Nanophysics 16

Nanoelectronics (3) SET

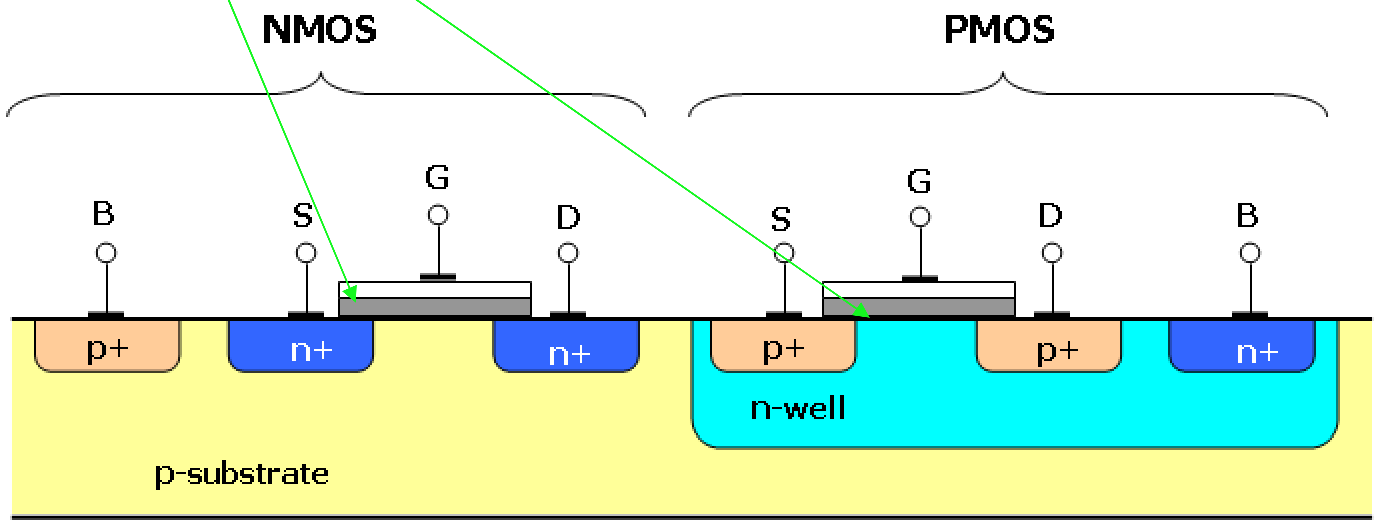
Supplementary materials

Outline

- Review of tunnelling
- Single Electron Transistor
  - Introduction
  - Discreet charging
  - Coulomb blockade
- Appendix: dielectric function of coinage metals
  - Contribution from intraband and interband transitions
  - Lorentz oscillator modelling

CMOS, the workhorse of IC

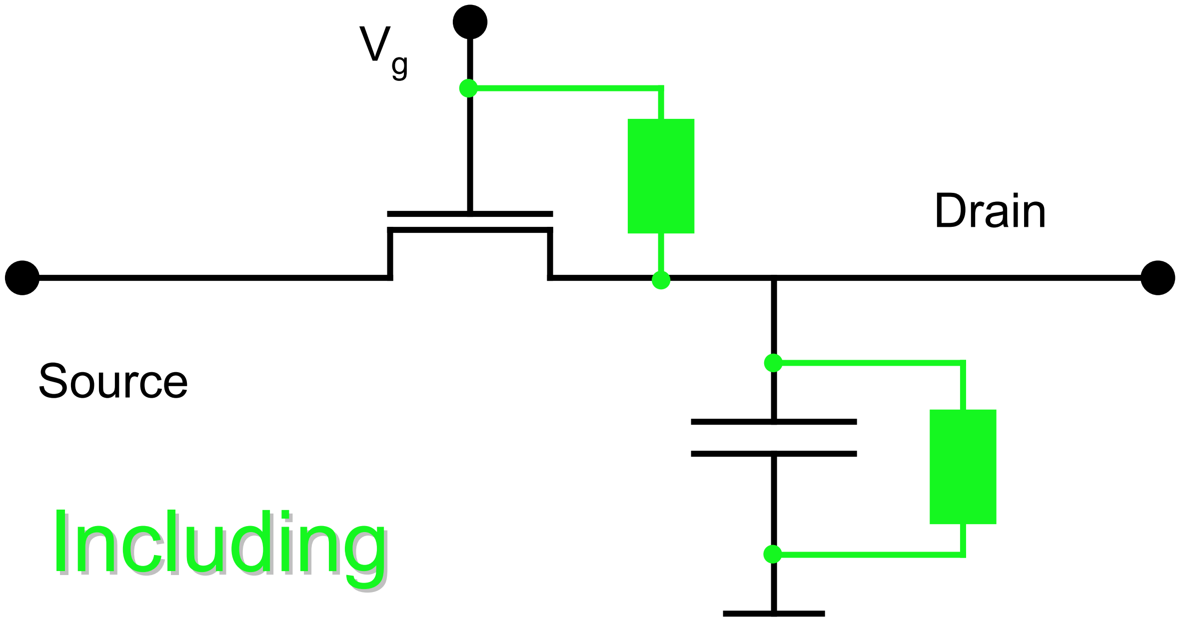
- Smallest dimension, the thickness of gate oxide layer



