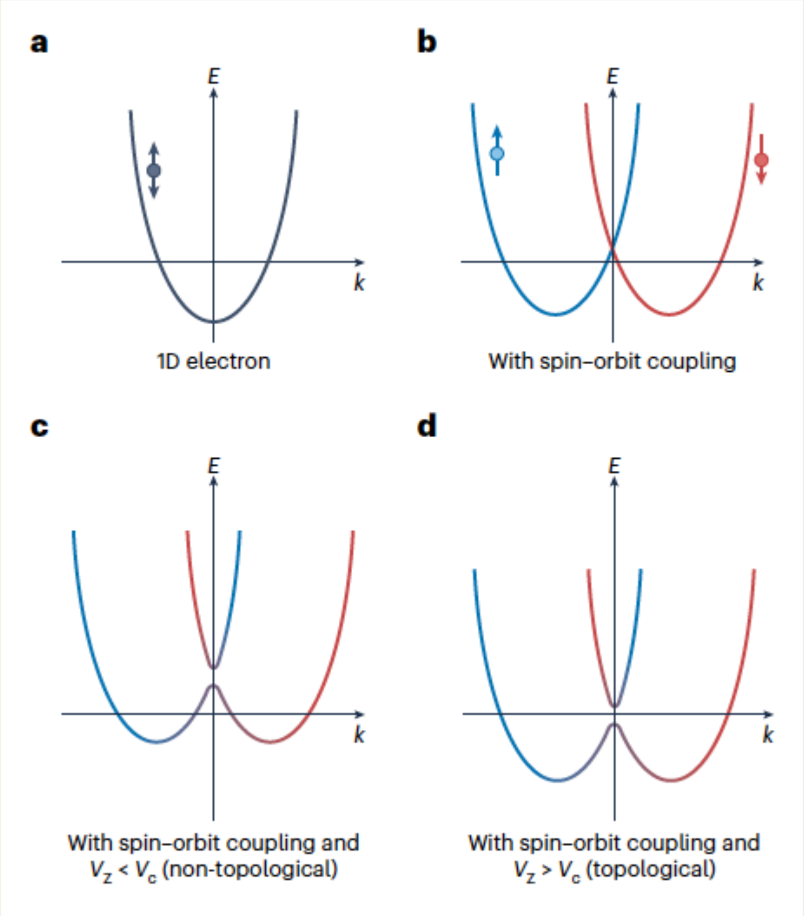
c, Calculated tunnel conductance spectra as a function of bias voltage for different values of V_Z (with Vc = 0.5 meV), showing MZM-induced ZBCPs for V > Vc.

d, Calculated ZBCP strength for V > Vc (= 0.5 meV) as a function of wire length a, showing Majorana oscillation becoming more prominent with increasing Majorana overlap from the two ends for shorter wires.

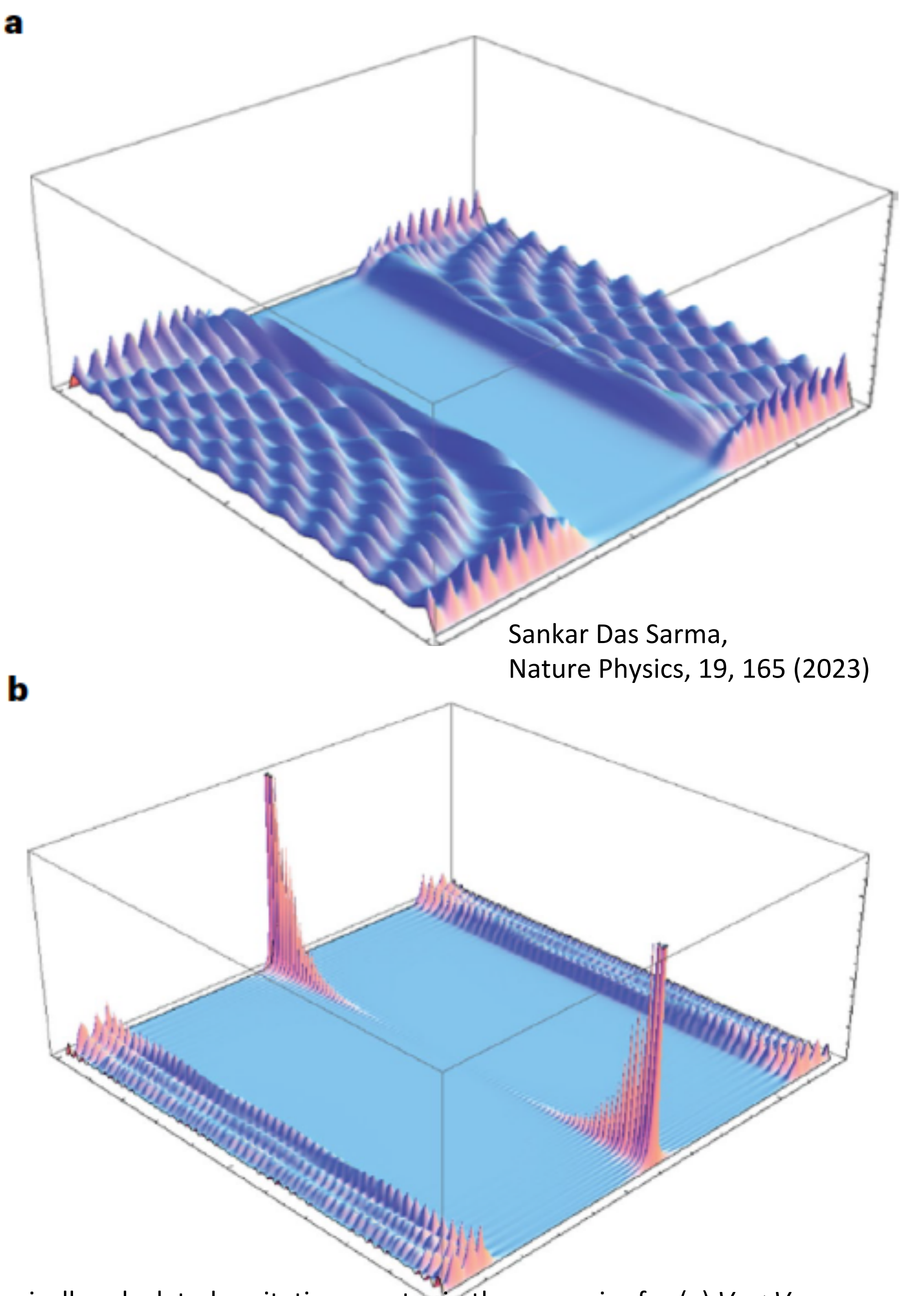
In search of Majorana

Sankar Das Sarma, Nature Physics, 19, 165 (2023)

SM/SC hybrids for topological superconductivity



Engineering a 1D spinless *p*-wave superconductor in SM/SC nanowires. a, The spin-degenerate bandstructure of a 1D electronic system. b, Spin–orbit coupling shifts the spin-up (blue) and spin-down (red) bands in momentum space. c, An in-plane magnetic field adds a Zeeman coupling V_Z that mixes and splits the bands near $k = 0$. d, When the Zeeman field is strong enough, it shifts the Fermi energy into the gap at $k = 0$, and the system becomes topological. Adding superconductivity in this situation leads to a spinless *p*-wave order parameter.



Sankar Das Sarma,
Nature Physics, 19, 165 (2023)

Excitation spectra in the trivial and topological regimes. (a) Numerically calculated excitation spectra in the nanowire for (a) *Vz* < *Vc* (where *Vc* is the Zeeman splitting that corresponds to the TQPT) with no states in the superconducting), and (b) for *Vz* > *Vc* showing localized MZMs at the wire ends. There are no states in the gap other than the two MZMs localized at the wire ends for *Vz* > *Vc*, whereas there are continuum metallic electron-hole excitations above the SC gap.

Majorana qubits for topological quantum computing Ramón Aguado, and Leo P. Kouwenhoven, Physics Today 73, 6, 44 (2020)

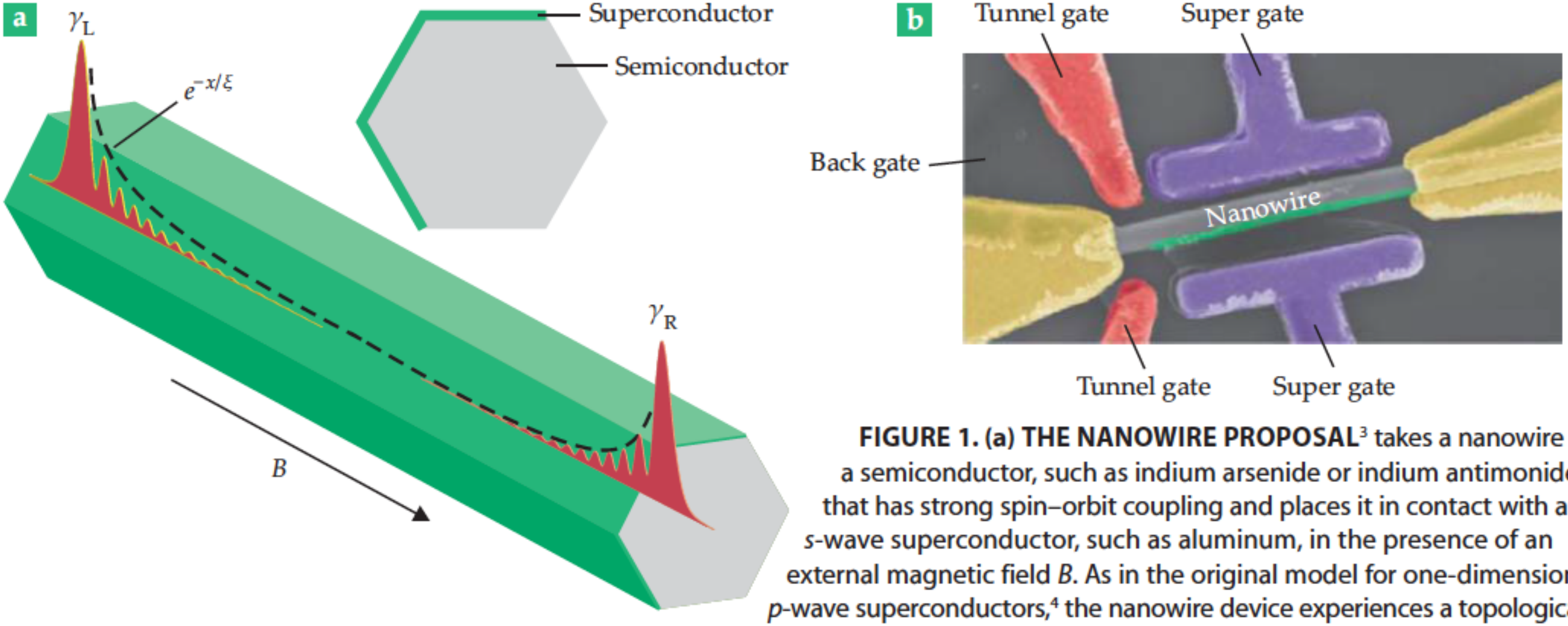


FIGURE 1. (a) THE NANOWIRE PROPOSAL[3] takes a nanowire of a semiconductor, such as indium arsenide or indium antimonide, that has strong spin–orbit coupling and places it in contact with an *s*-wave superconductor, such as aluminum, in the presence of an external magnetic field *B*. As in the original model for one-dimensional *p*-wave superconductors,[4] the nanowire device experiences a topological nontrivial phase with exponentially decaying Majorana bound states, denoted γ_L, at both ends of the nanowire. **(b)** An actual device from Delft University of Technology includes various metallic gates for tuning it to the topological phase by adjusting the nanowire's chemical potential.

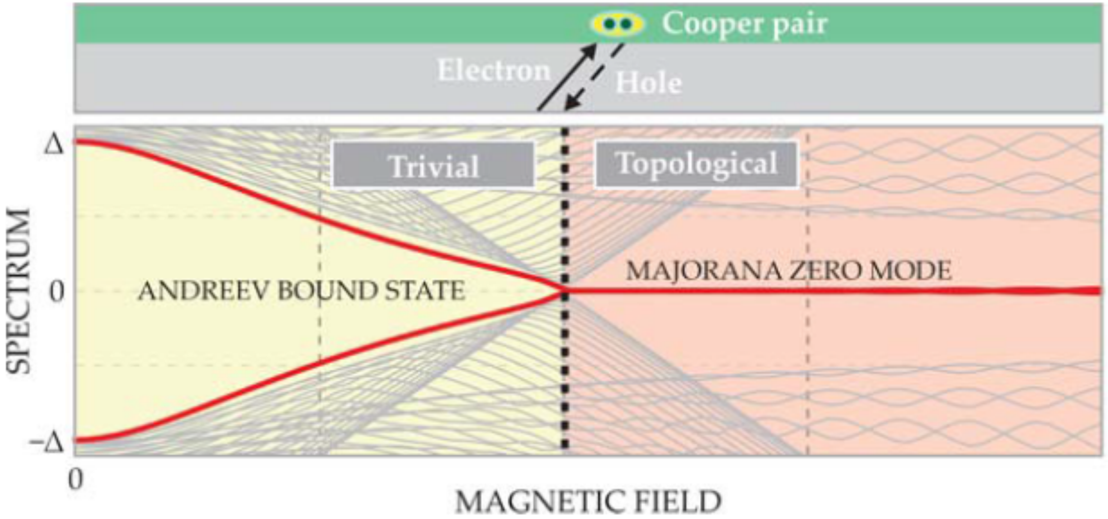


FIGURE 2. ANDREEV REFLECTIONS of electrons and holes to form Cooper pairs at the semiconducting–superconducting interface induce superconductivity in a nanowire. As a result, Majorana zero modes (flat red line) emerge in the energy spectrum as the external magnetic field increases. The Majoranas appear beyond some critical value of the external field (black dotted line) where the superconducting gap closes and reopens again, which signals a topological phase transition. Theory predicts that the emergent Majorana zero modes can be detected as a zero-bias anomaly in electrical conductance *dI*/*dV*. (Image by R. Aguado and L. P. Kouwenhoven.)

