Exceptional ballistic transport in epigraphene

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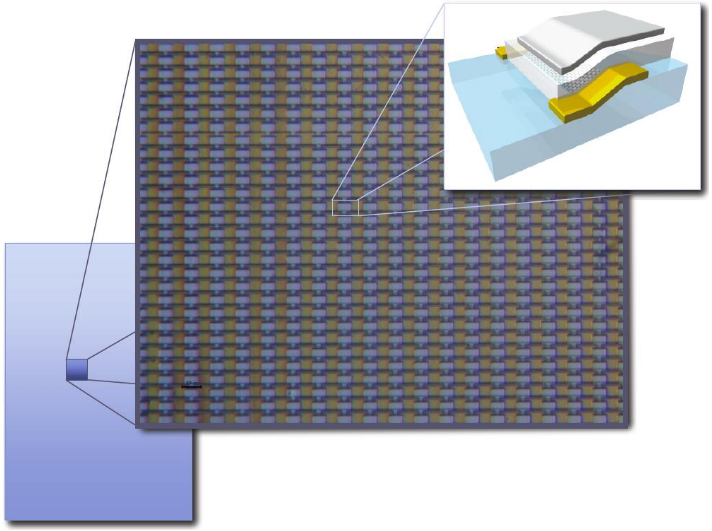
Georgia Institute of Technology

Program Objective

First formulated in 2001 and patented in 2003, our objective is to develop nanoelectronics based on epitaxial graphene on silicon carbide.

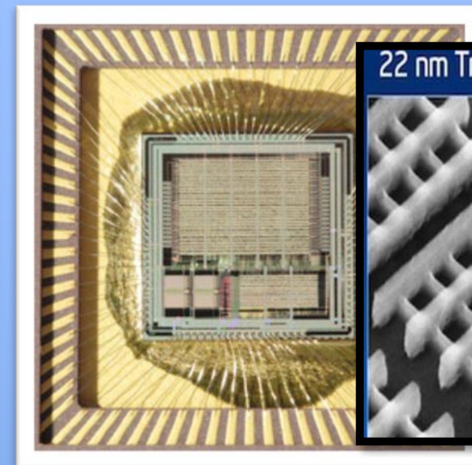


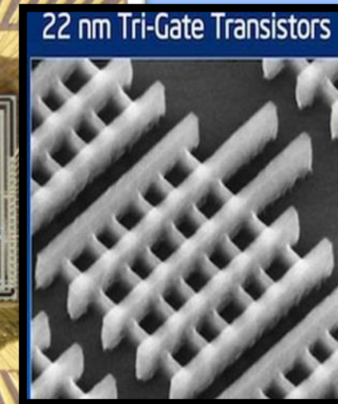
Sprinkle et al. Nature Nano, vol. 5, pp. 727-731,. 2010

Si crystal

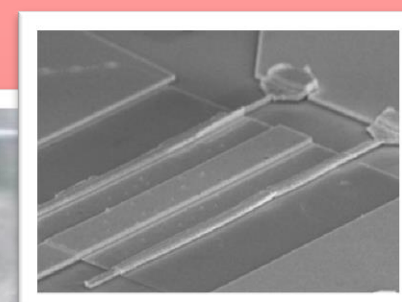
Si wafer

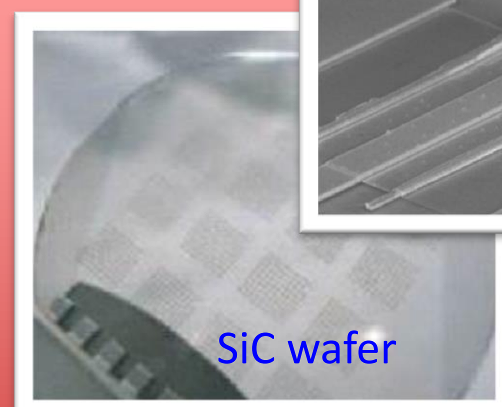
Si nanoelectronics





200 GHz **epitaxial graphene** transistor (GaTech)



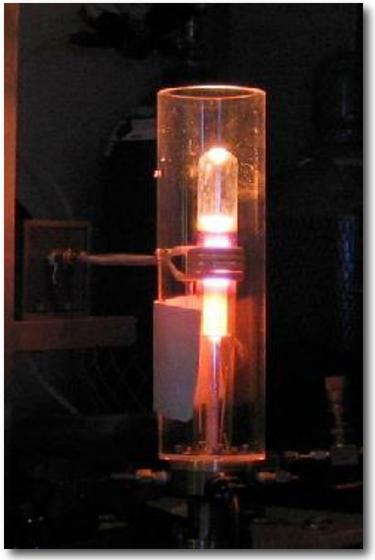


Intel funded the GIT Graphene project in 2003

Epitaxial graphene, by the CCS method

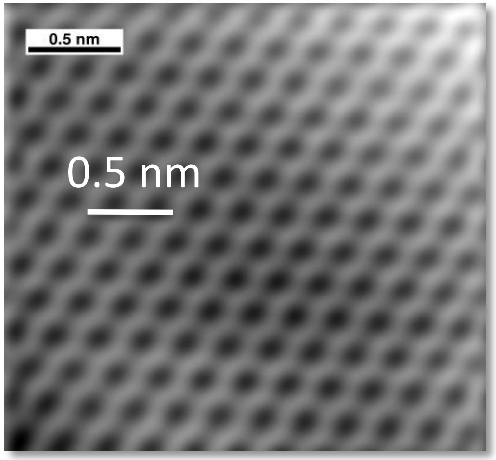
reviewed in PNAS 108, 16900 (2011)

Epitaxial graphene produced by vacuum sublimation of Si from electronics grade SiC.

