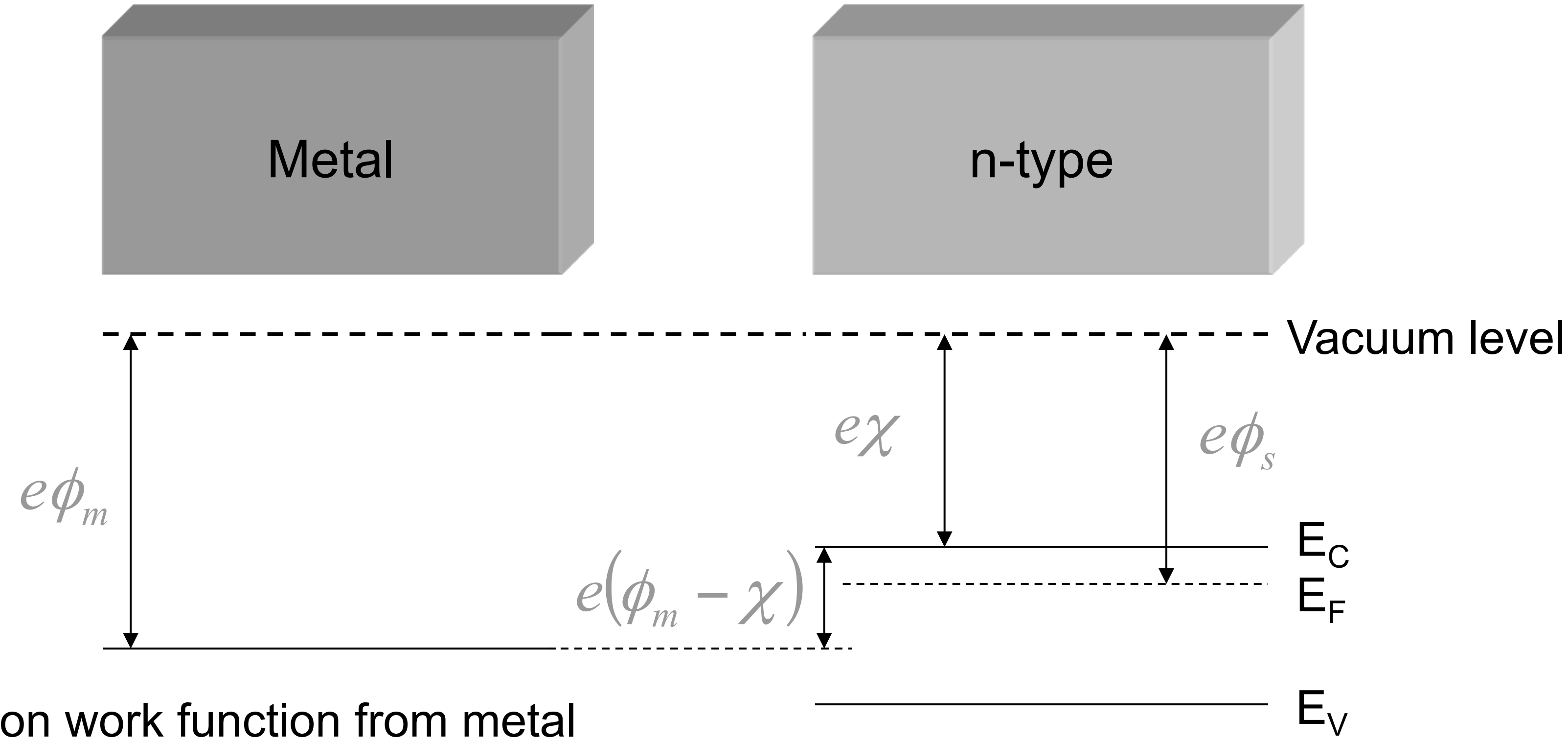
Metal-semiconductor junction

(Schottky barrier)



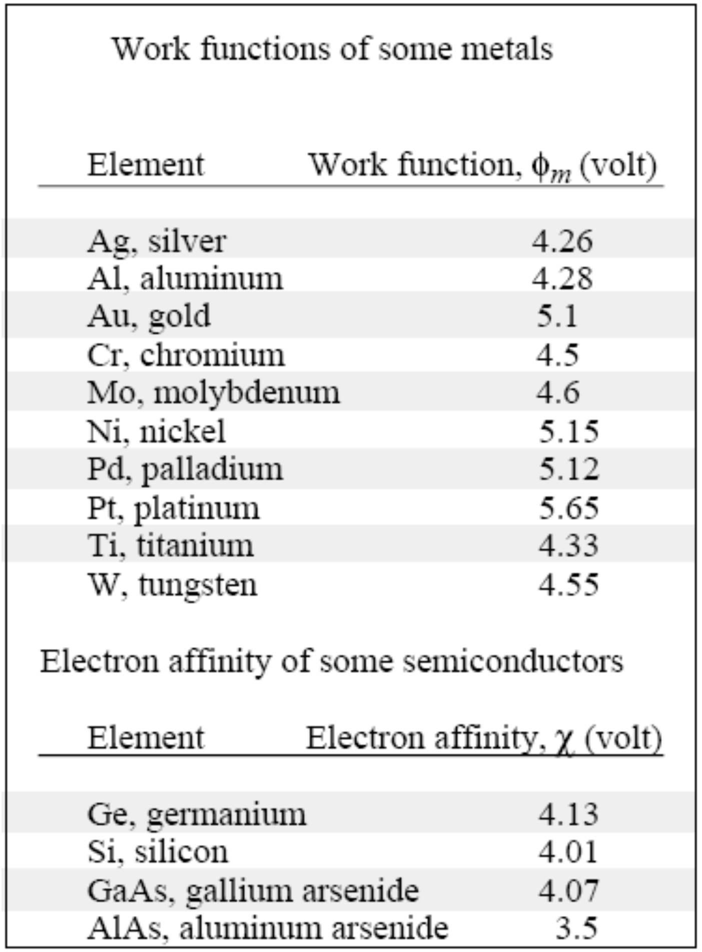
Φ_m –electron work function from metal
χ – electro affinity in semiconductor,
Φ_s- electron work function from semicond.

$$\boxed{\Phi_s = \chi + (E_C - E_F)}$$

What happens when we contact the metal and semiconductor in thermal equilibrium?

Metal-semiconductor junction

(Schottky barrier)



Work functions of some metals

Element	Work function, ϕ_m (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Electron affinity of some semiconductors

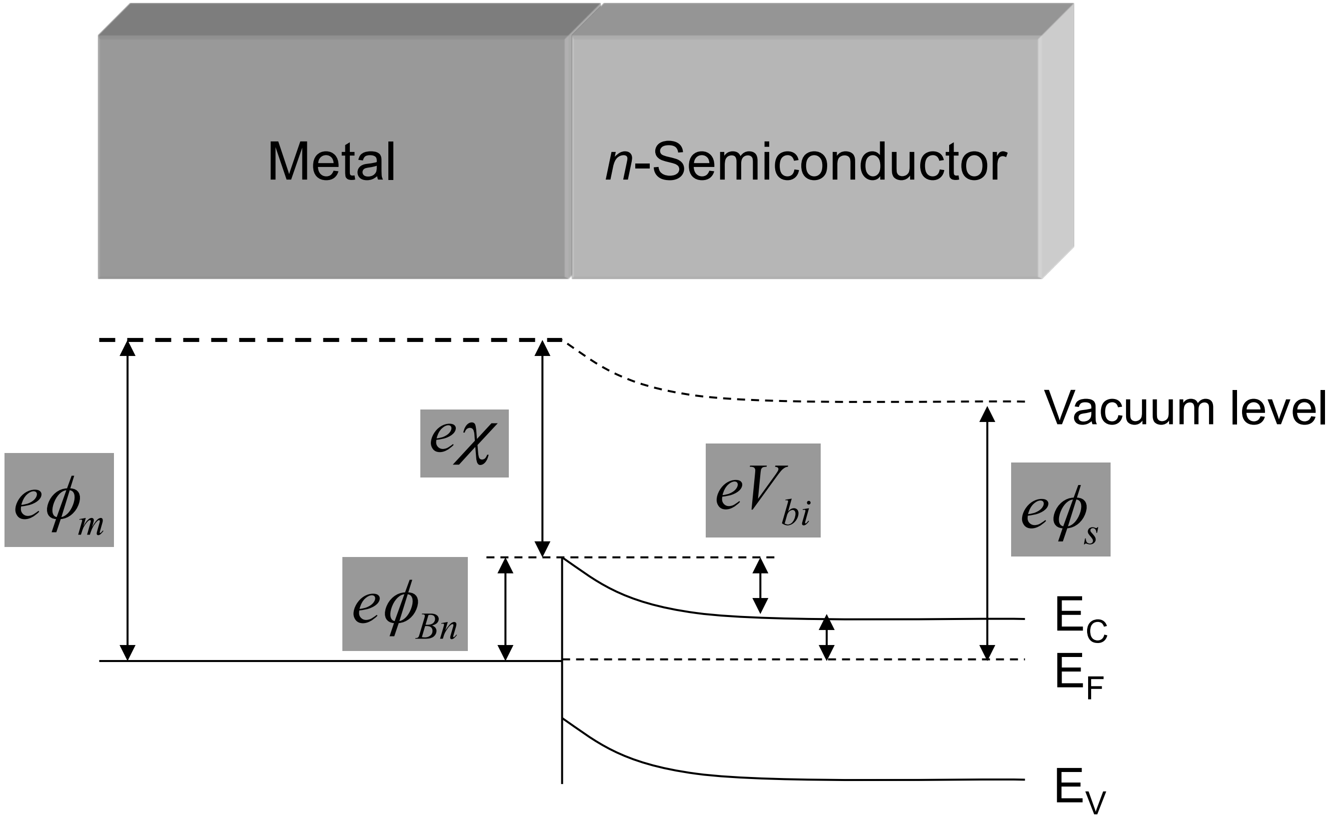
Element	Electron affinity, χ (volt)
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

METALS: Work functions

SEMICONDUCTORS: Electron affinity

Metal-semiconductor junction

(Schottky barrier)



The Fermi level must be constant at thermal equilibrium but the vacuum level must be continuous...

