Theory of Electrical Characterization of Semiconductors

P. Stallinga

Universidade do Algarve
U.C.E.H.
A.D.E.E.C.
OptoElectronics

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Overview

Devices:

- bulk
- Schottky barrier
- pn-junction
- FETs

Techniques:

- current-voltage (DC)
- capacitance, conductance (AC)
- admittance spectroscopy
- Hall
- Transient techniques:
  - capacitance transients
  - DLTS
  - TSC

Information:

- conduction model
- carrier type
- shallow levels
  - position
  - density
- deep levels
  - position
  - density
- dielectric constant
- carrier mobility
- barrier height

“Plastics are conductors ?!”

- Every semiconducting polymer has a “backbone” of under-coordinated carbon atoms

example: - CH – CH – CH – CH -

- 4^{th} electron is in weak p_z-p_z bonds. Loosely bound -> metal
- deformation of backbone: creation of alternating single and double bonds

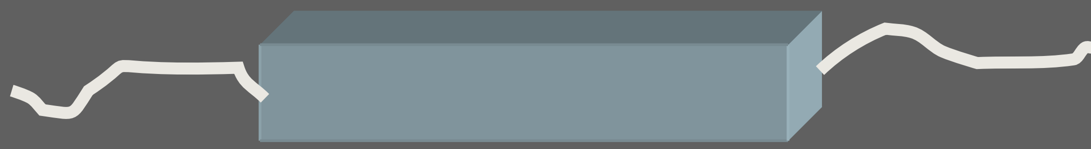
- CH = CH – CH = CH -

- This causes opening of a bandgap -> semiconductor
- bandgap ±2.5 eV
- wide bandgap ½con

Material	Band gap
SiO_2	>10 eV
C (diamond)	5.47 eV
GaN	3.36 eV
Polymers	2.5 eV
GaAs	1.42 eV
Si	1.12 eV
Ge	0.66 eV

Bulk Samples

- bar of material with only **ohmic** contacts



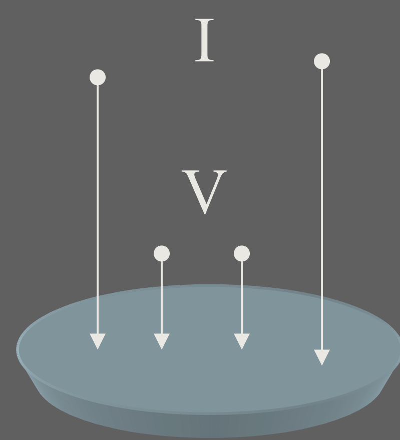
Conductivity: $\sigma = e\,\mu_p\,p$

$$p \sim T^{3/4} \exp(-E_A/kT)$$

acoustic phonons: $\mu_p \sim T^{-3/2}$

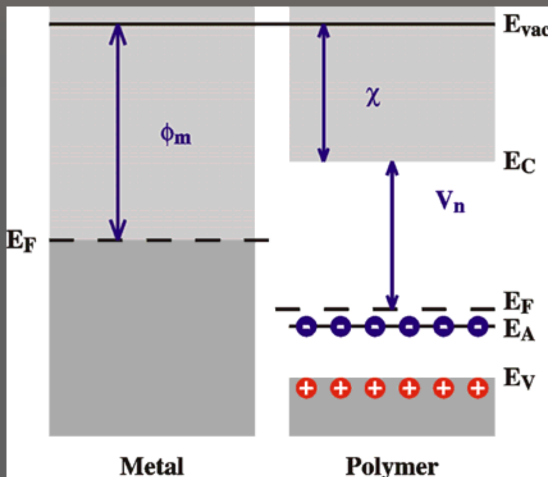
ionized impurities: $\mu_p \sim T^{3/2}$

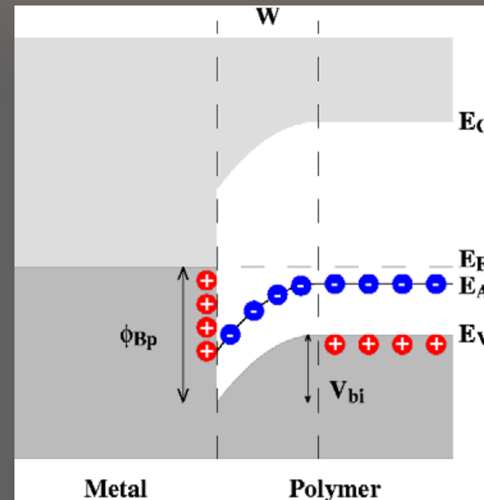
optical phonons: $\mu_p \sim T^{3/2}$



4-point probe

Schottky Barrier

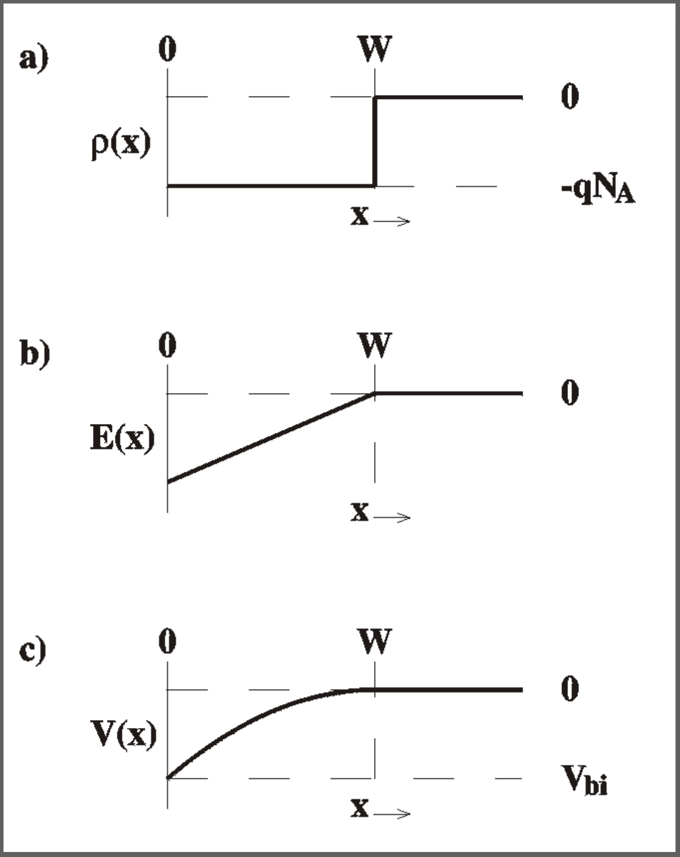




- metal and ½con have different Fermi level
- electrons will flow from metal to ½con
- build-up of (space) charge Q (uncompensated ionized acceptors)
- causes electric field and voltage drop (band bending, V_{bi})
- over a range W (depletion width)

