Quantum magnetotransport in non-singly connected Dirac nanostructures.

Nano-perforated graphene

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Yury Latyshev (26.02.1950 - **10.06.2014**)

Collaboration:

experiment:

Yu.I. Latyshev

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nano-perforation

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by helium ion microscope:

Yu.V. Petrov, O.F. Vyvenko — **St-Petersburg State University, Russia**

by heavy ion irradiation:

V.A. Skuratov — **JINR, Dubna, Russia**

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high magnetic fields:

P. Monceau, B. Piot — **LNCMI, Grenoble, France**

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AFM characterization:

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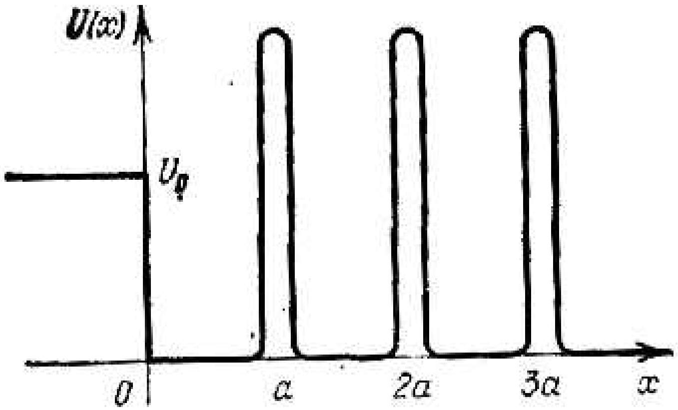
INTRODUCTION:
intrinsic surface (or edge) states

Model by I.E. Tamm (1932):
There are surface states
in semi-infinite Kronig-Penney potential.



13. *Kronig R., Penney W. G.*, Proc. Roy. Soc., **A130**, 499 (1931).
14. *Тамм И. Е.*, Zs. Physik, **76**, 849 (1932); Phys. Z. Sowjet., **1**, 733 (1932).
15. *Maue A. W.*, Zs. Physik, **94**, 717 (1935).
16. *Goodwin E. T.*, Proc. Cambridge. Phil. Soc., **35**, 205, 221, 232 (1939).
17. *Shockley W.*, Phys. Rev., **56**, 317 (1939).

The definition:

Tamm surface states ≡ Shockley surface states ≡ Tamm-Shockley surface states

Motivation

There are two types of intrinsic surface (or edge) states in solids. The first type is formed on the surface of topological insulators ($Bi_2 Se_3$ etc.). Recently, transport of massless Dirac fermions in the band of "topological" states has been demonstrated.

States of the second type were predicted by **Tamm and Shockley** long ago. But they do not have a topological background and are therefore strongly dependent on the properties of the surface. Usually, they are detected using local methods (such as *STM* and *ARPES*) ***on atomically clean surfaces*** of a number of metals and semiconductors ***in ultrahigh vacuum.***
However,
on real interfaces, such states typically do not exist.

We study the problems of the
1) very existence **and** **2)** ***conductivity***
of Tamm-Shockley edge states through
direct transport experiments in graphene in normal conditions**.**

OUTLINE

- Introduction. Massless Dirac fermions (DFs) in graphene
- Predicts. Тамм-Shockley states for the DFs ("***Tamm-Dirac*** states").

  Tamm-Dirac states near nanohole ("antidote") in graphene
- Technology. Nano-perforation of graphite and graphene
- Experiment at B=0. Resistance oscillations of nano-perforated graphene with gate voltage. Existence and orbital quantization of TD states on each nanohole
- Experiment at magnetic field: Aharonov-Bohm magneto-oscillations in graphene structures with a single nanohole.
- Conclusions
- Tamm-Dirac state in mountains

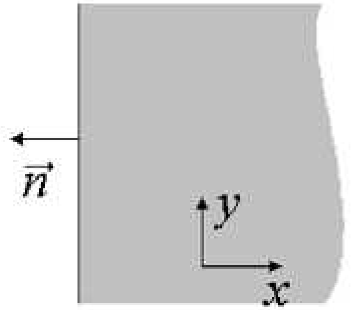
Why graphene ?

1. **Graphene is not topological insulator, but it is one of the Dirac materials.**

***2. Theory*:**
“Diracness” supports the Tamm-Shockley states

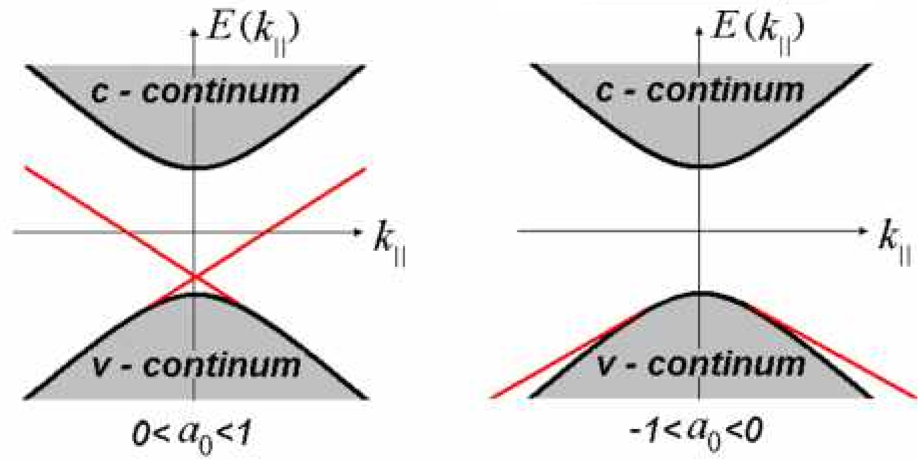
The Tamm-Shockley states for 3D Dirac Eq. on half-space

$$H_D = c^* \begin{pmatrix} \pm \vec{p} & mc^* \\ mc^* & -\pm \vec{p} \end{pmatrix} \quad \cdot \;= \begin{pmatrix} .. \\ i \end{pmatrix}$$



$$\hat{T}_D = i \begin{pmatrix} \sigma_2 & 0 \\ 0 & \sigma_2 \end{pmatrix} \hat{K}_0$$

K_0 - complex conjugate

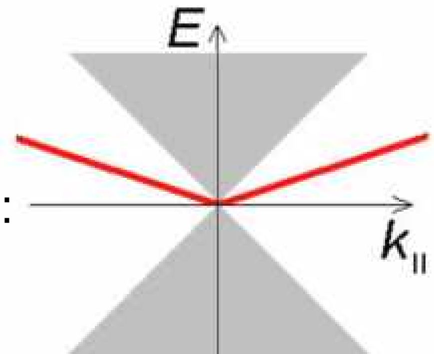


T_D-symm. boundary conditions:

$$\left(\varphi + e^{i a_0 \boldsymbol{\sigma} \boldsymbol{n}} \chi\right)\Big|_S = 0$$

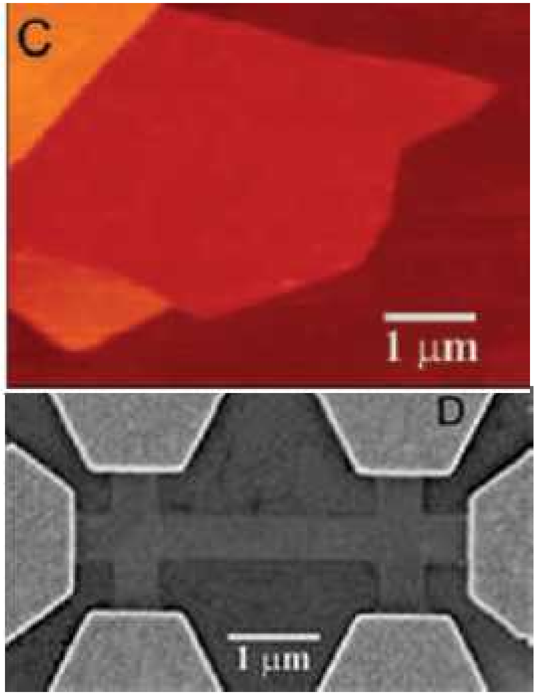
Phenom. parameter ***a₀*** depends on atomic structure of surface

Massless limit, m → 0:



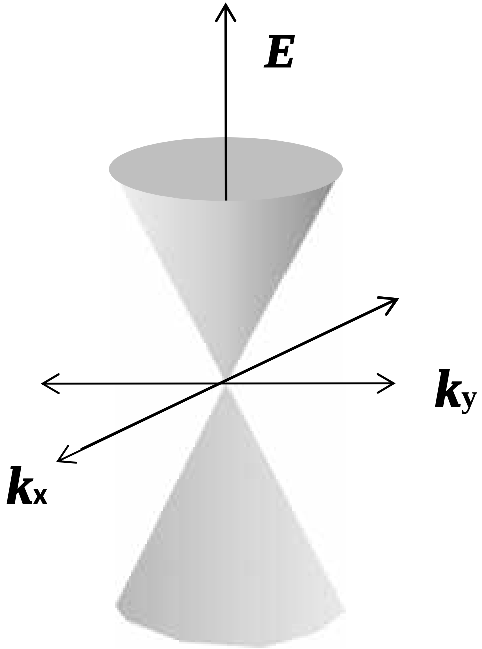
Volkov, V. A. & Pinsker, T. N. Spin splitting of the electron spectrum in finite crystals having the relativistic band structures. *Sov. Phys. Solid State* **23**, 1022 (1981).

Massless Dirac fermions in graphene



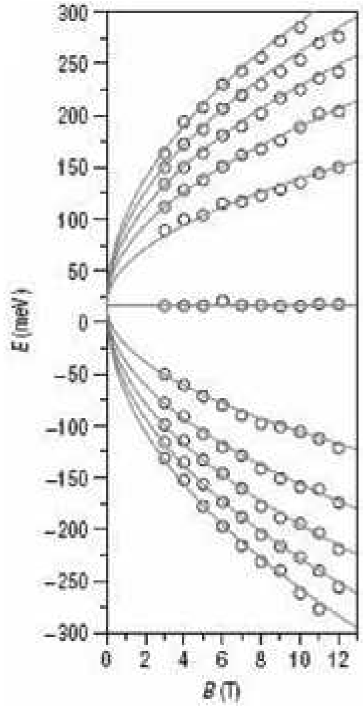
Graphene have been obtained in Manchester Uni.

K.S. Novoselov, A.K. Geim *et al*. *Science* (2004) *Nature* (2005).



