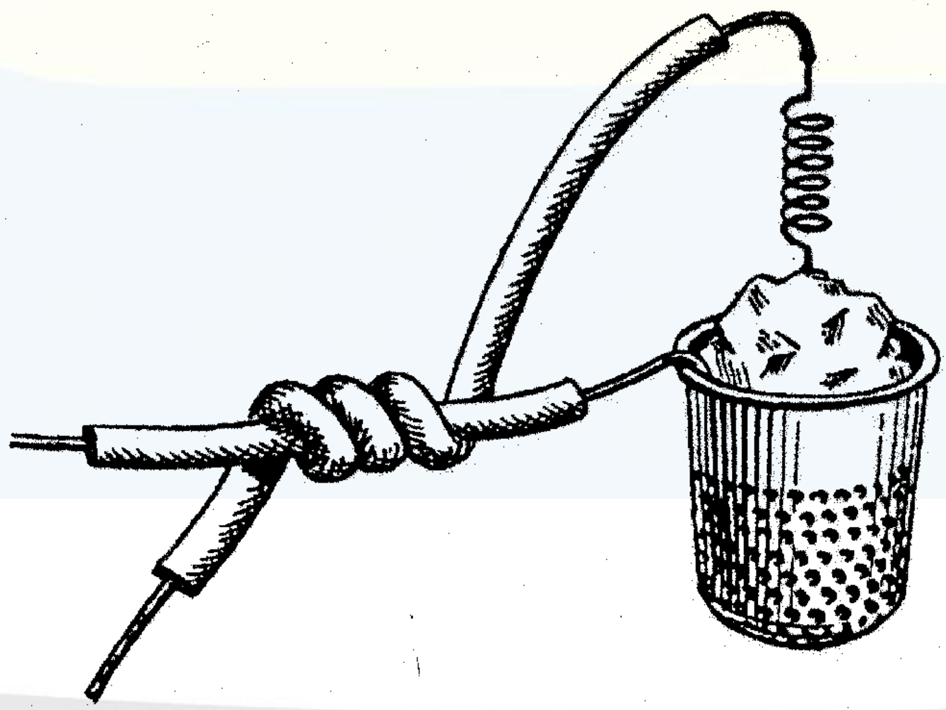
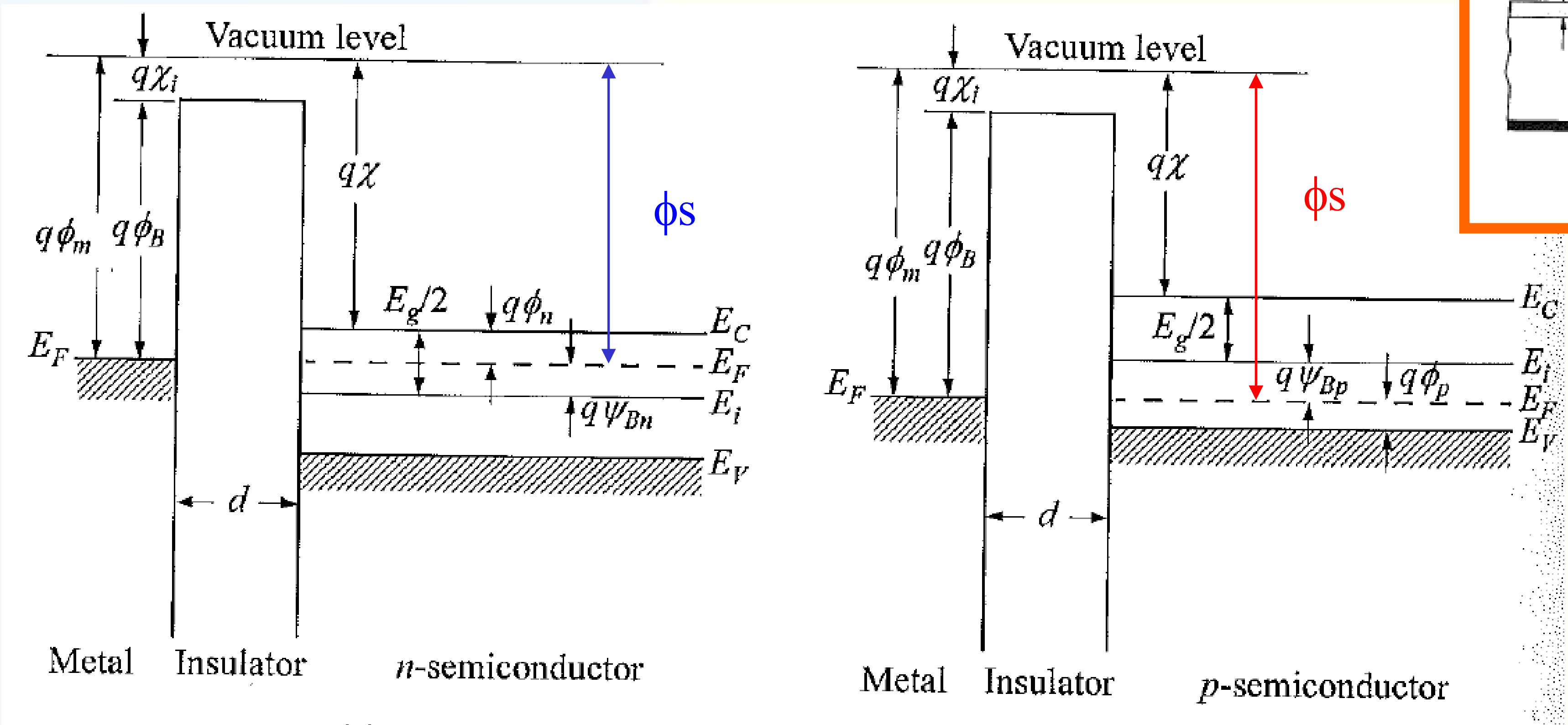
Semiconductor Devices
Lecture 4, MI(O)S Capacitor

