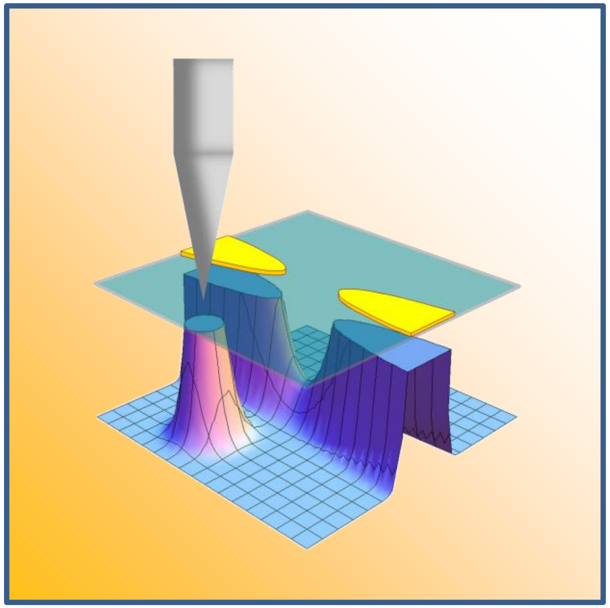
Scanning Gate Microscopy on low-dimensional nanostructures



Stefan Heun

NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy

NEST Pisa

National Enterprise for nanoScience and nanoTechnology

NEST

Research themes @ NEST Pisa

National **E**nterprise for nano**S**cience and nano**T**echnology

NEST is an interdisciplinary research and training centre where physicists, chemists and biologists investigate scientific issues at the nanoscale.

NanoPhysics

1. Quantum transport and phase coherent effects in superconductors
2. Physics of low-dimensional semiconductor systems
3. Graphene (**Flagship**)

NanoBioScience

1. Visualizing brain function and structure in the living mouse
2. Lab-on-a-chip technologies
3. Nanoscale and single-molecule spectroscopy and imaging of soft matter

Advanced Photonics

1. Intersubband polaritonics
2. Silicon-Germanium optoelectronics
3. THz photonics
4. OptoElectronics Materials: from nanoscale to bulk single crystals

Outline

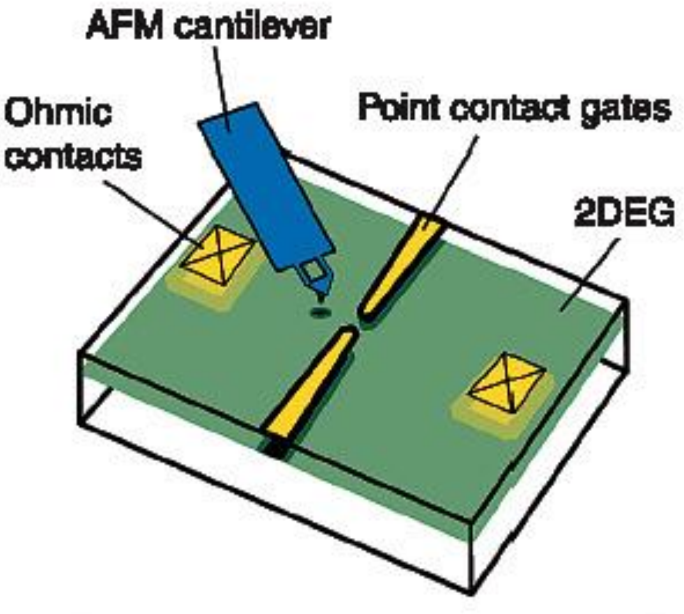
- Basics of Scanning Gate Microscopy (SGM)
- 0.7 Anomaly in Quantum Point Contacts
- Ongoing Activities

Outline

- **Basics of Scanning Gate Microscopy (SGM)**
- **0.7 Anomaly in Quantum Point Contacts**
- **Ongoing Activities**

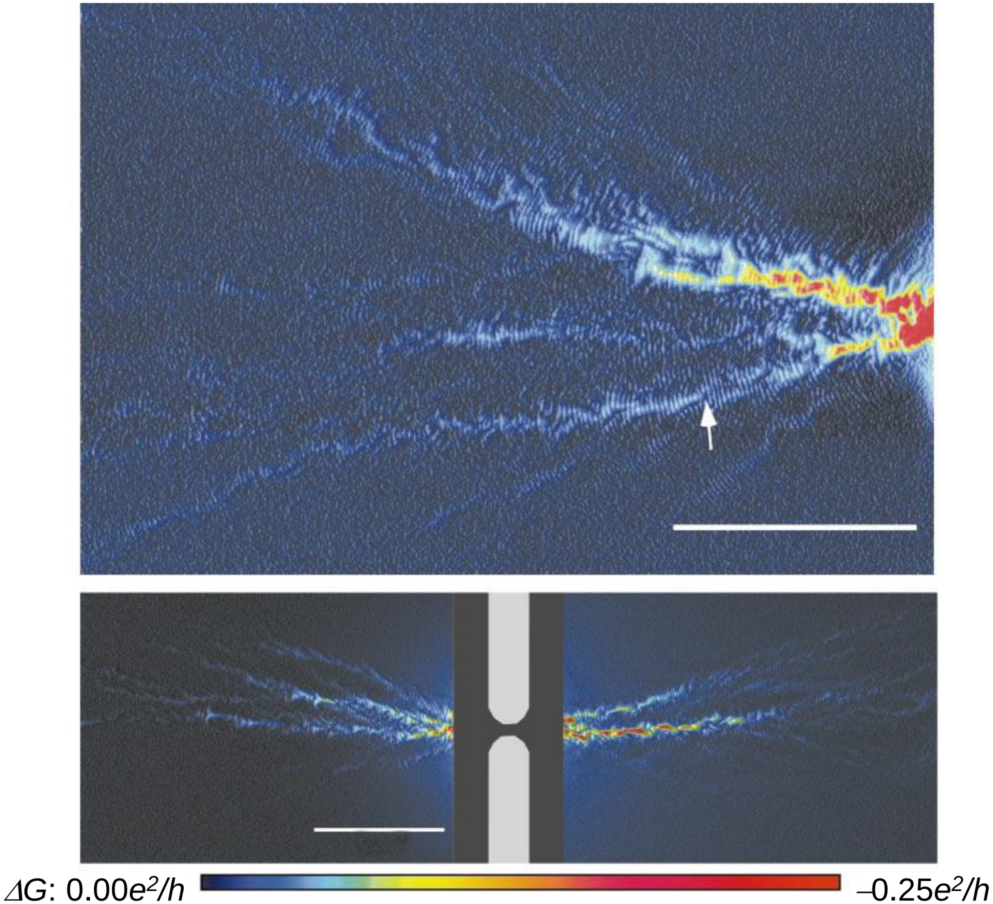
Scanning Gate Microscopy

- AFM with conductive tip
- SGM performed in constant height mode (10-50 nm above surface), no strain
- Tip at negatively bias (local gate - locally depletes the 2DEG), no current flows



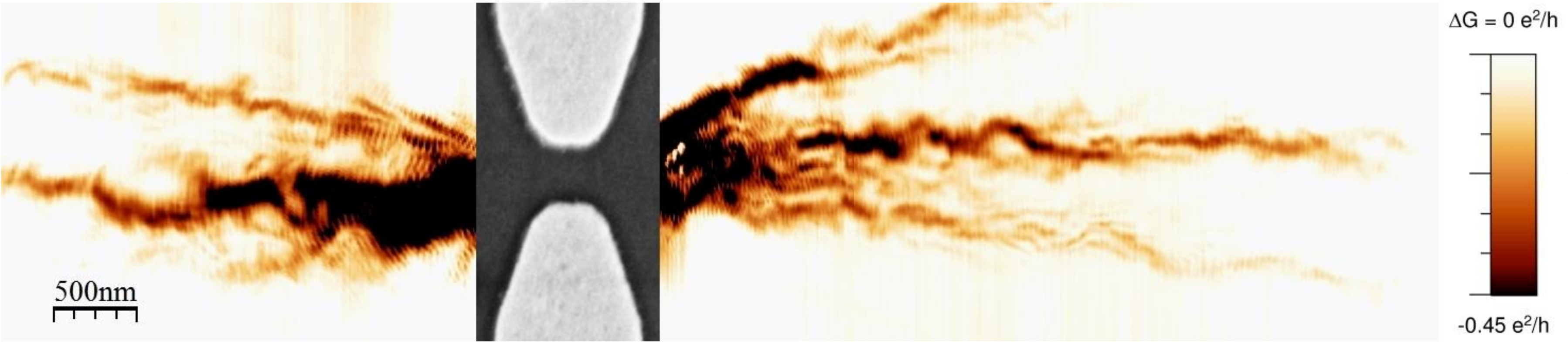
M. A. Topinka et al.: Science **289** (2000) 2323.

Coherent branched flow of electrons



M. A. Topinka et al., Nature 410 (2001) 183.

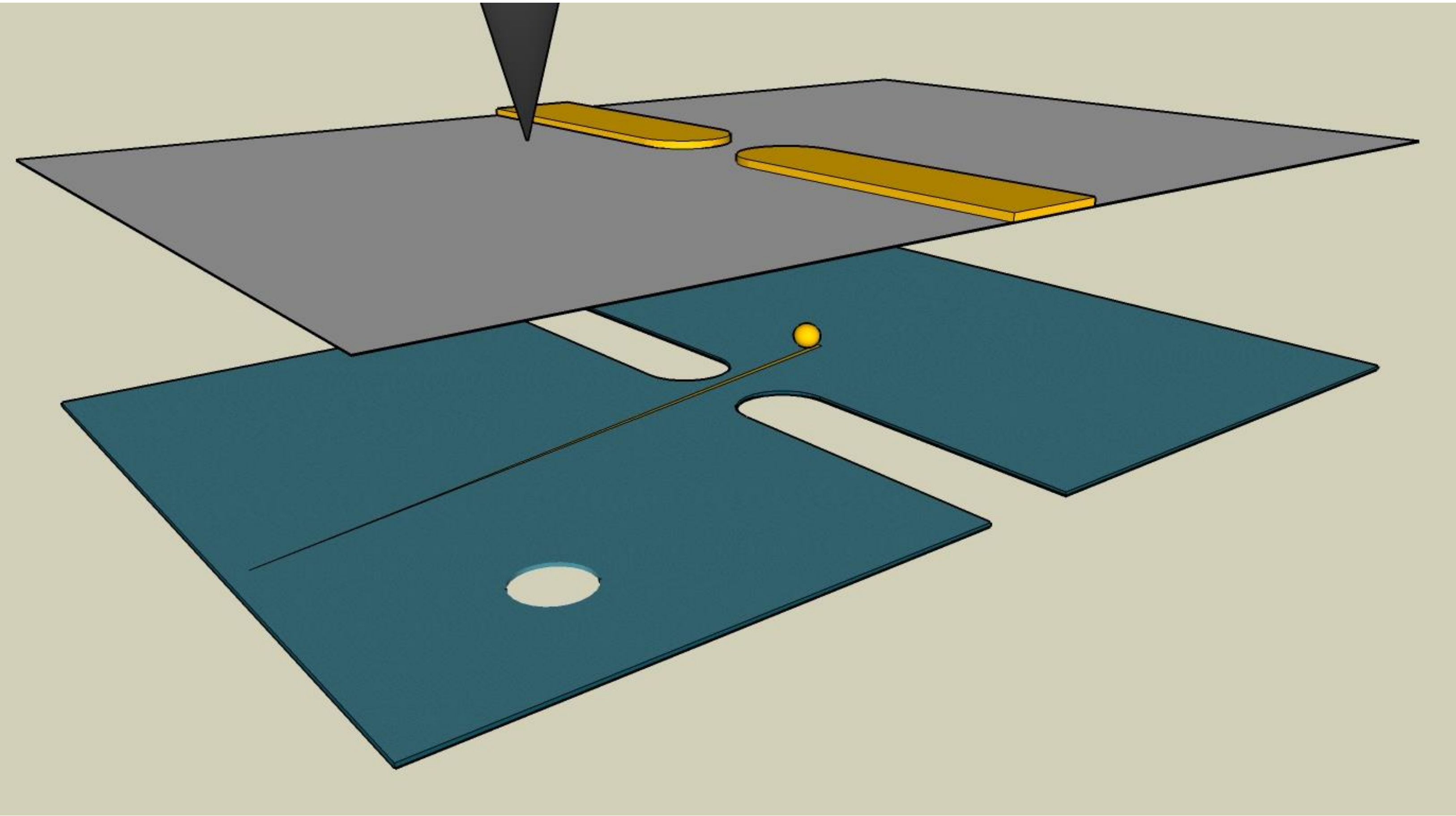
Branched flow of electrons



- No magnetic field (B = 0)
- QPC conductance G = 6 e^2/h (3rd plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm

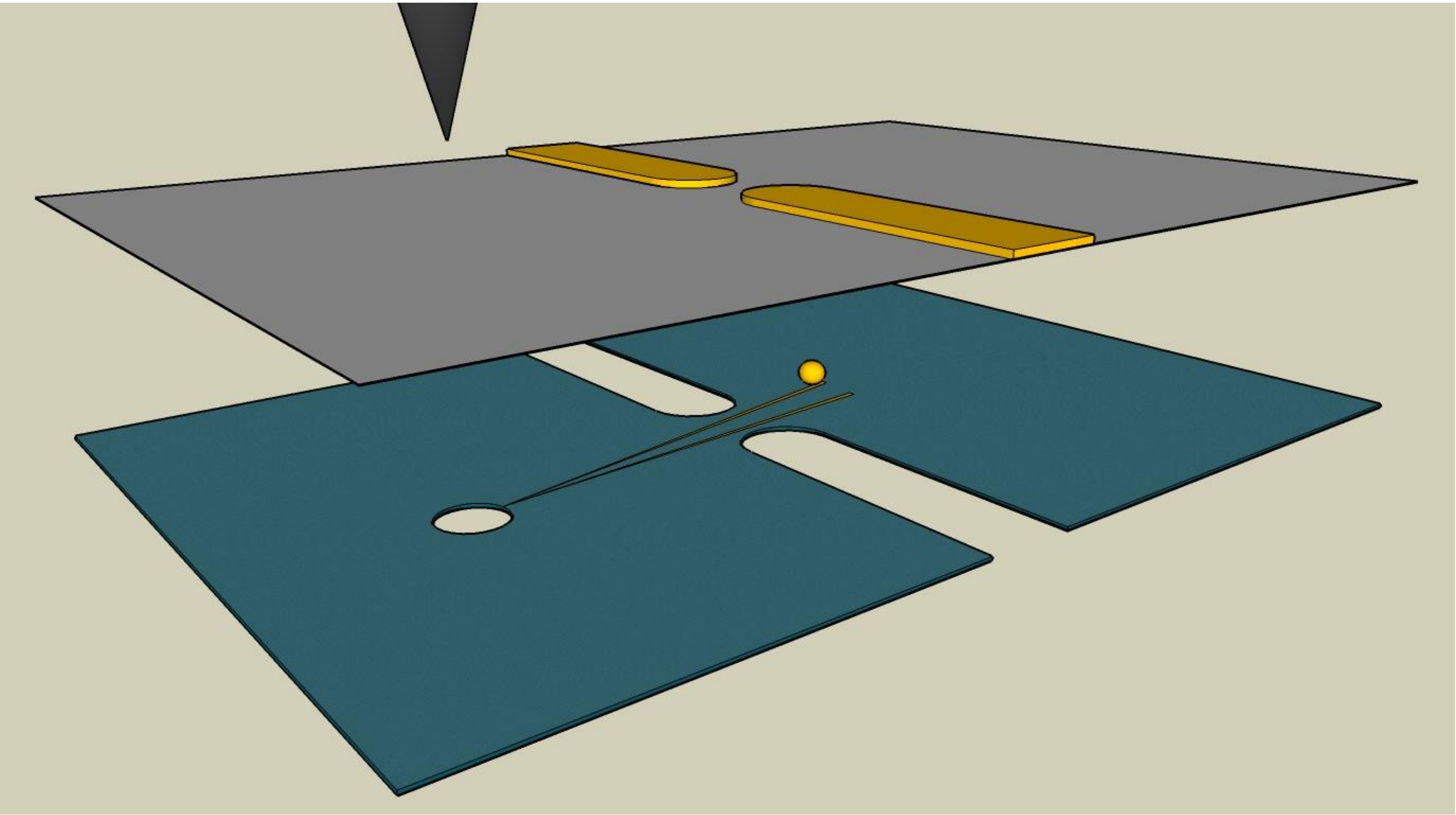
N. Paradiso et al., Physica E **42** (2010) 1038.

Tip-induced backscattering



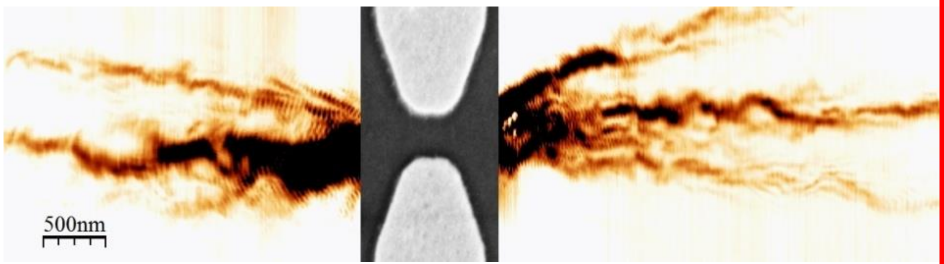
N. Paradiso et al., Physica E **42** (2010) 1038.

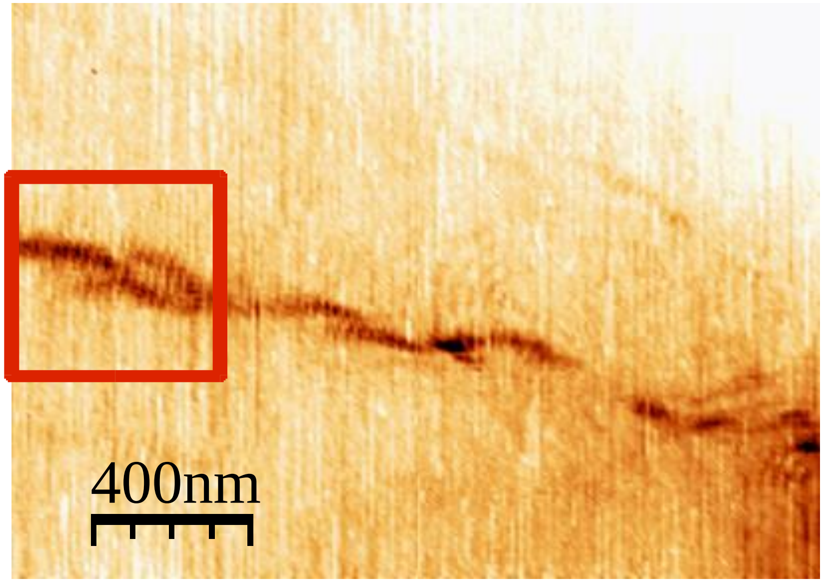
Tip-induced backscattering

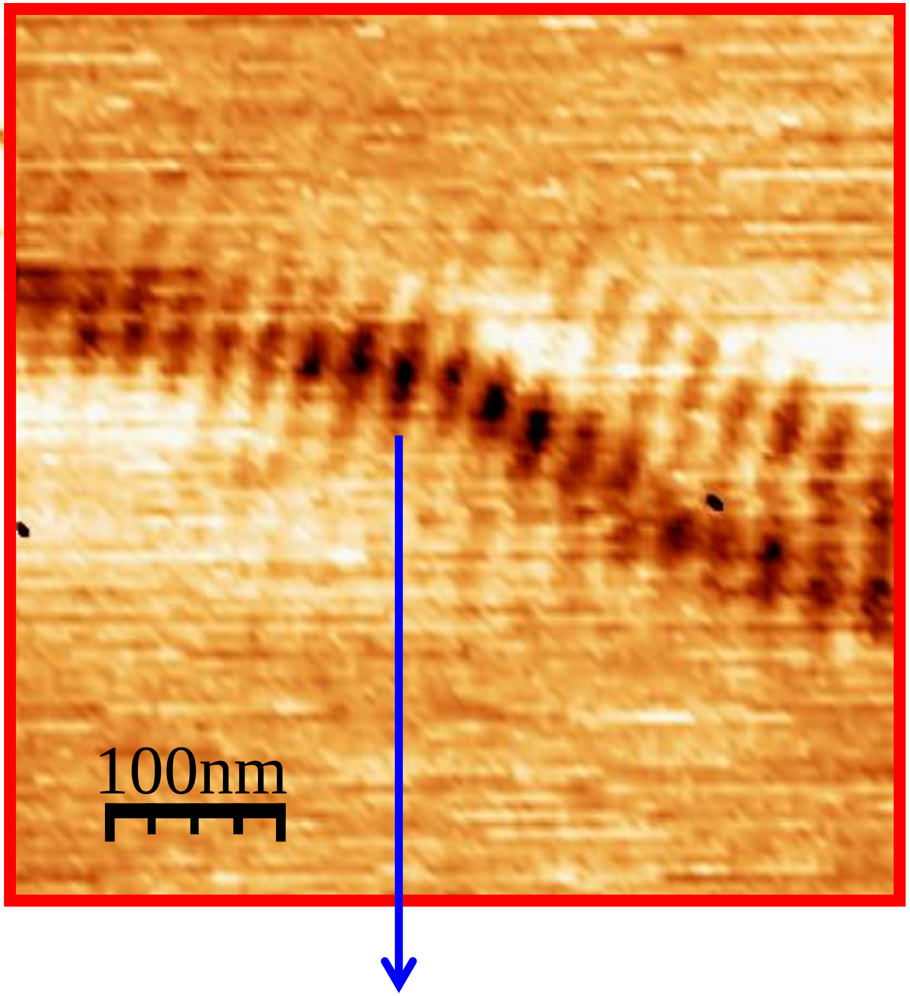


N. Paradiso et al., Physica E **42** (2010) 1038.

Branched flow and interference fringes







- QPC conductance $G = 6\ e^2/h$ (3rd plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm

Fringe periodicity: $\lambda_F/2$=20 nm

N. Paradiso *et al., Physica E 42 (2010) 1038.*

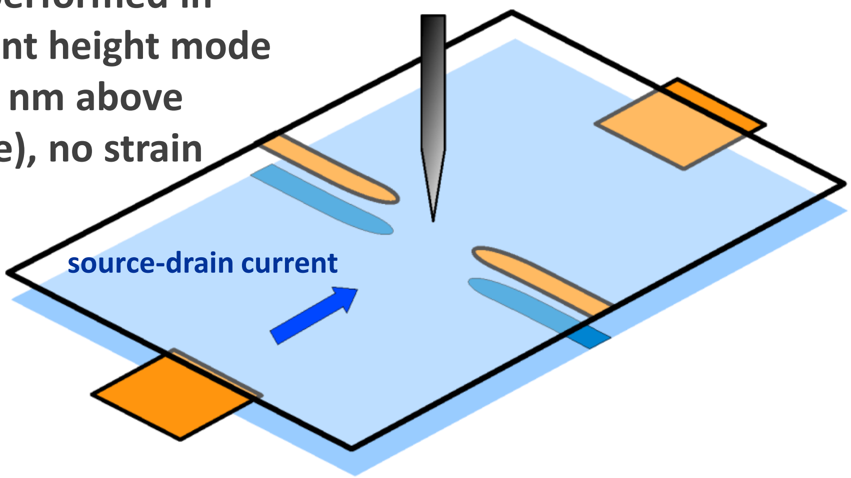
The SGM @NEST lab in Pisa

Setup:

- AFM non-optical detection scheme (tuning fork)
- With vibration and noise isolation system
- ^{3}He insert (cold finger base temp.: 300 mK)
- 9 T cryomagnet