http://upload.wikimedia.org/wikipedia/en/6/62/Cmos_impurity_profile.PNG

Equivalent circuit

- Classical Circuit for a Field Effect Transistor



Including

Tunneling resistence

Single Electron Transistor (SET)

- A quantum dot device showing Coulomb oscillation
- It turns on and off periodically as the electron occupancy of the dot is changed by e

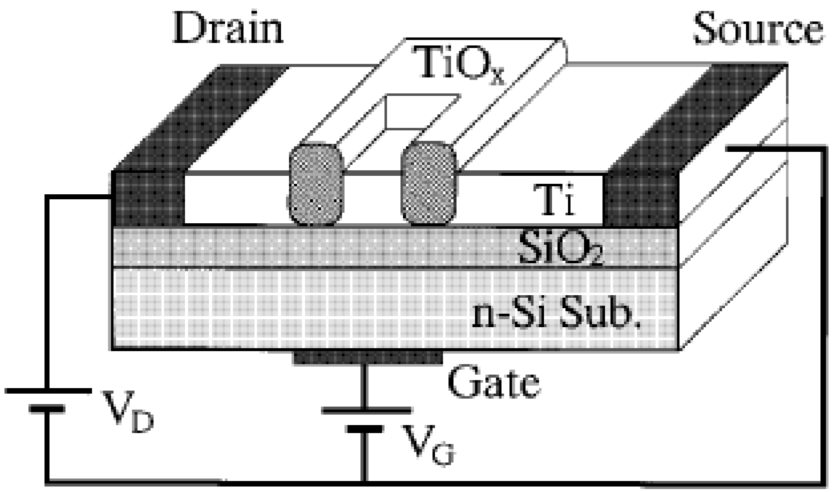
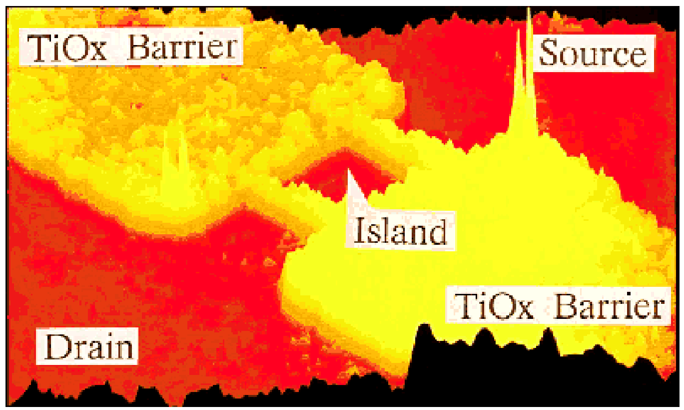
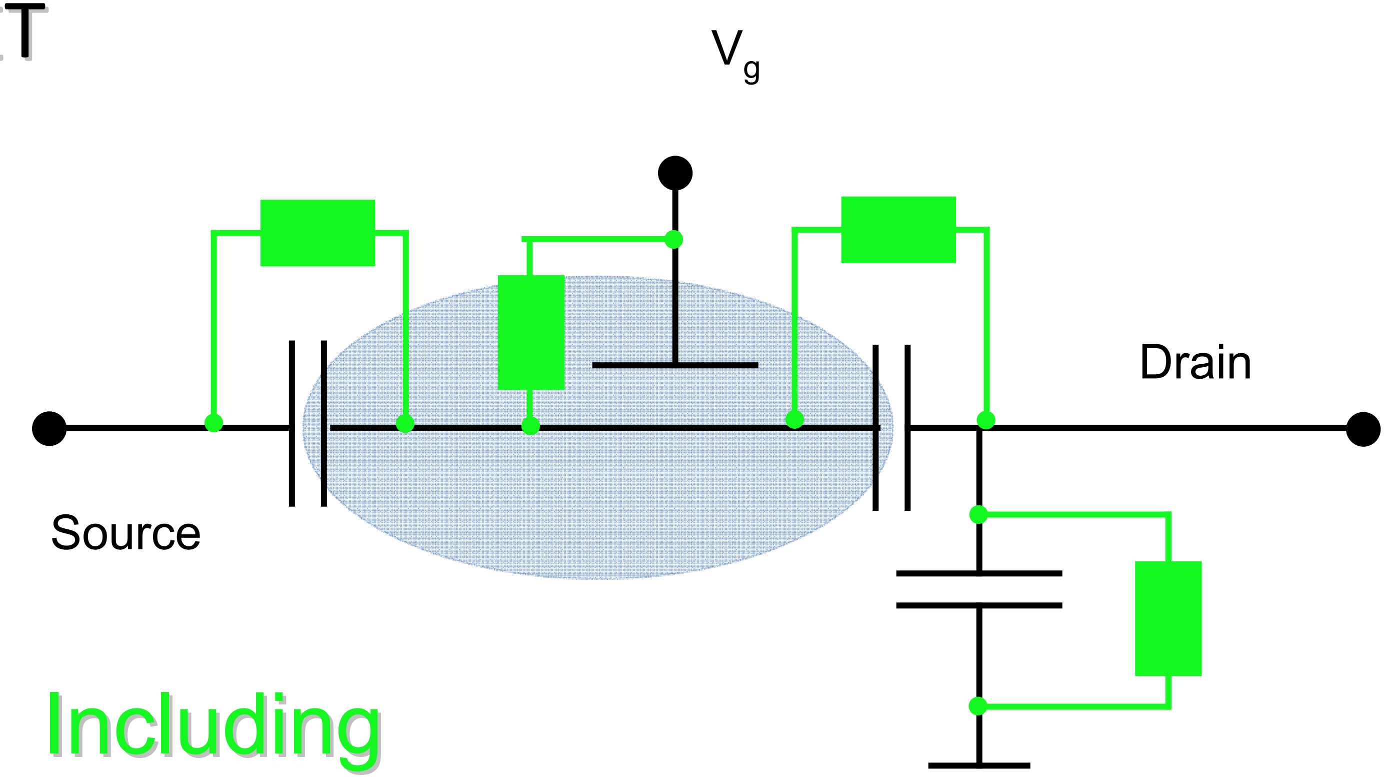


