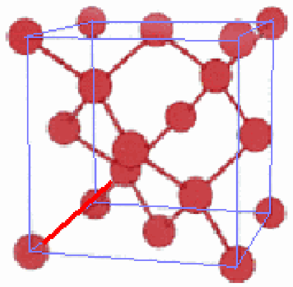
C_{60}，碳纳米管，石墨烯物性与器件研究

物理所 吕 力

2009年12月17日 北大

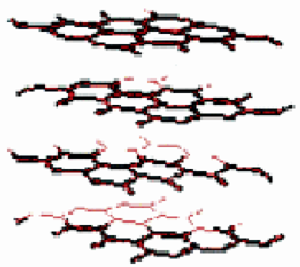
碳的一家

sp^3 sp^2



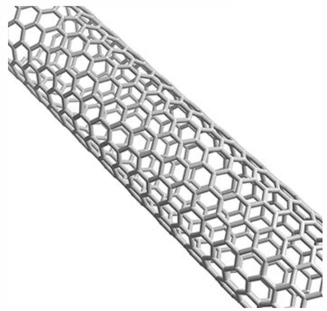
金刚石

3D



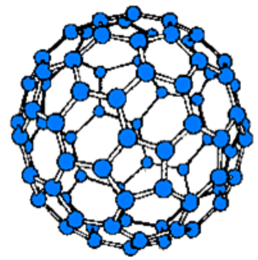
石墨

2D



碳纳米管

1D



C_{60}

0D

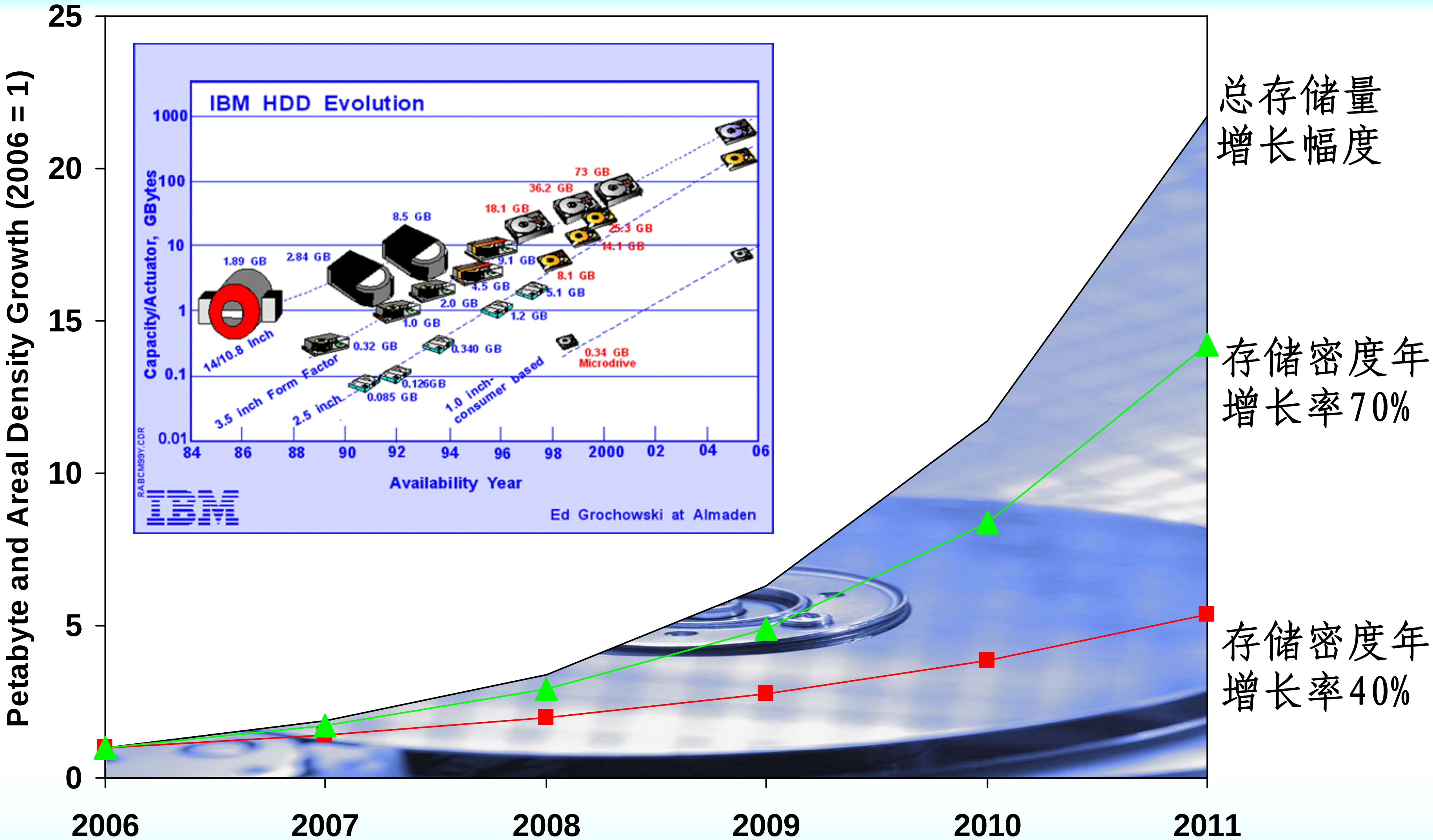
为什么对这些材料的物性感兴趣?

- 丰度：在自然界广泛存在
- 物理：是低维物理研究的理想对象，具有丰富多彩的物性
- 器件：可能用于构建更小、更快、更好的电子学器件

器件

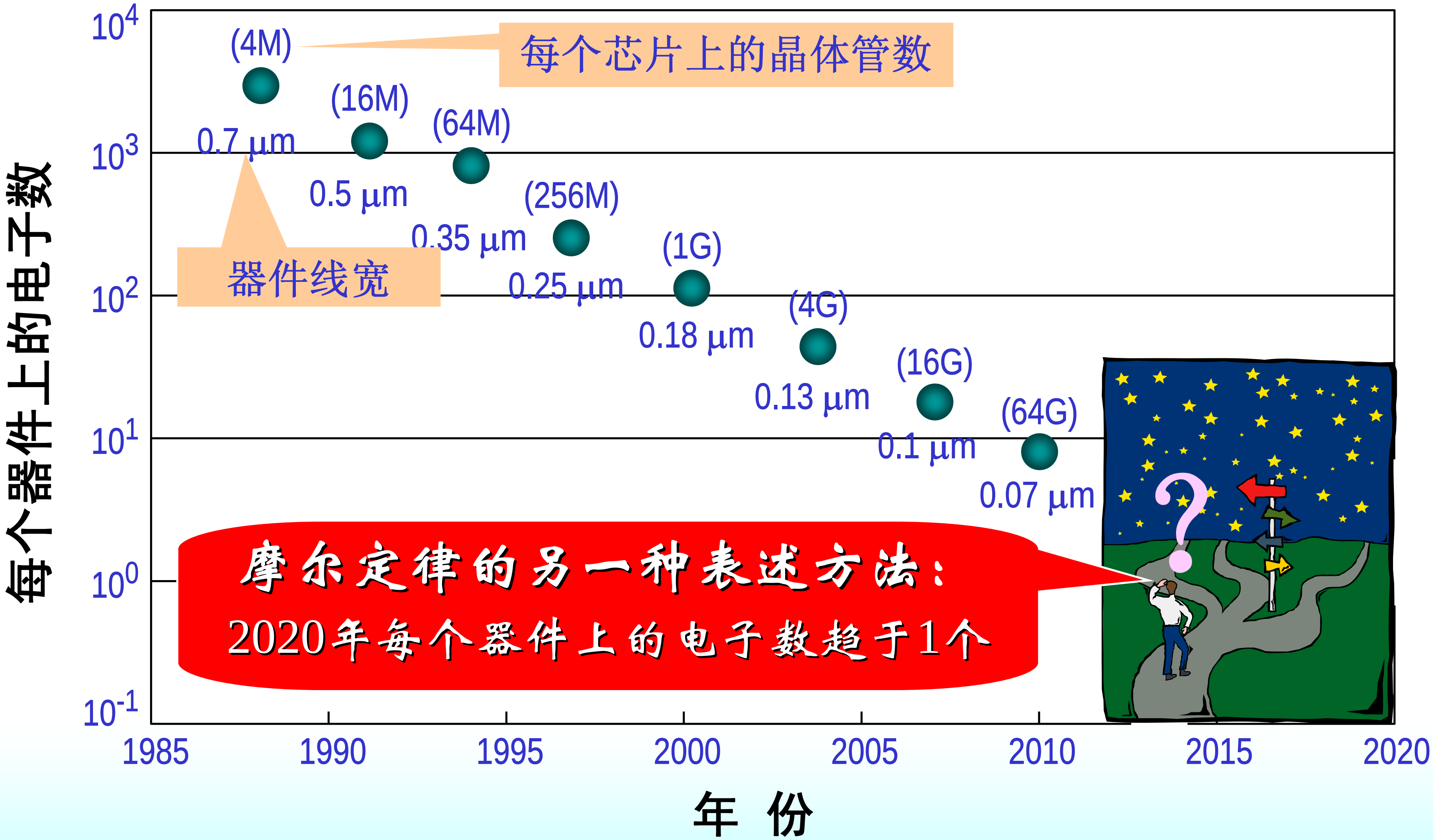
- 目前的信息技术所面临的困境
- 量子信息技术带来的希望
- 石墨烯能否用来做自旋量子比特?

五年内世界总信息存储需求量骤增20倍



Average Petabyte Growth Year on Year From 1995 to 2005 was > 85%, Seagate Analyst & Investor Meeting June 2006

器件越来越小，摩尔定律趋于极限！



解决方案

从物理学基本原理出发，解决下一代信息技术中的核心科学问题

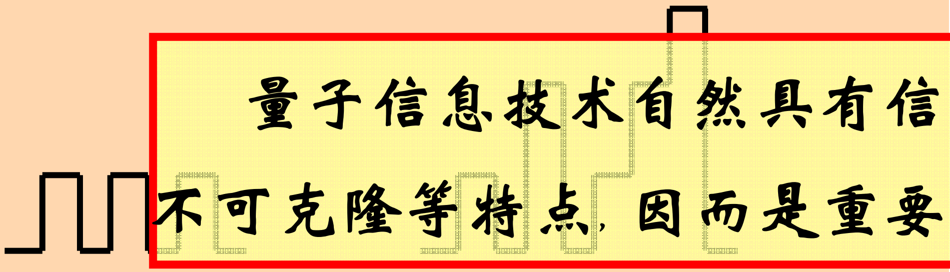
信息载体的物理对应：

- 经典/半经典/量子
- 群/系综/单个

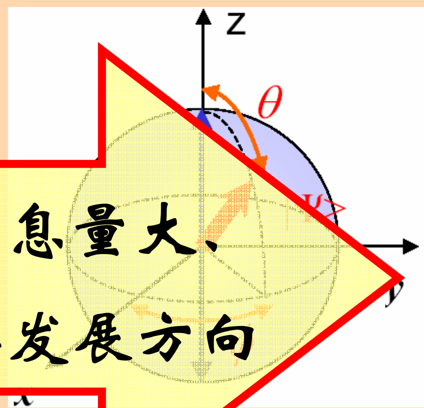
- 电子（电荷、自旋）
- 核自旋
- 原子，分子，离子，…
- 各种人造原子（人工量子结构）
- 各种量子激元（光子， 激子，NVC，…）