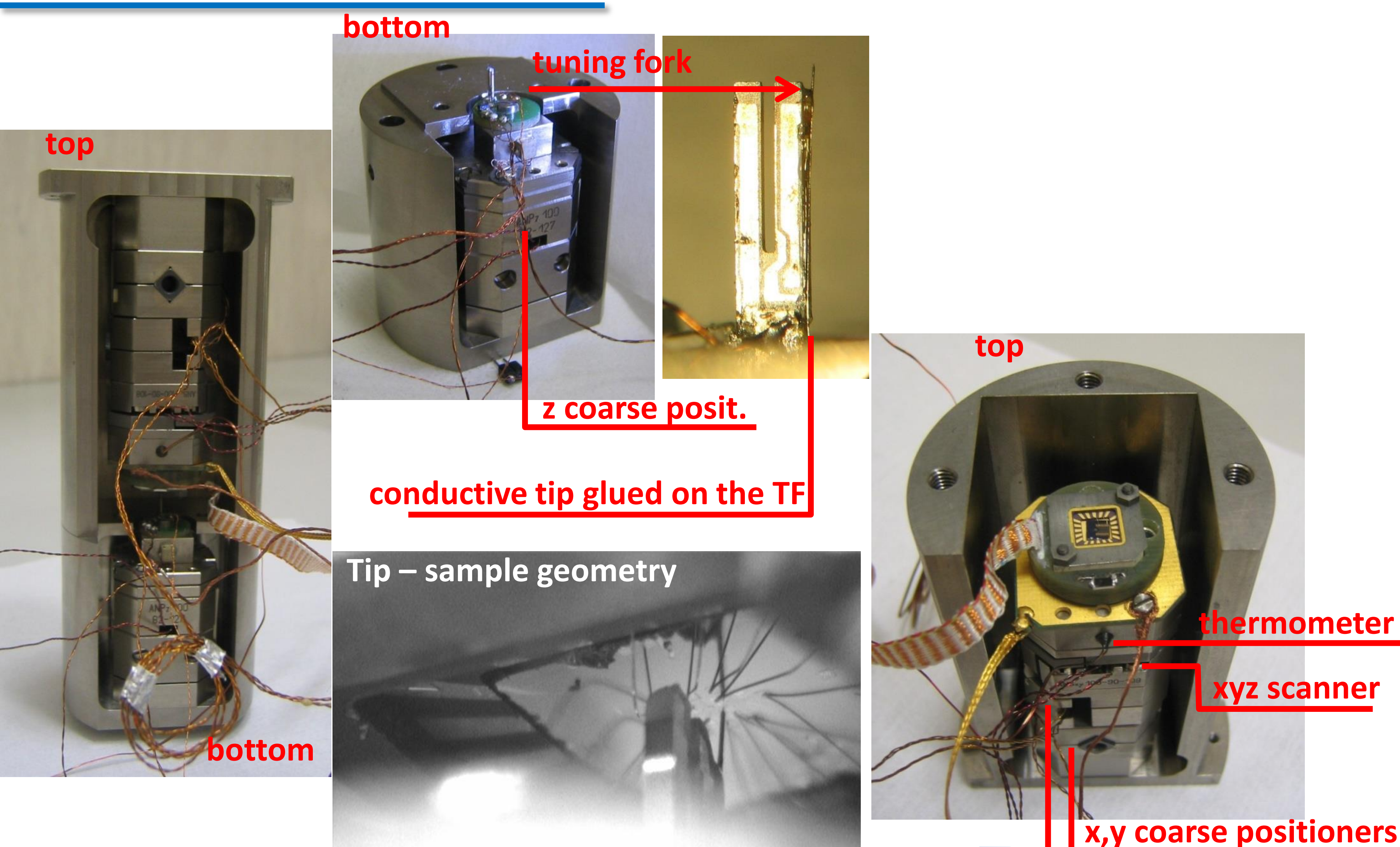
Tip at negative bias (moveable gate locally depletes the 2DEG)

SGM performed in constant height mode (10-50 nm above surface), no strain



attocube systems
explore your nanoworld

Tuning fork and sample holder

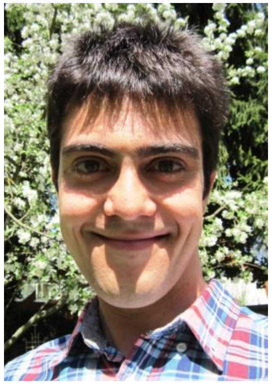


Outline

- **Basics of Scanning Gate Microscopy (SGM)**
- **0.7 Anomaly in a Quantum Point Contact**
- **Ongoing Activities**

Coworkers

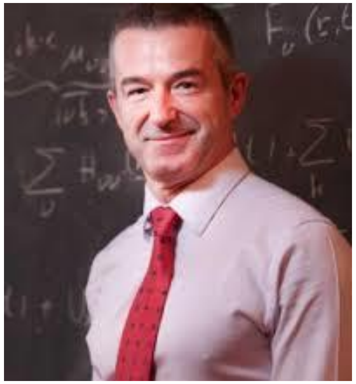
A. Iagallo



N. Paradiso

S. Roddaro

L. Sorba

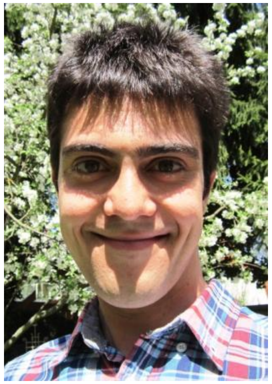


F. Beltram

National Enterprise for nanoScience and nanoTechnology

Coworkers

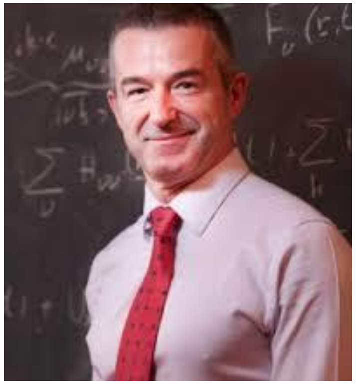
A. Iagallo



N. Paradiso

S. Roddaro

L. Sorba



F. Beltram

Materials from:

Laboratorio TASC, Trieste, Italy:

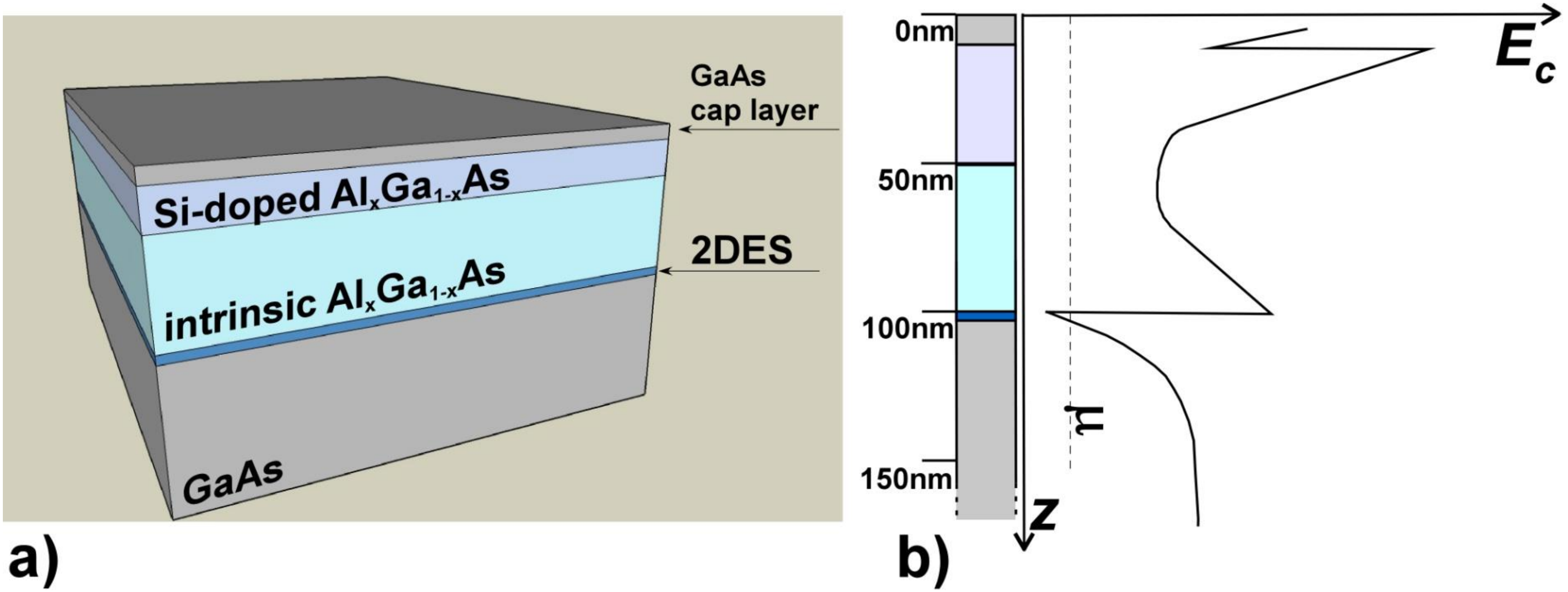
Giorgio Biasiol

ETH Zurich, Switzerland:

Christian Reichl, Werner Wegscheider

Enterprise for nanoScience and nanoTechnology

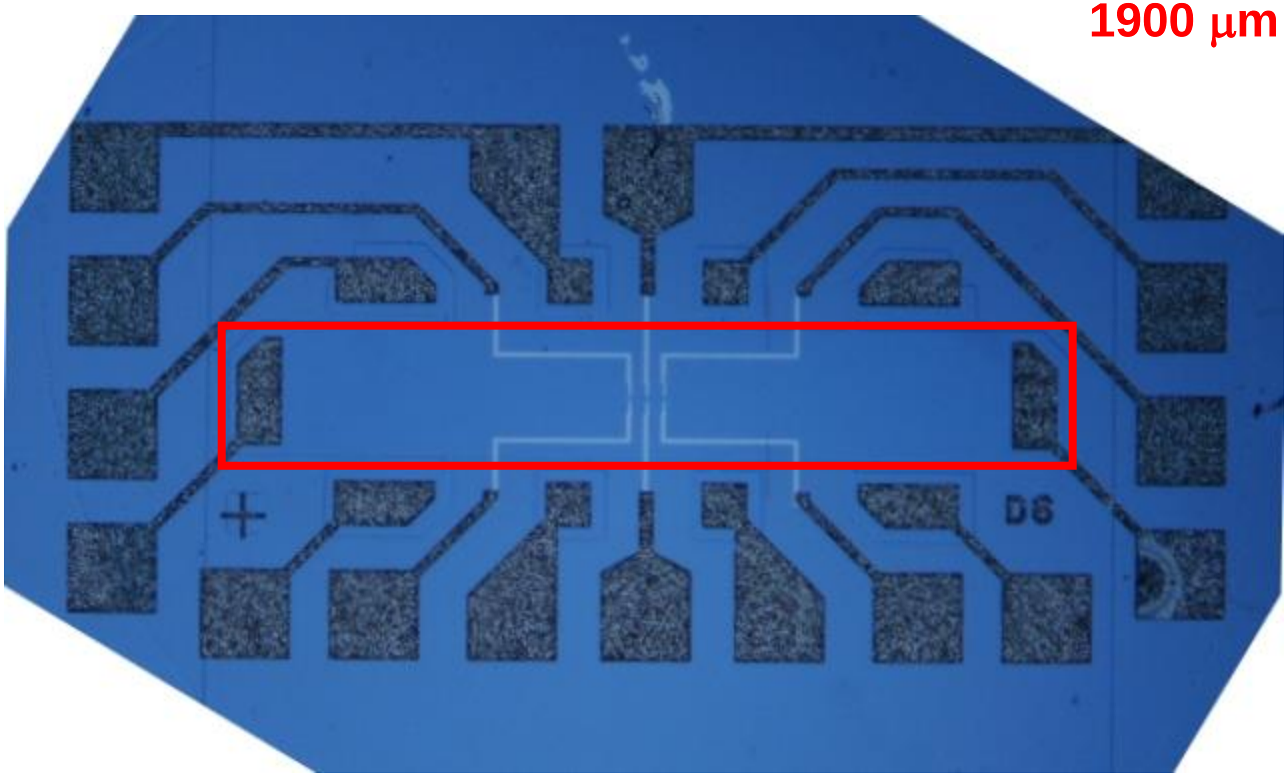
2 Dimensional Electron System



see also: Horst L. Stoermer, Nobel Lecture, December 8, 1998

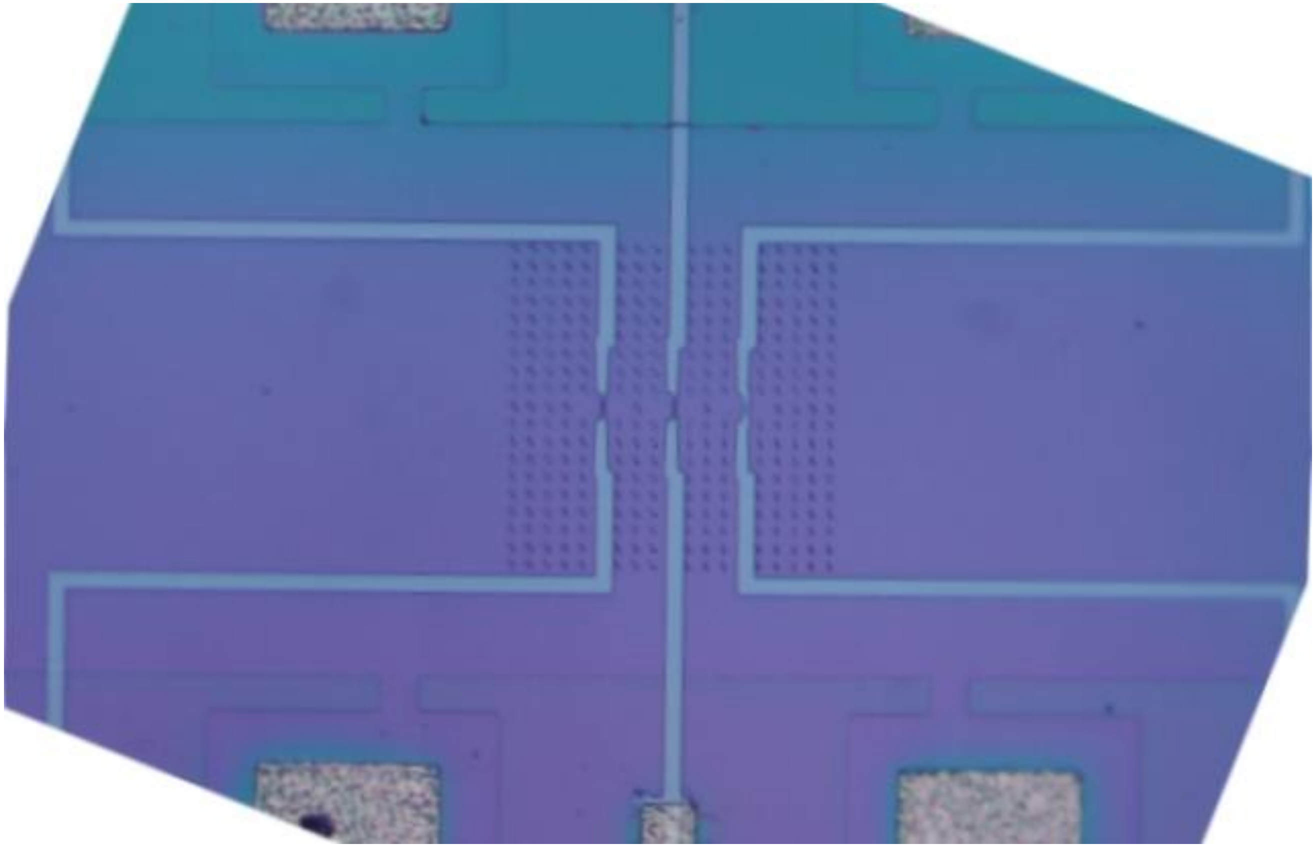
Hall-bar samples

1900 μm x 300 μm



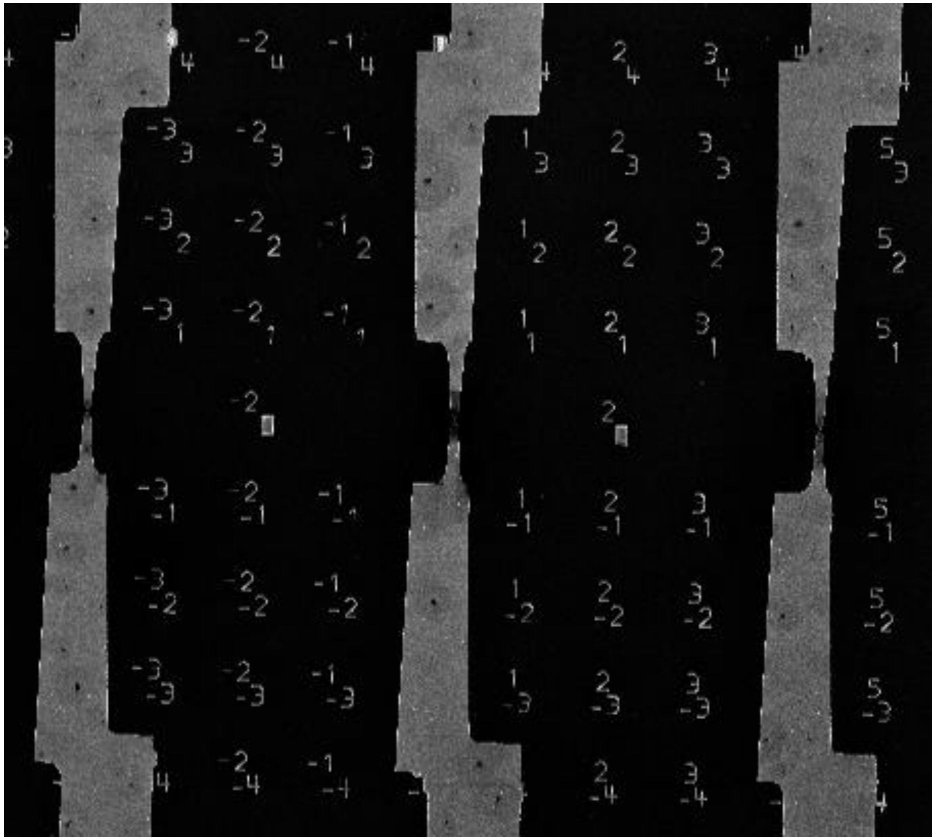
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



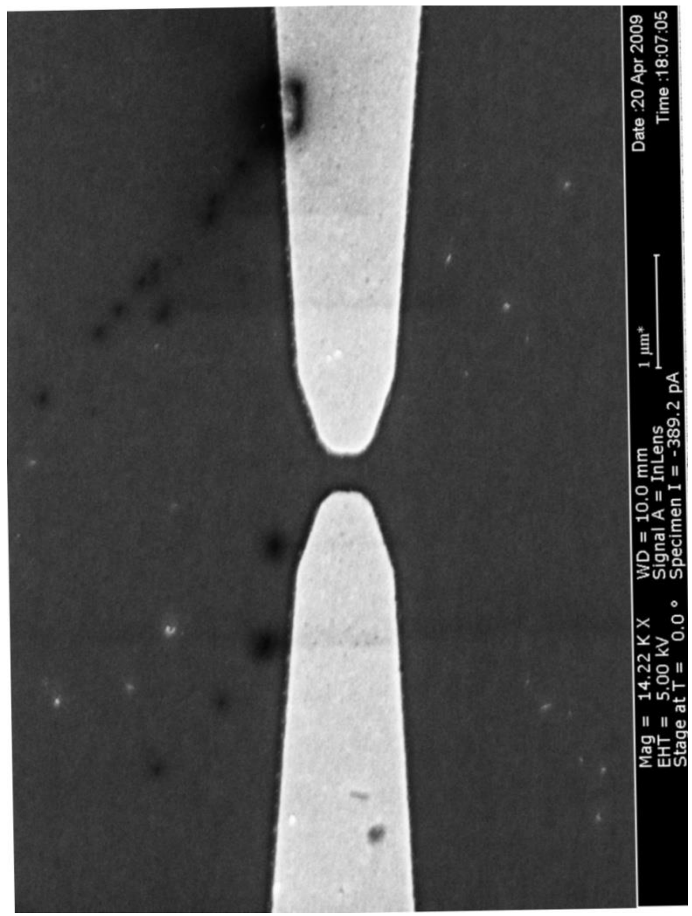
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



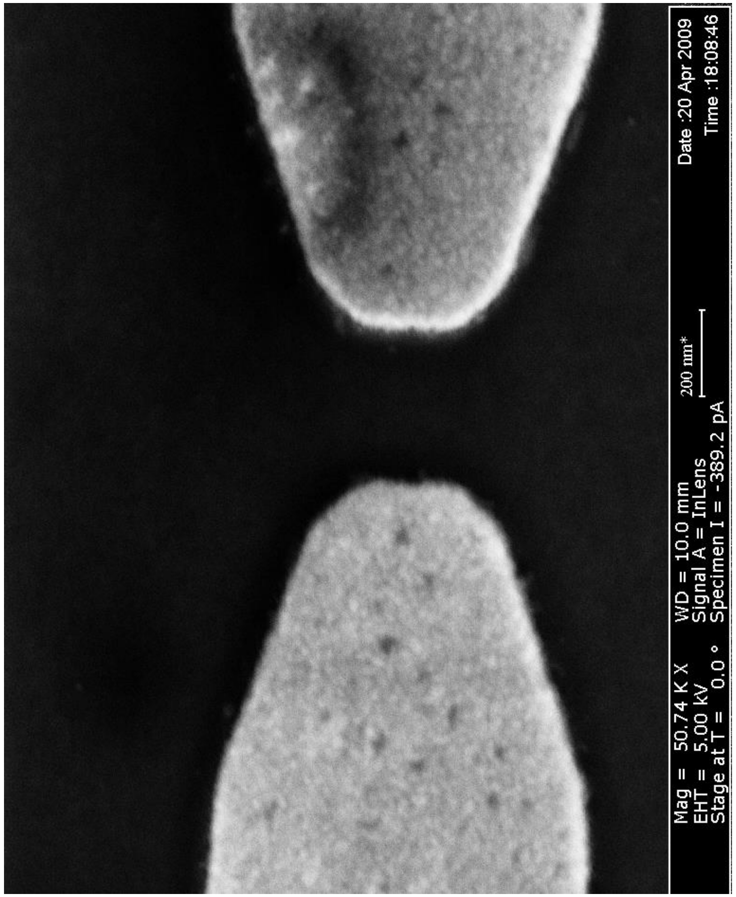
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



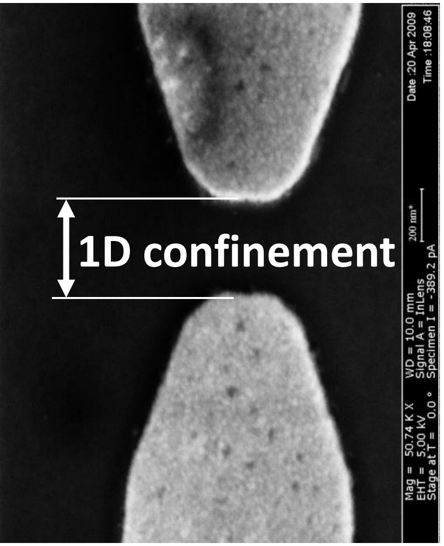
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples

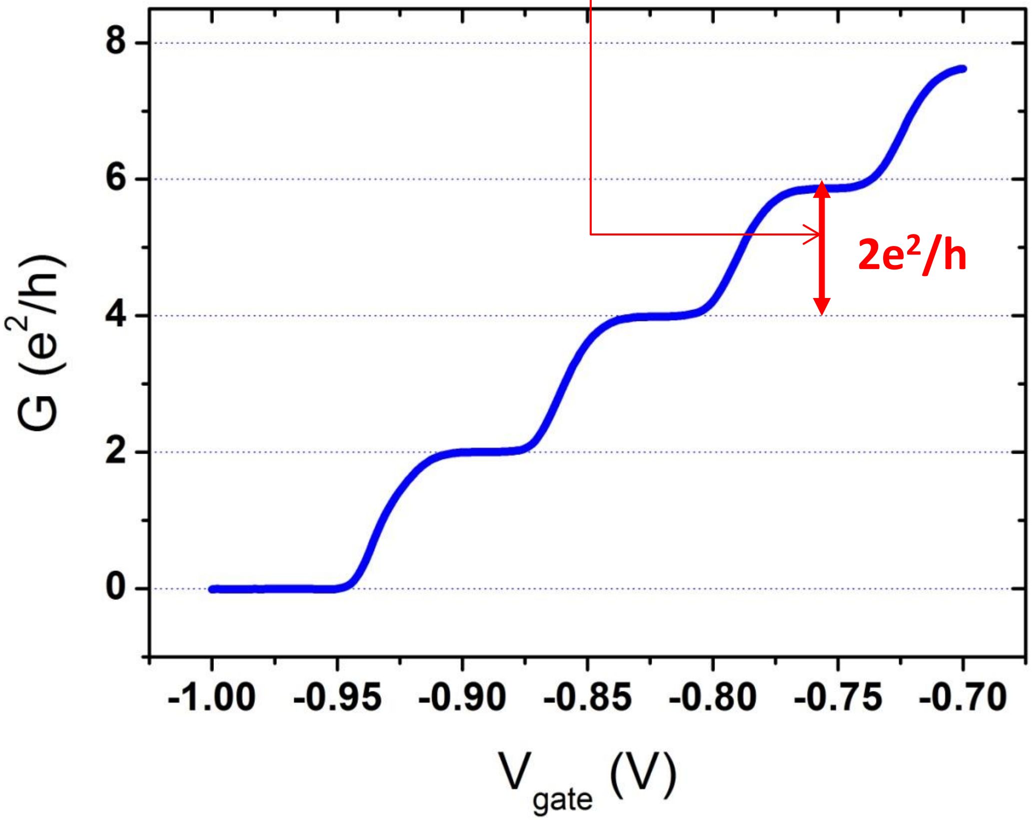


N. Paradiso et al., Physica E **42** (2010) 1038.

Conductance quantization in QPCs

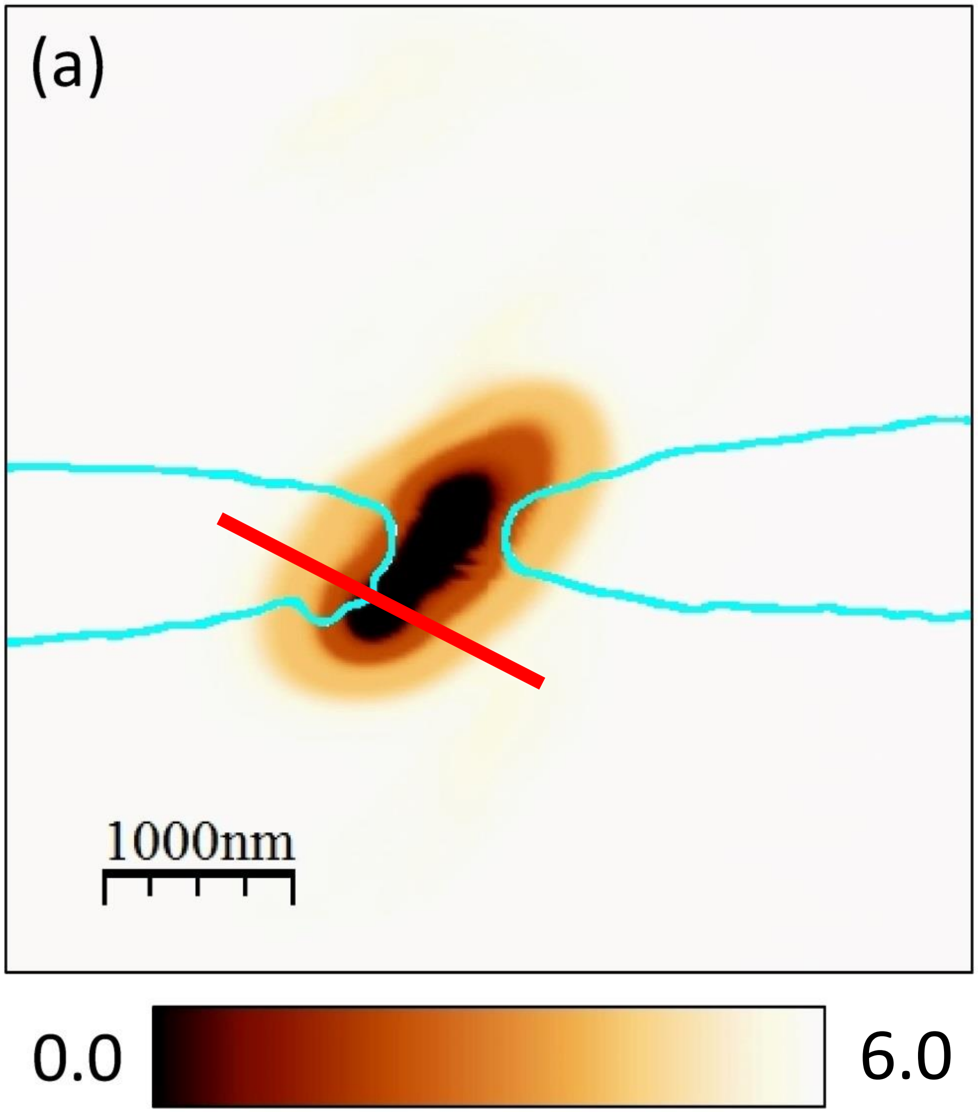


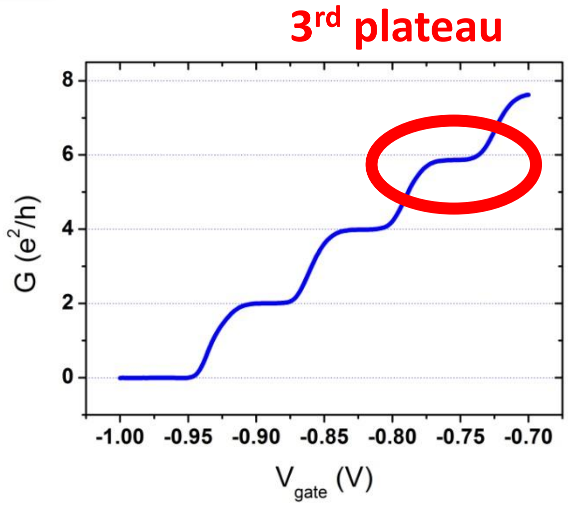
In 1D systems the current is carried by a finite number of modes (arising from confined subbands) . Each mode contributes two quantum of conductance.

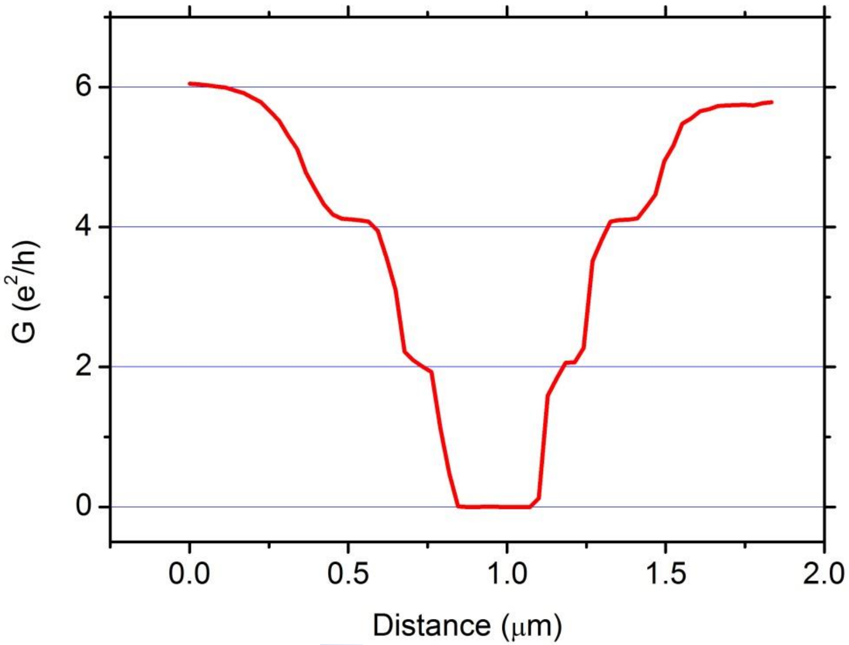


First we fix the mode number (QPC setpoint), then we start scanning the biased tip at a fixed height.

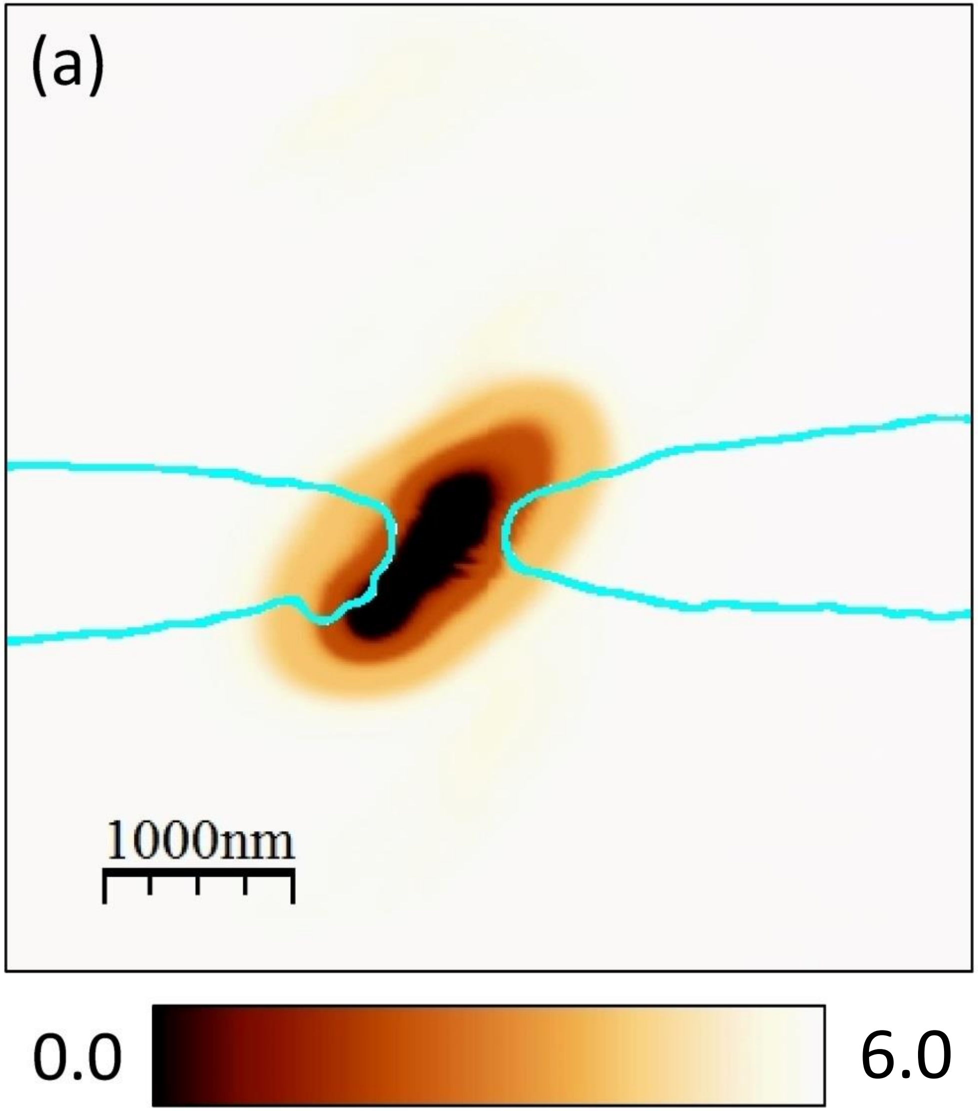
QPC at 3rd plateau

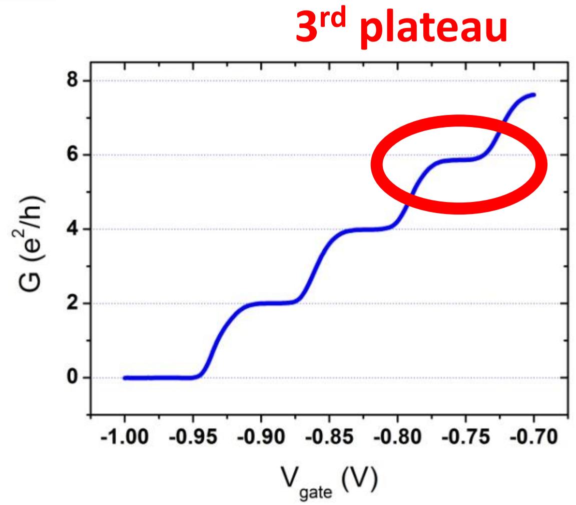


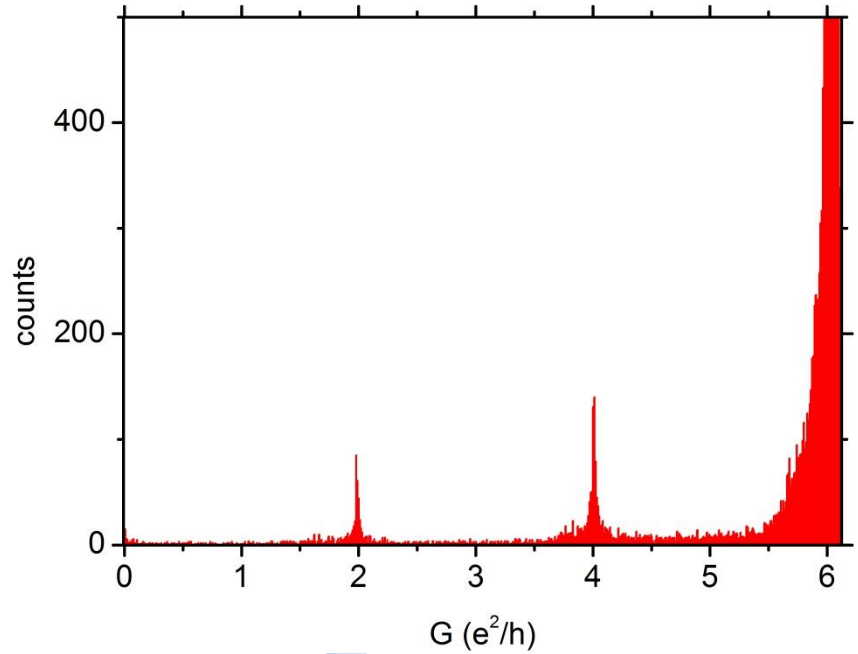




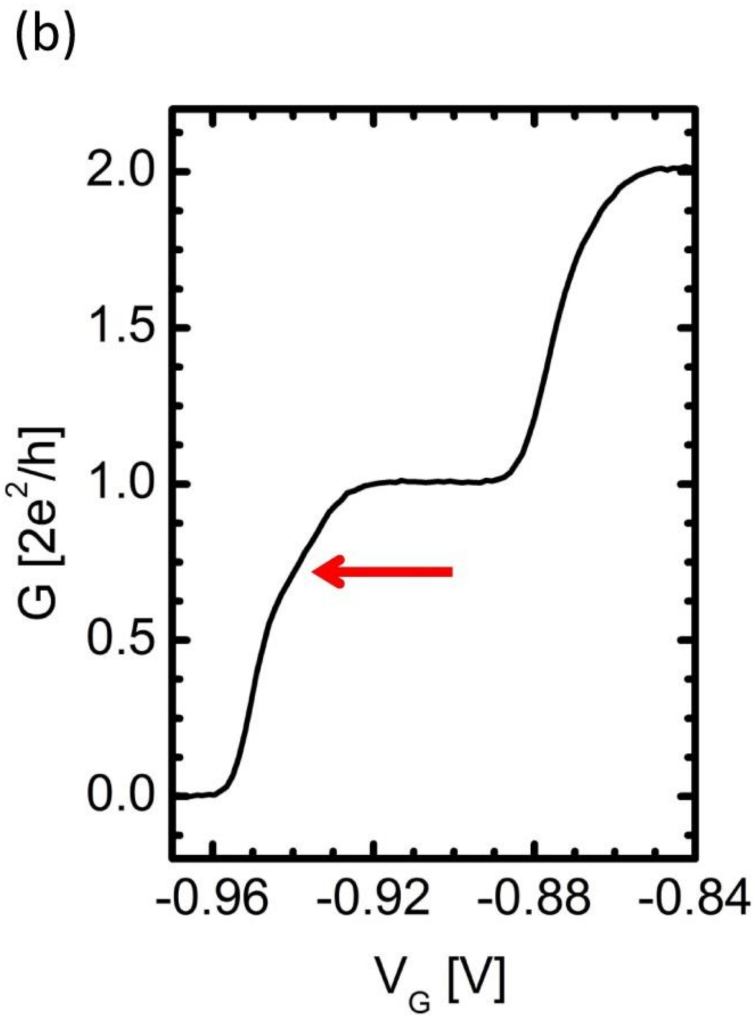
Histogram analysis







0.7 Anomaly



Origin still debated

Intrinsic or extrinsic?

- Quantum interference
- Spin polarization
- Kondo effect
- Wigner crystallization

A. Iagallo *et al.*, Nano Research 8, 948 (2015).

0.7 Anomaly

LETTER

doi:10.1038/nature12421

Microscopic origin of the '0.7-anomaly' in quantum point

Florian Bauer[1]
Werner Wegsc

d

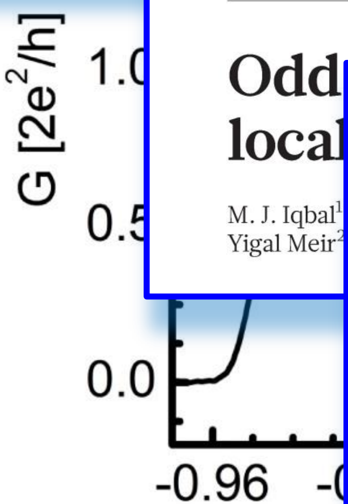
sic?

LETTER

doi:10.1038/nature12491

Odd
local

M. J. Iqbal[1]
Yigal Meir[2]



A. Iagallo *et al.*, Nano R

nature COMMUNICATIONS

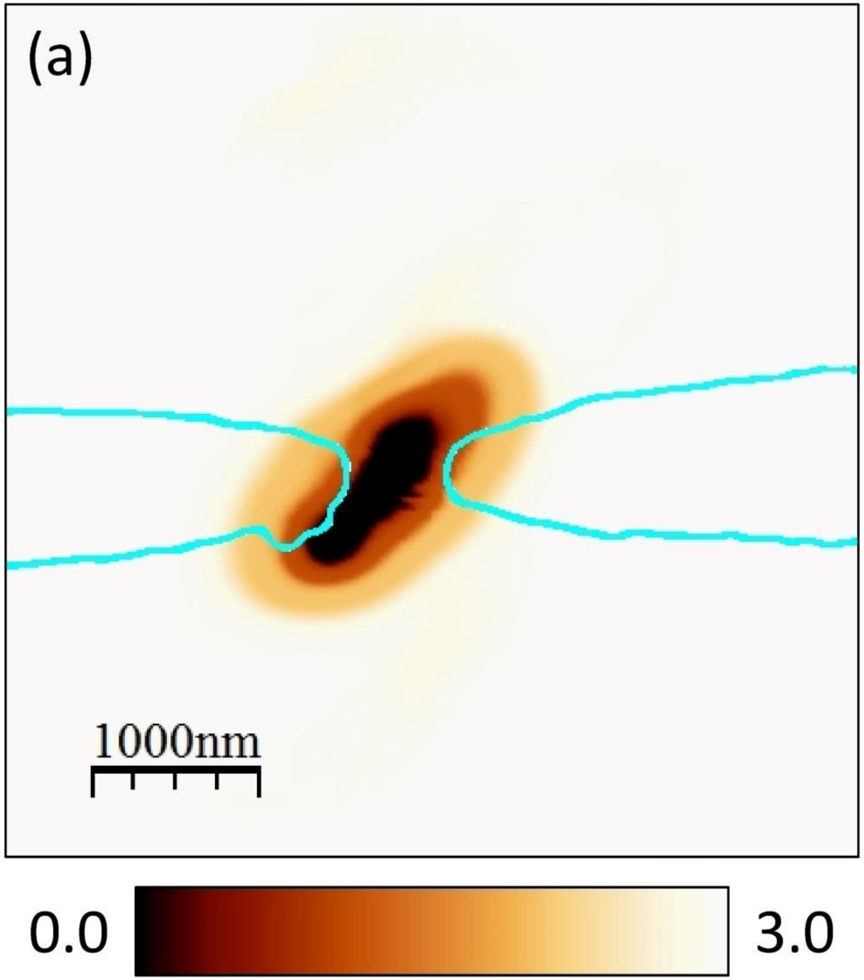
ARTICLE

Received 27 Nov 2013 | Accepted 4 Jun 2014 | Published 30 Jun 2014
DOI: 10.1038/ncomms5290

Wigner and Kondo physics in quantum point contacts revealed by scanning gate microscopy

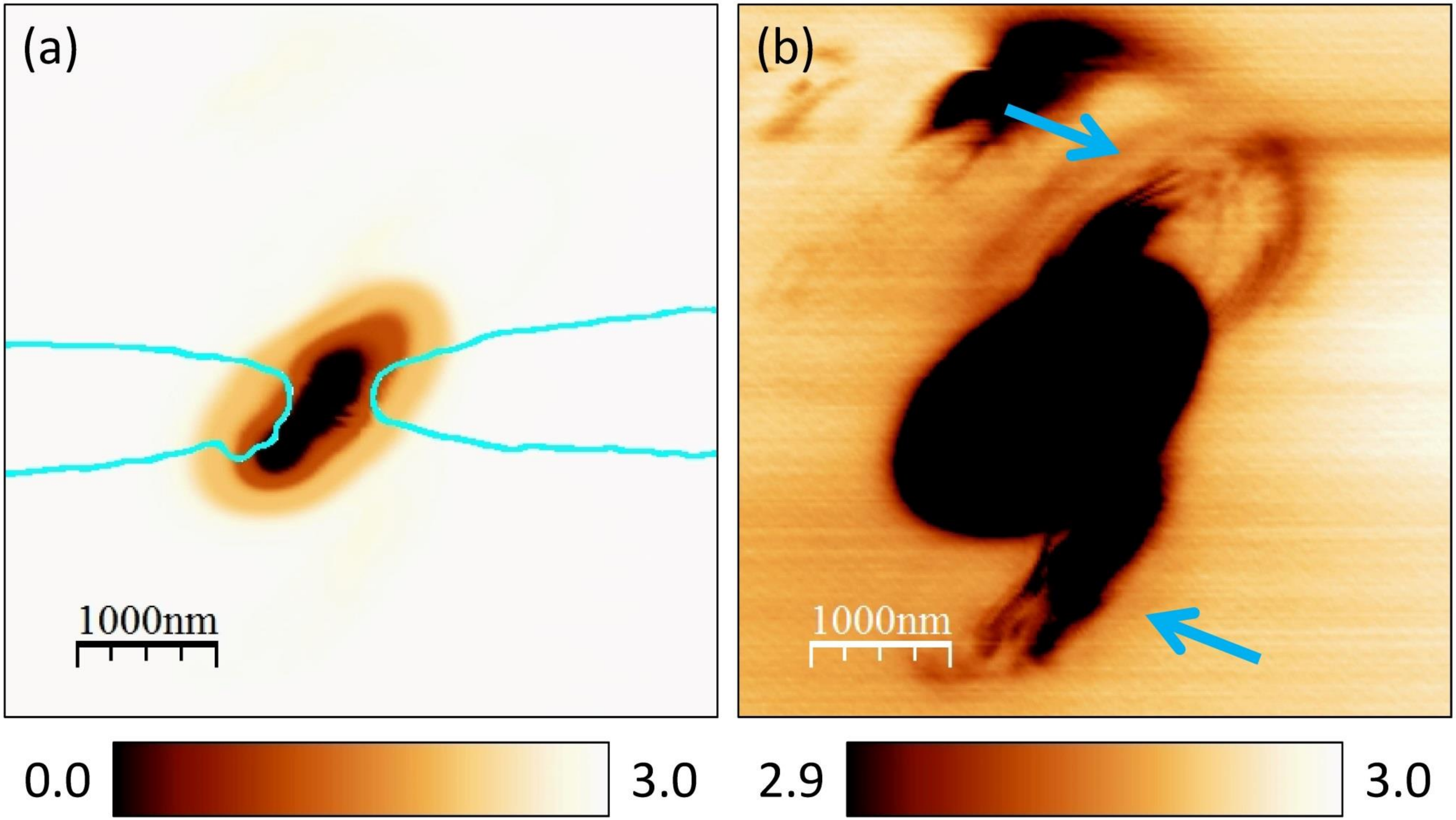
B. Brun[1,2], F. Martins[3], S. Faniel[3], B. Hackens[3], G. Bachelier[1,2], A. Cavanna[4], C. Ulysse[4], A. Ouerghi[4], U. Gennser[4], D. Mailly[4], S. Huant[1,2], V. Bayot[1,3], M. Sanquer[1,5] & H. Sellier[1,2]

Device A: QPC with localized impurities



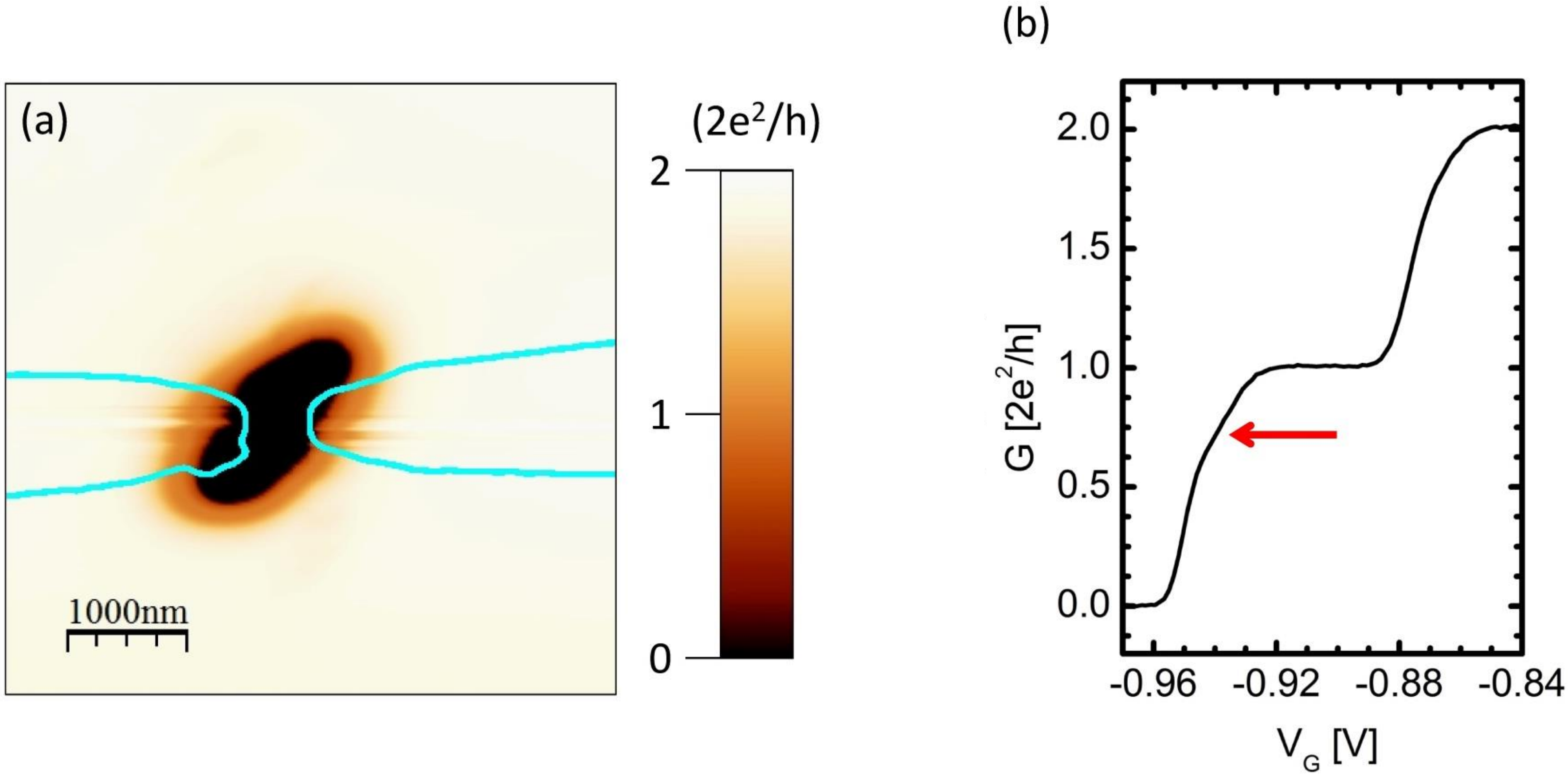
A. Iagallo *et al.,* Nano Research 8, 948 (2015).