Corrections & amendments

Retraction Note: Quantized Majorana conductance

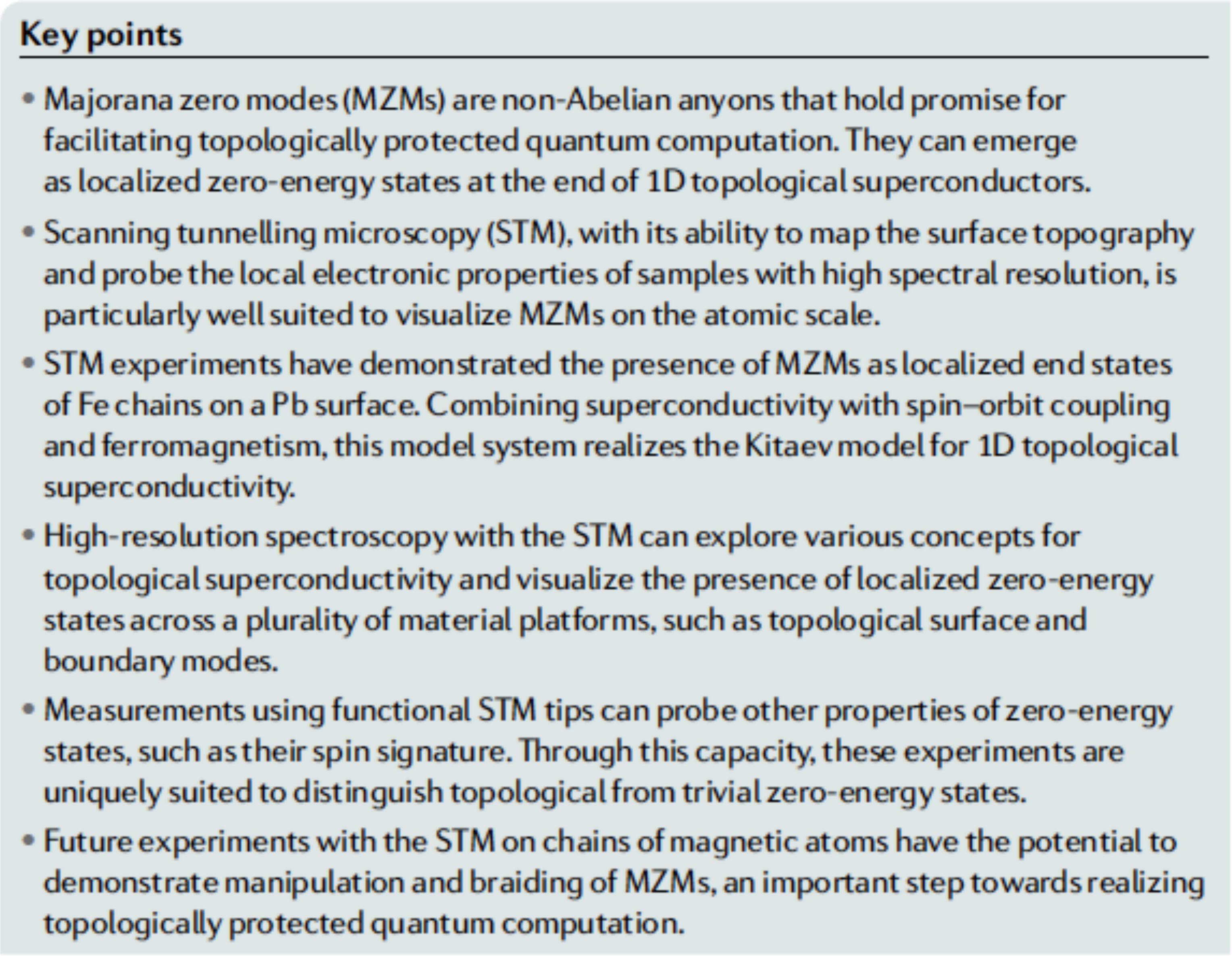
https://doi.org/10.1038/s41586-021-03373-x

Retraction to: *Nature* https://doi.org/10.1038/nature26142

Hao Zhang, Chun-Xiao Liu, Sasa Gazibegovic, Di Xu, John A. Logan,
Guanzhong Wang, Nick van Loo, Jouri D. S. Bommer,
Michiel W. A. de Moor, Diana Car, Roy L. M. Op het Veld,
Petrus J. van Veldhoven, Sebastian Koelling, Marcel A. Verheijen,
Mihir Pendharkar, Daniel J. Pennachio, Borzoyeh Shojaei,
Joon Sue Lee, Chris J. Palmstrøm, Erik P. A. M. Bakkers, S. Das Sarma
& Leo P. Kouwenhoven

Detecting and distinguishing Majorana zero modes with the scanning tunnelling microscope

Berthold Jäck, Yonglong Xie, and Ali Yazdani, Nature Reviews Physics, 3, 541 (2021)



Key points

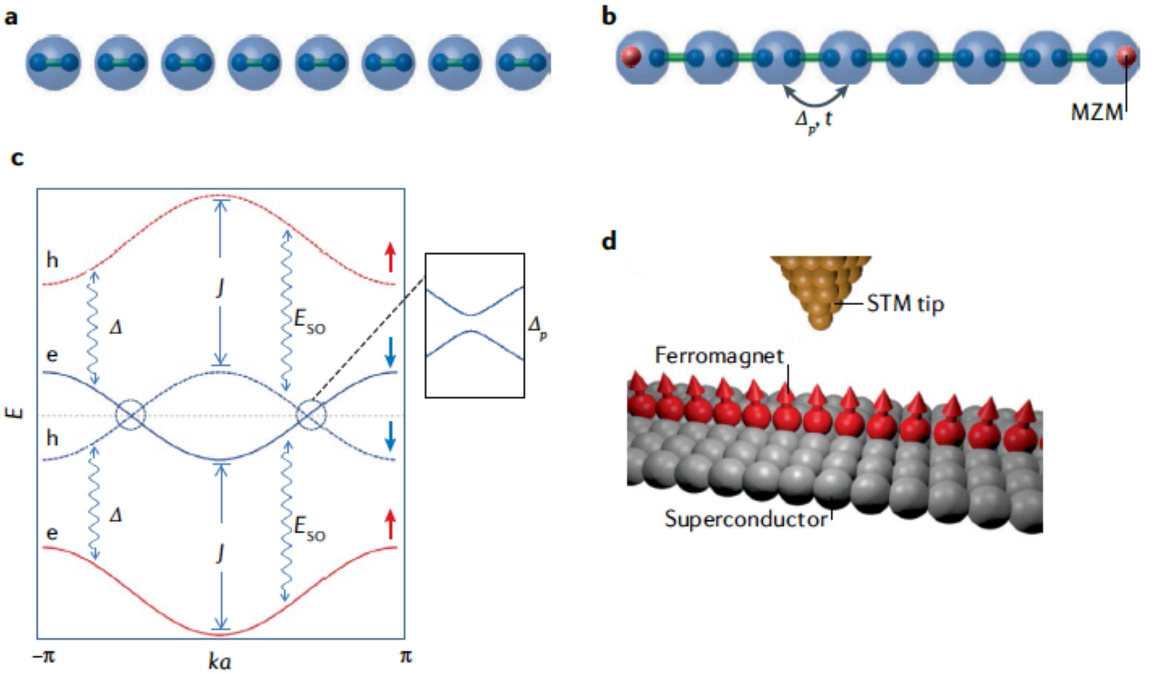
- Majorana zero modes (MZMs) are non-Abelian anyons that hold promise for facilitating topologically protected quantum computation. They can emerge as localized zero-energy states at the end of 1D topological superconductors.
- Scanning tunnelling microscopy (STM), with its ability to map the surface topography and probe the local electronic properties of samples with high spectral resolution, is particularly well suited to visualize MZMs on the atomic scale.
- STM experiments have demonstrated the presence of MZMs as localized end states of Fe chains on a Pb surface. Combining superconductivity with spin–orbit coupling and ferromagnetism, this model system realizes the Kitaev model for 1D topological superconductivity.
- High-resolution spectroscopy with the STM can explore various concepts for topological superconductivity and visualize the presence of localized zero-energy states across a plurality of material platforms, such as topological surface and boundary modes.
- Measurements using functional STM tips can probe other properties of zero-energy states, such as their spin signature. Through this capacity, these experiments are uniquely suited to distinguish topological from trivial zero-energy states.
- Future experiments with the STM on chains of magnetic atoms have the potential to demonstrate manipulation and braiding of MZMs, an important step towards realizing topologically protected quantum computation.

Box 1 | Visualizing Majorana zero modes with scanning tunnelling microscopy

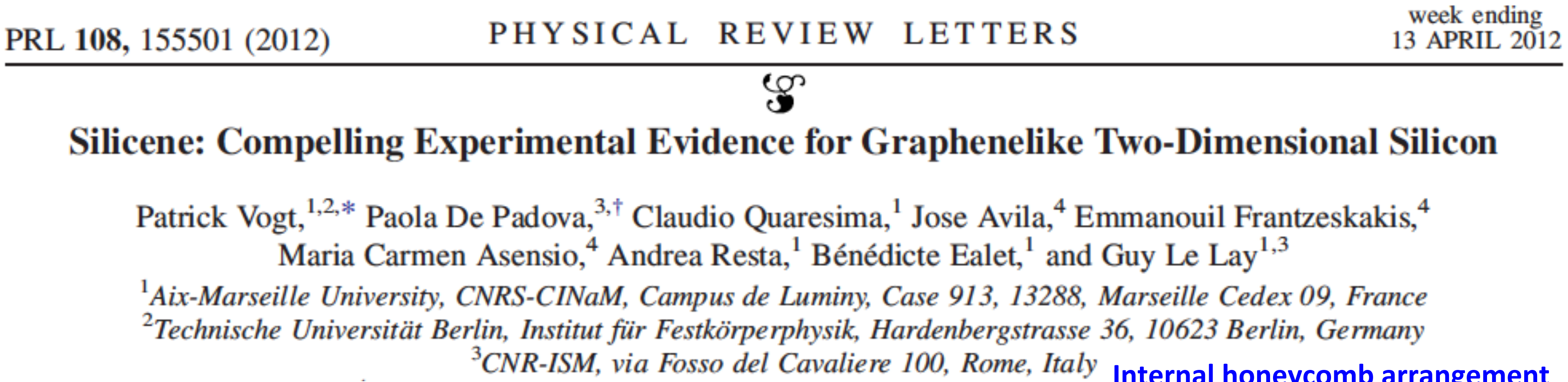
The Kitaev model[1] describes the hopping (with strength *t*) of spinless electrons between sites of a 1D chain in the presence of *p*-wave superconducting pairing, Δ_p. Fractionalizing the fermionic modes into pairs of Majorana quasiparticles, the system can assume topologically distinct ground states: a topologically trivial state with on-site pairing (part **a** of the figure) and a topologically non-trivial state with nearest-neighbour pairing of Majorana quasiparticles (part **b** of the figure). Intuitively, in the topologically non-trivial case, two individual Majorana quasiparticles remain localized at the chain ends.

Material realization of the Kitaev model of 1D topological superconductivity can be achieved by considering the normal-state band structure of a 1D ferromagnet under the influence of Rashba spin–orbit coupling (SOC) with amplitude E_{SO} (part **c** of the figure)[11,47]. (*a*, lattice constant; *E*, energy; *k*, wave vector.) Ferromagnetic exchange splitting of strength *J* separates minority and majority bands. When the Fermi level lies in the minority band, only one spin species is populated, and the system can be regarded as spinless. Rashba SOC imprints a momentum-dependent spin texture on these 1D states, which facilitates proximity-induced pairing by an *s*-wave superconductor of the electrons in the otherwise fully spin-polarized minority band. This combination of magnetism and superconductivity therefore realizes a 1D topological superconducting state with *p*-wave pairing symmetry that can host zero-dimensional Majorana zero modes (MZMs) at its ends.

