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SPRING COLLEGE ON SCIENCE AT THE NANOSCALE
(24 May - 11 June 2004)

ELECTRONIC / THERMAL TRANSPORT - Part III

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These are preliminary lecture notes, intended only for distribution to participants.

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Electric and Thermal Transport in Nanoscale Materials –Part III

Philip Kim

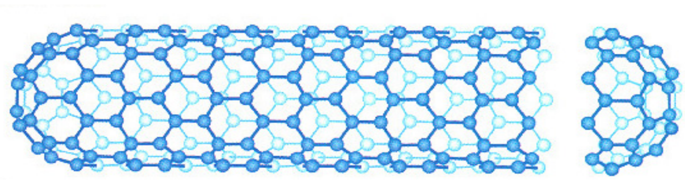
Department of Physics
Columbia University

Outline

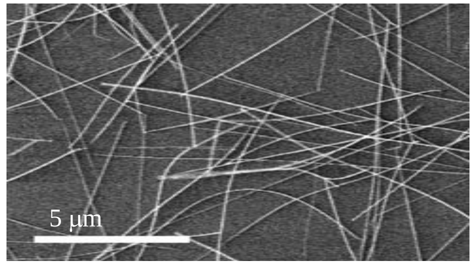
- Charge Transport and Energy Dissipation
- Mesoscopic Heat Transport Measurements
- Mesoscopic Thermoelectric Effects
- Field Effect Transport in 2D Crystallites

Nanoscale Materials

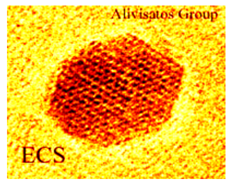
- Carbon Nanotubes

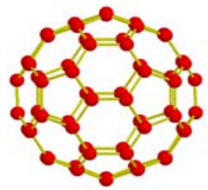


- Nanowires

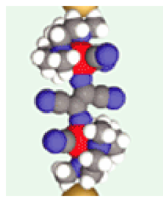


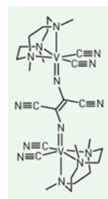
- Nanocrystals, Fullerenes



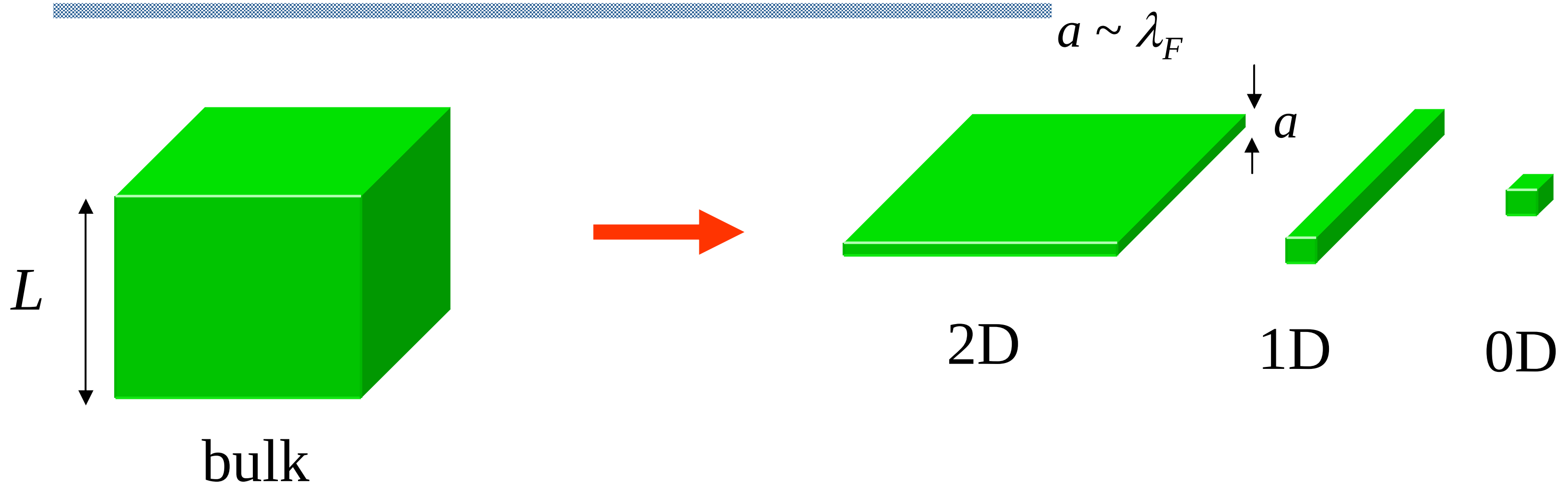


•Molecules





Electron Transport Low dimensional Nanostructures



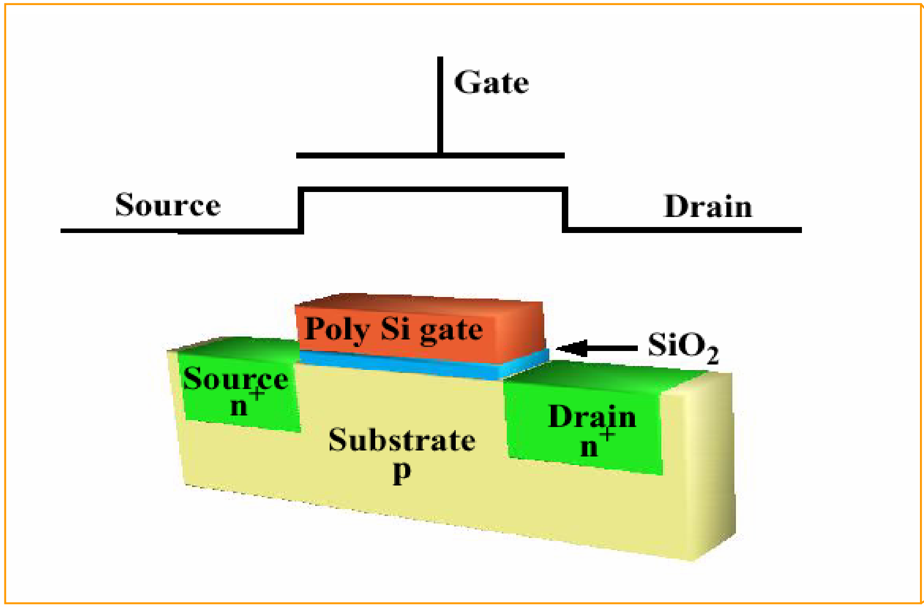
Why low dimensions?

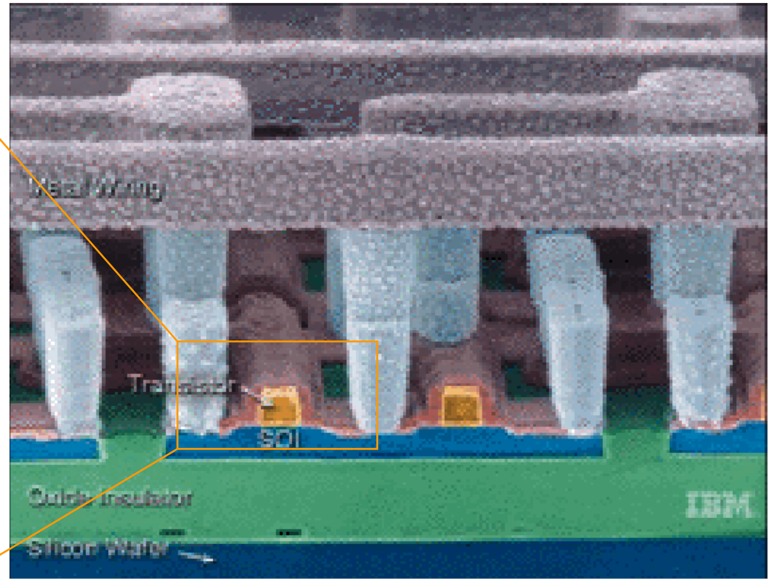
- Fermi surface topology
- Singularities in Density of State
- Strong Interactions
- Strong Fluctuations

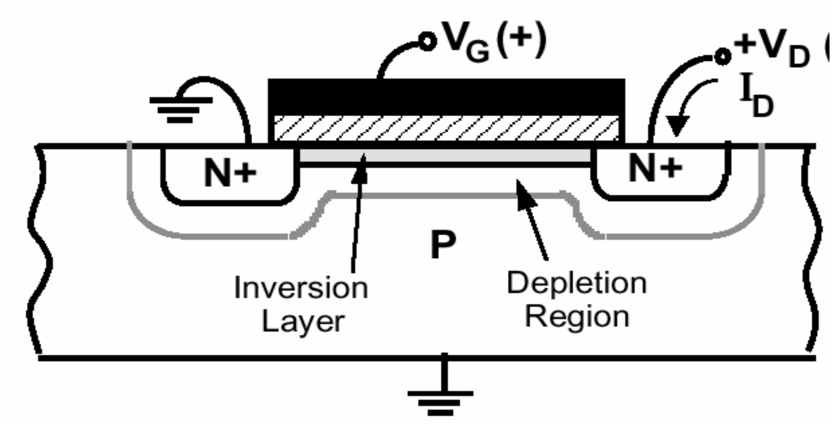
→ New Phenomena

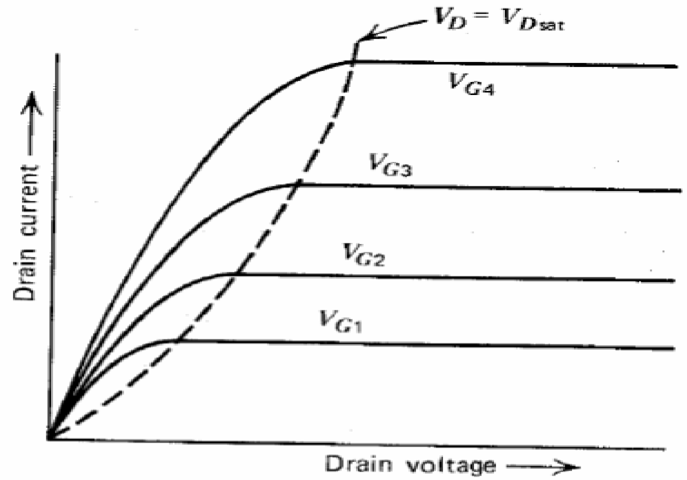
Gate Electric Field Effect: tuning charge density in the samples

Semiconducting Field Effect Device

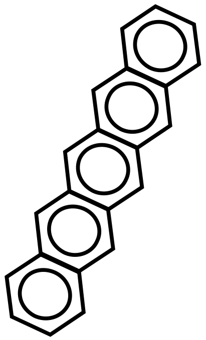




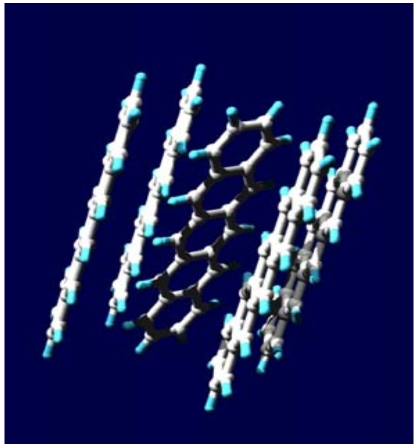




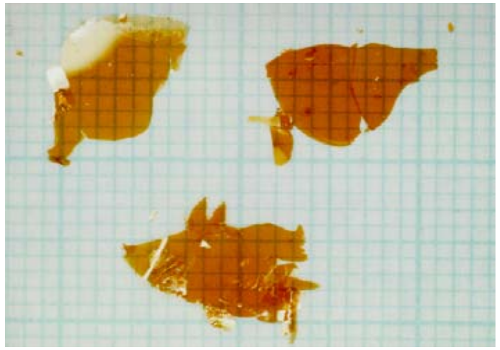
Organic Thin Film : 2D Array of organic molecules