$$V_{bi} = \chi + V_n - \phi_m$$

Calculation of Depletion Width



Poisson's equation:
$V = \iint \rho(x)/\varepsilon \, dx^2$

∫ is integral sign

$$\rho(x) = \begin{cases} N_A & (x<W) \\ 0 & (x>W) \end{cases}$$

$$E(x) = \int \rho(x)\, dx = (qN_A/\varepsilon)(x-W)$$

$$V(x) = (qN_A/2\varepsilon)(x-W)^2 \qquad V_{bi} = V(0)$$

$$W = \sqrt{2\varepsilon(V_{bi}-V_{ext})/qN_A} \qquad Q = N_A W$$

Capacitance (Schottky Barrier)

- Every time the bias is changed a new depletion width is formed
- More (or less) space charge Q

$$C = \mathrm{d}Q/\mathrm{d}V = A\sqrt{q\varepsilon N_A/2(V_{bi}-V)}$$

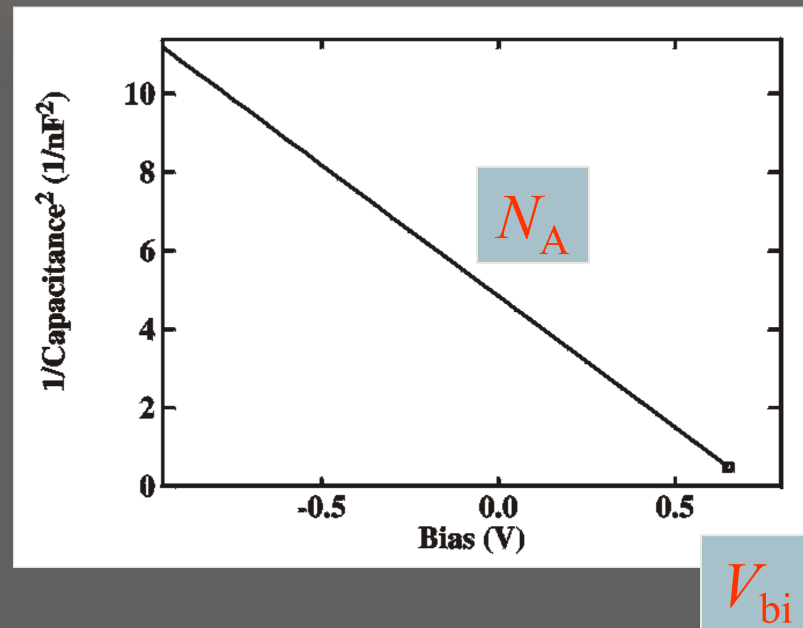
$$C = A\varepsilon/W$$

A Schottky barrier is equivalent to metal plates (area *A*) at mutual distance *W*, filled with dielectric ε

Capacitance 2 — doping density

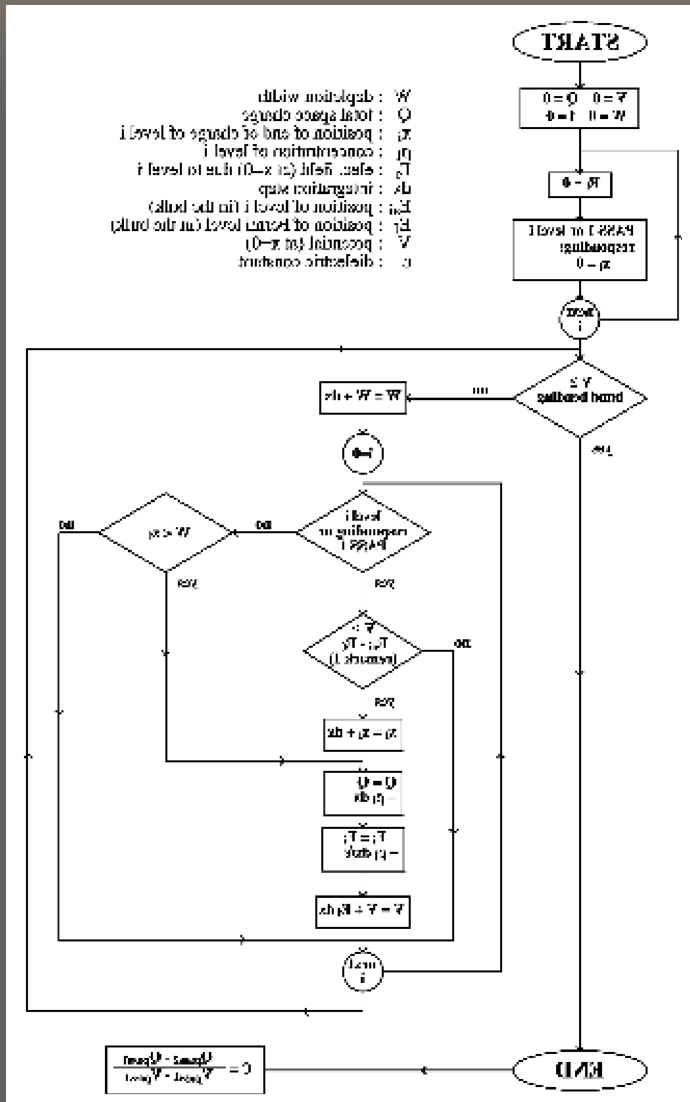
$$C = A\sqrt{q\varepsilon N_A/2(V_{bi}-V)}$$