FIG. 2. Cross-sectional view of single electron transistor fabricated by STM nano-oxidation process. Island area is surrounded by two TiO_x line and two large TiO_x barrier regions.



Equivalent circuit

- SET



Including

Tunneling resistence

Discrete Charge State

- Within the Thomas-Fermi approximation, the electrochemical potential for adding the (N+1) electron to a quantum dot containing N electrons is given by

$$\mu_{N+1} = \varepsilon_{N+1} - e\phi = \varepsilon_{N+1} + NU - \alpha e V_g$$

  - U, the Coulomb interaction energy between any two electrons on the dot, also called charging energy
  - V_g, the gate voltage
  - α, a dimensionless quantity describing the efficiency of applying V_g in shifting the electrostatic potential ϕ of the dot

Charging energy

- In general, U is a function of the electronic states in the dot, but for our discussion, we will assume that it is constant as in classical metal:

$$U = \int_0^e V dq = \int_0^e \frac{q}{C} dq = \frac{e^2}{2C}$$

  - C, the total electrostatic potential of the dot
- Also

$$\alpha = \frac{C_g}{C}$$

  - C_g, the capacitance between the dot and the gate.

Example of the charging energy

- U depends on the geometry as well as the local electrostatic environment
- A simple example:
  - A spherical dot of radius R surrounded by a spherical metal shell of radius R+d
  - Charging energy is given by an application of Gauss's law

$$U = \frac{e^2}{4\pi\varepsilon\varepsilon_0 R} \frac{d}{R+d}$$

$$\frac{1}{C} = \frac{1}{4\pi\varepsilon\varepsilon_0 R} \frac{d}{R+d}$$

Order of magnitude estimate

- Charging energy for a nanoparticles
  - For, R=2nm, d=1nm and epsilon =1
    - U=0.24eV
- Thermal energy
  - kT=0.026eV, thermal fluctuation of charge of the dot will be strongly suppressed
- Electronic level spacing (between lowest two states)
  - CdSe (R=2nm) 0.76eV the same order of U
  - Metal: 2meV <<U; the additional energy of a metallic dot is dominated by the charging energy