Conic spectrum of massless Dirac fermions in graphene

$$E(k) = \pm v_F \hbar |k|$$



Specific character of Landau quantization in graphene

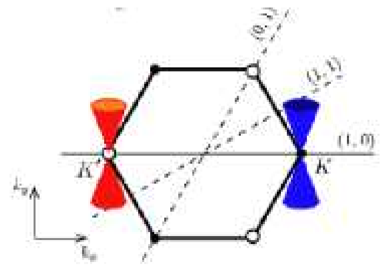
$$E_n = \mathrm{sgn}\, n \, v_F \sqrt{2e\hbar |n| H}$$

$$E_n \propto \sqrt{nH}$$

G. Li *et al*. *Nature Phys.* (2007)

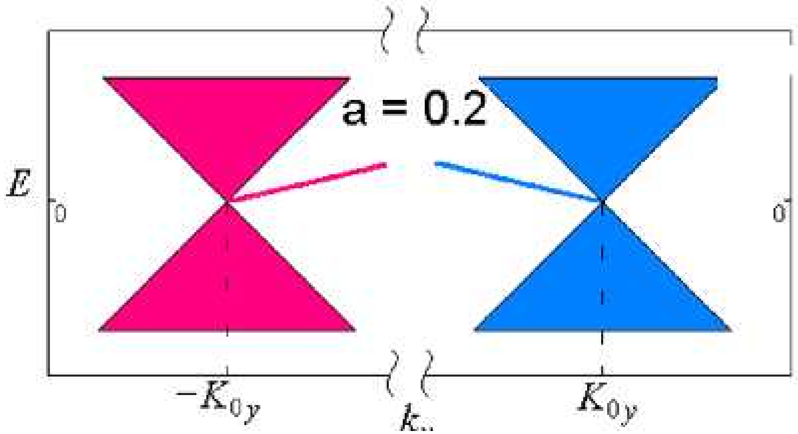
Theory: there are robust edge states of the Tamm-Shockley type for the Dirac fermions in graphene

Tamm-Shockley states for Dirac fermions =
=Tamm-Dirac states

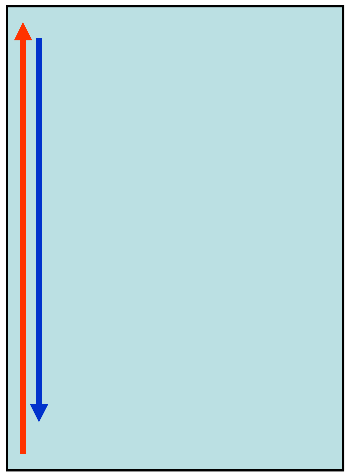


The Tamm-Dirac edge states have a linear spectrum but velocity **v=dE/dp much less then bulk v_F**

The Tamm-Dirac edge states are slow states.



Edge of graphene

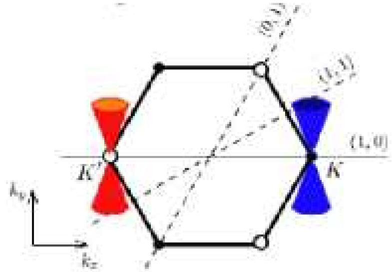


$$E_2\,(k_\parallel) = \frac{2a}{1+a^2}\,2\,v k_\parallel , \qquad 2\,k_\parallel \geq 0 \qquad 2 = \pm 1$$

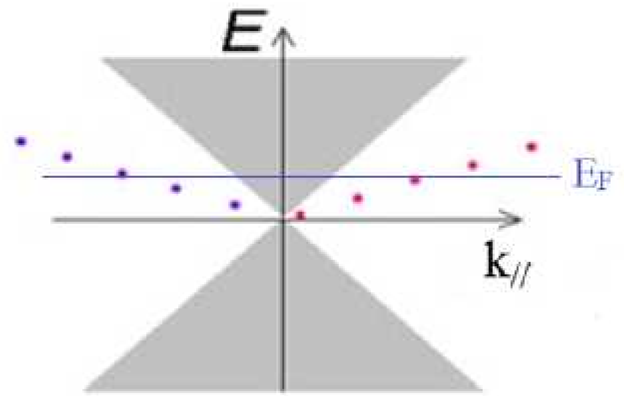
a **– an edge parameter (enters into boundary condition for Dirac Eq.)**

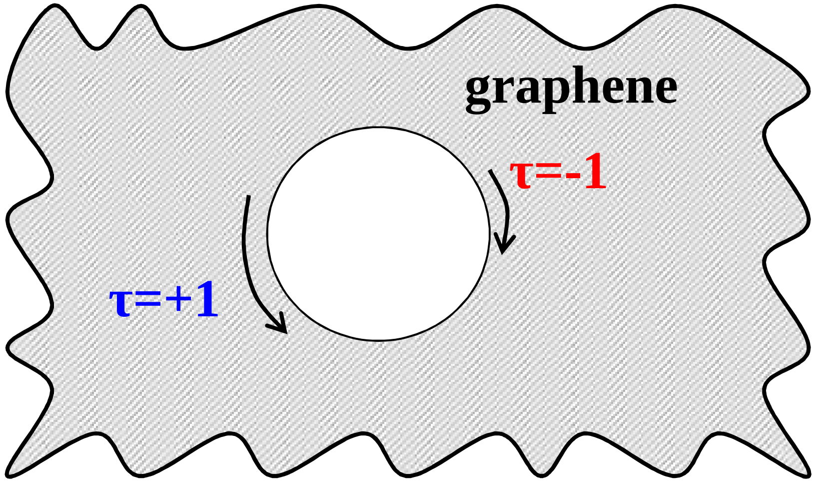
Volkov, V. A. & Zagorodnev, I. V. Electrons near a graphene edge. *Low Temp. Phys.* **35**, 2–5 (2009).

Nanohole in graphene: theory of the Tamm-Dirac states



The edge states rotate around antidot for both **clockwise** and **counterclockwise** **circulations**





They experience **the orbital quantization:**

$$k_{\parallel} = 2® \left(j - ^{2} / 2 \right) / 2® R$$

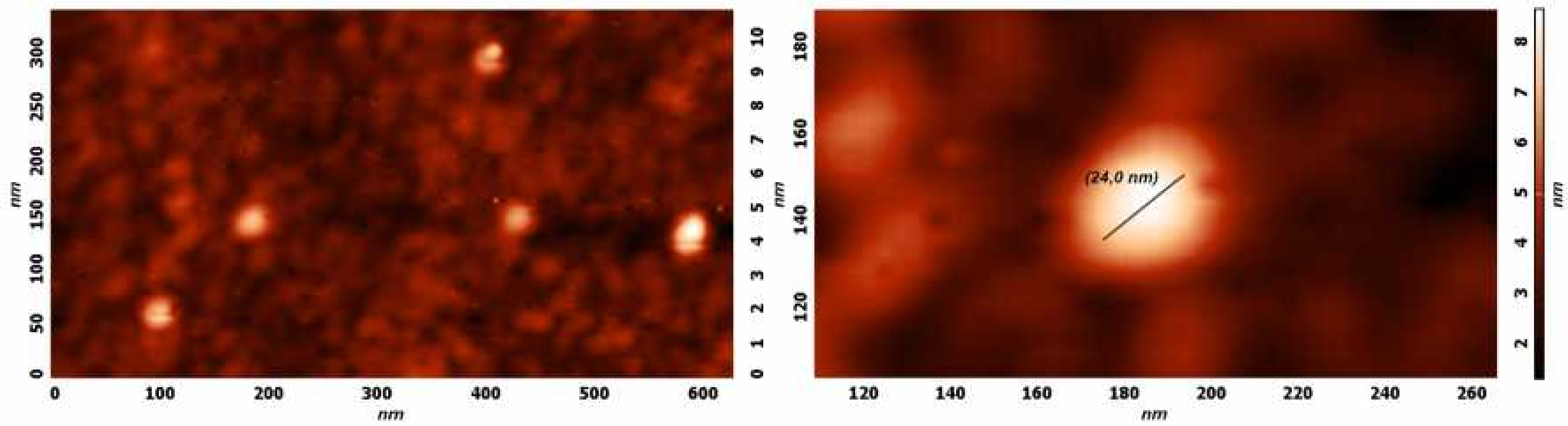
$$j = \pm 1/2, \pm 3/2, \pm 5/2, \ldots$$

Technology of nano-perforation

1) ***an array of "nanoholes"*** **(columnar defects)**
by Heavy ion irradiation
at Dubna (Russia) or Caen (France)

2) ***a single nanohole***:
by FIB (Kotelnikov IRE RAS, Moscow)
or
by focused He ion beam on Helium Ion Microscope (St-Petersburg State University, SPb, Russia)

Fabrication of an array of columnar defects



1) GANIL accelerator at Caen, France (Xe^{+26}- energy of 90 МэВ),

nanohole diameter **D ≈ 24 nm**

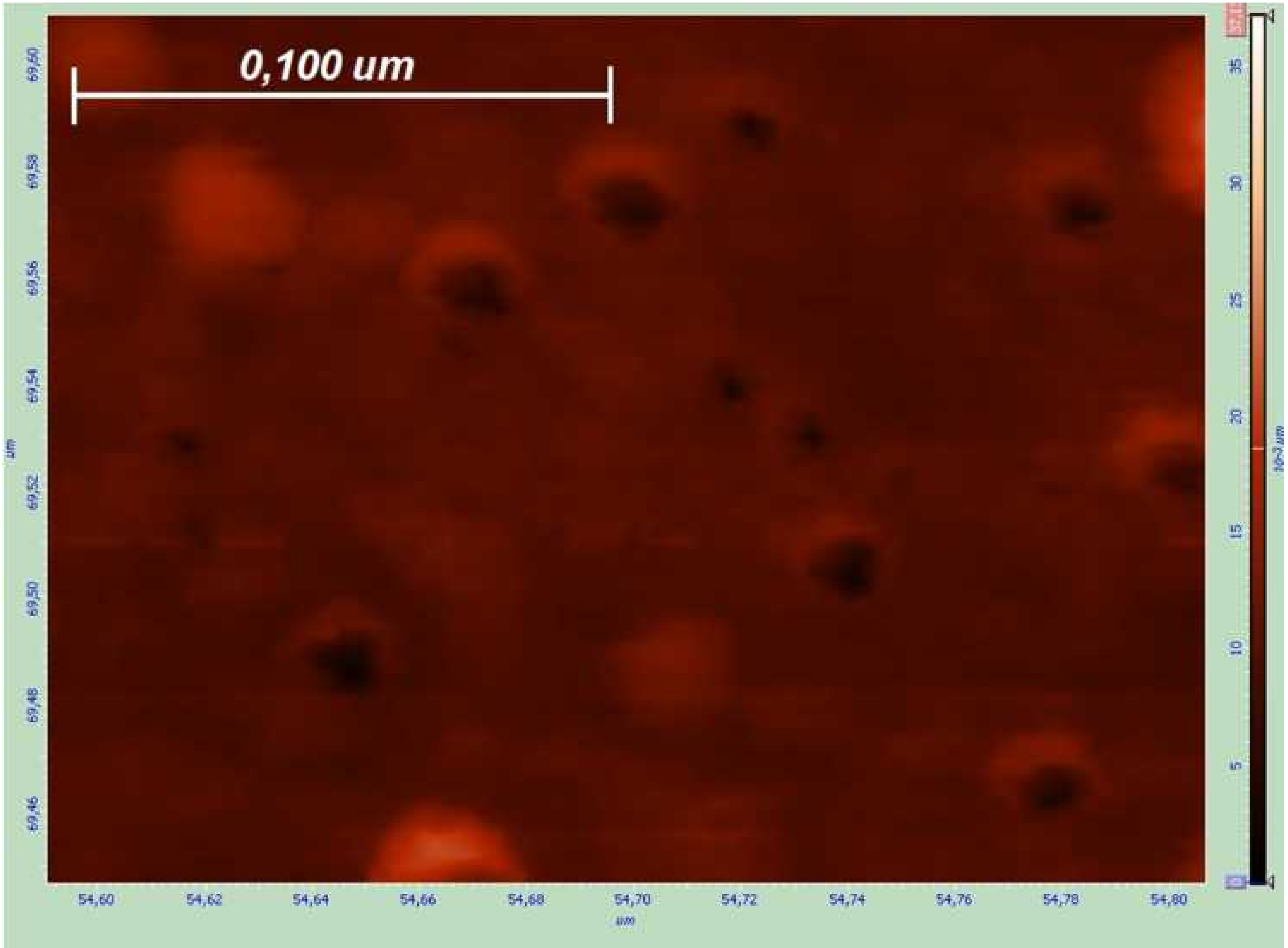
2) Cyclotron ИЦ-100 at Dubna, Russia (167 MeV),