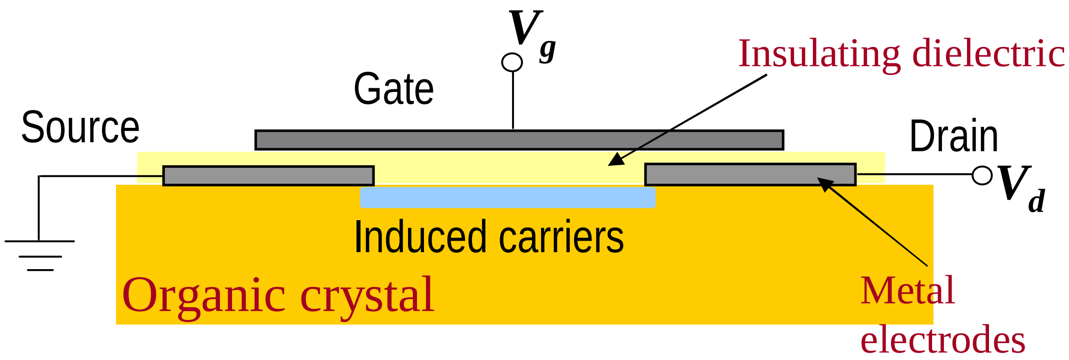
Pentacene

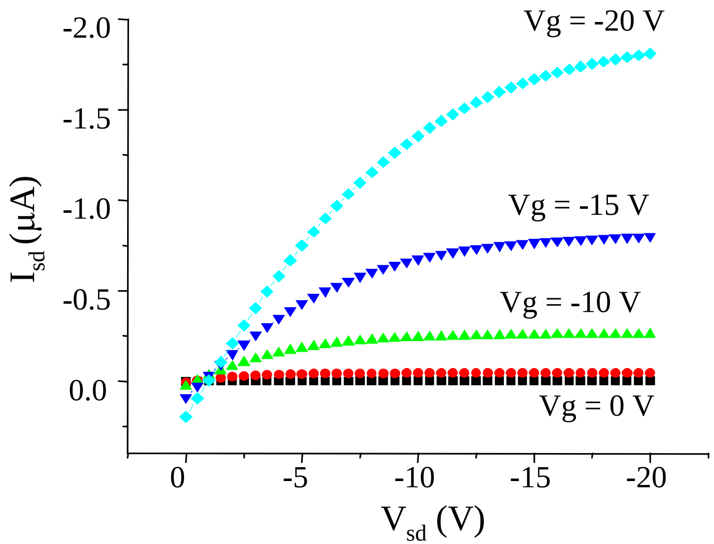


Herringbone packing



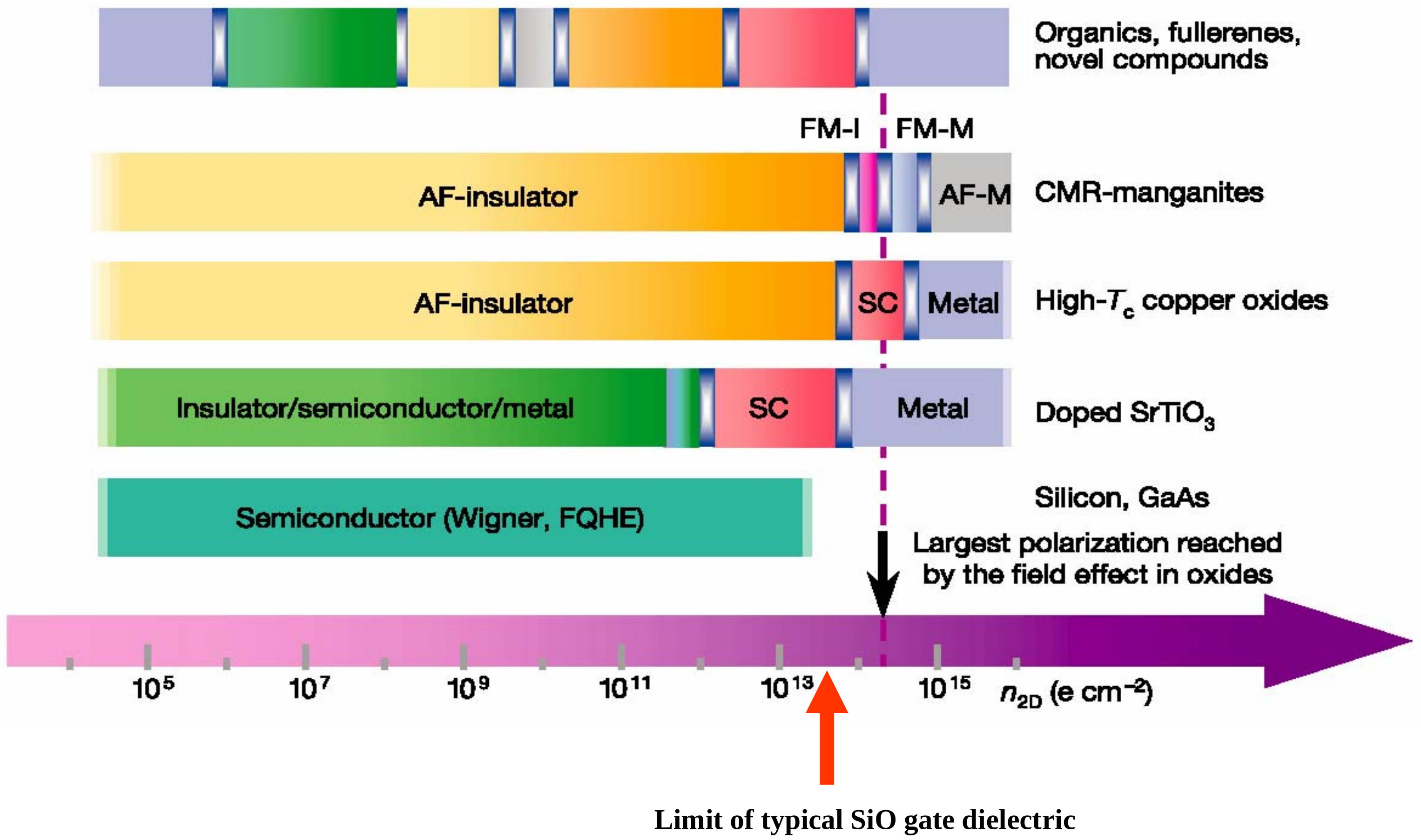
Organic single crystal



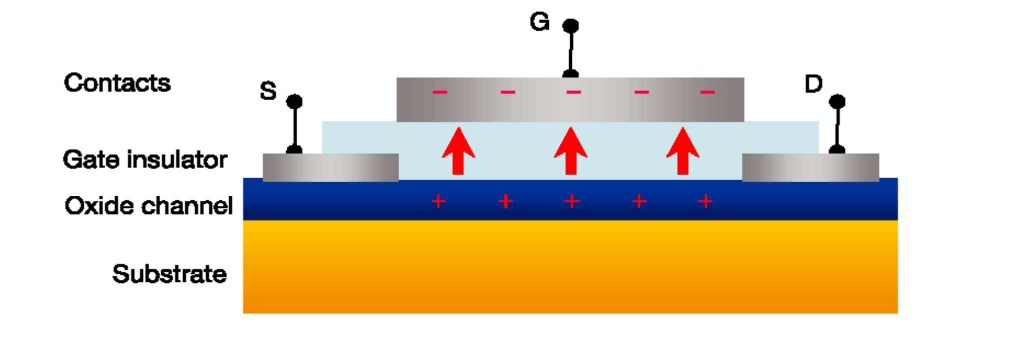


Electric Field Effect in Various Materials

Ahn, Triscone, and Mannhart, Nature 424, 1015 (2003)

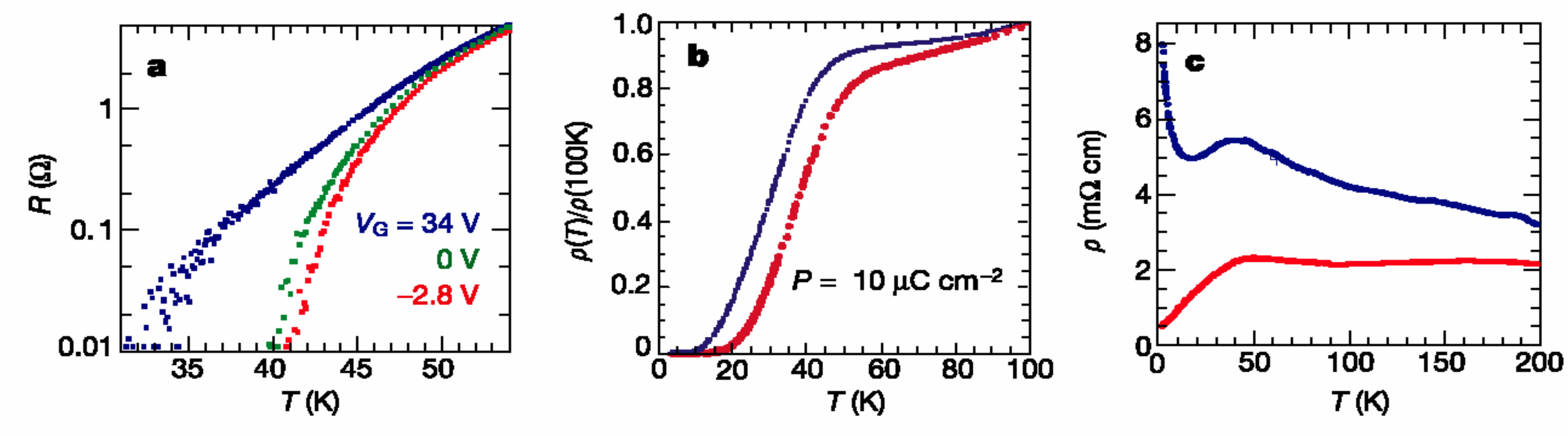


Field Effects in Superconducting Films



Mannhart, J. High-T_c transistors. *Supercond. Sci. Technol.* **9,** 49–67 (1996).

Ahn, C. H. *et al.* Electrostatic modulation of superconductivity in ultra-thin $GdBa_2Cu_3O_7$ films. *Science* **284,** 1152–1155 (1999).

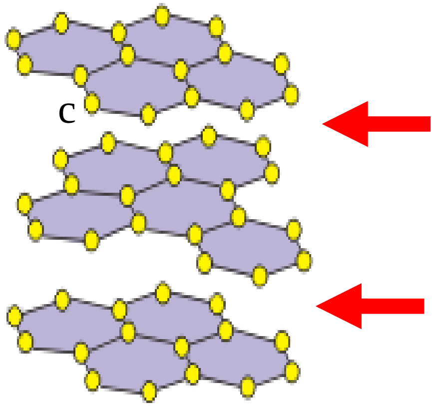


8 nm thick $YBa_2\ Cu_3\ O_{7-d}$ / $BaSrTiO_3$ gate dielectric

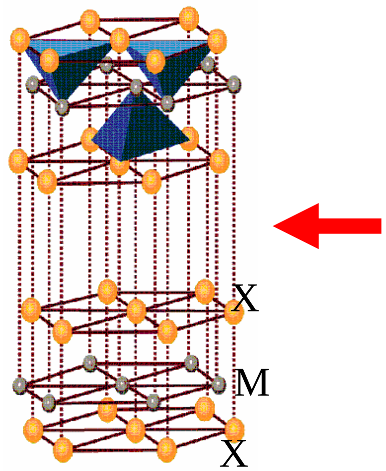
2 nm thick $GdBa_2Cu_3O_{7-d}$ / PZT layer gate dielectric

2 nm thick $GdBa_2Cu_3O_{7-d}$, doped / PZT layer gate dielectric

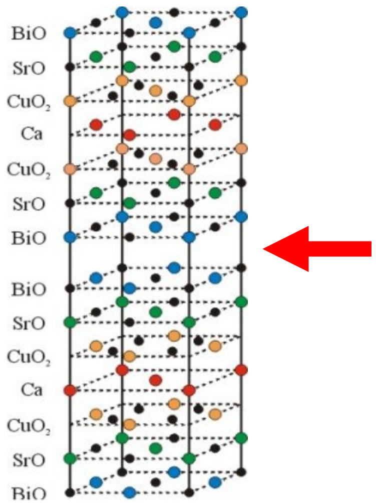
Van der Waals Layered Materials



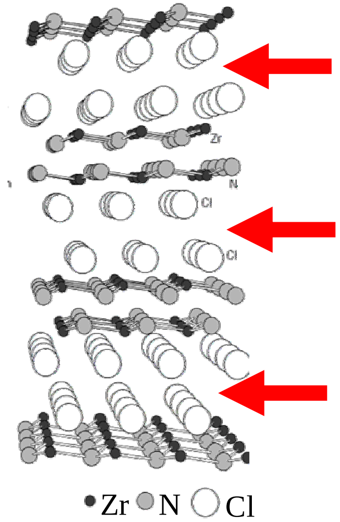
Graphite



Metal-Chalcogenide
(M= Nb, Ta, Va, …
X= S, Se, Te)



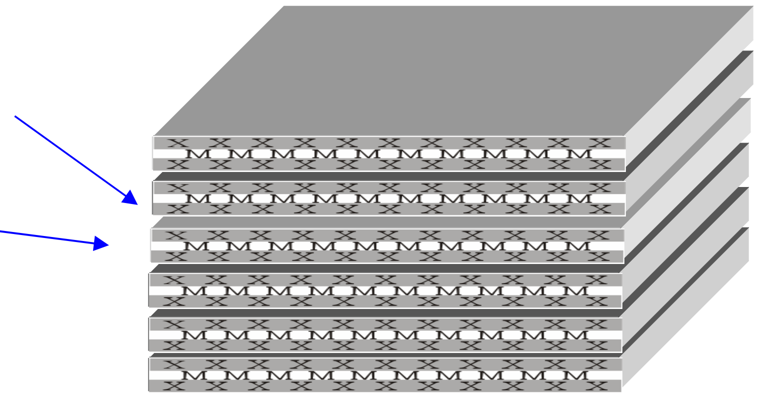
$Bi_2Sr_2CaCu_2O_{8-x}$



β- ZrNCl

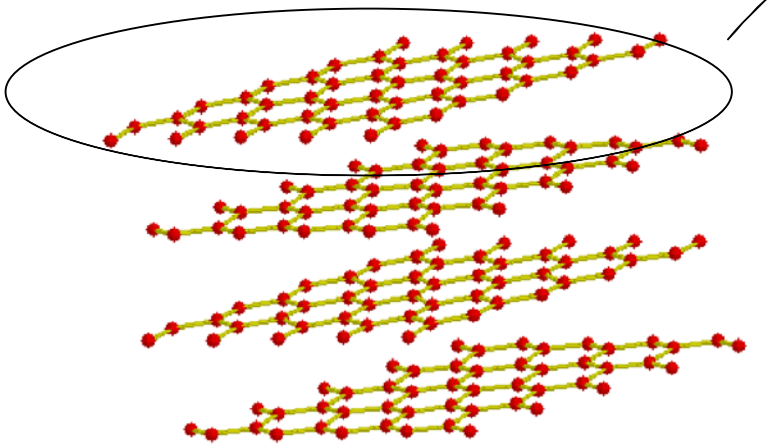
Van der Waals bonding between layers

Covalent bonding within layers

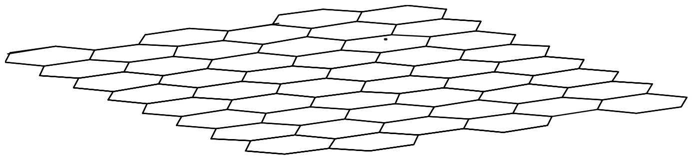


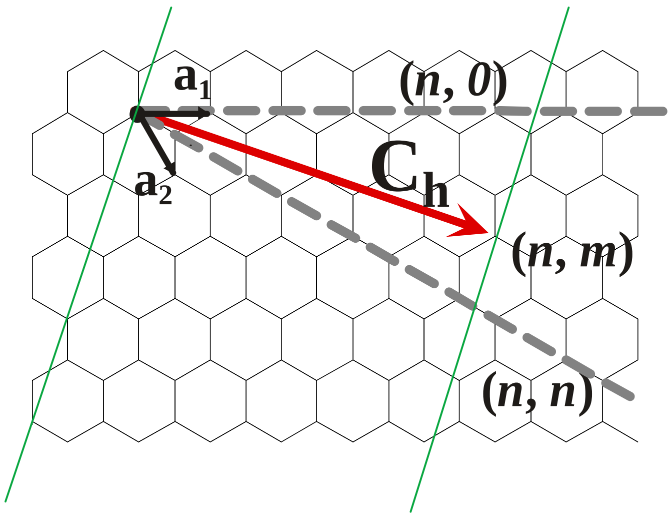
Graphene : Single Sheet of Graphite Layer