$$C^{-2} = 2(V_{bi}-V)/A^2 q\varepsilon N_A$$



- slope reveals N_A
- extrapolation reveals V_{bi}

Numerical calculation of C



Riemann integration until

$$V = (V_{bi} - V_{ext})$$

then:

$$C = \mathrm{d}Q/\mathrm{d}V$$

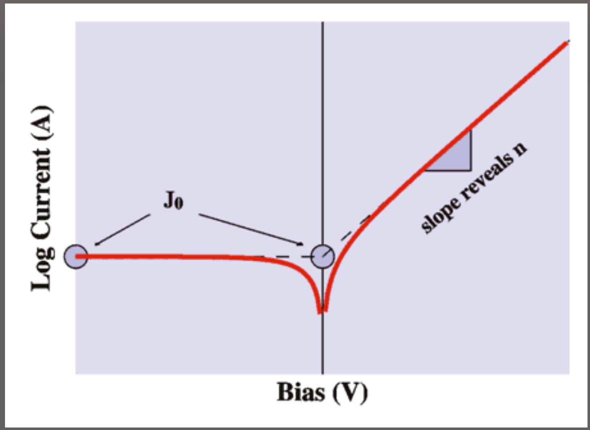
$$C = (\mathrm{d}Q/\mathrm{d}x) \,/\, (\mathrm{d}V/\mathrm{d}x)\,|_{x=W}$$

or: two-pass calculation:

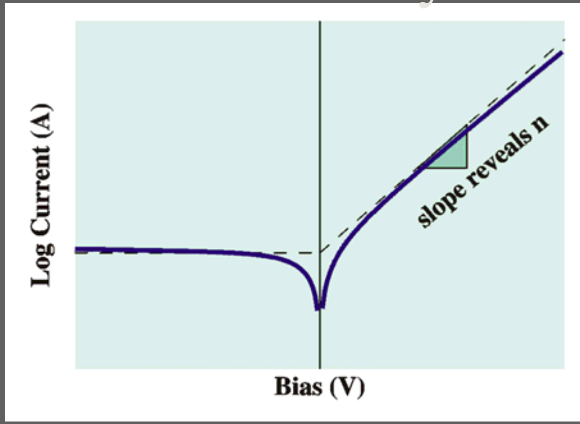
$$C = \Delta Q/\Delta V$$

DC conduction (Schottky barrier)

Thermionic-emission:



Diffusion theory:



Thermionic emission theory:

$$J = A^* T^2 \exp(-q\phi_{Bp}/kT)\,[\exp(qV/nkT) - 1]$$
$$= J_0\,[\exp(qV/nkT) - 1]$$

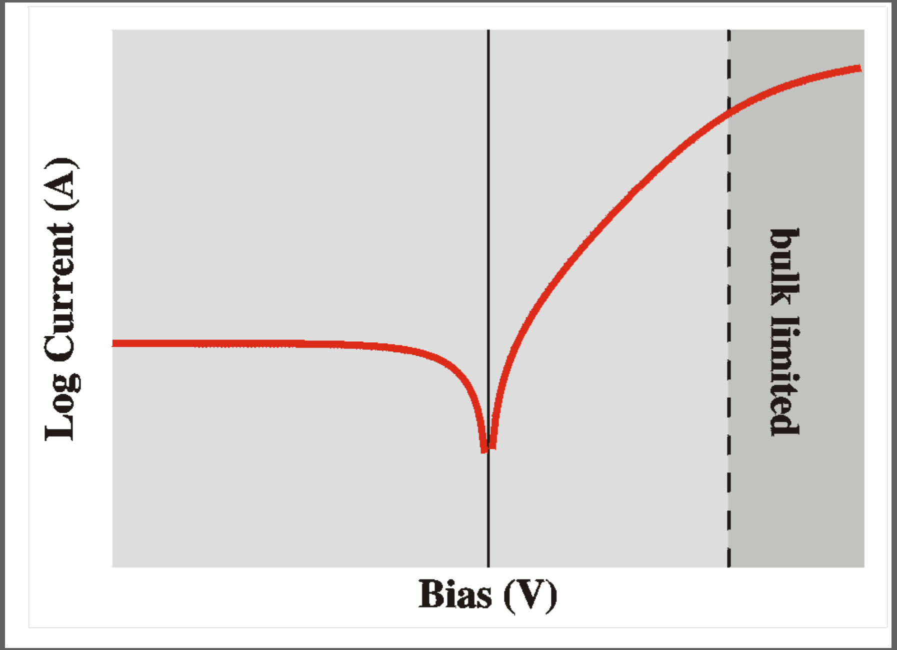
From a single scan we can find

- the rectification ratio (J_0)
- the ideality factor, n
- the conduction model

Repeating with different T:

- barrier height, ϕ_{Bp}

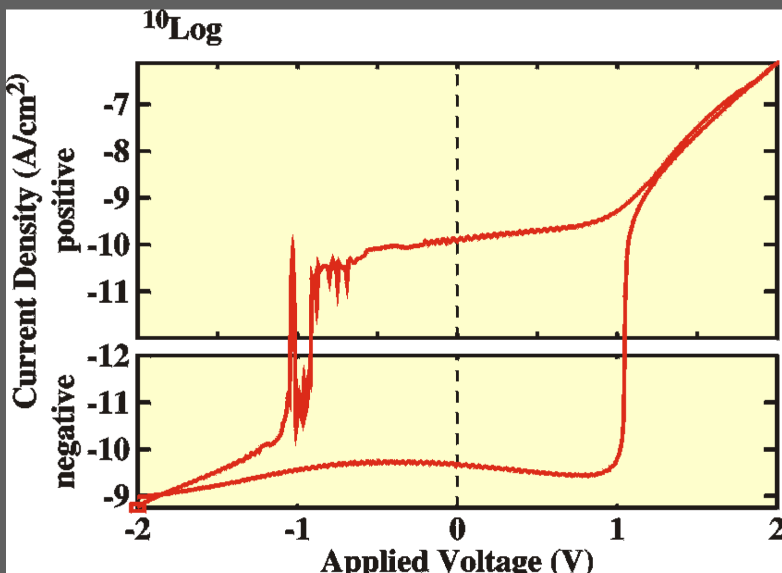
Bulk-limited Current (Schottky barrier)



- Large bias: bulk resistance dominates
- This causes a bending of IV
- Theory for bulk currents can be applied again.