Device A: QPC with localized impurities



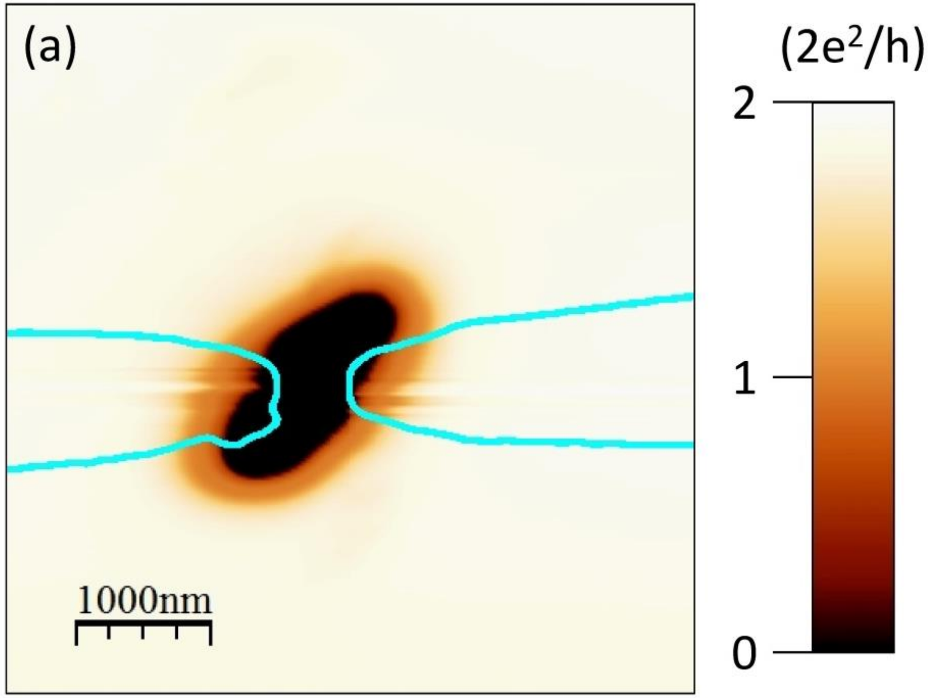
A. Iagallo *et al.,* Nano Research 8, 948 (2015).

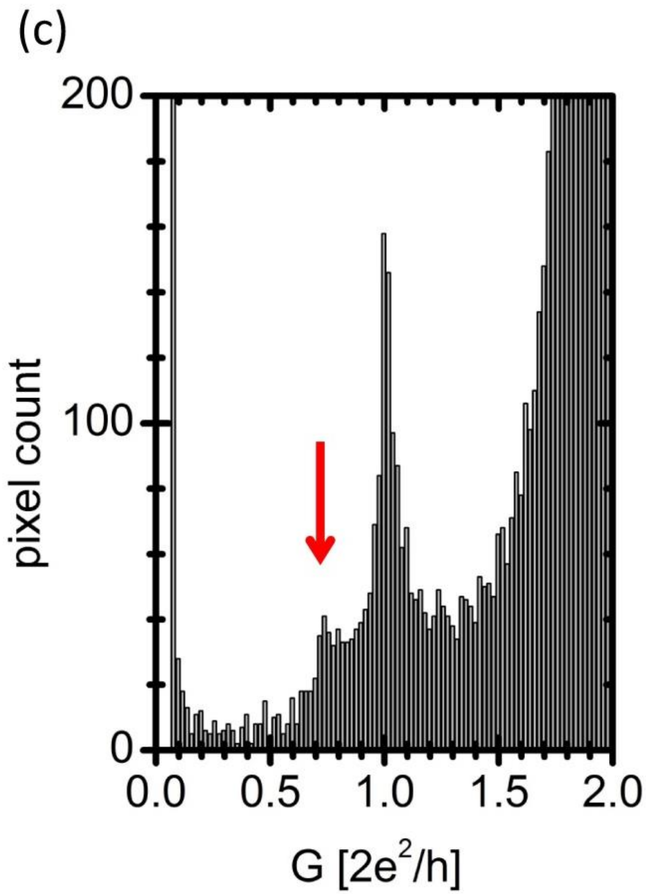
0.7 Anomaly in Device A



A. Iagallo *et al.,* Nano Research 8, 948 (2015).

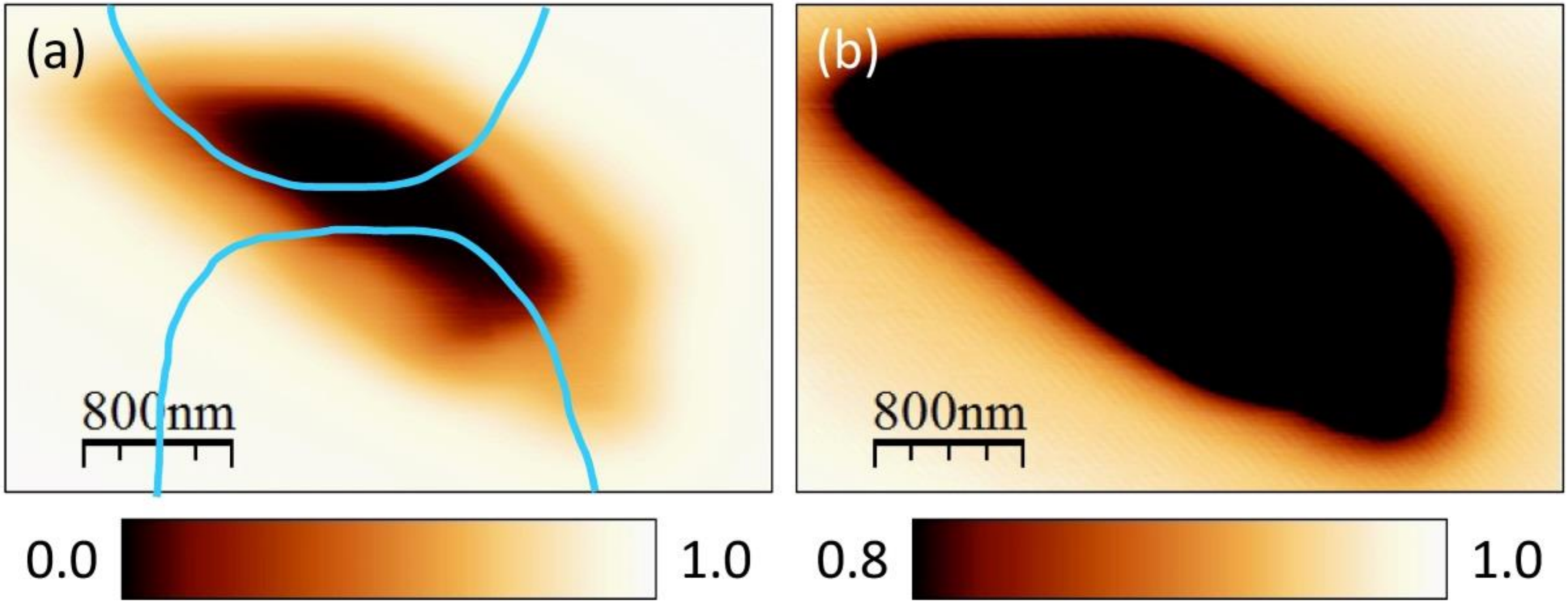
0.7 Anomaly in Device A





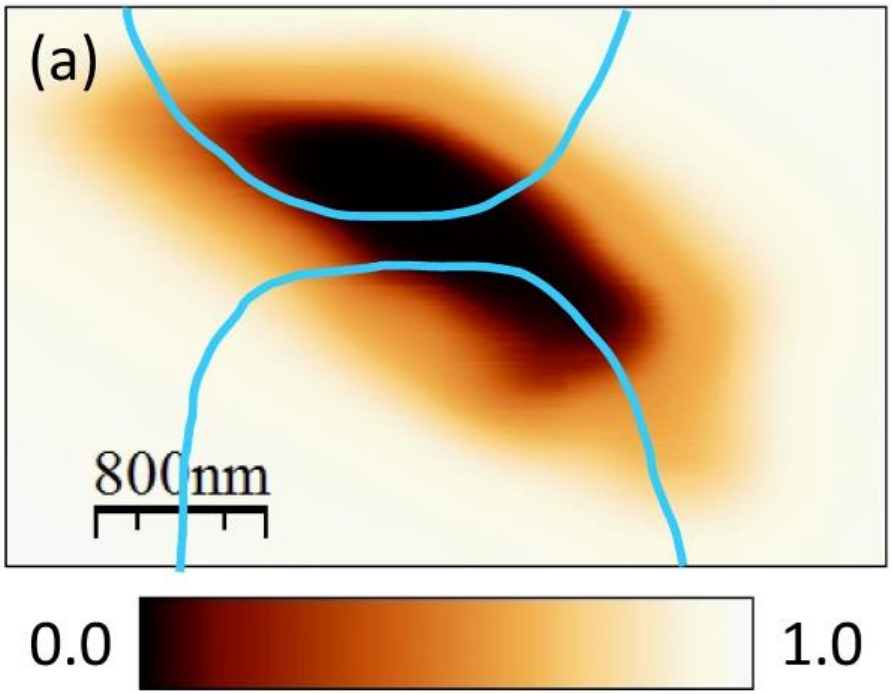
A. Iagallo *et al.,* Nano Research 8, 948 (2015).

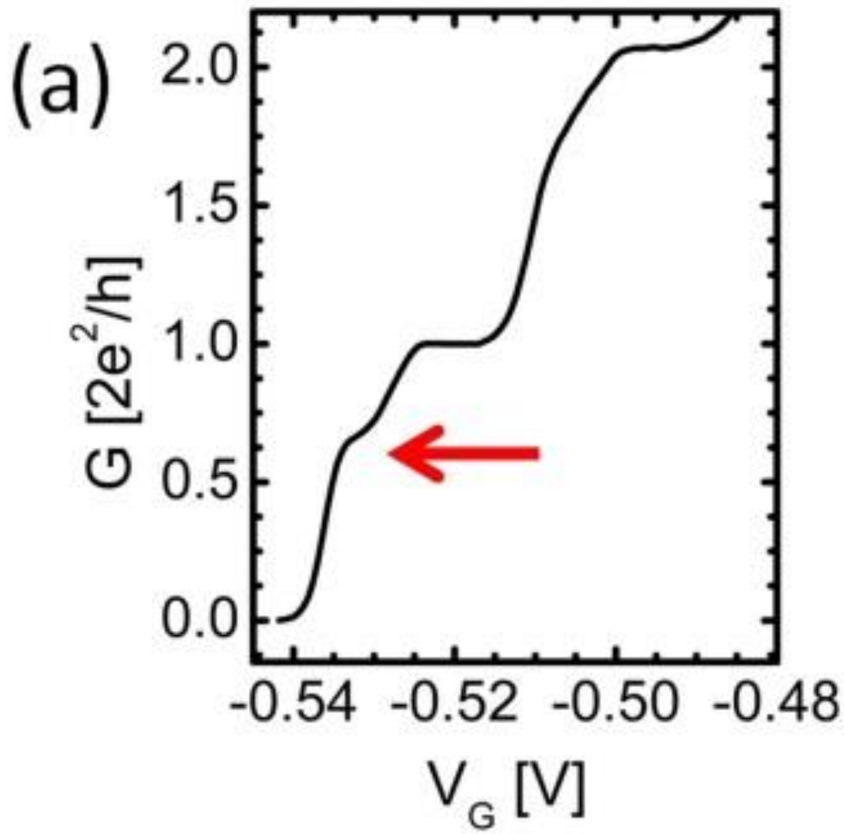
Device B: QPC without localized impurities



A. Iagallo *et al.,* Nano Research 8, 948 (2015).

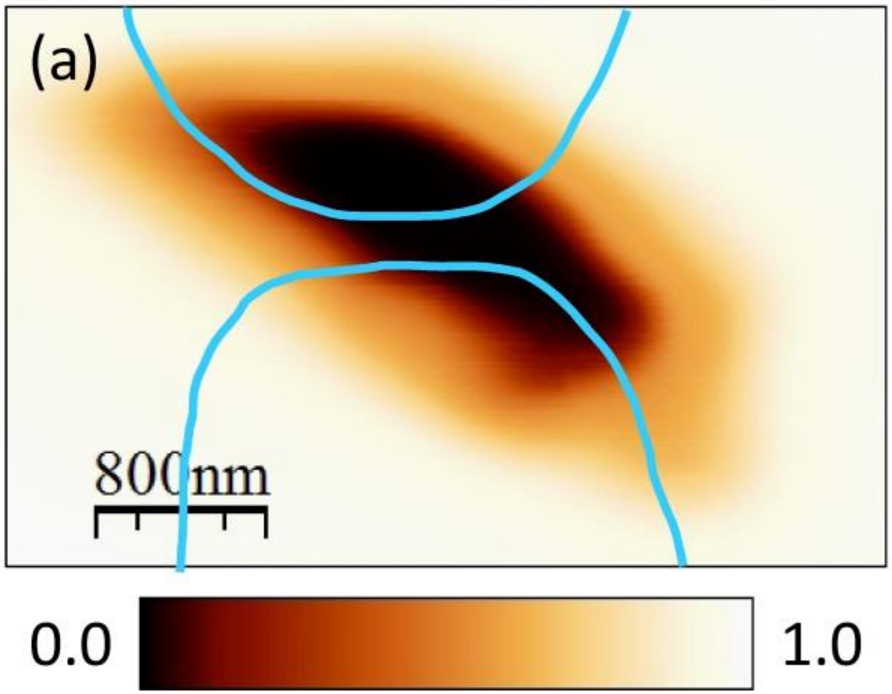
0.7 Anomaly in Device B

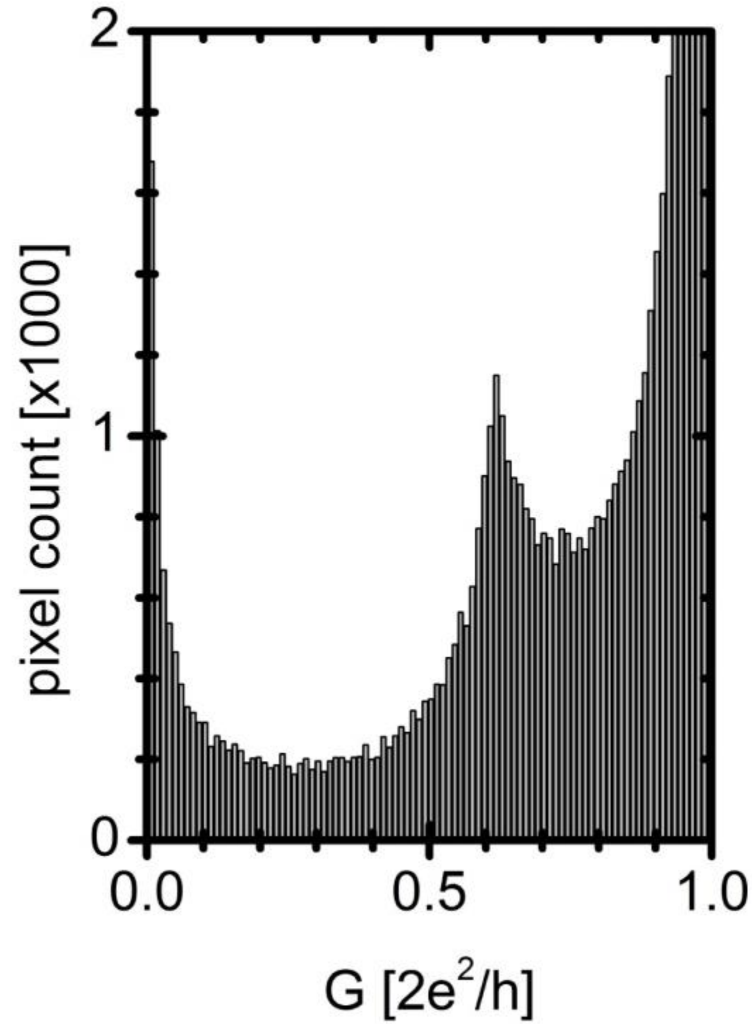




A. Iagallo *et al.,* Nano Research 8, 948 (2015).

0.7 Anomaly in Device B





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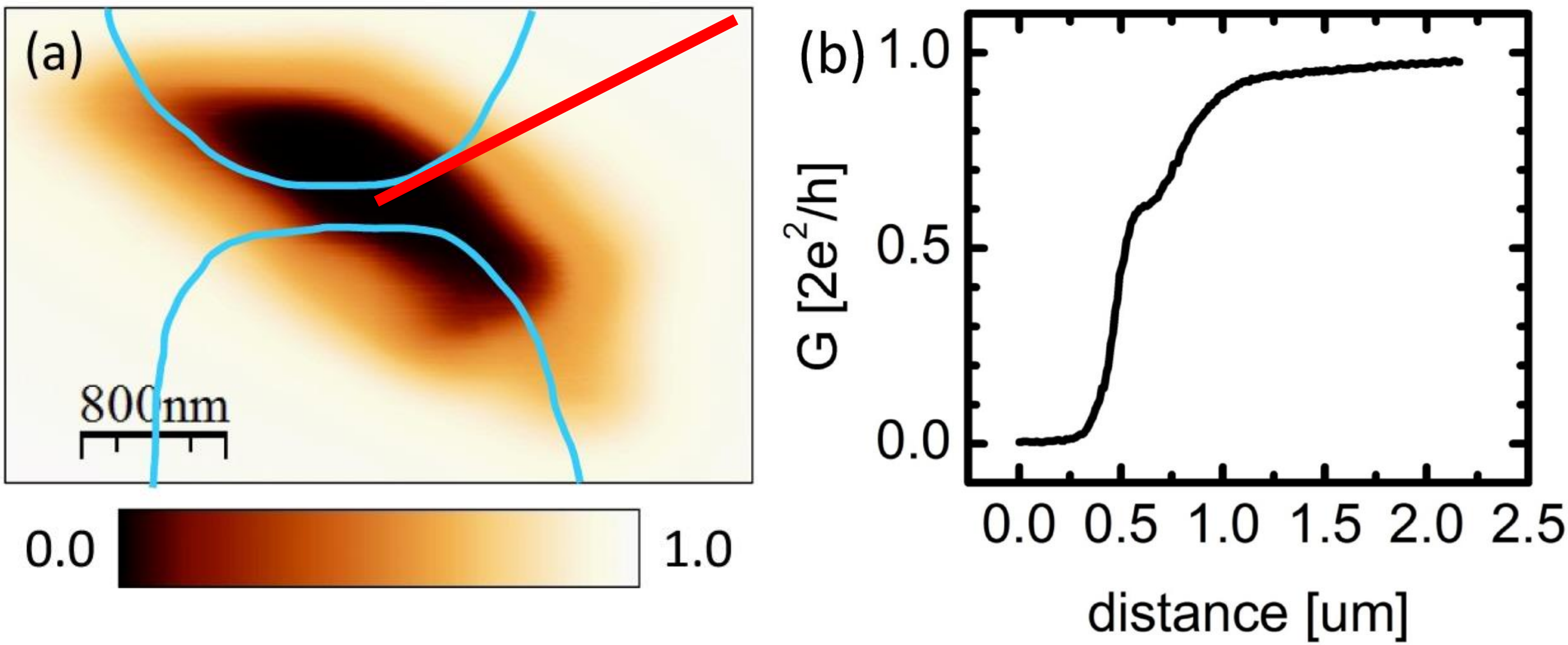
0.7 Anomaly in Device B



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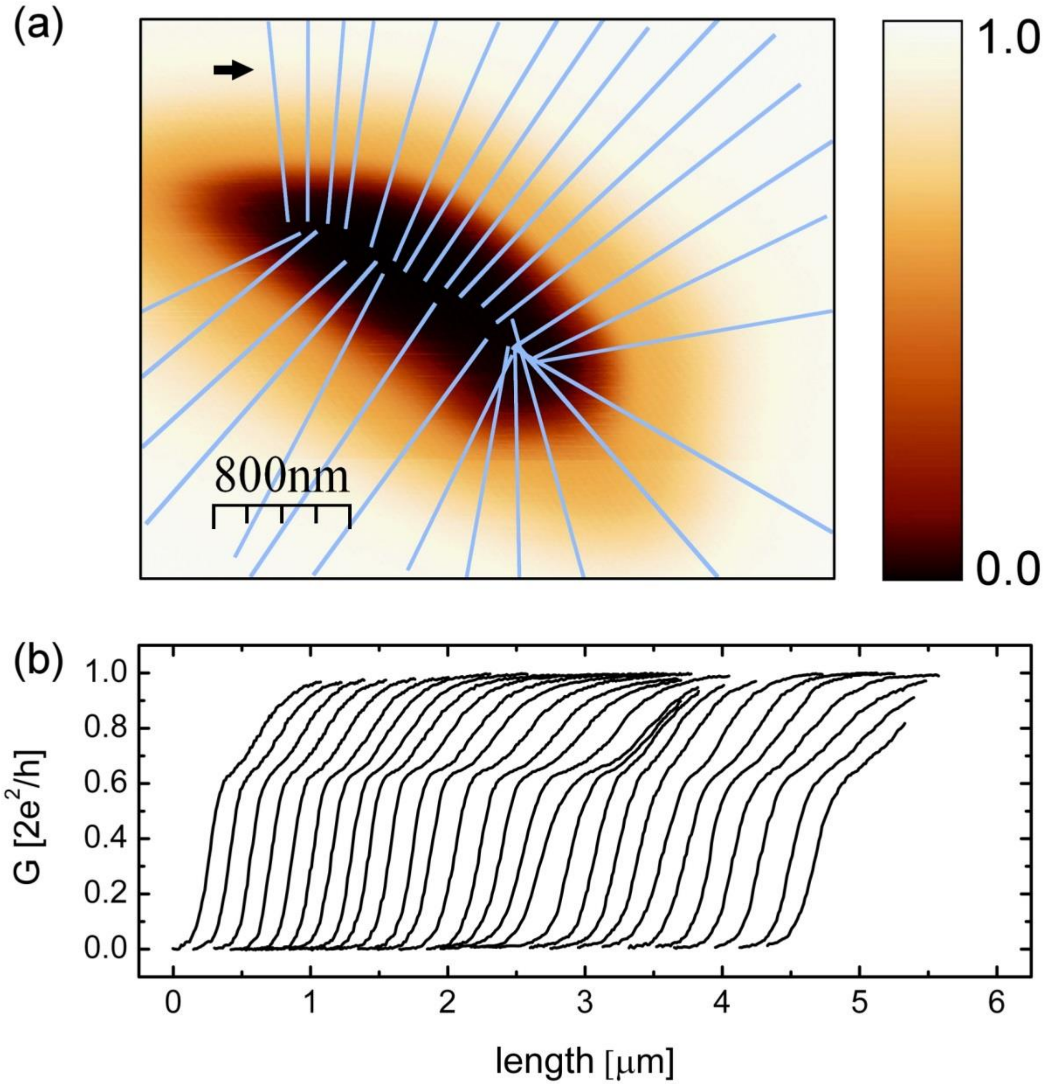
0.7 Anomaly in Device B



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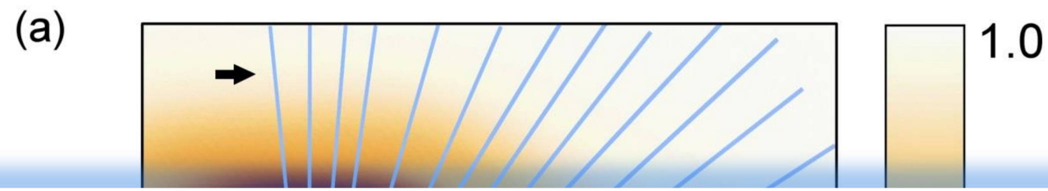
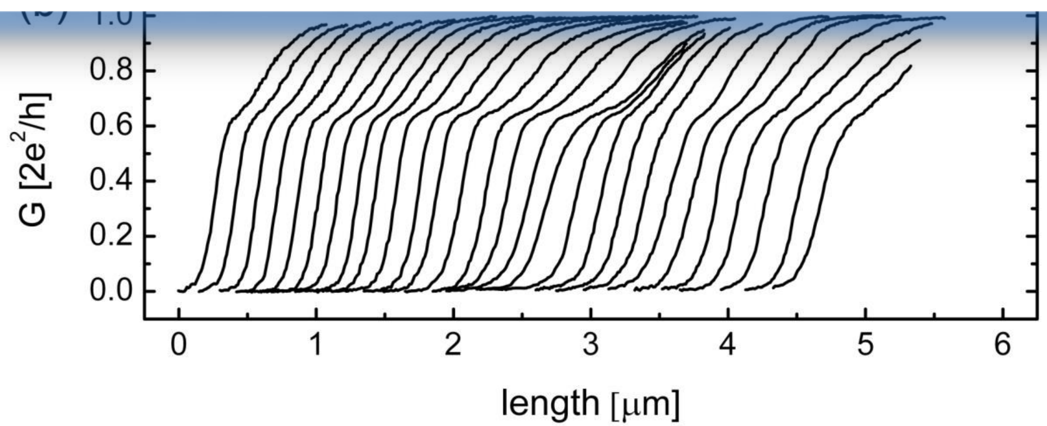
0.7 Anomaly in Device B



The 0.7 anomaly is observed irrespective of the presence of localized defects and is therefore a fundamental property.