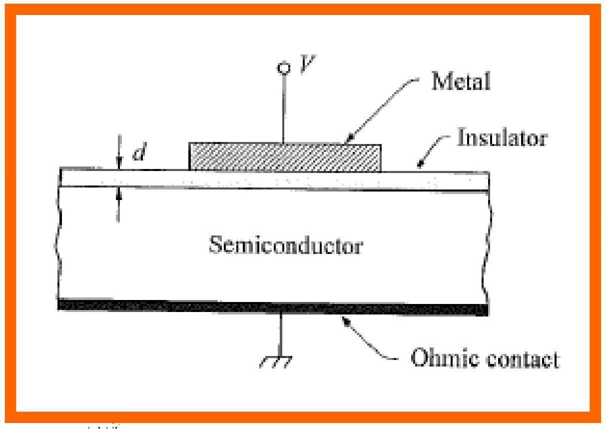


Content

– Ideal MIS Capacitor
– Silicon MOS Capacitor

Ideal MIS Capacitor, V=0

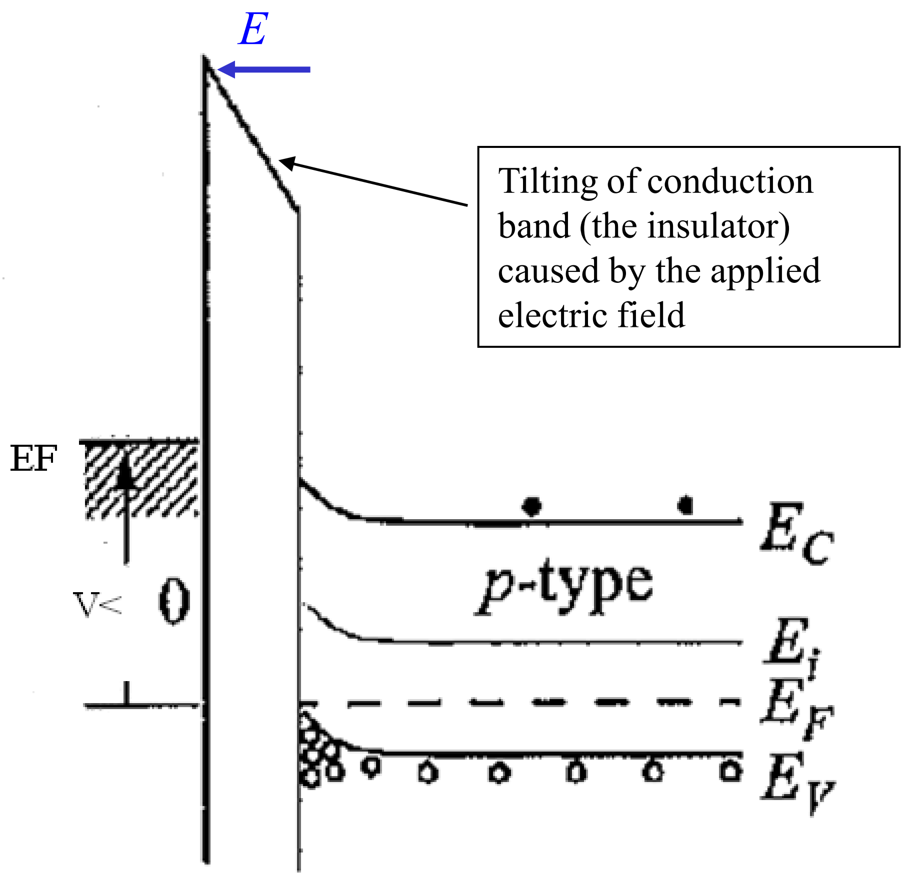


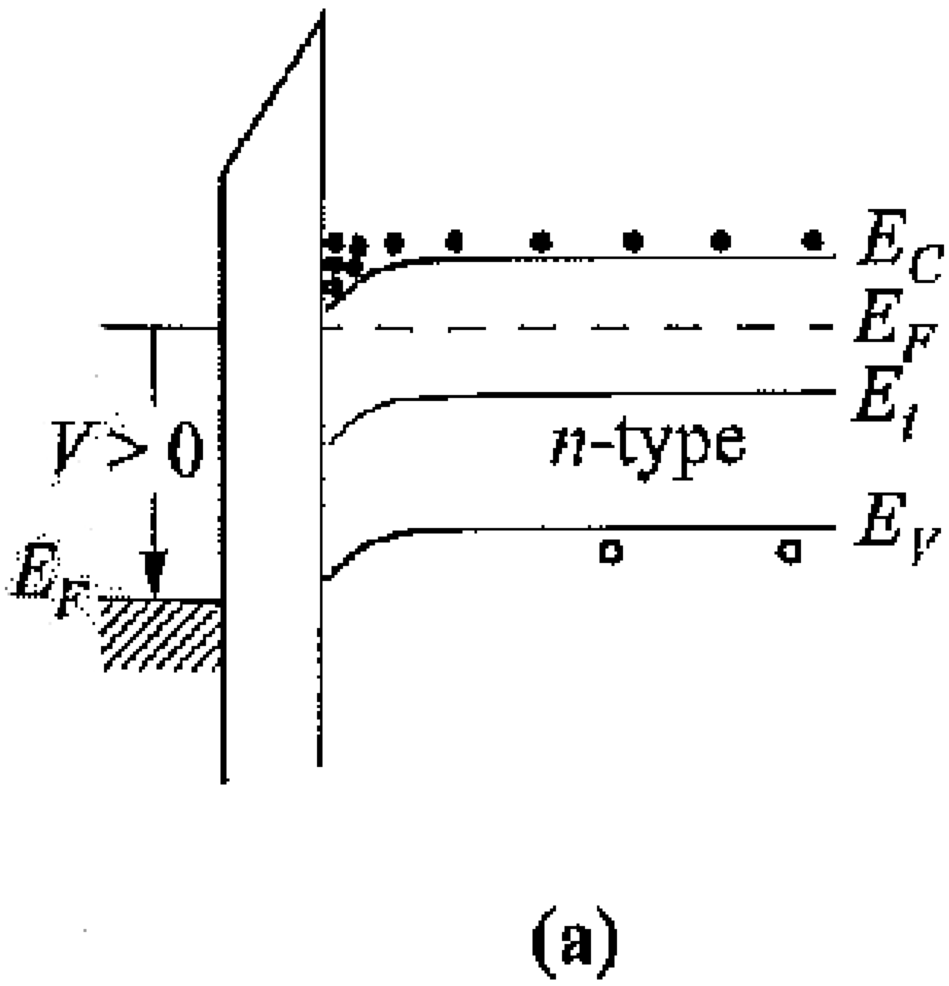


$$\phi_{ms} \equiv \phi_m - \left(\chi + \frac{E_g}{2q} - \psi_{Bn}\right) = \phi_m - (\chi + \phi_n) = 0 \qquad \text{for } n\text{-type}$$

$$\phi_{ms} \equiv \phi_m - \left(\chi + \frac{E_g}{2q} + \psi_{Bp}\right) = \phi_m - \left(\chi + \frac{E_g}{q} - \phi_p\right) = 0 \qquad \text{for } p\text{-type}$$