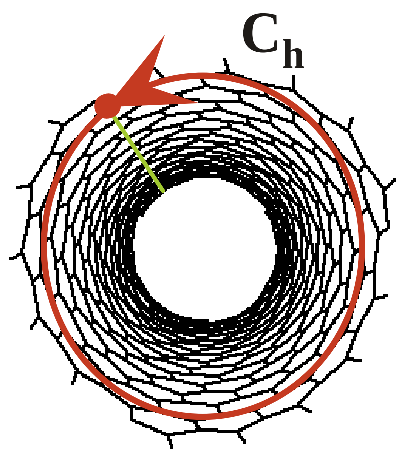
Graphite



Single layer of graphite: graphene



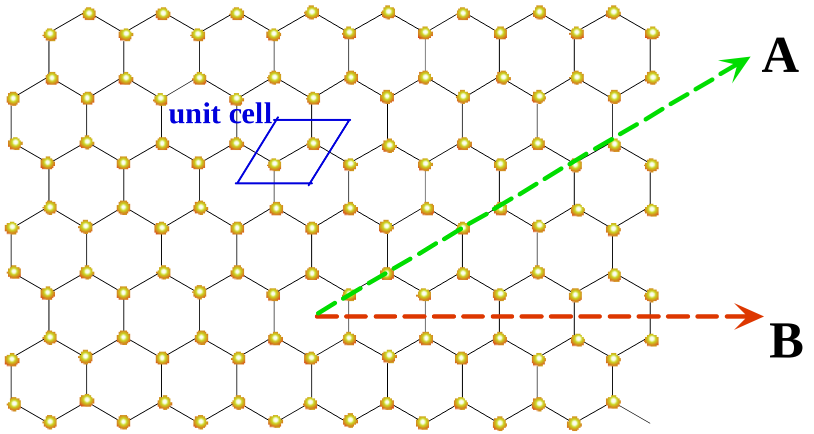




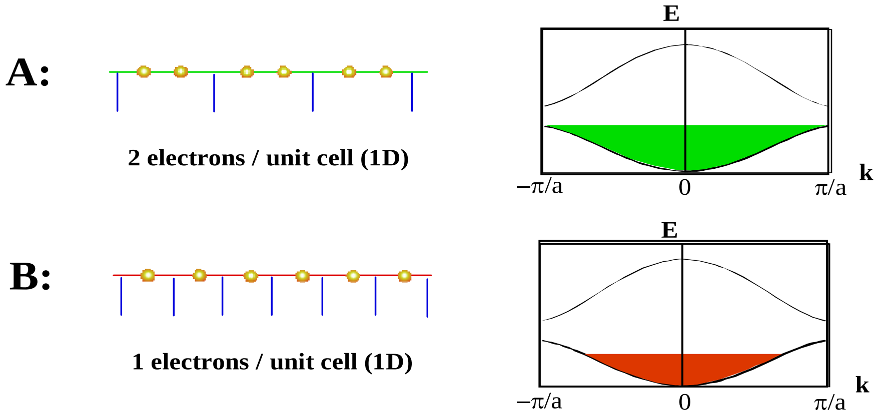
Rolling up graphene along C_h imposes a Periodic boundary condition :

$$\mathbf{C_h} \cdot \mathbf{k} = 2\pi q$$

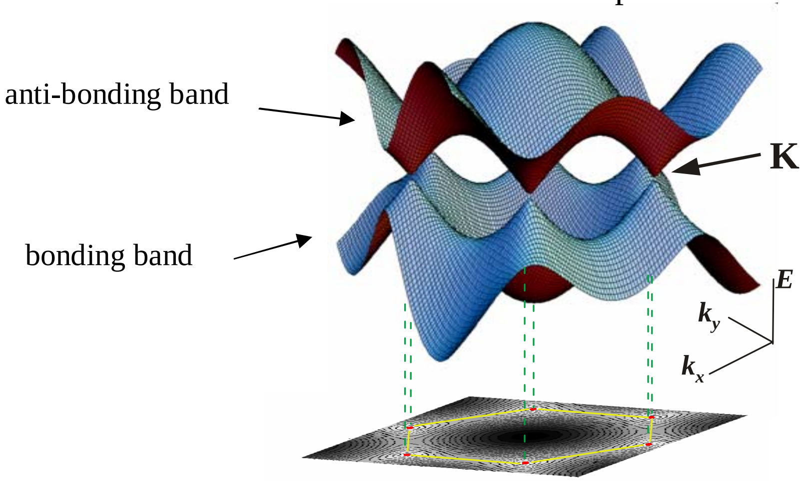
Electronic Band Structure of Graphene



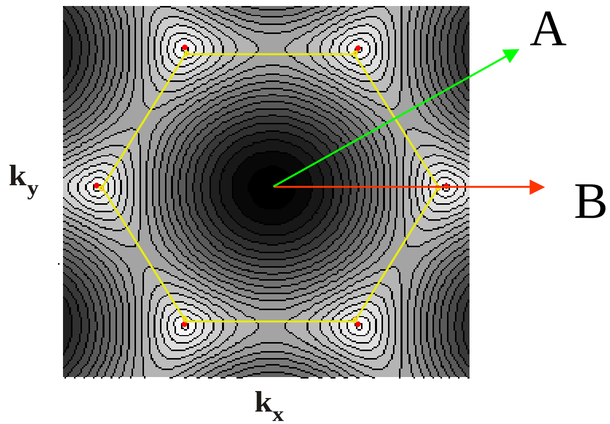
2 electrons / unit cell (2D)



π/π* band of Graphene

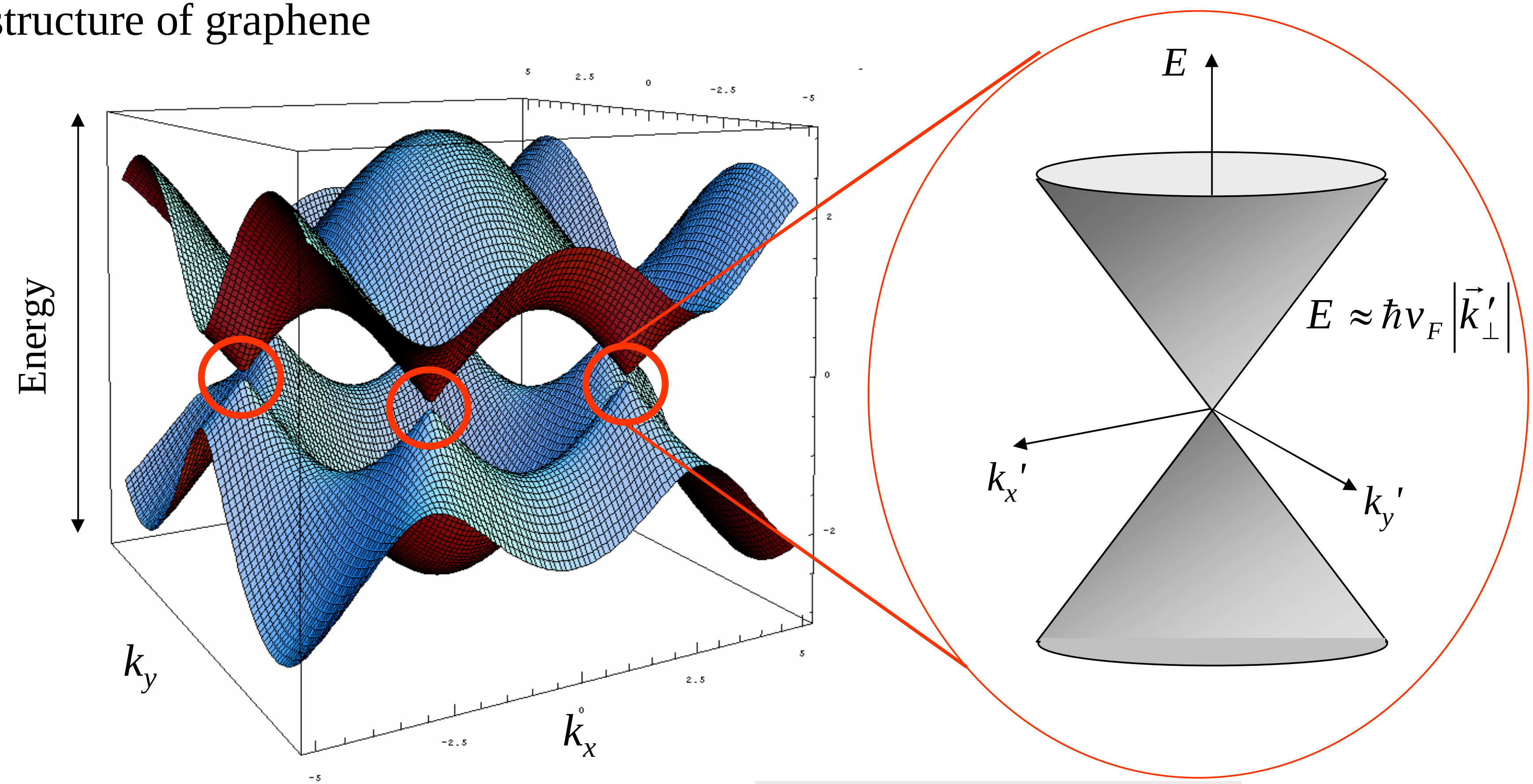


2D Brillouin Zone



Graphene : Dirac Particles in 2D Box

Band structure of graphene



k·p perturbation → Effective Hamiltonian:

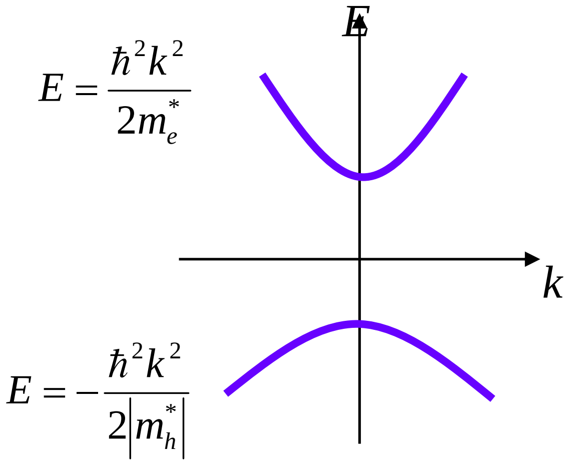
$$H_{eff} = \hbar v_F \, \vec{\sigma} \cdot \vec{k}'_\perp$$

→ "helicity"

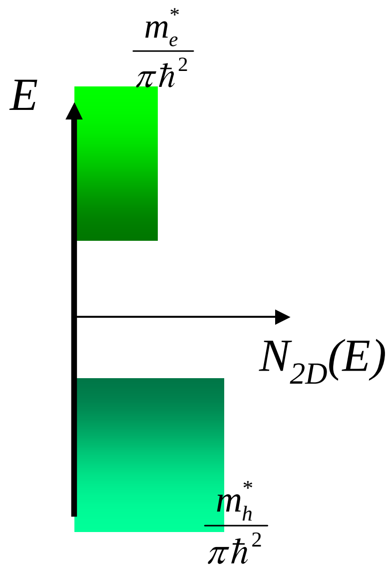
Divincenzo and Mele, PRB (1984)

Graphene v.s. Conventional 2D Electron System

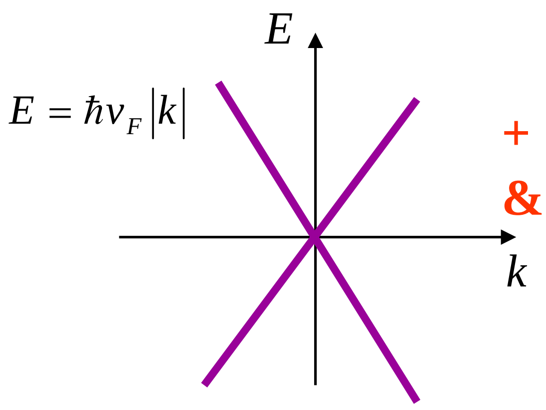
Conventional 2D Electron System



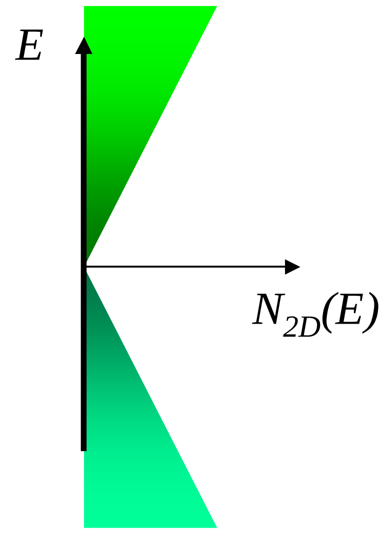
+ Spin



Graphene

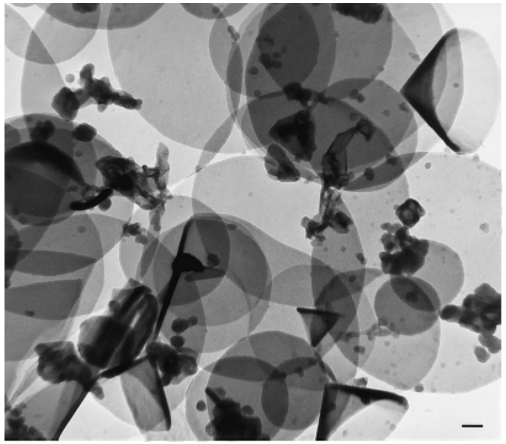


+ Spin
& 'helicity'