Metal-semiconductor junction

(Schottky barrier)

To ensure the continuity of the vacuum level, the Fermi level must move deeper into the semiconductor bandgap at the interface.

This involves electrons moving out from the semiconductor into the metal (which has so many electrons already that its Fermi level or band profile is unaffected).

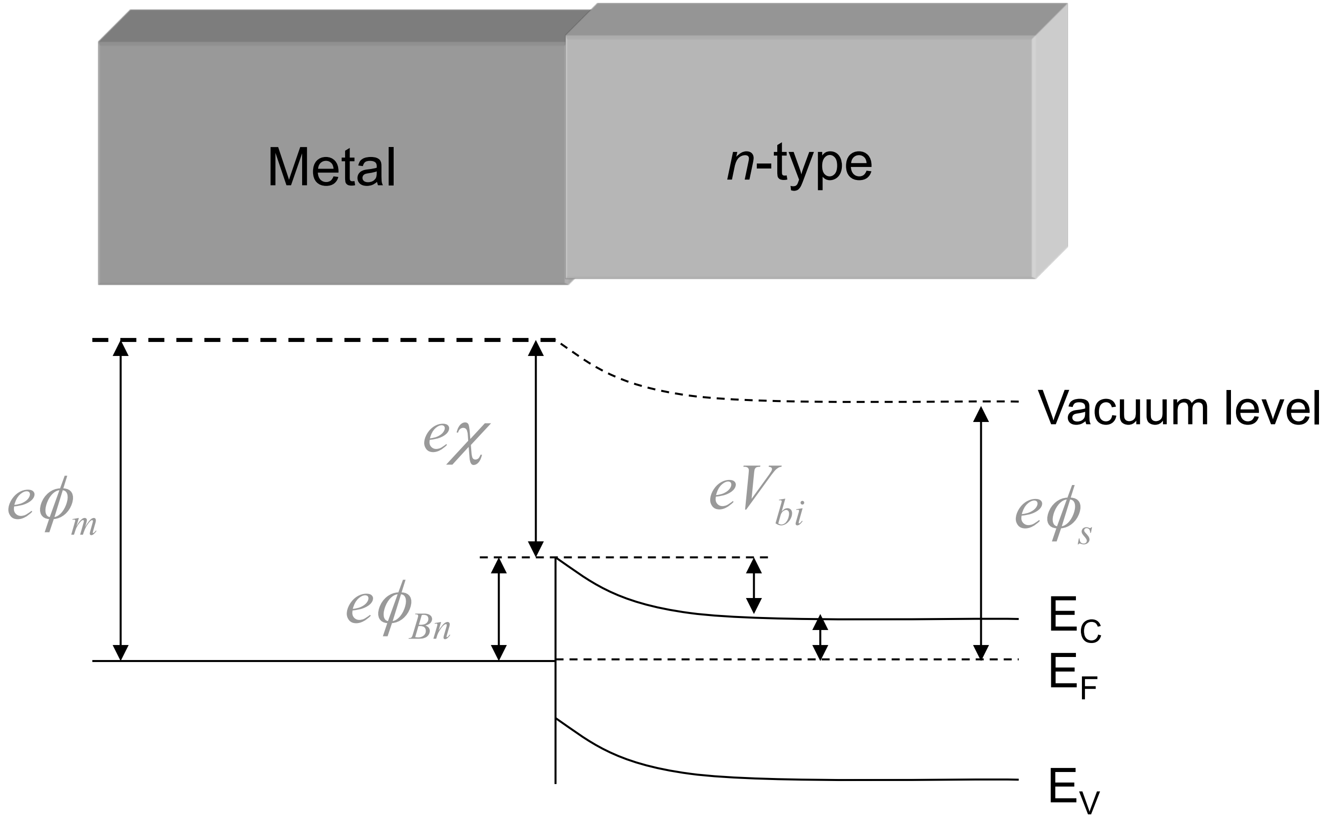
As electrons move out, they leave behind uncompensated ionised donor atoms (as in a *p-n* junction) and a depletion region is formed.

The Schottky barrier height at the junction is the difference between the semiconductor conduction band and the metal Fermi level so that,

$$e\phi_{Bn} = e\phi_m - e\chi$$

Metal-semiconductor junction

(Schottky barrier)



$$\boxed{e\phi_{Bn} = e\phi_m - e\chi}$$

Metal-semiconductor junction

(Schottky barrier)

Electrons moving from the semiconductor to the metal encounter an energy barrier given by the built-in potential,

$$eV_{bi} = e\phi_m - e\phi_s$$

For the junction between a metal and a *p*-type semiconductor the barrier height and built in voltage are given by,

$$e\phi_{Bp} = E_g - \left(e\phi_m - e\chi\right)$$

$$eV_{bi} = e\phi_s - e\phi_m$$

Depletion width

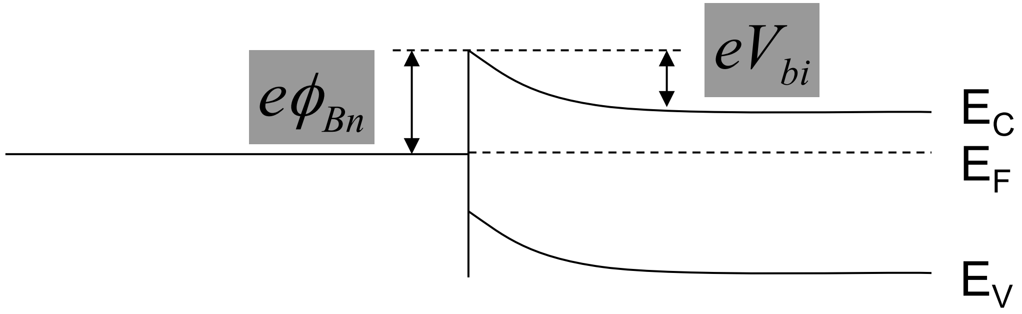
Once the Schottky barrier height is known we can calculate the electric field profile, depletion width etc.

The problem for a Schottky barrier on an n-type semiconductor is identical to that for a one-sided abrupt p^+-n junction (no depletion width on the metal side)…

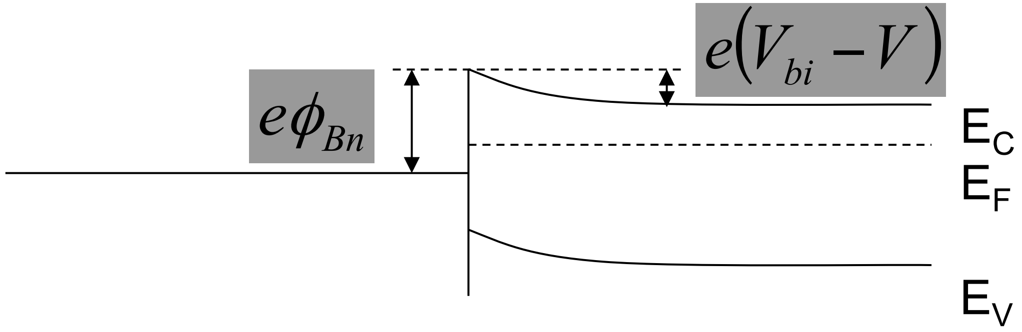
$$\boxed{W = \sqrt{\frac{2\varepsilon_s\left(V_{bi} - V\right)}{eN_D}}}$$

N_D is the donor concentration
V is the applied bias (positive forward, negative reverse)