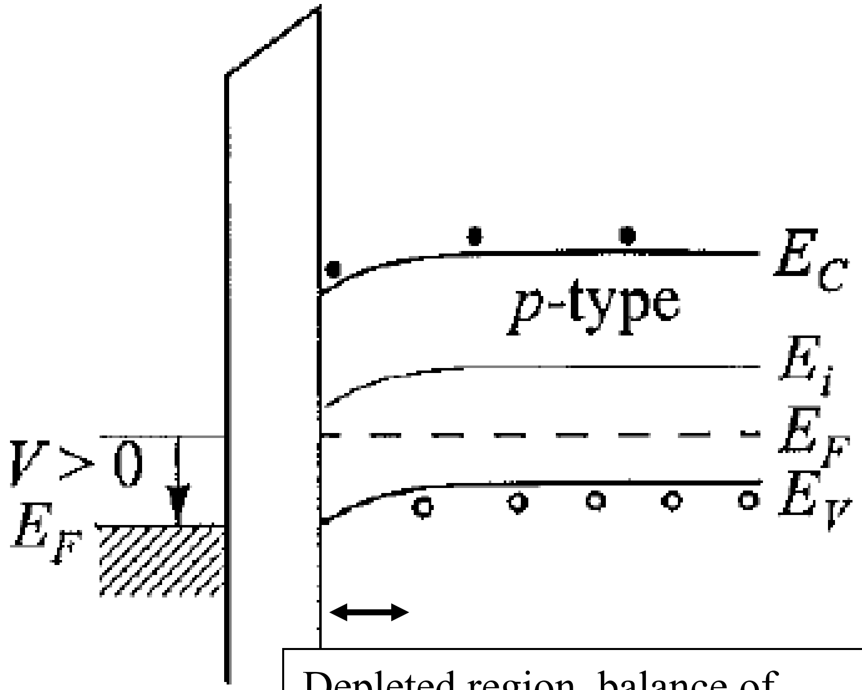
MIS in Accumulation



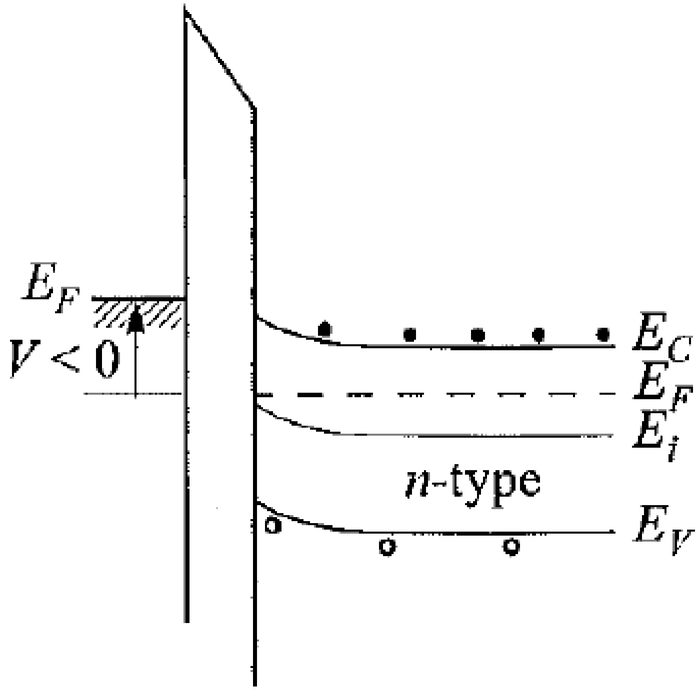


$$\mathscr{E}(x) = \frac{1}{q}\frac{dE_i}{dx}$$

MIS in Depletion

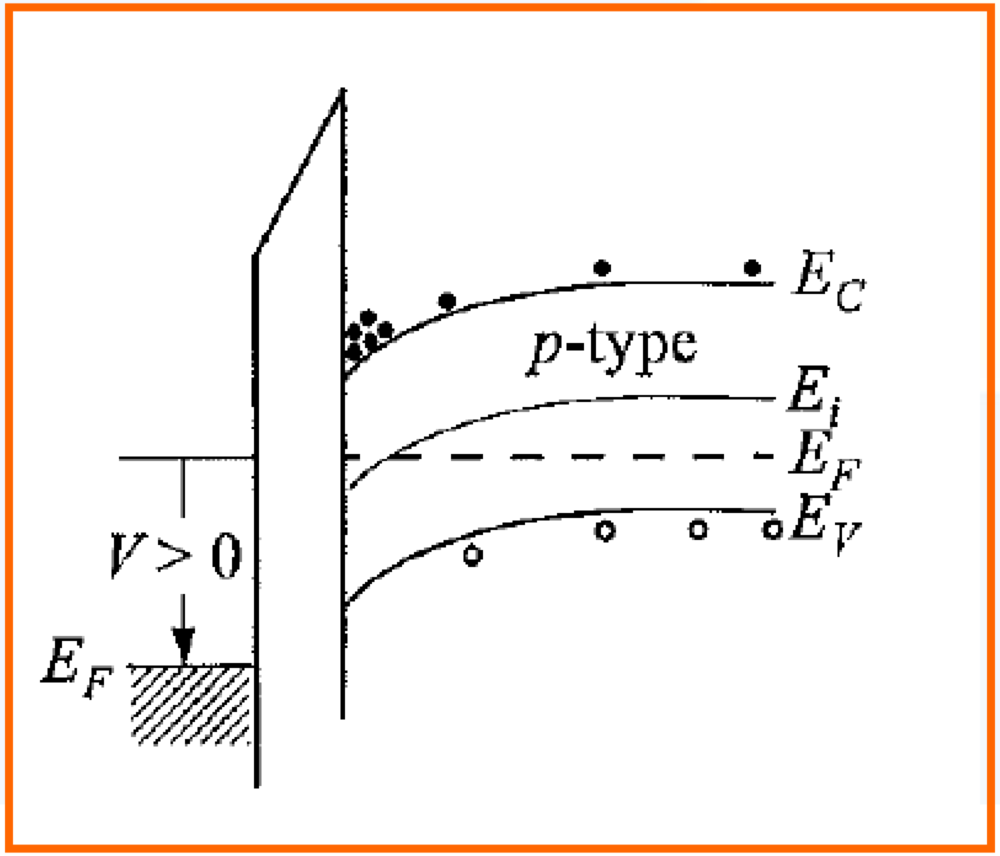


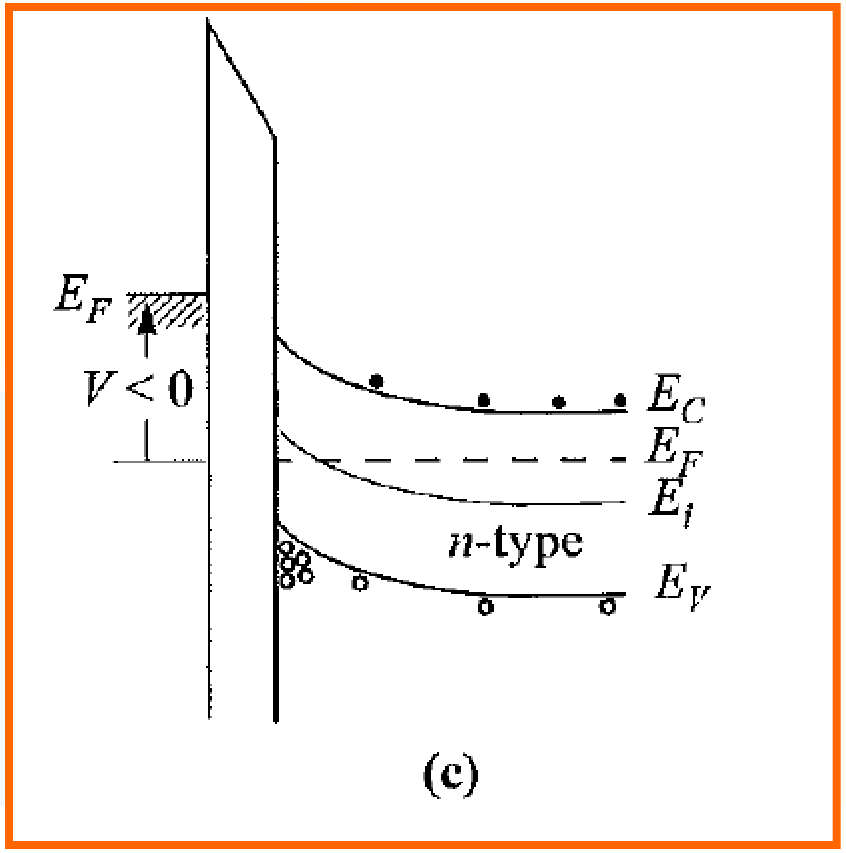
Depleted region, balance of negative fixed ions in semiconductor and positive charges in metal contact



(b)

MIS in Inversion





When increasing the applied voltage even more, the depletion region stops to grow. Instead the minority carrier form a thin layer close to the oxide interface.