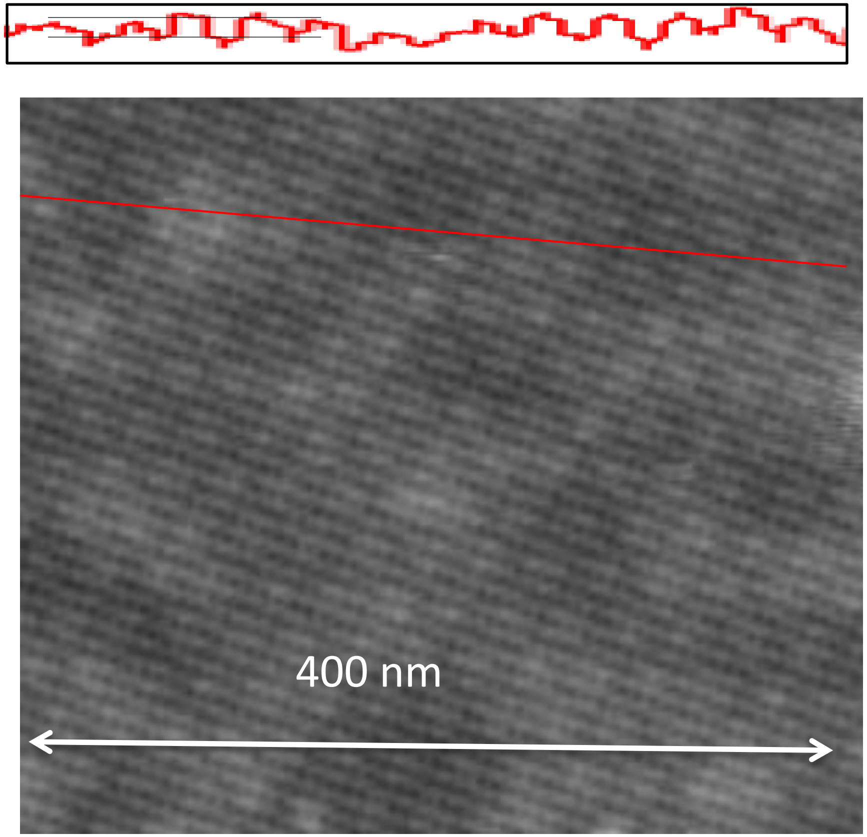


First CCS Induction Furnace

(2004)



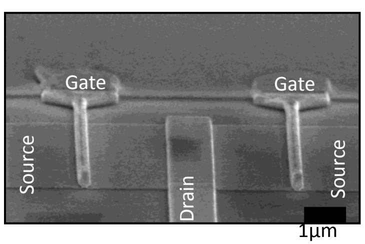
STM
(Courtesy J. Stroscio)

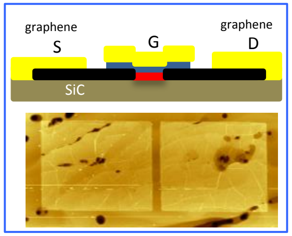


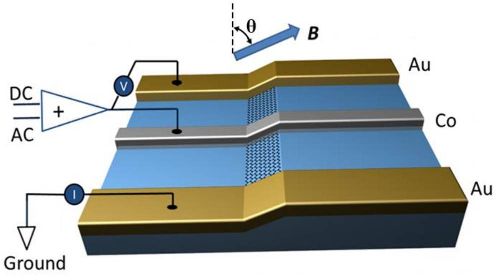
The graphene sheet continuously covers the entire surface.
Its major disadvantage is, that it cannot be back gated.

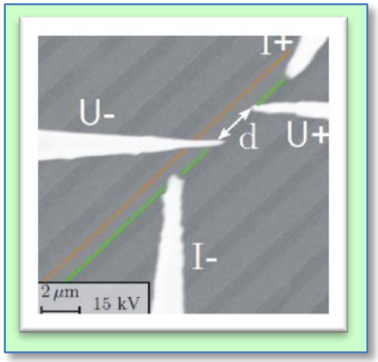
Important achievements

- Record breaking high- speed analog FETs.
- Demonstration of high quality semiconducting epigraphene and related FETs.
- Demonstration of novel spintronic devices.
- Record breaking room temperature exceptional (not understood) single channel ballistic transport, involving new physics.









Exfoliated graphene nanoribbons have transport gaps

This realization essentially ended exfoliated nanoelectronics research!

PRL **104,** 056801 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Electron Transport in Disordered Graphene Nanoribbons

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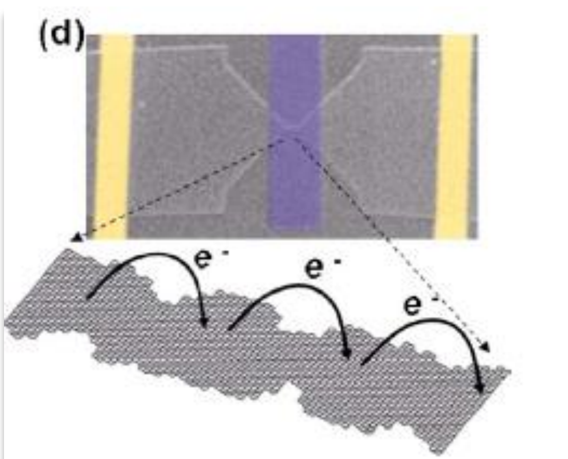
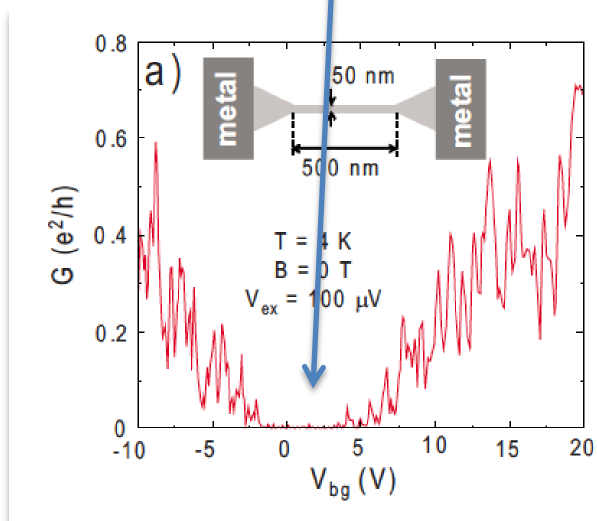
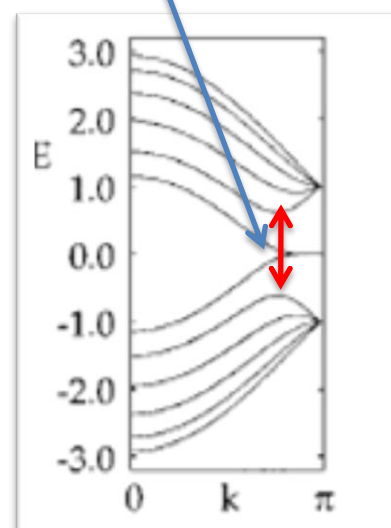
(Received 26 October 2009; published 1 February 2010)