因为信息需要物理载体，所以突破的希望寄托于物理学基础研究

信息载体的取值空间：



二进制　　多进制



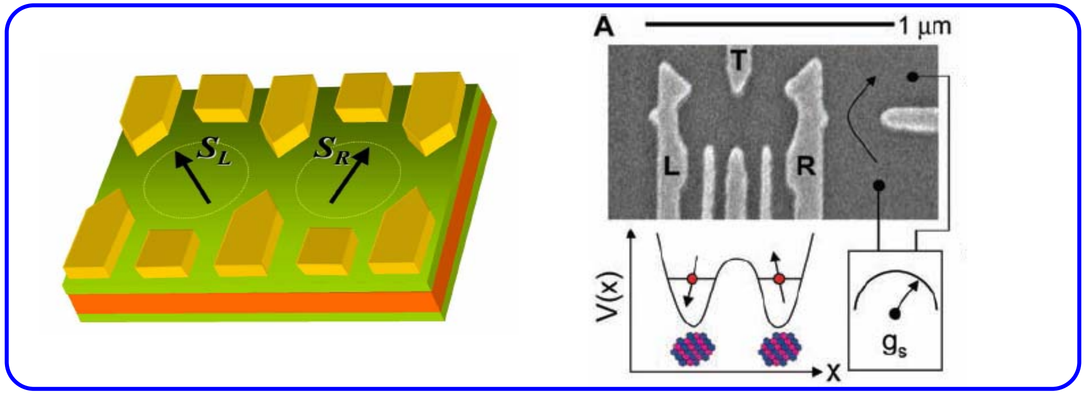
Bloch球

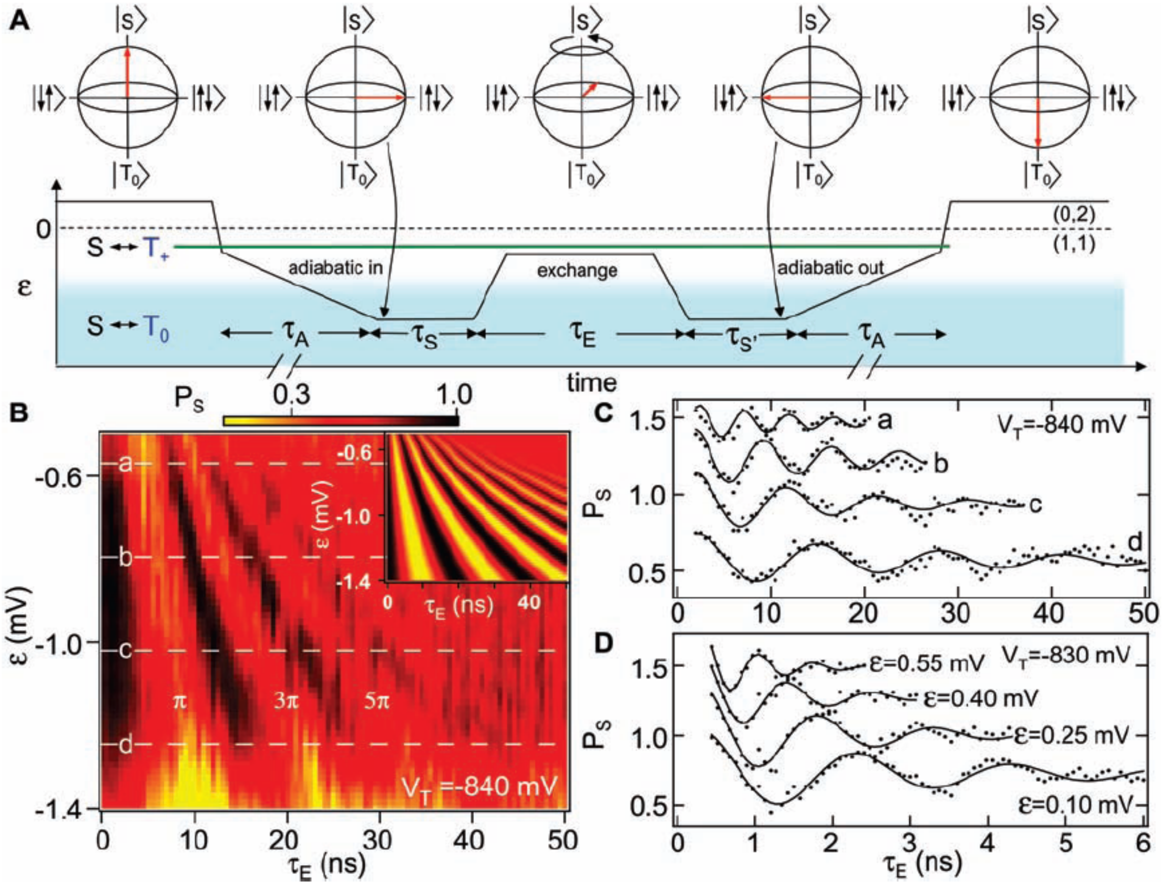
量子平行计算

量子信息技术自然具有信息量大、不可克隆等特点，因而是重要发展方向

$|\Psi|$　　$|\Psi|e^{i\theta}$

Spin qubits in semiconducting quantum dots systems





AlGaAs/GaAs:

Very short decoherence time, due to:

- Hyperfine interaction
- Spin-orbital interaction

Other materials ?

- Si or Si/Ge system
- Graphene
- Carbon nanotubes

- Marcus group
- Vandersypen group
- … … …

For Graphene:

- SO coupling is weak :

  $2\Delta_{so}$ ~ 1 μeV (10 mK) (Y.G. Yao, et al, PRB'06)

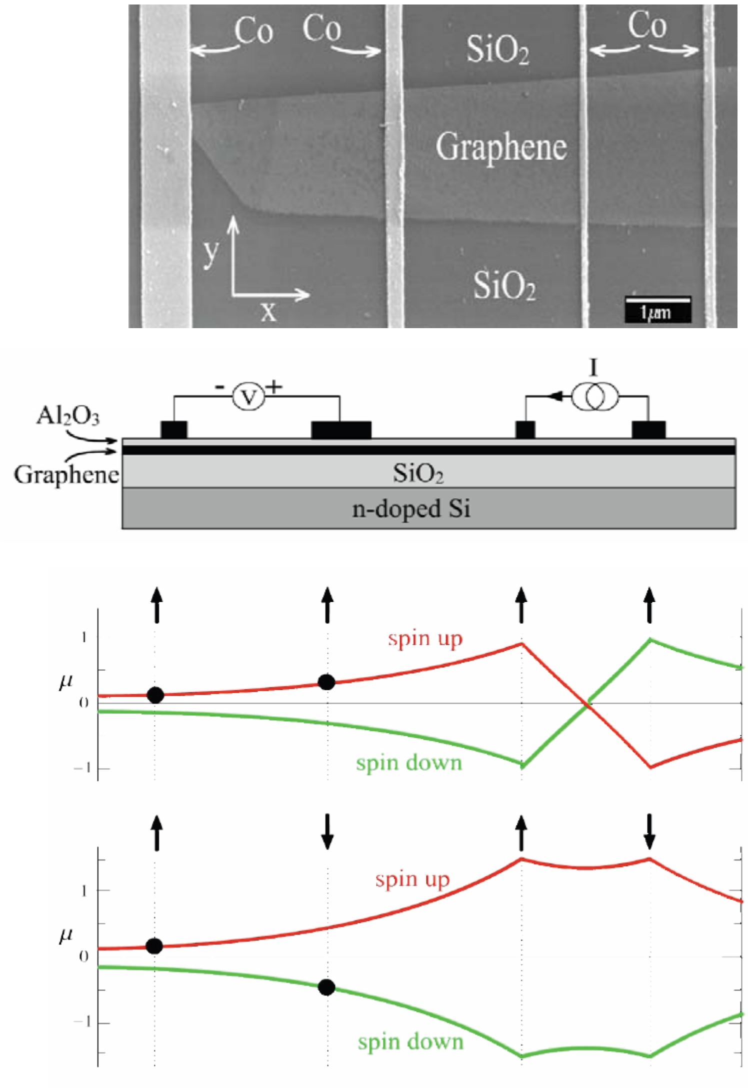
- Hyperfine interaction is weak:

  ^{13}C (spin ½) abundance ~1%

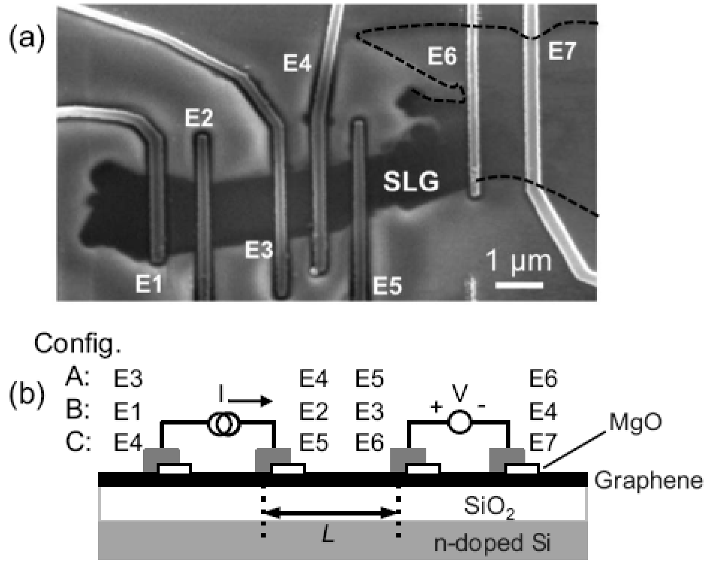
Longer T_1 and T_2 ?

Answer: No.

Spin polarized electron injection and non-local detection



van Wees group



C. N. Lau group

	van Wees	C. N. Lau
τ_{SO}	~ 150 ps	~ 84 ps
l_{SO}	~ 1.6-2.0 μm	~ 1.5 μm

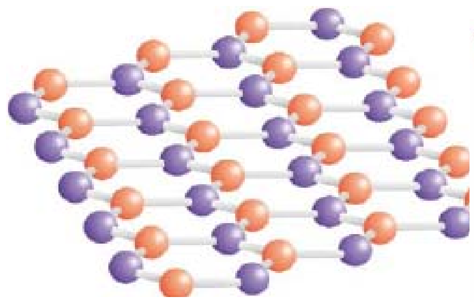
What is the cause of spin decoherence in graphene ?

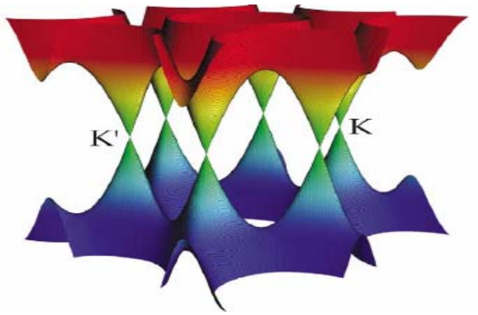
Graphene

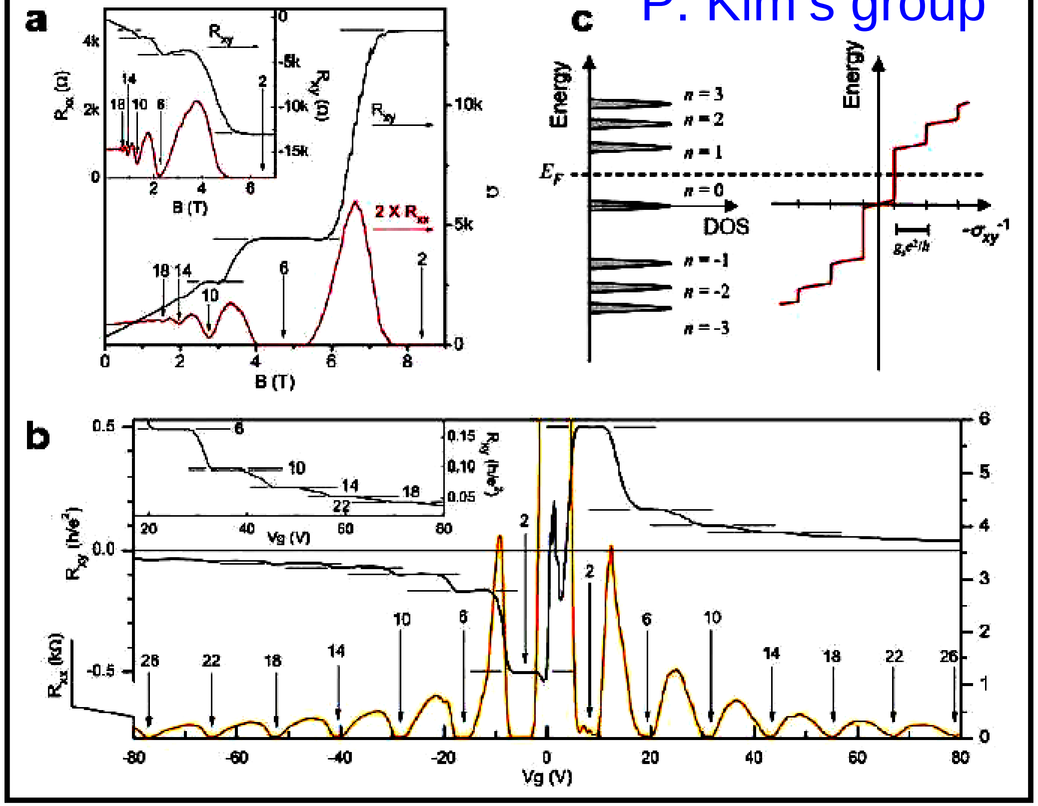
Novel Properties:

$$R_{xy}^{-1} = g_s (N + \frac{1}{2}) \frac{e^2}{h}$$

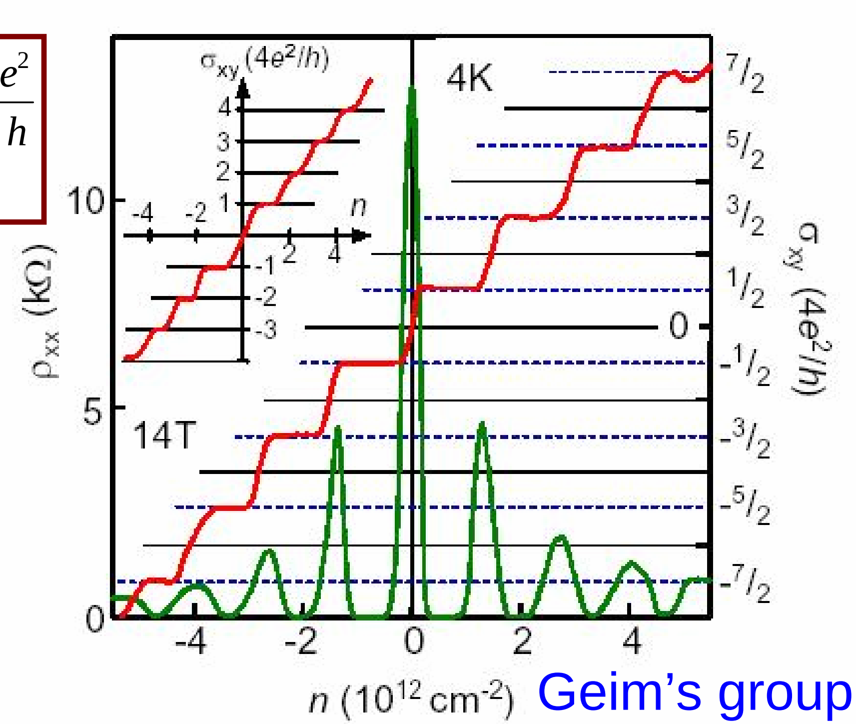
$$g_s = 4$$







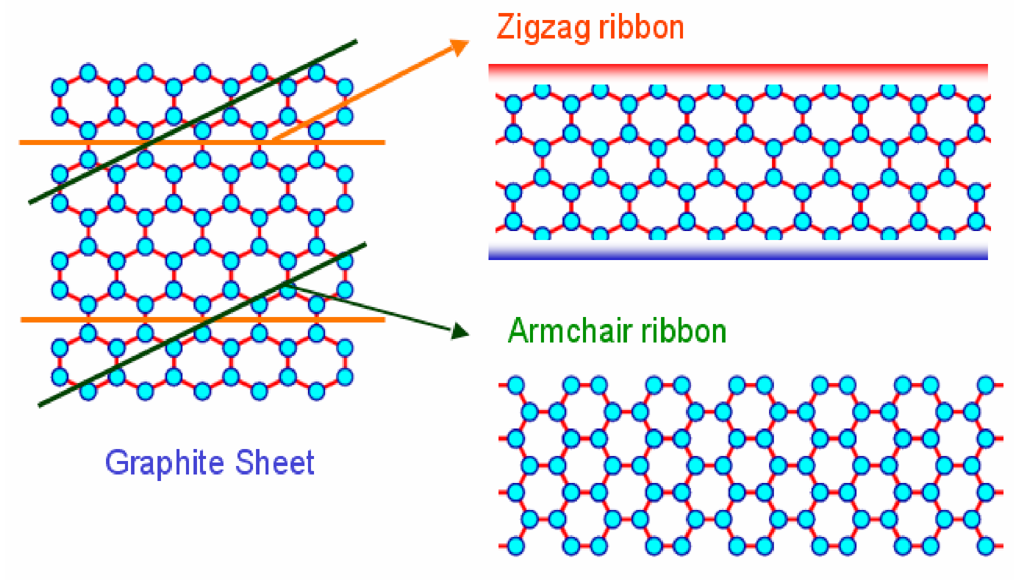
P. Kim's group

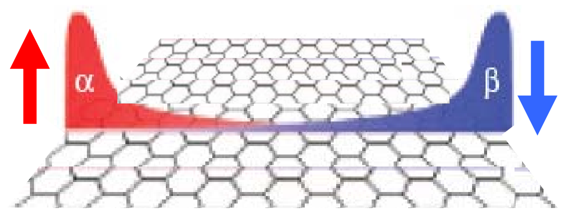


Geim's group

- Two sublattices
- Pseudospin
- Four-fold degeneracy (valley x 2 + spin x 2)
- Berry phase
- Half integer QHE
- Klein Tunneling
- … … …

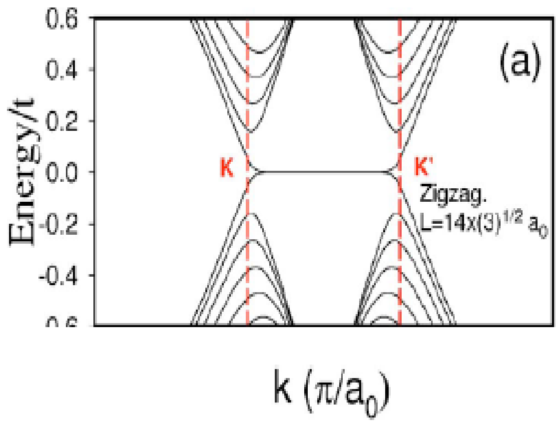
Edges of graphene nanoribbon (GNR)

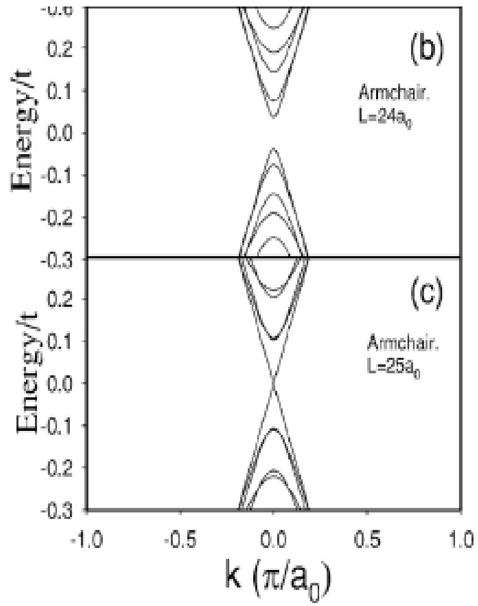


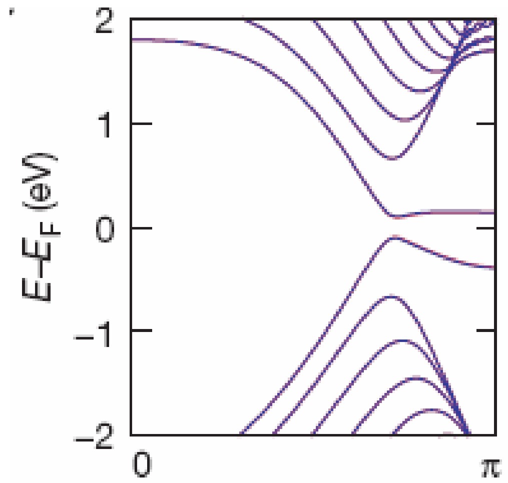


Theoretical prediction:

- Zigzag GNR has spin polarized edge states.
  W.Y. Son et al., Nature'06
  L. Pisani et al., PRB'07
- Same for bilayer GNR.
  E.V. Castro et al., PRL'08





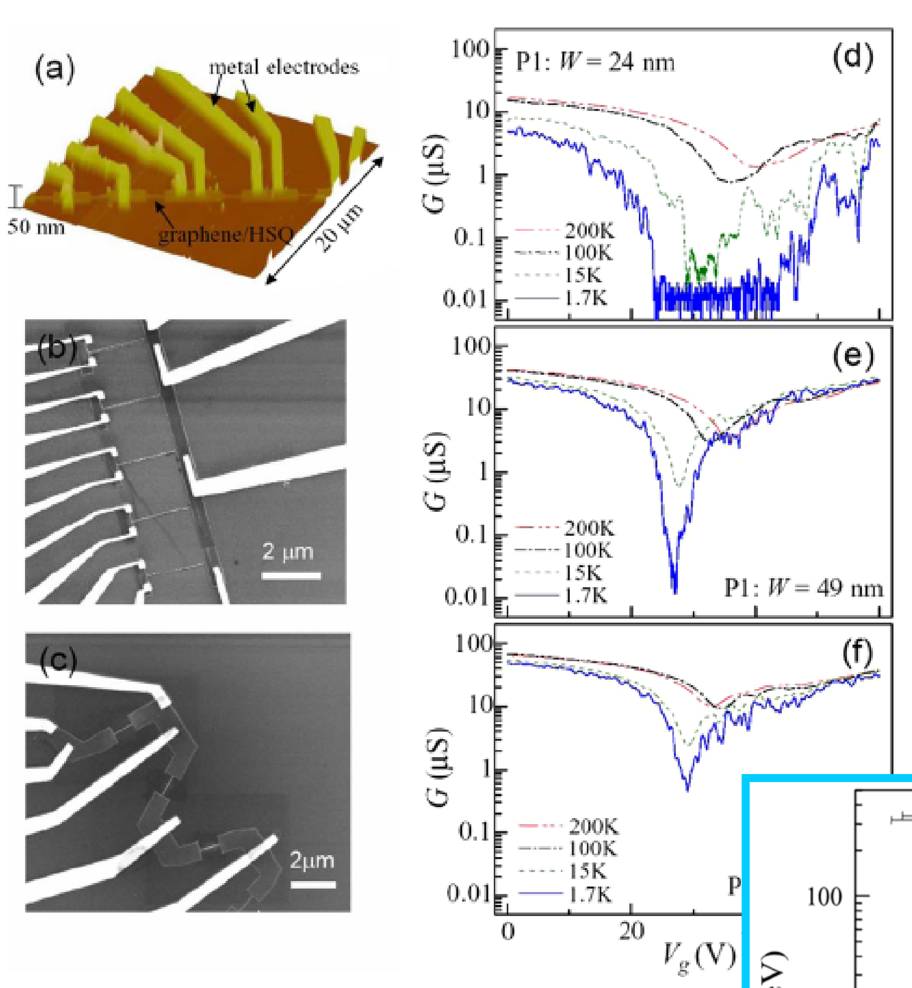


- zig-zag are gapless (edge modes)
- armchairs: gapped or gapless

W = 3N, 3N+2 (gapped) W = 3N+1 (gapless)