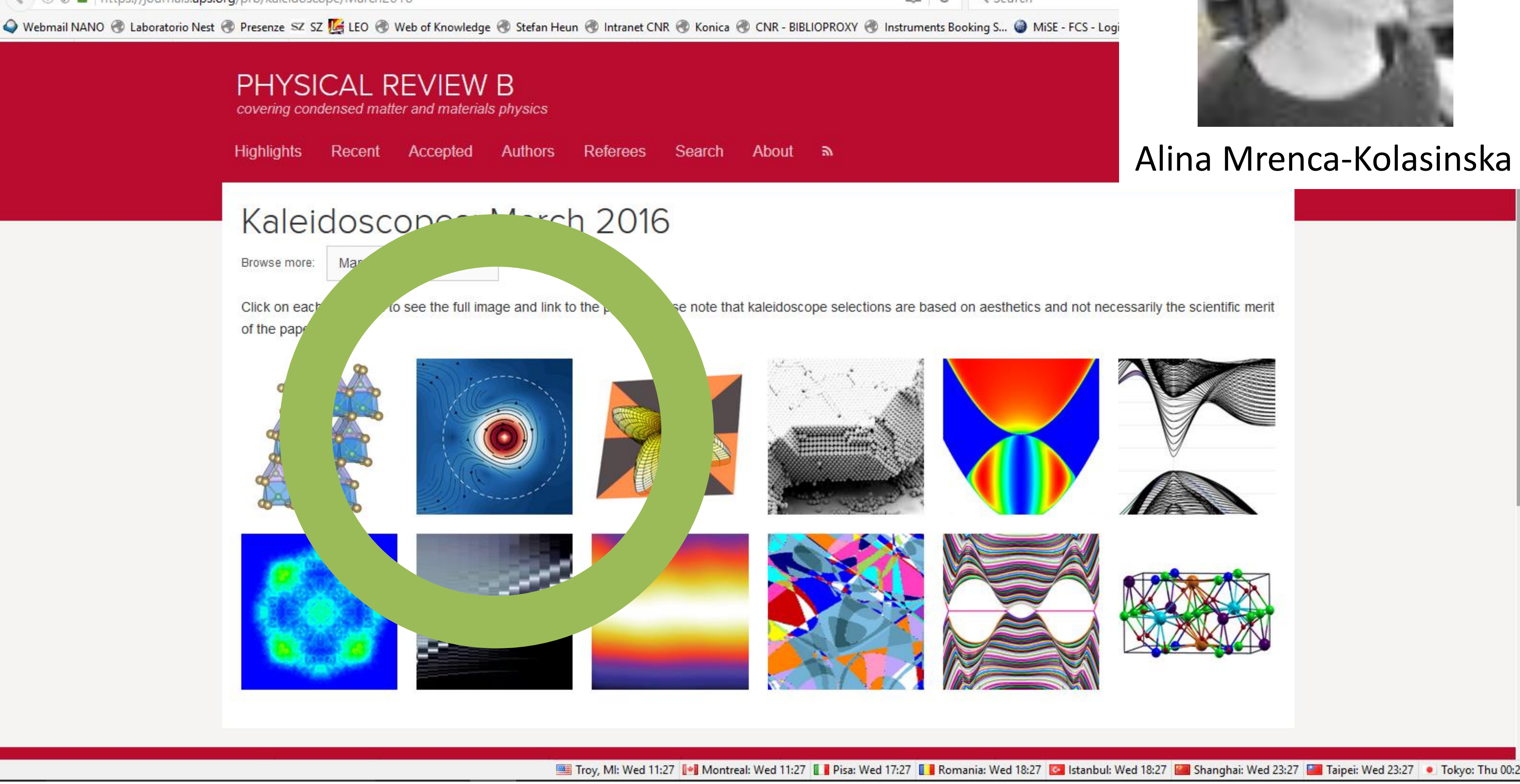


A. Iagallo *et al.*,
Nano Research 8, 948 (2015).

Outline

- Basics of Scanning Gate Microscopy (SGM)
- 0.7 Anomaly in a Quantum Point Contact
- Ongoing Activities
  - Graphene Nanoribbons
  - Split Gates in Graphene
  - Phosphorene
  - Hybrid (S-N-S) Systems

Alina Mrenca-Kolasinska



PHYSICAL REVIEW B **93**, 125411 (2016)

Aharonov-Bohm interferometer based on *n-p* junctions in graphene nanoribbons

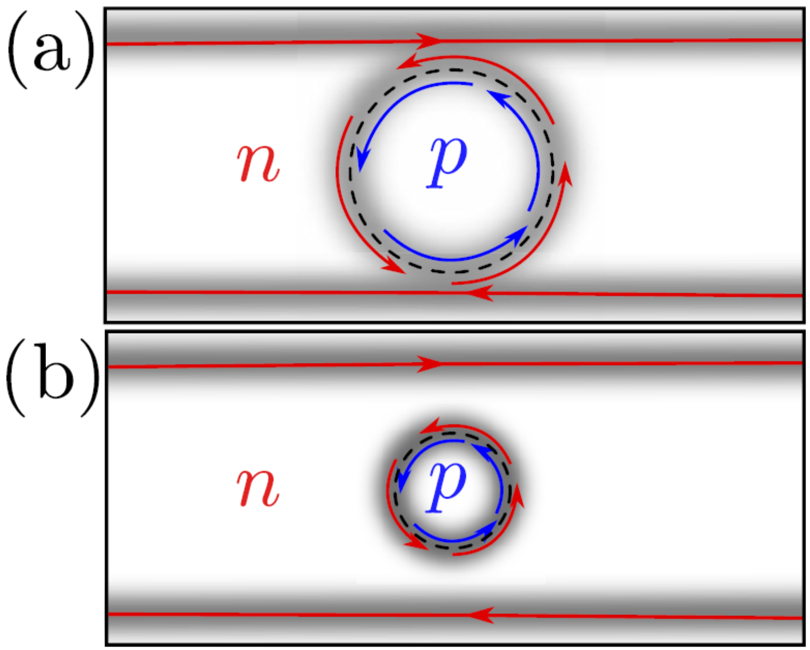
A. Mreńca-Kolasińska,[1,2,*] S. Heun,[2] and B. Szafran[1]

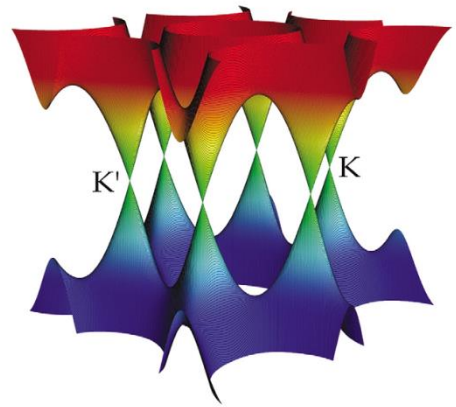
[1]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland*

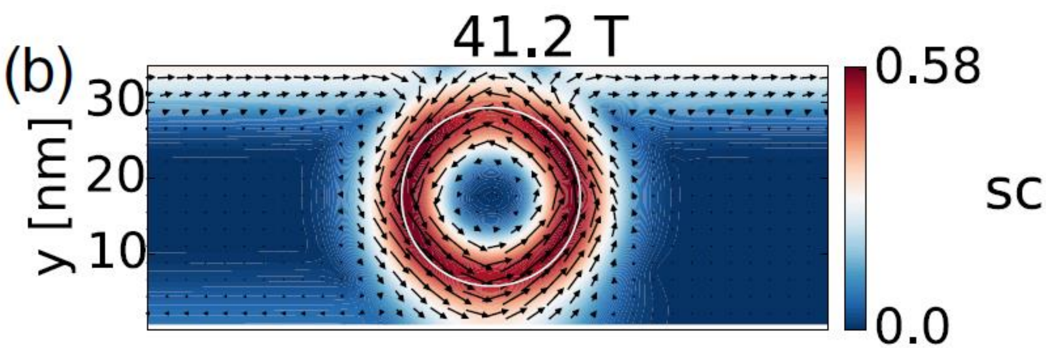
[2]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy*

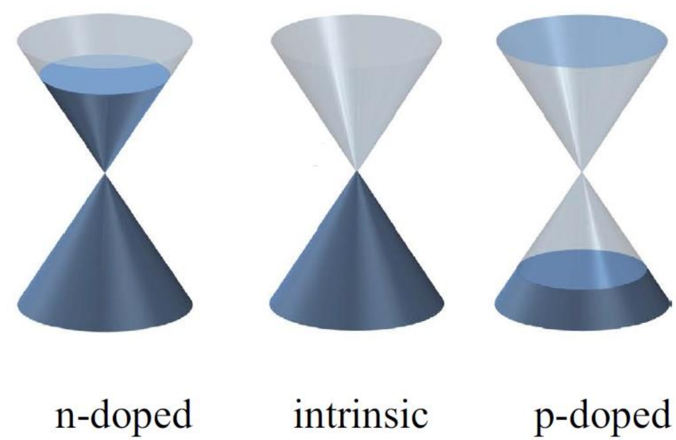
(Received 12 November 2015; revised manuscript received 28 January 2016; published 8 March 2016)

Alina Mrenca-Kolasinska







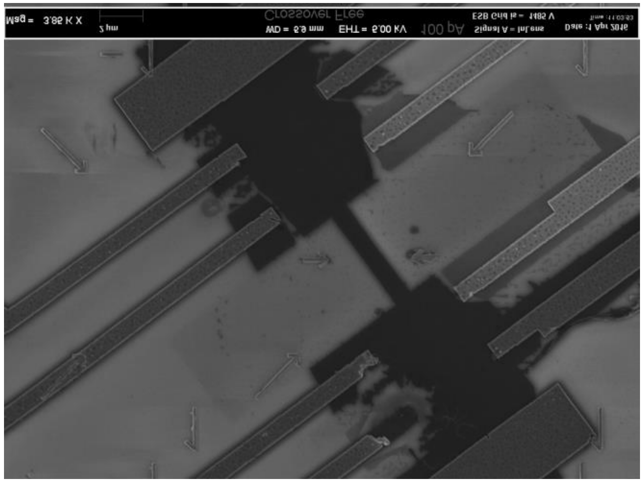


Ribbon design

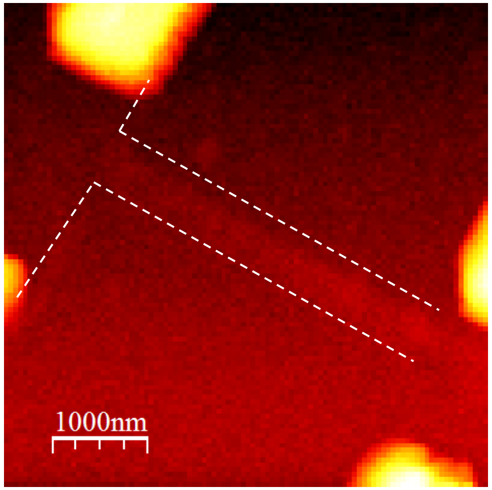
Lennart Bours

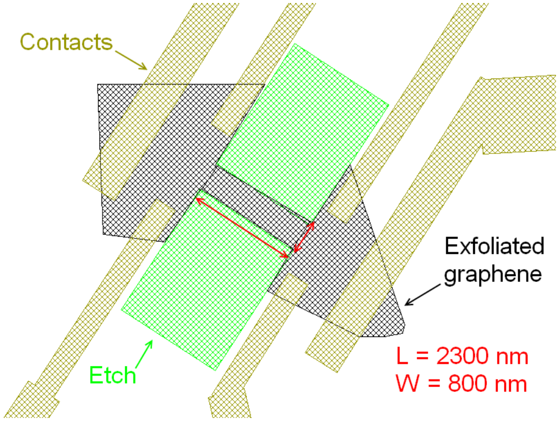
1. Scanning Electron Microscope picture of the heavily damaged C9 device
2. AFM scan of the G4 device (used for SGM)
3. Design of the G4 device

C9: 5000 x 900 nm

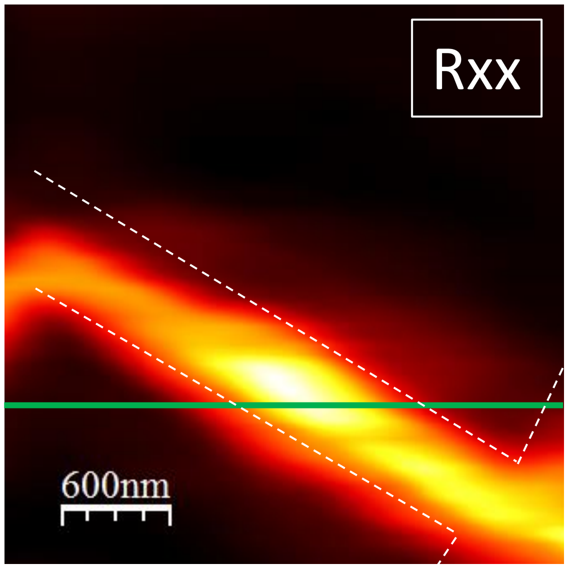


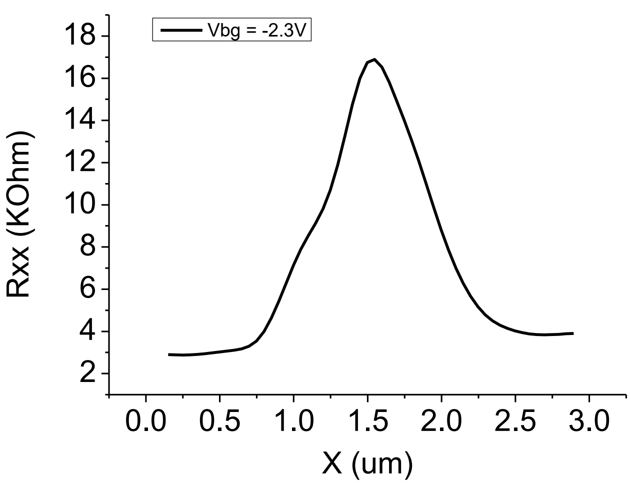
G4: 2300 x 800 nm





G4

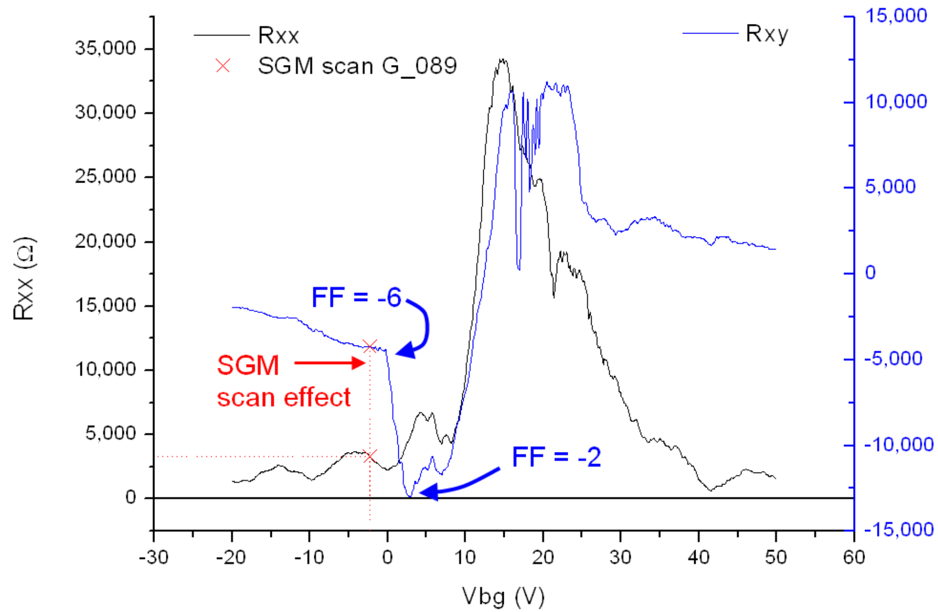




SGM scan:
Vbg = -2.3V, Vtip = 20V, d = 26nm,
B = 8T, T = 0.42K

G4: 2300 x 800 nm

Lennart Bours



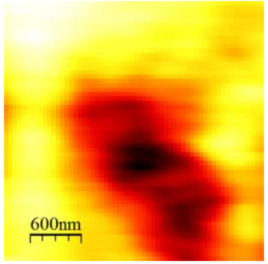
G4

SGM scan: Vbg = -4.2V, Vtip = 20V, d = 26nm, B = 8T, T = 0.42K

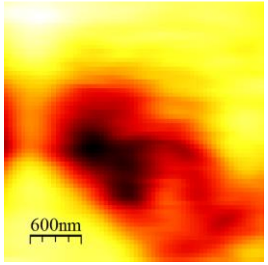
Lennart Bours

- At low tip bias the ribbon shows inhomogenity
- With increasing bias the ribbon becomes better defined

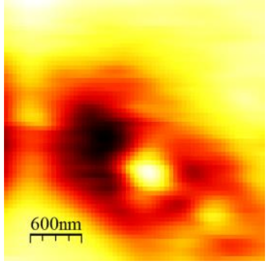
Rxx Vtip = 0V



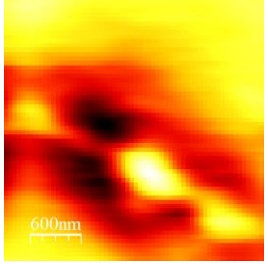
Rxx Vtip = 1V



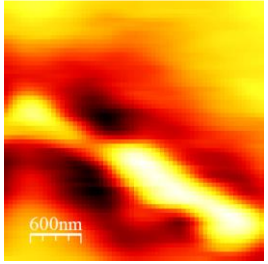
Rxx Vtip = 3V



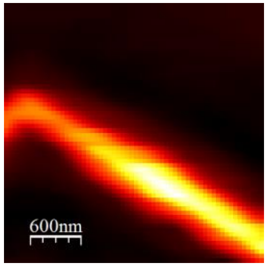
Rxx Vtip = 4V



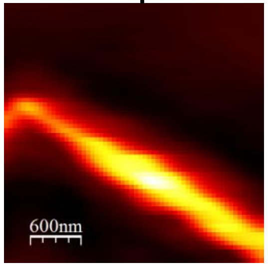
Rxx Vtip = 5V



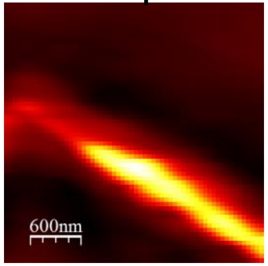
Rxx Vtip = 20V



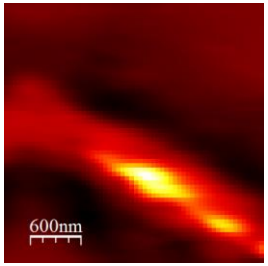
Rxx Vtip = 15V



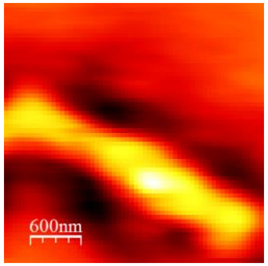
Rxx Vtip = 12V



Rxx Vtip = 10V



Rxx Vtip = 7.5V

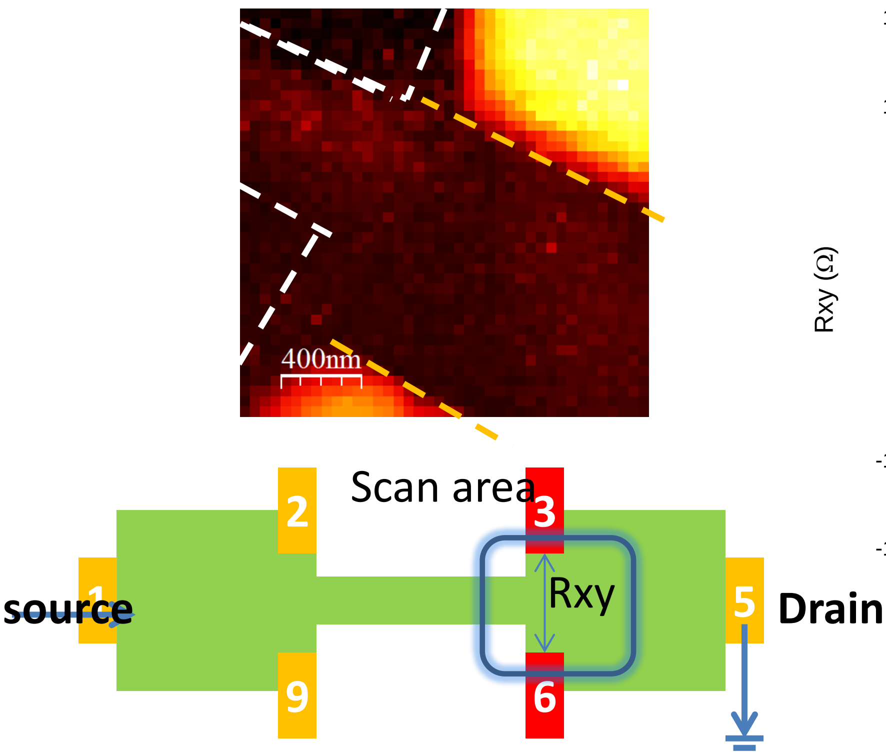


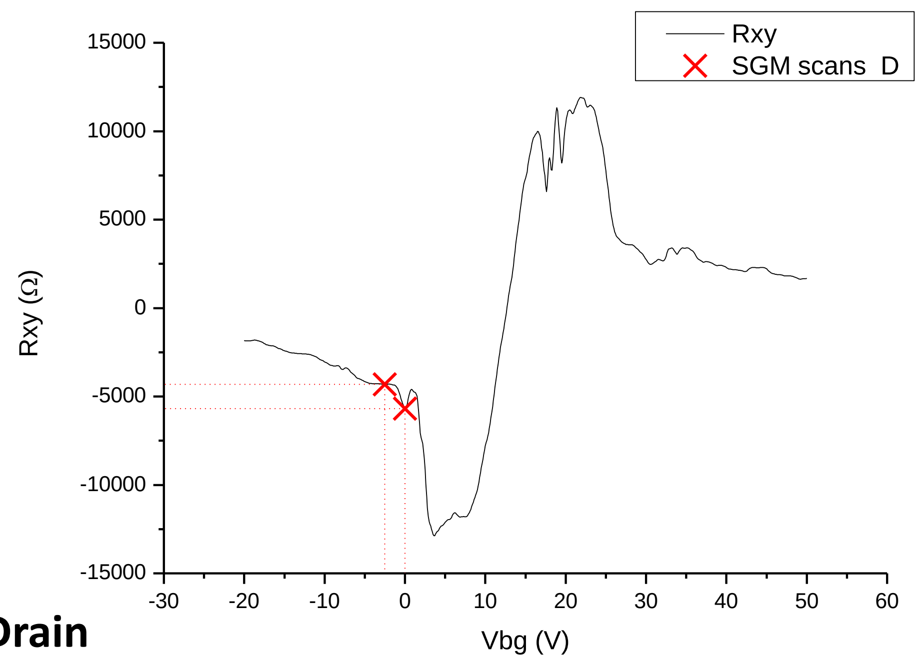
G4

SGM scan: Vbg = -4.2V, Vtip = 20V, d = 26nm, B = 8T, T = 0.42K

Lennart Bours

- Two series of scans;
- One starting from the filling factor = -6 plateau
- One starting between filling factor = -6 and = -2





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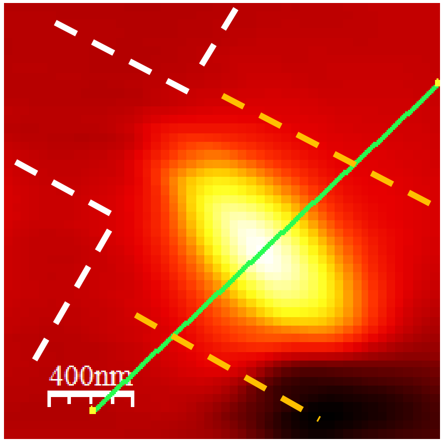
G4