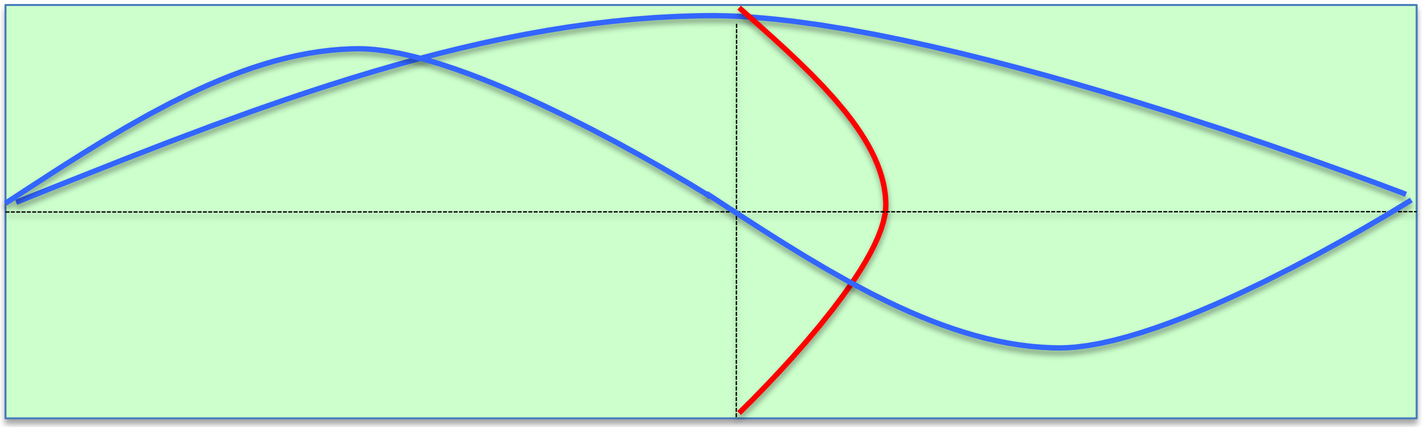
"Edge disorder"→ Transport gap (not a band-gap)







Ribbons as waveguides



$$E_{n,m} = \pm\hbar c^* \sqrt{\left(\frac{n\pi}{W}\right)^2 + \left(\frac{m\pi}{L}\right)^2}$$

$c^* \approx 10^6$ m/s

for W=40 nm and L=1 μm

$E_{1,0}/k_B$=600 K,

$E_{0,1}/k_B$=23 K,

Caveat:

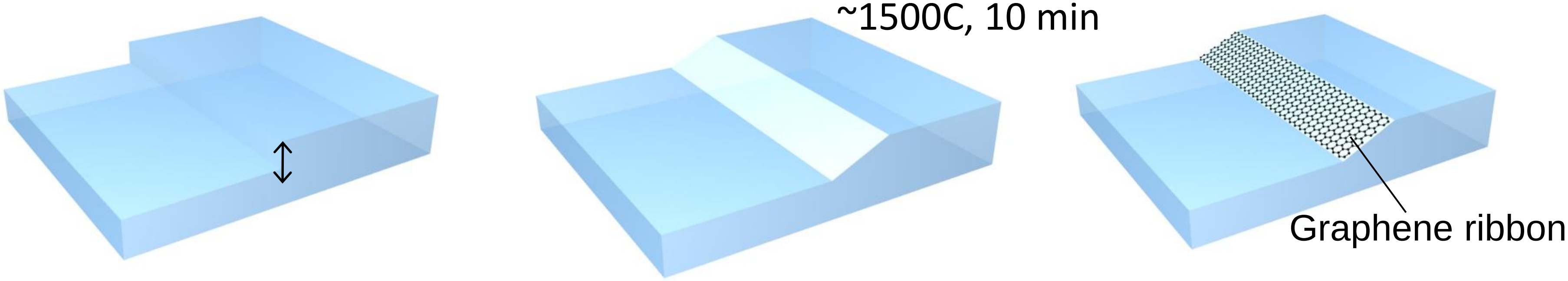
Micron length graphene ribbons are quantum dots!

Structured graphene growth on sidewalls

Selective growth on sidewalls etched into SiC
Avoids disorder at edges

Photo-lithography defined Ni mask
Plasma etched SiC step

Preferential graphene growth
on the recrystallized (1-10n) facets
~1500C, 10 min



Graphene grows rapidly on substrate steps and sidewalls.
The sidewall first re-crystallizes (facets) and then graphitizes