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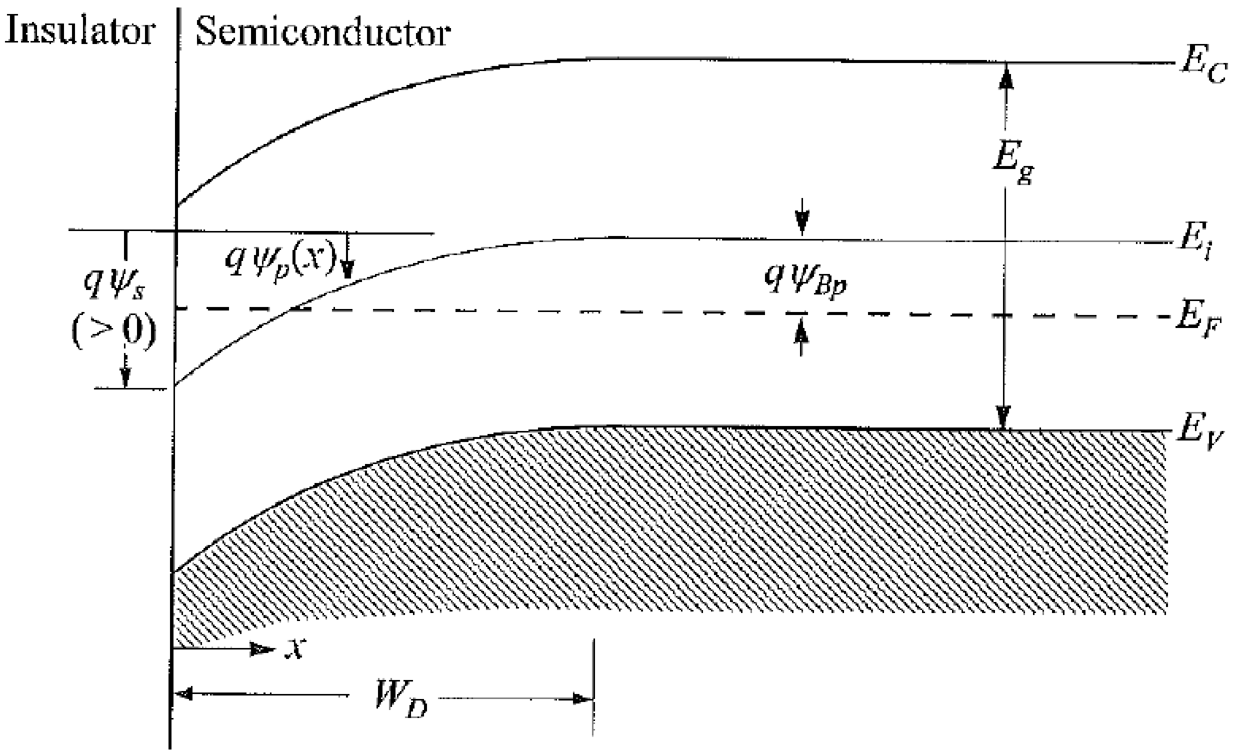
Surface Space-charge region, p-type semiconductor



$$\psi_p(x) \equiv -\frac{[E_i(x) - E_i(\infty)]}{q}.$$

$$\psi_p(0) \equiv \psi_s$$

$$n_p(x) = n_{po}\exp\left(\frac{q\psi_p}{kT}\right) = n_{po}\exp(\beta\psi_p)$$

$$p_p(x) = p_{po}\exp\left(\frac{-q\psi_p}{kT}\right) = p_{po}\exp(-\beta\psi_p)$$

$\psi_s < 0$	Accumulation of holes (bands bending upward).
$\psi_s = 0$	Flat-band condition.

$2\psi_{Bp} > \psi_s > \psi_{Bp}$	Weak inversion [electron enhancement, $n_p(0) > p_p(0)$].
$\psi_s > 2\psi_{Bp}$	Strong inversion [$n_p(0) > p_{po}$ or N_A].

$\psi_{Bp} > \psi_s > 0$	Depletion of holes (bands bending downward).
$\psi_s = \psi_{Bp}$	Fermi-level at midgap, $E_F = E_i(0)$, $n_p(0) = p_p(0) = n_i$.

Strong inversion (min, condition, p doped semiconductor), the surface conc. of n = p level in the bulk