Displacement Current (Schottky barrier)

- Every time the bias is changed the capacitance has to reach the new amount of charge stored
- This flow of charges is the displacement current, I_{disp}



$$I_{\text{disp}} = C\,(\mathrm{d}V/\mathrm{d}t) + V\,(\mathrm{d}C/\mathrm{d}t)$$

$$= C\,\mathrm{d}V/\mathrm{d}t + V\,(\mathrm{d}C/\mathrm{d}V)(\mathrm{d}V/\mathrm{d}t)$$

So, scan slower!

AC: Conductance (schottky barrier)

$V(t) = V + v\sin(\omega t)$ ⟶ $I(t) = I + i\sin(\omega t)$

DC: $1/R = I/V$, AC: $G = i/v$

Small v: conductance G is the derivative of the IV-curve

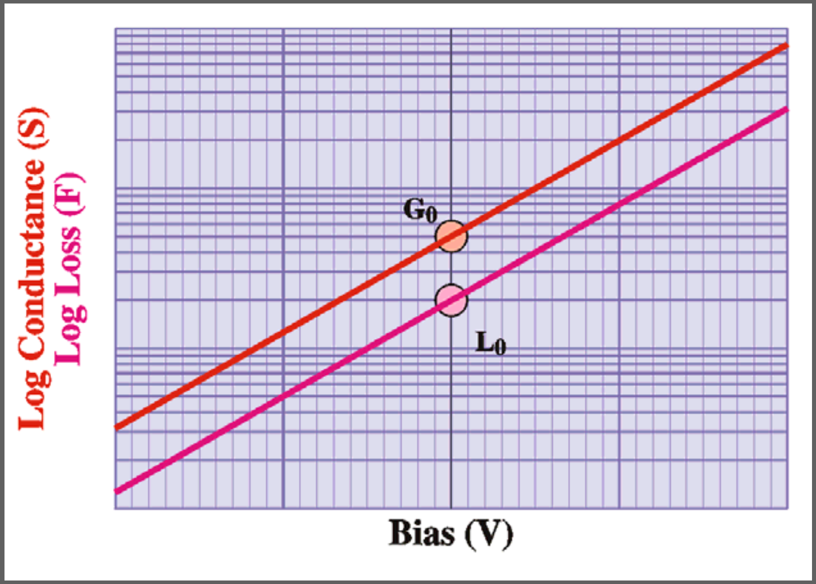
$$J = J_0\,[\exp(qV/nkT) - 1]$$

$$G = G_0 \exp(qV/nkT)$$

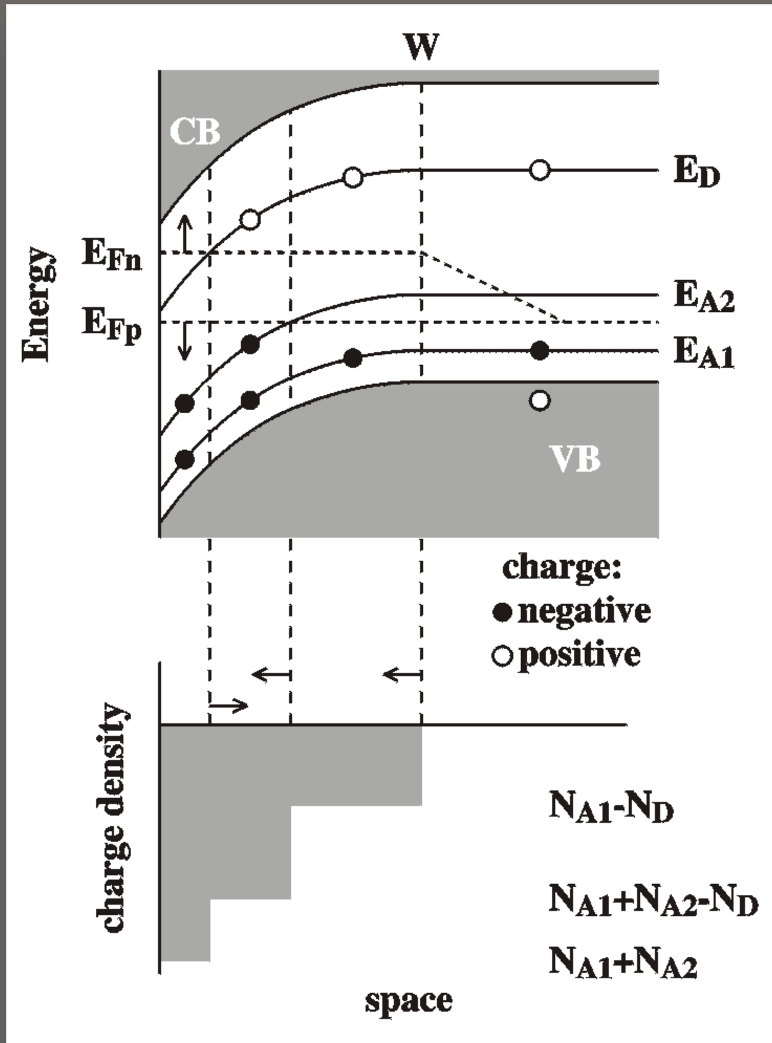
Frequency independent