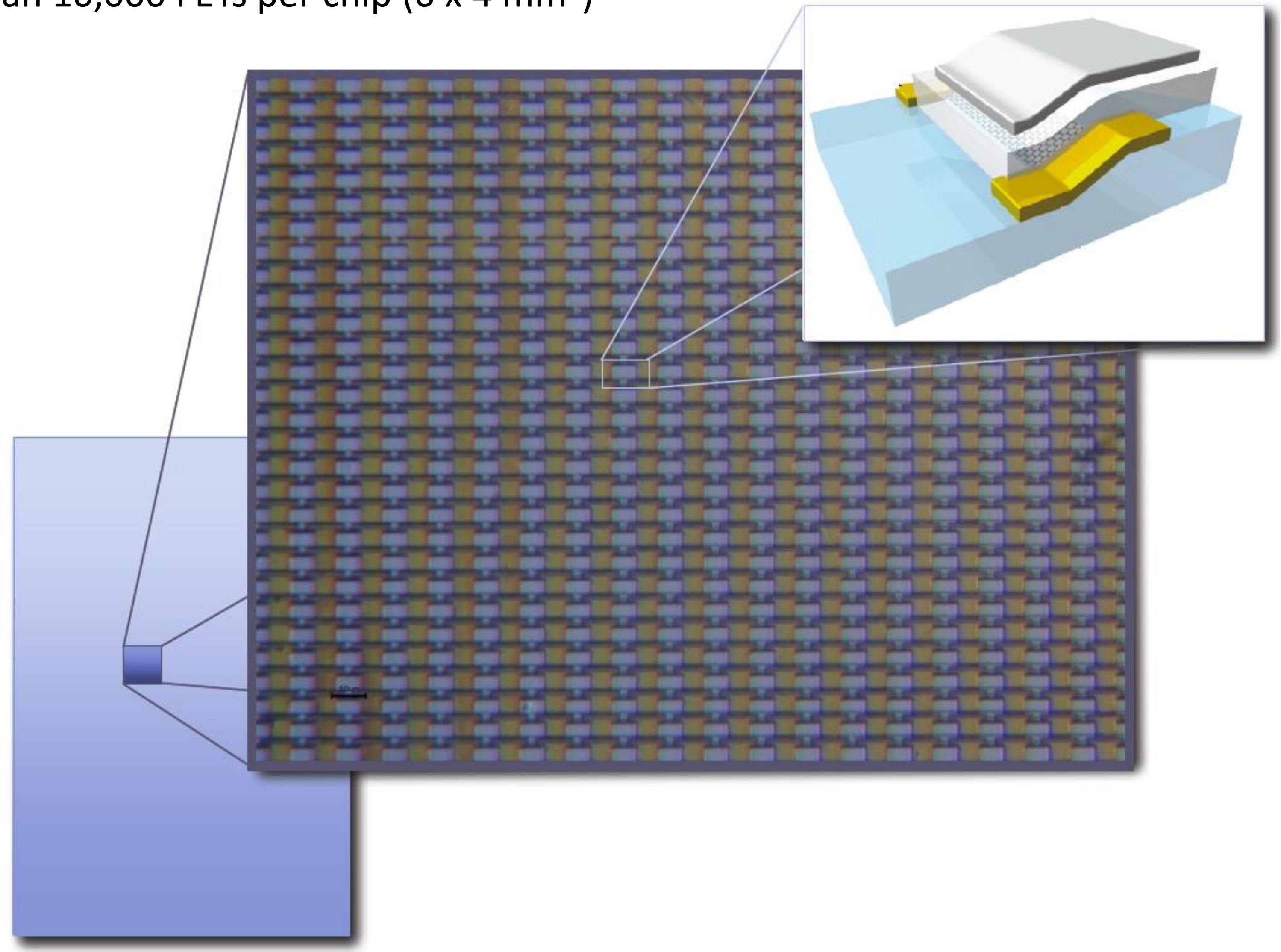
M.Sprinkle, Nature Nano 2010

High device density

Scalable method

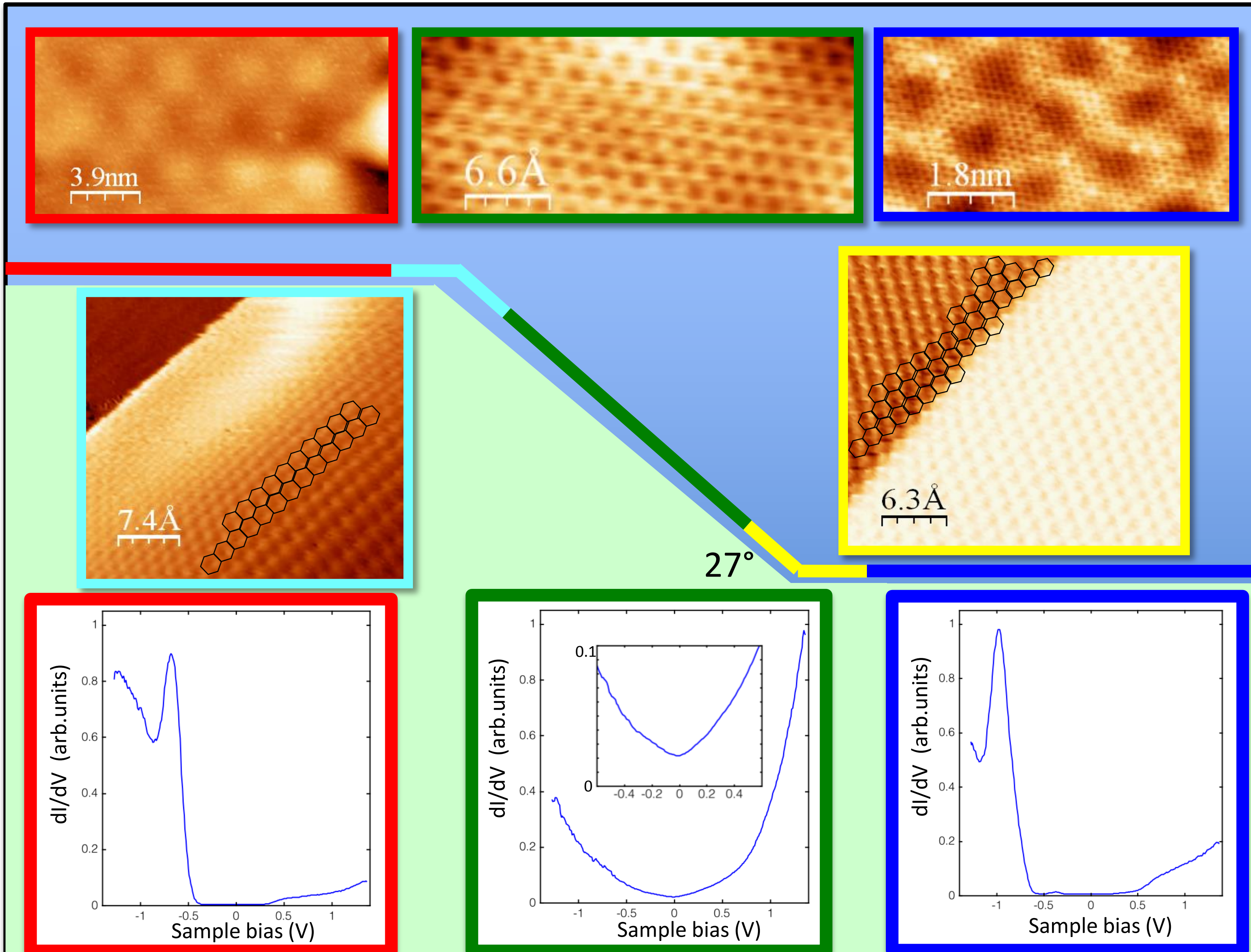
More than 10,000 FETs per chip (6 x 4 mm^2)