Metal-semiconductor junction under bias

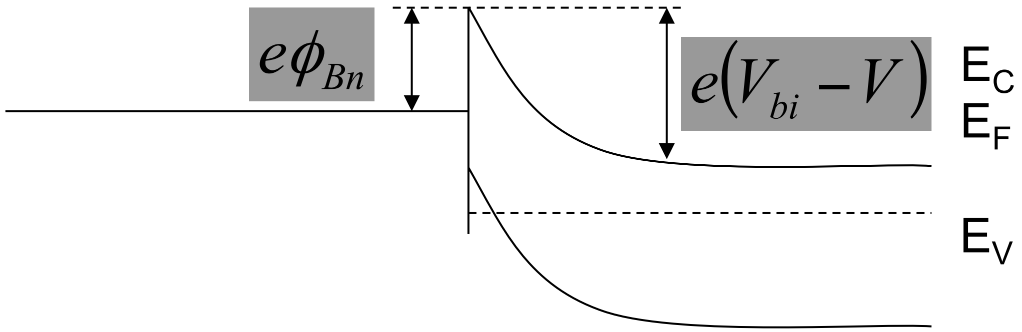


Zero bias



Forward bias (V is positive)

Decreased barrier to electrons flow from the semiconductor to the metal



Reverse bias (V is negative)

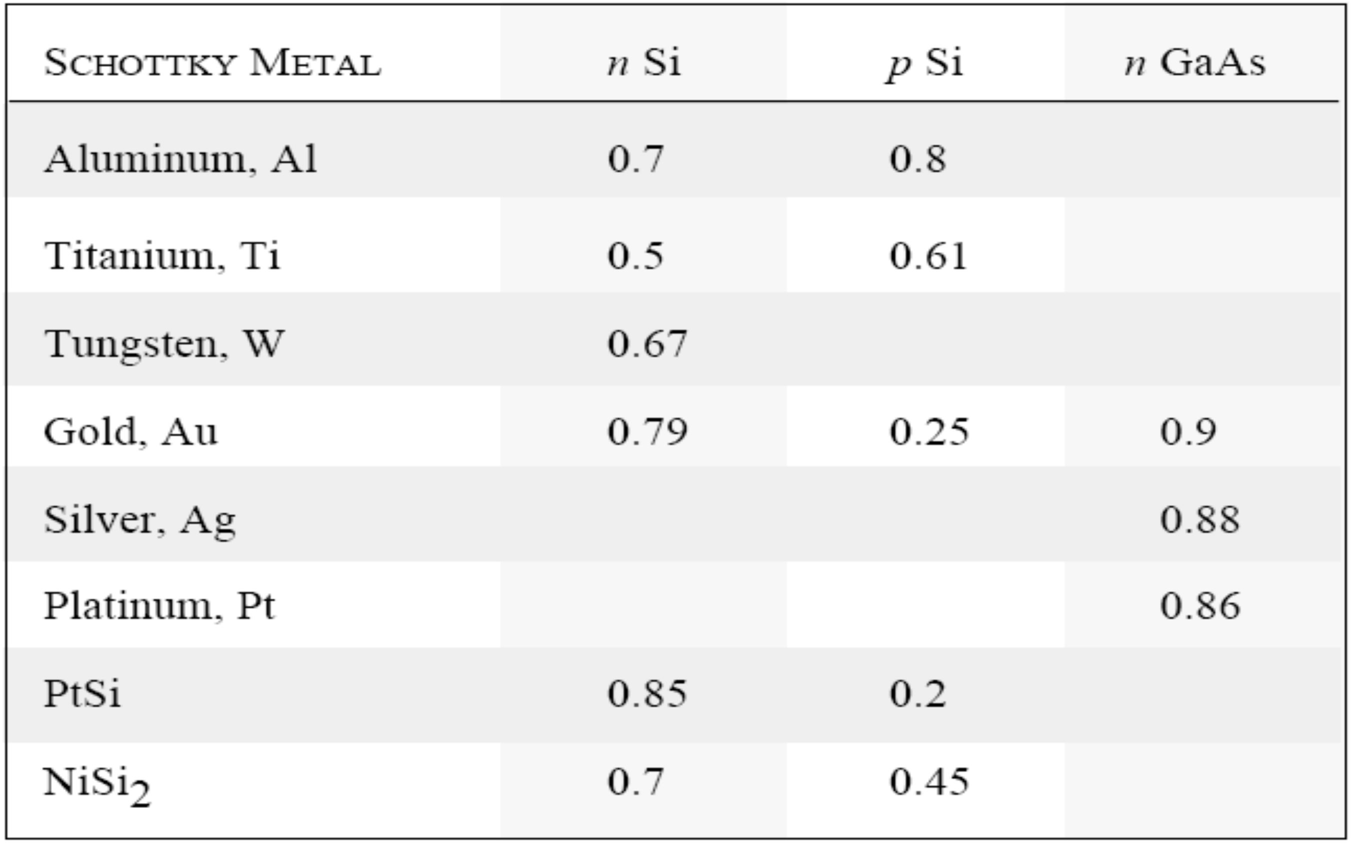
Increased barrier to electrons flow from the semiconductor to the metal

…rectification

Metal-semiconductor junction

(Schottky barrier)

Barrier heigths for some metals and semiconductors, Φ_{Bn} (V)



SCHOTTKY METAL	n Si	p Si	n GaAs
Aluminum, Al	0.7	0.8	
Titanium, Ti	0.5	0.61	
Tungsten, W	0.67		
Gold, Au	0.79	0.25	0.9
Silver, Ag			0.88
Platinum, Pt			0.86
PtSi	0.85	0.2	
$NiSi_2$	0.7	0.45	

Metal-semiconductor junction

(Schottky barrier)

ADVANTAGES:

- Simple to prepare.
- Faster than p-n diodes!
- Ohmic contacts.

Current flow in a Schottky barrier

The dominant mechanism for current flow across a Schottky barrier is thermionic emission, in which electrons with energy greater than the barrier height $e(V_{bi}-V)$ can pass across from the semiconductor to the metal.

As we have just seen…change the bias – change the barrier

Assuming a Boltzmann distribution of electrons in the semiconductor, the fraction of electrons with energy greater than the barrier $e(V_{bi}-V)$ is,

$$n_{th} = n_o e^{-e(V_{bi}-V)/kT}$$

Where n_o is the electron density in the neutral region which is given by,

$$n_o = N_C e^{-(E_C-E_{Fs})/kT}$$

N_C is the effective density of states in the conduction band

Current flow in a Schottky barrier

Referring back to our band diagram we see that the barrier height on the metal side is

$$e\phi_{Bn} = eV_{bi} + \left(E_C - E_{Fs}\right)$$

So combining all three equations we get,

$$n_{th} = N_C e^{-e\left(\phi_{Bn} - V\right)/kT}$$

The current flowing from semiconductor to metal is therefore,

$$J_{s \to m} = CN_C e^{-e\left(\phi_{Bn} - V\right)/kT}$$

where C is simply a proportionality constant

Current flow in a Schottky barrier

At thermal equilibrium the flow of electrons from the semiconductor to the metal is exactly balanced by the flow of electrons from the metal to the semiconductor so,

$$J_{m\rightarrow s} = J_{s\rightarrow m} = CN_C e^{-e\phi_{Bn}/kT}$$

Since the barrier height on the metal side is not dependent on the applied bias the current from metal to semiconductor will always be the same so the net current under bias is then,

$$J = J_{s\rightarrow m} - J_{m\rightarrow s} = CN_C e^{-e\phi_{Bn}/kT}\left(e^{eV/kT} - 1\right)$$