Loss: $L = G/\omega$

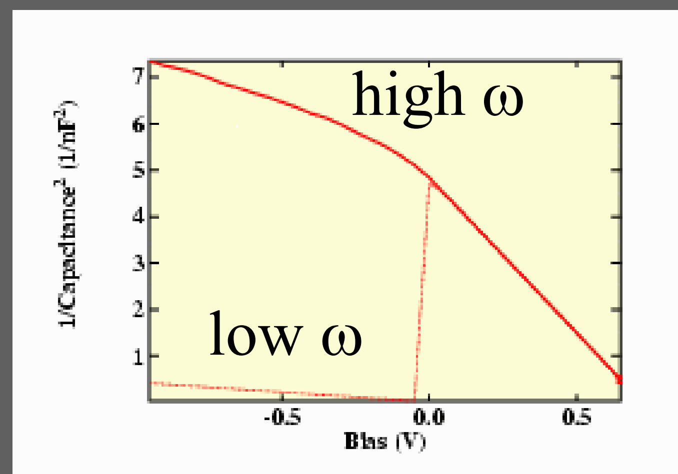
Loss-tangent: $\tan\delta = G/\omega C$



Deep levels



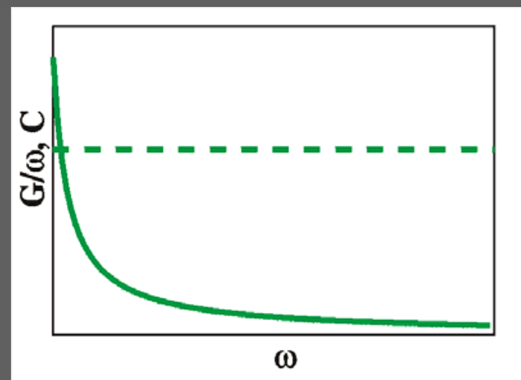
- Increasing bias
- less band-bending
- (EF moves down)
- at $V>V_x$ deep level completely above E_F. Stops contributing
- reduced capacitance and increased slope in C^{-2}-V plot

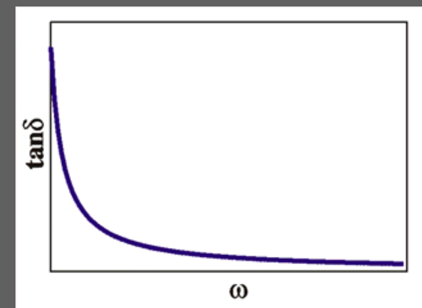


Frequency response

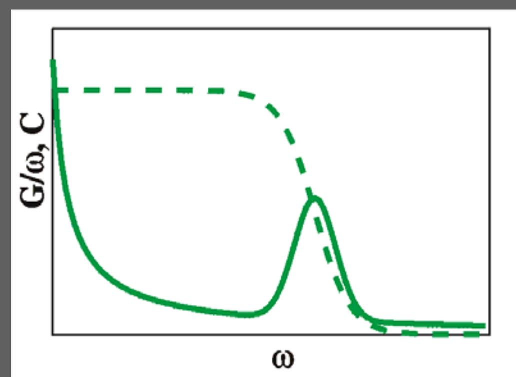
C, G/ω $\qquad$ $\tan\delta = G/\omega C$

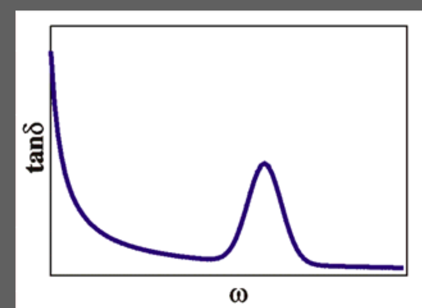
Only shallow levels:





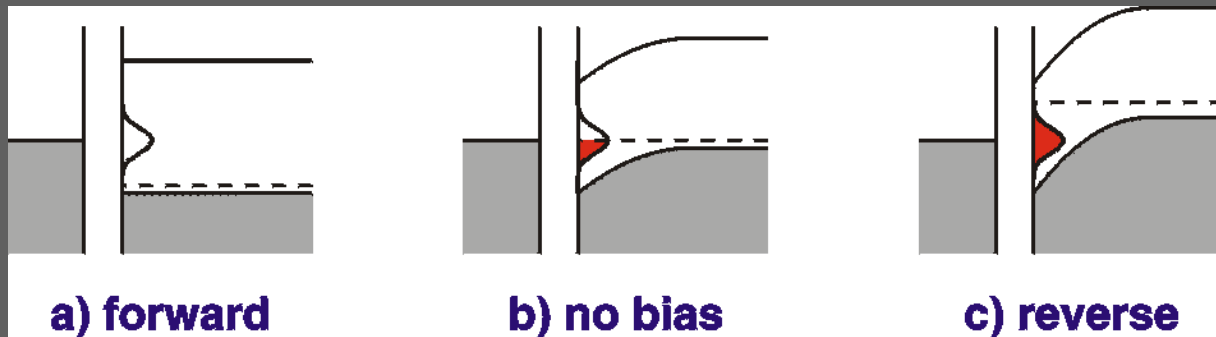
Plus deep levels:





Interface states

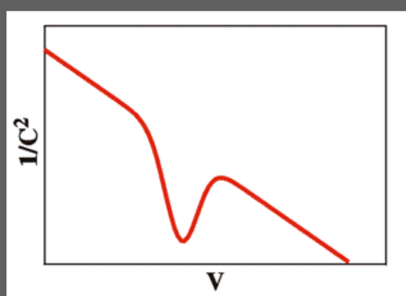
Special type of deep states: only present at interface