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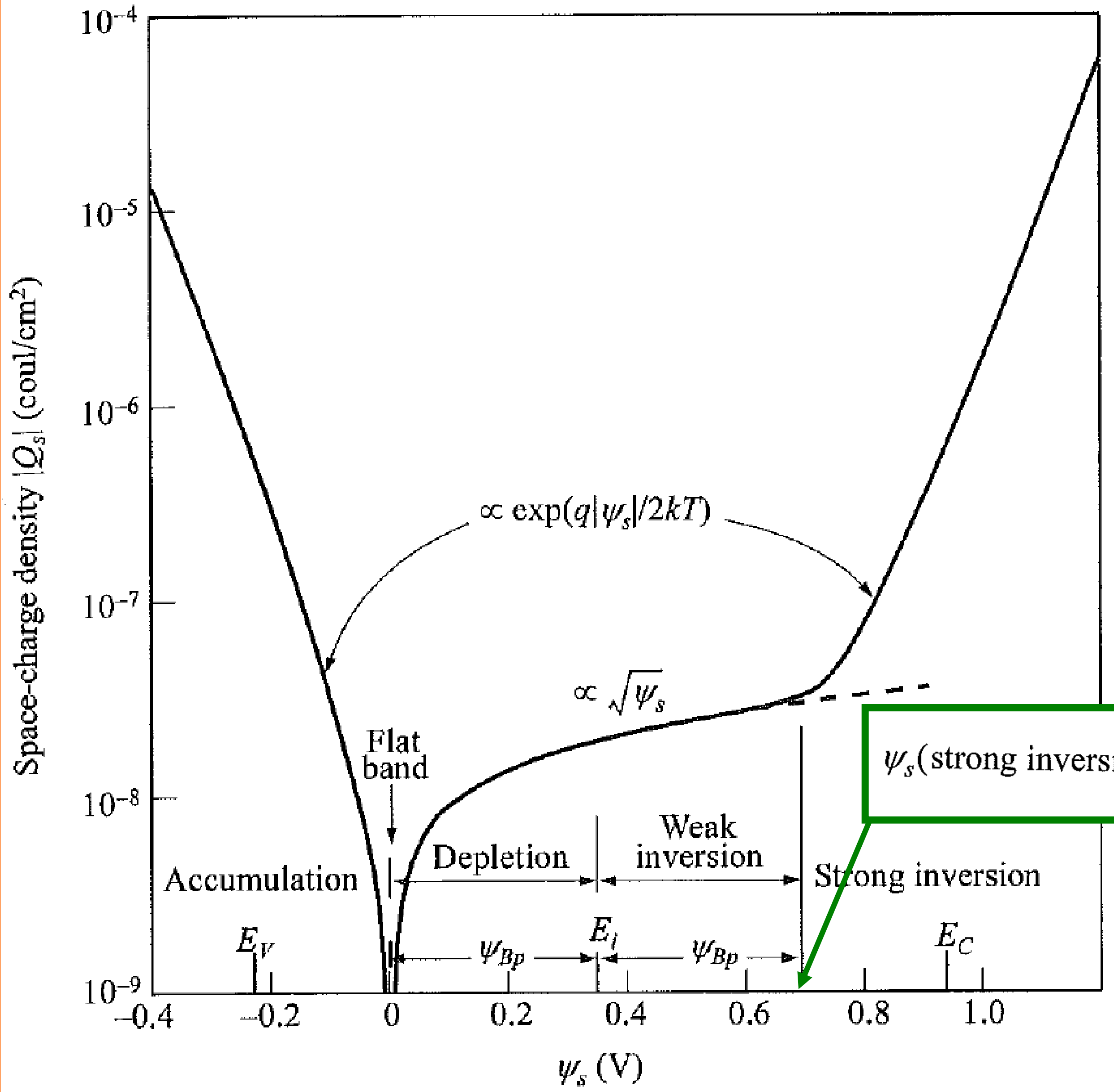
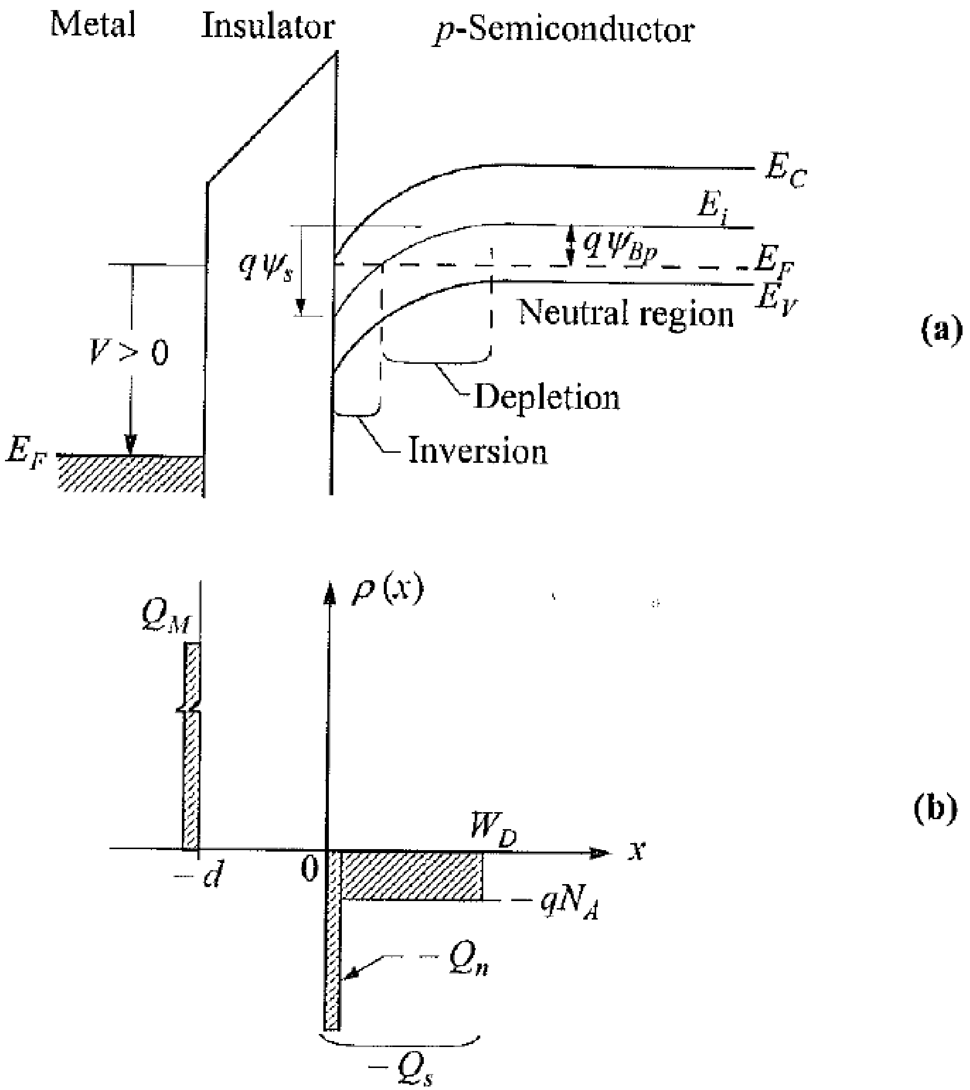
Space charge density versus surface potential for p-type silicon, p=4*10^{15} cm^{-3}



$$\psi_s(\text{strong inversion}) \approx 2\,\psi_{Bp} \approx \frac{2kT}{q}\ln\left(\frac{N_A}{n_i}\right).$$