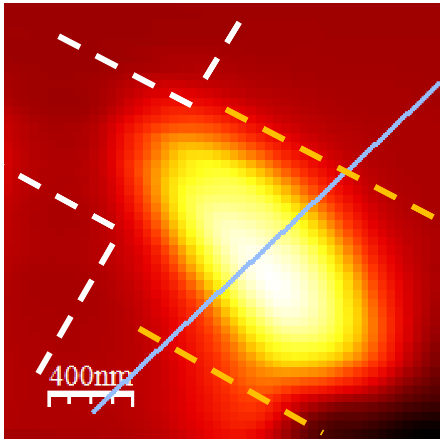
SGM scan: Vbg = -4.3V, B = 8T, T = 0.42K, d = 104nm

Lennart Bours

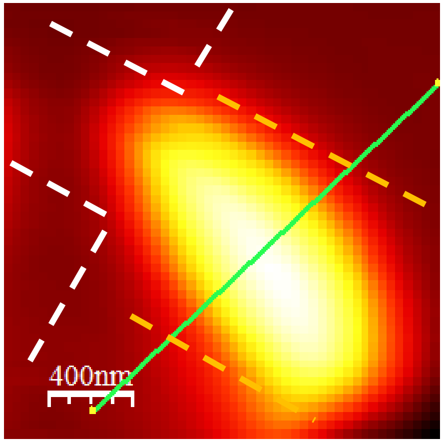
G_087 Vtip = 20V

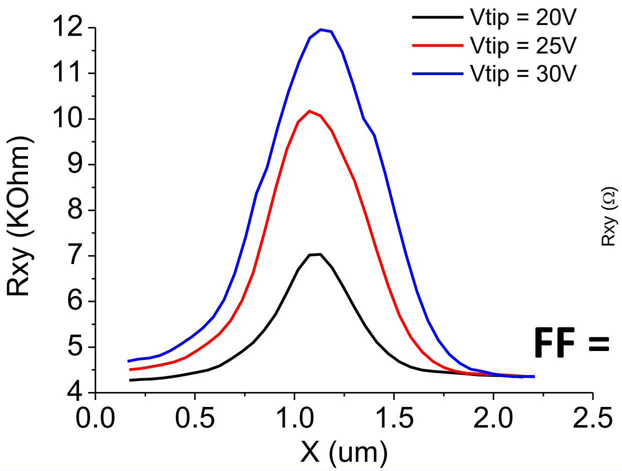


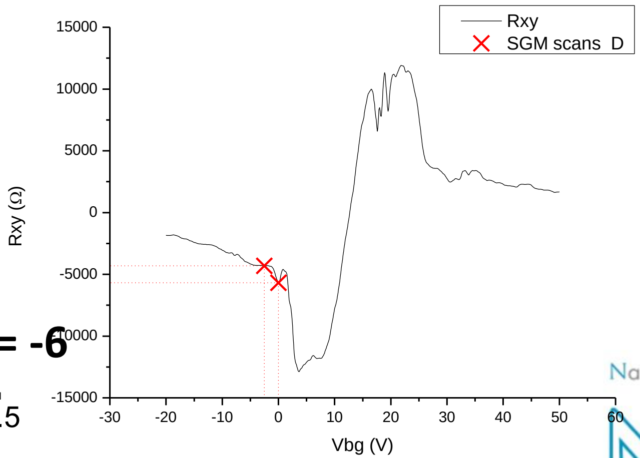
G_088 Vtip = 25V



G_088 Vtip = 30V







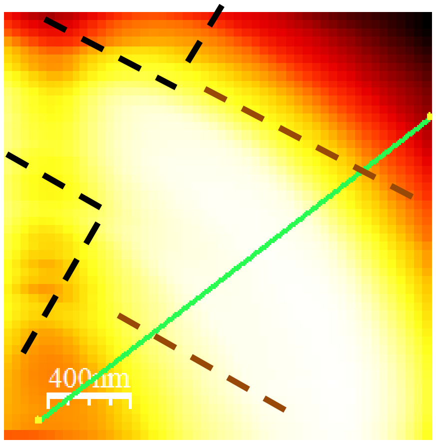
FF = -6

G4

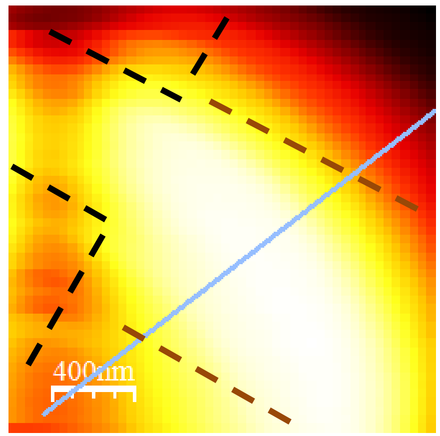
SGM scan: Vbg = -2.5V, B = 8T, T = 0.42K, d = 104nm

Lennart Bours

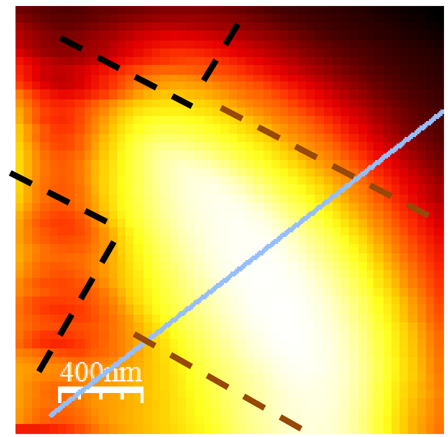
G_090 Vtip = 30V

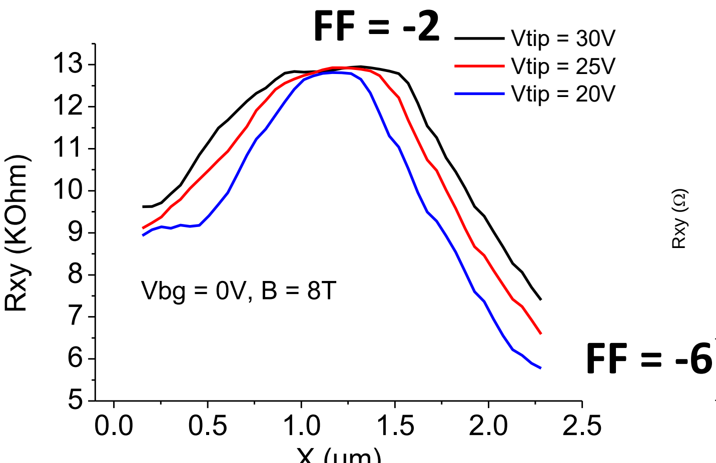


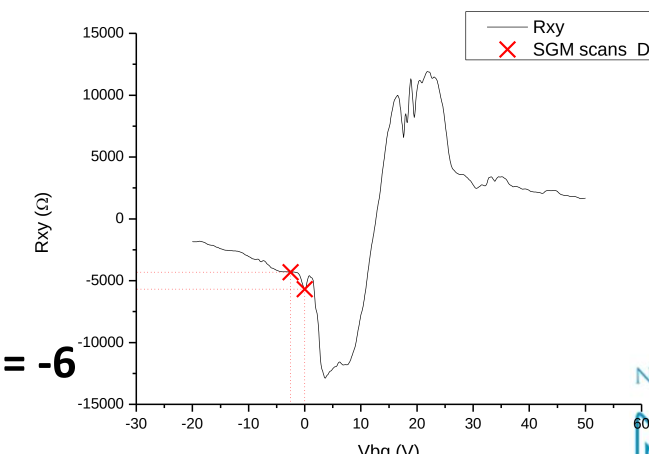
G_091 Vtip = 25V



G_092 Vtip = 20V



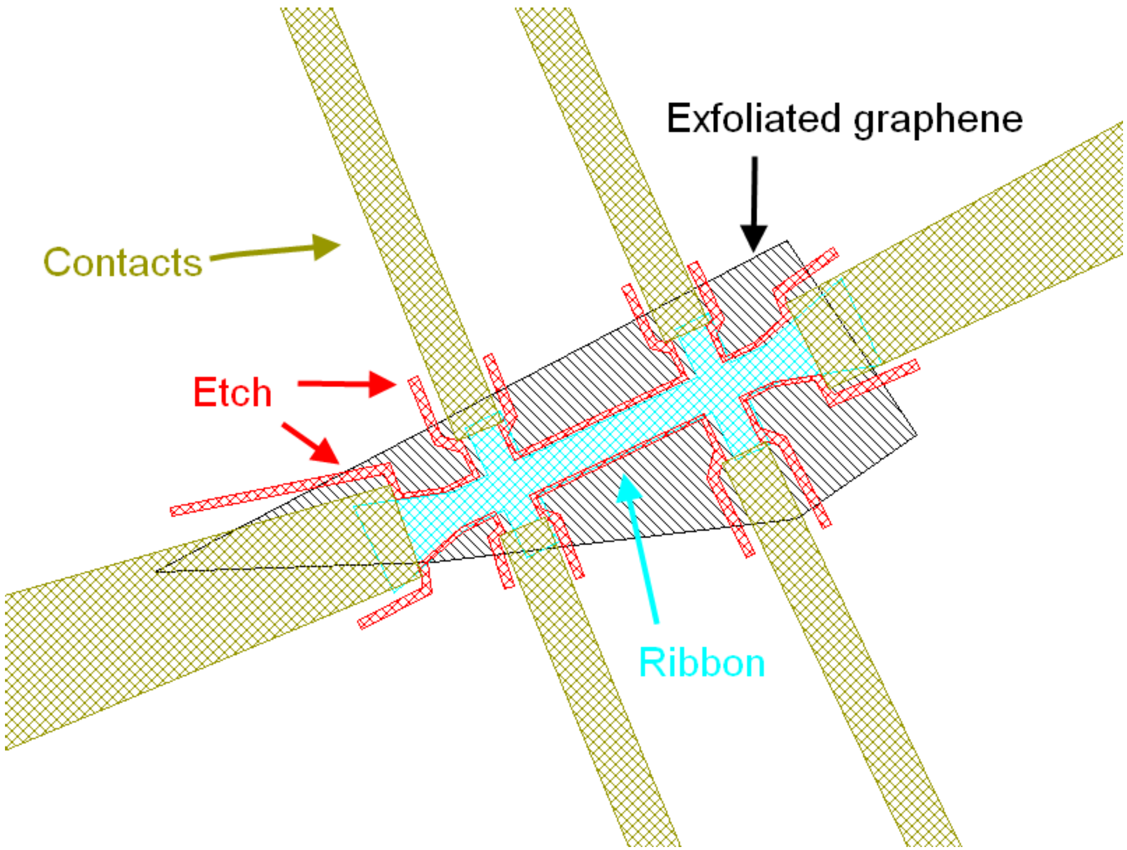


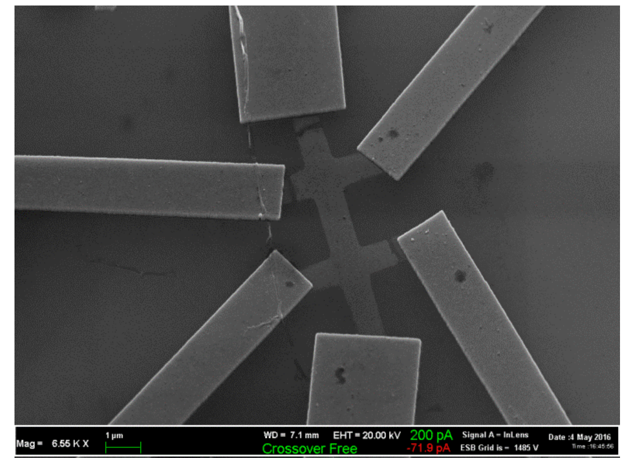


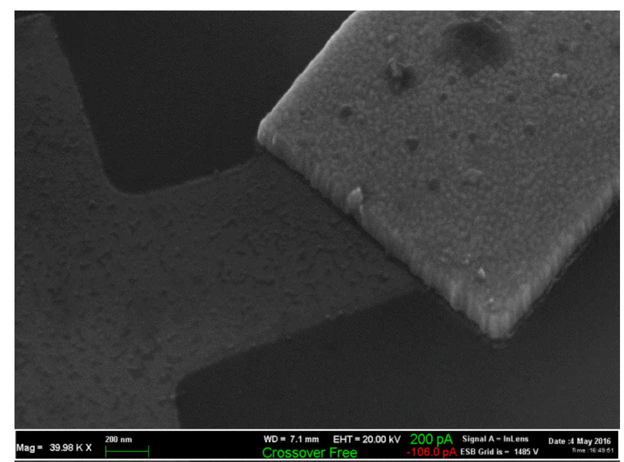
Outlook

Lennart Bours

New Design







Outline

- Basics of Scanning Gate Microscopy (SGM)
- 0.7 Anomaly in a Quantum Point Contact
- Ongoing Activities
  - Graphene Nanoribbons
  - Split Gates in Graphene
  - Phosphorene
  - Hybrid (S-N-S) Systems

Gate-defined QPC in the QH regime

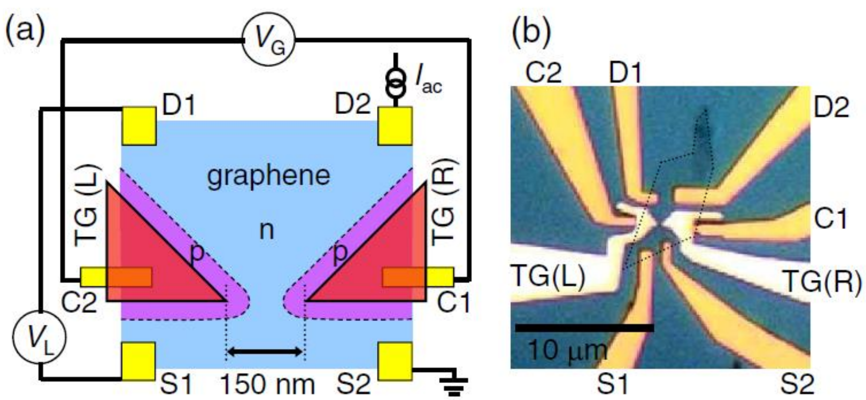
PRL **107,** 036602 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Gate-Defined Graphene Quantum Point Contact in the Quantum Hall Regime

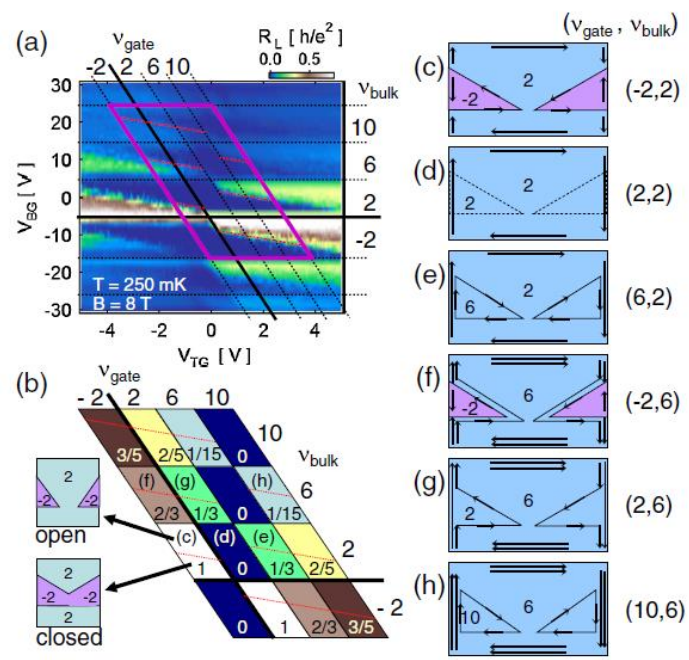
S. Nakaharai,[1,2] J. R. Williams,[1,3,*] and C. M. Marcus[1]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Toshiba Research and Development Center, Kawasaki 212- 8582, Japan*
[3]*School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

(Received 11 October 2010; published 14 July 2011)

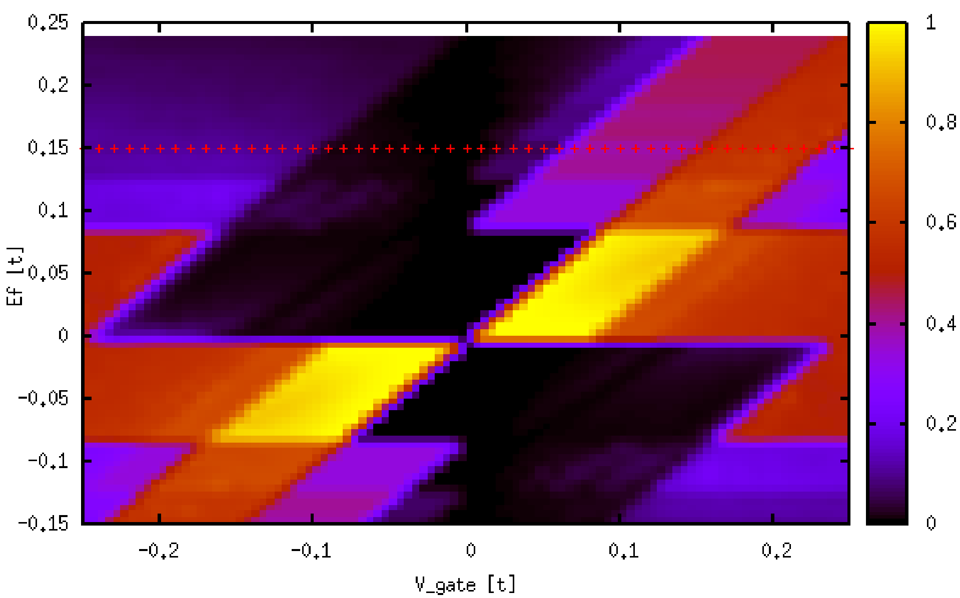


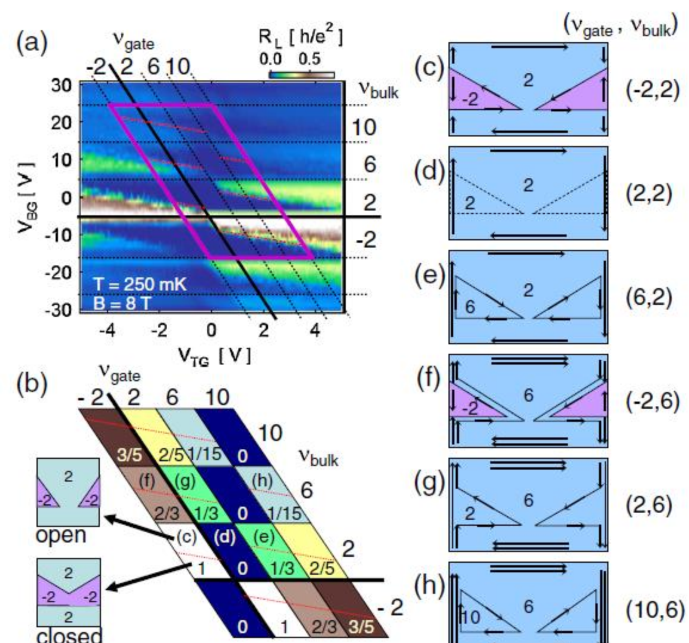
$$R_{xx} = \frac{|\nu_b - \nu_g|}{|\nu_b||\nu_g|} \cdot \frac{h}{e^2}$$



Gate-defined QPC in the QH regime

Alina Mrenca-Kolasinska





Gate-defined QPC in the QH regime

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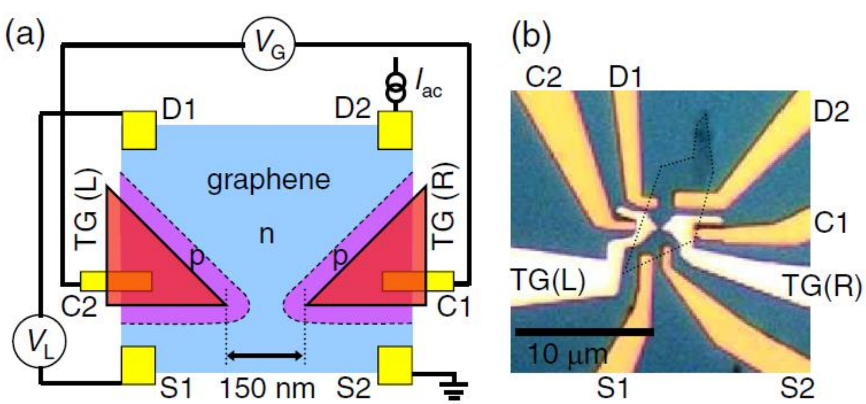
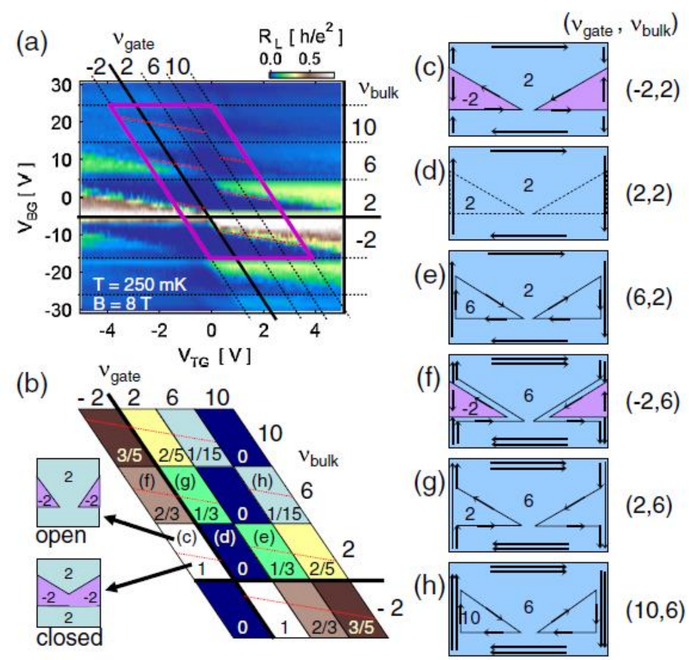
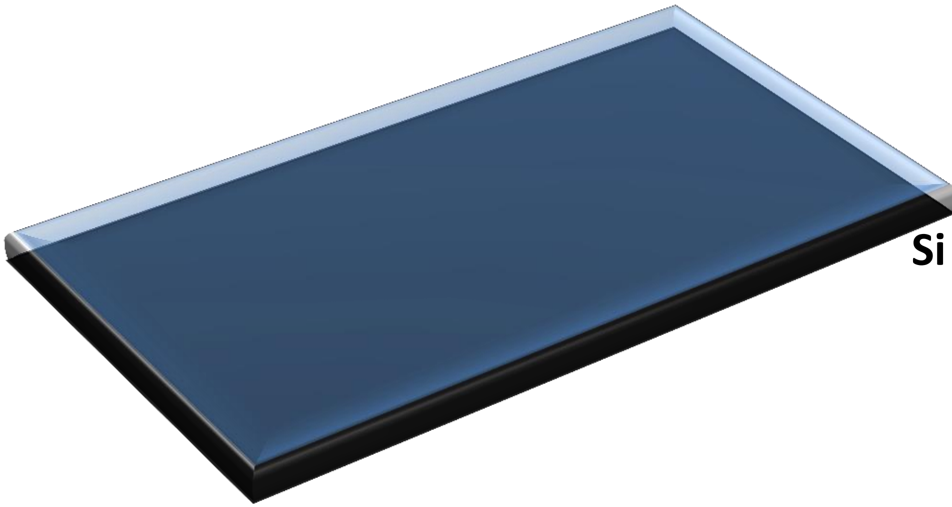