M.Sprinkle, Nature Nano 2010



STM - STS: graphene on side wall - buffer on Si-face

Antonio Tejeda, Muriel Sicot, CNRS, France



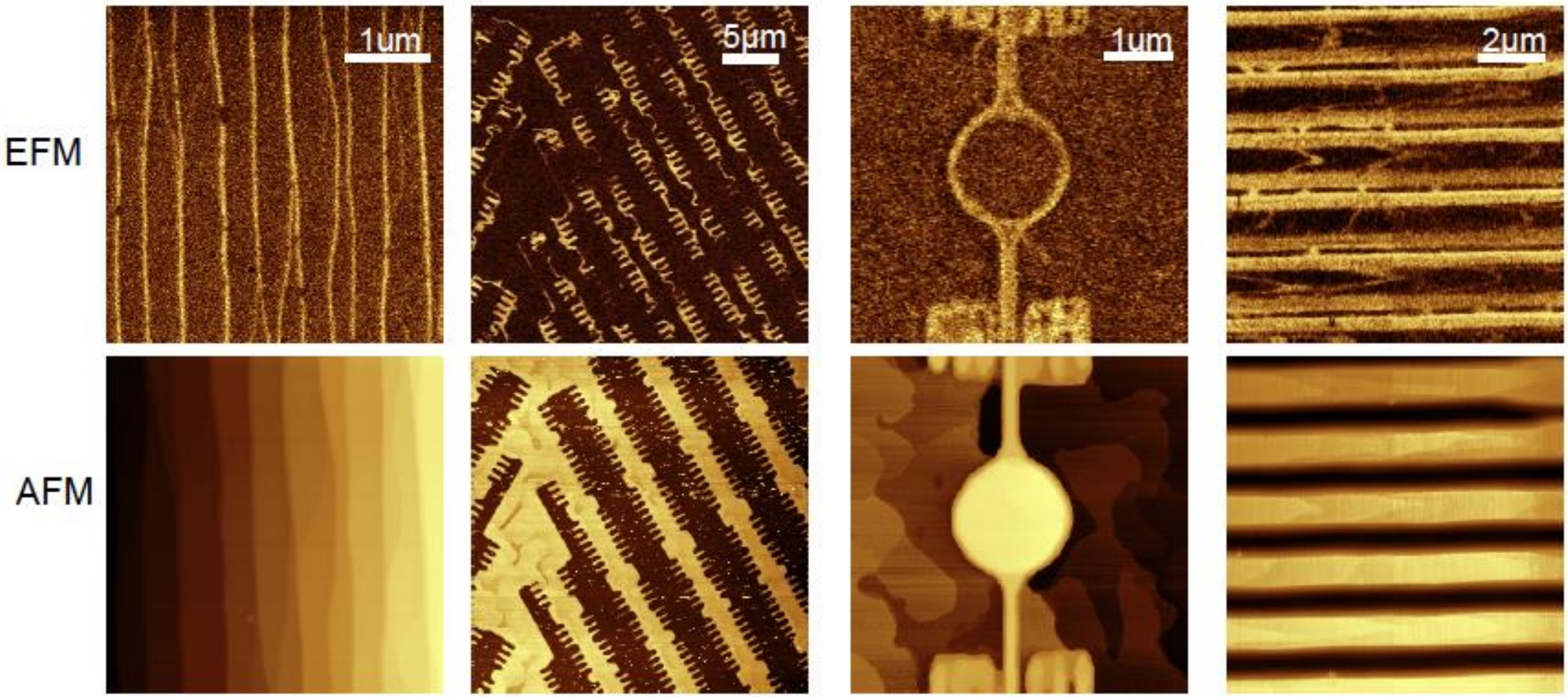
Ribbons and beyond: Structured graphene

Parallel ribbons arrays
(vicinal steps)

Serpentine graphene contacts
(Shallow etch: 15 nm)

Rings
(graphitized pillars)

Nanoribbon arrays
(deep etch:150 nm)



Exceptional Room temperature Ballistic Transport in Epitaxial Graphene Nanoribbons

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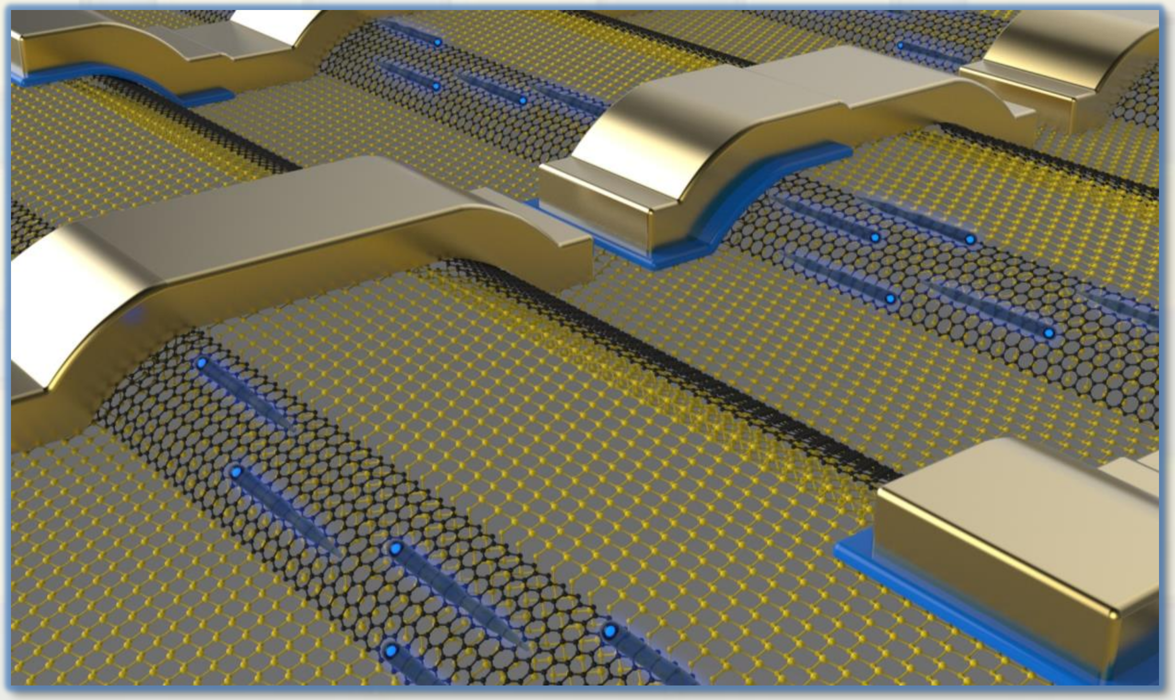
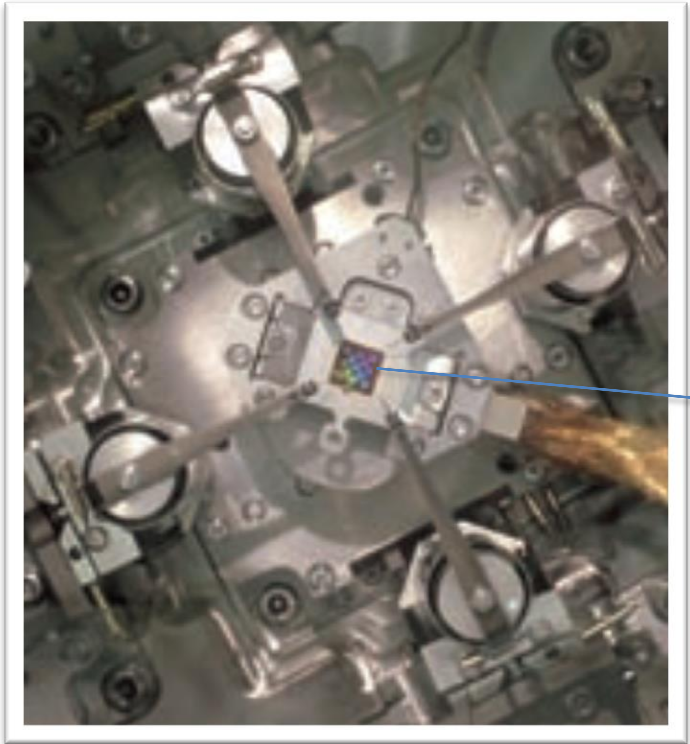
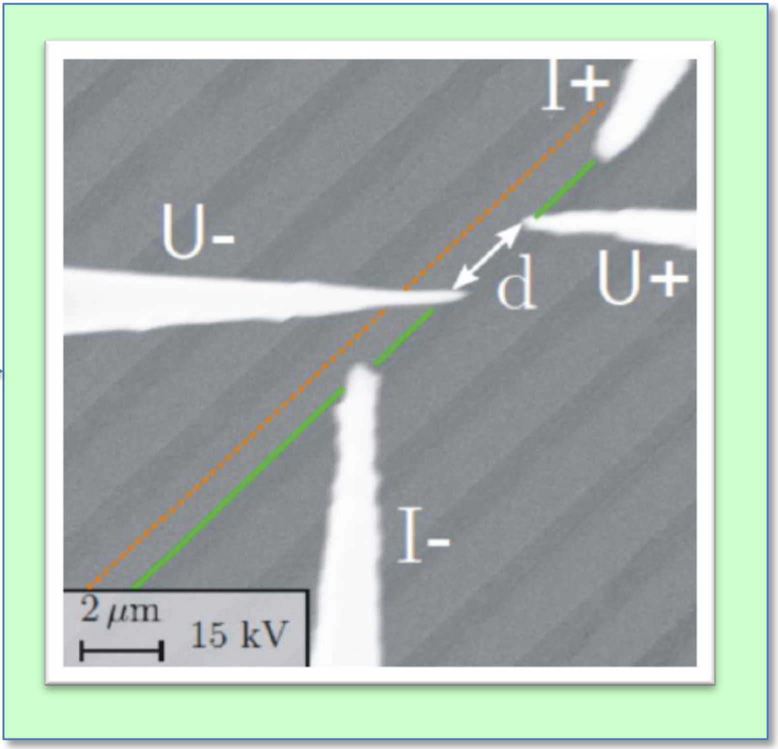
(Nature 506, 349, 2014)