Scanning tunnelling microscopy (STM) experiments are ideally suited to study topological superconductivity and MZMs across nanoscopic material platforms (part **d** of the figure). In addition to the study of topographical sample properties[103], STM experiments can visualize localized MZMs at the ends of 1D topological superconductors, such as ferromagnetic chains of atoms placed on top of a superconducting surface[24]. MZMs would appear as zero-energy states inside a superconducting gap in the measured conductance (d*I*/d*V*) spectrum of scanning tunnelling spectroscopy measurements. The use of functional tips diversifies the spectroscopic toolbox of STM measurements, aiding the measurement of electron–hole symmetry[45] or spin signatures of MZMs[31,46,47], as discussed in the section on distinguishing trivial and topological zero-bias peaks.



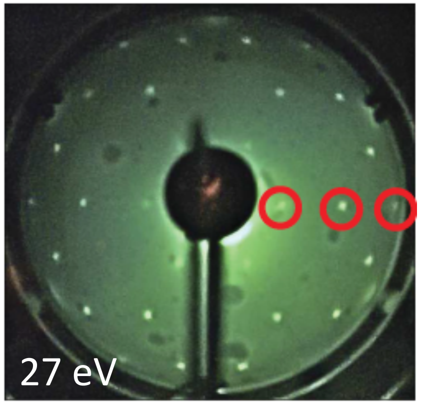
From 2D to 1D silicon topological nanostructures



PRL 108, 155501 (2012) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2012

Silicene: Compelling Experimental Evidence for Graphenelike Two-Dimensional Silicon

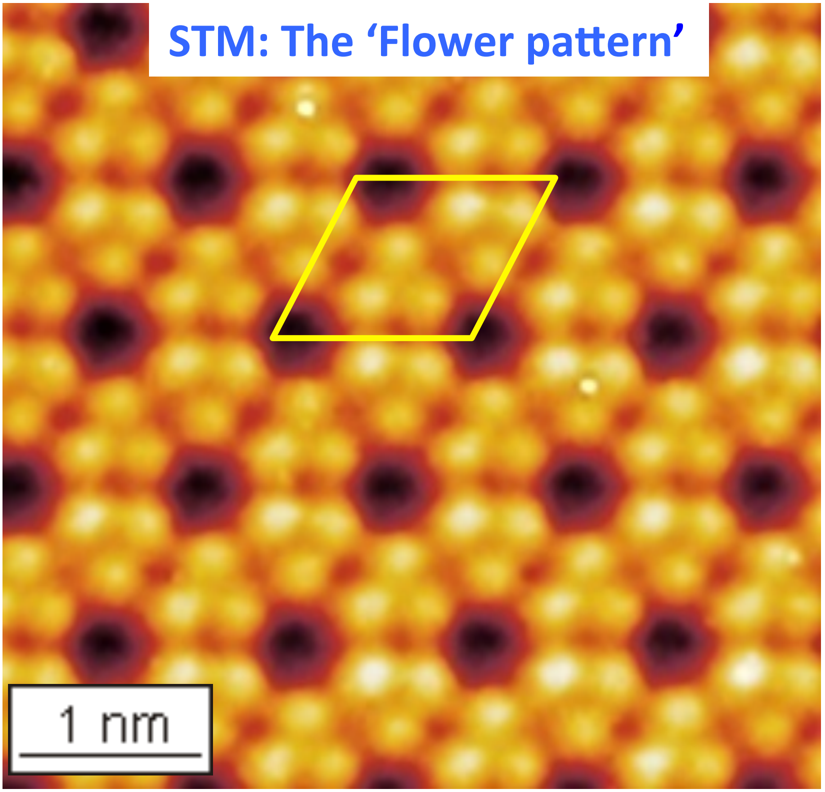
Patrick Vogt,[1,2,*] Paola De Padova,[3,†] Claudio Quaresima,[1] Jose Avila,[4] Emmanouil Frantzeskakis,[4]
Maria Carmen Asensio,[4] Andrea Resta,[1] Bénédicte Ealet,[1] and Guy Le Lay[1,3]
[1]Aix-Marseille University, CNRS-CINaM, Campus de Luminy, Case 913, 13288, Marseille Cedex 09, France
[2]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstrasse 36, 10623 Berlin, Germany
[3]CNR-ISM, via Fosso del Cavaliere 100, Rome, Italy



Growth at 220 °C
LEED/STM

Archetype structure

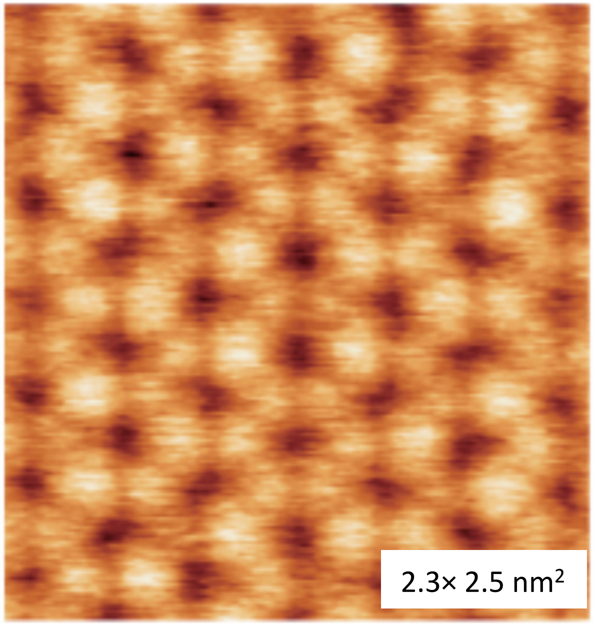
3 × 3 reconstructed
silicene
matching a
4 ×4 supercell on Ag(111)
$\Theta_{Si} = 18/16 = 1.125$



STM: The 'Flower pattern'

WOS citations: 3093 on June 15, 2023

Internal honeycomb arrangement unveiled only in 2017 !

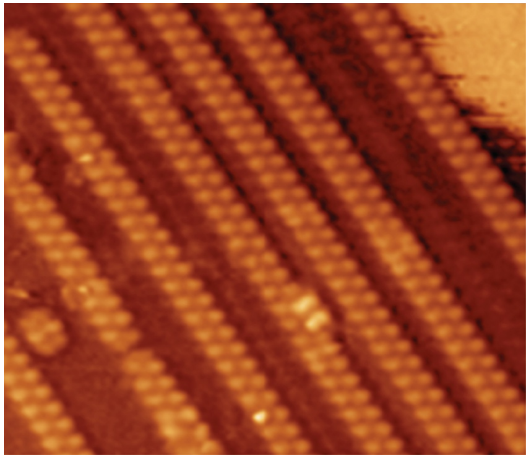


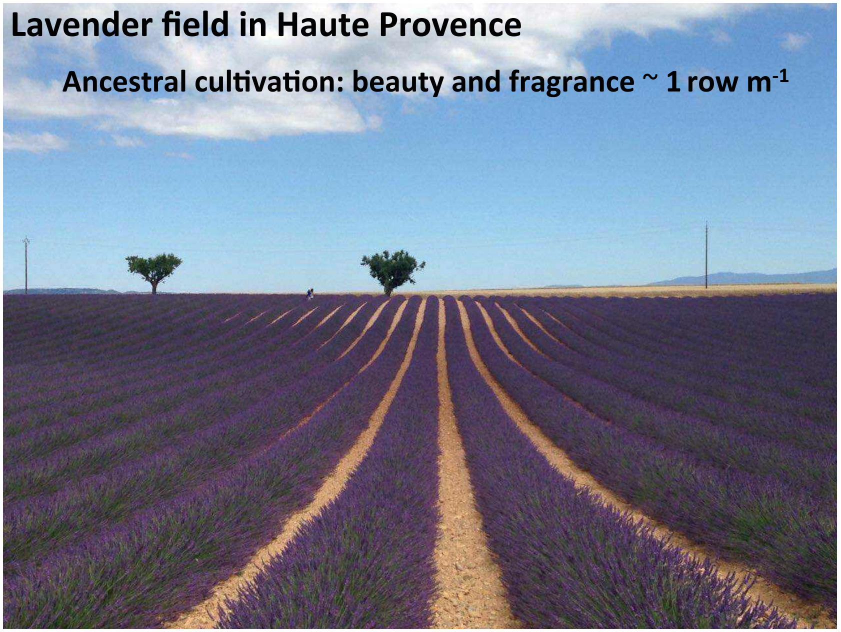
Only uncovered by near contact
Atomic Force Microscopy
5 years later by
Onoda *et al.*,
PRB 96, 241302(R) (**2017**)

Initially refused by 'Elite' Journals without even sending the manuscript to referees !

Massively parallel silicon nanoribbons (SiNRs) grown on the Ag(110) surface (2004)

Nano-cultivation at RT,
single strand SiNRs 8 Å in width

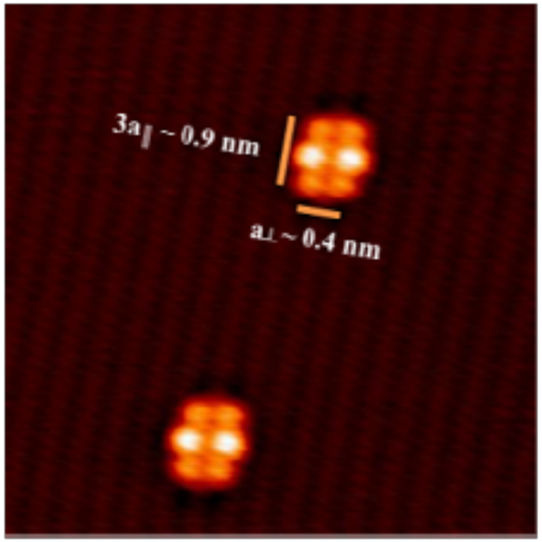




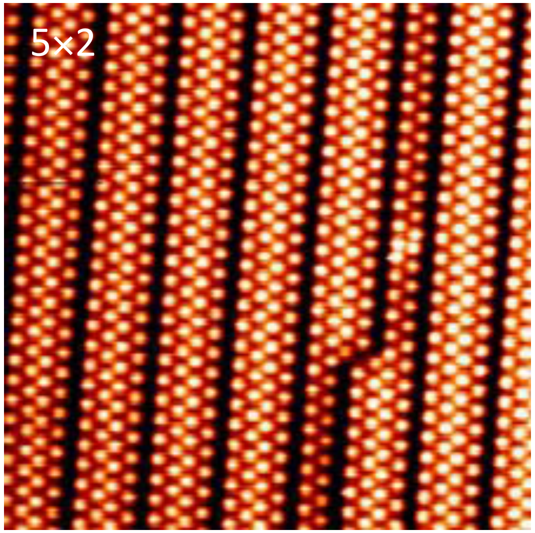
Lavender field in Haute Provence

Ancestral cultivation: beauty and fragrance ~ 1 row m^{-1}

Nanodots, all identical, have mirror symmetry: Si$_{12}$ molecules



Nano-cultivation at 200°C 2 nm pitch
Nearly perfect array: ~ 5 10^8 rows m^{-1}



Serendipity !

0D Nanodots and 1D Nanoribbons, single- or double-strand, i.e., 0.8 / 1.6 nm in width grown at RT/200°C

Aligned, high aspect ratio, symmetry breaking 1D nanostructures!

Indication of superlubricity ?