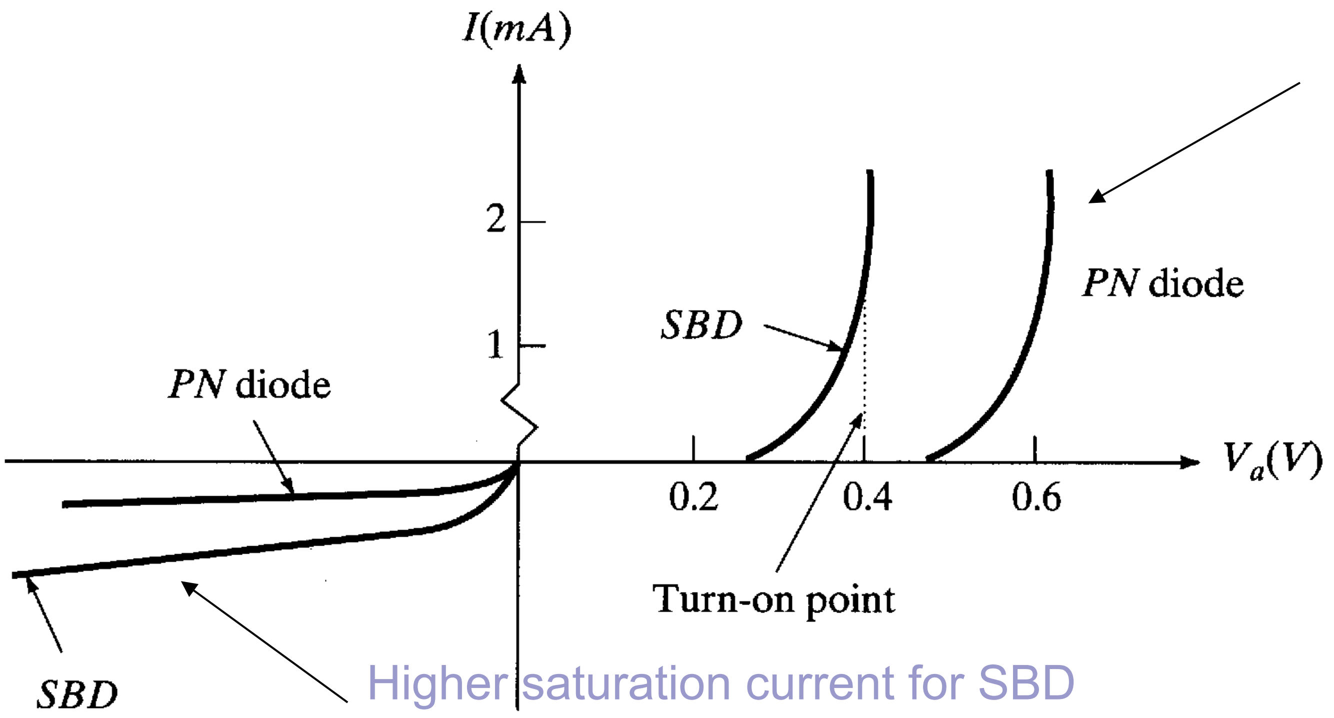
Saturation current density, J_s

$$\boxed{J = J_s\left(e^{eV/kT} - 1\right)}$$

…rectification

Current flow in a Schottky barrier

PN ja SBD diodes



Higher voltages for p-n diodes

Higher saturation current for SBD

In SBD only major carriers are moving- no diffusion capacitance-faster than p-n diode.

Current flow in a Schottky barrier

- Saturation current:

SBD:

$$J_{sT} = A^{*}T^{2}\exp\left[\frac{-e\phi_{Bn}}{k_BT}\right] \sim 10^{-5}\,\mathrm{A/cm^2}$$

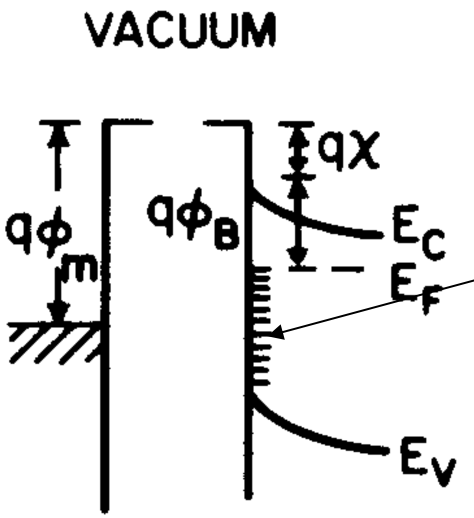
A^{*}- Richardson constant

$$A^{*} = \frac{4\pi q m^{*} k^{2}}{h^{3}}$$

p-n diode:

$$J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right] \sim 10^{-11}\,\mathrm{A/cm^2}$$

Role of surface states

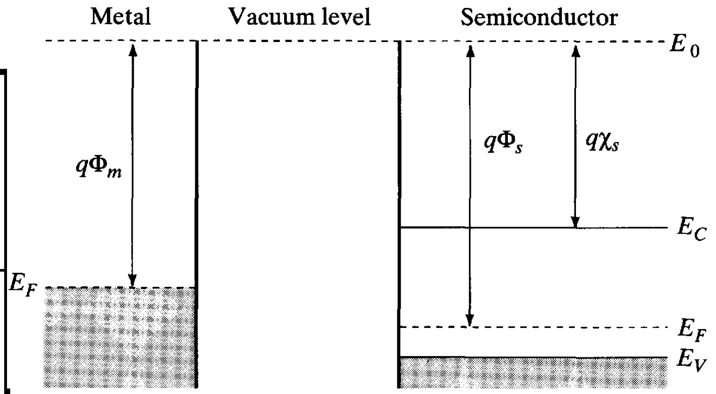


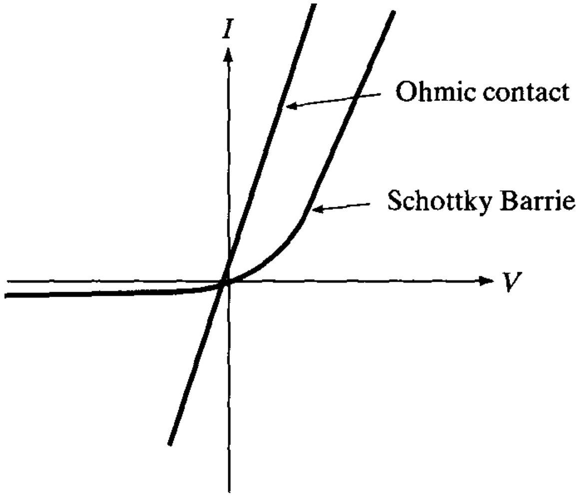
Surface states

Fermi level could be pinned
when the concentration of surface states is high

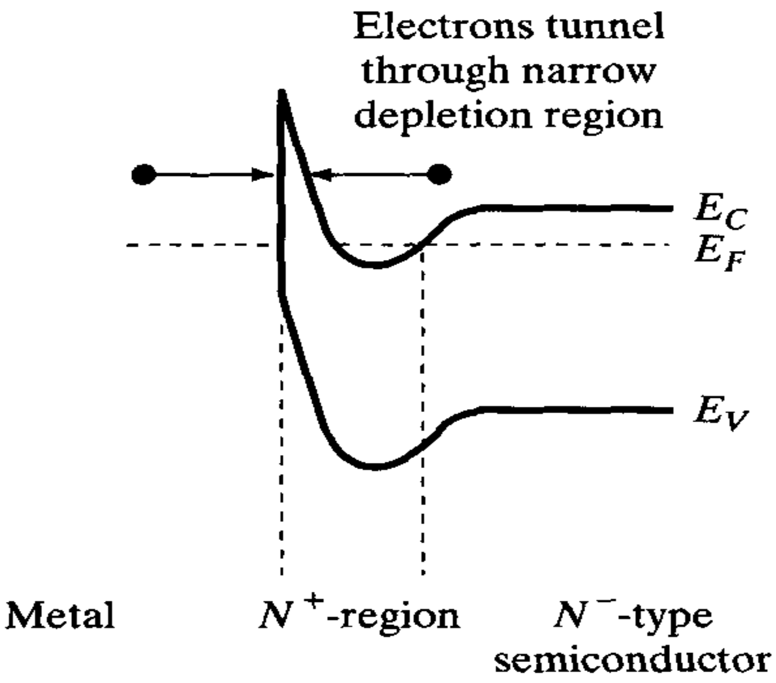
Contacts

Material / condition	Contact type
n-type – Metal $\Phi_m > \Phi_s$	barrier
p-type -Metal $\Phi_m < \Phi_s$	barrier
n-type - Metal $\Phi_m < \Phi_s$	ohmic
p-type – Metal $\Phi_m > \Phi_s$	ohmic





Contacts



Tunnel contact

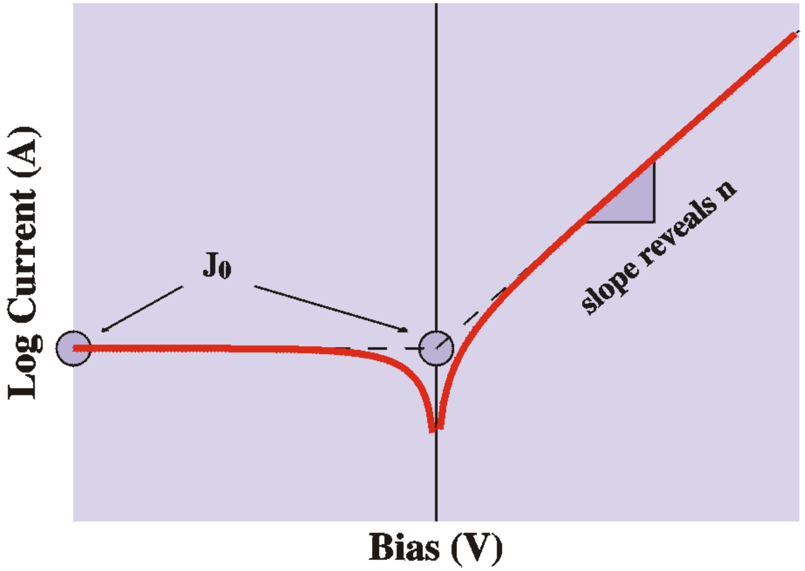
highly doped region
(N+ or P+) is required

DC properties of Scottky barrier

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

From I-V curve we can get

- saturation current (J_0)
- ideality factor, n



when measured at different T:

- barrier height, ϕ_{Bp}

AC: Conductance (schottky barrier)