Charging by tunnelling

- Charging effect requires a tunnelling contact of certain ‘resistance’

$$\delta\varepsilon\delta t \geq \frac{\hbar}{2}$$

  - If resistance is small, i.e. tunnelling rate high, the lifetime of a well-defined charge state is small:

$$\frac{e^2}{2C}RC \geq \frac{\hbar}{2}$$

  - By the uncertainty principle, the energy level will be broadened to be comparable when $R \neg R_{min}$

$$R_{\min} = \frac{\hbar}{e^2}$$

Operation conditions of SET

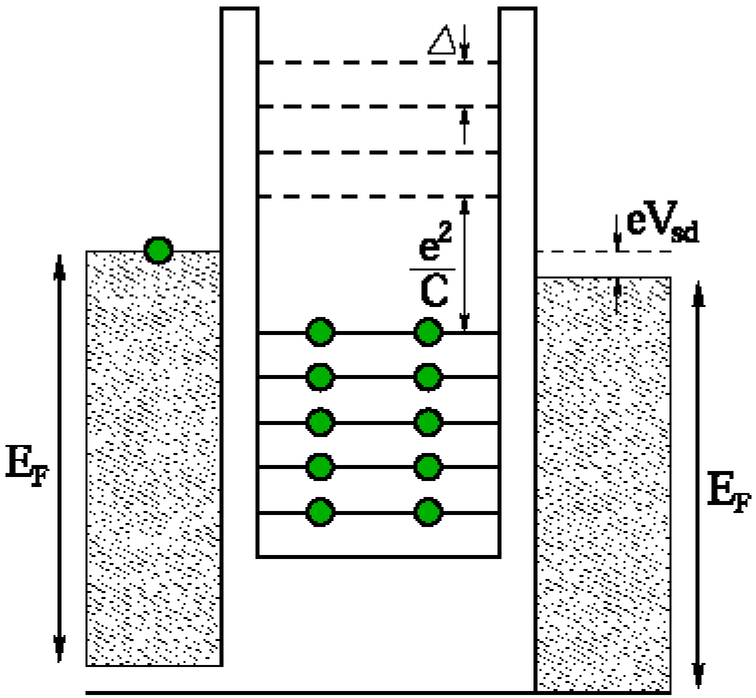
- Operating Conditions:

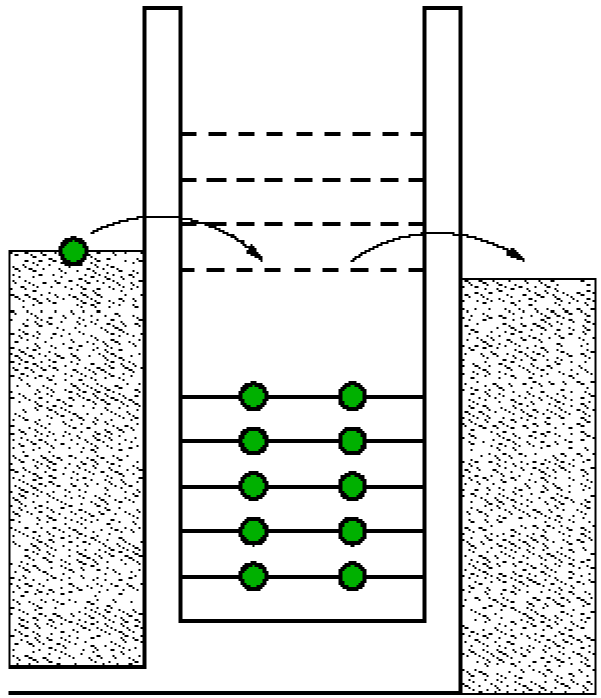
$$R >> \frac{h}{e^2} \qquad\qquad \frac{e^2}{C} >> k_B T$$

- At temperature $T<(U+\Delta E)/K_B$, the charging energy and level spacing controls the flow of electrons through a quantum dot

Coulomb blockade

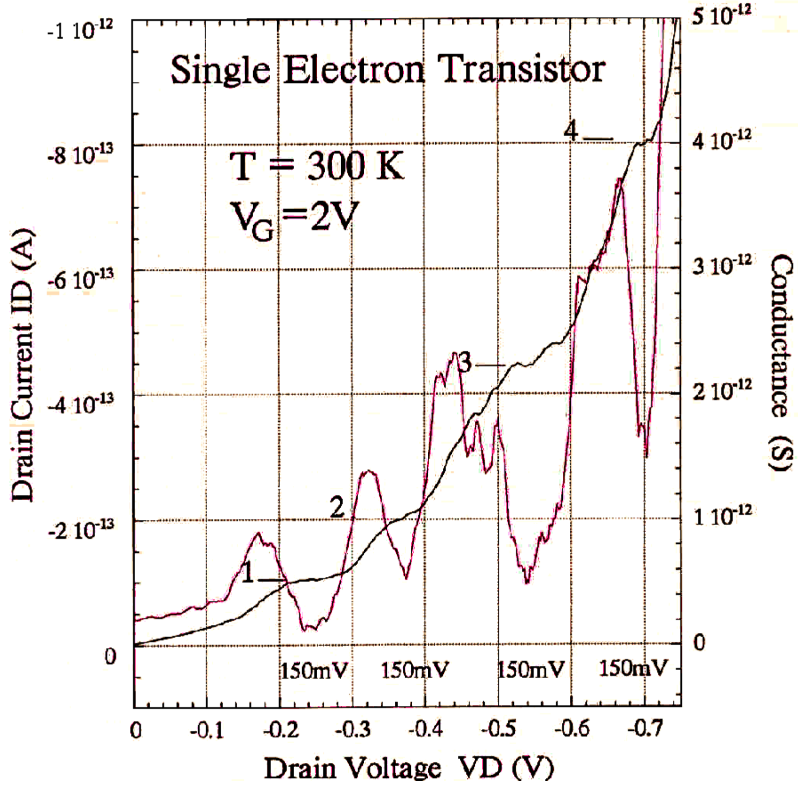
- Transport through the dot is suppressed when the fermi level is suppressed where the Fermi levels of the lead lies between the electrochemical potential for the N and N+1 charge states.