Leandri *et al.*, Surf. Sci., 574, L9 (2005)
Sahaf *et al.*, Appl. Phys. Lett. **90**, 263110 (2007)
Ronci *et al.*, Phys. Status Solidi C 7, 271 (2010)
Salomon and **Ango**t Science of Advanced Materials, 3 (2011) 1
Davila et al., in 2D Semiconductors Materials and Devices Dongzhi Chi, K.E. Johnson Goh, Andrew T.S. Wee Eds., Elsevier, 1rst edition (2019)

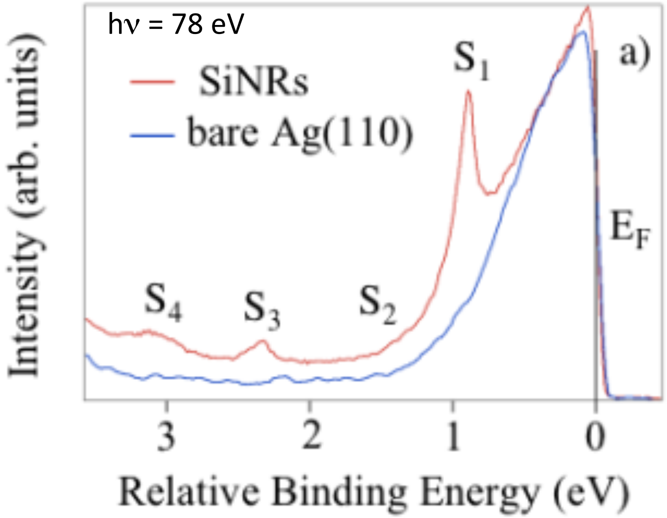
Electronic Structure (Serendipity)

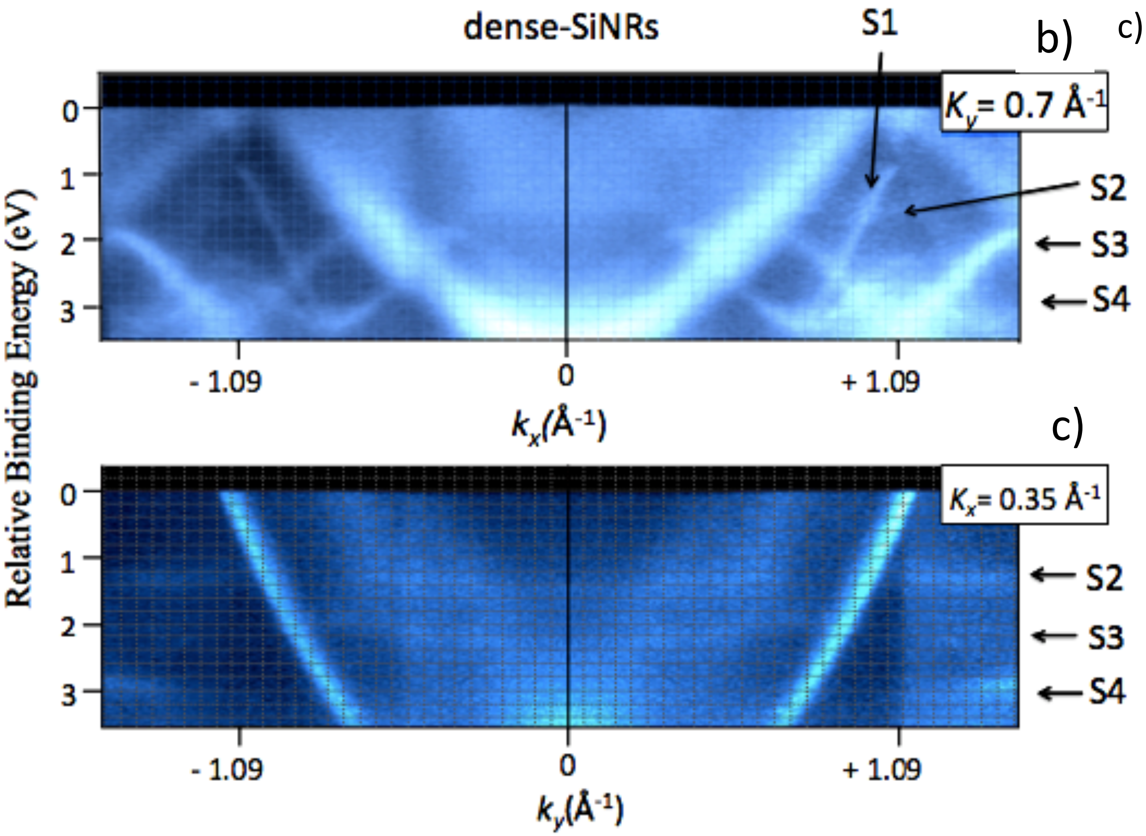
The presence of 1D structures on the Ag(110) surface was inferred from tiny wiggles on the s region of the silver valence band noticed by chance at the Elettra facility in Trieste, Italy. The SiNRs were observed weeks later by STM !

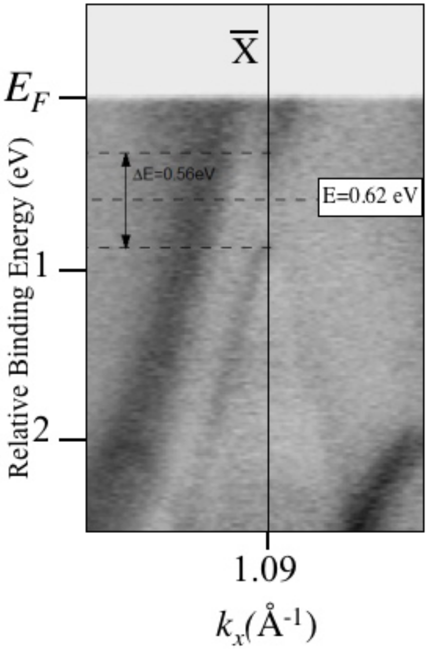
a) Energy distribution curves for bare Ag(110) and for the dense array of SiNRs: **Quantized states !**

b) band dispersion for the array of SiNRs vs kx along the Si NRs at $k_y = 0.7$ Å^{-1}

c) and vs ky perpendicular to the Si NRs at $k_x = 0.35$ Å^{-1}: **Flat bands !**







Cone-like dispersion

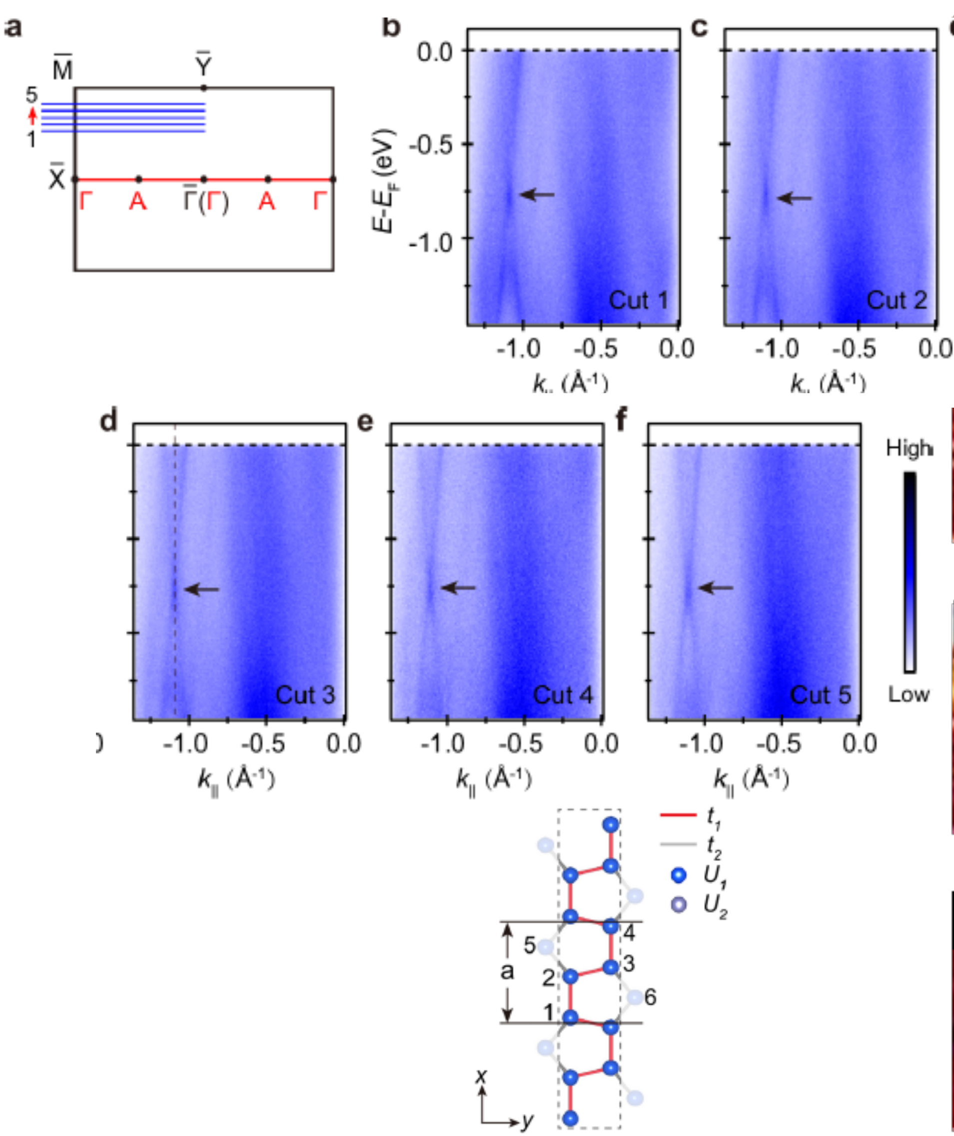
Fermi velocity 2.5 10^5 m/s

(graphene: ~1 10^6 m/s)

De Padova *et al.*, APL 96 (2010) 261905,
J. Phys.: Condens. Matter 24 (2012) 223001

1D Dirac fermions

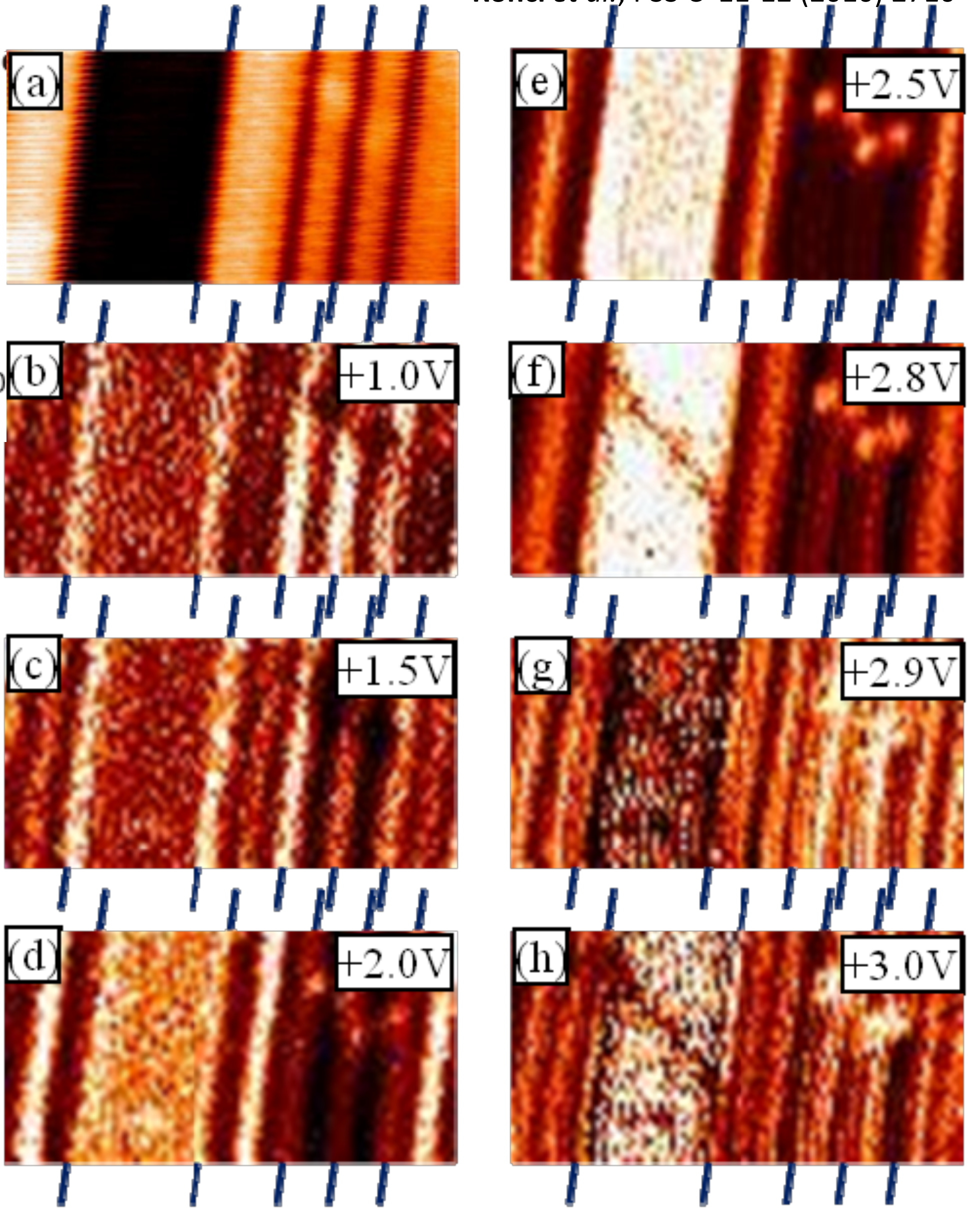
Yue *et al.*, 22 (2022) 695



ARPES measurements of the band structures. **(a)** Schematic drawing of the Brillouin zones of Ag(110) (black) and SiNRs (red). The blue lines indicate the five momentum cuts (Cuts 1−5) where (b−f) were taken.
(b−f) ARPES intensity plots along Cuts 1−5 in **(a)**. **(g)** Sheme of the TB model