nanohole diameter **D= 10 nm**

3) Helium ion microscope ORION at SPbSU (Peterhof, Russia),

nanohole diameter (assessment) **D= 2 nm**

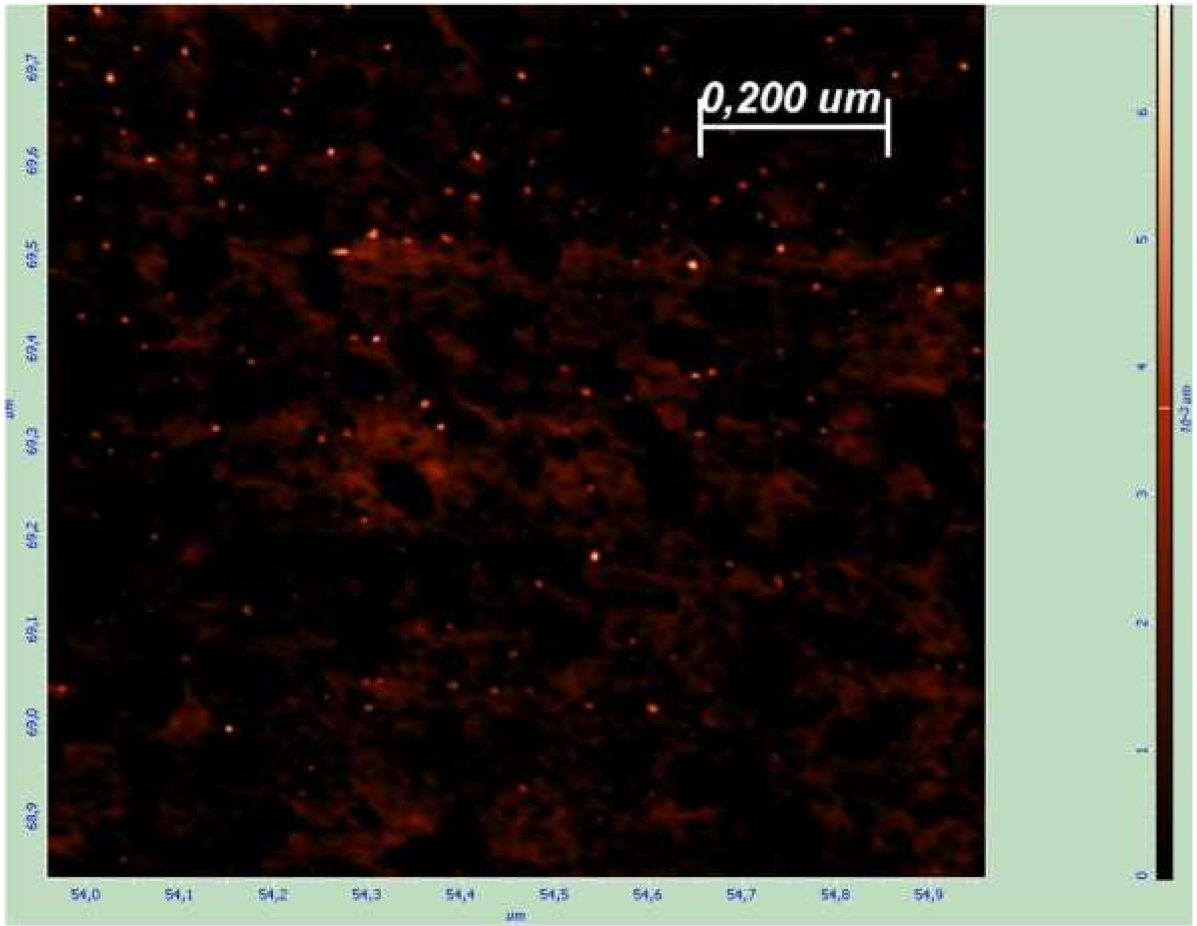
AFM image, area 0.2µm x 0.2µm, direct contrast



D =10 nm

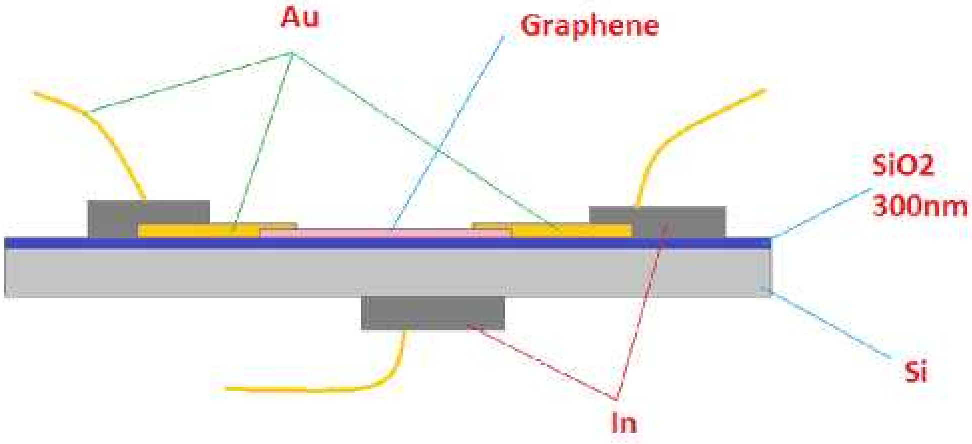
NT MDT: A.S. Kalinin and V.A. Bykov

AFM image, area 1µm x 1µm, reverse contrast



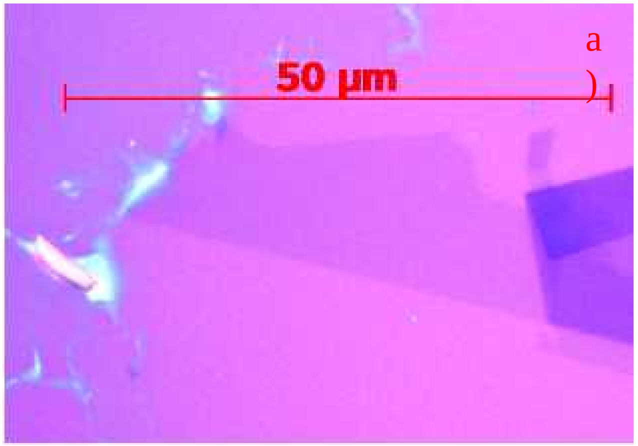
c = 3*10^{9} def/cm^{-2}

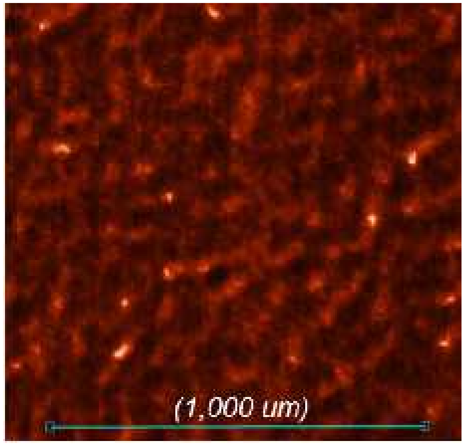
Back-gate FET-structure based on perforated graphene

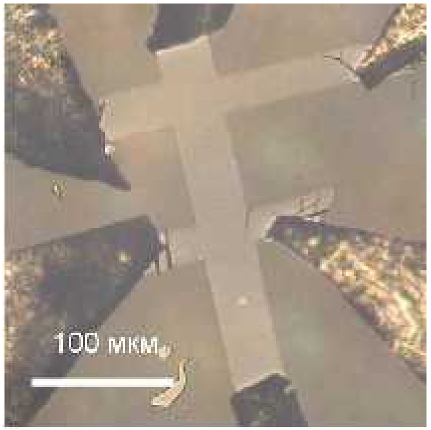


Nano-perforated graphene

1) Irradiation with heavy ions: D=10 nm.
2) Irradiation with a focused helium ion beam: D=2 nm.