Coulomb oscillation

- Current can flow only when $\mu_e(N+1)$ is lowered to lie between the Fermi levels of the left and right leads. Then an electron can hop on the dot from the left electrode and off the dot to the right electrode, resulting in current flow
- Spacing of peaks



$$\Delta V_g = \frac{1}{\alpha e}\left(\varepsilon_{N+1} - \varepsilon_N + \frac{e^2}{C}\right)$$

Applications

- Ultrasensitive electrometer, based on quantization of charge

- Single electron turnstiles and pumps

  Current standard $$I = ef$$

- Electric field sensor (equivalent to SQUID for magnetic field)

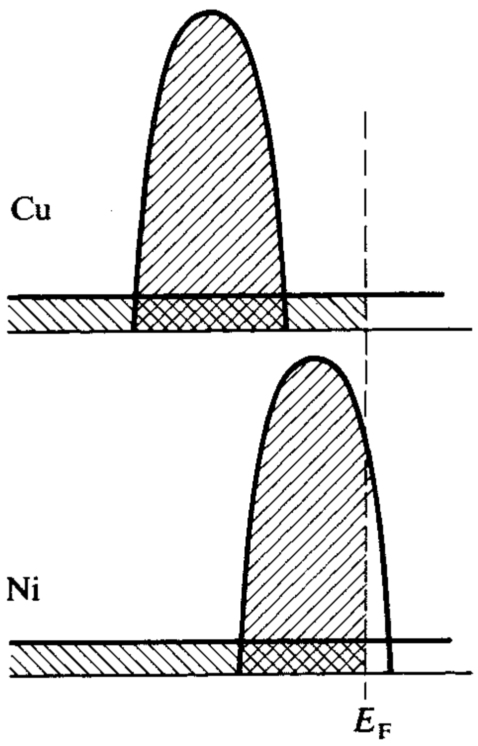
Summary

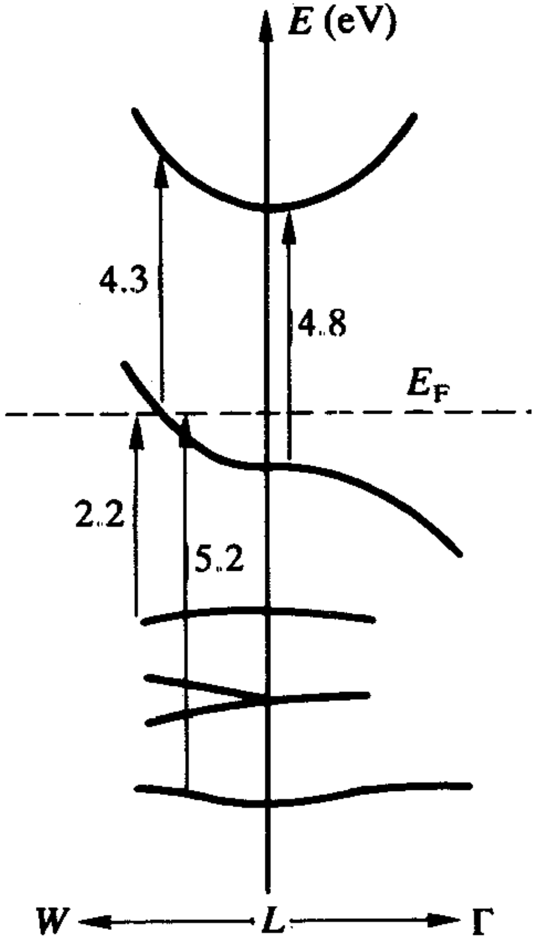
- Single electron devices utilizes quantum confinement of quantum dots, quantum tunnelling as well as discreet charge transfer in tunnelling process to create a field effect transistor
- Single electron operation can create many new applications