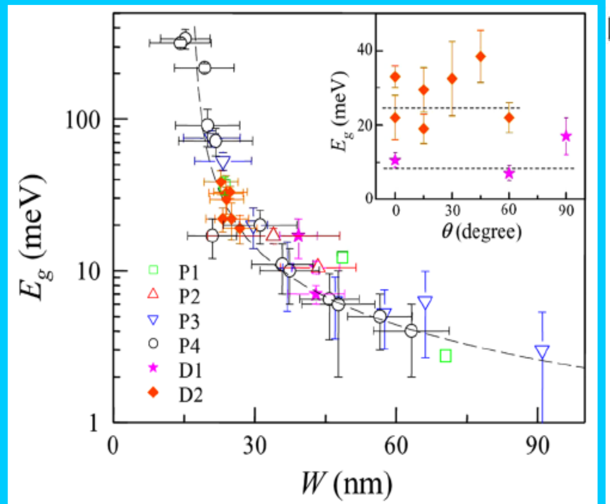
Ezawa, PRB 2006; Brey-Fertig, PRB 2006

Experiments on GNR

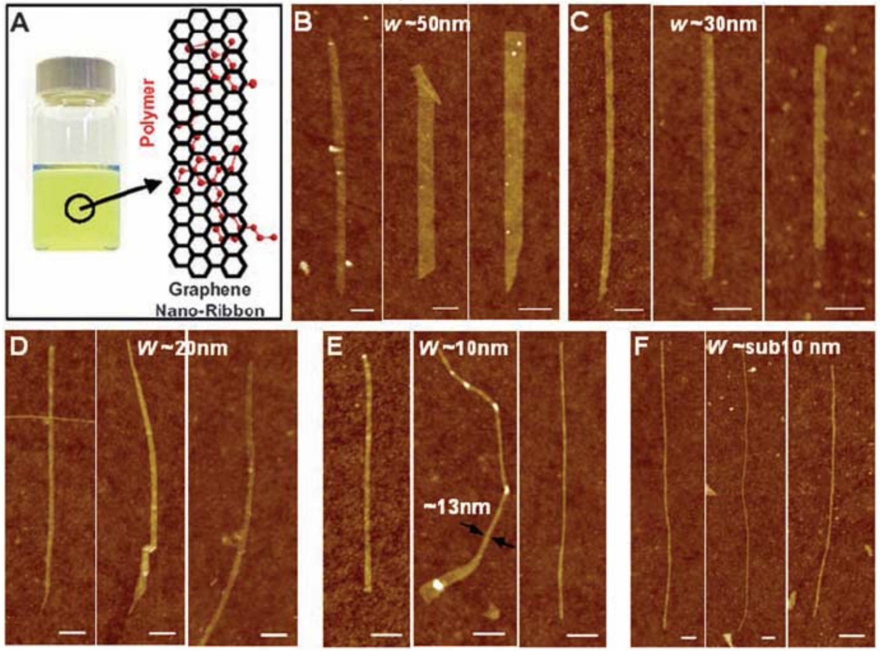


Kim Group, PRL'07

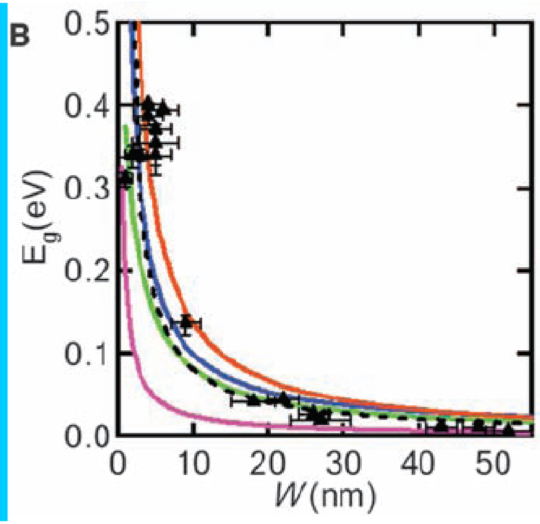
Lithograph-made GNRs



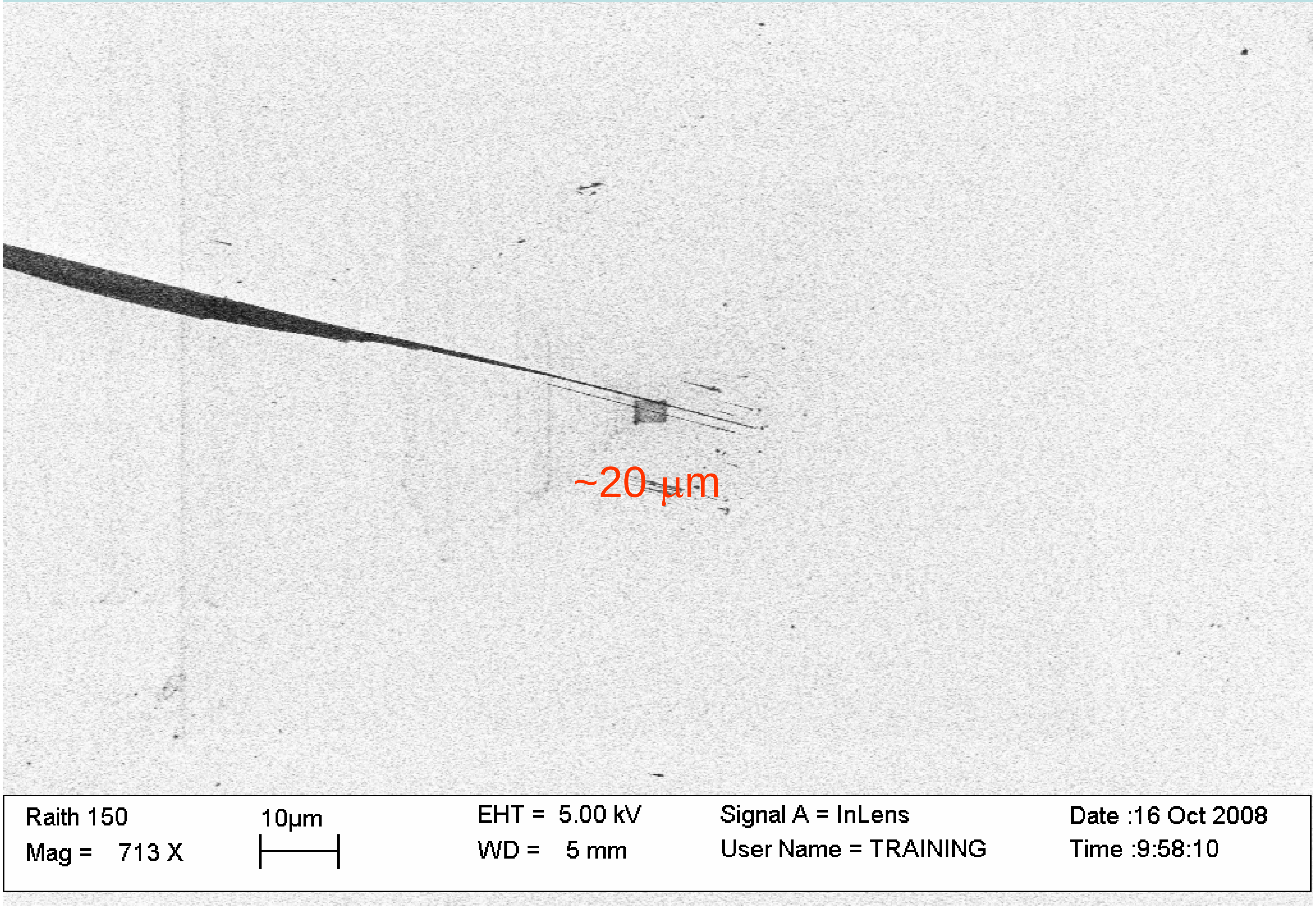
Chemically derived GNRs



Dai Group, Science'08



Our samples: mechanically exfoliated GNRs



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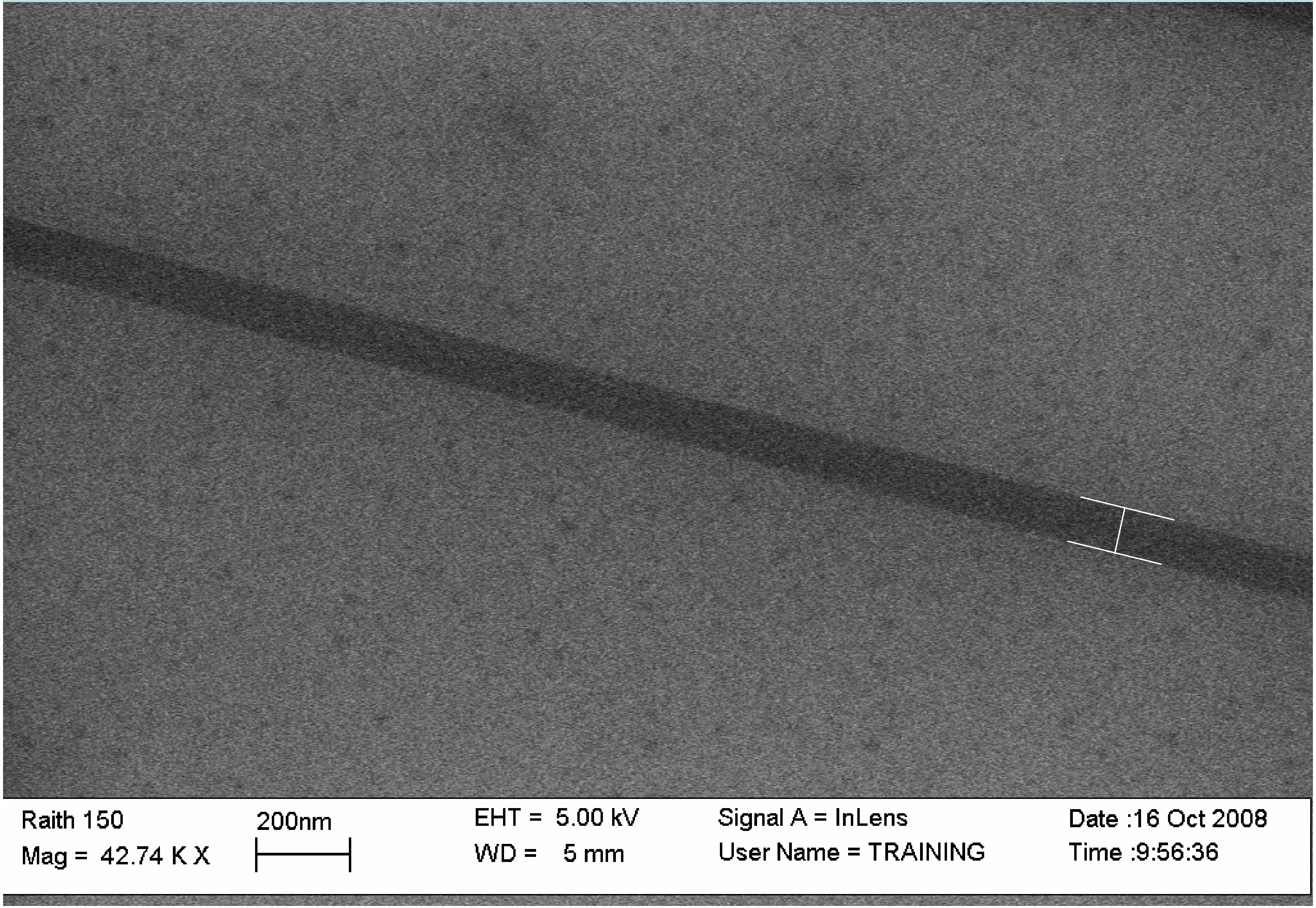
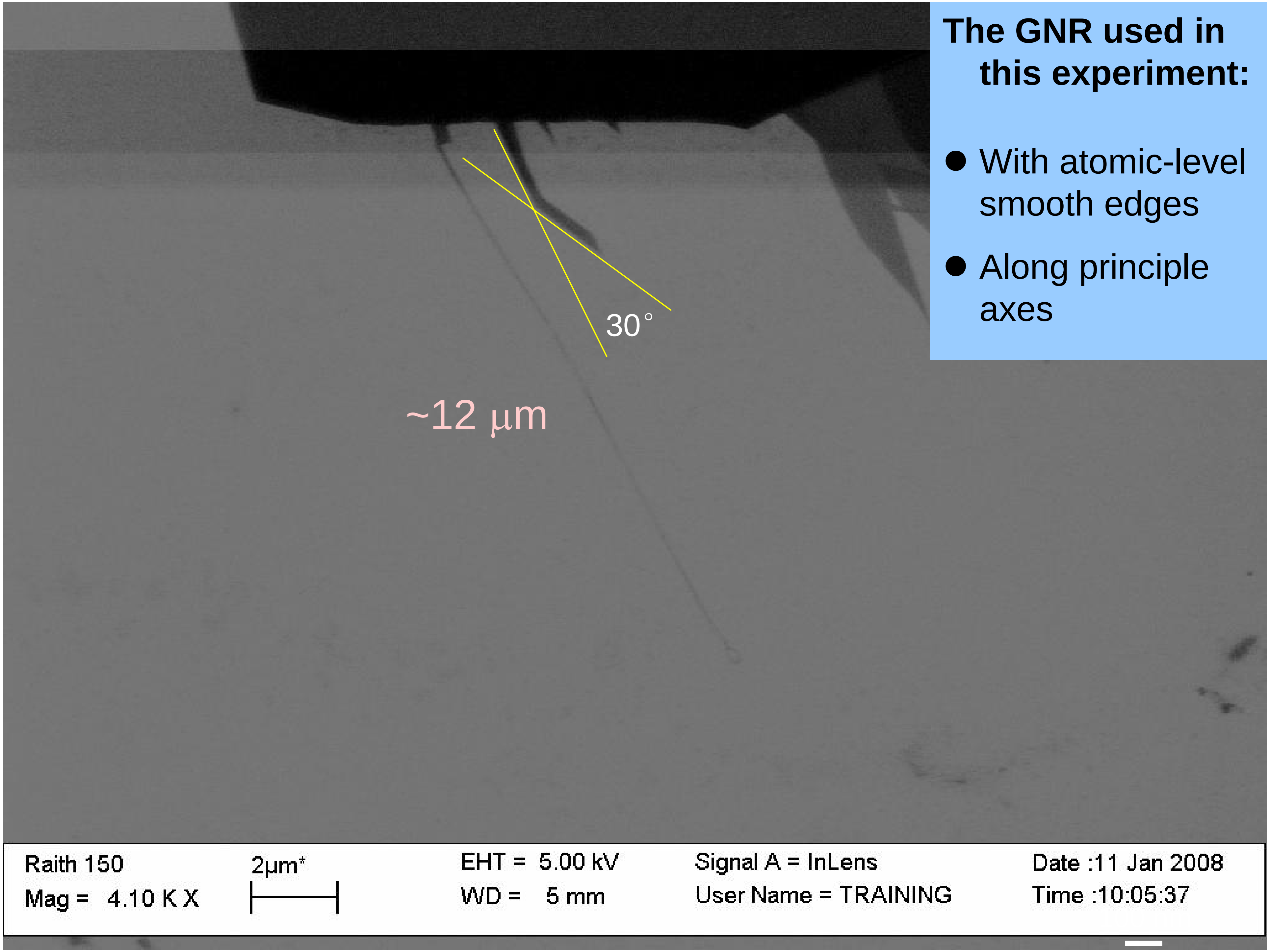
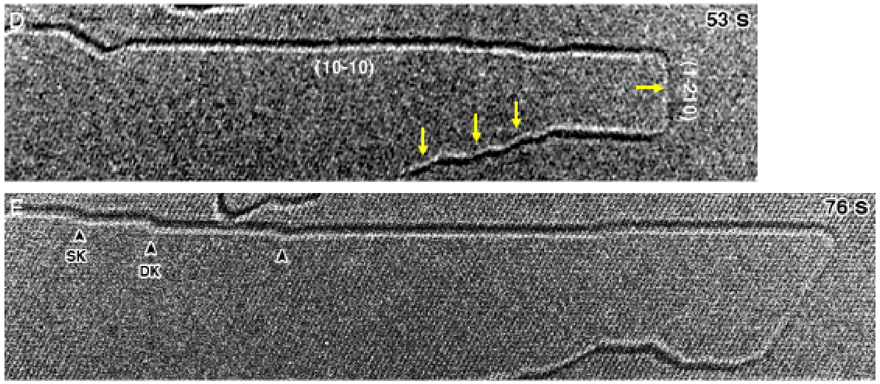


The GNR used in this experiment:

- With atomic-level smooth edges
- Along principle axes



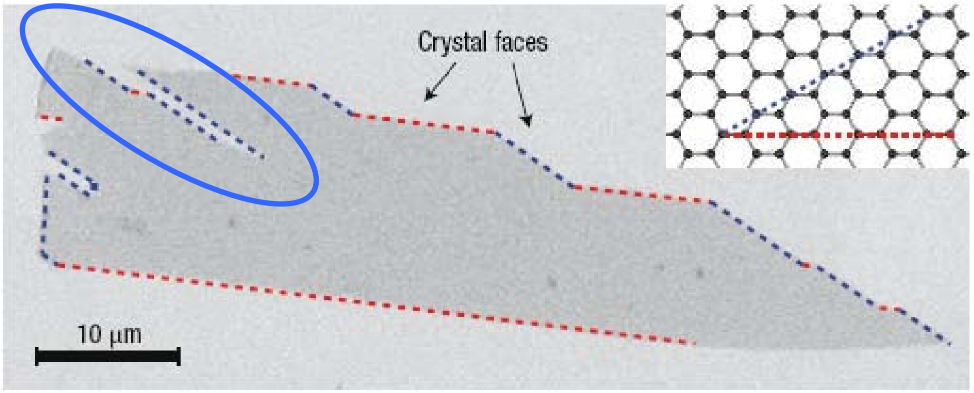
Edges of graphene nanoribbon (GNR)