Multiprobe, in-situ transport measurements

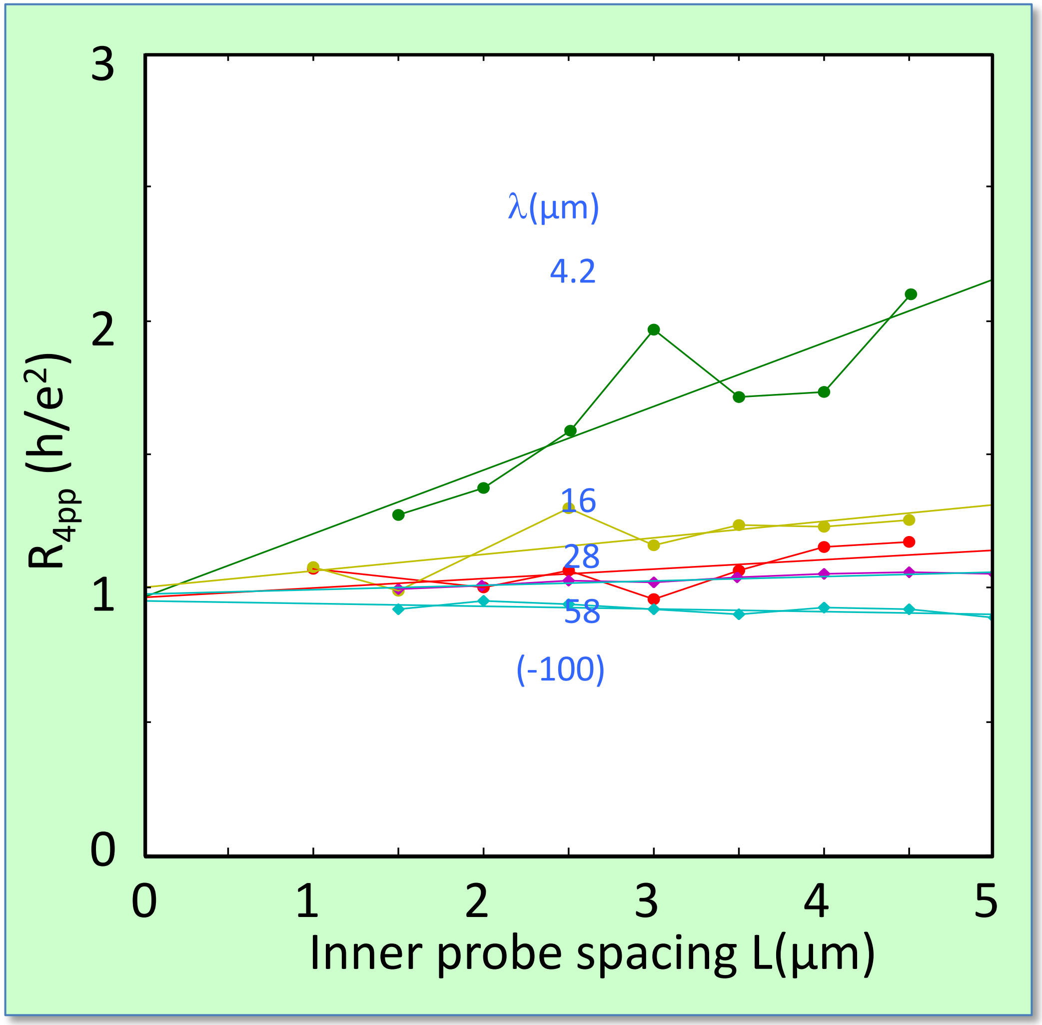


Omicron nanoprobe system
(Tegenkamp group Hannover)