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

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

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

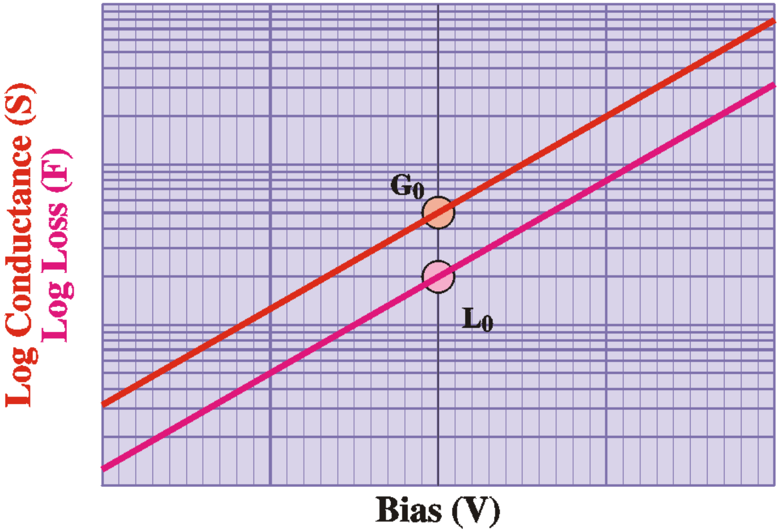
$J = J_0 \, [\exp(qV/nkT) - 1]$

$$\boxed{G = G_0 \exp(qV/nkT)}$$

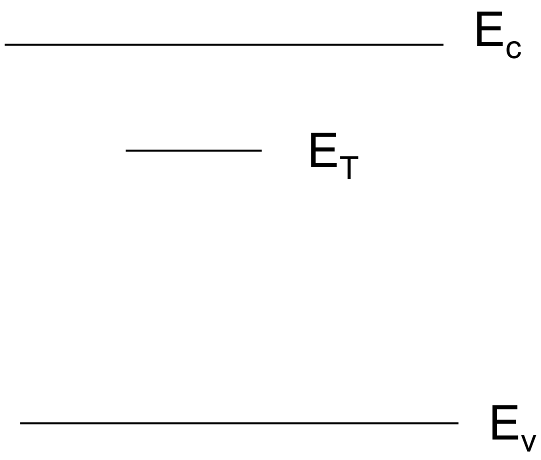
Frequency independent

$\boxed{\text{Loss: } L = G/\omega}$

$\boxed{\text{Loss-tangent: } \tan\delta = G/\omega C}$



Deep defect states



Every energy level E_T has a time constant:

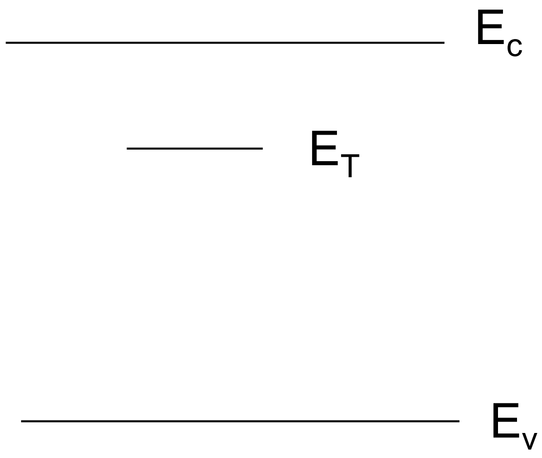
$$\tau = \tau_o \exp(E_T / kT)$$

Deeper level= bigger time constant!

Bigger time constant-> lower frequency to respond

response= exchange of charge carriers between zone and level= **CAPACITANCE**

Deep defect states



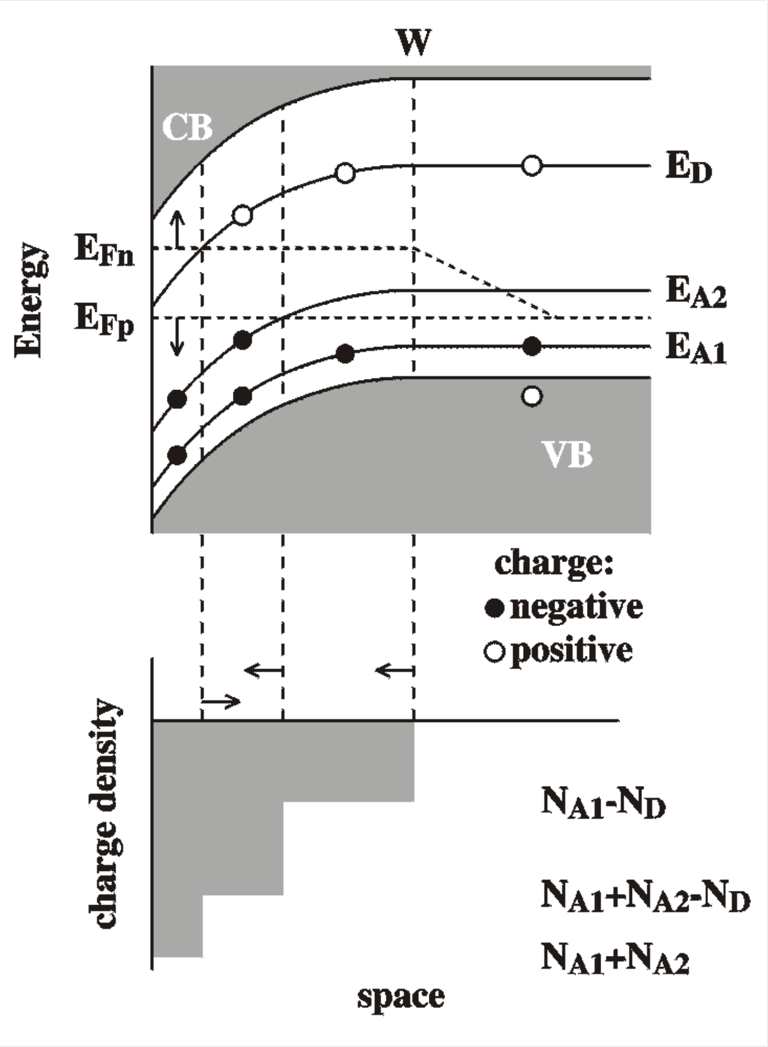
So by measuring capacitance at low frquency we have

$$C=C_S+C_D$$

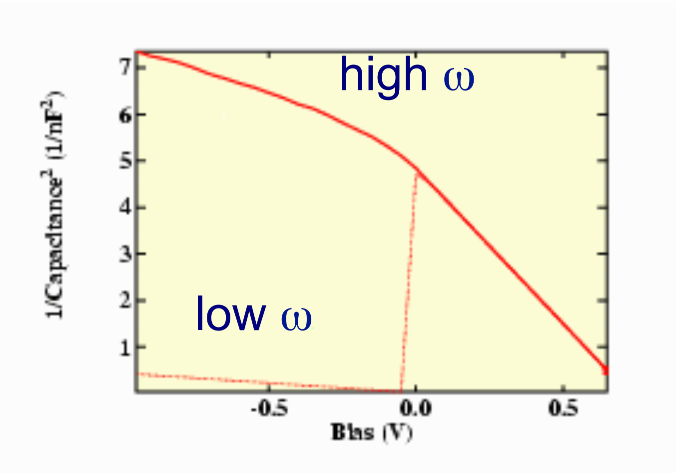
at high frequency we have

$$C=C_S$$

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

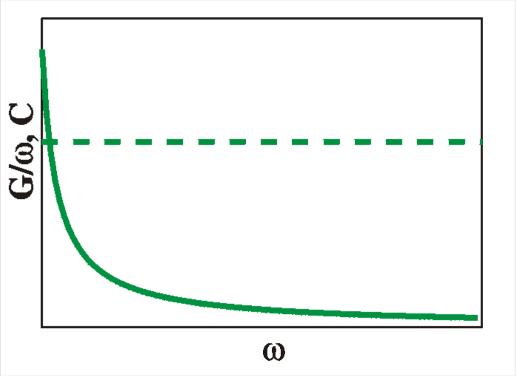


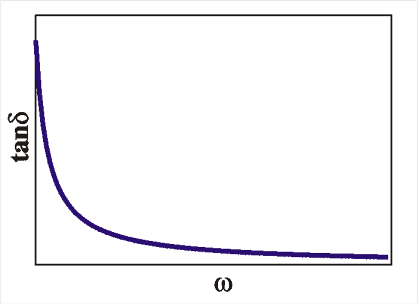
Frequency response

C, *G*/ω

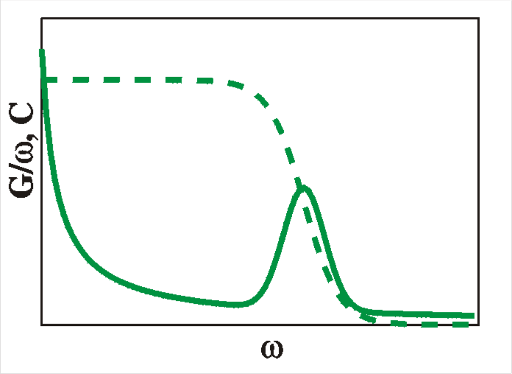
tanδ = *G*/ω*C*

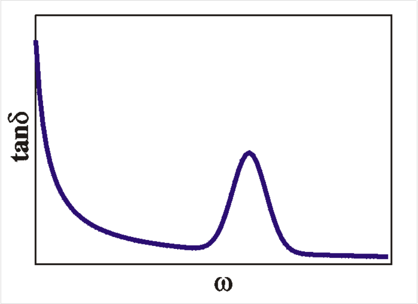
Only shallow levels:





Plus deep levels:

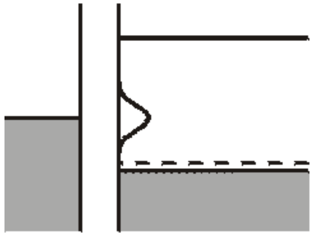




Maximum at $\omega_{\max} = \dfrac{1}{\tau}$

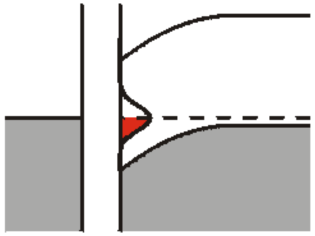
Interface states

Special type of deep states: only present at interface



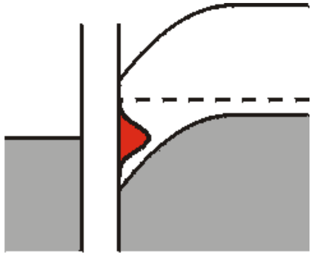
a) forward

not visible in C, G



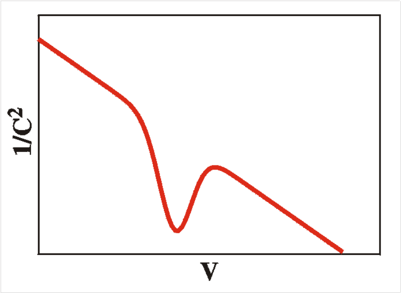
b) no bias

increased C and G

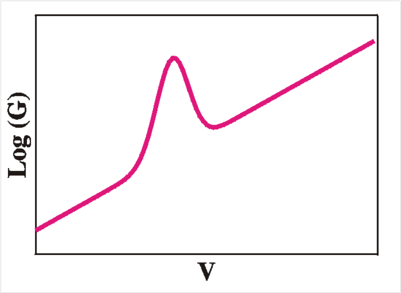


c) reverse

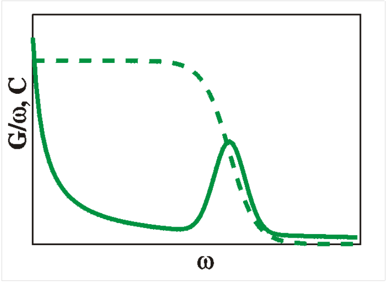
not visible in C,G



C^{-2}-V



Log(G)-V



G/ω, C - ω

Summary of C-V vs ω and G-V vs ω

Spectra

C^{-2}-V

Log(G)-V

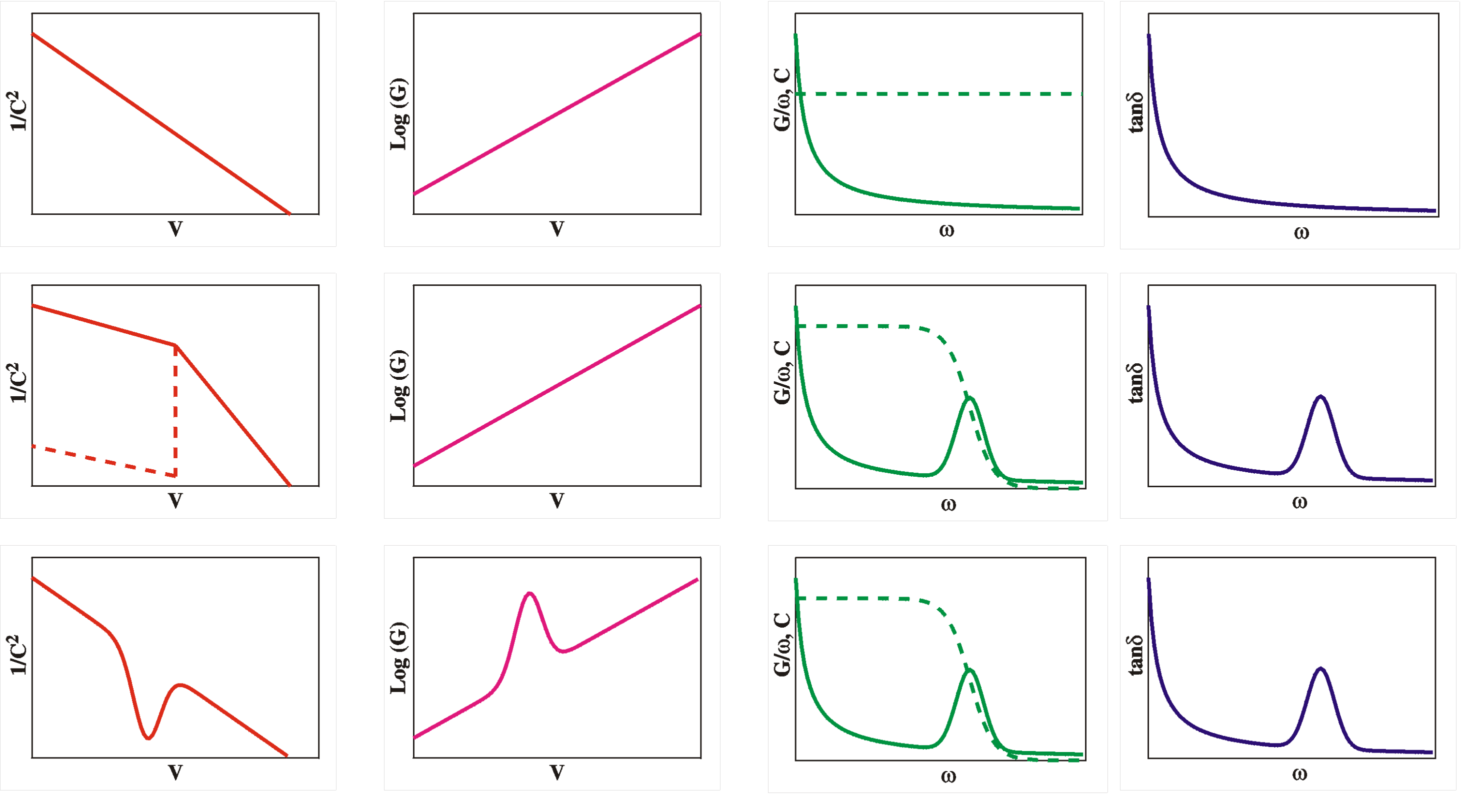
C, G/ω-ω

tanδ-ω

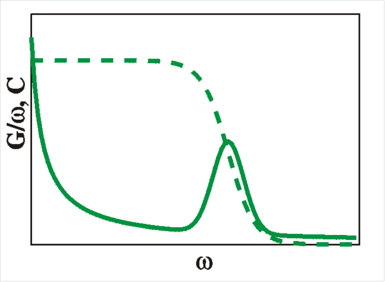
shallow homogeneous

+ deep homogeneous

+ interface



Interface states



G/ω, *C* - ω

Deep defects and interface states give the same characteristics

How do we know then?

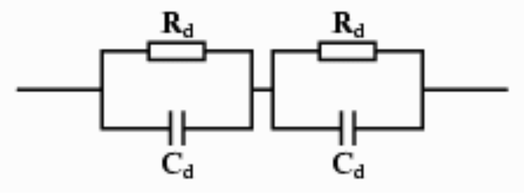
We must measure at different reverse bias

In case of interface states maximum should shift.

No shift in case on deep defects!!!

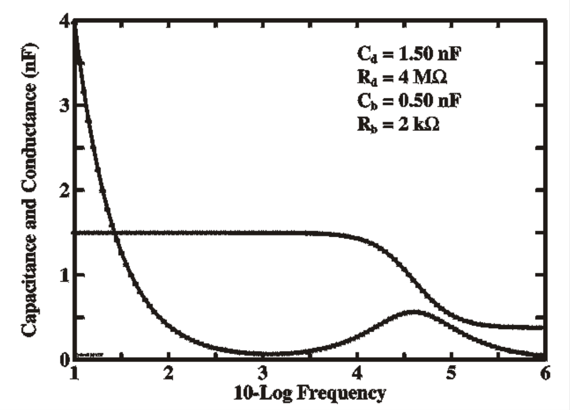
Admittance Spectroscopy
Equivalent circuits

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



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

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



Resembles deep states picture:

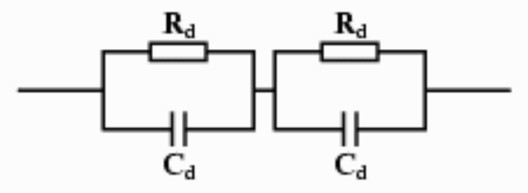
”Hey, that is nice, we can simulate deep states with equivalent circuits!”