99% edges are zigzag

Jian Yu Huang et al., PNAS’09

Zigzag ribbon

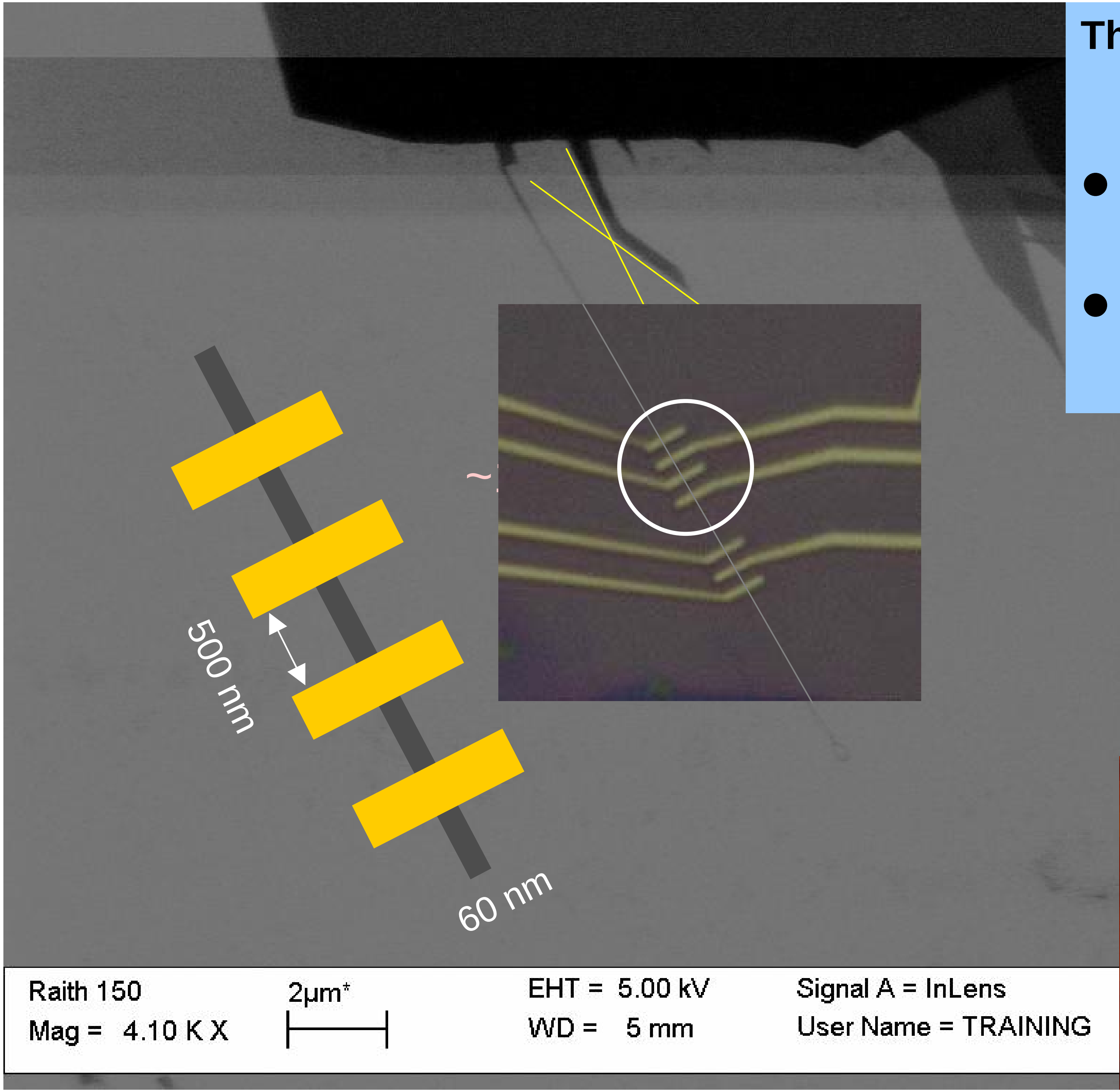


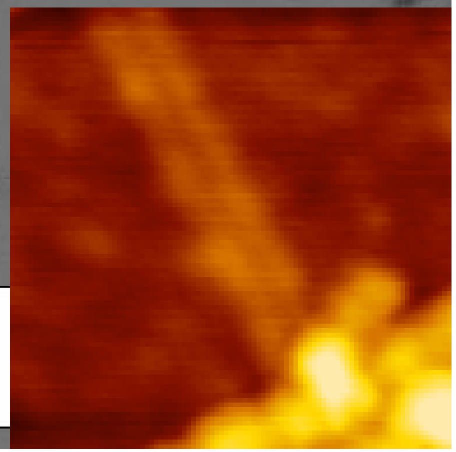
Edges are along principle axes.

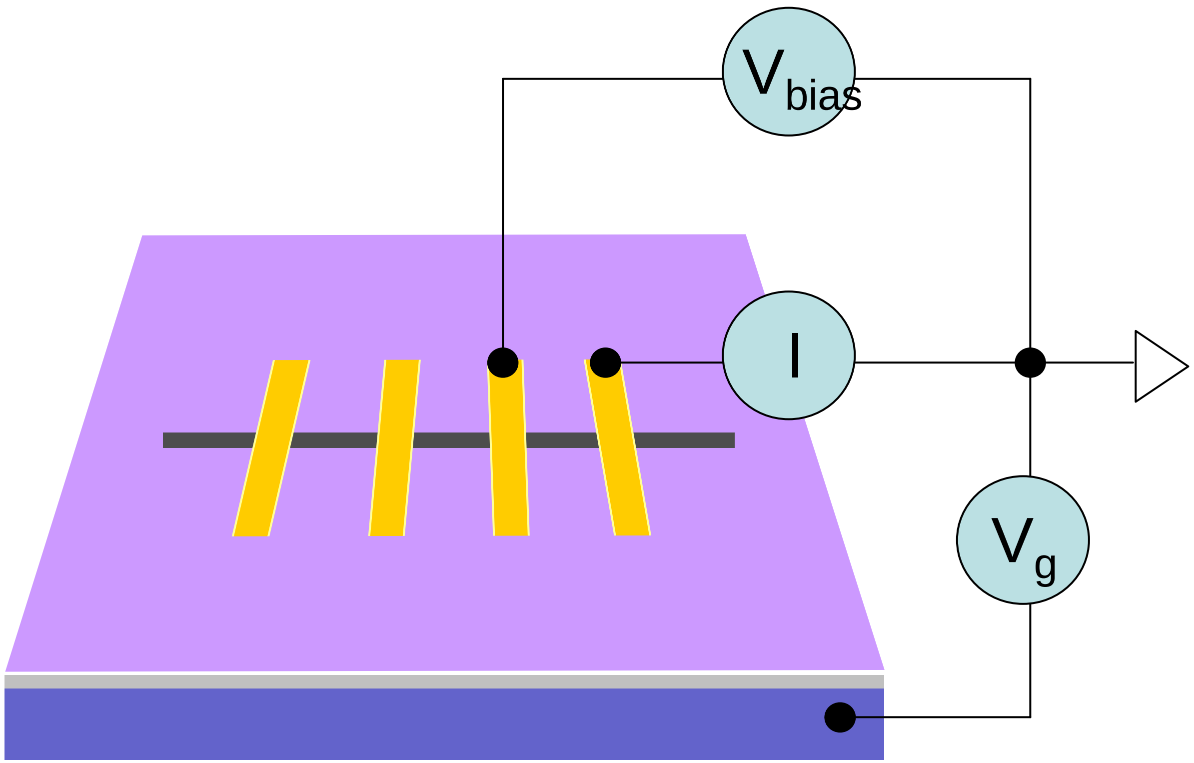
A. K. Geim, Nature Materials’07

The GNR used in this experiment:

- With atomic-level smooth edges
- Along principle axes

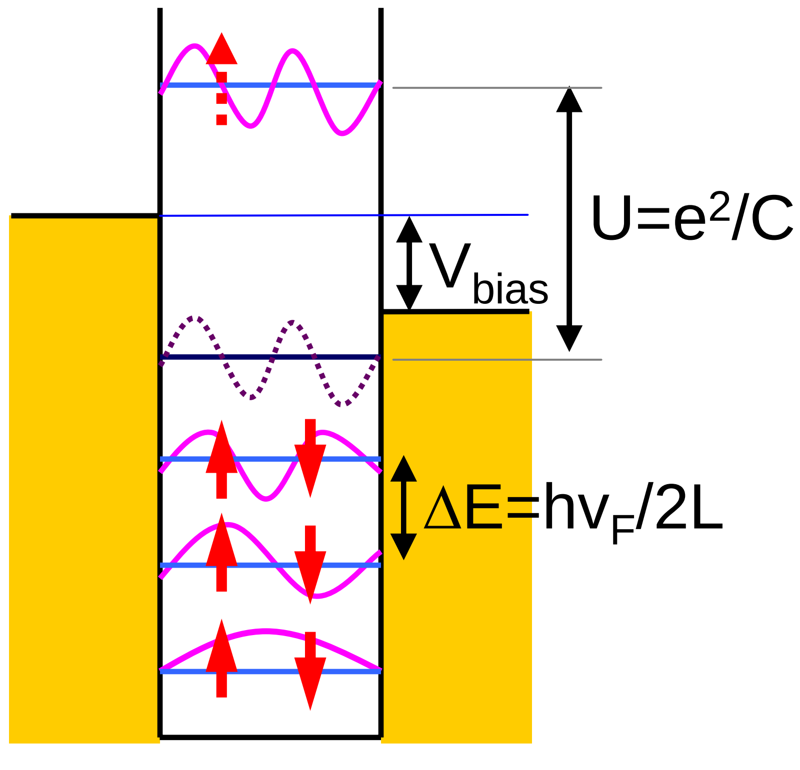


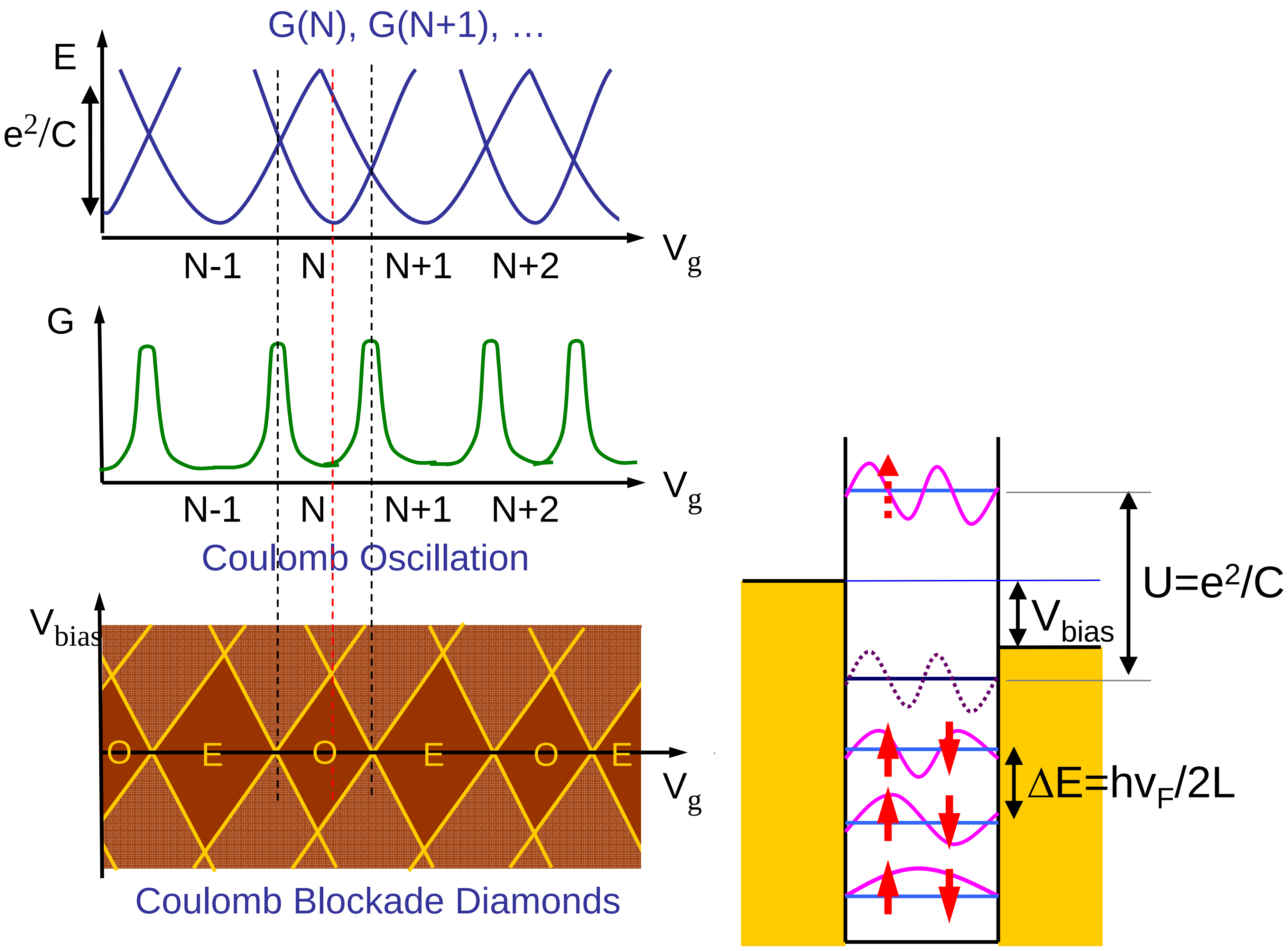




Interplay of different energy scales:

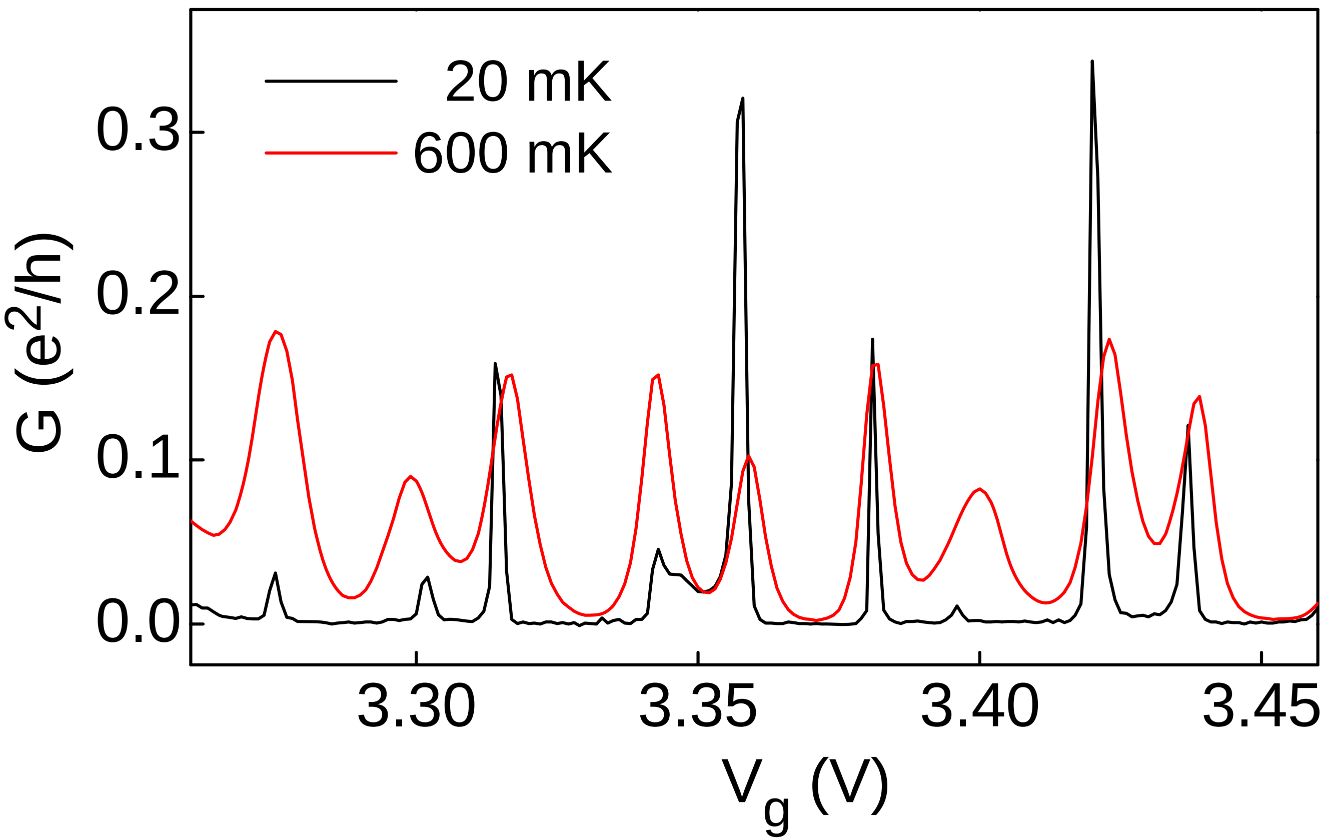
- ΔE, level spacing (excited energy)
- V_g, shifts the levels in the QD
- V_{bias}, the bias window
- U, Coulomb charging energy



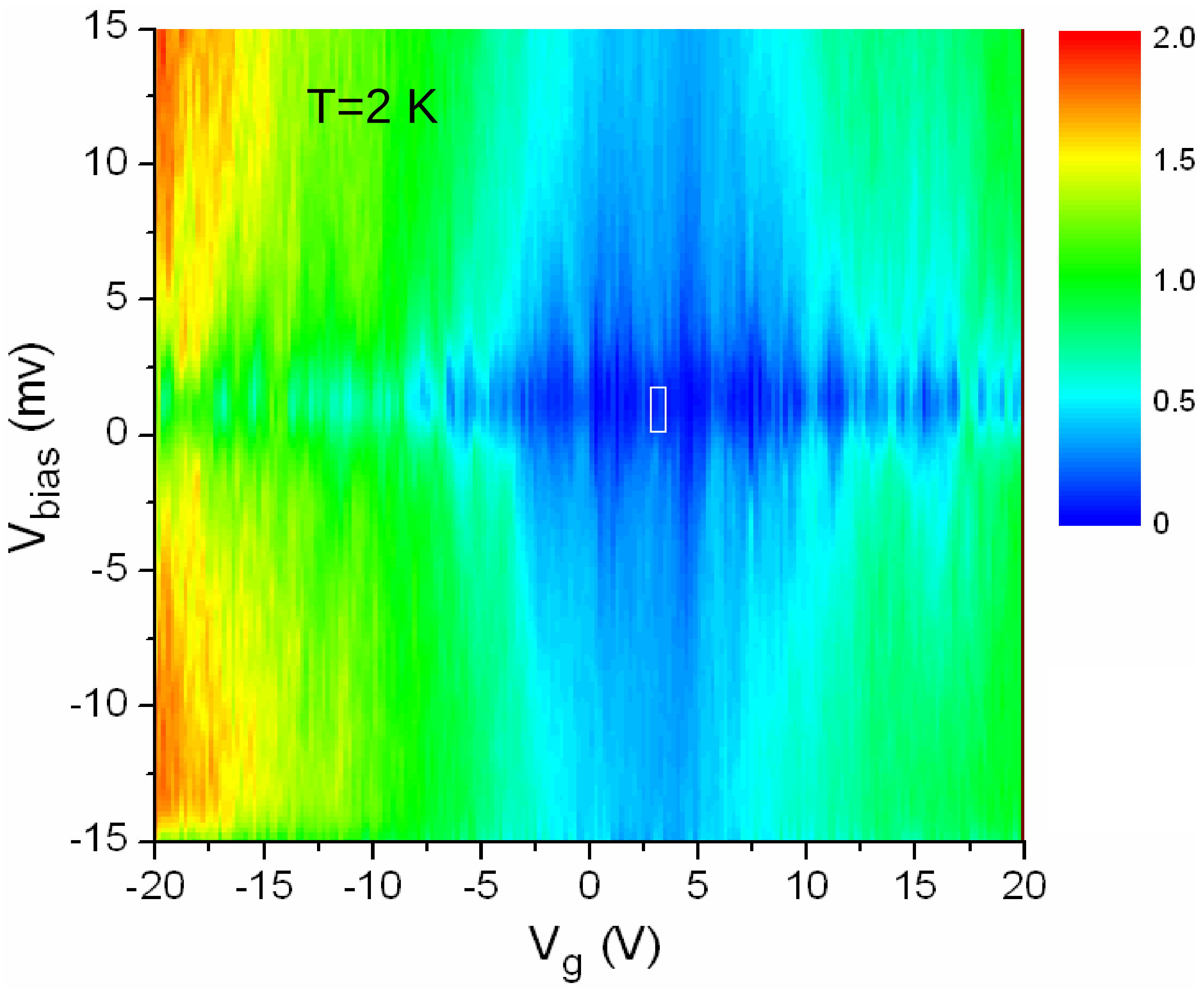


G(N), G(N+1), ...
E
e²/C
N-1
N
N+1
N+2
Vg
G
N-1
N
N+1
N+2
Vg
Coulomb Oscillation
Vbias
O
E
O
E
O
E
Vg
Coulomb Blockade Diamonds
U=e²/C
Vbias
ΔE=hvF/2L

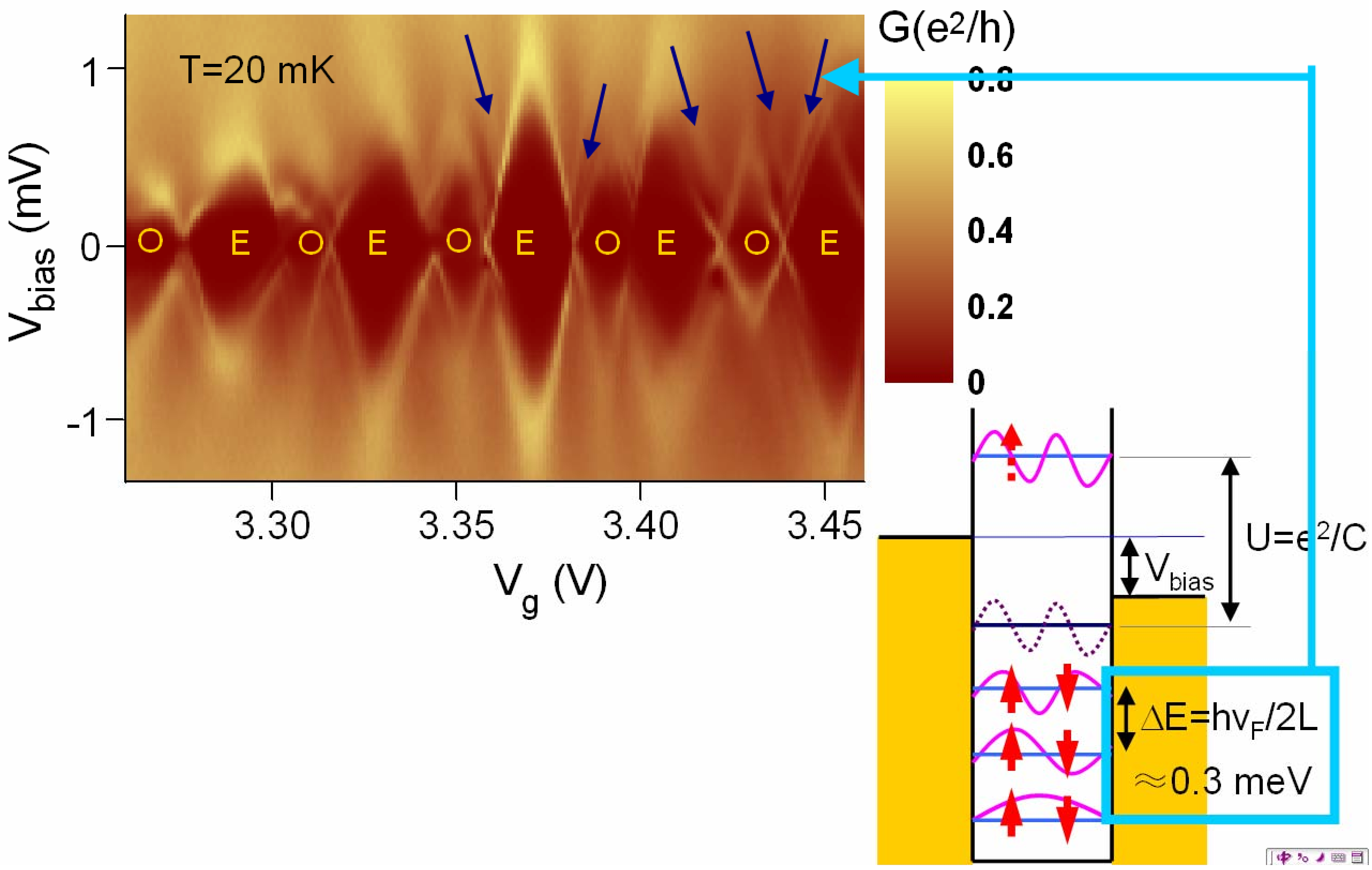
Coulomb oscillation: G peak gets sharper at low T



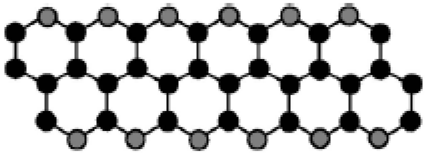
Conductance as a function of V_{bias} and V_g

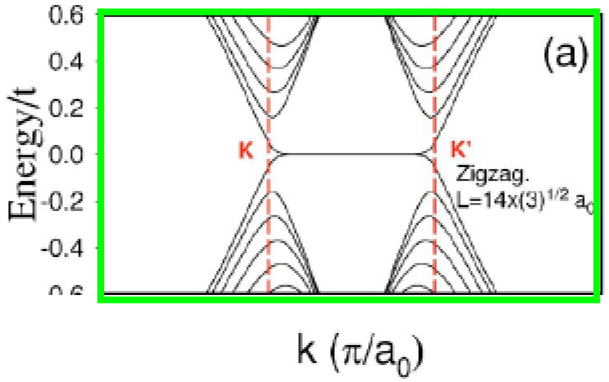


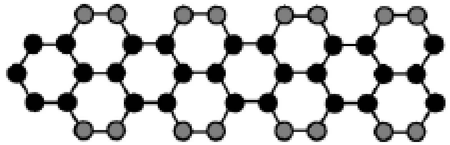
Two-fold spin shell filling in a bar-like QD
→ Break down of K and K' degeneracy

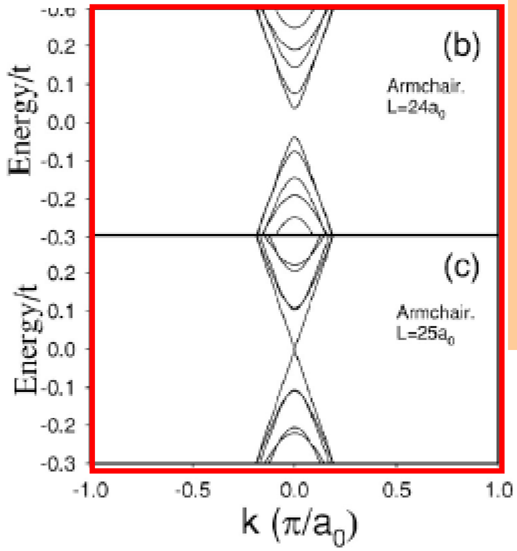


Excited energy → Zigzag ribbon









If armchair:

V_F=1e6m/s, $\Delta E \approx$12meV

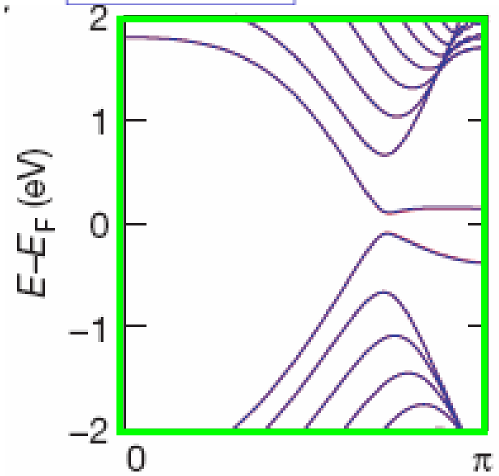
To get ΔE <0.3meV, more than 10 subbands must be filled with ~700 elec.

i.e, Dirac point is 10V away from the V_g window.