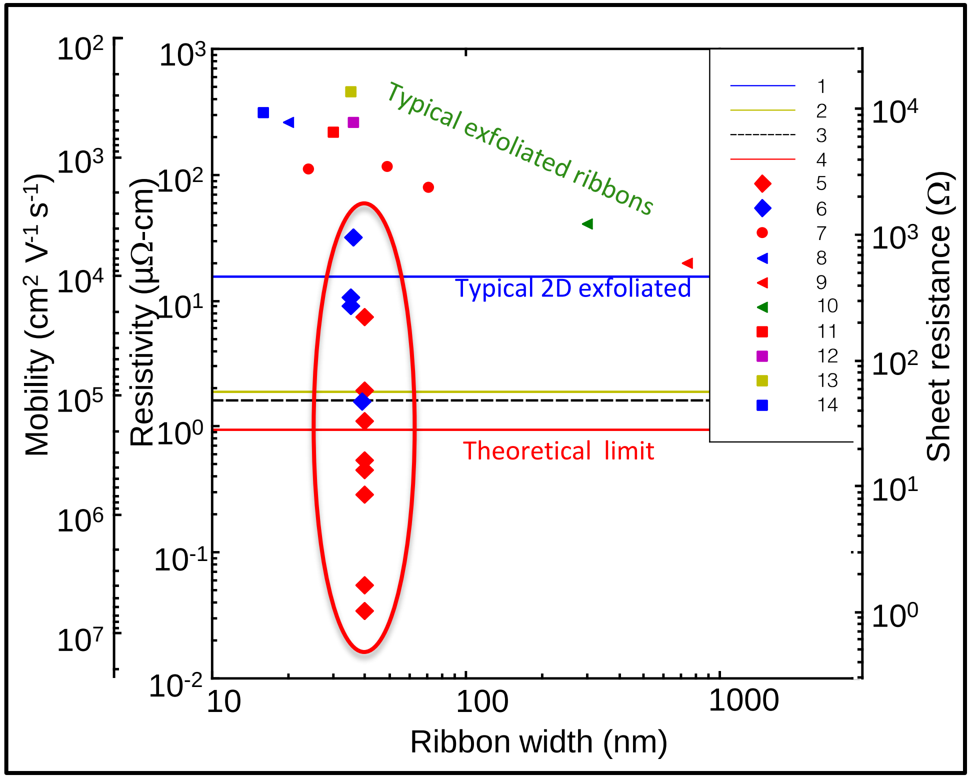
SEM image of 4 probes positioned on a sidewall ribbon
Outer probes supplying a current.
Inner probes measure potential.

Multiprobe, in-situ transport measurements



Four-point (R4pt) and two-point (R2pt) resistances as a function of probe spacing L.

Room temperature resisitivies and mobilities

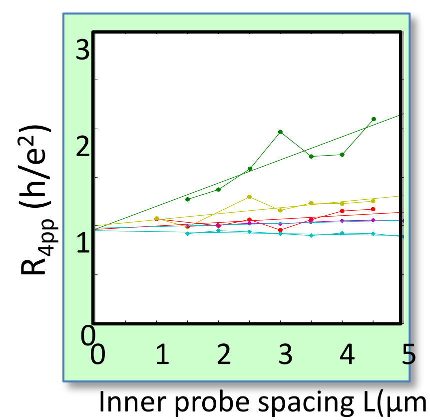


How to determine resistivity unambiguously

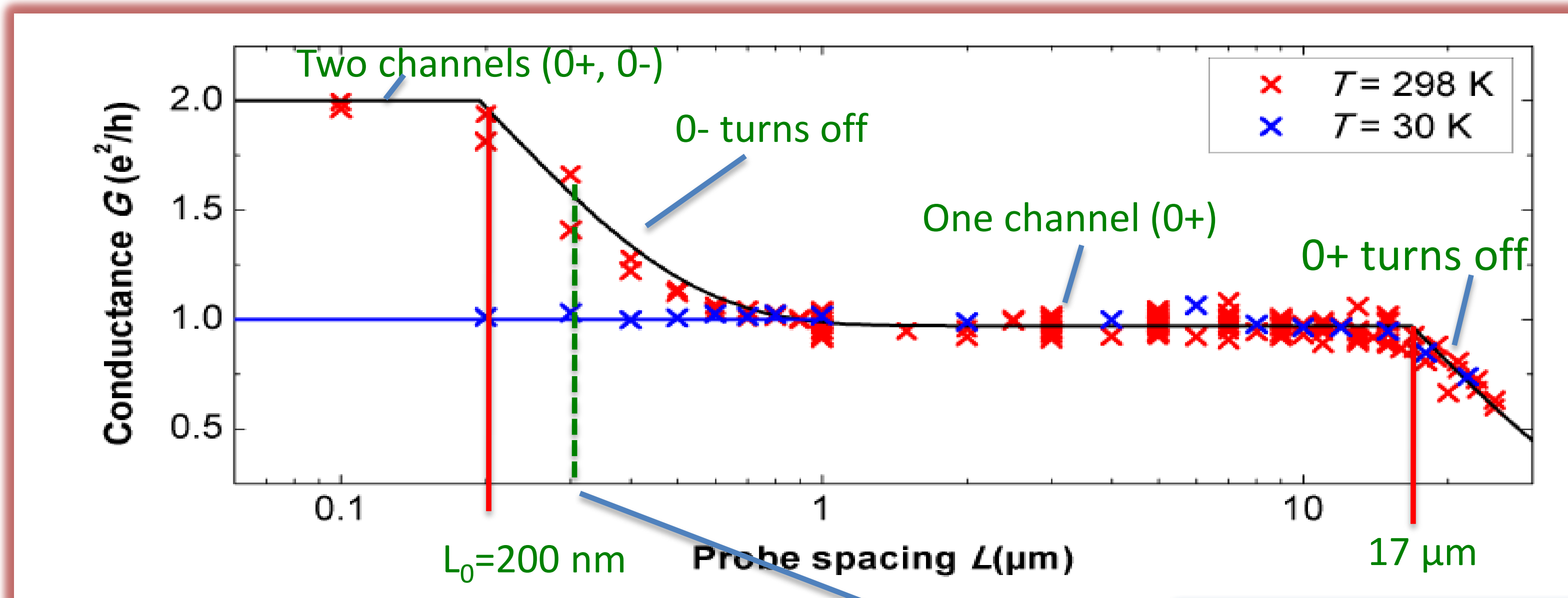
$$R = r \frac{Length}{Width.Thickness}$$

$$r = \frac{¶R}{¶L} W.T$$

Measuring dR/dL eliminates contact resistances



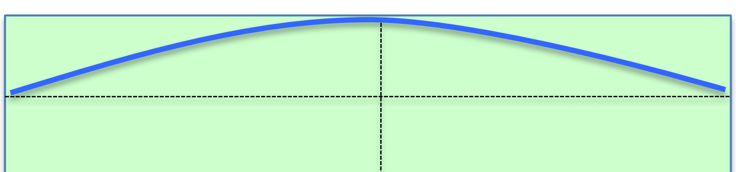
Ribbon conductance versus probe spacing and temperature