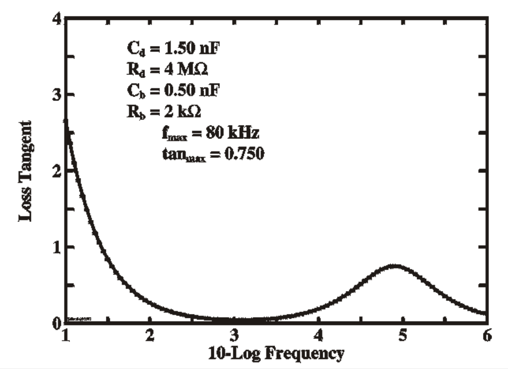
(even if it has no physical meaning)

or: $\tau = RC$

B- bulk D- deep defects

Admittance Spectroscopy
Loss tangent



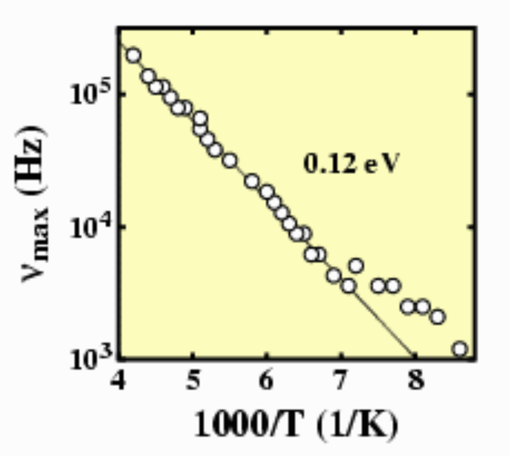


Maximum at

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

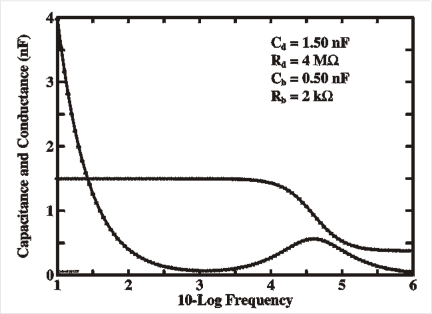
$R_b \sim \exp(-E_a/kT)$

resistivity of bulk samples



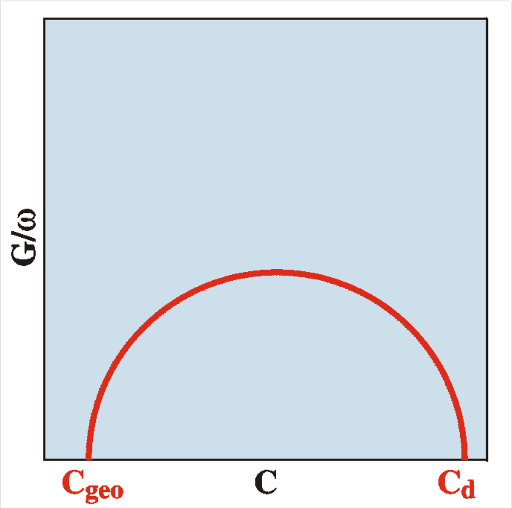
We can determine the bulk activation energy from the tanδ data

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”)



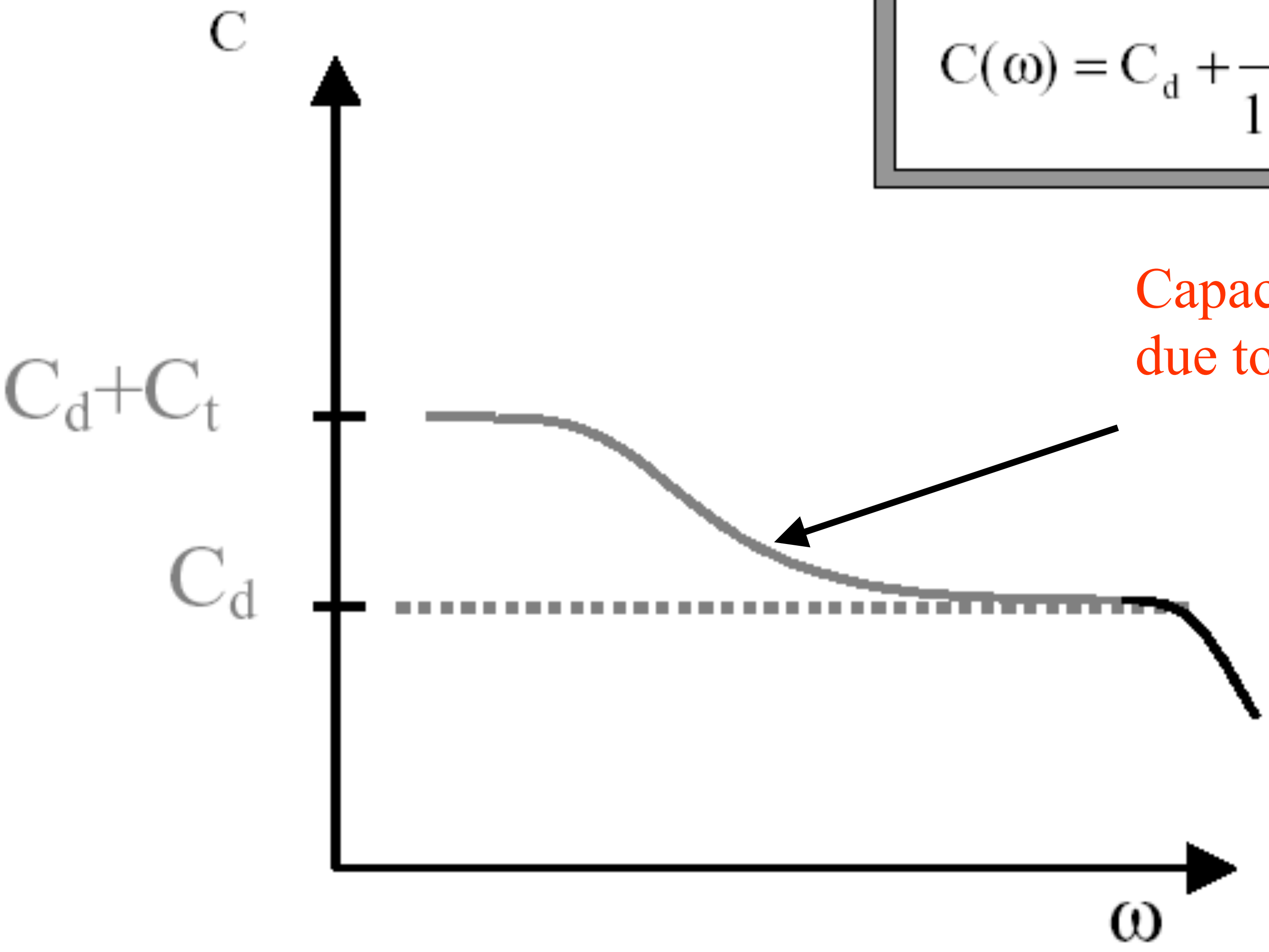
Cole-Cole plot is
G/ω vs. V

yields ε

(if we know electrode area and film thickness)