Edges states

Ronci *et al.*, PSS C 11-12 (2010) 2710

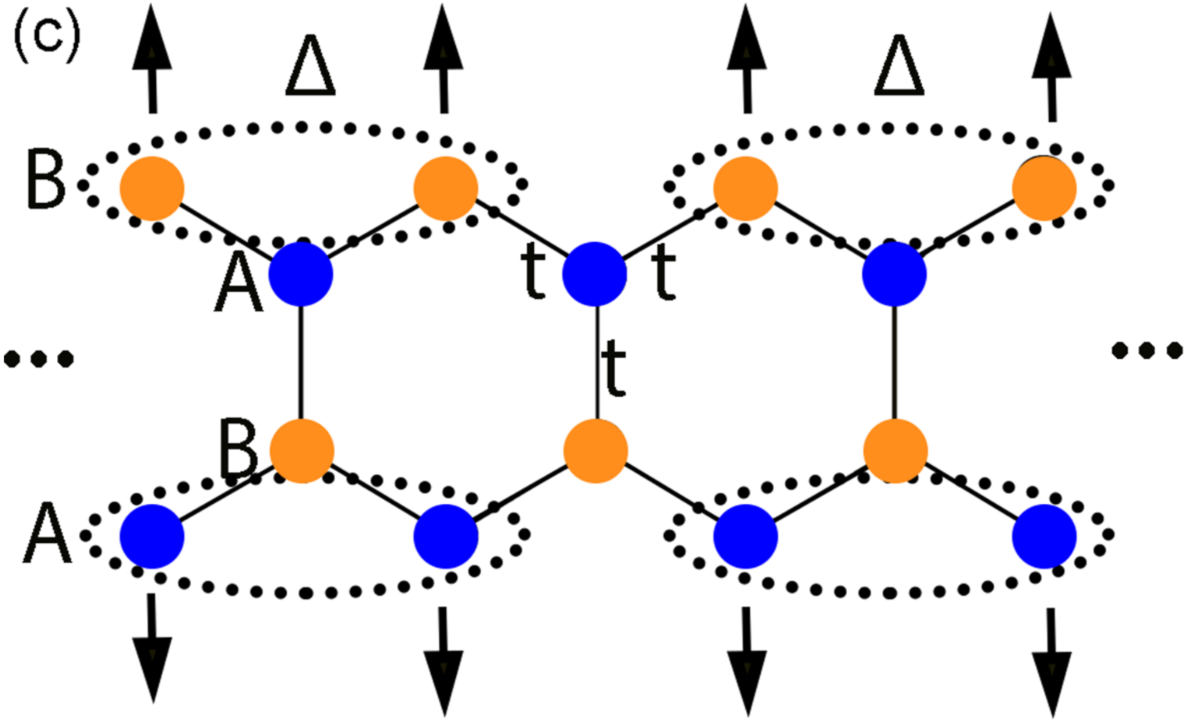


(a) Constant current 10×5 nm^2 STM image, V = +1.0 V, I = 10 nA, T = 80 K
(b)-(h) Differential conductivity (dI/dV) images as a function of bias voltage
Marks are as a guide for better localizing the nanoribbons

MZMs: Design Concept with pentasilicene NRs

Inspiration

Theoretical prediction of the possibility of obtaining **spin-polarized Majorana Zero Modes** at opposite edges of *free standing* **double zigzag honeycomb nanoribbons,** considering a tight-binding chain in a zHNR geometry.



Schematic of a zigzag honeycomb nanoribbon mimicking two parallel **Kitaev chains** connected by the hopping t (KzHNR). The equivalent B (A) atoms of the upper (lower) KzHNR are paired with each other via a p-wave superconducting parameter .

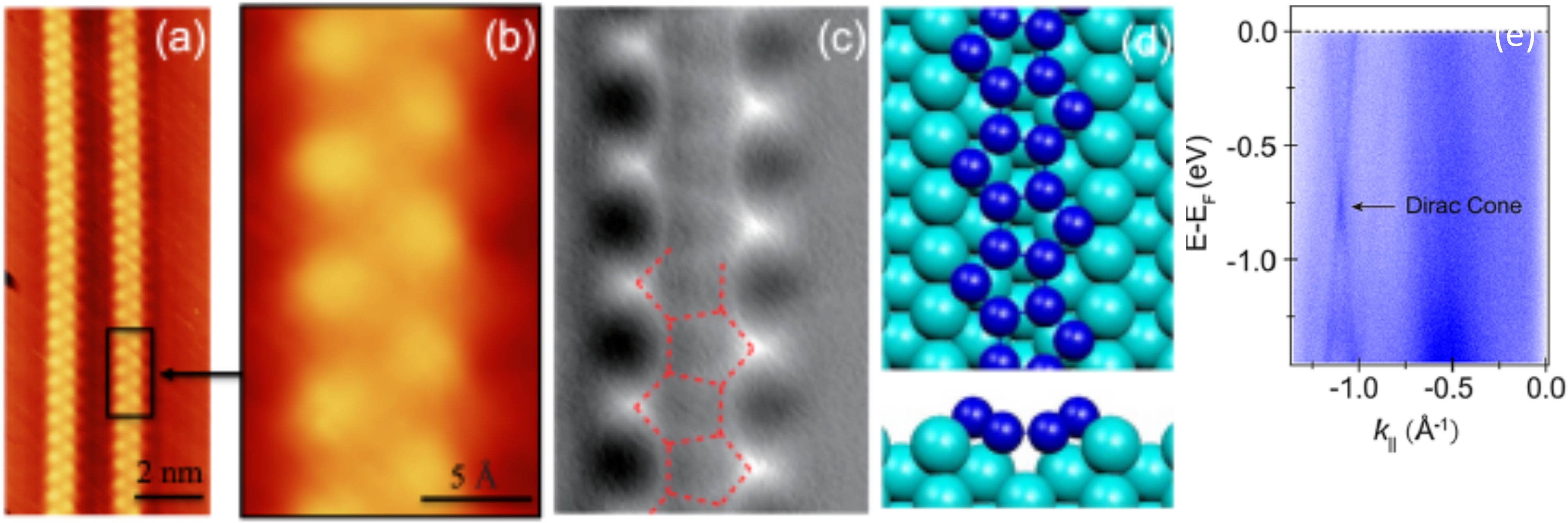
To properly break the spin degeneracy of the system, two additional effects in the spinless Hamiltonian $\boldsymbol{H_t + H_\Delta}$ are introduced: the extrinsic Rashba spin-orbit coupling (RSOC) and an external magnetic field (EMF). The extrinsic RSOC lifts the corresponding bands' spin degeneracy, unless at k = 0. Additionally, the EMF applied perpendicularly to the ribbon plane drives the system through topological phase transitions (TPTs) exhibiting spin-polarized MZMs. In this situation, spin-discriminated MZMs emerge at the ends of the double-spin KzHNR structure. The corresponding generalized Hamiltonian is given by $\boldsymbol{H_{total} = H_t + H_\Delta + H_R + H_Z}$

Spin-polarized Majorana zero modes in double zigzag honeycomb nanoribbons

R. C. Bento Ribeiro, J. H. Correa, L. S. Ricco, A. C. Seridonio, and **M. S. Figueira**, Phys. Rev B 105, 205115 (2022)

The Hardware

Perfectly clean, atomically thin and precise, massively parallel single strand penta-silicene nanoribbons, 0.8 nm in width and several hundred nanometers in length, grown in situ under UHV on a Ag(110) surface.

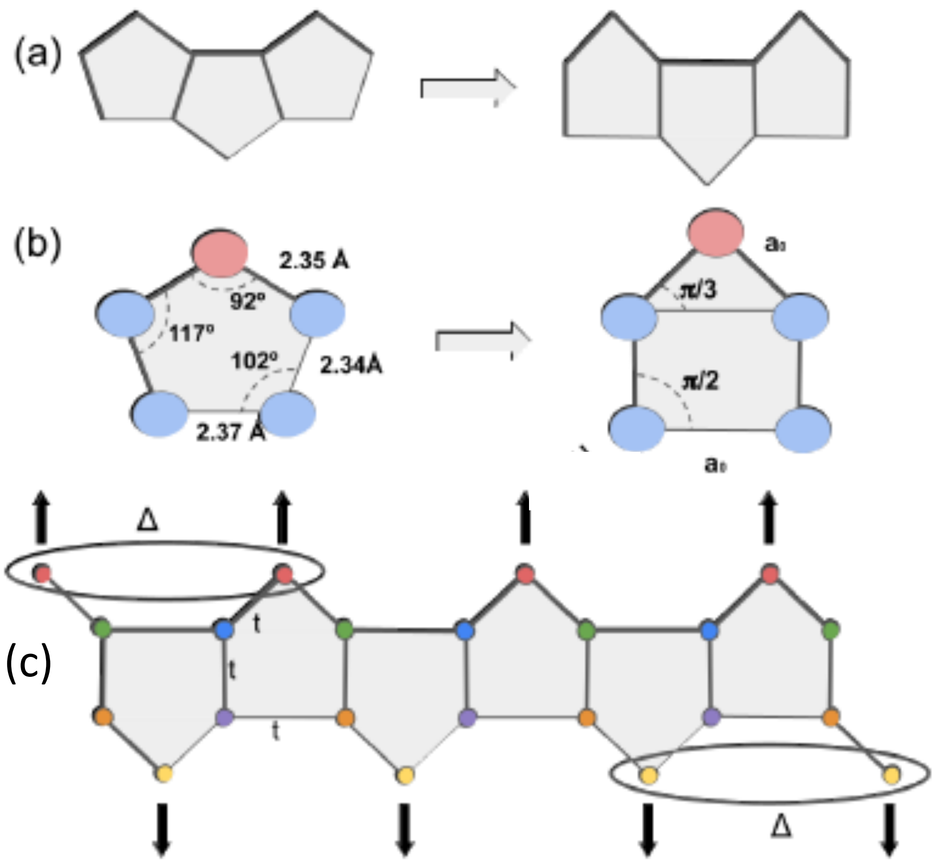


(a) and (b) Experimental STM images (uncorrected drift, courtesy Eric Salomon, PIIM Marseille).
(c) Highresolution nc-AFM image.
(d) Top and cross view of the arrangement of the **Si pentagonal building blocks**.
(e) Confirmation of the presence of a **Dirac cone.**

(c) Sheng *et al*., Nano Lett. 2018, 18, 2937
(d) Cerda et al., Nature Comm., 7 (2016) 13076
(e) Yue *et al*., Nano Lett. 2022, 22, 695

Emergence of spin-polarized Majorana zero modes in penta-silicene nanoribbons

R. C. Bento Ribeiro, Mucio A. Continentino, J. H. Correa, L. S. Ricco, I. A. Shelykh, A. C. Seridonio, M. Minissale, G. Le Lay, **M. S. Figueira**, *Submitted Scientific Reports*



(a) Penta-silicene (p-SiNRs) lattice transformation adopted. (b) Penta-silicene angles. (c) Sketch of nonequivalent Si atoms placed at the vertices of the“square” pentagonal lattice.
The penta-silicene system can be viewed as a top and a bottom Kitaev chains hybridized via hopping t. The ellipses represent the superconducting p-wave pairing between the pink (above) and yellow (below) silicon atoms (in the real material, these atoms correspond to the buckled one). The arrows only indicate the spin polarization needed to define a Kitaev chain.

The calculations:

- *to simplify we choose right angle chains with all hoppings (first neighbors) equal to ‘t’*
- *Rashba spin-orbit interaction* λ_R
- *External magnetic field* E_z *perpendicular to the NR plane, introducing a Zeeman effect, to properly account for the spin degree of freedom in the superconducting p-SiNR.*
- *Superconductor p-wave pairing Δ*

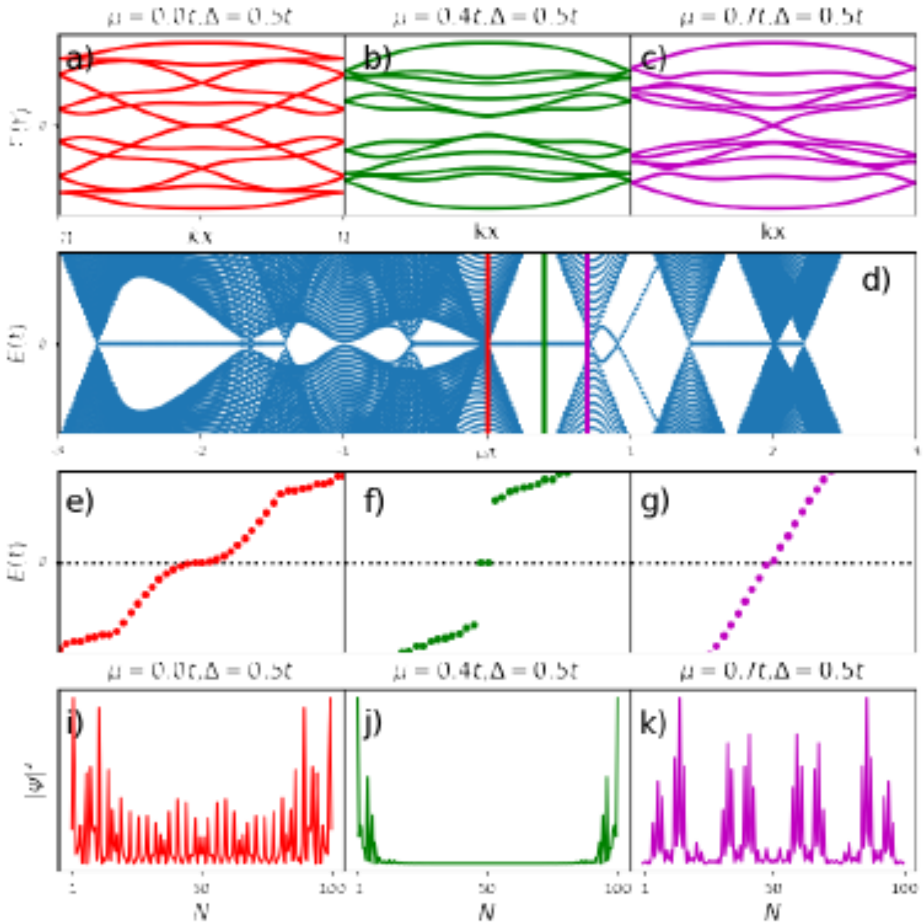
The total system Hamiltonian, considering also the spin degree of freedom on both H_t *and* H_Δ *is defined as* $\boldsymbol{H_{total} = H_t + H_Z + H_R + H_\Delta}$

The realization:

since silver is not a superconductor, to generate a p -wave pairing Δ on the pink atoms of (c), we overlay *in situ* a thin *unreactive* lead film evaporated through a mask. Under the presence of a strong RSOC coming from the Pb atoms and an applied magnetic field, the s -wave Cooper pairs of the Pb film can enter into the p-SiNR region via proximity effect, giving rise to a p -wave-induced pairing in the double chain structure.