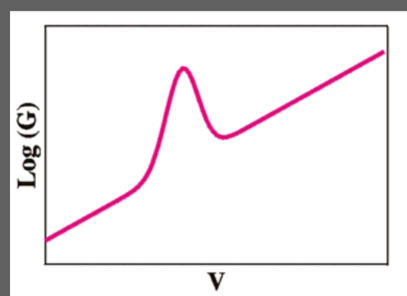
not visible in C, G

increased C and G

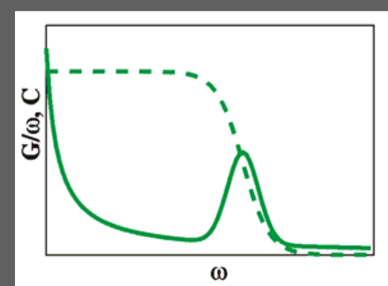
not visible in C,G



C^{-2}-V



Log(G)-V



G/ω, C - ω

Summary of C-Vω and G-Vω

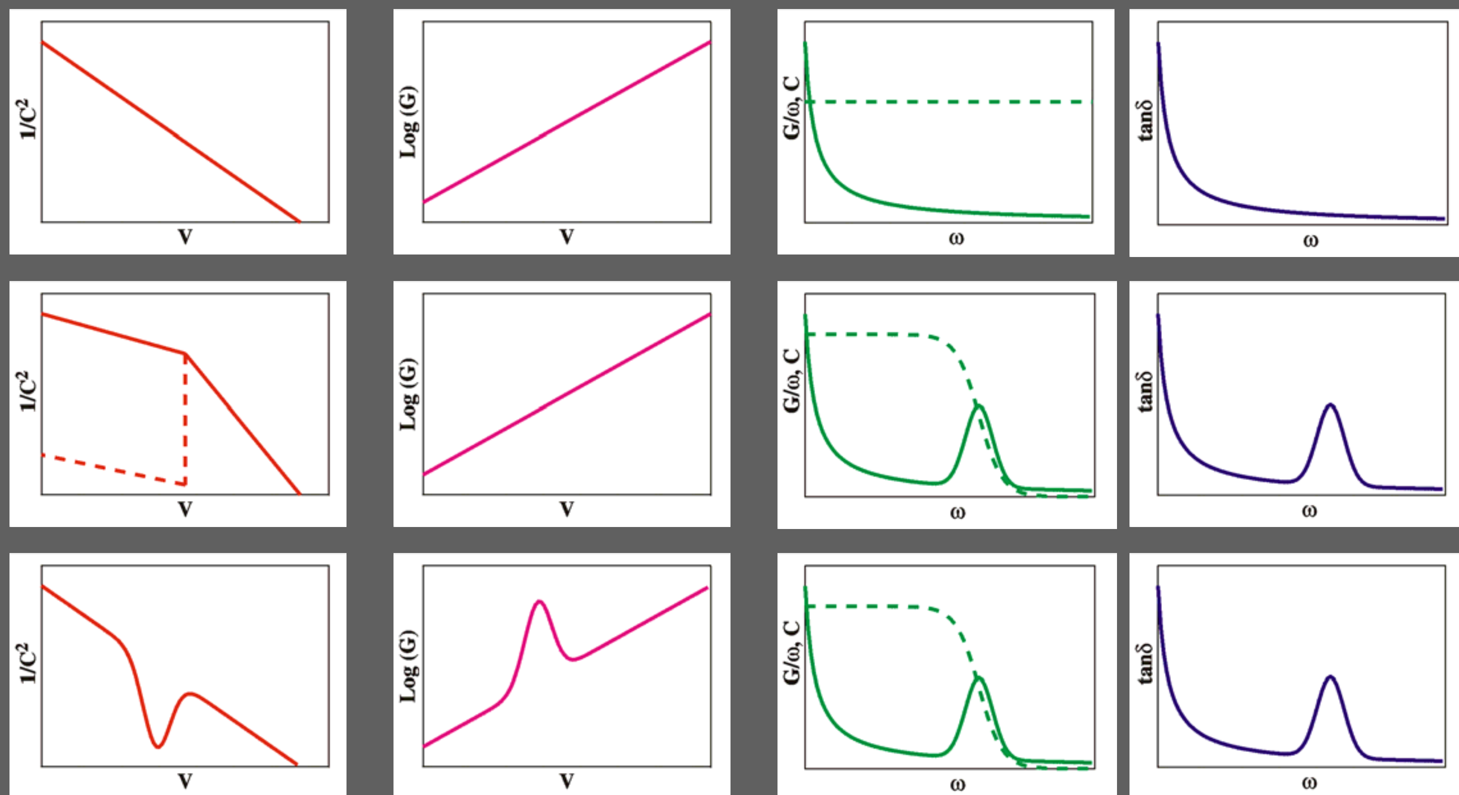
Spectra

C^{-2}-V | Log(G)-V | C, G/ω-ω | tanδ-ω

shallow homogeneous

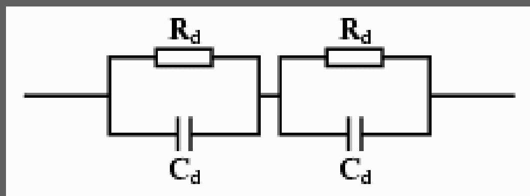
+ deep homogeneous

+ interface



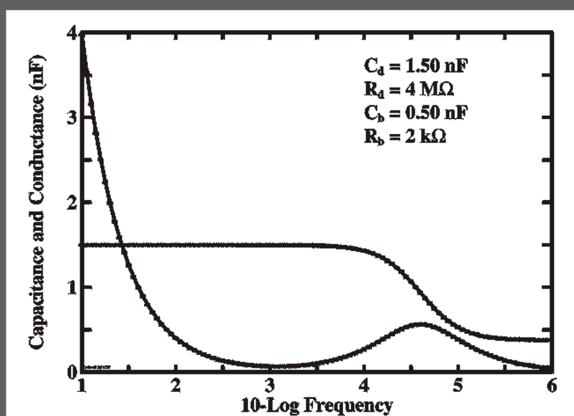
Admittance Spectroscopy
Equivalent circuits

Admittance spectroscopy: *C*, *G*, tanδ as function of ω



$$C = \frac{R_d^2 C_d + R_b^2 C_b + \omega^2 R_d^2 R_b^2 C_d C_b (C_d + C_b)}{(R_d + R_b)^2 + \omega^2 R_d^2 R_b^2 (C_d + C_b)}$$

$$G = \frac{R_d + R_b + \omega^2 R_d R_b (R_d C_d^2 + R_b C_b^2)}{(R_d + R_b)^2 + \omega^2 R_d^2 R_b^2 (C_d + C_b)}$$



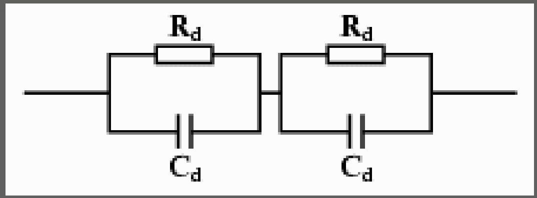
Resembles deep states picture:

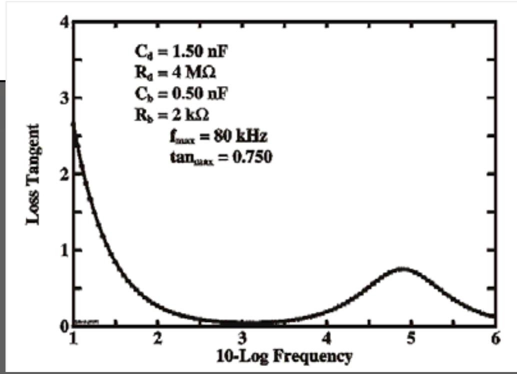
”Hey, that is nice, we can simulate deep states with equivalent circuits!”