Charge distribution, E-field, potential



$$\boxed{Q_M = -(Q_n + qN_A W_D) = -Q_s}$$

$$\boxed{\phi_{ms} = 0}$$

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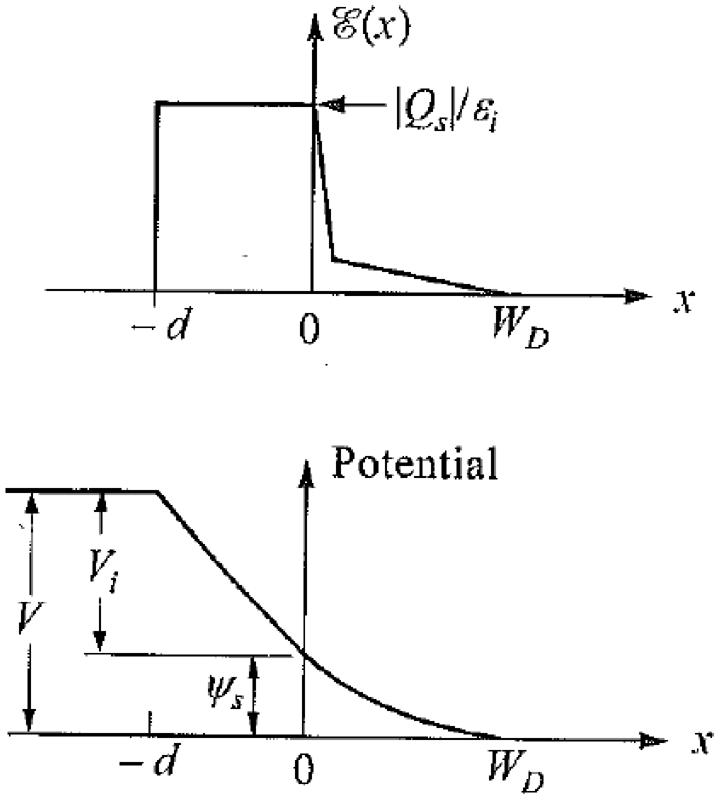
Charge distribution, E-field, potential