$$R_{xx} = \frac{|\nu_b - \nu_g|}{|\nu_b||\nu_g|} \cdot \frac{h}{e^2}$$

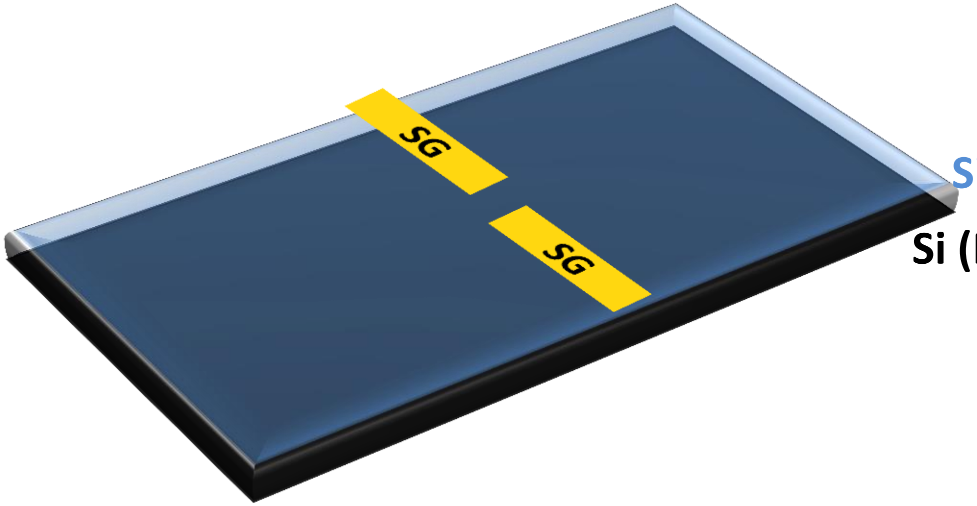
Buried split-gate device



Shaohua Xiang

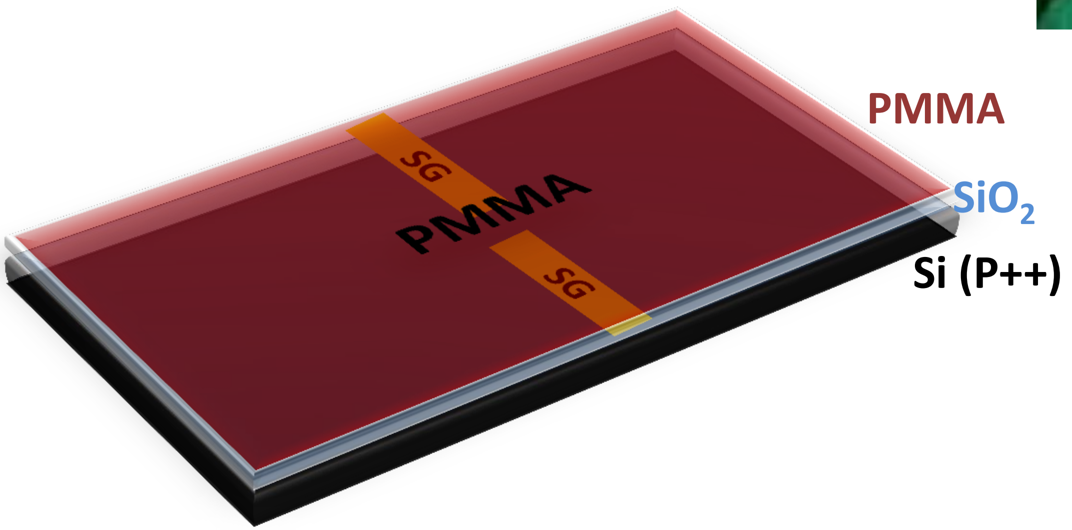
Buried split-gate device

Shaohua Xiang

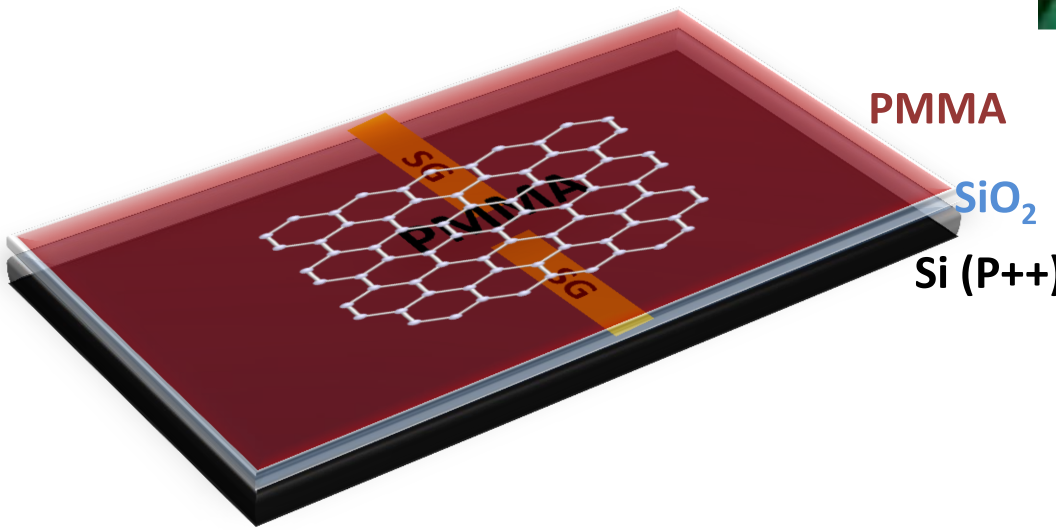


Buried split-gate device

Shaohua Xiang



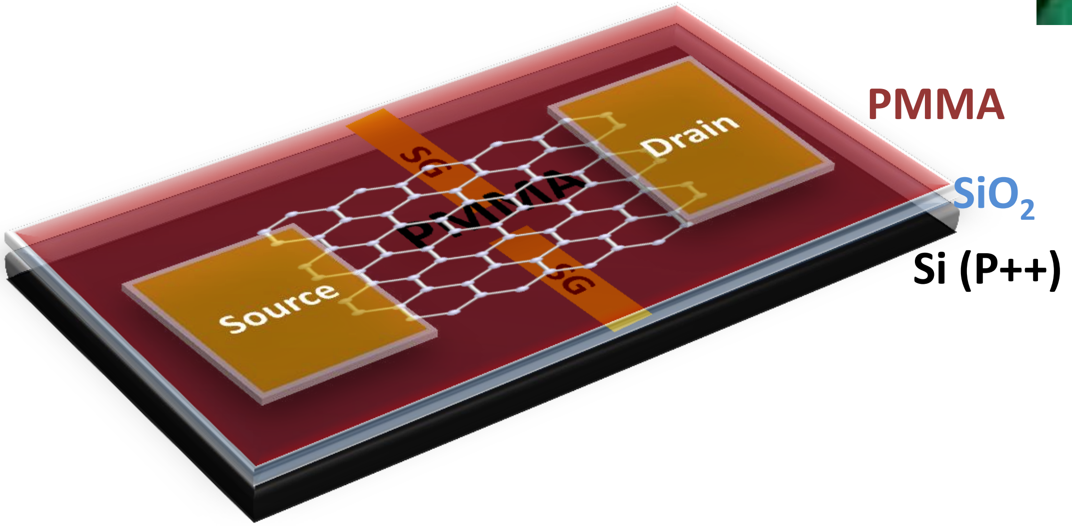
Buried split-gate device



Shaohua Xiang

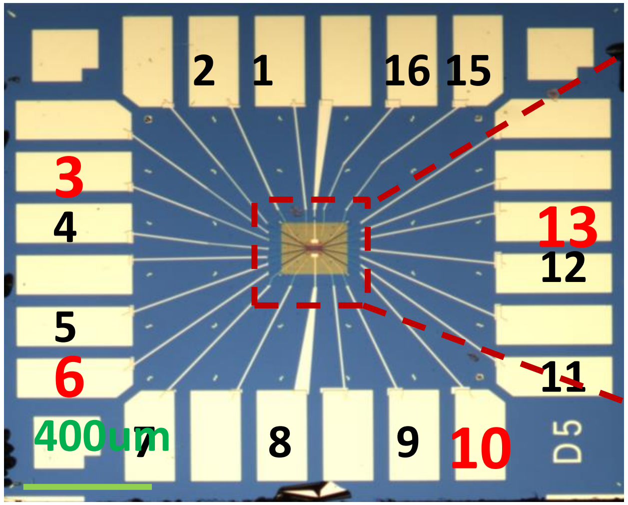
Buried split-gate device

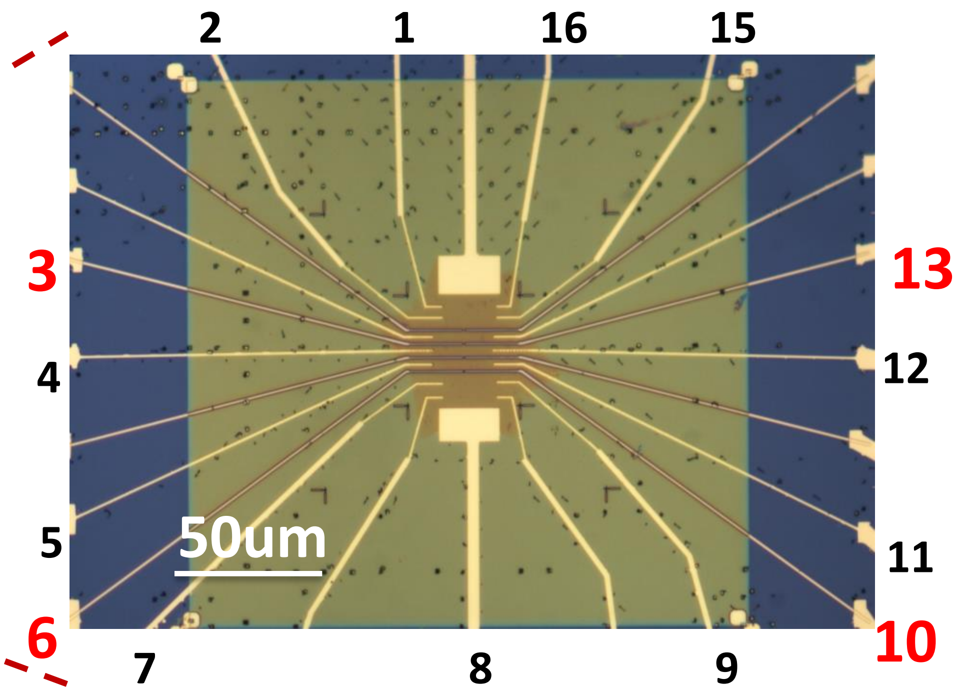
Shaohua Xiang



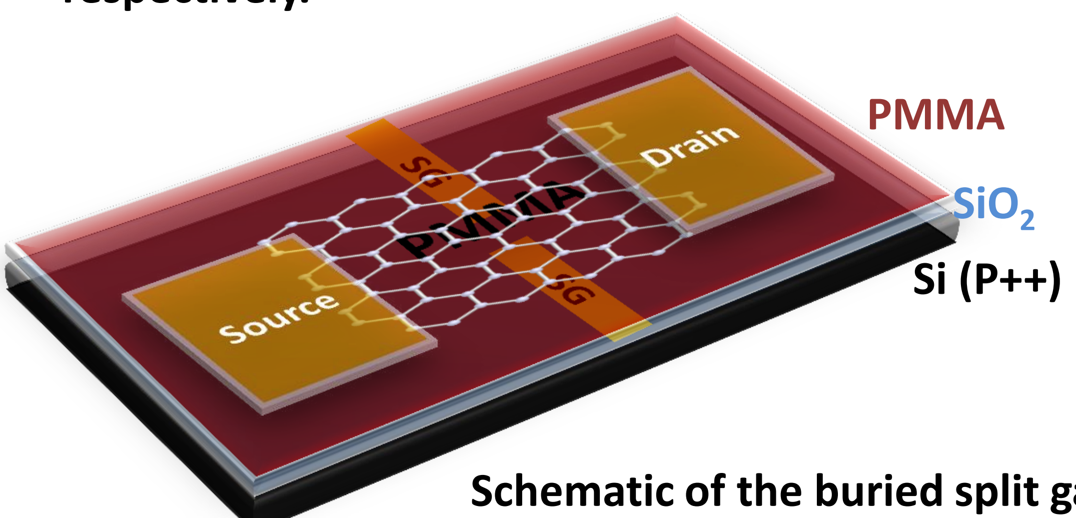
The buried split gate device

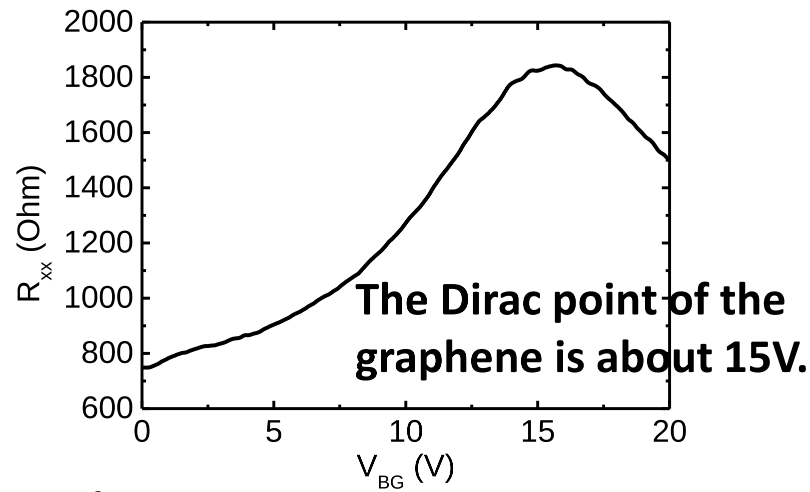
The optical image of our device





Two out of the four buried split gate devices have been measured in this study. They are SG(6 - 10) and SG(3 - 13), the width of these two pairs split gate are 400nm and 800nm, respectively.

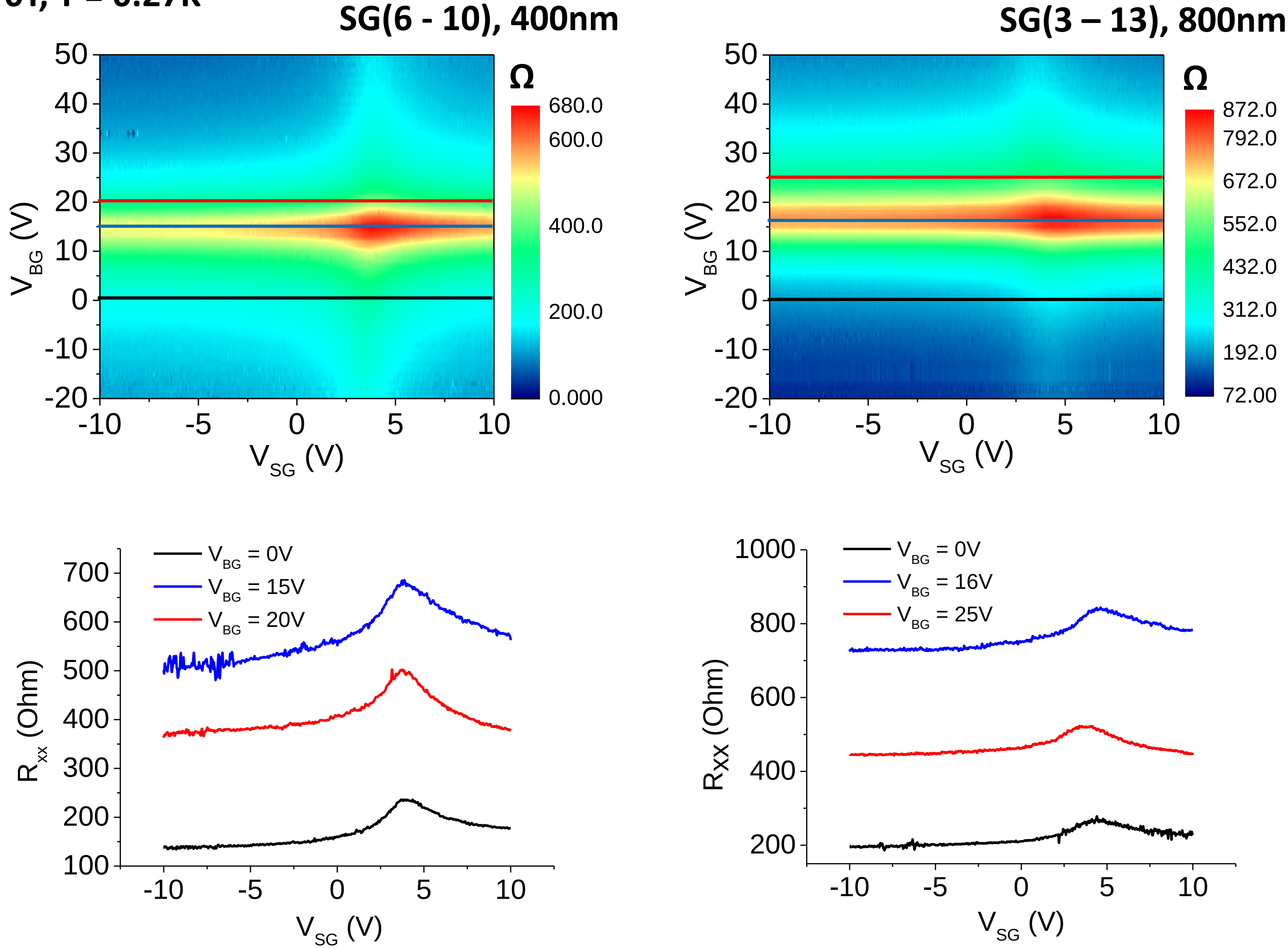




Schematic of the buried split gate device

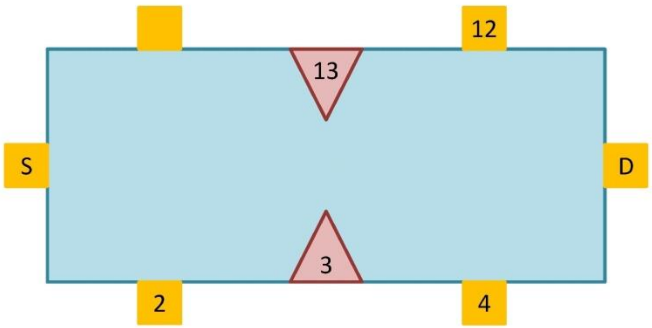
Transport measurement at B = 0T

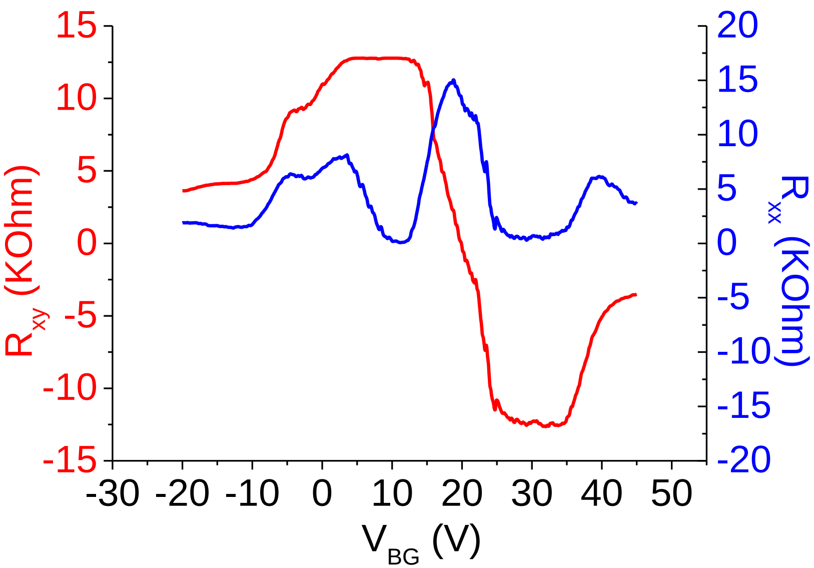
B = 0T, T = 0.27K



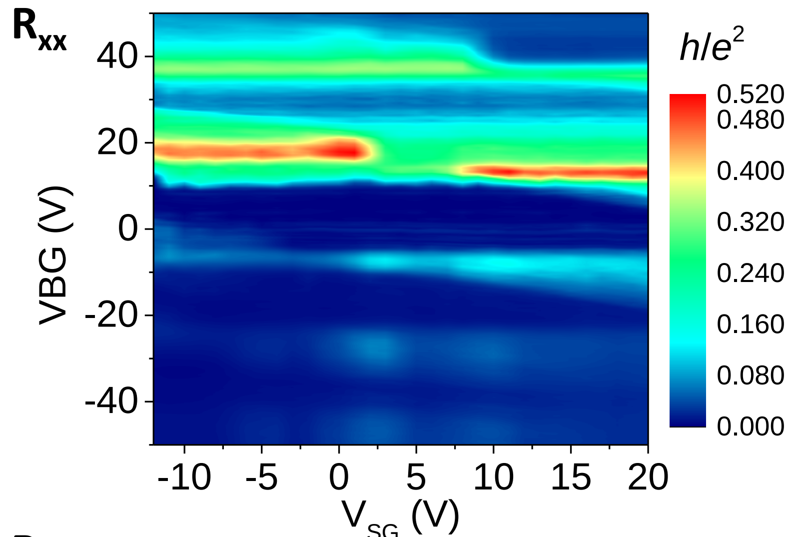
Transport measurement at B = 10T

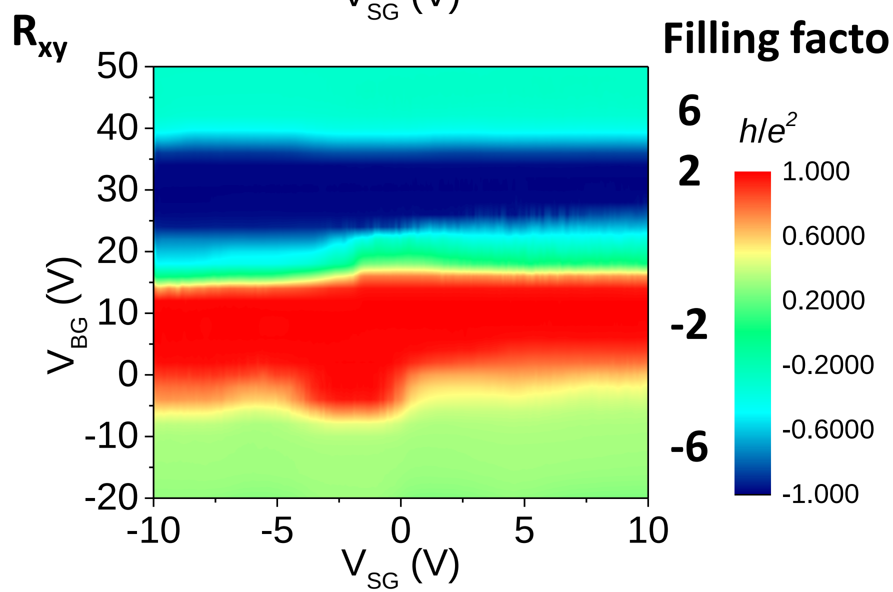
B = 10T, T = 0.27K, SG (3-13), 800nm





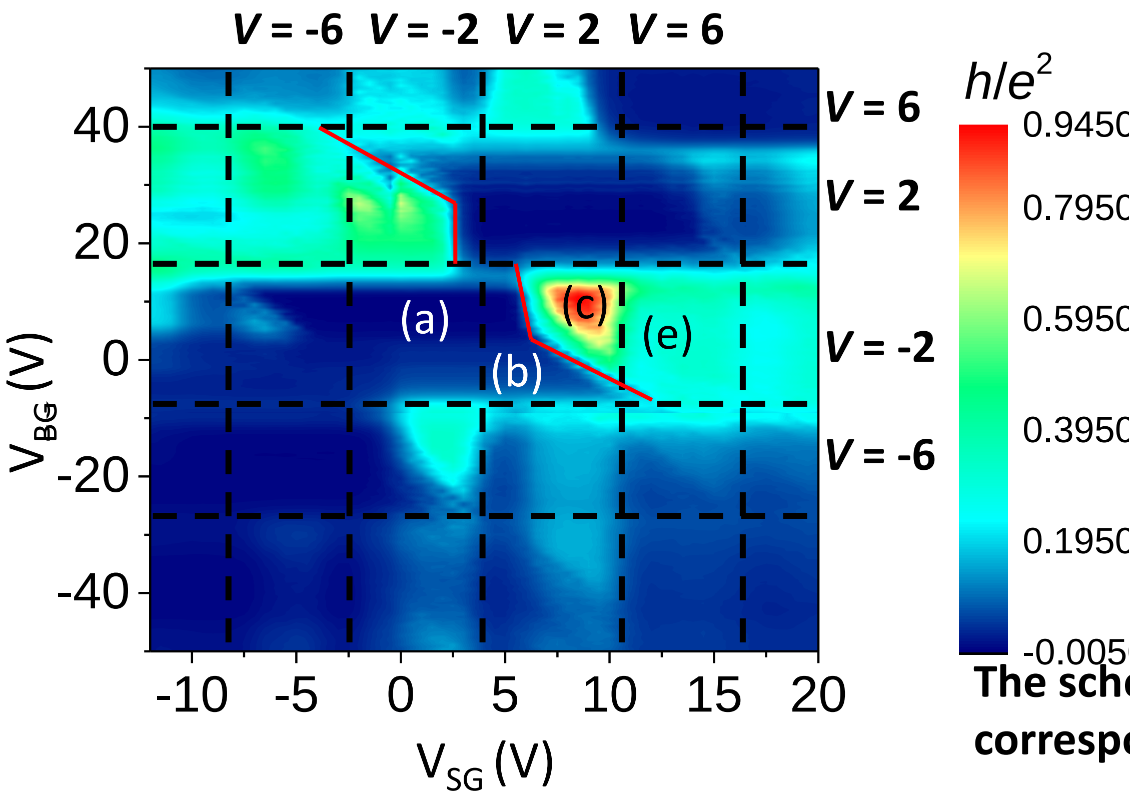
The quantum Hall measurement at V_{SG} = 0V for SG (3-13)