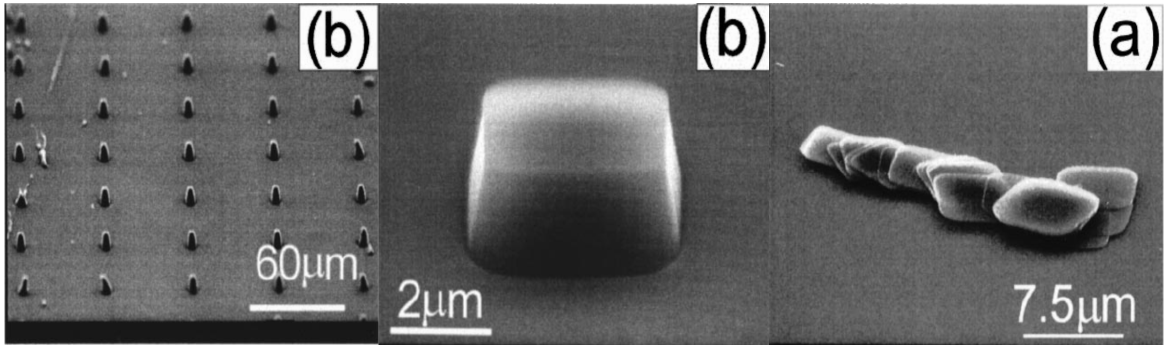
- Zero band mass
- Strict electron hole symmetry
- Electron hole degeneracy