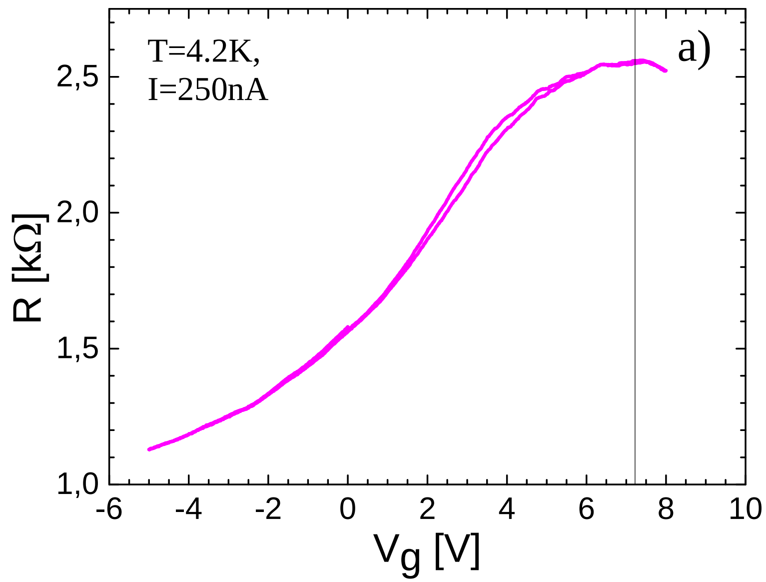


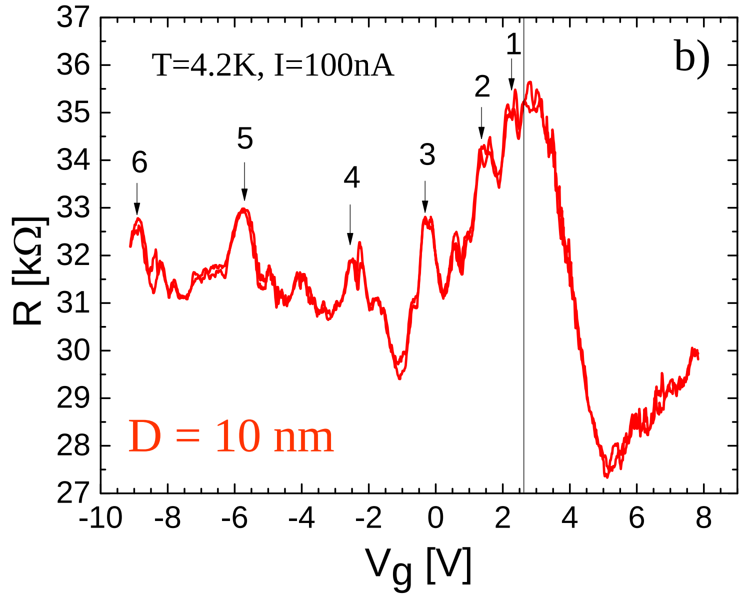


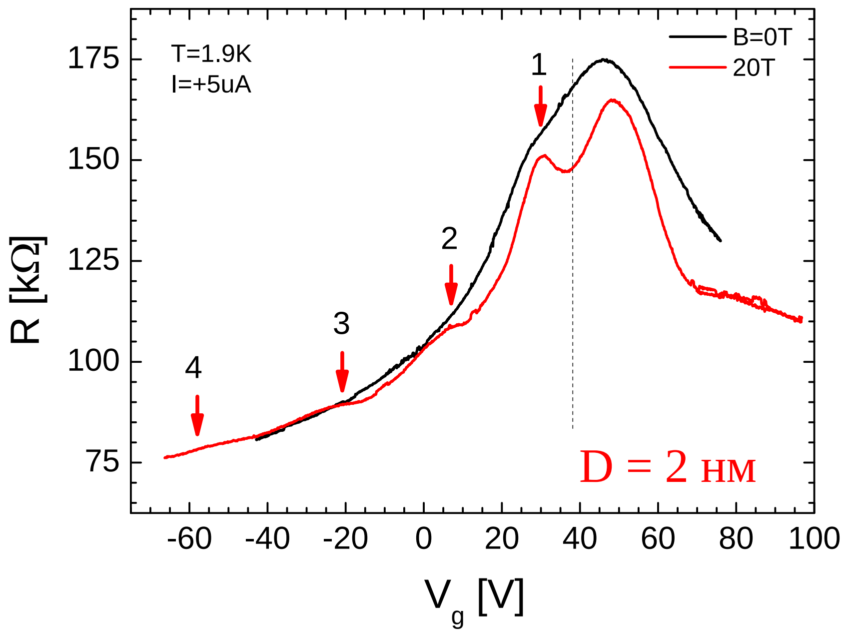


Hall bar configuration of contacts

Resistance oscillations of nano-perforated graphene with gate voltage (w/o magnetic field)



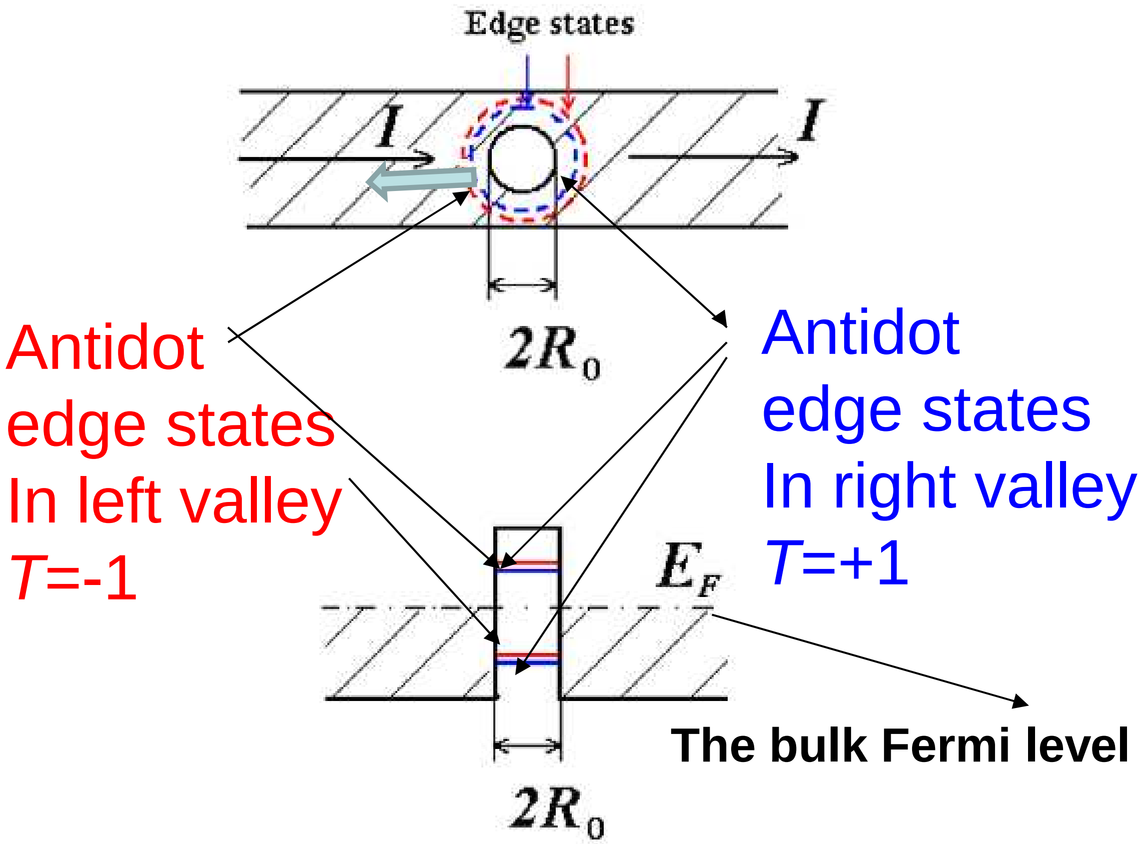


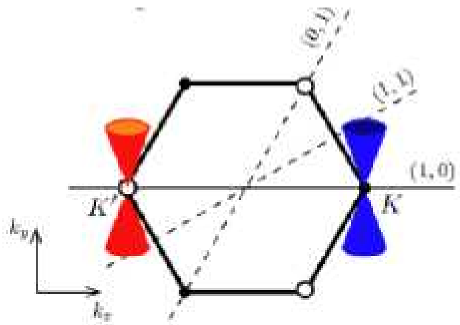


Yu.I. Latyshev, A.P. Orlov, A.V. Frolov, V.A. Volkov, I.V. Zagorodnev, I.A. Skuratov, Yu.V. Petrov, O.F. Vyvenko, D.Yu. Petrov, M. Konzikowski, P. Monceau.

"Orbital Quantization in a System of Edge Dirac Fermions in Nanoperforated Graphene", JETP Lett. 98, 214 (2013)

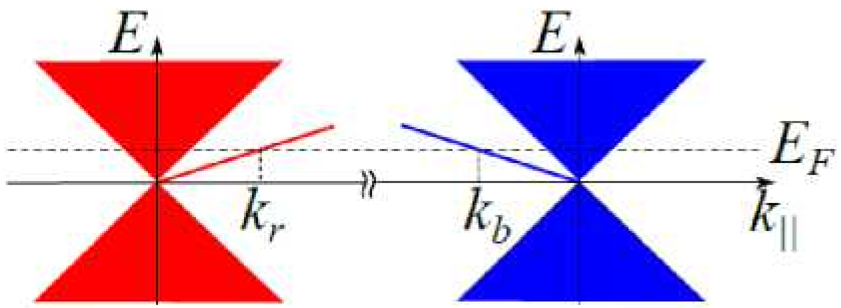
INTERPRETATION:
Resonant scattering of DFs on edge states in antidots leds to resistance oscillations





Perimetric quantization of DF energy near each nanohole

Bulk and edge states of DFs at graphene half-plane:



$v_{edge} = a v_{fermi} \quad a \ll 1$

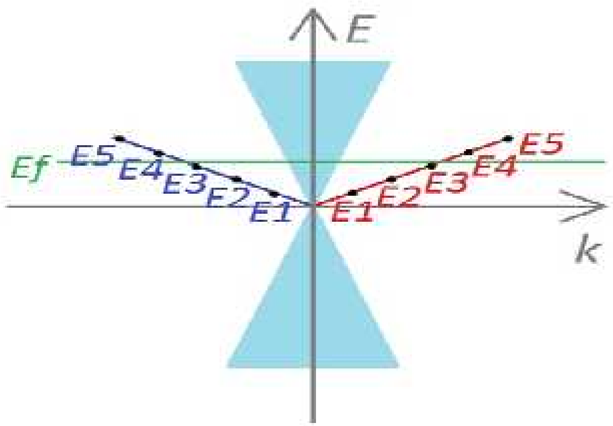
$E_N = \hbar v_{edge} N/R \qquad (N = j \pm ½ = 1, 2, \ldots)$

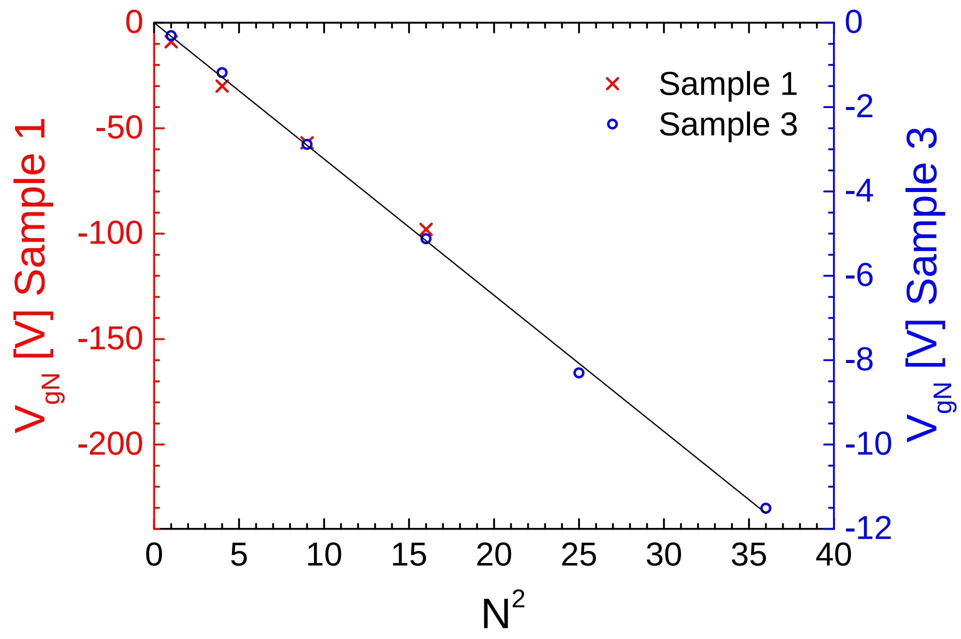
From capacity and DoS in gated graphene:

$E^2{}_{fermi} \sim V gate.$

$$V_{gateN} = (16\, a^2 ed/ \pi\, \varepsilon_0 \varepsilon)\ (N/D)^2$$

Orbital (perimetric) quantization of DFs in edge states around nanohole: $k_{||} = 2® \left(j - ² / 2 \right) / 2® R$





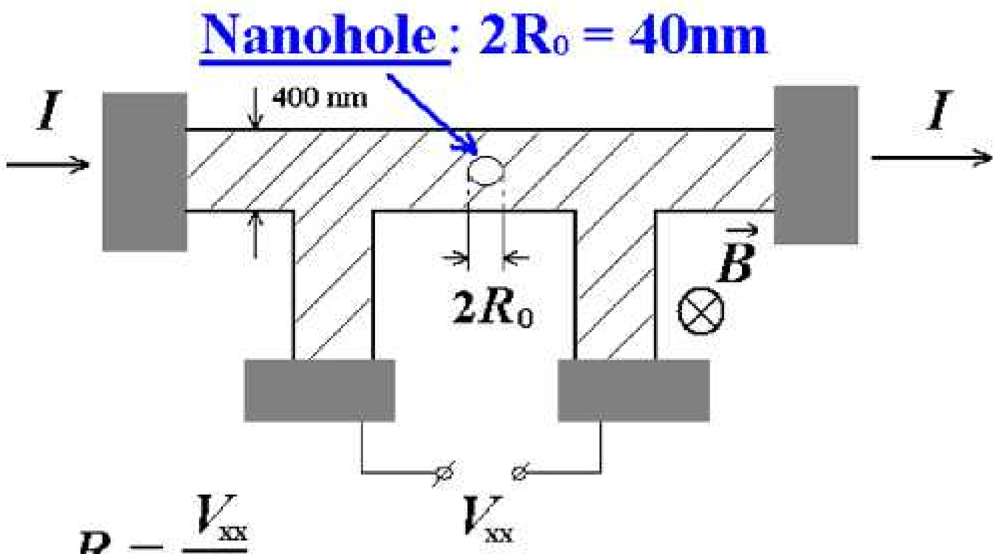
From the slope of the line V_{gN} (N^2)
at D=10 nm (right) and D= 2 nm (left)
we extract edge parameter of the theory: ***a*** **≈ - 0.07**

Geometry of FIB-samples

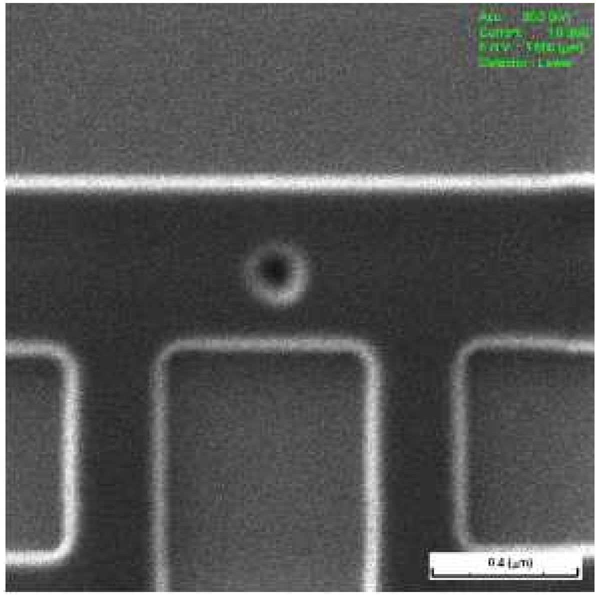
Typical sample made by FIB:

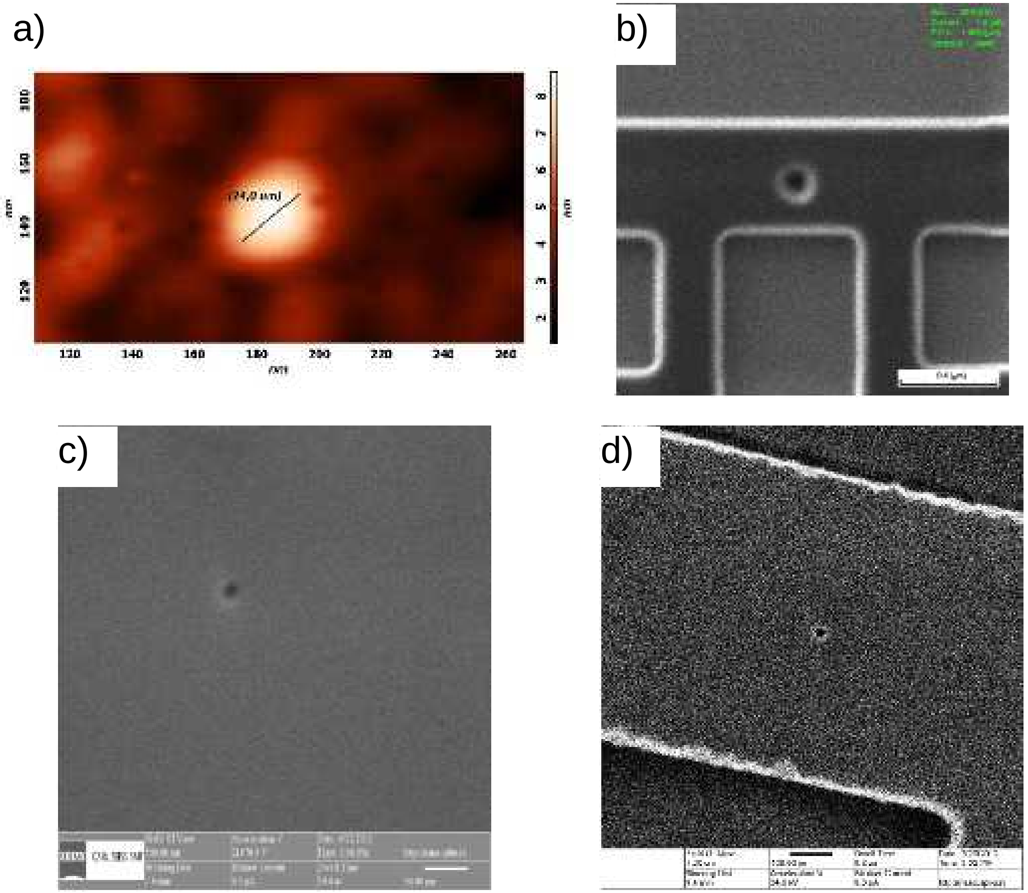
a single nano-hole in nano-thin structure

“graphene-on-graphite”



$$R_{xx} = \frac{V_{xx}}{I}$$

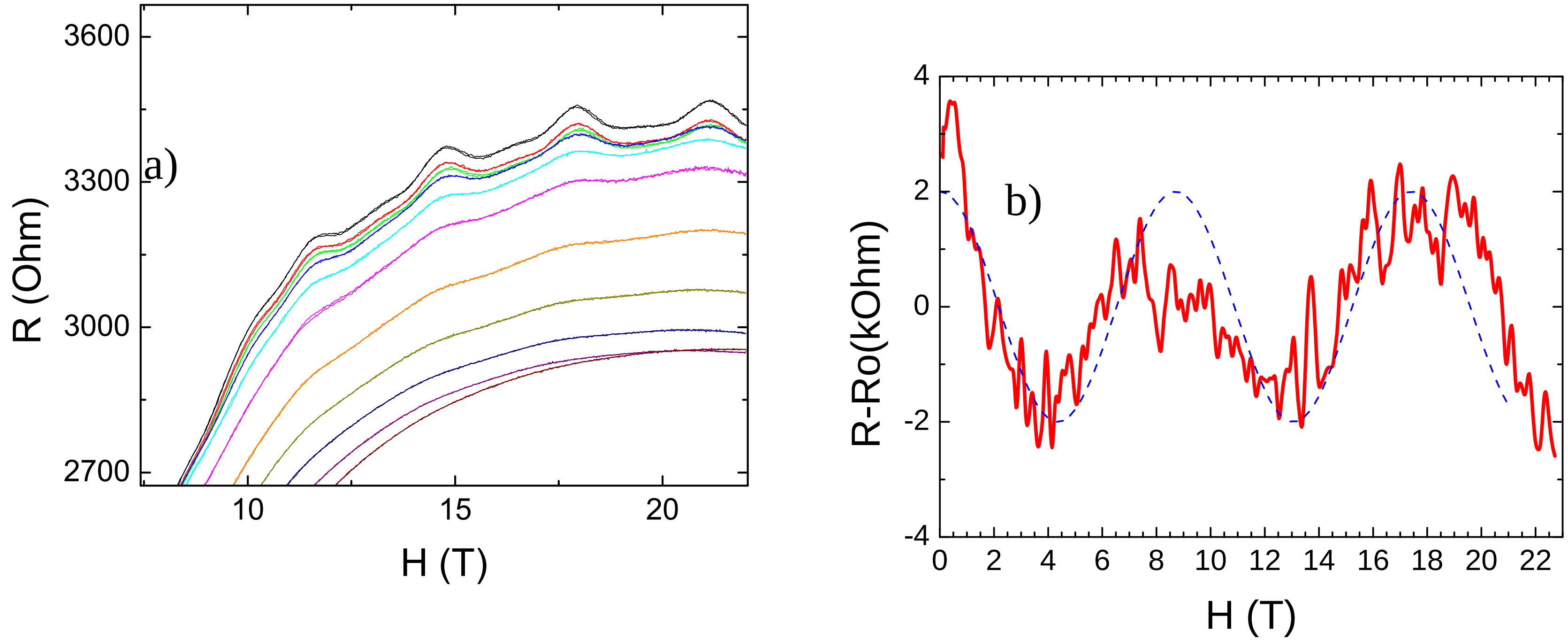




Yu.I. Latyshev et al (2009 - 2014)

Experimental realization of graphene nanohole structures

a, Single holes produced by heavy ion irradiation (AFM image),
b, by FIB (SEM image) and
c, by helium ion microscope (SHIM image) on graphene (**c)** and thin graphite (**a, b, d**).