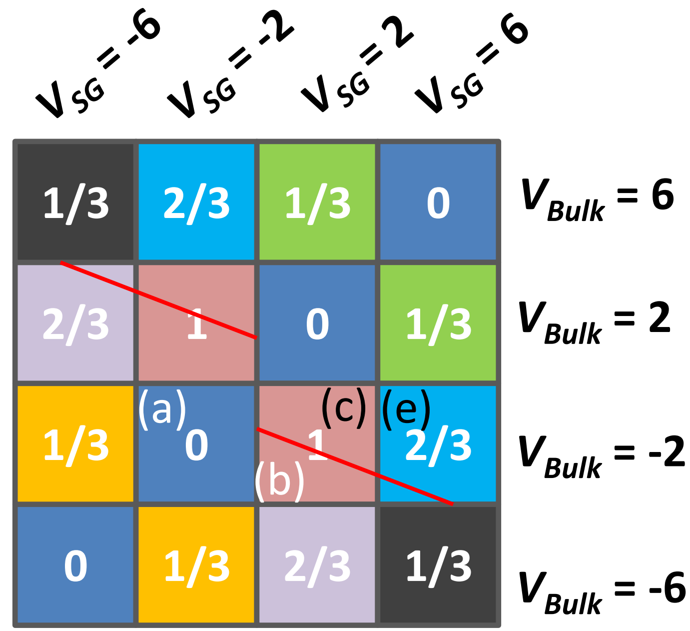




Transport measurement at B = 10T

B = 10T, T = 0.27K, SG (6-10), 400nm



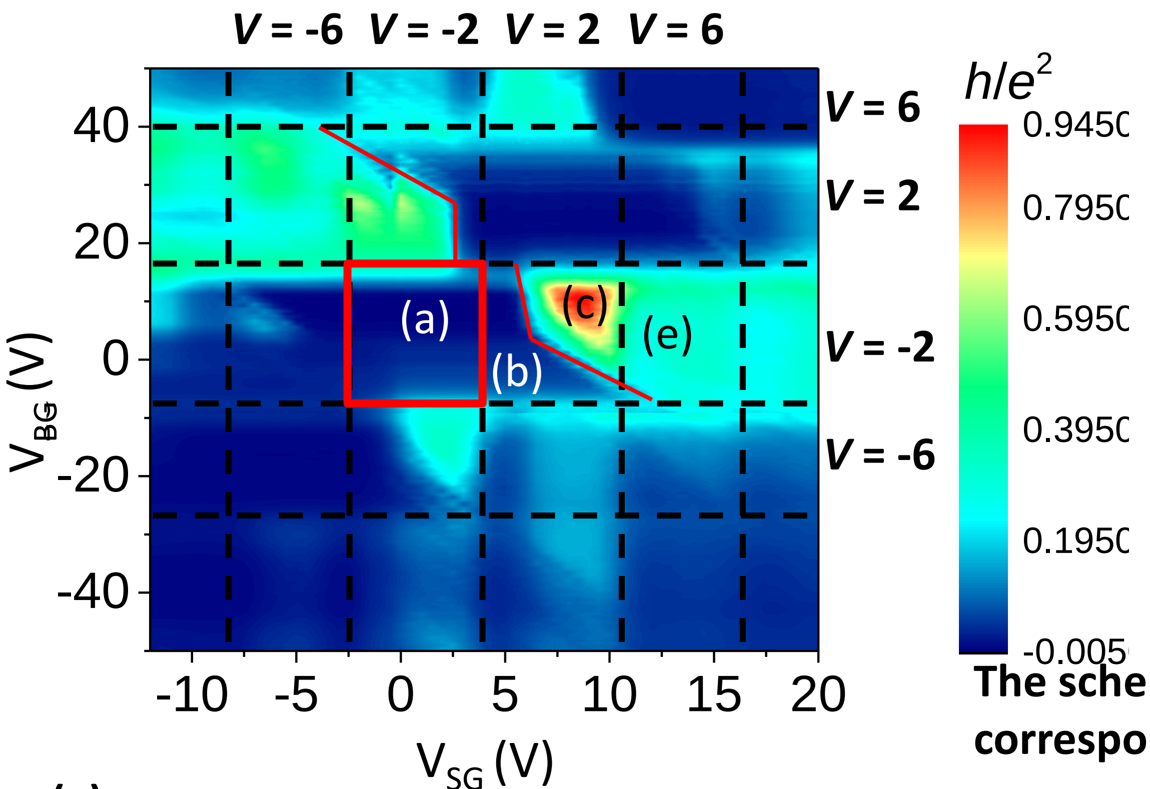


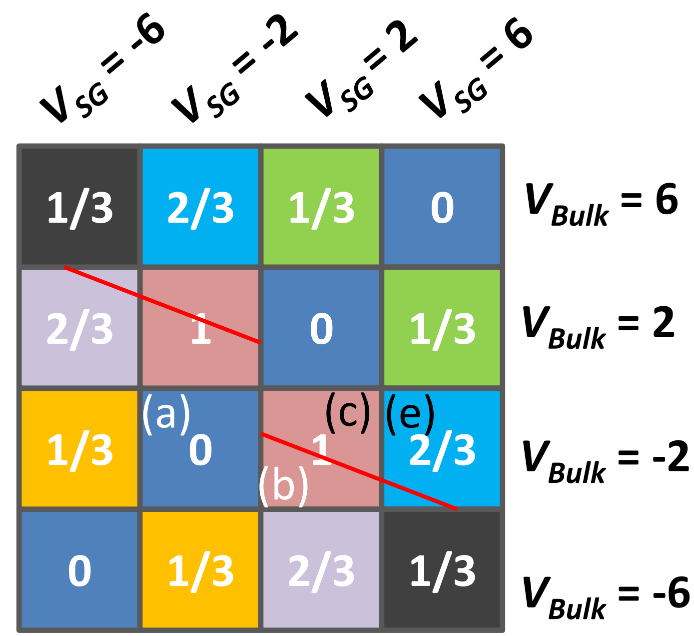
The rectangle of the theoretical calculation

The schematics of current flow corresponding to color map.

Transport measurement at B = 10T

B = 10T, T = 0.27K, SG (6-10), 400nm

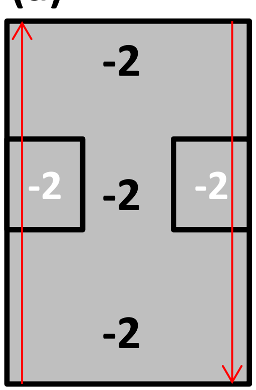




The rectangle of the theoretical calculation

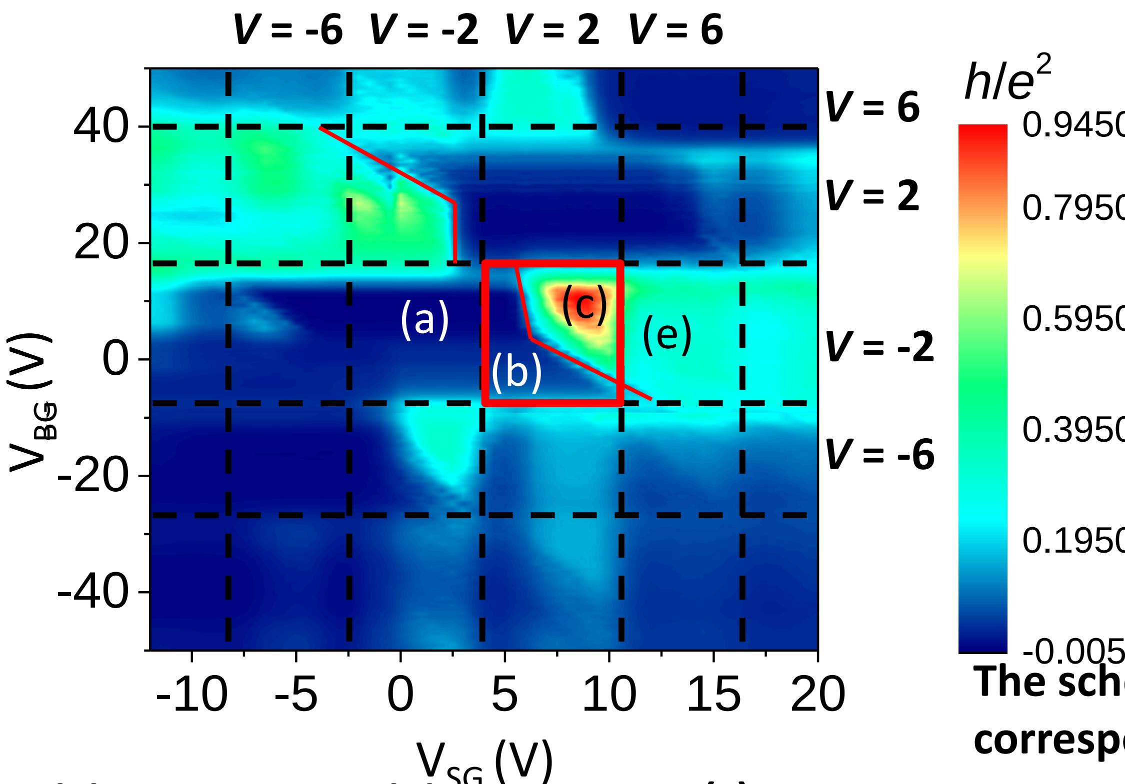
The schematics of current flow corresponding to color map.

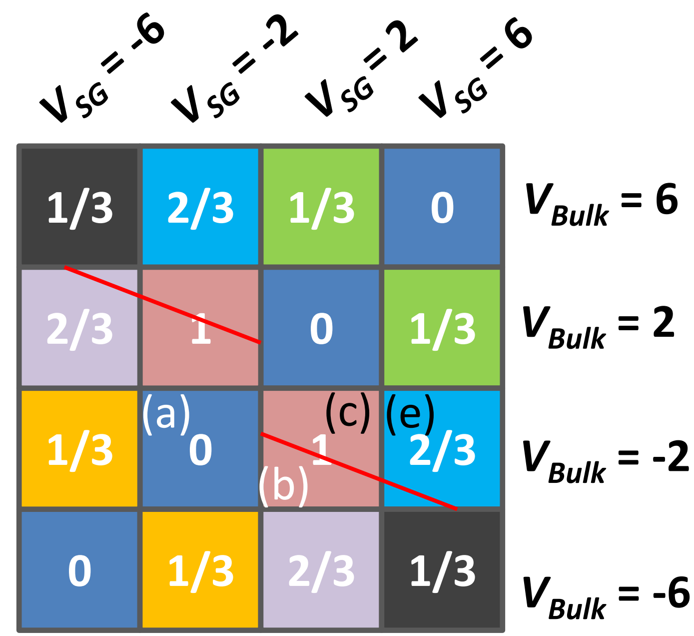
(a)



Transport measurement at B = 10T

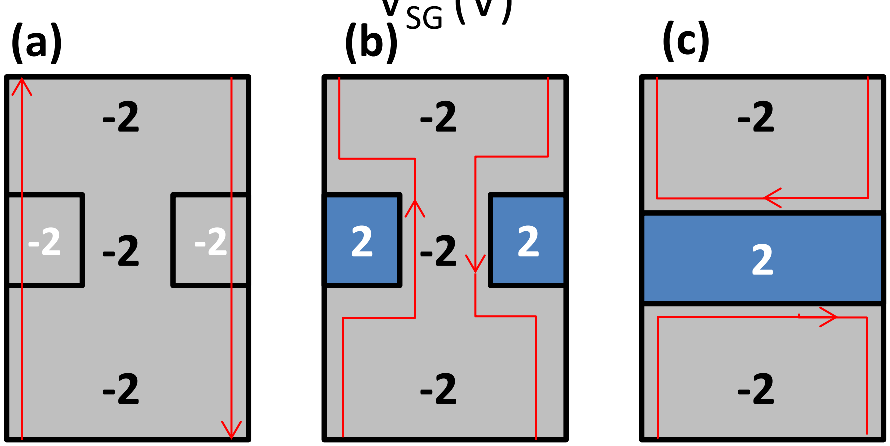
B = 10T, T = 0.27K, SG (6-10), 400nm





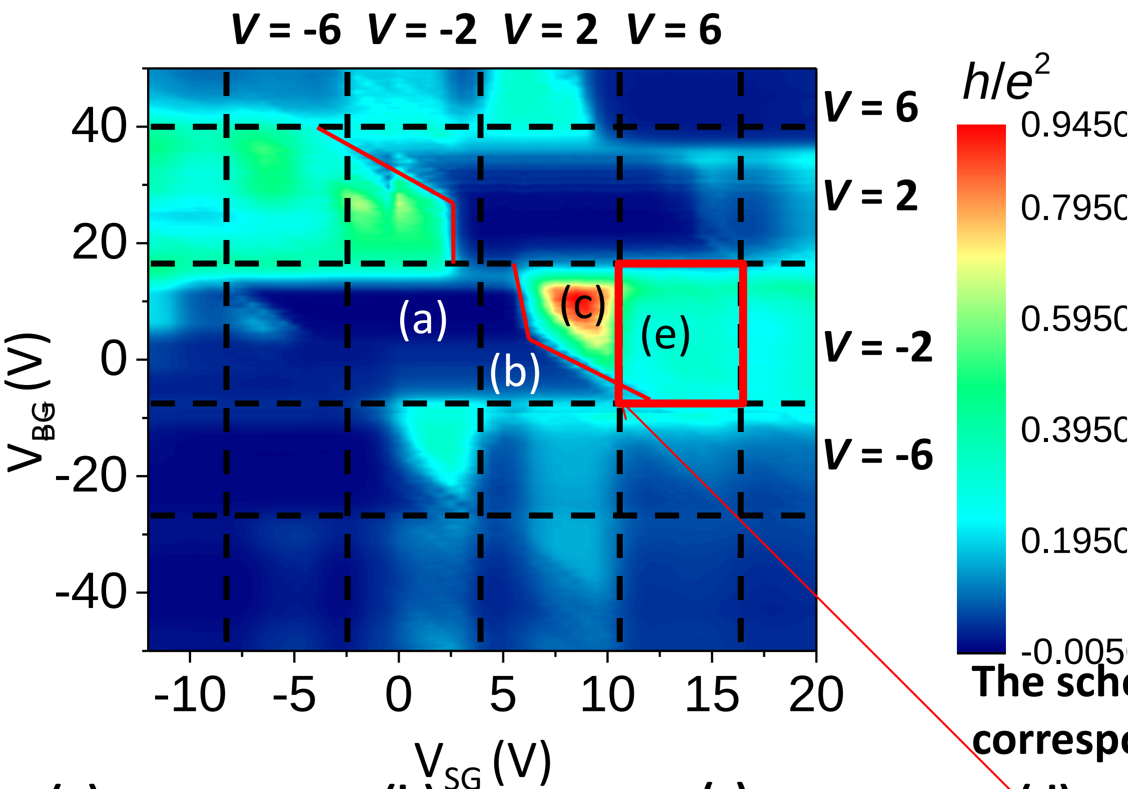
The rectangle of the theoretical calculation

The schematics of current flow corresponding to color map.



Transport measurement at B = 10T

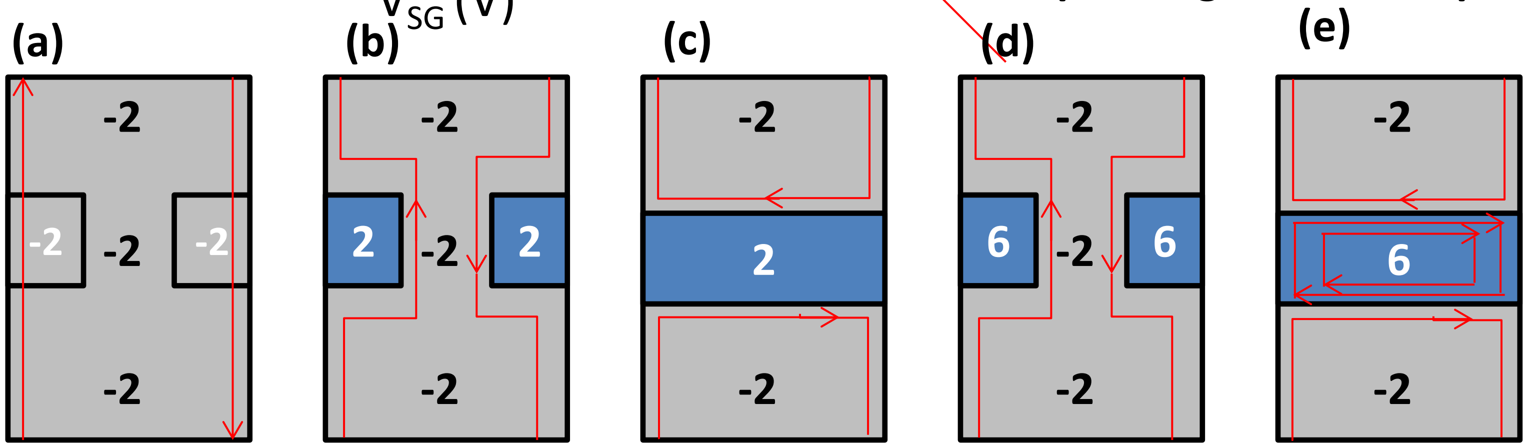
B = 10T, T = 0.27K, SG (6-10), 400nm



	$V_{SG} = -6$	$V_{SG} = -2$	$V_{SG} = 2$	$V_{SG} = 6$
V_{Bulk} = 6	1/3	2/3	1/3	0
V_{Bulk} = 2	2/3	1	0	1/3
V_{Bulk} = -2	1/3	(a) 0	(c) (b) 1	(e) 2/3
V_{Bulk} = -6	0	1/3	2/3	1/3

The rectangle of the theoretical calculation

The schematics of current flow corresponding to color map.



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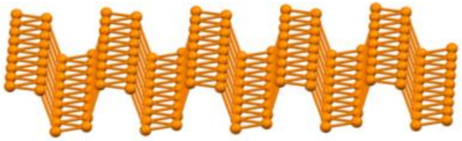
  - Phosphorene
  - Hybrid (S-N-S) Systems

Weak localization in phosphorene

Francesca Telesio

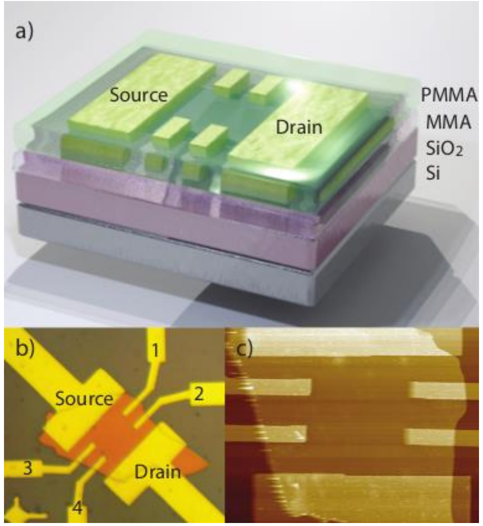
Phosphorene is a recent 2D material, obtained by exfoliation from black phosphorus.

It has a layered puckered structure.



Differently from graphene, it is a semiconductor with gap dependent from the number of layer (from 0.3eV in bulk to 2eV for the monolayer).

Our study is about low temperature magnetotransport on an Hall bar device made with a phosphorene flake.



Temperature down to 0.26K
Magnetic field up to 14T

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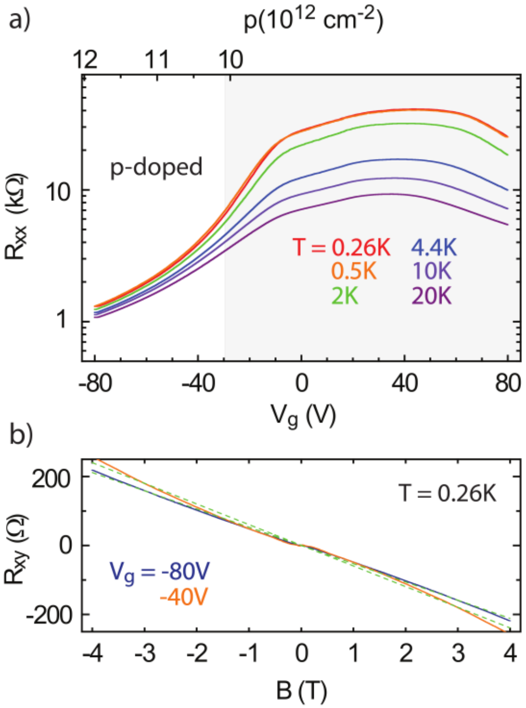
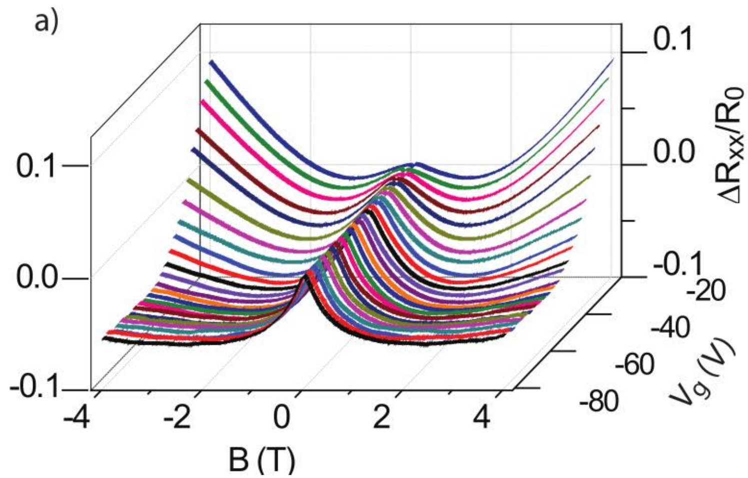
Weak localization in phosphorene

Francesca Telesio

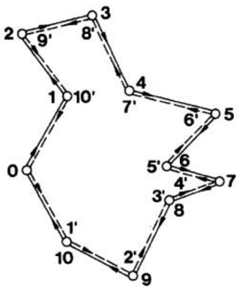


At negative bias voltage we are in hole doped regime, while increasing bias voltage towards positive voltages we go through the band gap.

Weak localization is a quantum effect related to coherent scattering at low temperatures.



A peak in magnetoresistance at low field is a signature of weak localization.



Picture from Bergmann, Weak localization in thin films, Physics Reports 107, 1984

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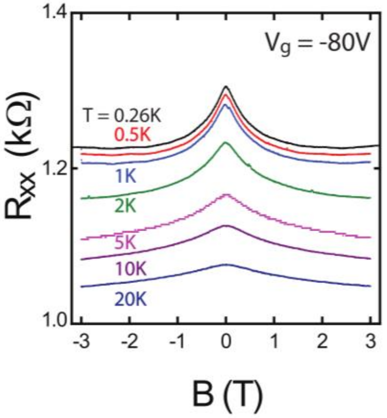
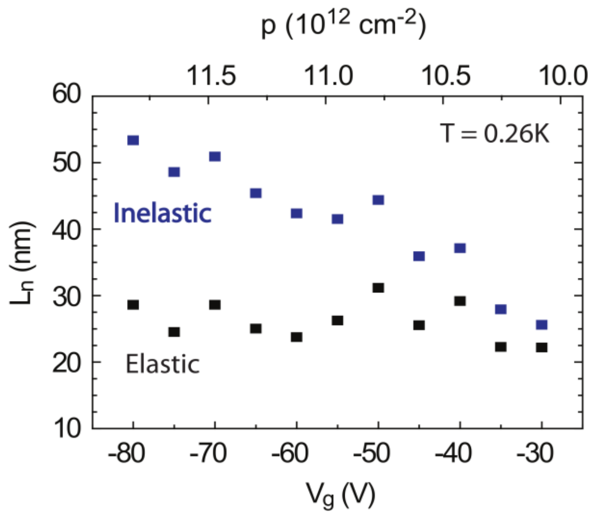
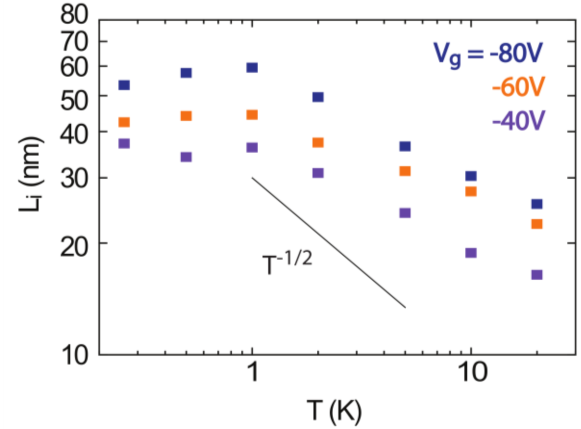
Weak localization in phosphorene

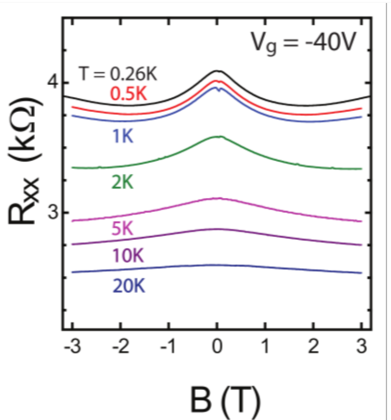


The low field peak can be fitted with Hikami-Larkin-Nagaoka model in order to extract information on scattering times.





Further analysis is in progress…



Since it's a coherence effect, it's suppressed by temperature.

Collaboration with CNR-ICCOM that provided the bP (PHOSFUN ERC project) and Mc Gill University, Montreal

Outline

- Basics of Scanning Gate Microscopy (SGM)
- 0.7 Anomaly in a Quantum Point Contact
- Ongoing Activities
  - Graphene Nanoribbons
  - Split Gates in Graphene
  - Phosphorene
  - Hybrid (S-N-S) Systems

Funding

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