- zig-zag are gapless (edge modes)
- armchairs: gapped or gapless

W = 3N, 3N+2

W = 3N+1

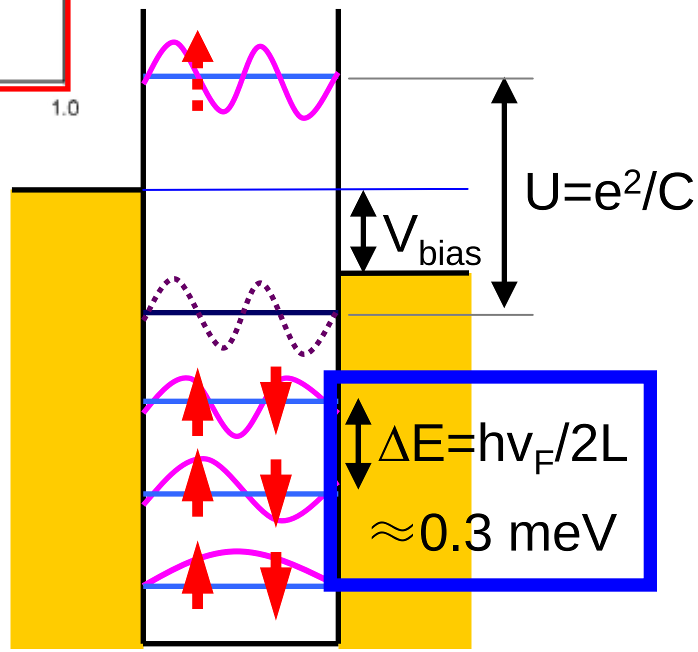


PRB 2006; Brey-Fertig, PRB 2006

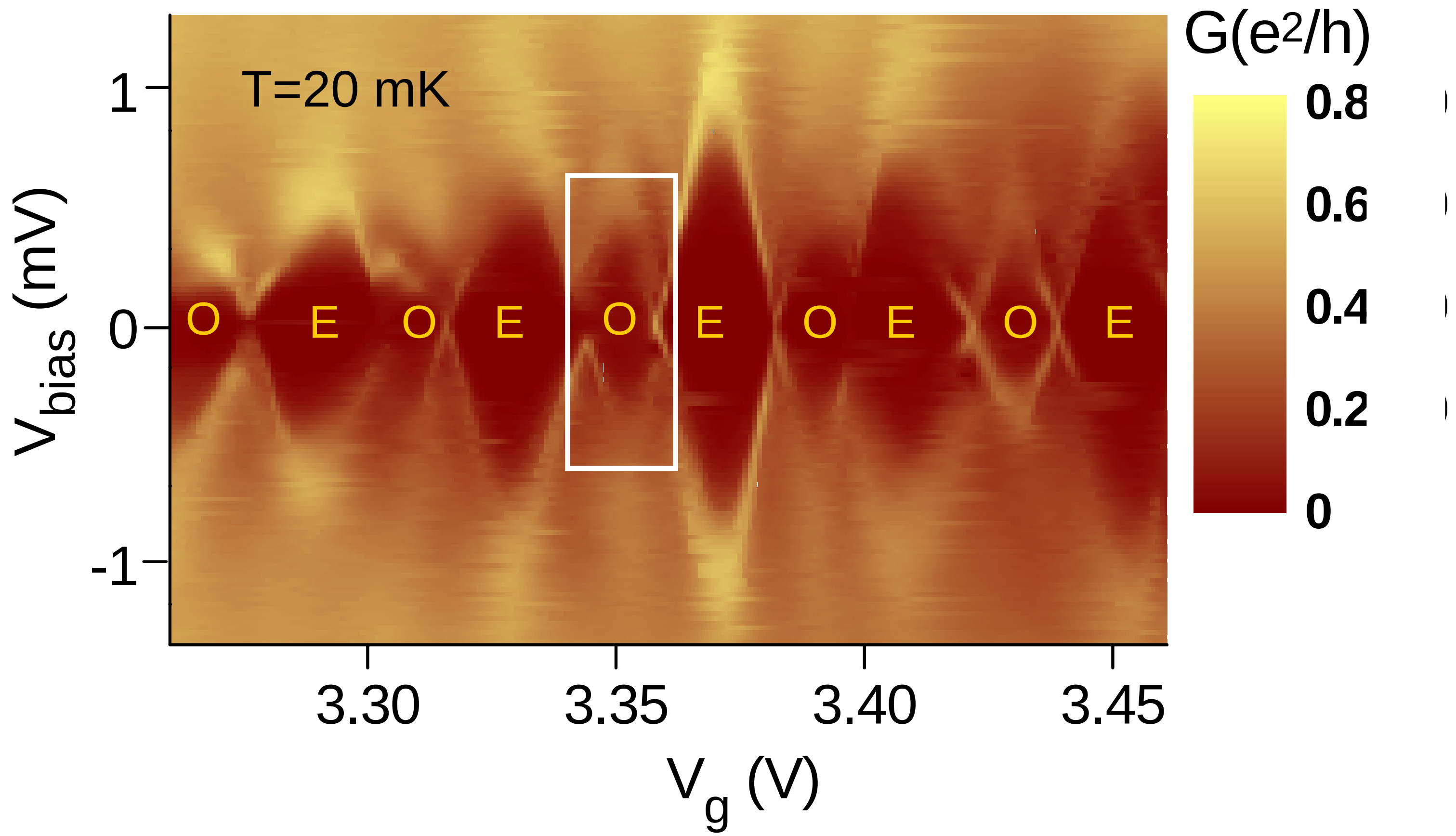
If zigzag:

$V_F'/V_F \sim t'/t \approx 1/30$

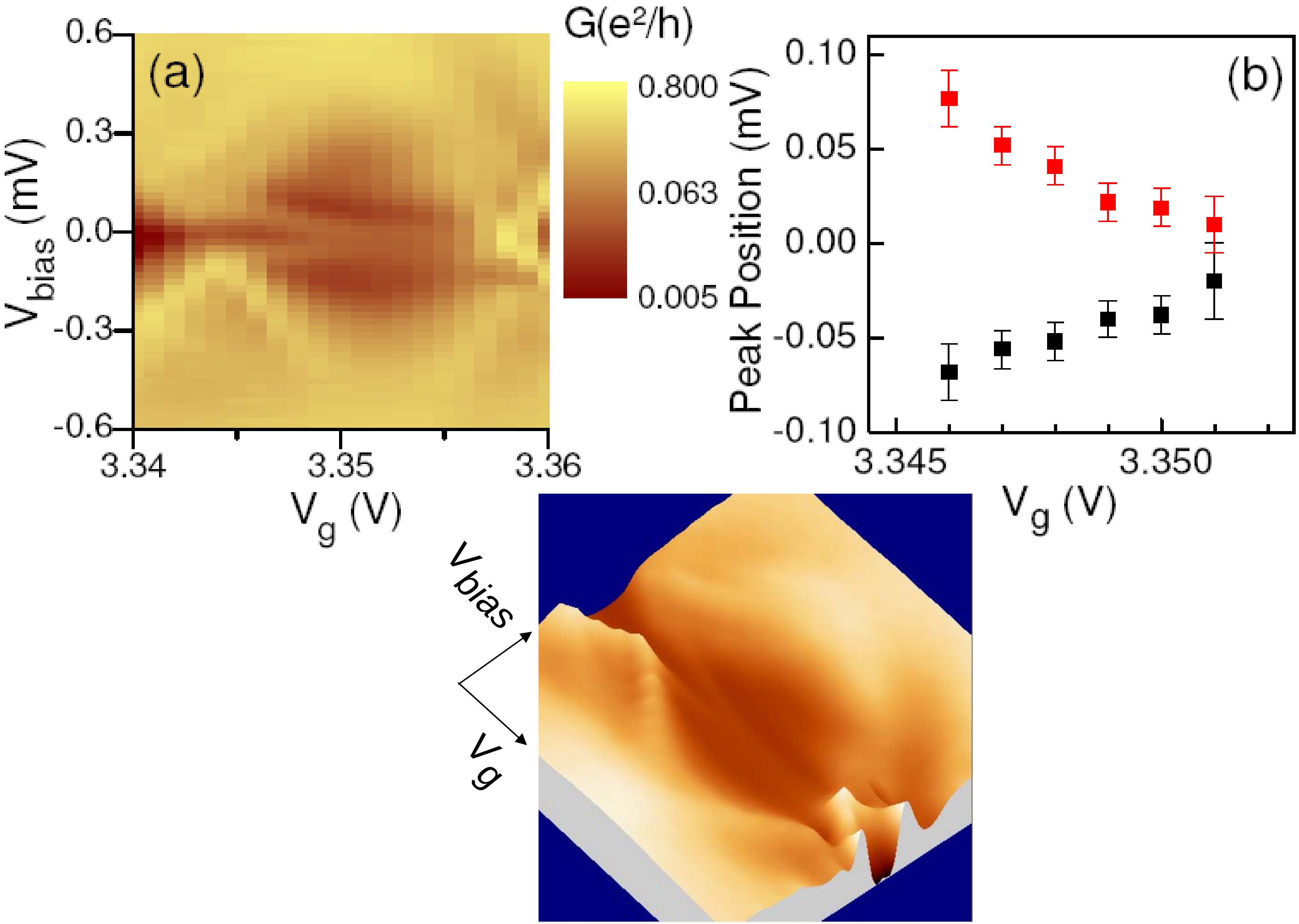
$\Delta E = hV_F'/2L^* \approx 0.4$ meV



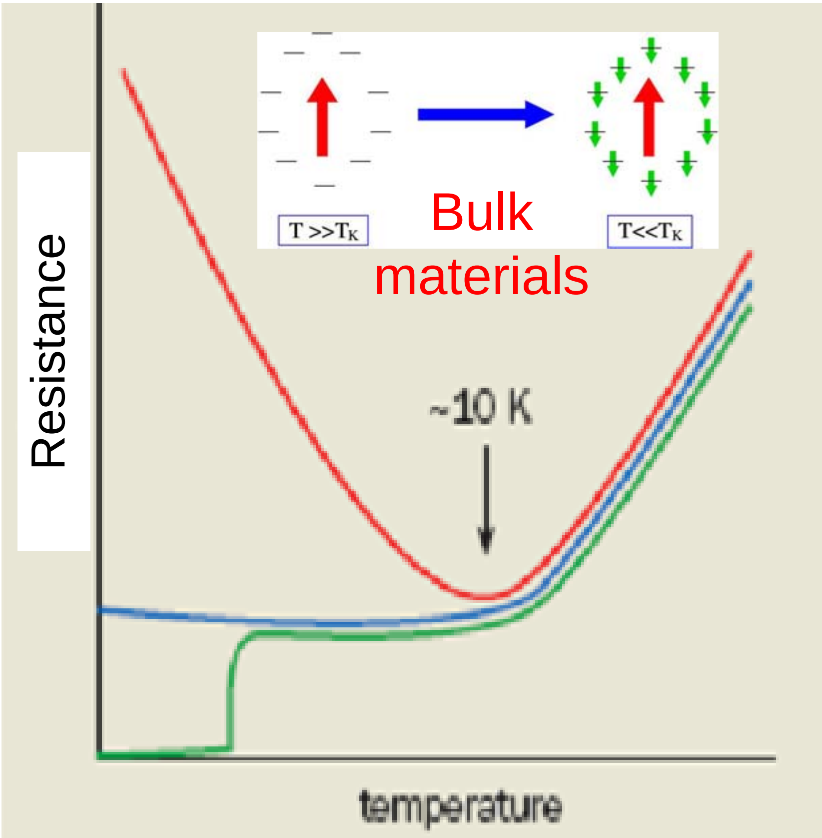
Kondo resonance

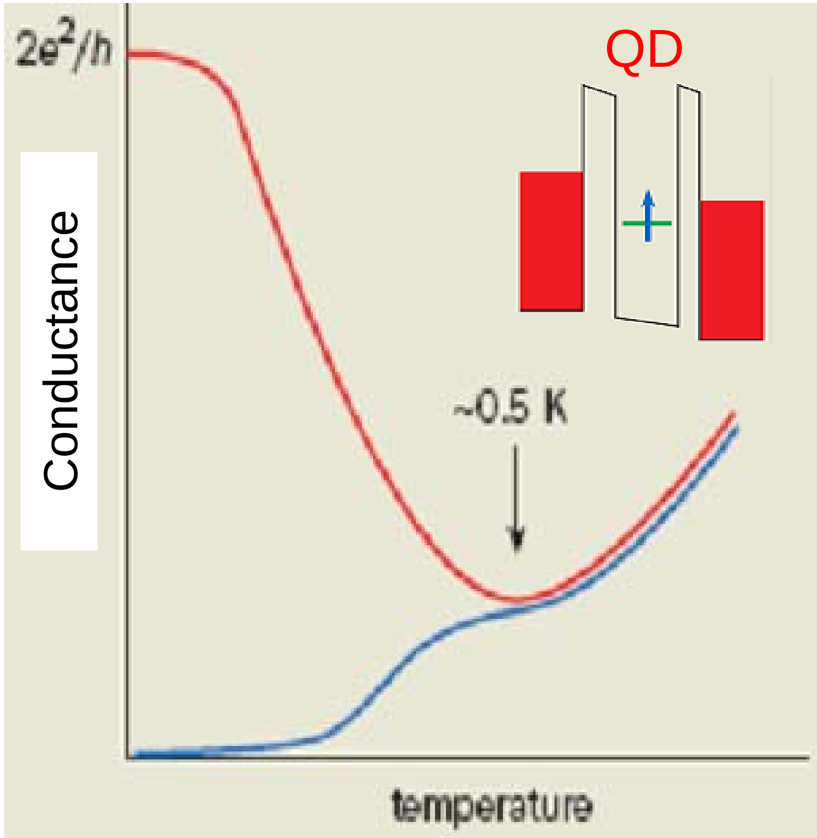


Inelastic Kondo resonance



Kondo problem





Scattering and screening:

R ↑@ low T

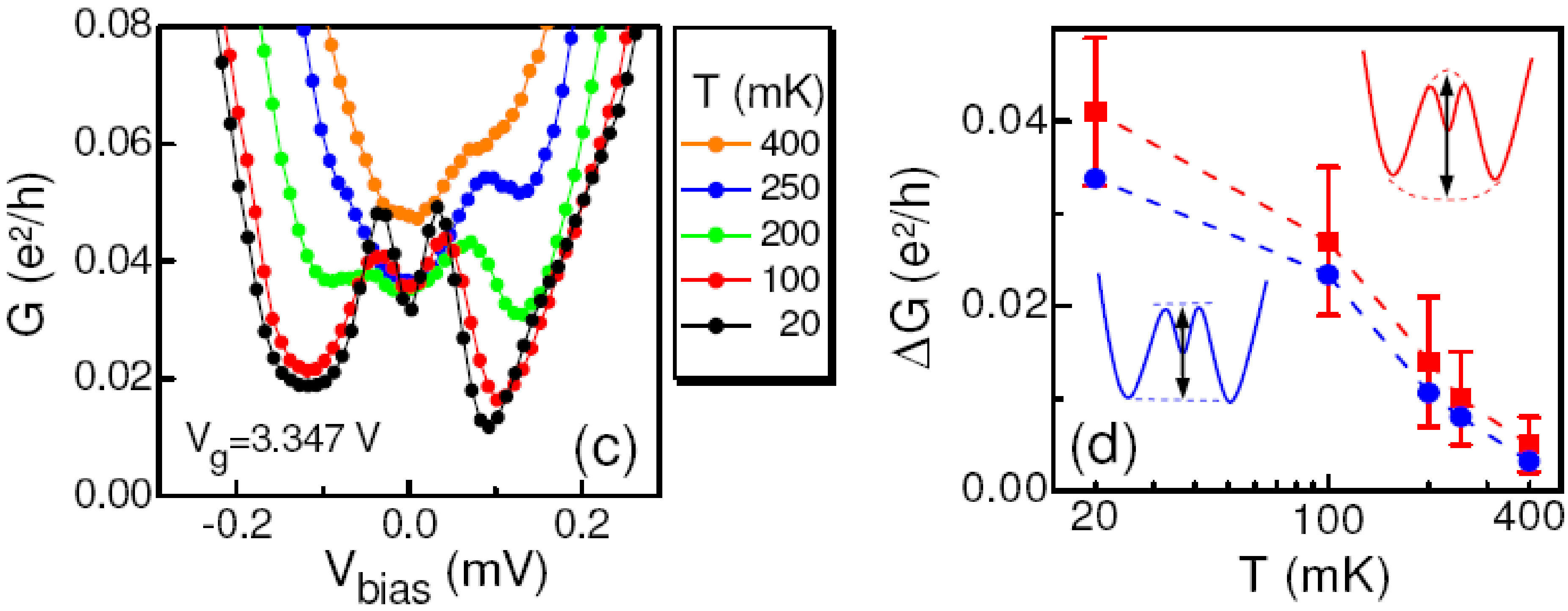
Kondo

Resonant co-tunneling:

Provides a conduction mechanism in the CB regime.

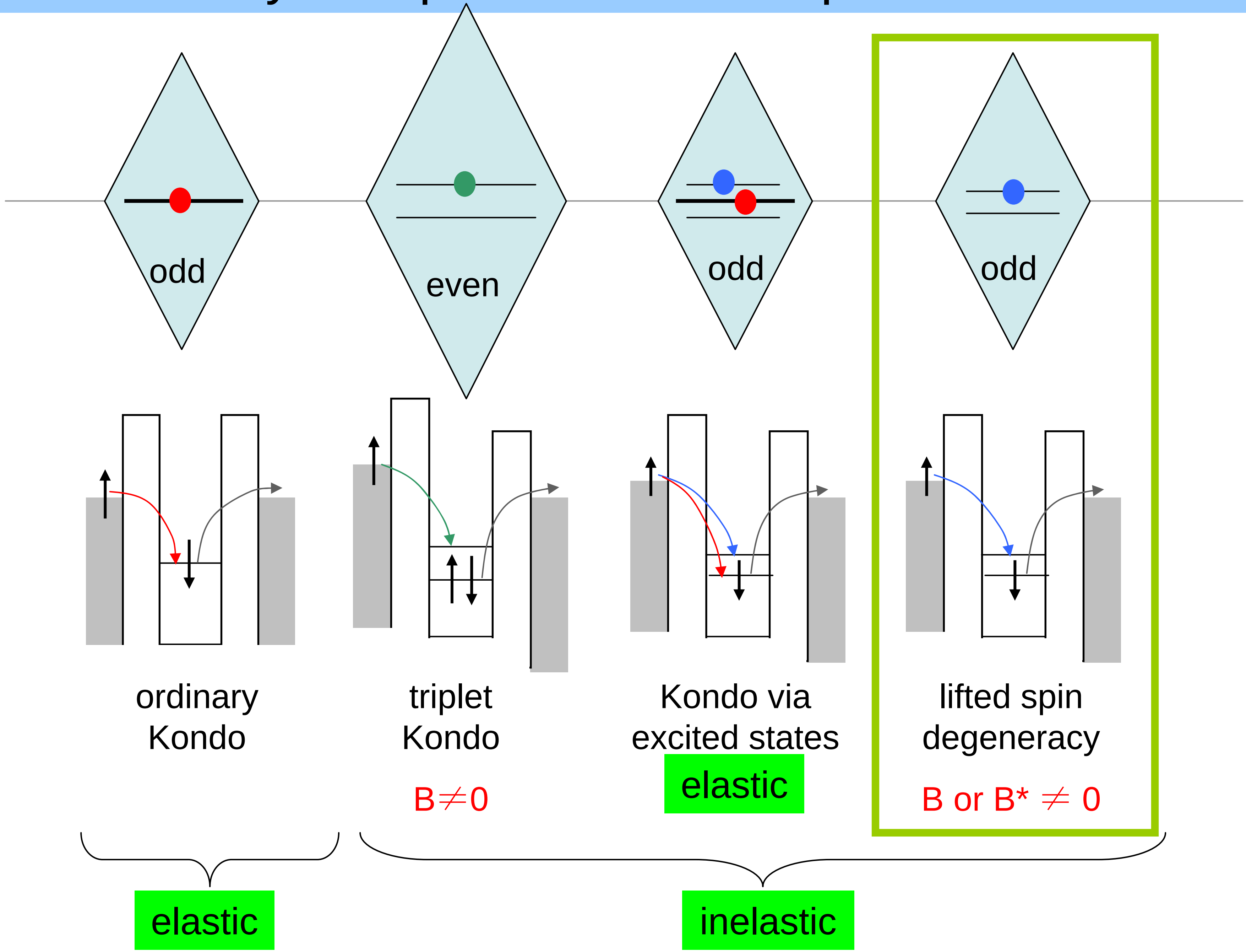
T. K. Ng and P. A. Lee' 1988
L. I. Glazman, et al.'1988

Logarithmic temperature dependence

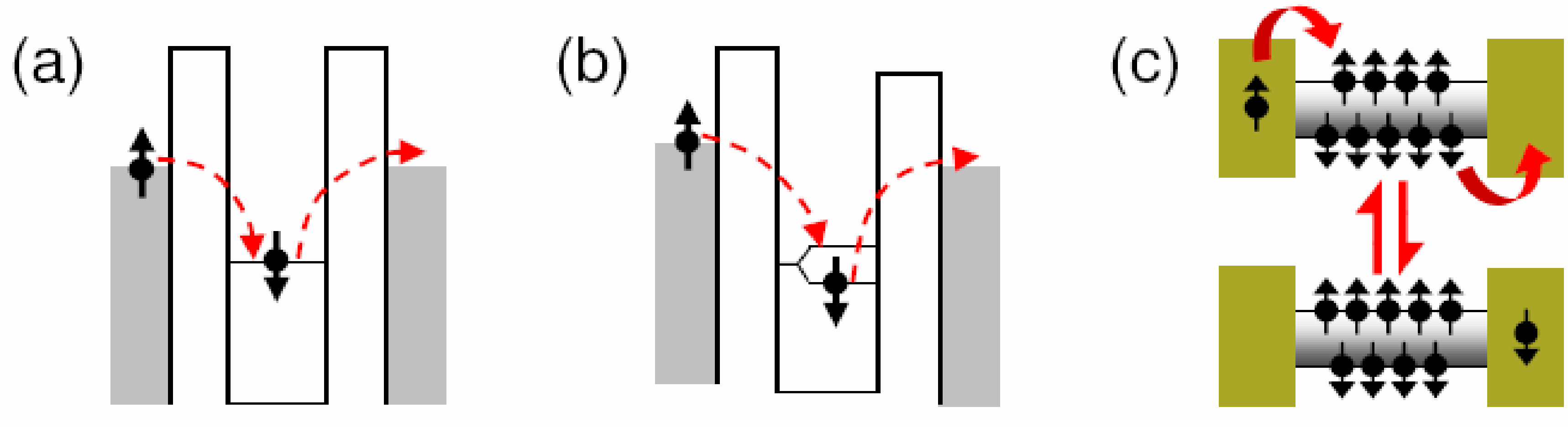


Kondo-like

Why multiple conductance peaks ?

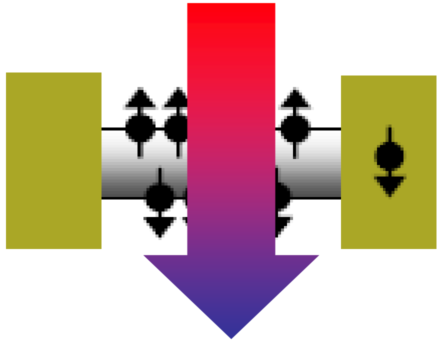


A toy model for inelastice Kondo resonance involving spin-polarized edge states



Elastic Kondo

Inelastic Kondo



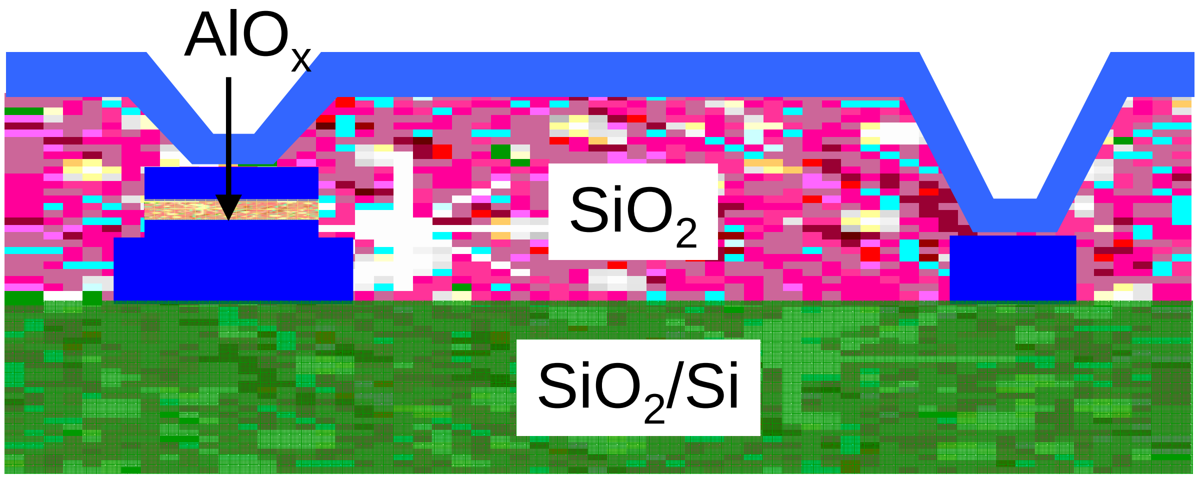
Inelastic Kondo realized in a zigzag GNR at B=0,

When the electrostatic potential of the two edges are different,

due to applied transverse electric field or trapped charge vacancies.

Spin qubits made of graphene quantum dots ?

- There are mobile charges in SiO_2



Decoherence
by S. Oh

- Unfortunately the spins in zigzag GNRs are coupled to mobile charges in the environment.

Summary

- Measured the transport properties of a zigzag GNR.
- Observed two-fold spin shell filling in CB regime.
- Provided transport evidence of spin polarization in the zigzag GNR.

C. L. Tan, et al, submitted

感　谢

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