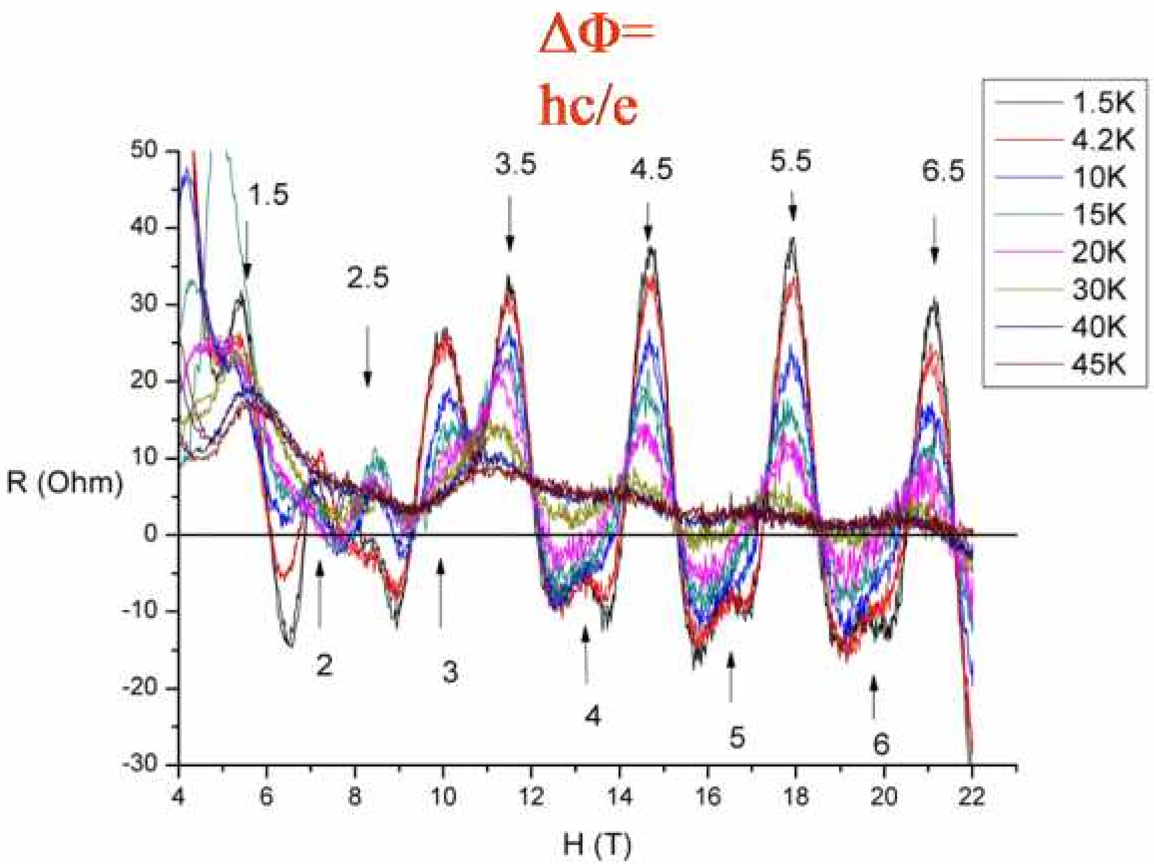


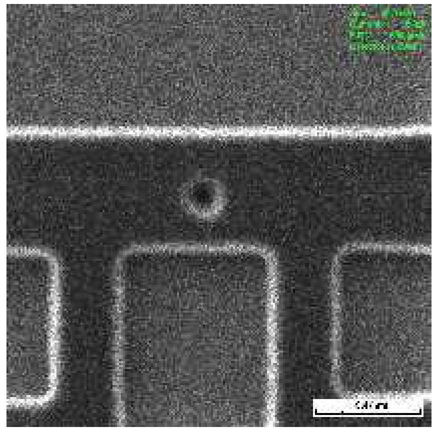
The Aharonov-Bohm resistance magneto-oscillations.

a. Field-periodic resistance oscillations for thin graphite single hole structure with FIB made nanohole with D= 37 nm ,

b, graphene structure with a single nanohole made by helium ion microscope, D=20 nm.

Yu.I. Latyshev et al. Scientific Reports (December 19, 2014)



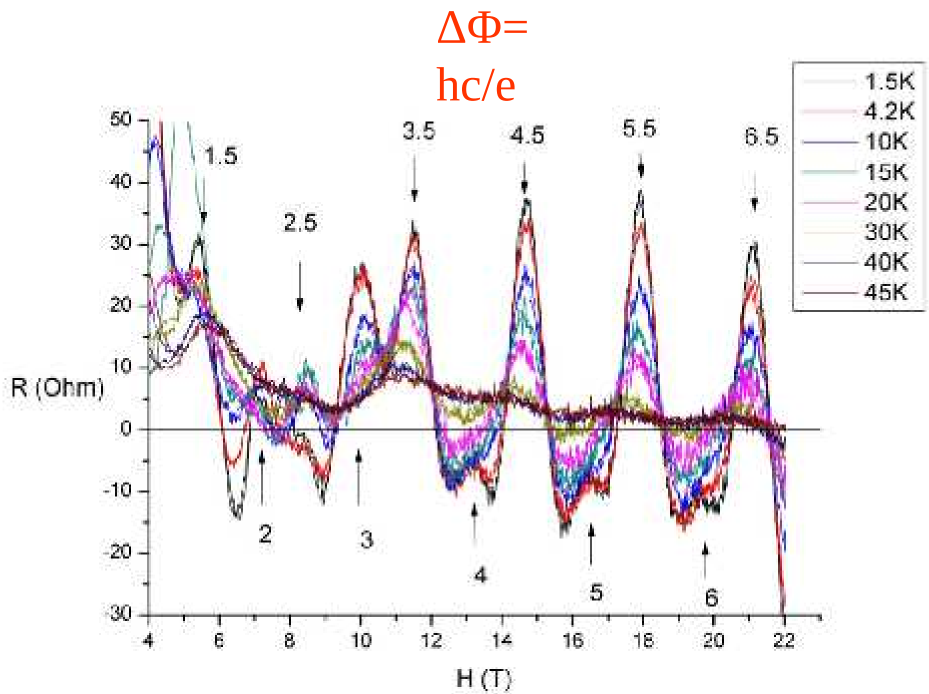


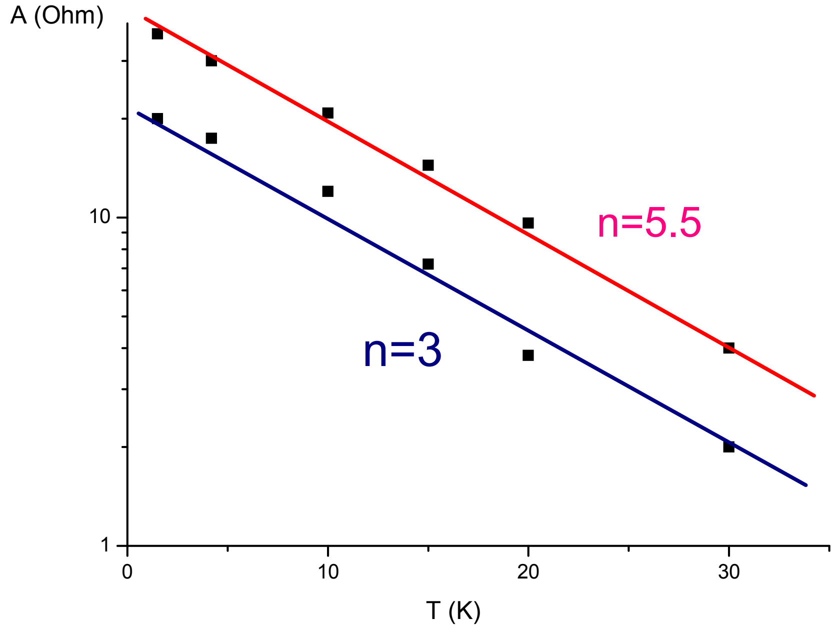
Aharonov-Bohm magneto-oscillations in “graphene-on-graphite” structure with FIB made single nanohole

Oscillating part of the resistance at various temperatures. The downward arrows indicate the main series, whereas the upward arrows mark an additional series.

$\Delta\Phi \approx hc/e = \Phi_0$

Yu.I. Latyshev et al, (SciRep 2014)





Oscillating part of magnetoresistance of structure #2 at various temperatures. Downward arrows show main series corresponding to condition $\Phi_{\downarrow} = n\ \Phi_0 + 1/2$ while upward arrows mark an additional series at $\Phi_{\uparrow} = n\ \Phi_0$

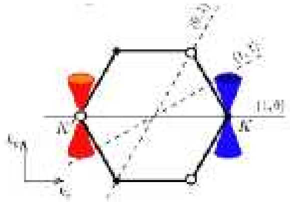
$A / A_0 = \exp(-T/T_0)$

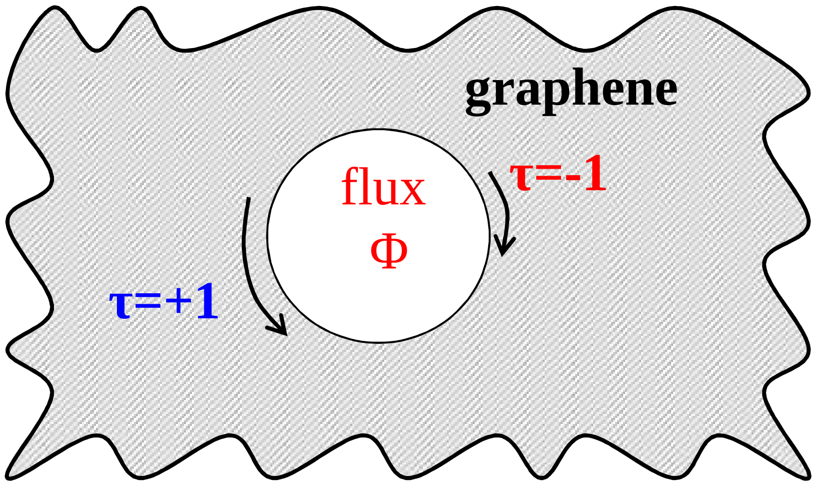
with T_0 = 17 K for D=37 nm

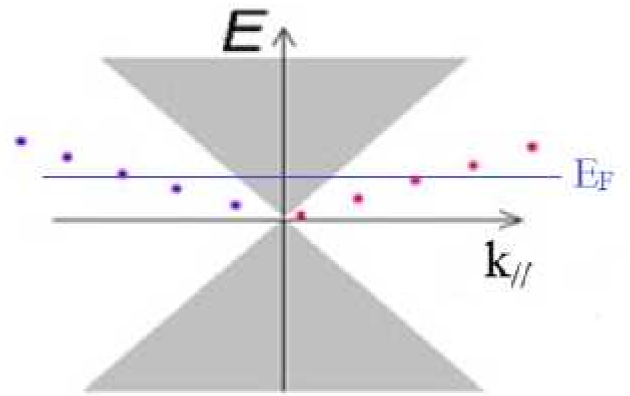
T_0 = 28 K for D=25 nm

Nanohole in graphene: TD states at magnetic field

The edge states rotate around antidot for
both clockwise and counterclockwise circulations







$$E_2 R = {}^2\, 2va(j + \Phi/\Phi_0 - {}^2/2)$$

They experience the **orbital quantization**

$$k_{||} = 2® \left(j - {}^2/2 \right) / 2® R$$

$$j = \pm 1/2, \pm 3/2, \pm 5/2, \ldots$$

Φ/Φ_0– the number of magnetic flux quanta through the antidot.