Obtaining thin graphite crystallites – Previous Efforts



A. Krishnan et. al. Nature 1997

By product of carbon nanotubes: disordered



Patterned Graphite Crystallites

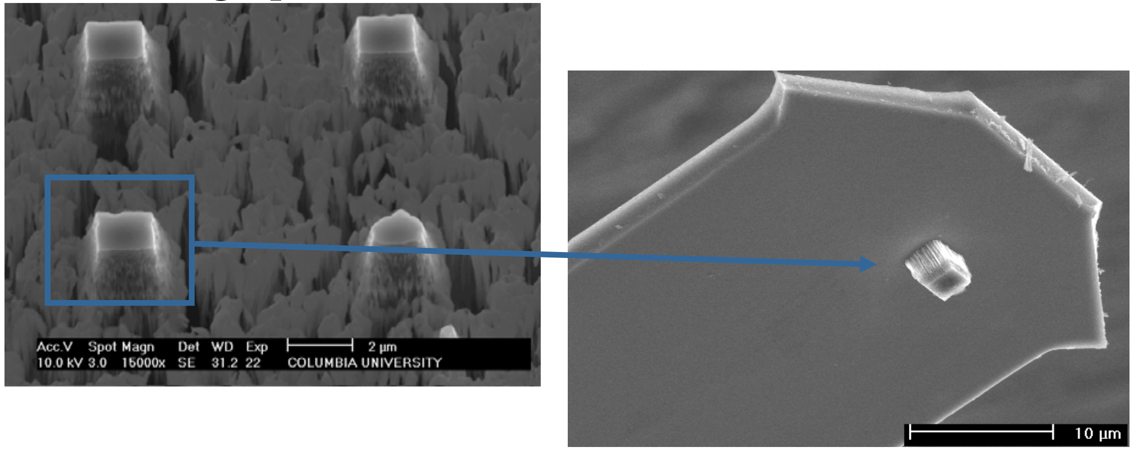
Xuekun Lu et. al. APL 1999

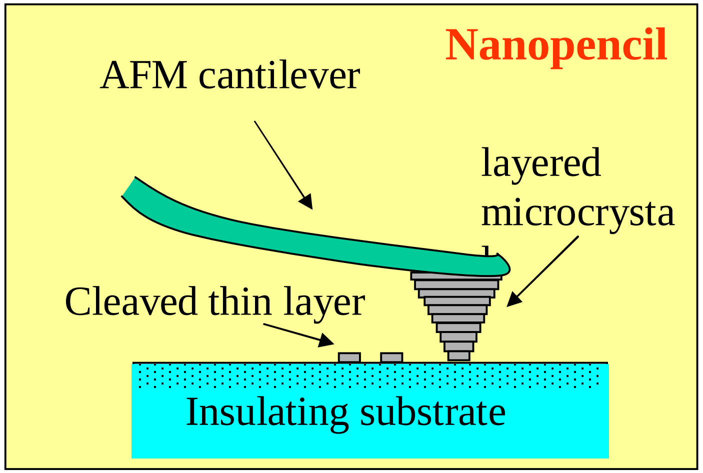
Thinnest crystal reported ~ 30nm

No Systematic transport study

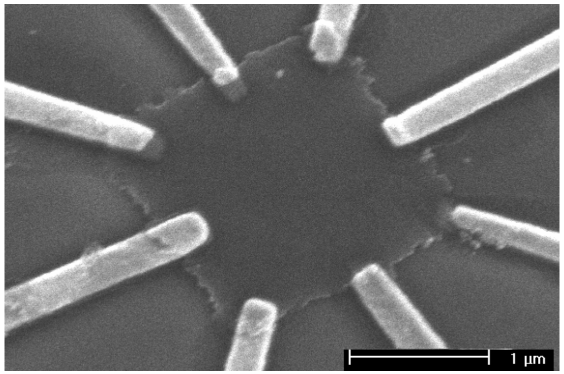
Graphite Nanocrystals Hybrid Device

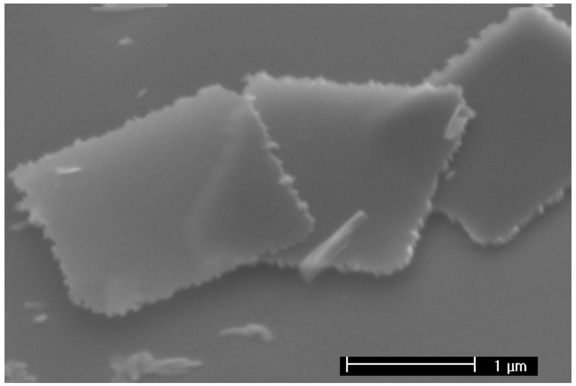
Patterned graphite blocks





microfabricated device

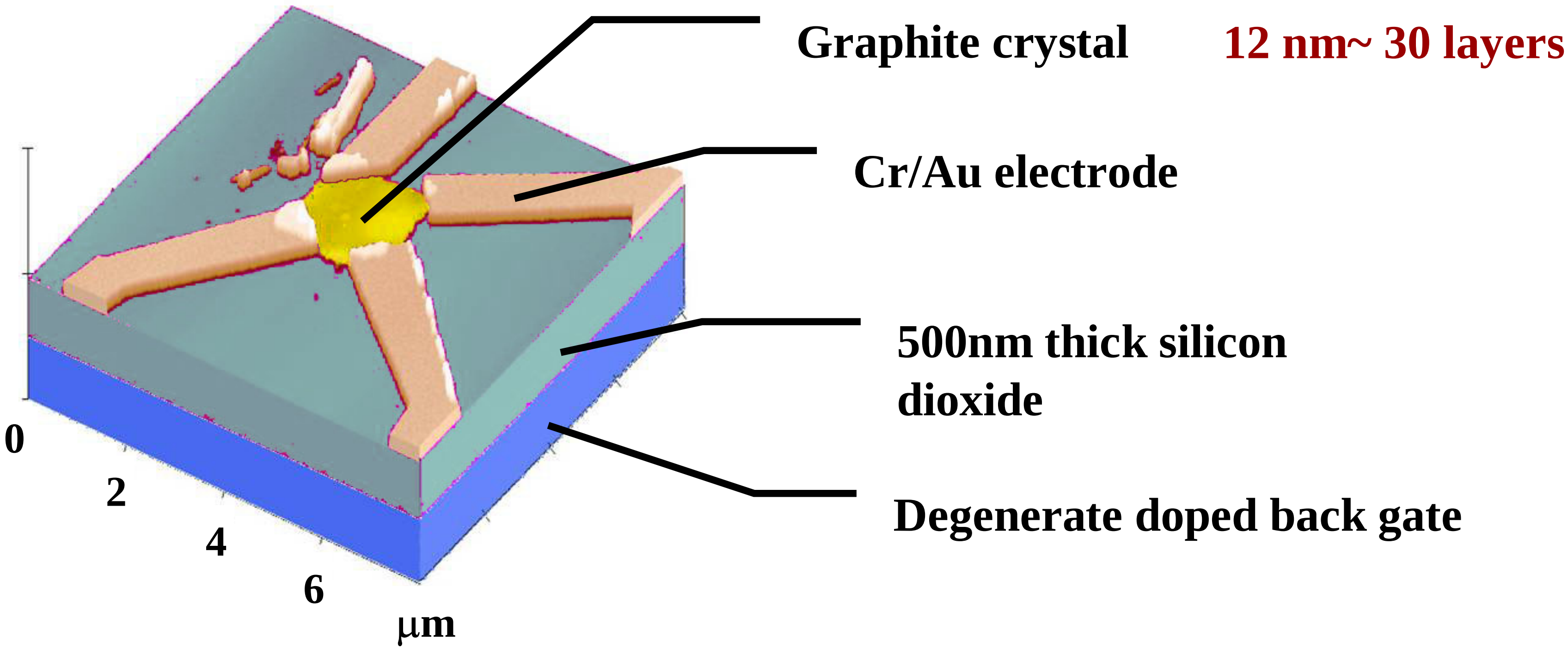




cleaved nanocrystals
5 - 100 nm thick

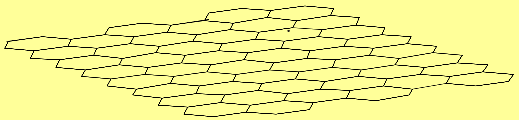
Device Structure

Thin Graphite Crystal Device Fabricated Using Electron Beam Lithography

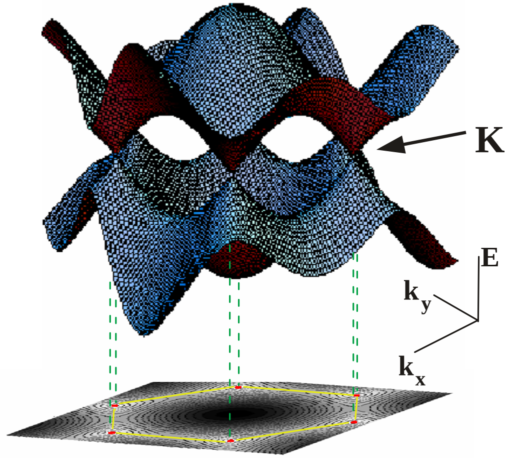


Band Structure of Graphite

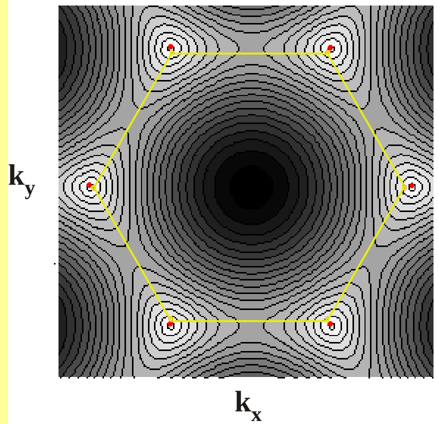
Graphene



π/π* band of Graphene

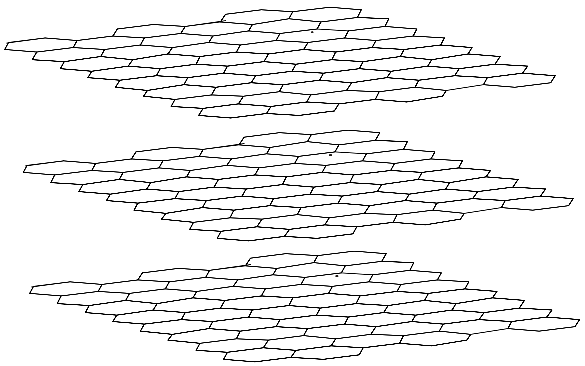


2D Brillouin Zone

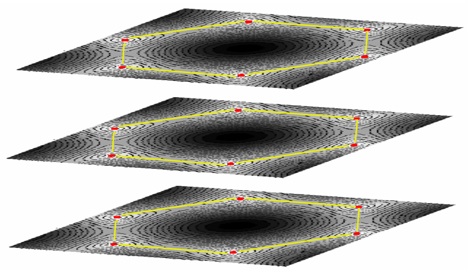


Graphite

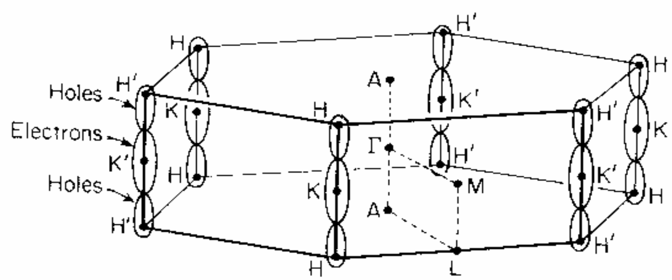
real space



k space

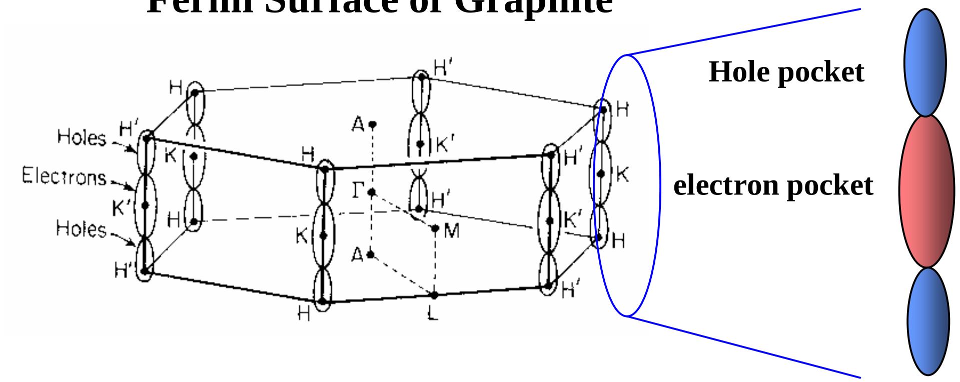


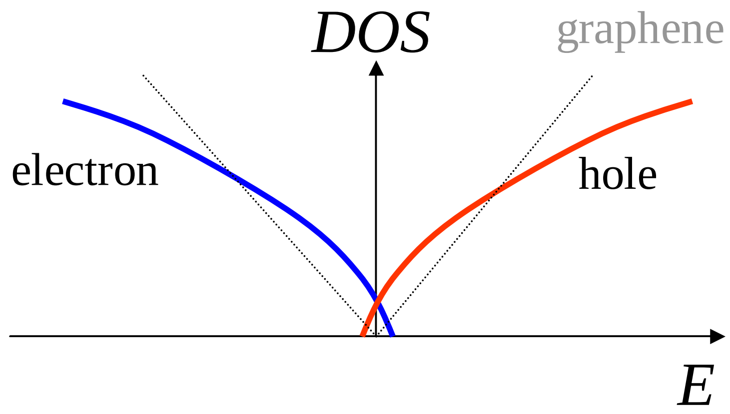
Fermi surface

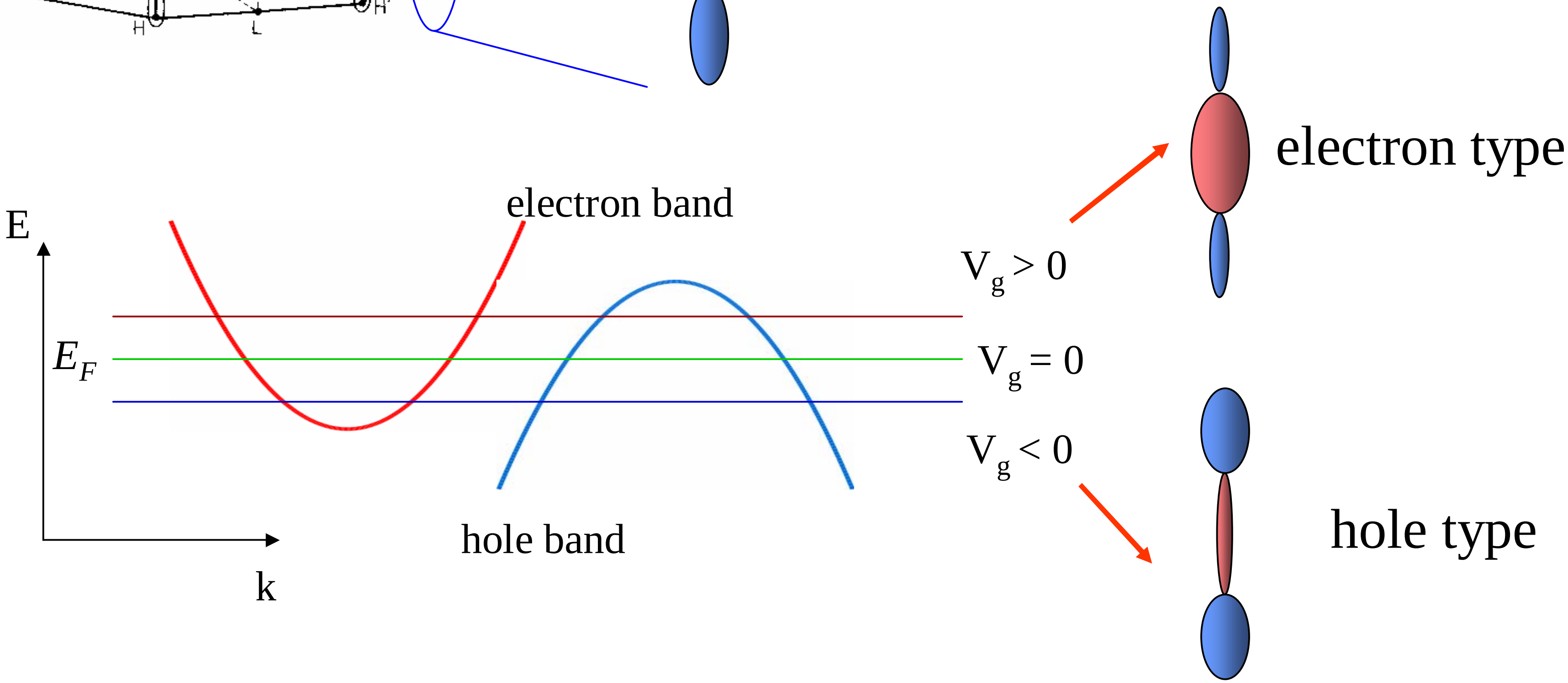


Two Band Model

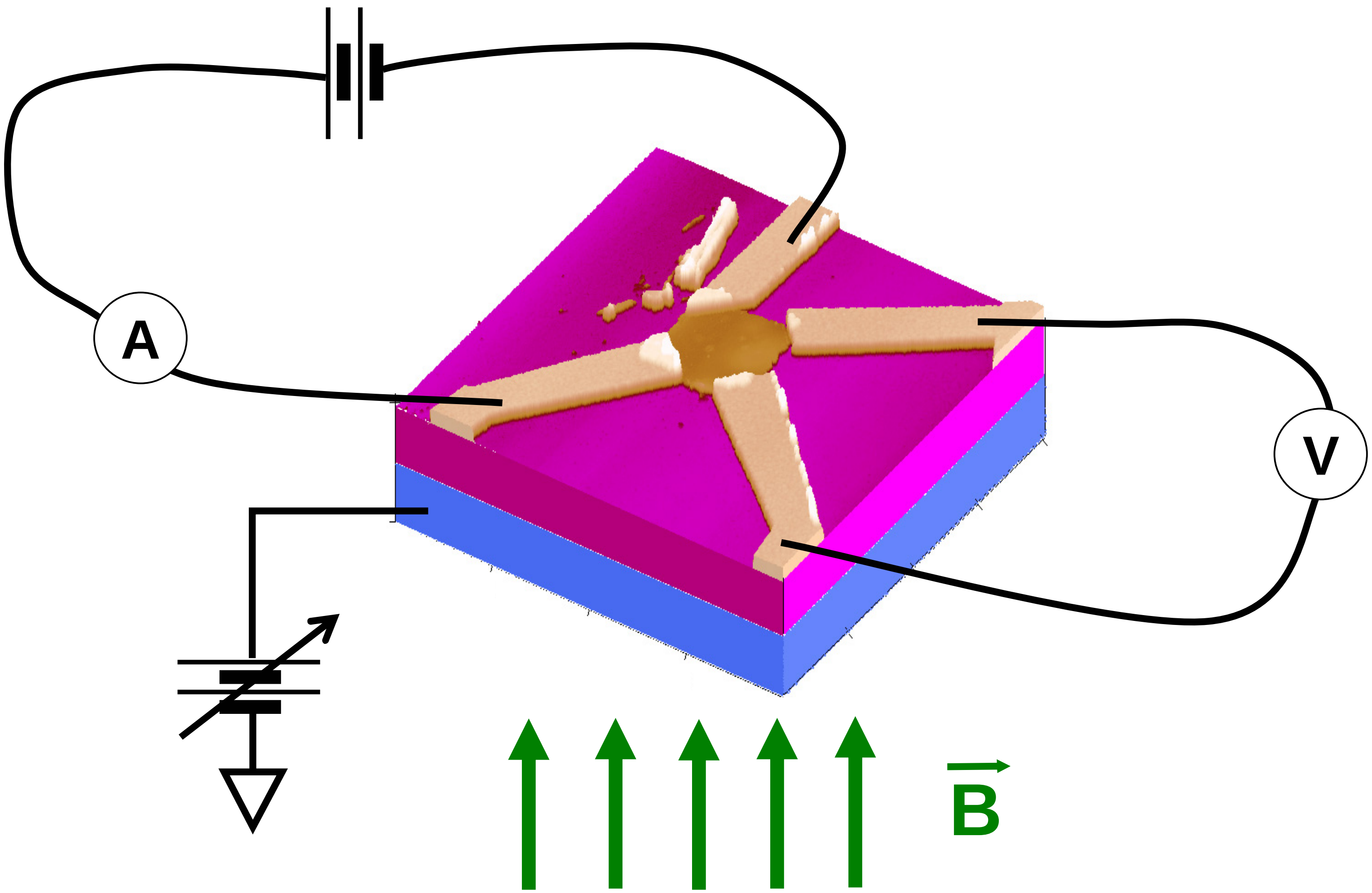
Fermi Surface of Graphite



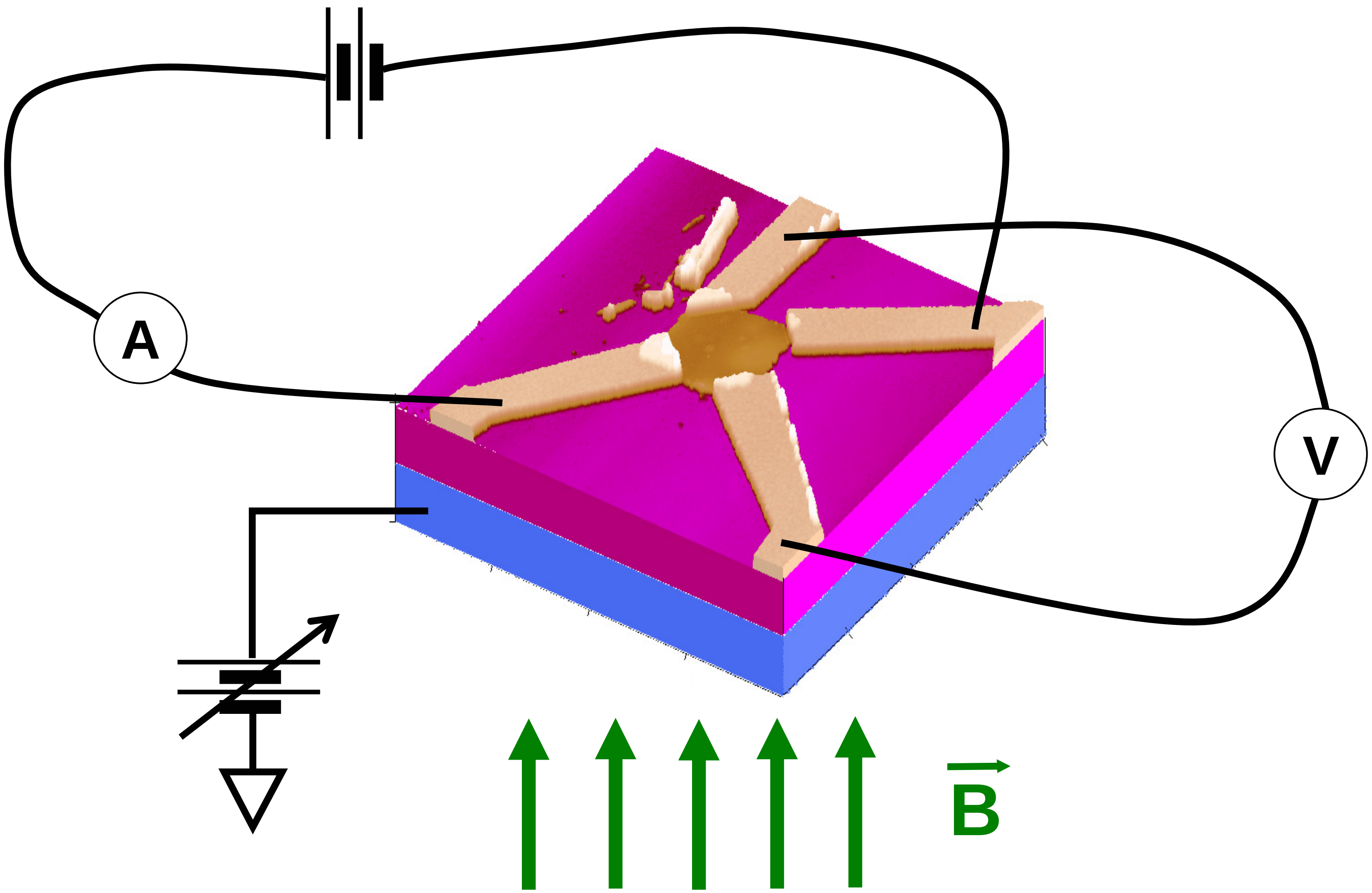




Magneto-resistance Measurement



Hall Measurement



Magneto and Hall Resistance in Two Band Model

resistivity tensor: $\overleftrightarrow{\rho}_j = \begin{pmatrix} \rho_j & -R_j B \\ R_j B & \rho_j \end{pmatrix}$ j: band index, R_j=-1/en_j, ρ_j= 1/$e\mu_j n_j$

$$\rho = \frac{\rho_1\rho_2(\rho_1+\rho_2)+(\rho_1 R_2{}^2+\rho_2 R_1{}^2)B^2}{(\rho_1+\rho_2)^2+(R_1+R_2)^2 B^2}$$