Results for p-SiNRs

Spinless case



(a)-(c) Bulk energy dispersion for the spinless p-SiNRs as a function of kx, for μ = 0.0t, 0.4t, and 0.7t, respectively. (d) Energy spectrum as a function of the chemical potential. Vertical lines indicate the chosen values of chemical potential shown on top panels. (e)-(g) The energy spectrum with labels the energy levels in increasing order for μ = 0.0t, 0.4t, and 0.7t, respectively. (i)-(k) Probability density associated with zero-energy states, as a function of the lattice site N = 1 . . . 100.

Spinfull case

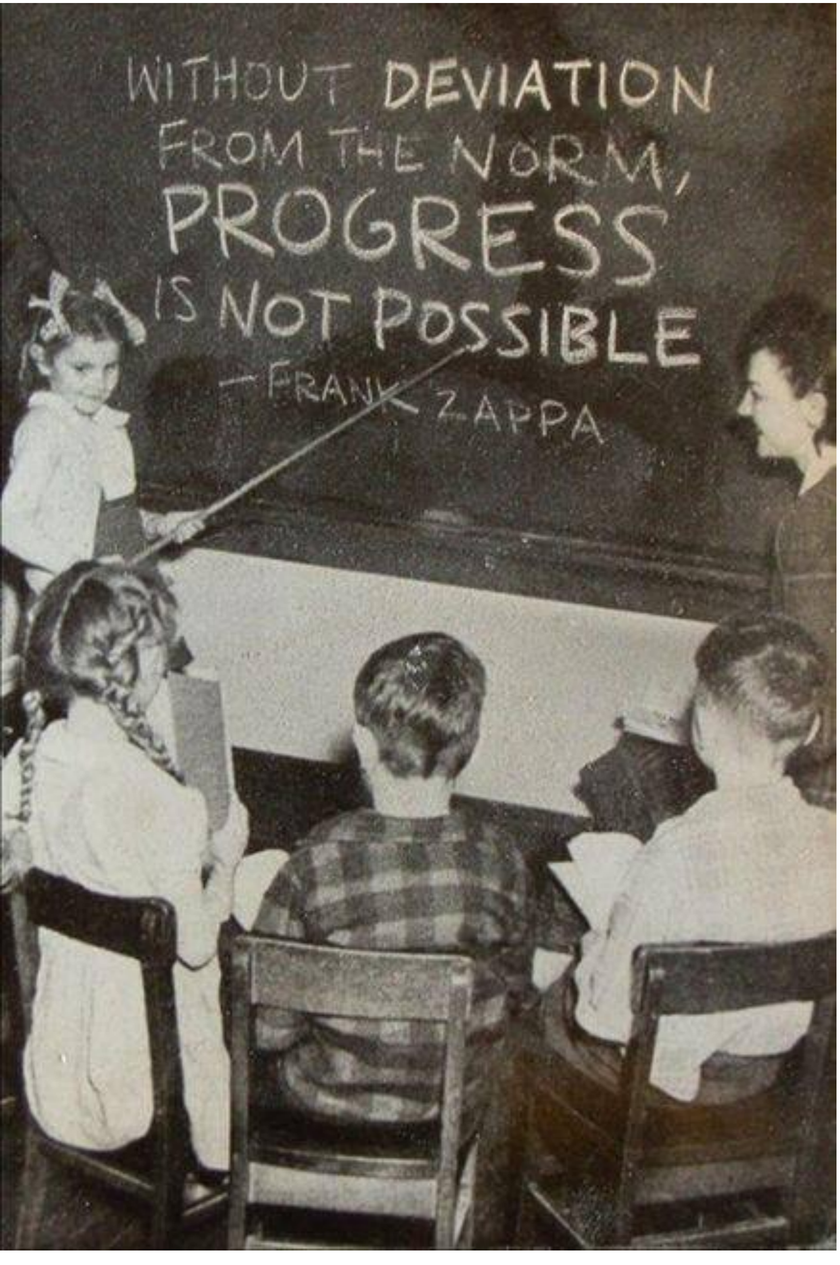
See the manuscript...

Take home message

The MZMs are spin discriminated, and their polarization can be controlled by varying the chemical potential or the magnetic field.

Hence, the p-SiNRs appear as candidates for realizing topological qubits based on MZMs with well-defined spin orientation, suggesting a possible route for performing Majorana spintronics.

The Mantra


WITHOUT DEVIATION
FROM THE NORM,
PROGRESS
IS NOT POSSIBLE
– FRANK ZAPPA

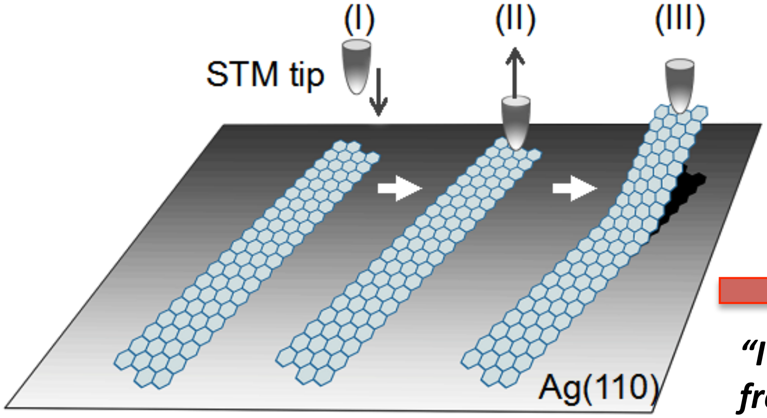

Serendipity

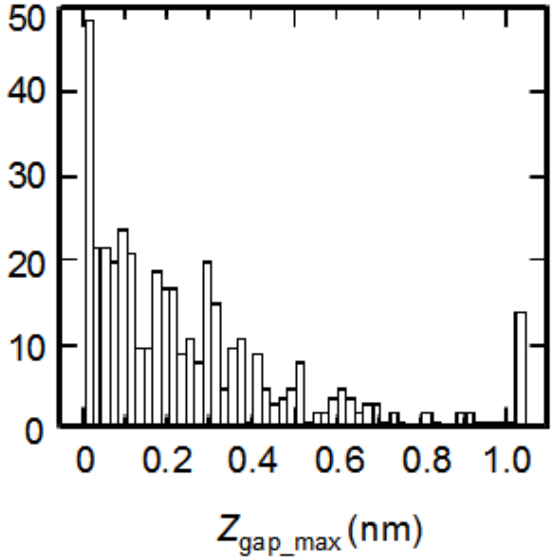
Lifting off double-strand SiNRs with an STM tip

R. Hiraoka *et al.***,** Beilstein J. Nanotechnol. 2017, 8, 1699
From the group of Prof**. Maki Kawai**

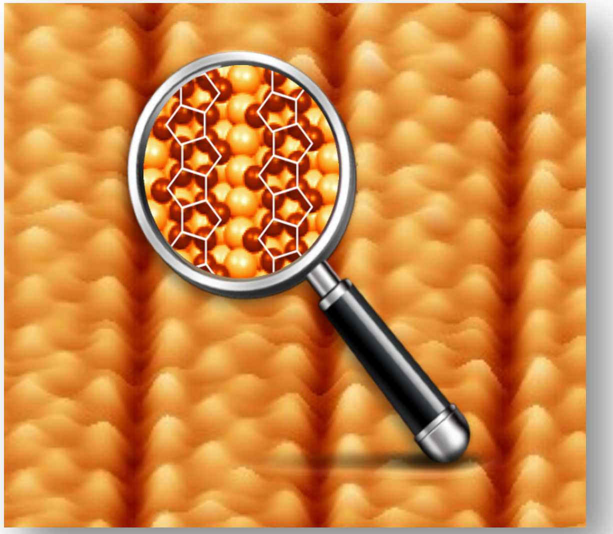
Free-standing pentasilicenelike nanoribbon !

"I don't often say something categorical, but I will say that a pristine free-standing single layer sheet of silicene (or a Si nanotube) will not be made." **R. Hoffmann** Angew. Chem. Int. Ed. 52, 93 (2013).





Histogram of the maximum distance the tip travels before the SiNR nanojunction is broken after contacting the tip to the SiNR.

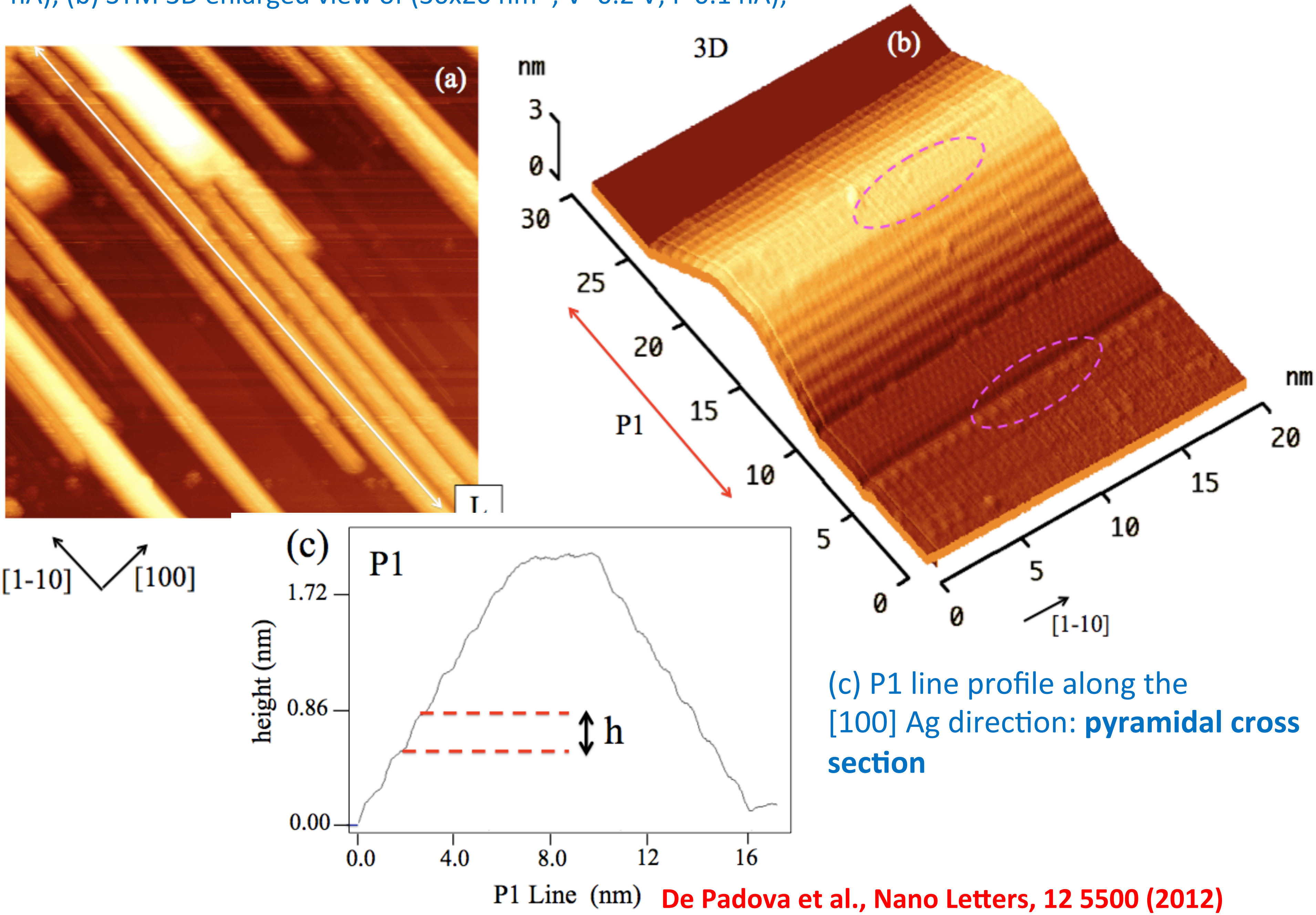


Open Questions:

Why *symmetry-breaking Single Strand* SiNRs develop on a Ag missing row from *symmetric* NanoDots on a Ag divacancy? What is the polymerisation process?