$\Phi = ® H R_0^2$

SCIENTIFIC REPORTS

OPEN

Transport of Massless Dirac Fermions in Non-topological Type Edge States

SUBJECT AREAS:
ELECTRONIC PROPERTIES AND DEVICES
SURFACES, INTERFACES AND THIN FILMS

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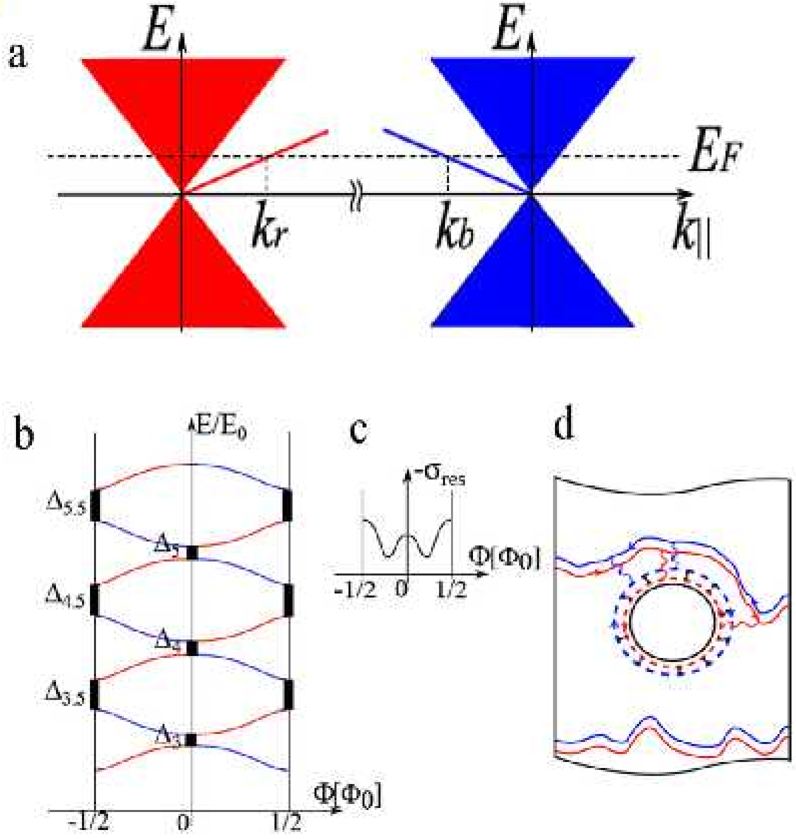
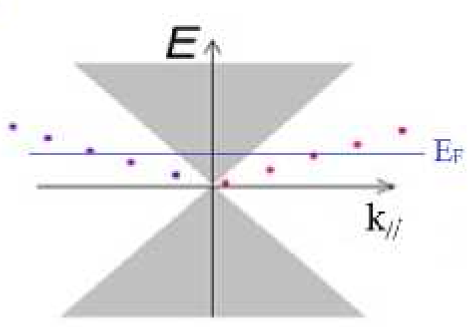
Table 1 | The table includes the following samples: #1 – graphene structure with a hole produced by HIM, #2 – thin graphite structure with a hole produced by FIB, and #3 – thin graphite structure with a hole produced by HIM. The thicknesses of the thin graphite structures were varied in the range of 30-50 nm. The parameter D_{eff} was calculated using Eq. (1)

Sample No	ΔH, T	$D_{geom.}$, nm	$D_{eff.}$, nm	$(D_{geom} - D_{eff})/2$, nm
#1	9.0	20 ± 1	24 ± 0.1	2.0 ± 0.5
#2	3.2	37 ± 2	41 ± 0.2	2.0 ± 1.0
#3	6.0	25 ± 1	30 ± 0.2	2.5 ± 0.5

Tamm-Dirac edge states around the graphene nanohole in magnetic field: Aharonov-Bohm effect in transport



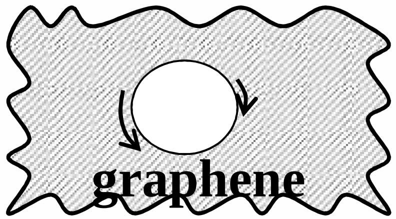


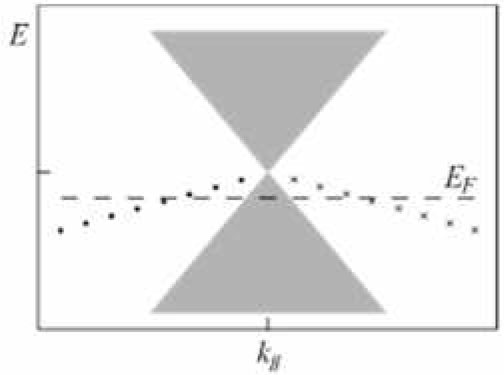
$$\Delta\Phi \approx hc/e = \Phi_0$$

a) *The red and blue rays are the TD states contra-propagating along the graphene semi-plane: in the red valley and in the blue valley.*
b) *Spectrum of TD states in an antidot as a function of the magnetic flux through the antidot area.*
c) *Inter-valley contribution to the conductivity.*
d) *Contra –propagating trajectories of the orbit centres for different valleys for the zero Landau level in a smooth-impurity potential. One of the orbits is close to the antidot and can experience inter-valley back-scattering.*

SUMMARY

- **Using gated structures based on nanoperforated graphene we found orbital quantization of the energy of edge Dirac fermions cycling *around each nanohole* even in zero magnetic field.**
- **The Aharonov-Bohm magneto-oscillations of resistance are found on graphene samples that contain *a single nanohole*.**
  The effect is explained by the conductivity of the Dirac fermions in the edge states cycling *around the nanohole.*





- **The results prove**

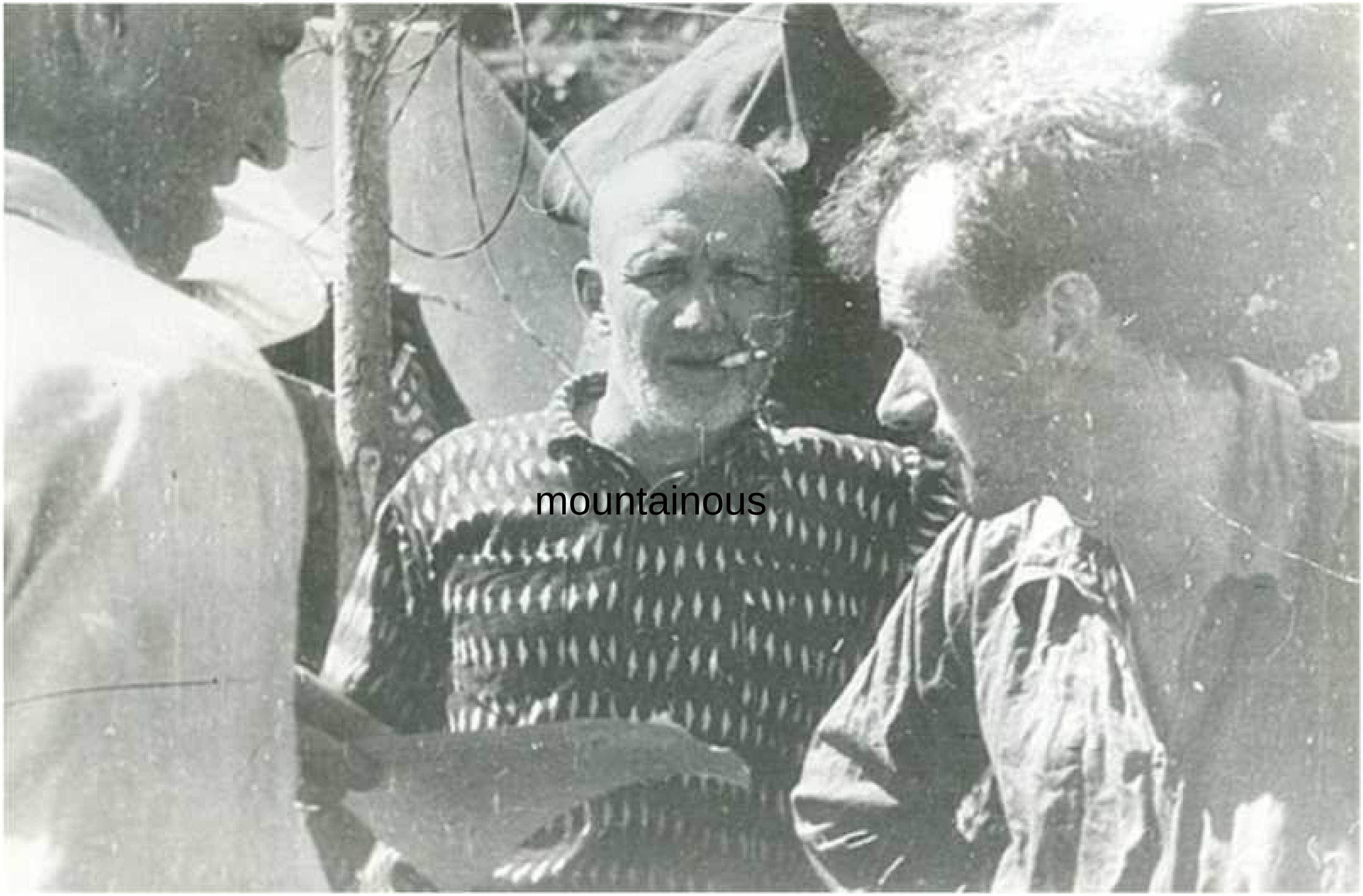
1) the existence and

2) conducting nature

of Tamm-Dirac edge states in graphene.

- **The results demonstrate the deep connection between topological and non-topological edge states in 2D systems of massless Dirac fermions.**
- So, there are two sorts of co-existing and interacting DFs in perforated graphene, **fast and slow DFs : fast bulk massless DFs, and**

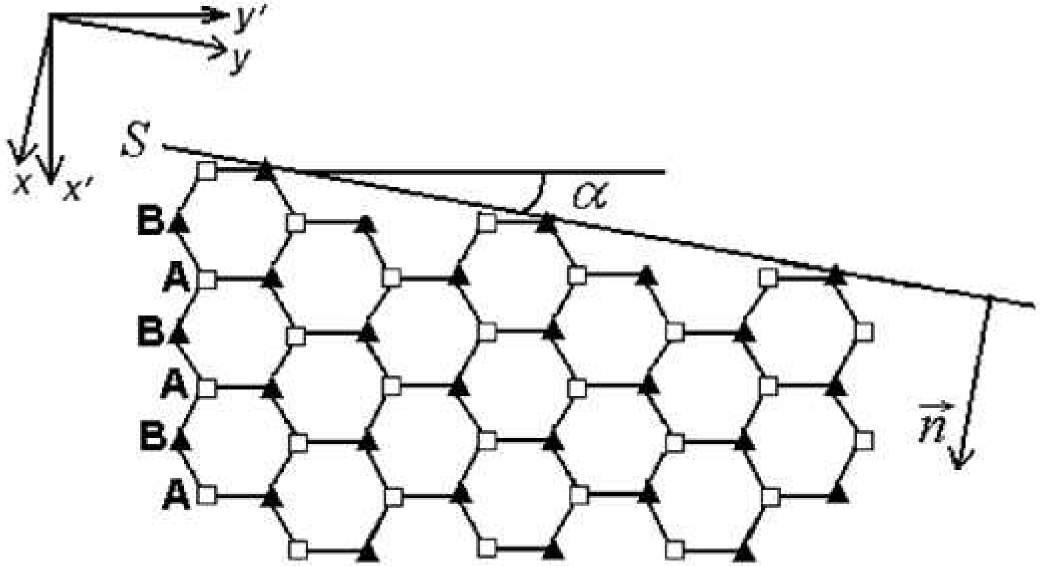
slow (v = 0.05-0.07 of bulk velocity) rotated (typically f ~ 1THz) quasi-localized (localisation length: 2 nm) DFs in Tamm-Dirac states of p-type.



