Nanophysics 14

Nanoelectronics (1)

Supplementary materials

Recap

- NanoPlasmon
  - Collective excitation of valence electrons
  - Energy for Nanoparticle plasmon in Drude-like metals
- Dielectric function
  - Definition
  - Relation to optical properties
  - Condition for bulk plasmon excitation in real solids
  - Transparency of metals

Outline

- Review of conduction in bulk metals
  - Drude model
- Nanoelectrons
  - *Ballistic transport*
  - •*Mesoscopic (quantum) effects*

Macroscopic conductors

- Ohm's law:
  - the conductance G of a given sample is directly proportional to its cross-sectional area S and inversely proportional to its length L, i.e.

$$G = \sigma \frac{A}{L}$$

  - where σ is the conductivity of the sample

Physical basis of Ohm’s laws

- Drude theory
  - Electrons are in thermal equilibrium by randomly scattered off by ions, net motion is zero for random motion
  - Under an electric field, the net drift motion is produced

$$I = \frac{\delta q}{\delta t} = -neAvd$$

Classical theory

- Conductivity in a diffusive metal

$$\frac{m^* v_d}{\tau} = eE$$

$$\sigma = \frac{ne^2\tau_m}{m^*}$$

$$v_d = \frac{e\tau_m}{m^*}E$$

$$j = nev_d = \sigma E$$

- n = density of all valence electrons

Semi-classical theory

- $V_d = v_f$
- Only kT/E_f fraction of valence electrons contribute
- Mean free path

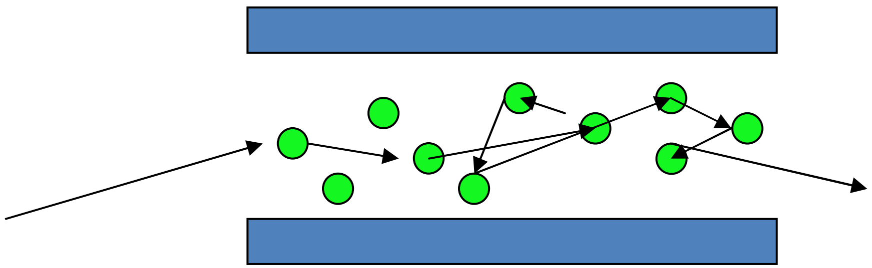
$$\ell = v_d \tau_m$$

Mesoscopic conductor

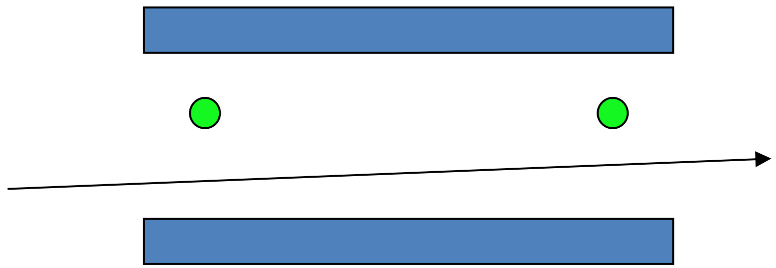
- Transport process depends on the scattering mechanisms
  - Classical diffusive transport
  - Ballistic transport
  - Coherent transport
  - Quantum transport
  - Tunnelling (next lecture)

Elastic scattering length ℓ

- Characteristic length between elastic collisions with static impurities
- Diffusive region ($L \gg \ell$)
  - Typical values: 1 μm for Au at 1K
  - Electron in random walk
- Ballistic region ($L \ll \ell$)
  - The electron momentum is assumed to be constant



Diffuse transport



Ballistic transport

Phase coherence length

- Characteristic length the within which the phase of electron wave is preserved
  - Typical values: 1 μm for Au at 1K
  - Weak localization experiment, diffraction experiment
  - Phase coherence destroyed by electron-electron scattering, electron phonon scattering,magnetic field
- Coherent transport
  - Electron waves adds coherently
  - Magnetoresistance: phase can be manipulated with application of magnetic fields
  - Important for quantum computing

Fermi wavelength λ_F

- Characteristic length, the wave length of electrons at the Fermi surface

$$\lambda_F = \frac{2\pi}{k_F}$$

- Full quantum limit:
  - Have to treat electrons as a quantum waves and mesoscopic conductors as waveguide
  - Quantum conductance
- Examples
  - Atomic size metal contact

Quantum conductance

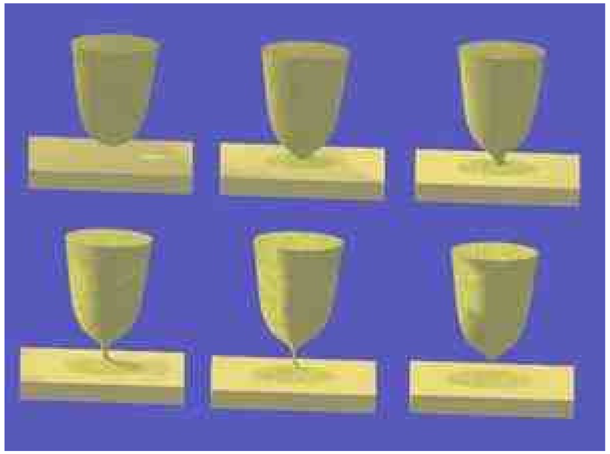
$$j = v\left|\phi_n\right|^2 = G_0\varepsilon$$