Admittance spectroscopy

$$C(\omega) = C_d + \frac{C_t}{1+(\omega/\omega_t)^2}$$



Capacitance step due to deep level t

Admittance spectroscopy

Basic formulas

$$C_{tot} = C_d + \frac{C_t}{1+(\tau\omega)^2},$$

$$G_{tot} = G_d + \frac{G_t(\tau\omega)^2}{1+(\tau\omega)^2},$$

$$\frac{1}{\tau} = \omega_t = 2\nu_0 e^{-\left(E_t/kT\right)},$$

$$\nu_0 = \beta_p N_v = \sigma_p \langle v_{Th} \rangle N_v$$

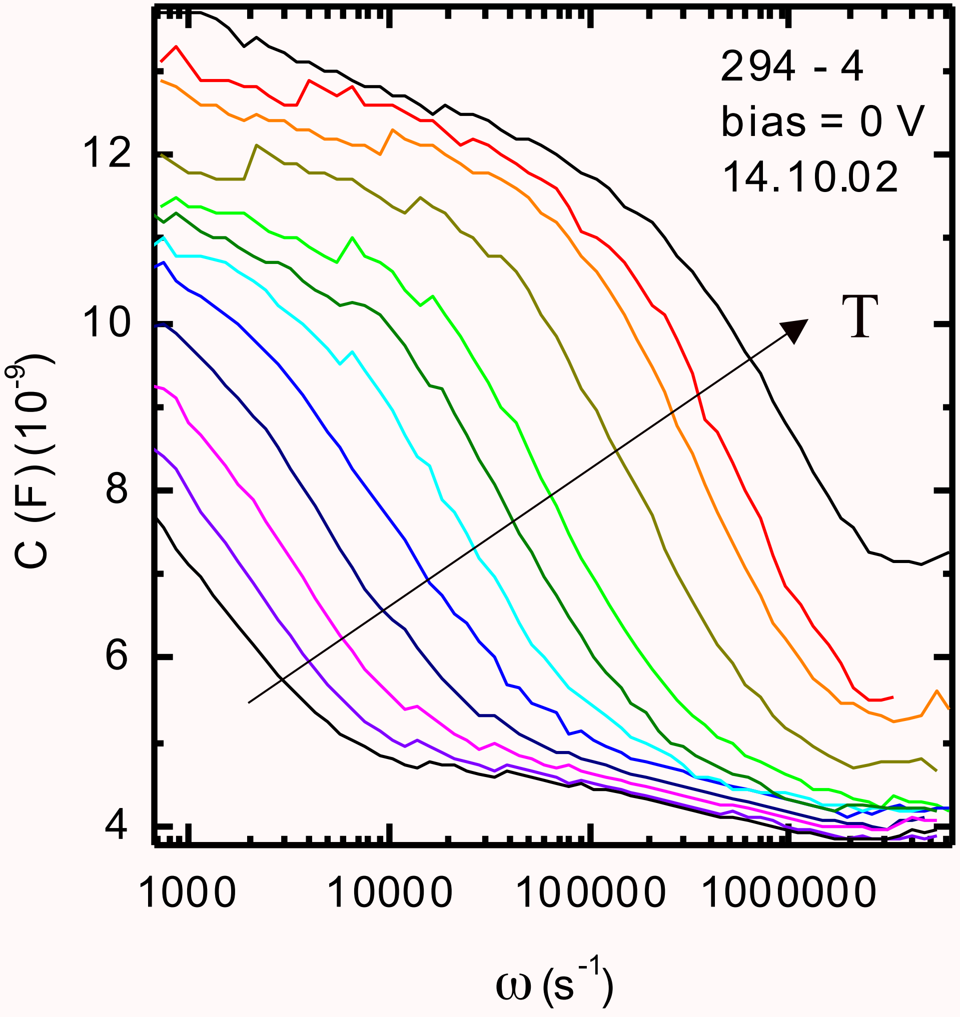
admittance

$$Y = G + i\omega C$$

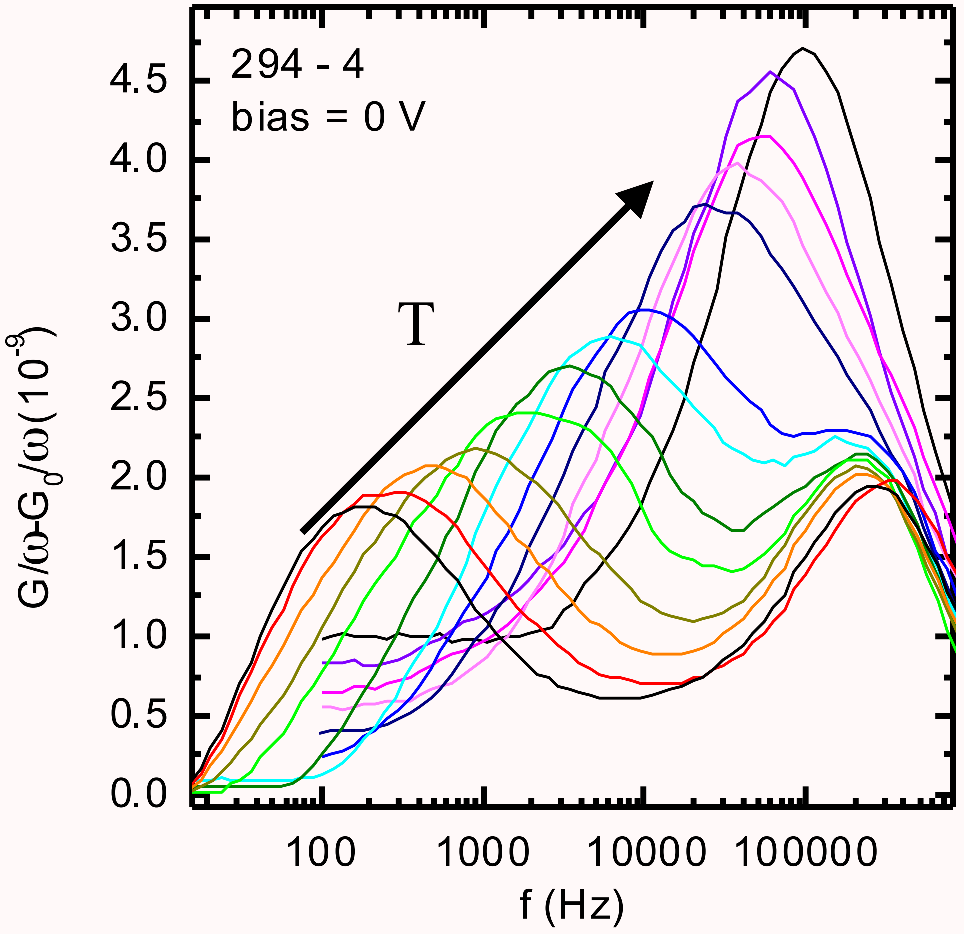
conductance

capacitance

Admittance spectroscopy



Admittance spectroscopy

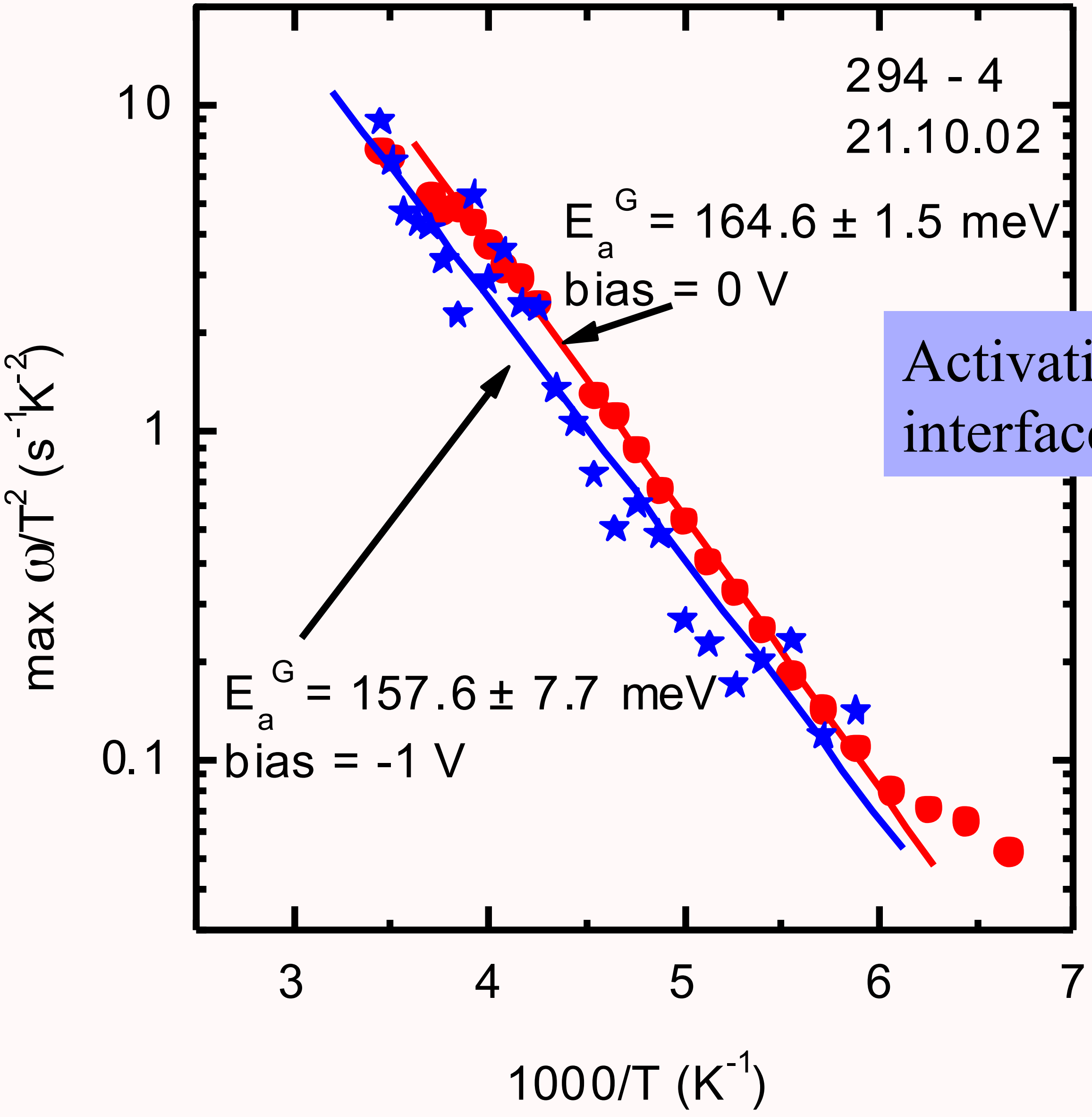


$$C_{tot} = C_d + \frac{C_t}{1+(\tau\omega)^2},$$

$$G_{tot} = G_d + \frac{G_t(\tau\omega)^2}{1+(\tau\omega)^2},$$

C(w) has a step
G(w) has a maximum

$$\omega_{\max}(T) = 2N_{C,V}v_{th}\boxed{\sigma_{n,p}}\exp(-E_T/kT) = 2\chi_0\boxed{T^2}\exp(\boxed{-E_T}/kT)$$



Activation energy of interface states