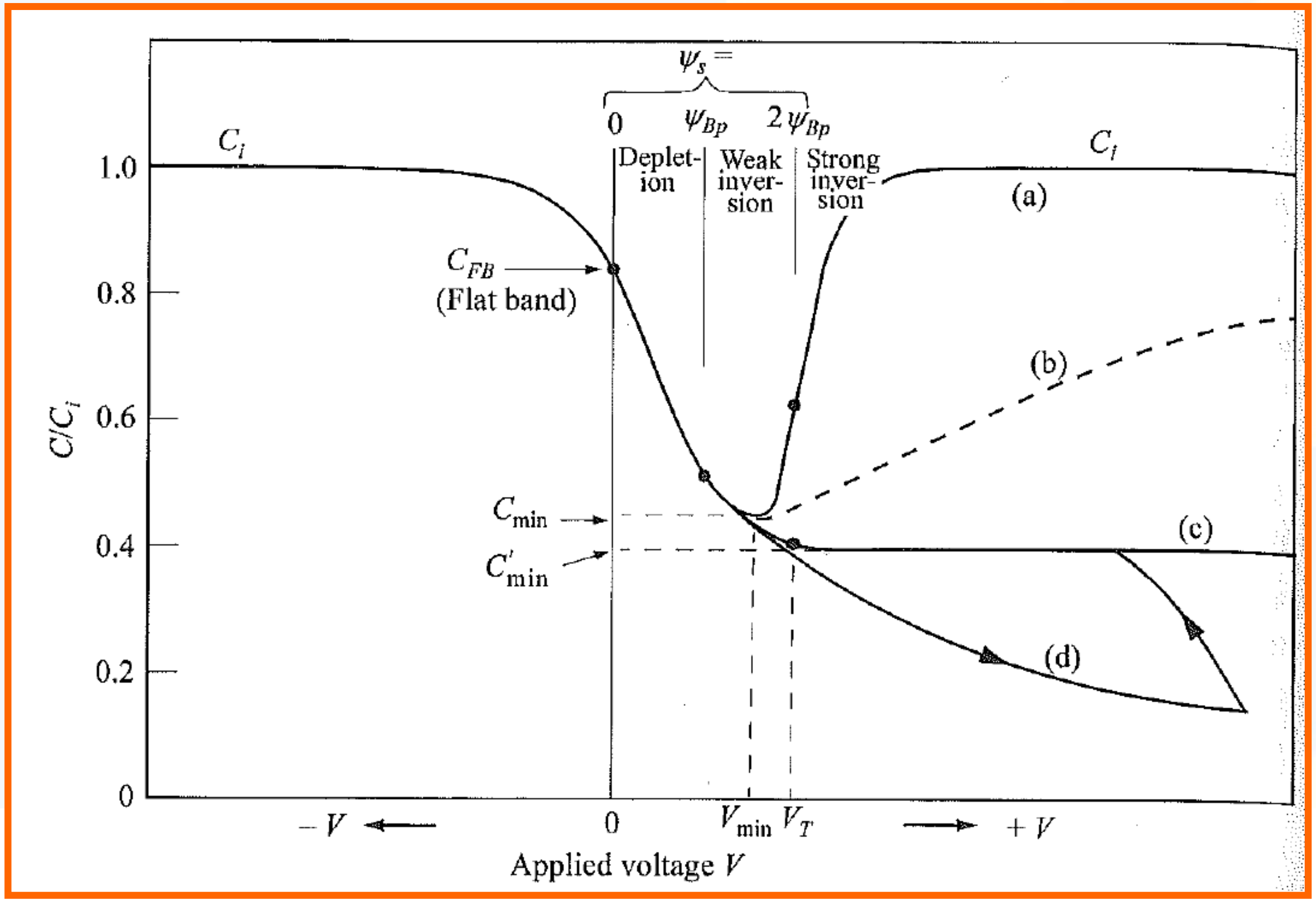
$$V = V_i + \psi_s$$

$$V_i = \mathscr{E}_i d = \frac{|Q_s| d}{\varepsilon_i} = \frac{|Q_s|}{C_i}.$$

$$C_i = \frac{\varepsilon_i}{d},$$

$$C = \frac{C_i C_D}{C_i + C_D}.$$

MIS CV-graph, p-type semiconductor



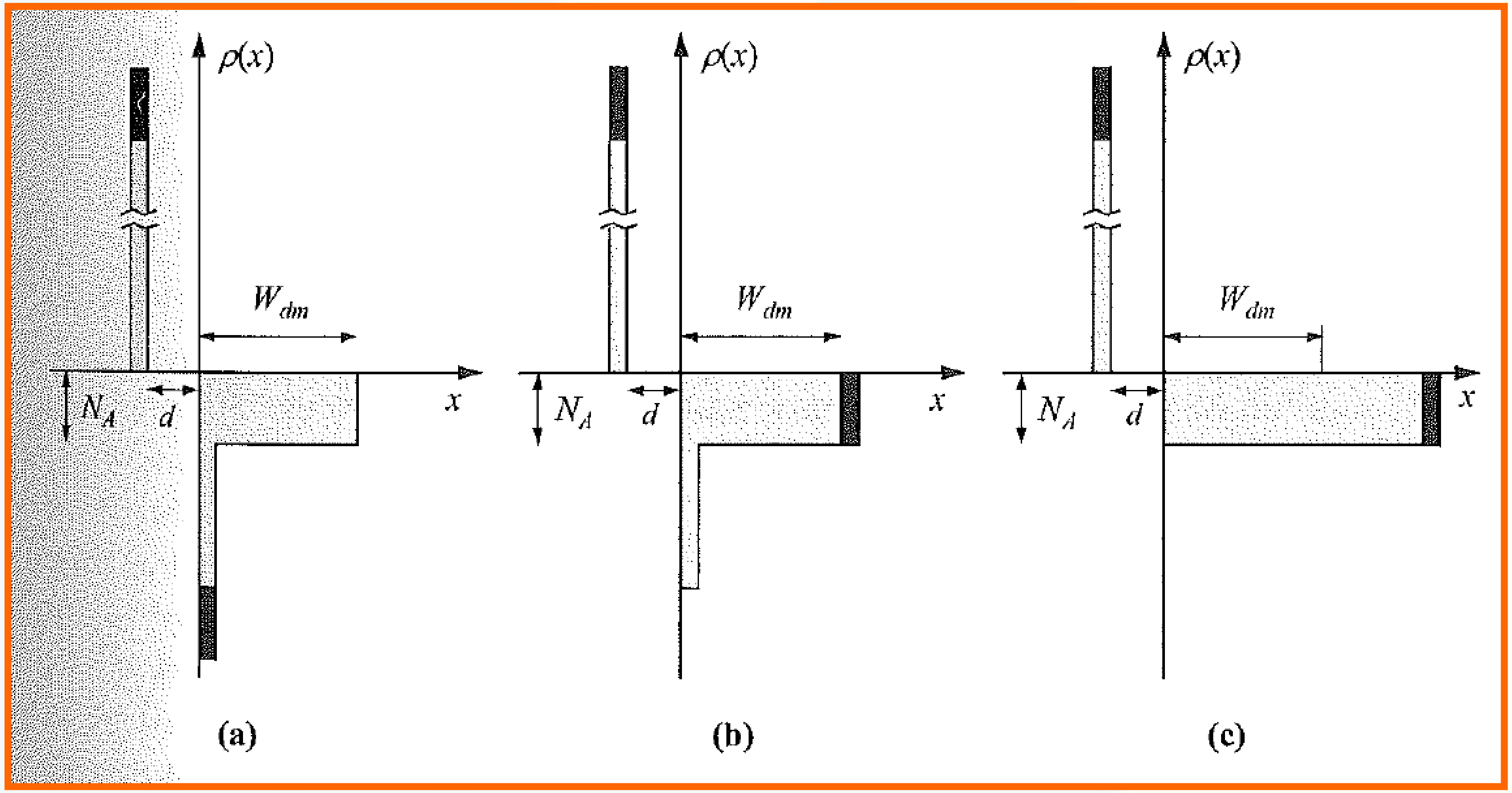
a) Low frequency (~Hz)