How *Single Strand* SiNRs, which form a 3 × 2 arrangement, evolve to *Double Strand* SiNRs and form the highly perfect 5 × 2 grating? Lateral compaction? Superlubricity?

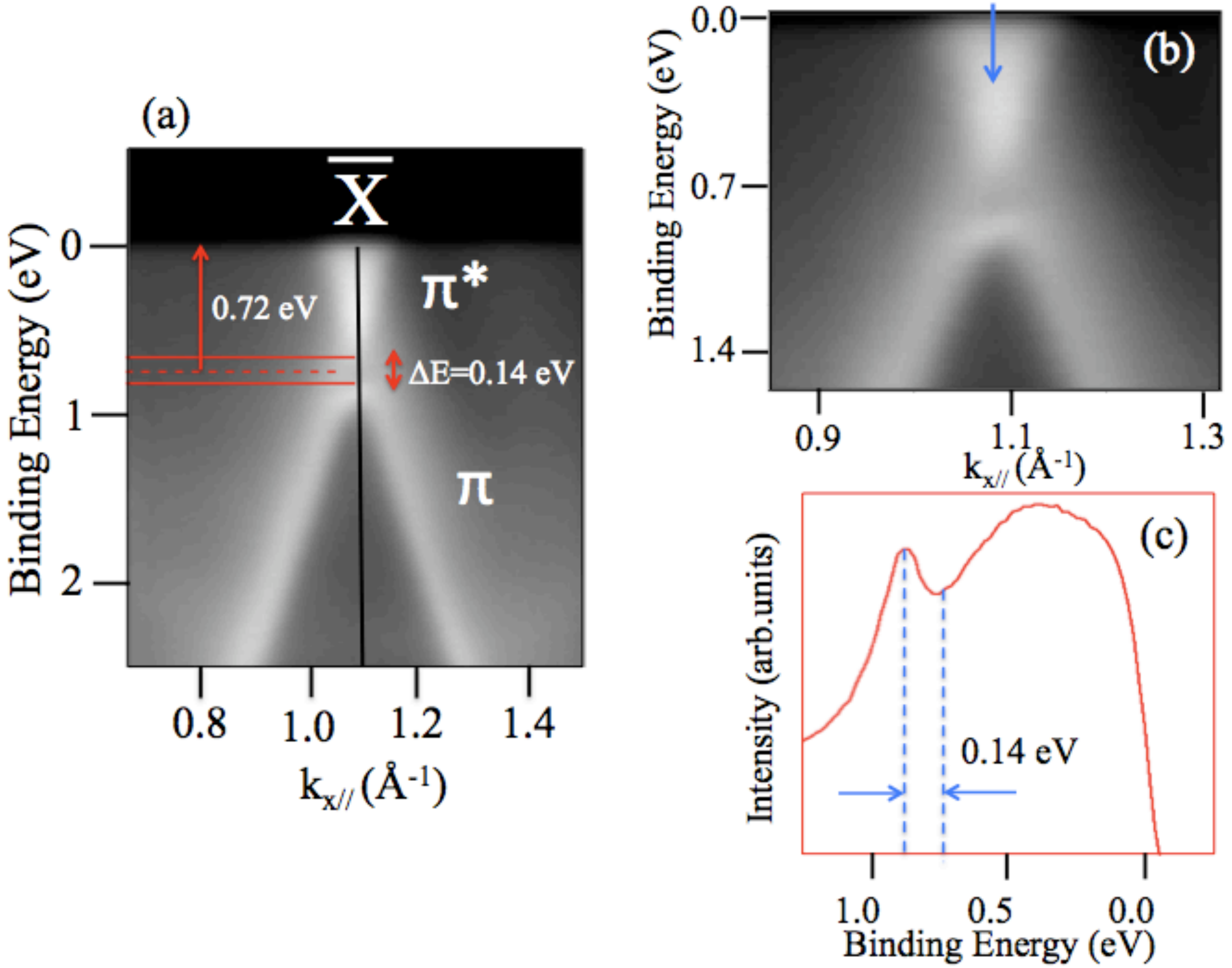
(a) STM image of an ensemble of **multilayer-thick SiNRs** on Ag(110) (400×400 nm^2 ; V=-0.6 V; I= 1 nA); (b) STM 3D enlarged view of (30x20 nm^2 ; V=0.2 V; I=0.1 nA);



(c) P1 line profile along the [100] Ag direction: **pyramidal cross section**

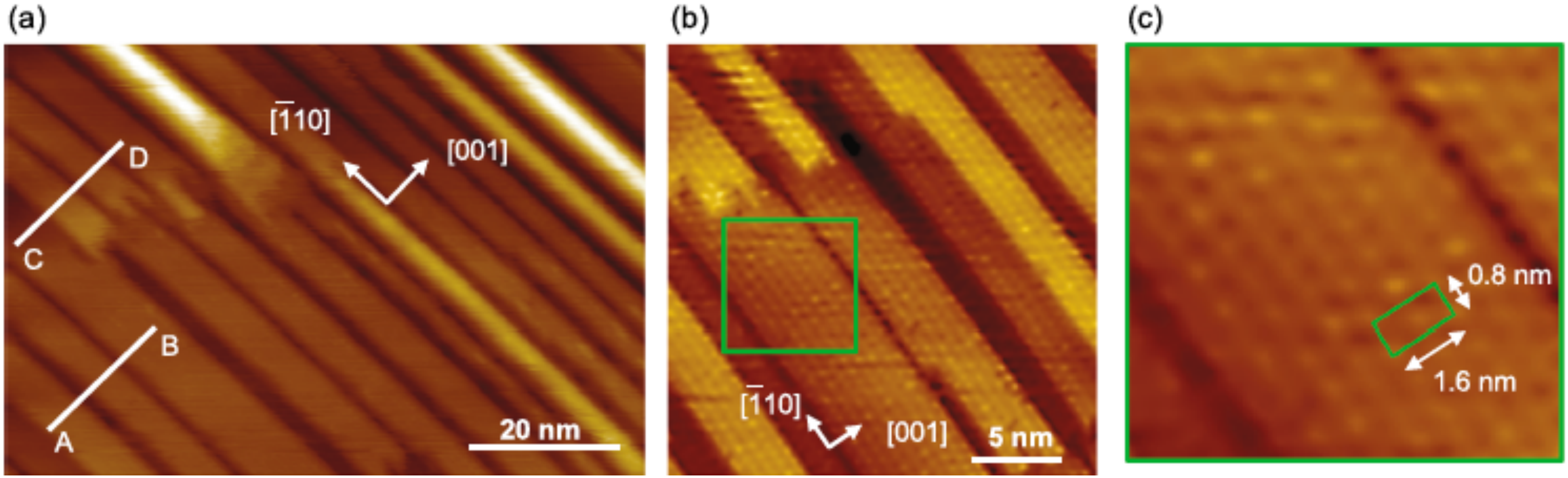
De Padova et al., Nano Letters, 12 5500 (2012)

Dirac fermions in multilayer-thick SiNRs

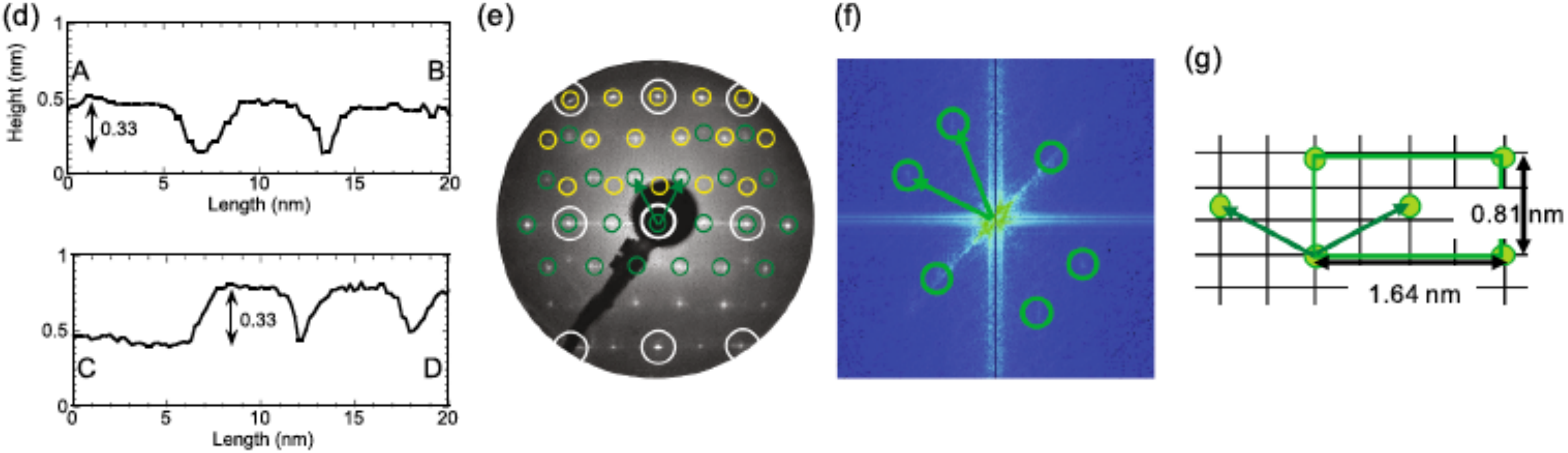


(a) ARPES intensities (hν = 126 eV) from multilayer-thick 5×4 SiNRs recorded along their lengths the (Γ→ X) direction ; (b) zoom-in ; (c) vertical cut along the blue arrow in (b)

De Padova et al., Nano Letters, 12 5500 (2012)



Massively parallel, high aspect ratio, Germanium NRs prepared by surface segregation on a Ag(110) thin film grown on a Ge(110) surface



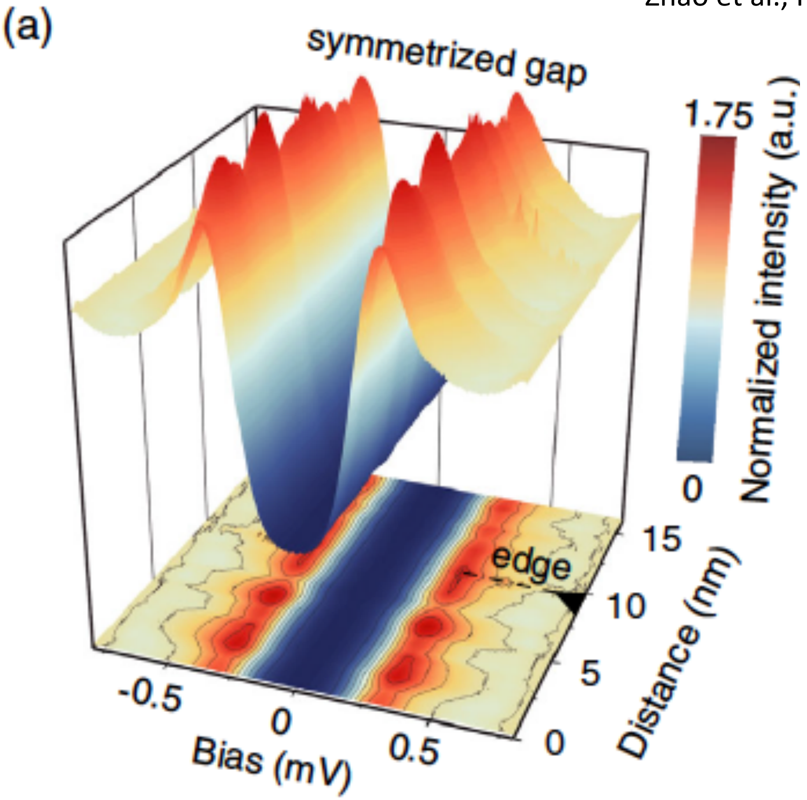
The Ag(110) thin film was grown on a Ge(110) substrate and annealed at 510°C

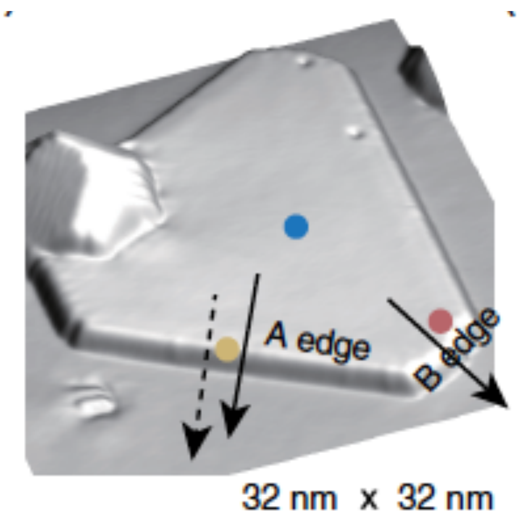
(a) Large-scale STM **(b)** Atomic scale STM image). **(c)** Zoomed-up STM image. **(d)** Section profiles along white lines in (a). **(e)** LEED pattern at 55 eV. White solid circles are primitive spots of Ag(110). Green solid circles are incommensurate spots of c(4 × 2.8) and yellow solid circles are multiple diffraction spots originating from (01), (10), (0-1), and (-10). **(f)** FFT image of (b). **(g)** Scheme of the incommensurate Ag(110)c(4 × 2.8) supercell.