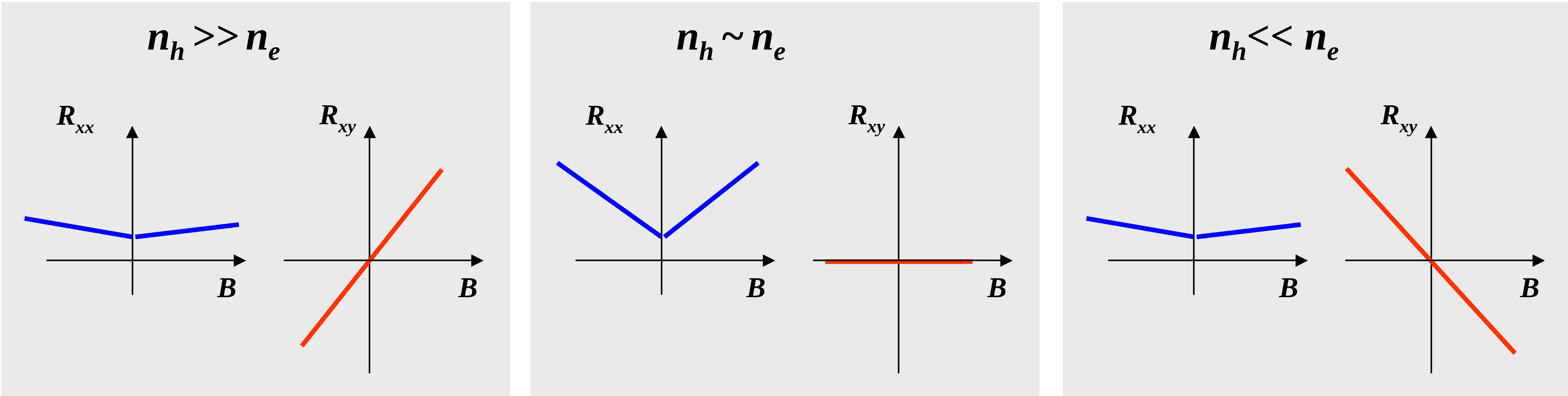
$$R = \frac{R_1\rho_2{}^2+R_2\rho_1{}^2+R_1R_2(R_1+R_2)B^2}{(\rho_1+\rho_2)^2+(R_1+R_2)^2 B^2}$$

Small B,
$\mu_e = \mu_h$
$n_e + n_h = const.$

→

Magnetoresistance: $\Delta R_{xx} \sim n_e\, n_h\, |B|^\alpha$

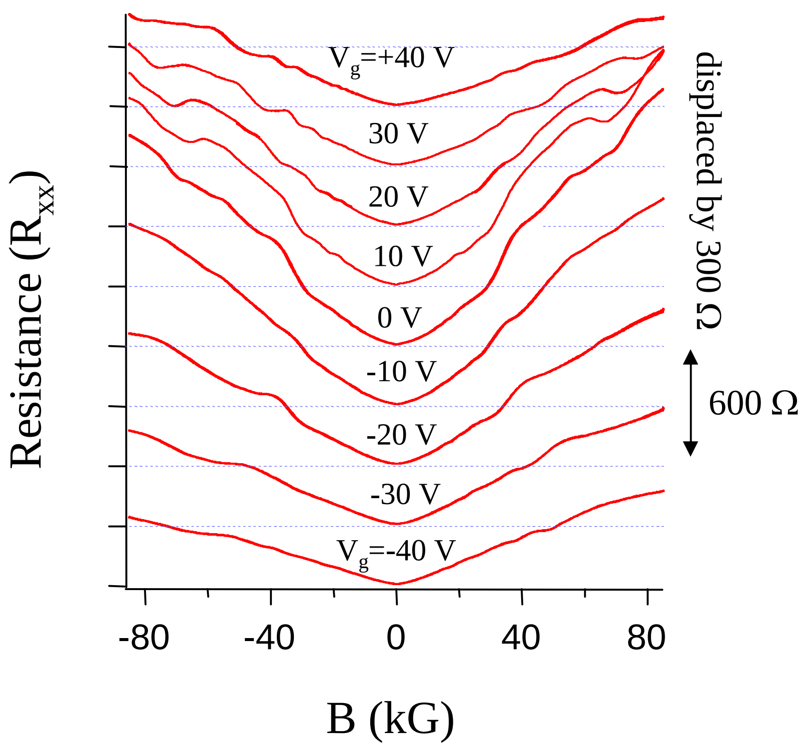
Hall resistance: $R_{xy} \sim (n_h - n_e)B$



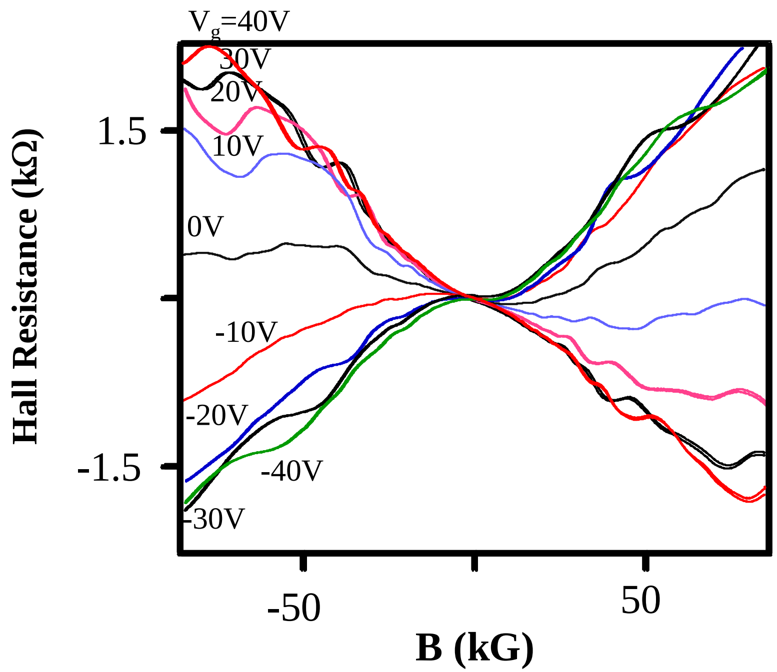
Hall Resistance and Magneto Resistance

Sample: 12 nm thick
T = 1.7 K

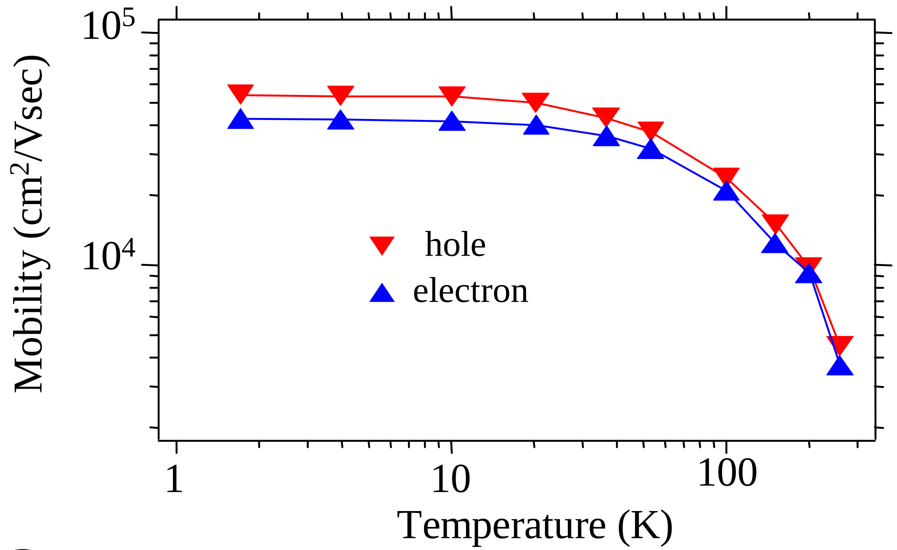
$\Delta R_{xx} \sim n_e n_h B^{\alpha}$

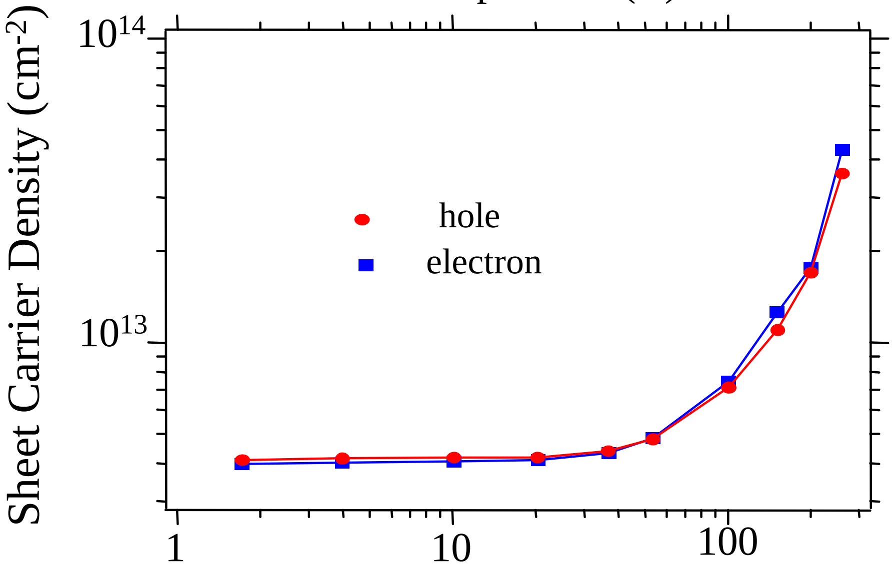


$R_{xy} \sim (n_h - n_e)B$



Mobility and Carrier Density





12 nm Graphite Crystal:

Mobility at 1.7K ~ 50000 cm^2/Vs

Carrier Density at 1.7K ~ $3.3x10^{18}$ cm^{-3}

(sheet charge density ~ $4.0x10^{12}$ cm^{-2}

per a graphene layer ~ $1.2x10^{11}$ cm^{-2})

Bulk graphite:

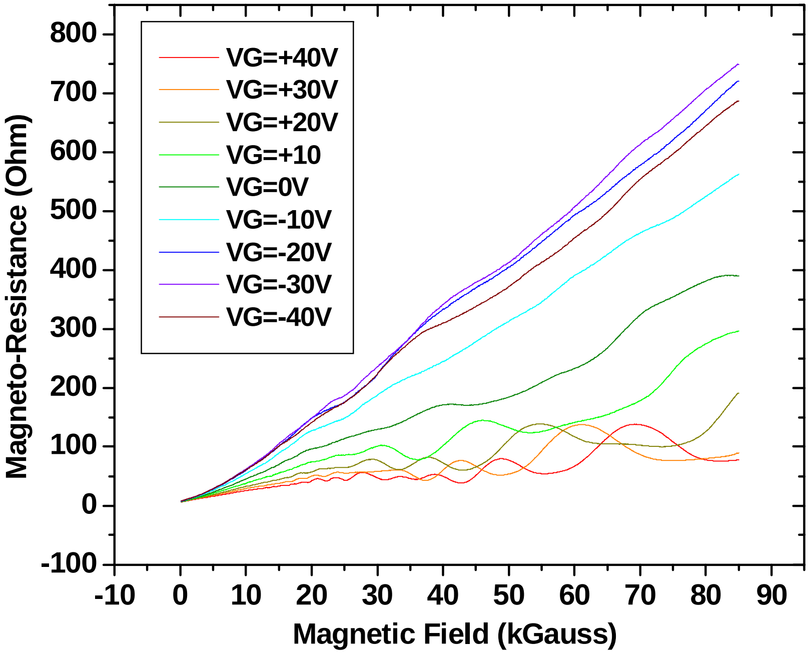
Mobility ~70000 cm^2/Vs

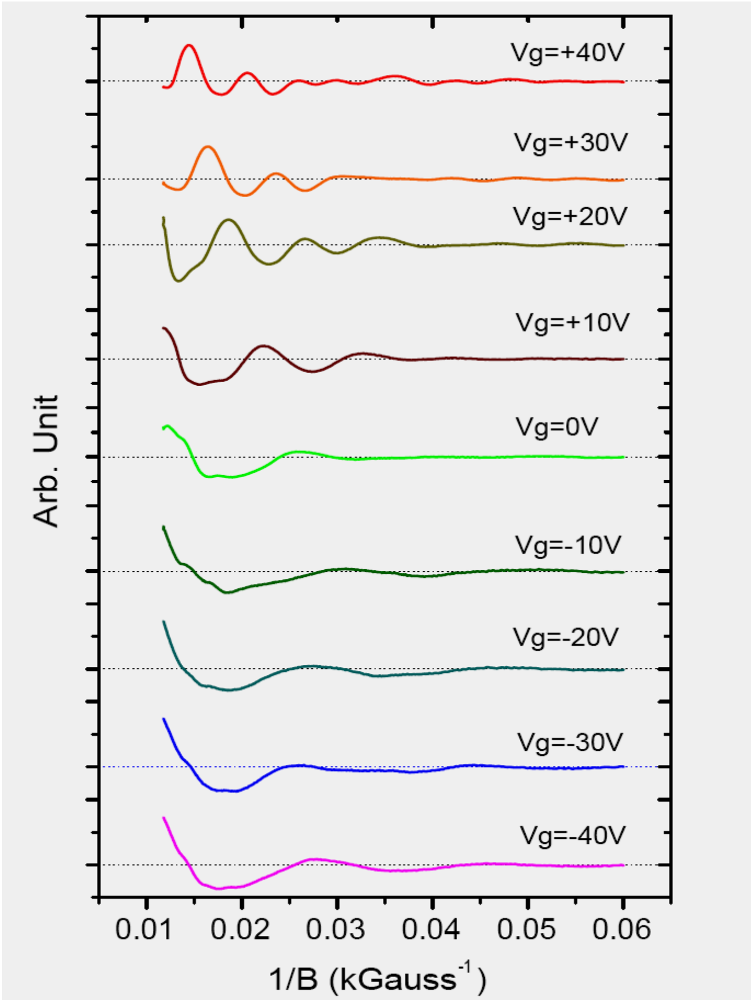
Carrier Density ~ $3x10^{18}$ cm^{-3}

I. Spain et. al., 1967

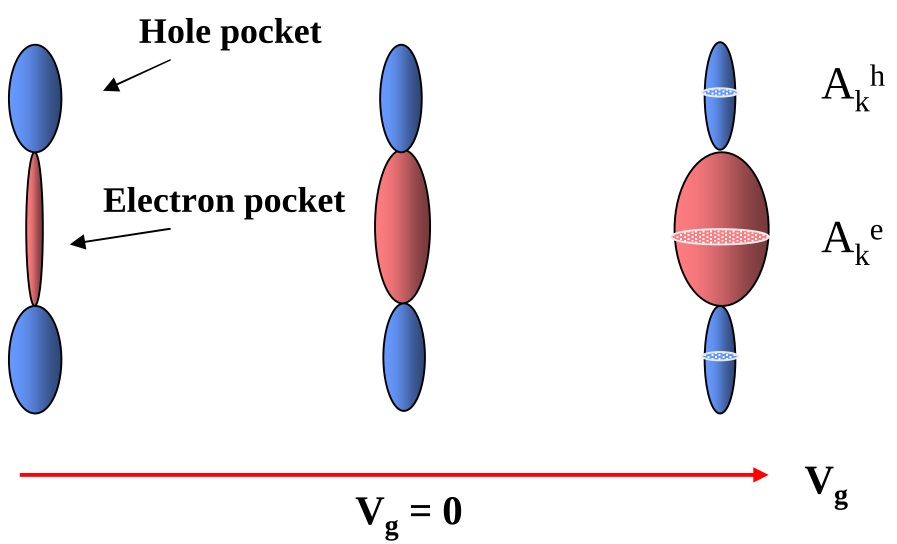
Shubnikov de Haas Oscillations

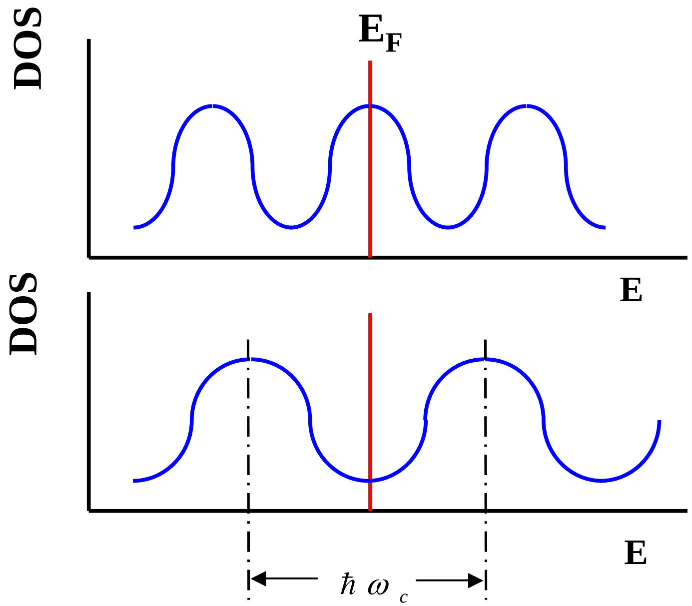
Sample: 12 nm thick
T = 1.7 K





Shubnikov de Haas Oscillation





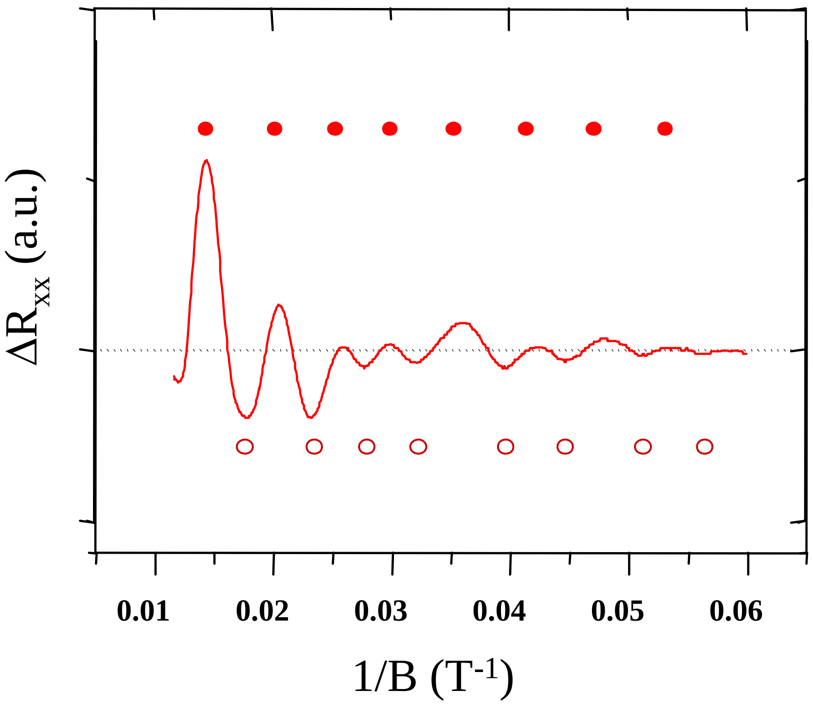
Shubnikov de Haas Oscillation

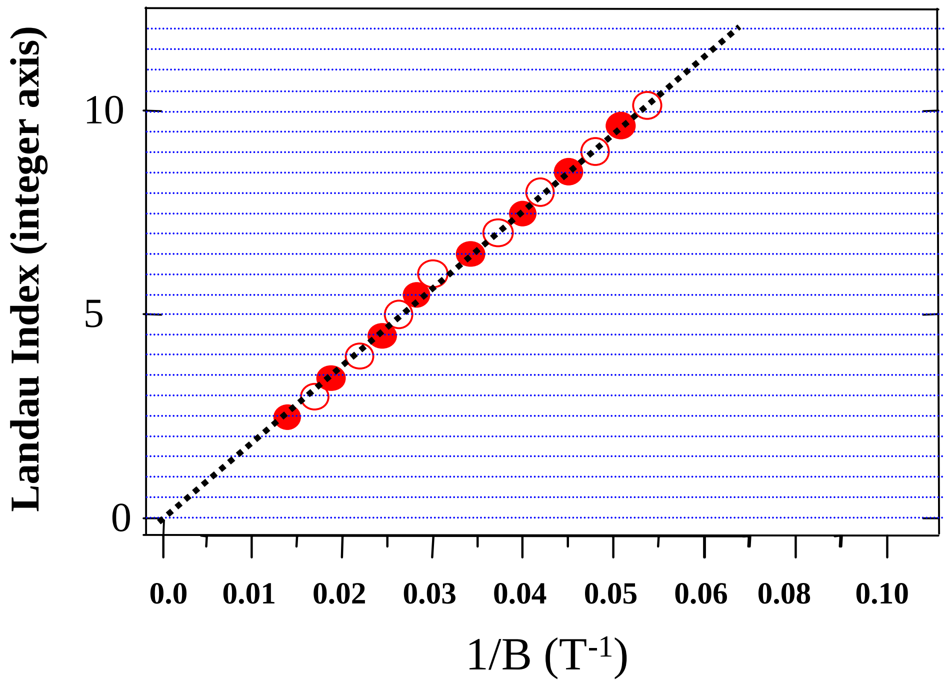
$$\Delta\left(\frac{1}{H}\right) = \frac{2\pi e}{\hbar c A_k}$$

Magneto-Resistance will show a peak whenever Fermi Level passes a Landau Level

A_k : maximal cross sectional area of pockets

SdH Period and Landau Plot



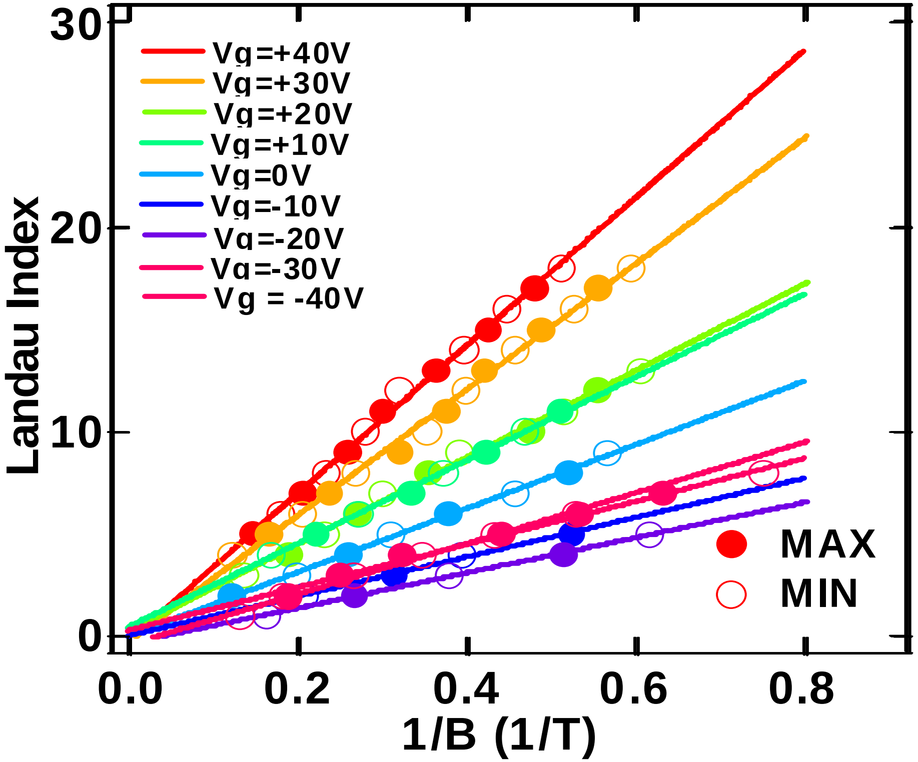


Slope of Landau Plot = Frequency of SdH oscillations

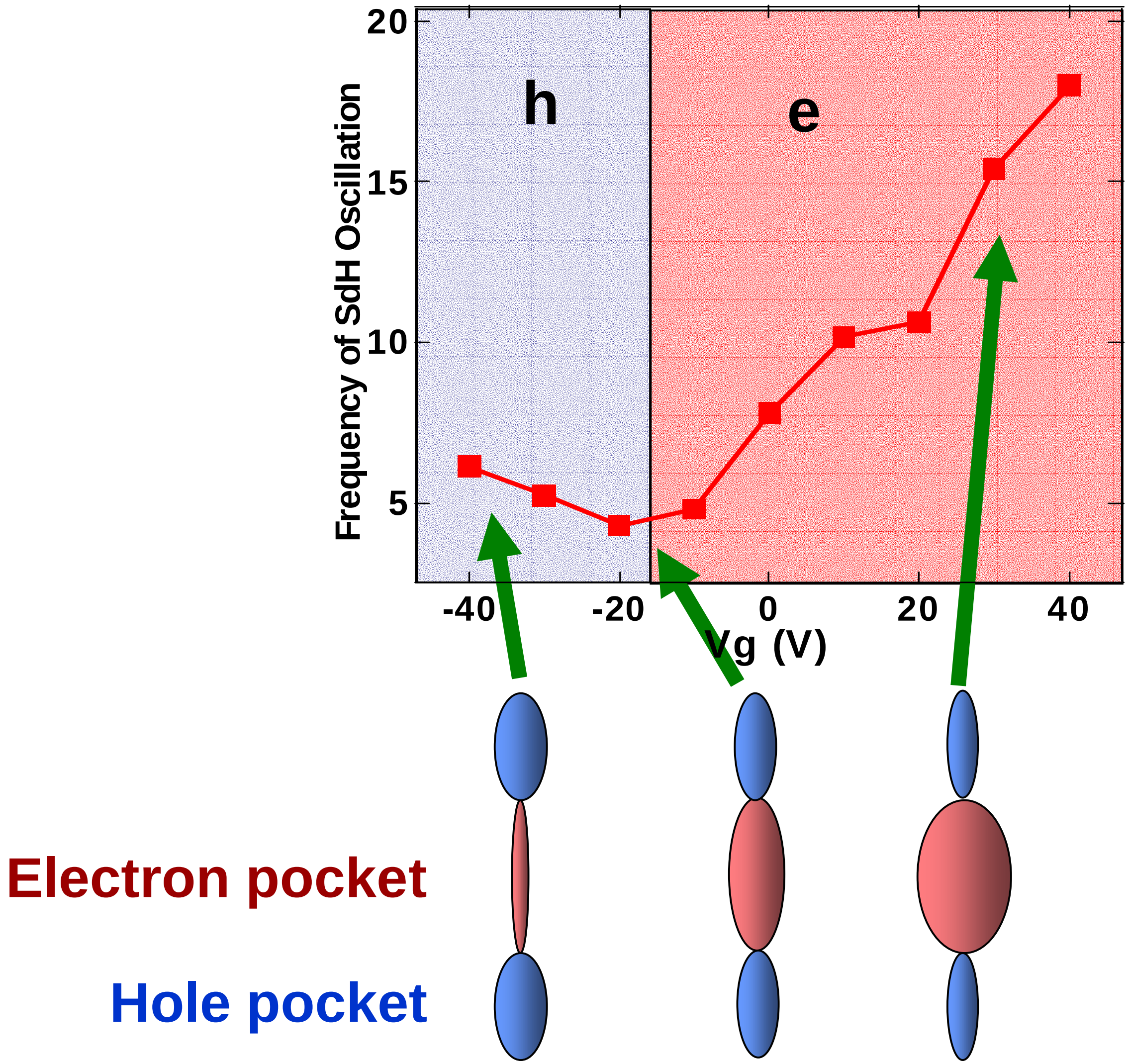
Gate Modulation of Shubnikov de Haas Oscillations