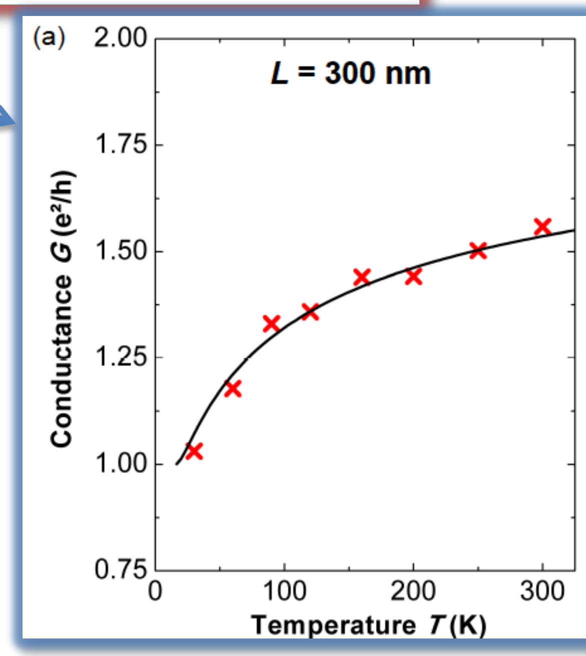


$G=1+\exp(-T/T_0)$ $(L\leq L_0)$

$G=1+\exp(1-L/L_0)\exp(-T/T_0)$ $(L>L_0)$

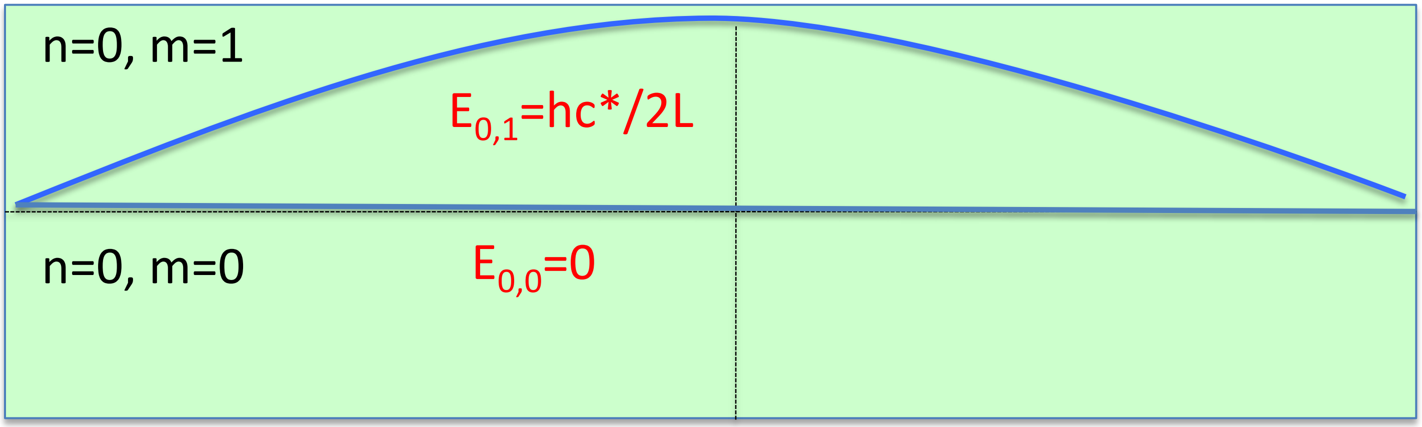
$T_0=hc^*/k_BL$





The 0- mode is the lowest longitudinal excitation of the ribbon,
i.e. the n=0, m=1 state

Longitudinal excitations of quasi particles



- *What are the quasi particles?*
- *They are Fermions and appear to have large magnetic moments.*
- *They seem to have finite, temperature independent lifetimes!*
- *Could they be composite particles (charged excitons)?*

Summary

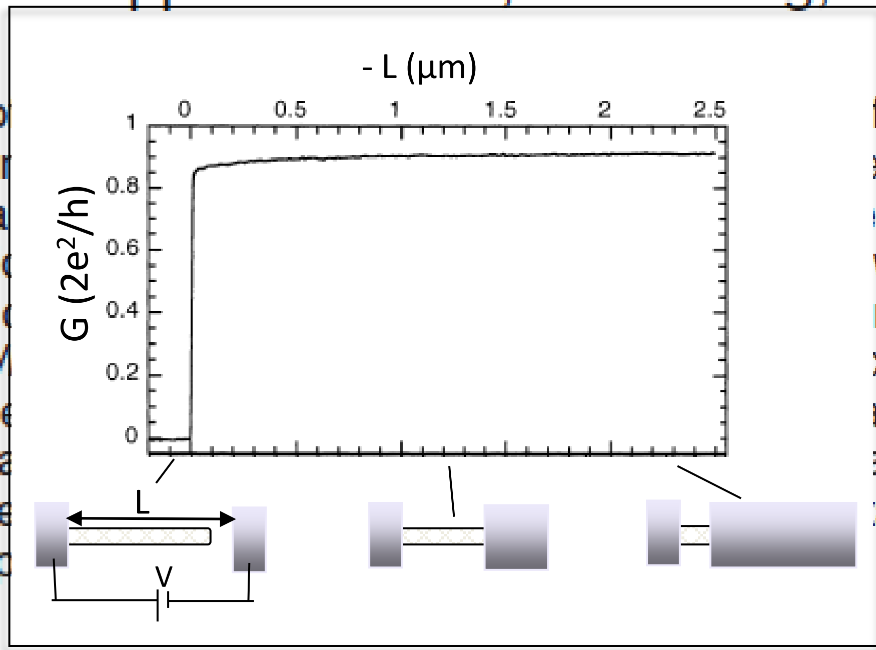
Transport in neutral epigraphene nanostructures is exceptional, with no counterpart in any other material system.
A new kind of quasiparticle is involved whose properties are ideal for a new form of electronics.

SCIENCE • VOL. 280 • 12 JUNE 1998

Carbon Nanotube Quantum Resistors

Stefan Frank, Philippe Poncharal, Z. L. Wang, Walt A. de Heer*

The conductance o[…] found to be quantized. The experimental r[…] of nanotubes by replacing the tip of a[…] fiber, which could be lowered into a liqui[…] with a nanotube at the tip of the fiber. The […]nit of the conductance quantum $G_0 = 2e^2/$[…] current ballistically and do not dissipate he[…]anometers wide and 4 micrometers long, a[…]and stability than other typical room-tempe[…]able current densities, $J > 10^7$ amperes p[…]



Conductance is ballistic at room temperature.

$G \approx G_0 = 2e^2/h$ ($\approx 1/13k\Omega$). Theoretically it should be $2G_0$

Current densities exceeding 10,000 µA/µm are sustained