Yuhara et al., AppL Surf. Sci., 550 (2021) 149236

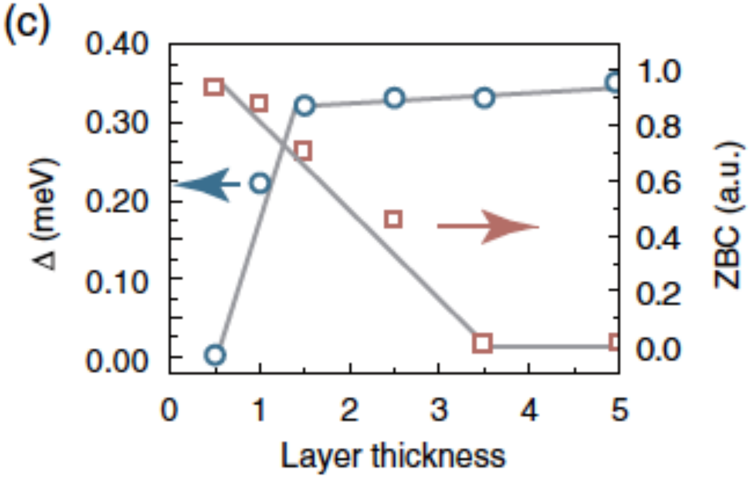
Coexistence of Robust Edge States and Superconductivity in Few-Layer Stanene

Zhao et al., PRL 128, 206802 (2022)

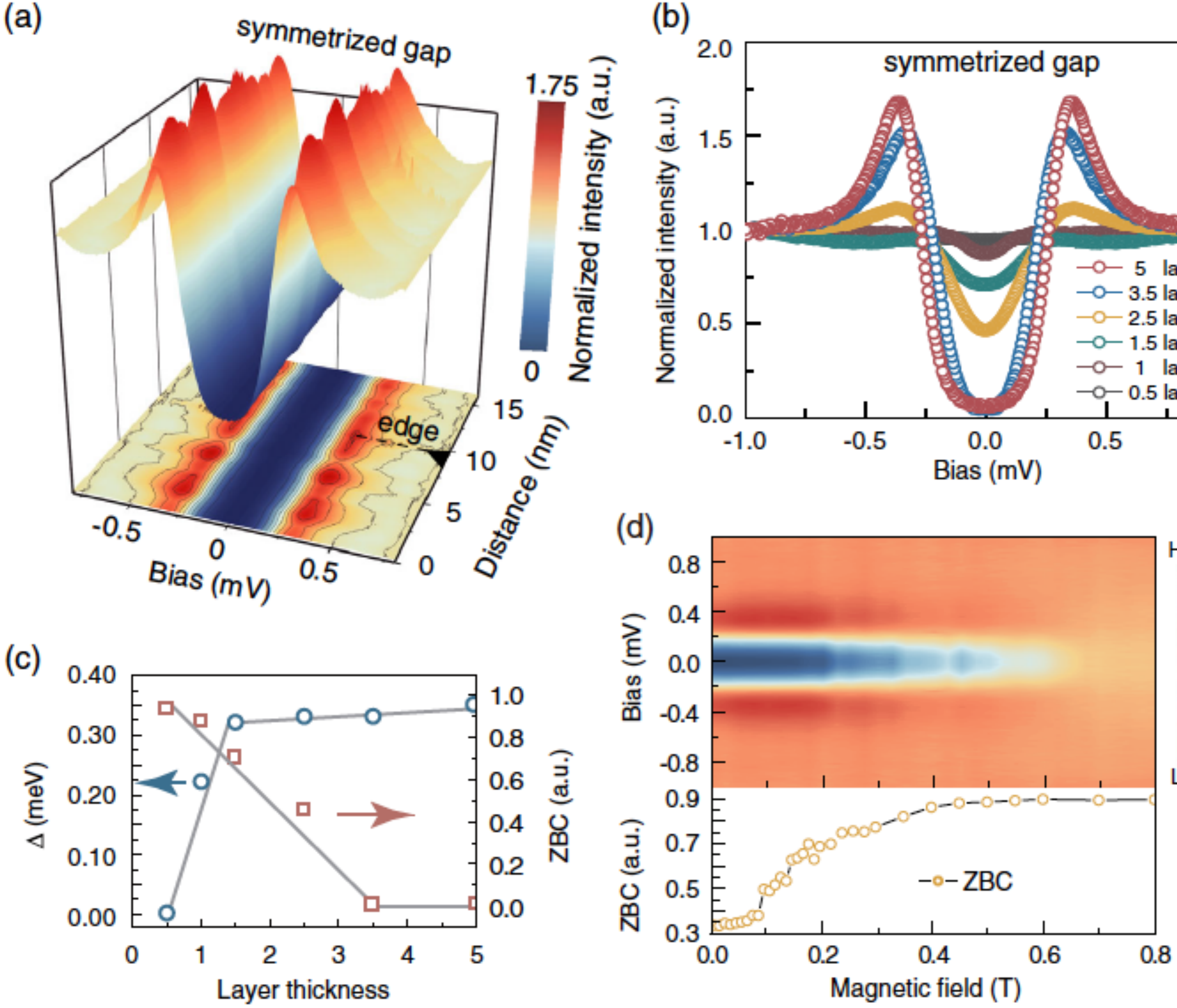




(a) Left: Spatial variation of the superconducting gap crossing the A edge along the dotted arrow in the image of the island (right). The contour map is projected underneath.



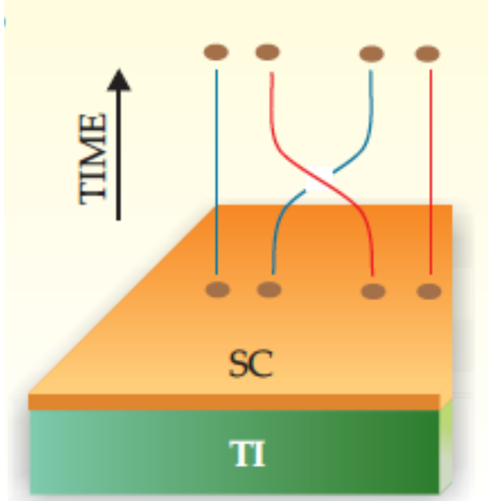
(b) Plots of the gaps (Δ) extracted by half the energy distance of two coherence peaks and the zero bias conductance (ZBC) that quantizes the degree of the superconducting gap compared with a full gap.


(a)
symmetrized gap
1.75
0
Normalized intensity (a.u.)
edge
-0.5
0
0.5
Bias (mV)
0
5
10
15
Distance (nm)
(b)
symmetrized gap
2.0
1.5
1.0
0.5
0.0
Normalized intensity (a.u.)
-1.0
-0.5
0.0
0.5
Bias (mV)
5 la
3.5 la
2.5 la
1.5 la
1 la
0.5 la
(c)
0.40
0.30
0.20
0.10
0.00
Δ (meV)
1.0
0.8
0.6
0.4
0.2
0.0
ZBC (a.u.)
0
1
2
3
4
5
Layer thickness
(d)
0.8
0.4
0.0
-0.4
-0.8
Bias (mV)
H
L
0.9
0.7
0.5
0.3
ZBC (a.u.)
ZBC
0.0
0.2
0.4
0.6
0.8
Magnetic field (T)

Searching for the soul of the new machines

By Kenneth Chang

The Hunt for the Topological Qubit for topological quantum computing



When a Topological insulator is coated by an s-wave superconductor, the superconducting vortices are **Majorana fermions**—they are their own antiparticles. Exchanging or braiding Majorana vortices leads to non-abelian statistics. Such behavior could form **the basis piece of hardware (Majorana Qubit)** for topological quantum computing. **Xiao-Liang Qi and Shou-Cheng Zhang**, Physics Today Jan. 2010, 33

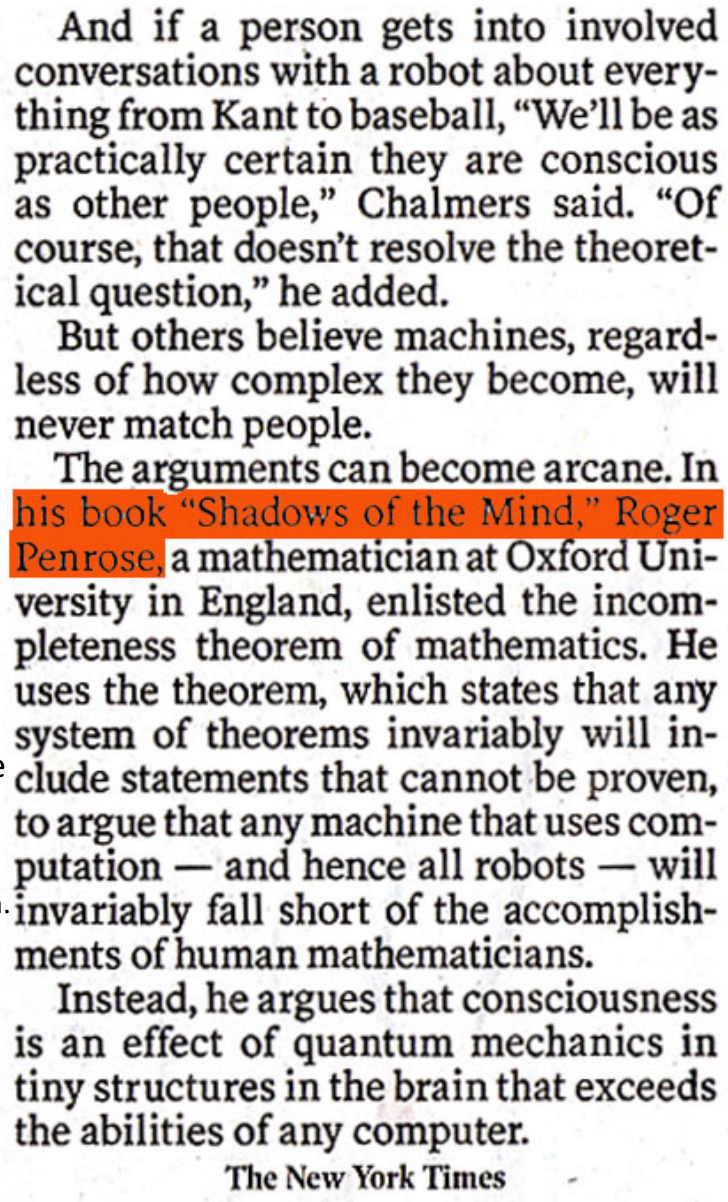
The Challenge: the Hardware

Experimental synthesis and characterization of **2D Topological Insulators** remain a major challenge at present, offering outstanding opportunities for innovation and breakthrough. **Kou *et al.***, J. Phys. Chem. Lett. 2017, 8, 1905

The way: create atomically controlled artificial structure ***by design***

Nanoarchitectonics!

The concept by **Prof. Masakazu Aono**
MANA, NIMS, Japon



And if a person gets into involved conversations with a robot about everything from Kant to baseball, "We'll be as practically certain they are conscious as other people," Chalmers said. "Of course, that doesn't resolve the theoretical question," he added.

But others believe machines, regardless of how complex they become, will never match people.

The arguments can become arcane. In his book "Shadows of the Mind," Roger Penrose, a mathematician at Oxford University in England, enlisted the incompleteness theorem of mathematics. He uses the theorem, which states that any system of theorems invariably will include statements that cannot be proven, to argue that any machine that uses computation — and hence all robots — will invariably fall short of the accomplishments of human mathematicians.

Instead, he argues that consciousness is an effect of quantum mechanics in tiny structures in the brain that exceeds the abilities of any computer.

The New York Times

Sir Roger Penrose, 2020 Nobel Prize in Physics