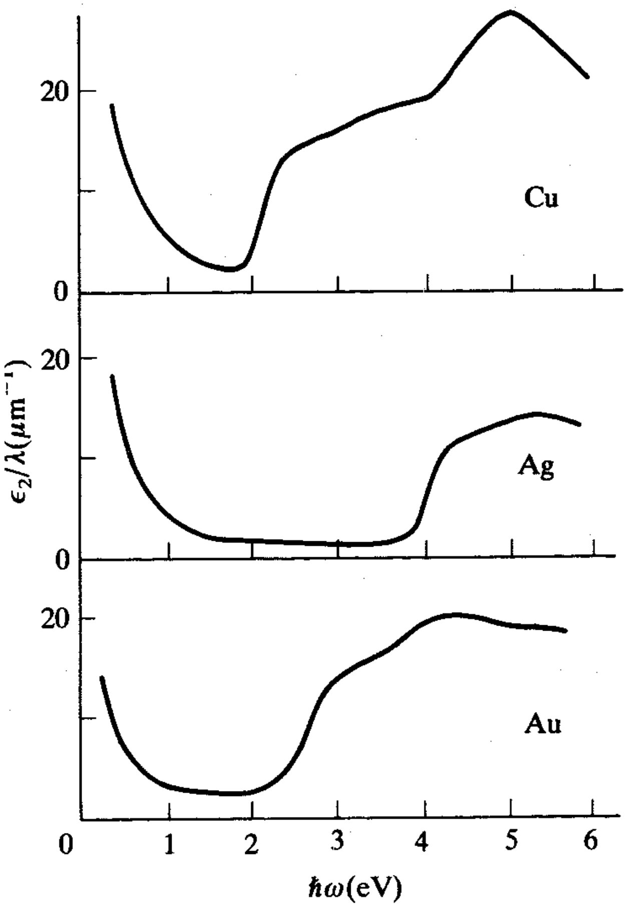
Appendix

- Additional notes on solving week 7 problems
  - Coinage metals (Cu, Ag, Au etc.)
  - Importance of interband transition in coinage metals due to the proximity of nearly filled d-band near the fermi level.
  - Dielectric function including intraband transitions and interband transition
  - Condition for plasmon oscillation in coinage metals