(even if it has no physical meaning)

or: $\tau = RC$

Admittance Spectroscopy
Loss tangent

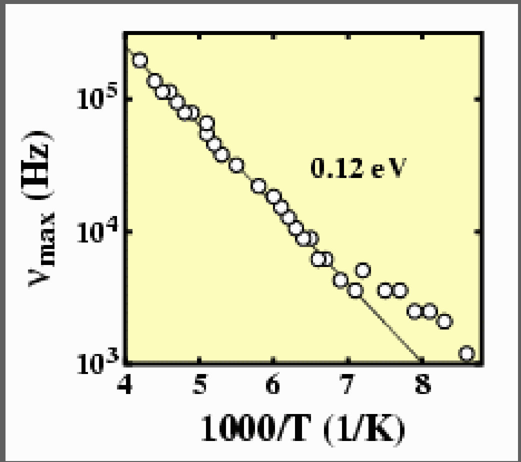




Maximum at

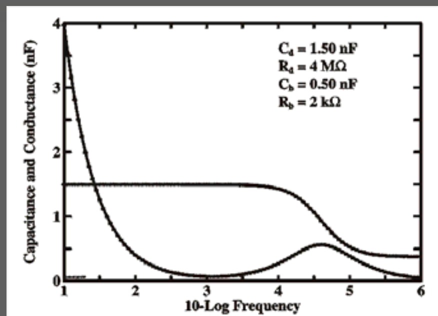
$$1/\omega_{max} = R_b\sqrt{C_b(C_b+C_d)}$$

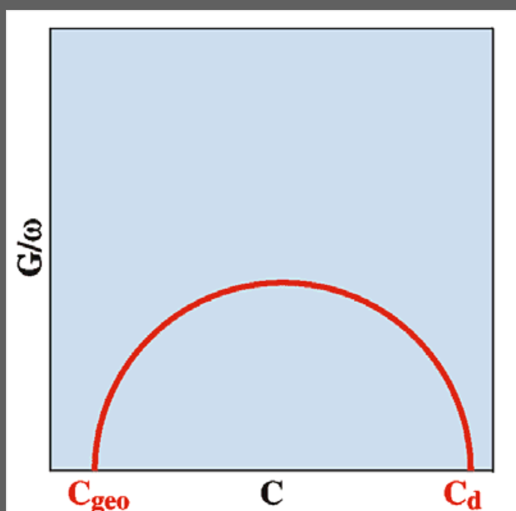
$R_b \sim \exp(-E_a/kT)$
(remember from bulk samples?)



We can determine the bulk activation energy from the tanδ data

Admittance Spectroscopy
Cole-Cole Plots





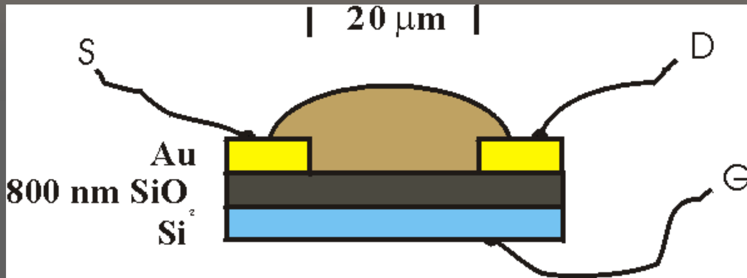
	ω=0	ω=00
C	C_d	C_b
R	R_d	R_b

$C_b = C_{geo} = \varepsilon A/d$ (“metal plates”)

Cole-Cole plot is
G/ω vs. V

yields ε
(if we know electrode area and film thickness)

Field Effect Transistor

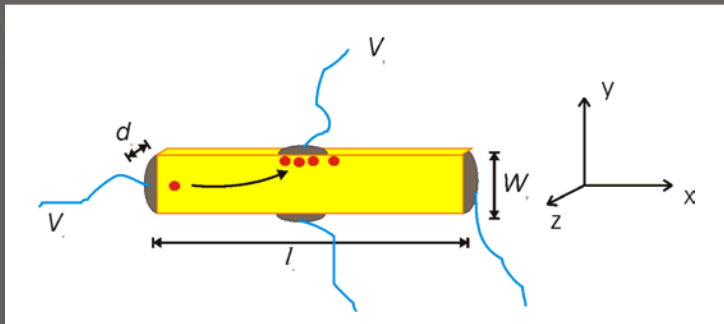


$$I_{SD} = (Z/L)\mu_p C[(V_G - V_T)V_D - \alpha V_D^2]$$

If we know the dimensions of the device (A, Z, L, d [C]) we can find the hole mobility μ_p

symbol	*Meaning*
L	Channel length
Z	Channel width
d	Oxide thickness
V_G	Gate voltage
V_D	Drain voltage
I_{SD}	Drain current
μ	(hole) mobility
C	Oxide capacitance = $A\varepsilon/d$