Slope of Landau Plot

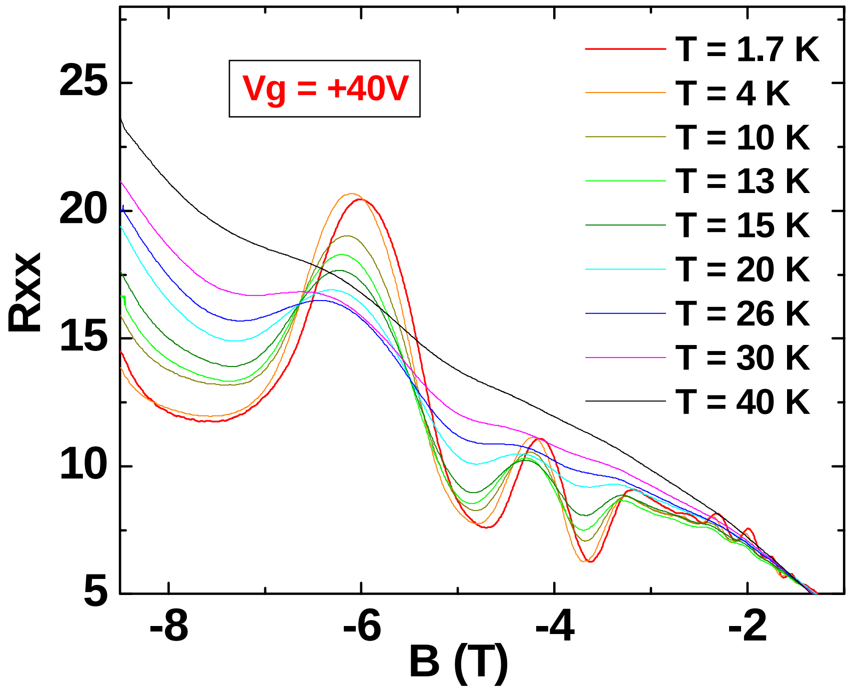
$$\frac{1}{\Delta\left(\frac{1}{B}\right)} = \frac{\hbar c}{2\pi e} \cdot A_k$$

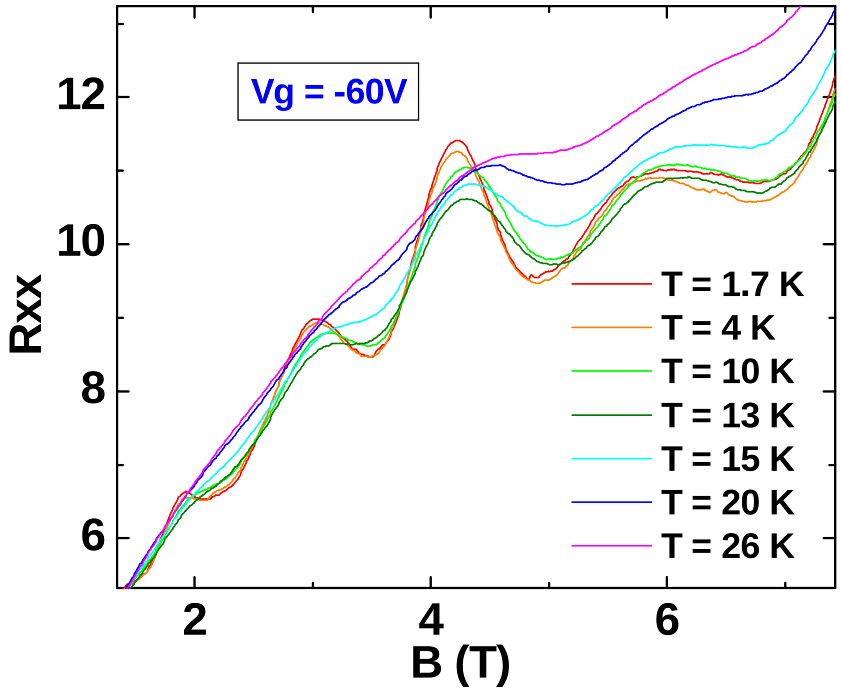


Gate Modulation of Shubnikov de Haas Oscillations



Temperature Damping of SdH Oscillations



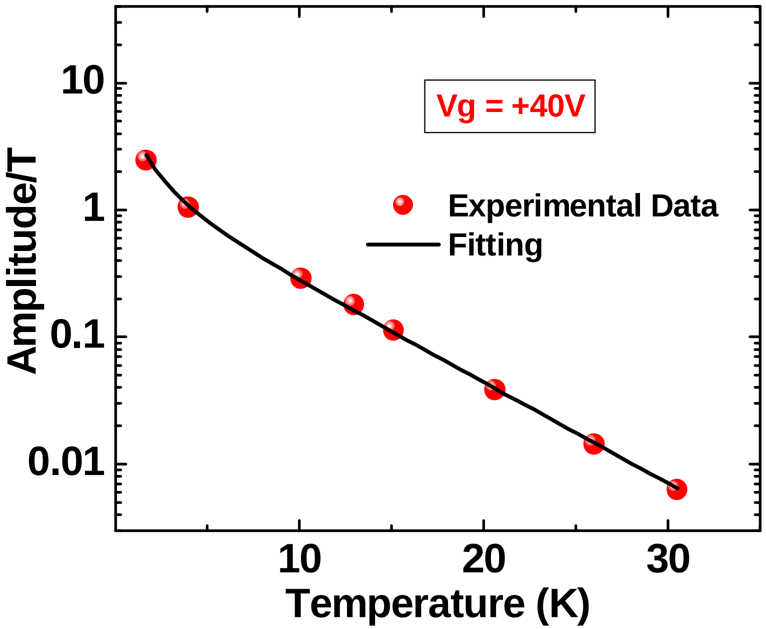


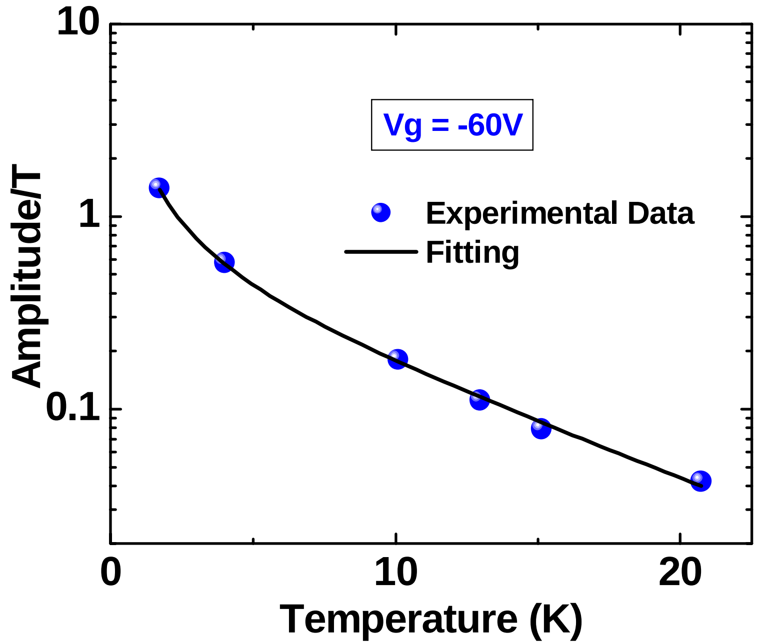
Electrons and Holes can be studied separately

Reduction Factor of SdH oscillation Amplitude

$$R_T \equiv \frac{2\pi^2 k_B T / \hbar\omega_c}{\sinh(2\pi^2 k_B T / \hbar\omega_c)} \qquad \omega_c = \frac{eB}{m^*}$$

Effective Mass of Electrons and Holes



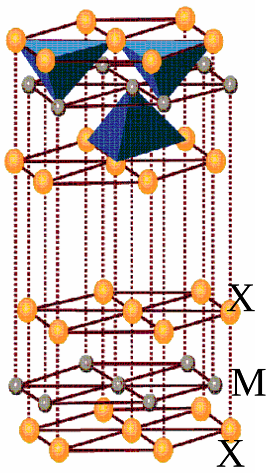


$$\frac{R_T}{T} \equiv \frac{2\pi^2 k_B / \hbar\omega_c}{\sinh(2\pi^2 k_B T / \hbar\omega_c)} \qquad \omega_c = \frac{eB}{m^*}$$

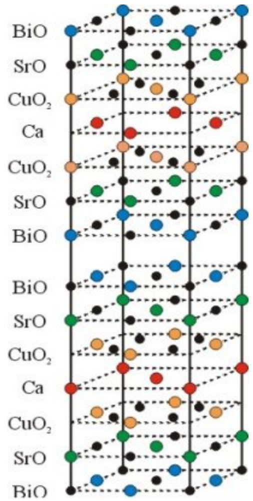
$m_e^* = 0.05\ m_e$

$m_h^* = 0.04\ m_e$

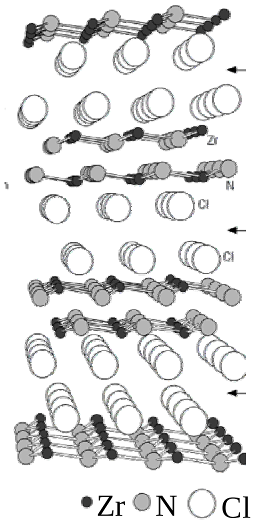
Field Effect in Other Correlated Materials



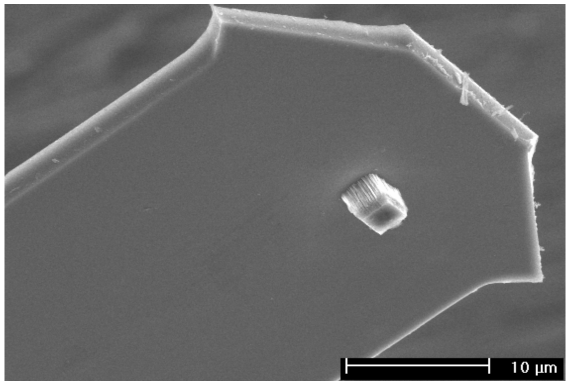
Metal-Chalcogenide
(M= Nb, Ta, Va, …
X= S, Se, Te)



$Bi_2Sr_2CaCu_2O_{8-x}$



β- ZrNCl



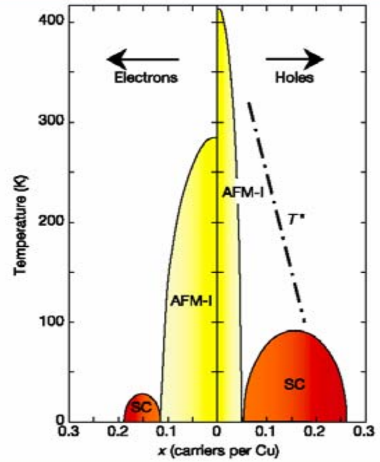


Figure 4 Phase diagram of the high-T_c superconductors. The electron-doped material represents $Nd_{2-x}Ce_xCuO_{4-y}$, and the hole-doped system represents $YBa_2Cu_3O_{7-\delta}$. The insulating, antiferromagnetic phases (AFM-I) are drawn in yellow, and the superconducting phases (SC) are in orange.

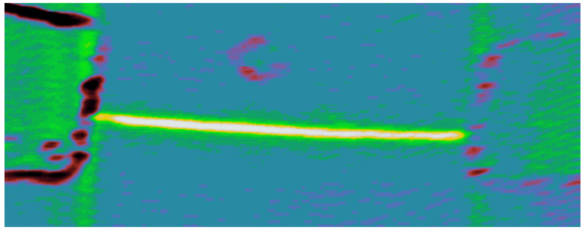
Conclusions

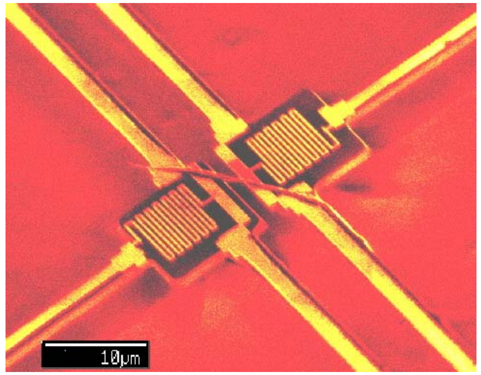
- Local temperature measurement energy dissipation in quantum transport limits

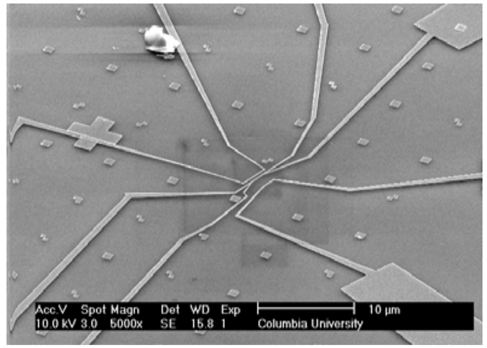
- Mesoscopic thermal conductance measurements

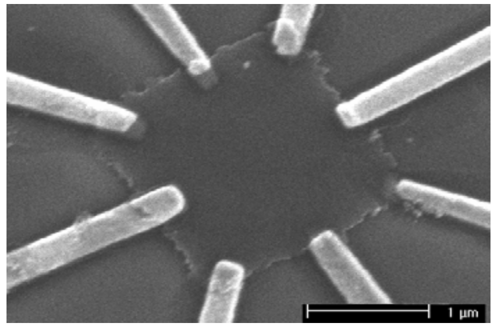
- Mesoscopic thermopower measurements

- Magneto-transport measurements in novel 2D-systems









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