Optical property of coinage metals

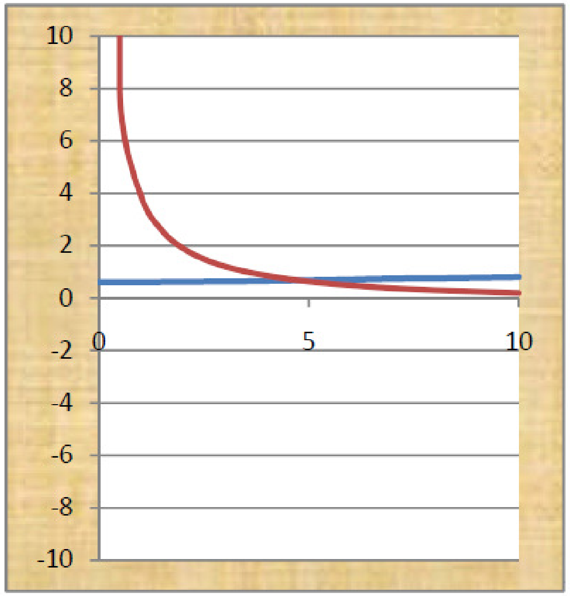




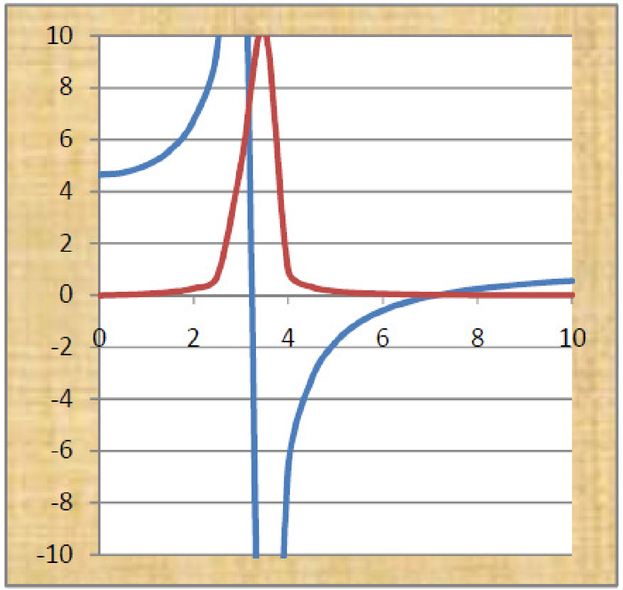


Dielectric function

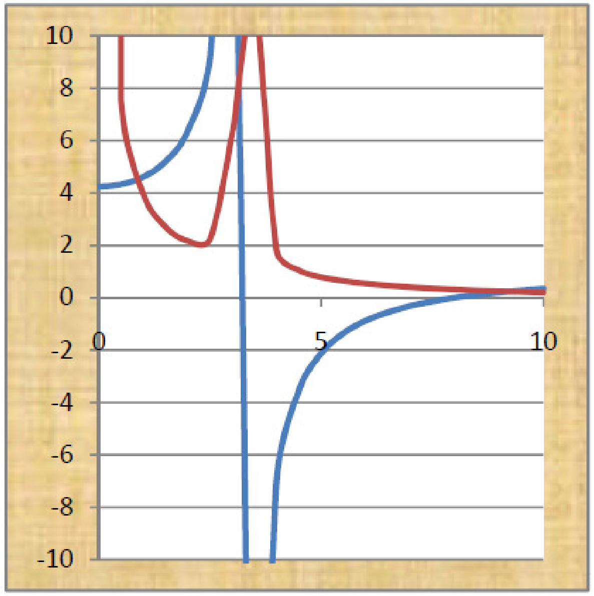
Intraband



Interband



Combined



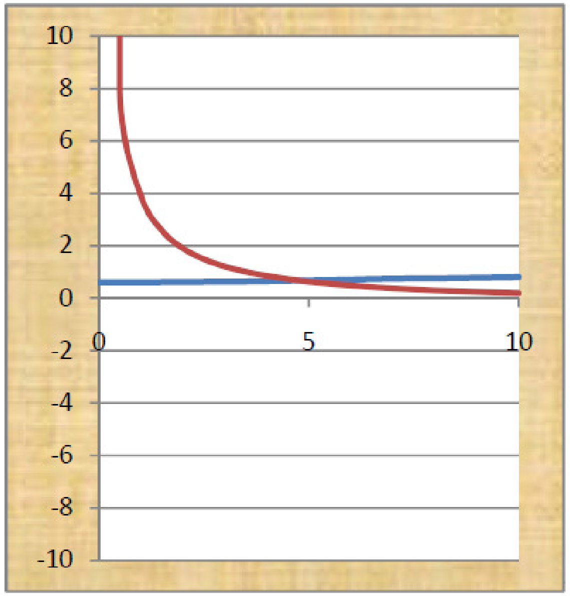
free electron plasmon energy =	6.3 eV
damping energy	10 eV

interband transition energy	3.3 eV
interband damping energy	0.16 eV

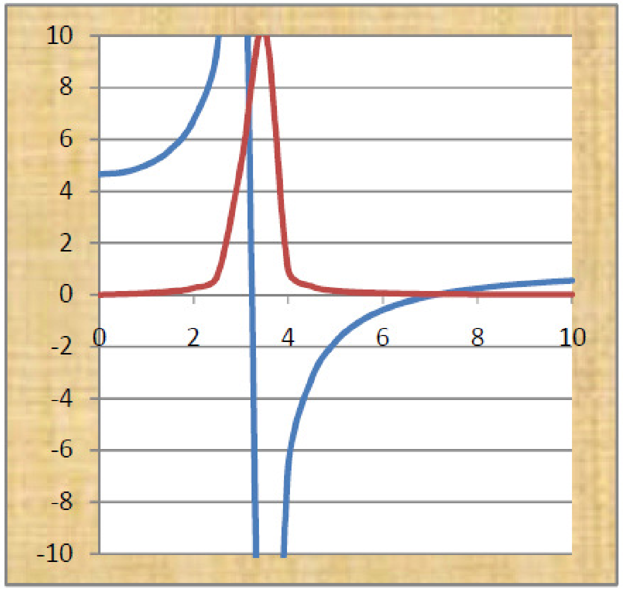
- Week 7 questions

Model dielectric function for Ag

Intraband



Interband



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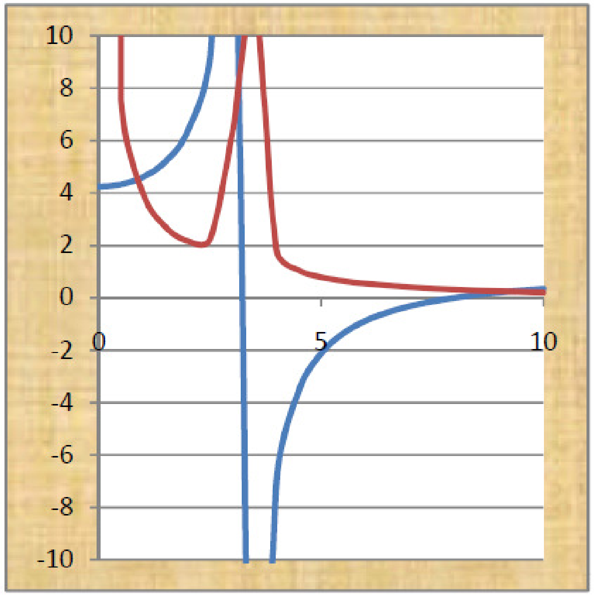


free electron plasmon energy =	6.3 eV
damping energy	10 eV

interband transition energy	3.3 eV
interband damping energy	0.16 eV

Modified data (1)