Hall measurements



(remember) conductivity:

$$\sigma = qp\,\mu_p$$

$$\sigma = (I/V_x)(l_x/W_y d_z)$$

$$F_y^{\,B} = q\,B_z\,v_x \qquad F_y^{\,E} = -qE_y$$

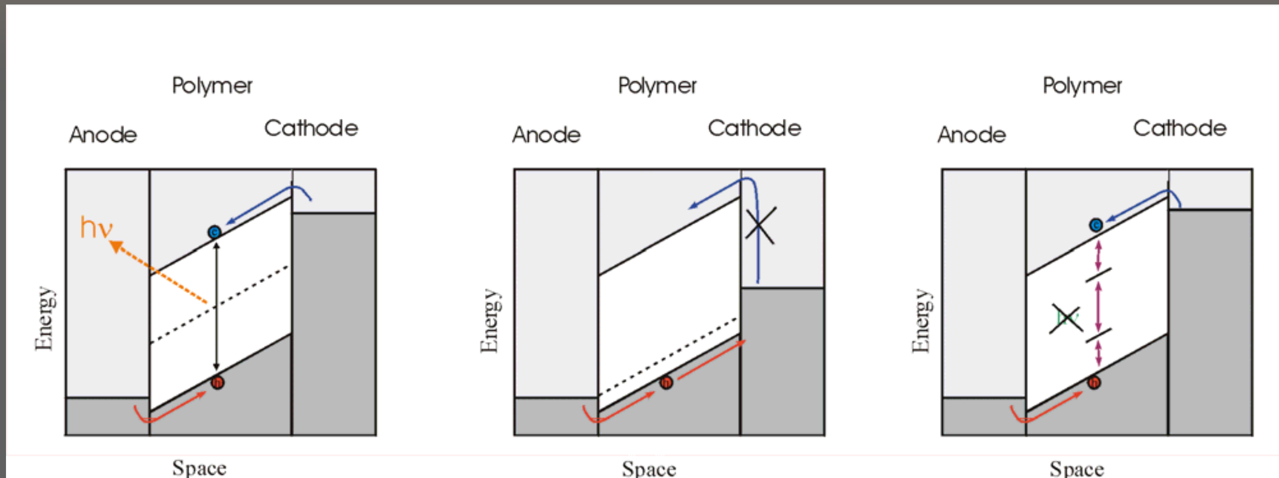
$$v_x = J_x/qp = I_x/(W_y d_z qp) \qquad E_y = V_y/W_y$$

$$qp = B_z I_x / V_y d_z$$

$$\mu_p = l_x V_y \,/\, B_z V_x W_y$$

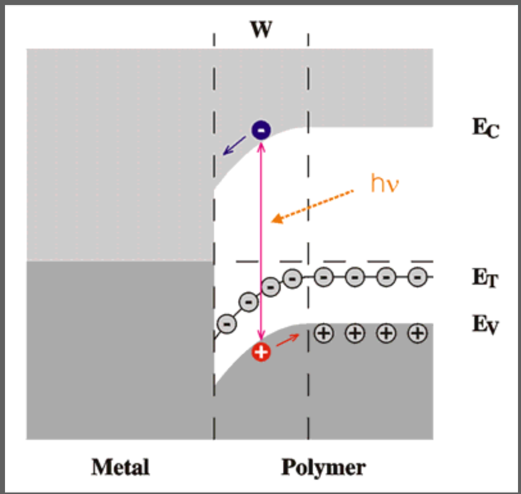
In the Hall measurements we can measure the hole mobility μ_p

Optical effects: LED



- electrons and holes are injected into the active region
- here they recombine -> photon
- "color" of photon is E_g. With polymers blue is possible
- Limiting mechanisms:
  - unbalanced carrier injection (choice of electrodes)
  - presence of non-radiating-recombination centers

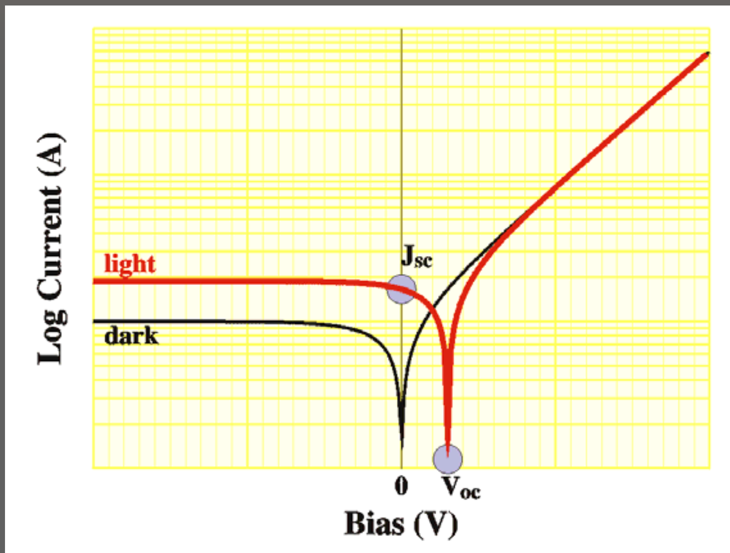
Optical Effects: Photo detector/solar cell

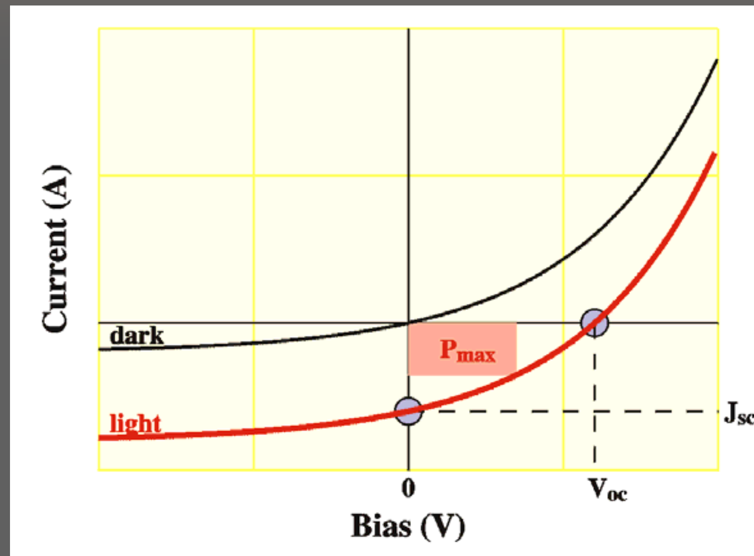


In photo-detectors / solar cells
The opposite process takes place:

- Energy of photon is absorbed by creation of e-h pair
- Electric field in active region breaks the e-h pair
- Individual carriers are swept out of region and contribute to external current

Solar Cell





Parameters that characterize a solar cell:

- open-circuit voltage (I=0) V_{oc}
- short-circuit current (V=0) J_{sc}
- maximum power output P_{max}

Tomorrow:

- Relaxation processes
- Time-resolved measurements
- (Transient techniques)