I.Tamm and P. Dirac in mountainous Tamm-Dirac state,
Elbrus (Kaukasus), 1936.

Theoretical attachments

Edge states in Gr: What known



Nearest neighbour tight-binding model

Nakada, Fujita et al (1996), Brey, Fertig (2006)

Results: simple BCs
ESs for zigzag edge: dispersionless Tamm band
ESs for armchair edge: no Tamm states

Next nearest neighbours tight-binding model

(Peres, Guinea, Castro Neto 2006)

Result: finite dispersion of Tamm band at zigzag edge

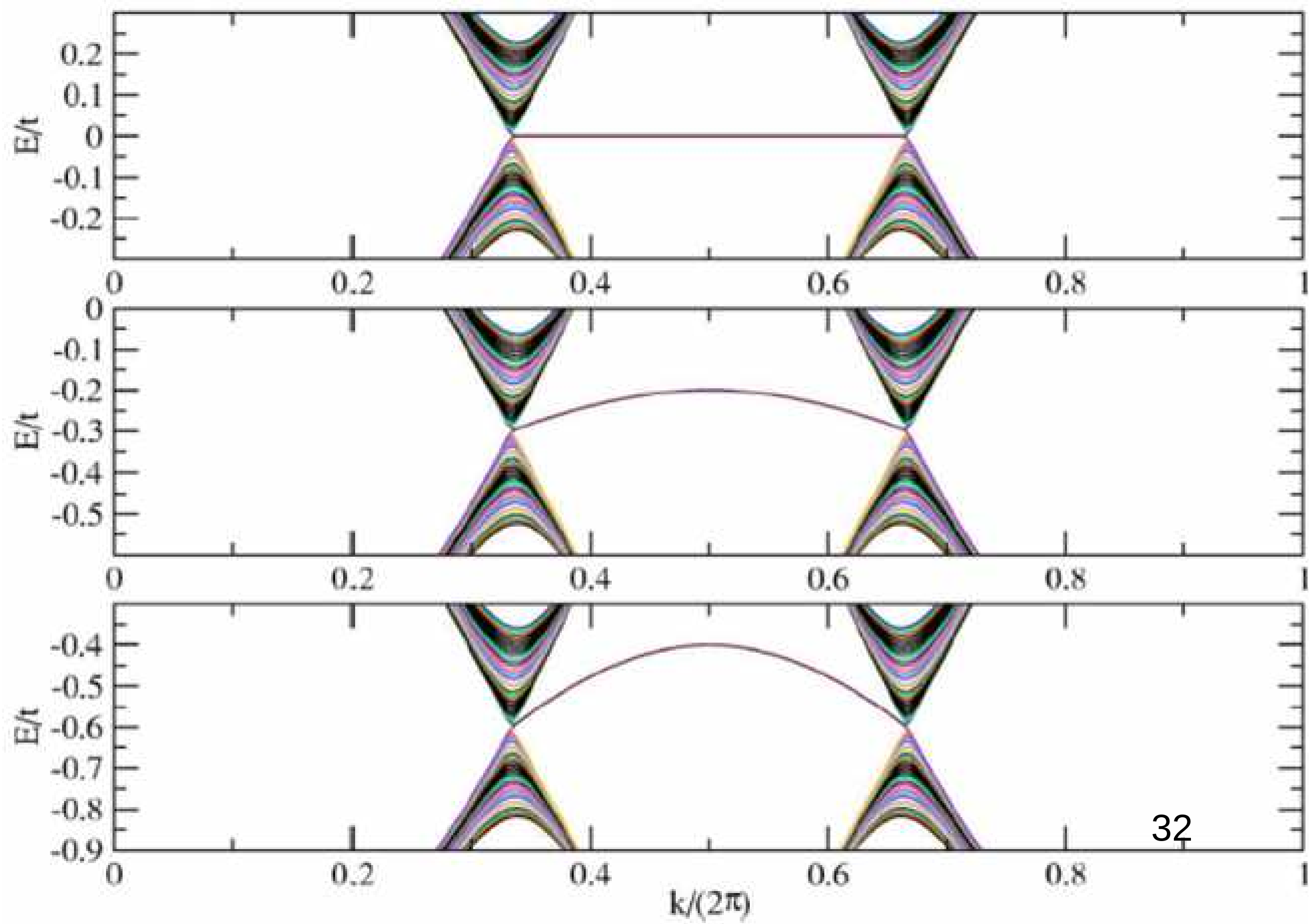
Infinite-mass" BCs : Berry, Mondragon (1987)

Result: very simple BC, no ESs.

Edge states in Gr-nanoribbon of zigzag type

t – tight binding (nearest neighbor approximation)
t’ - next-nearest approximation

top: t’=0;
middle: t’=−0.1t;
bottom: t’=−0.2t

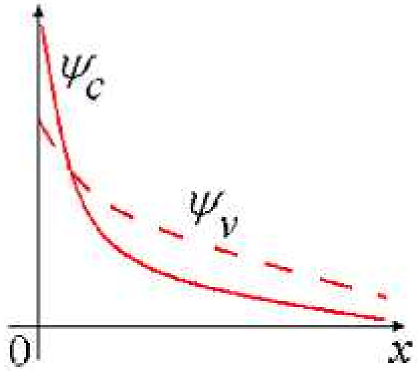


Peres et al., 2006

Envelope Functions and Boundary Problem

$$\cdot\cdot_{micro} = \sum_n u_{n0}(\vec{r}) \cdot {}_n(\vec{r})$$

$$\begin{cases} H\cdot = E\cdot \\ \mathrm{d}\cdot\,|_S = 0 \end{cases}$$



envelope functions column

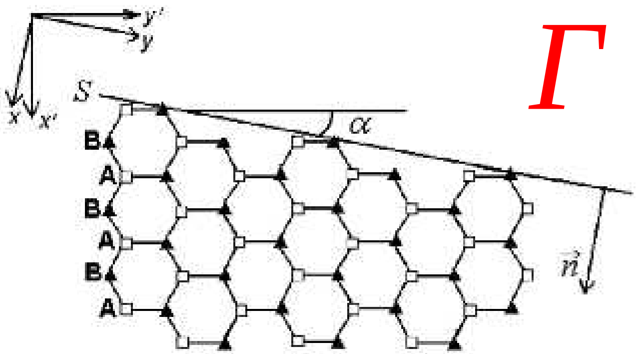
$$\cdot\cdot_{micro} \rightarrow \begin{pmatrix} \cdot_1(\vec{r}) \\ \vdots \\ \cdot_n(\vec{r}) \\ \vdots \end{pmatrix}$$

H - many-band effective-mass Hamiltonian

$$\mathrm{H}_W = c\pm\vec{p}$$

Γ - boundary operator.

$$\Gamma = ?$$



V.Volkov, T.Pinsker (1981)
B.Volkov, O.Pankratov (1985)
M.Berry, R. Mondragon (1987)
E. McCann, V. Fal'ko (2004)
A.Akhmerov, C. Beenakker (2008)
V.Volkov, I. Zagorodnev (2009)

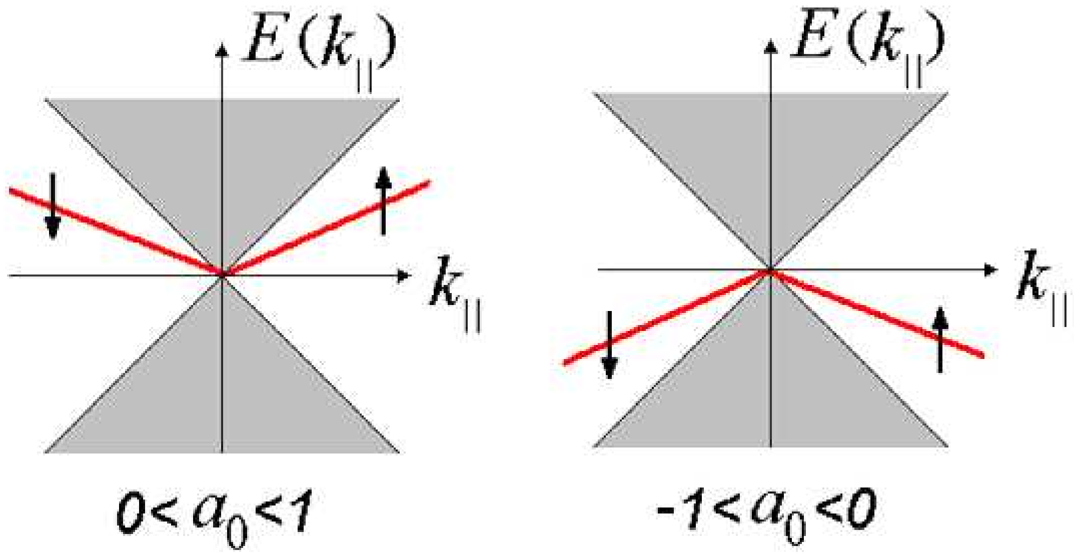
The Tamm-Dirac states on graphene semi-plane

(V.V., I. Zagorodnev, 2009)

$$H_{Dirac} = \begin{pmatrix} \pm \vec{\sigma}\vec{p} & mc^2 \\ mc^2 & -\pm \vec{\sigma}\vec{p} \end{pmatrix} \rightarrow \begin{pmatrix} H_W & 0 \\ 0 & -H_W \end{pmatrix} \qquad 2mc^2 \rightarrow 0$$

2x2 Weyl: $H_W = \pm \vec{\sigma}\vec{p}$

Tamm-Dirac spectra:



Boundary conditions:

$$\left(\cdot_{\,c} + i e^{i a_0 \pm \vec{\sigma}\vec{n}} \cdot_{\,v} \right)\Big|_S = 0$$

$$E = \frac{2a_0}{a_0^2 + 1} k_y,$$

$$where\ k_y \left(1 - a_0^2\right) > 0$$

For the antidot R_0 in quasiclassics: $k_y = n/R_0$