Improved dielectric function modelling for Ag

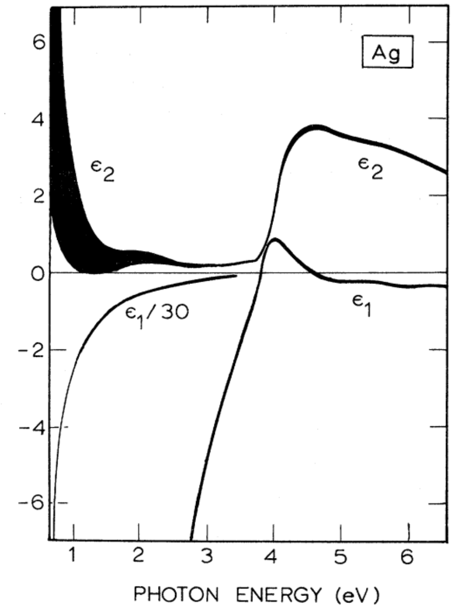
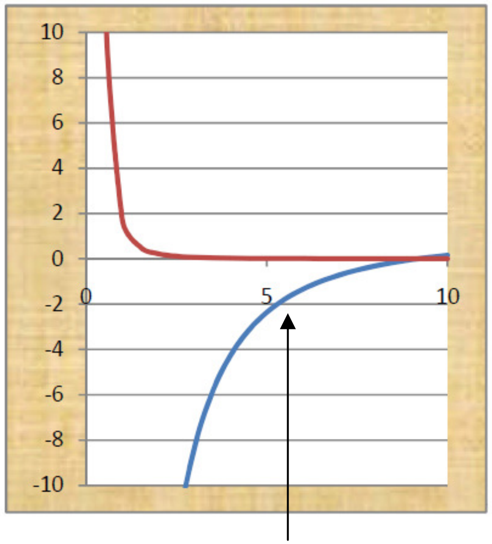


FIG. 3. Dielectric constants for silver as a function
vidth of the curves is represen-
ıl error.

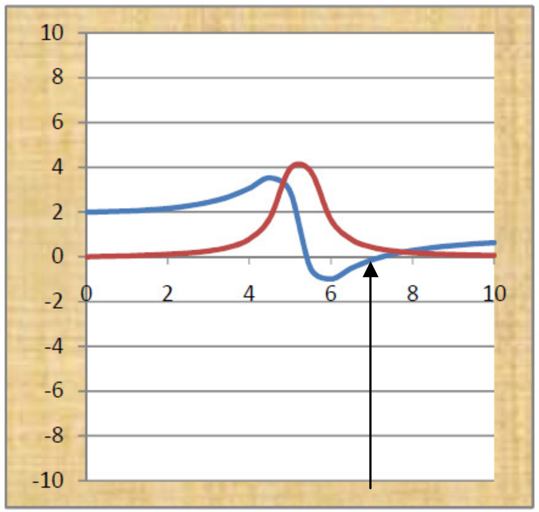
Modified data (2)

Intraband



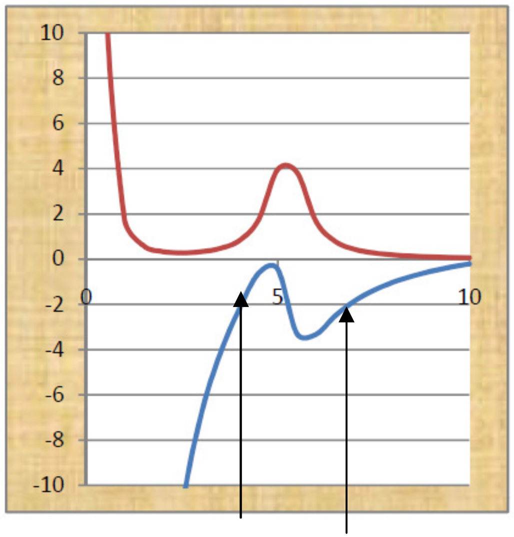
free electron plasmon energy = 9.17 eV
damping energy 0.021 eV

Interband



interband transition energy 5.27 eV
interband damping energy 1.14 eV

Combined



Arrows indicate the energy position corresponding to condition for bulk plasmon excitation