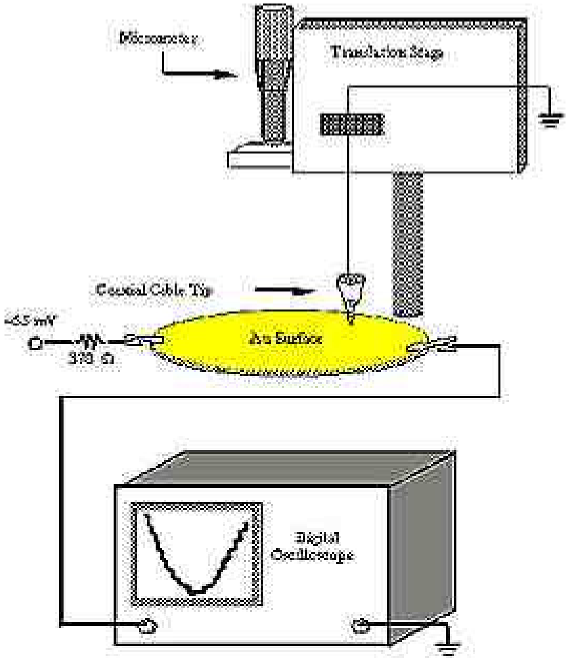
$$G_0 = \frac{2e^2}{h} = 12.9k\Omega^{-1}$$

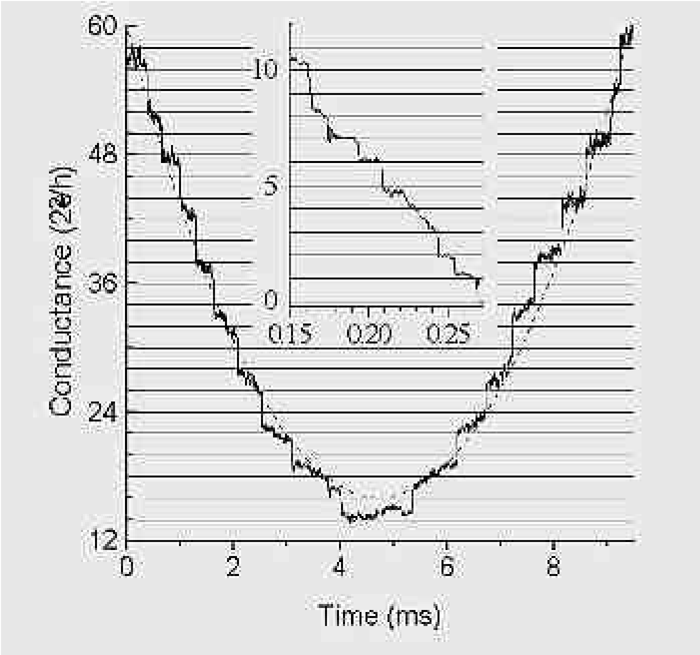
The conductance is constant for each one dimensional quantum transport

The total conductance shows steps corresponding to addition of new wavefunctions participating in the transport

Quantum conductance at point contact

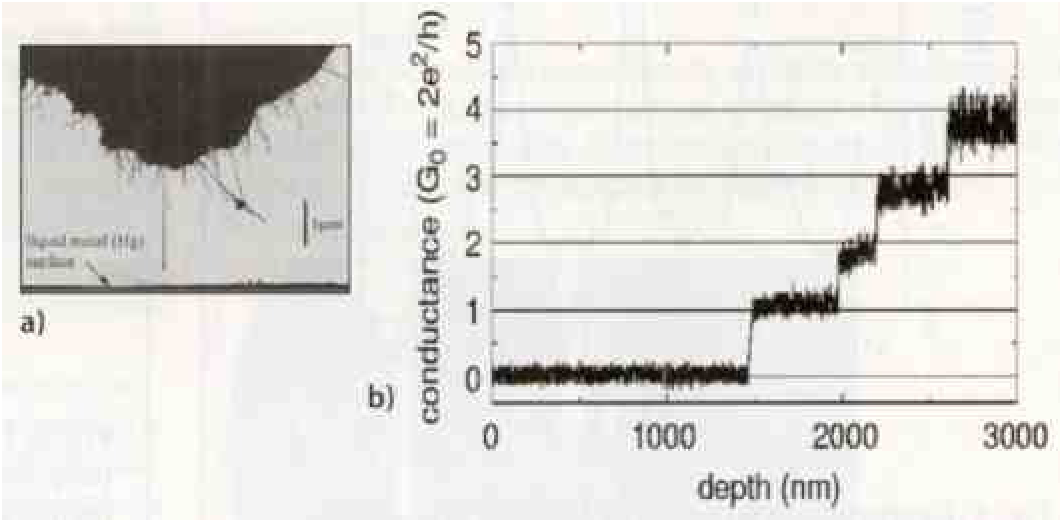






http://www.physics.gatech.edu/research/whetten/rec_results/quantum_cond.html

Quantum conductance of nanotube



- Sign of Quantum conductance, steps in G_0
- Ballistic transport, as conductance is independent of length of the nanotube

Summary

- Physical basis of Ohm's law valid for macroscopic conductor:
  - Diffusive scattering by phonons and impurities
  - Characteristic length: mean free path for inelastic scattering
- Transport in Mesoscopic conductors ($L<L_\phi$)
  - Characteristic length: Phase coherence length L_φ
    - Typical values: 1 μm for Au at 1K
    - Weak localization experiment, diffraction experiment
    - Phase coherence destroyed by electron-electron scattering, electron phonon scattering