c) High Frequency (>kHz)

d) High Frequency with fast sweep and no illumination

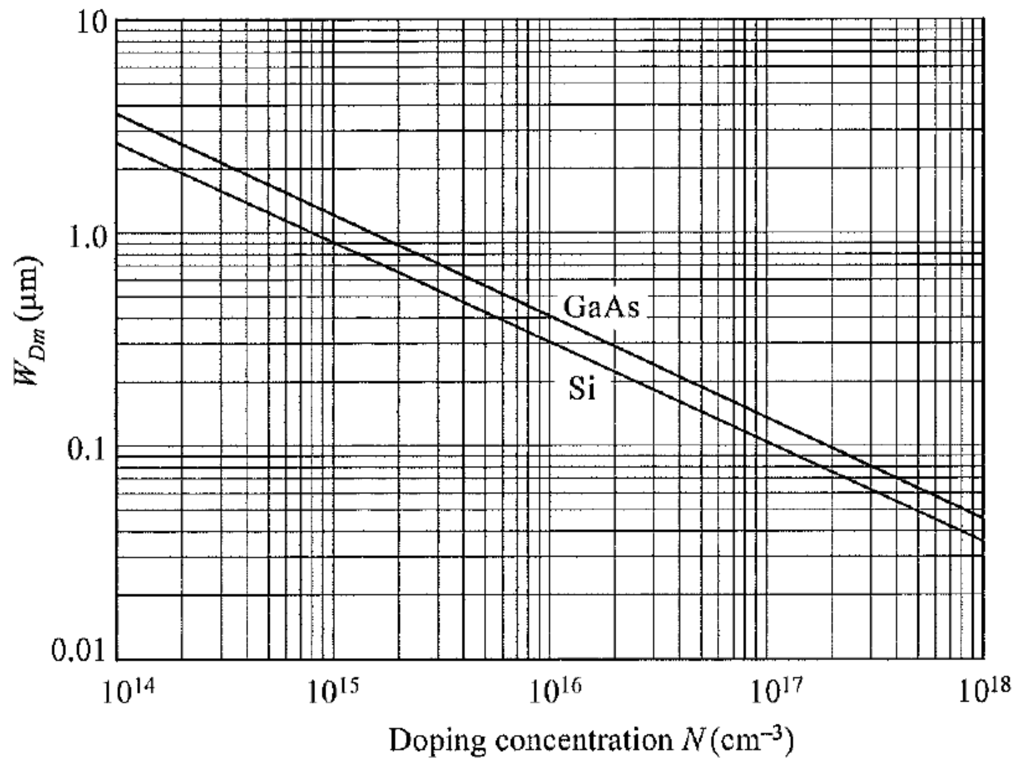
DC bias with a small AC voltage applied

Strong inversion, frequency behavior



a) Low frequency
b) High frequency
c) High frequency with fast sweep (Wd>Wdm)

The depletion layer

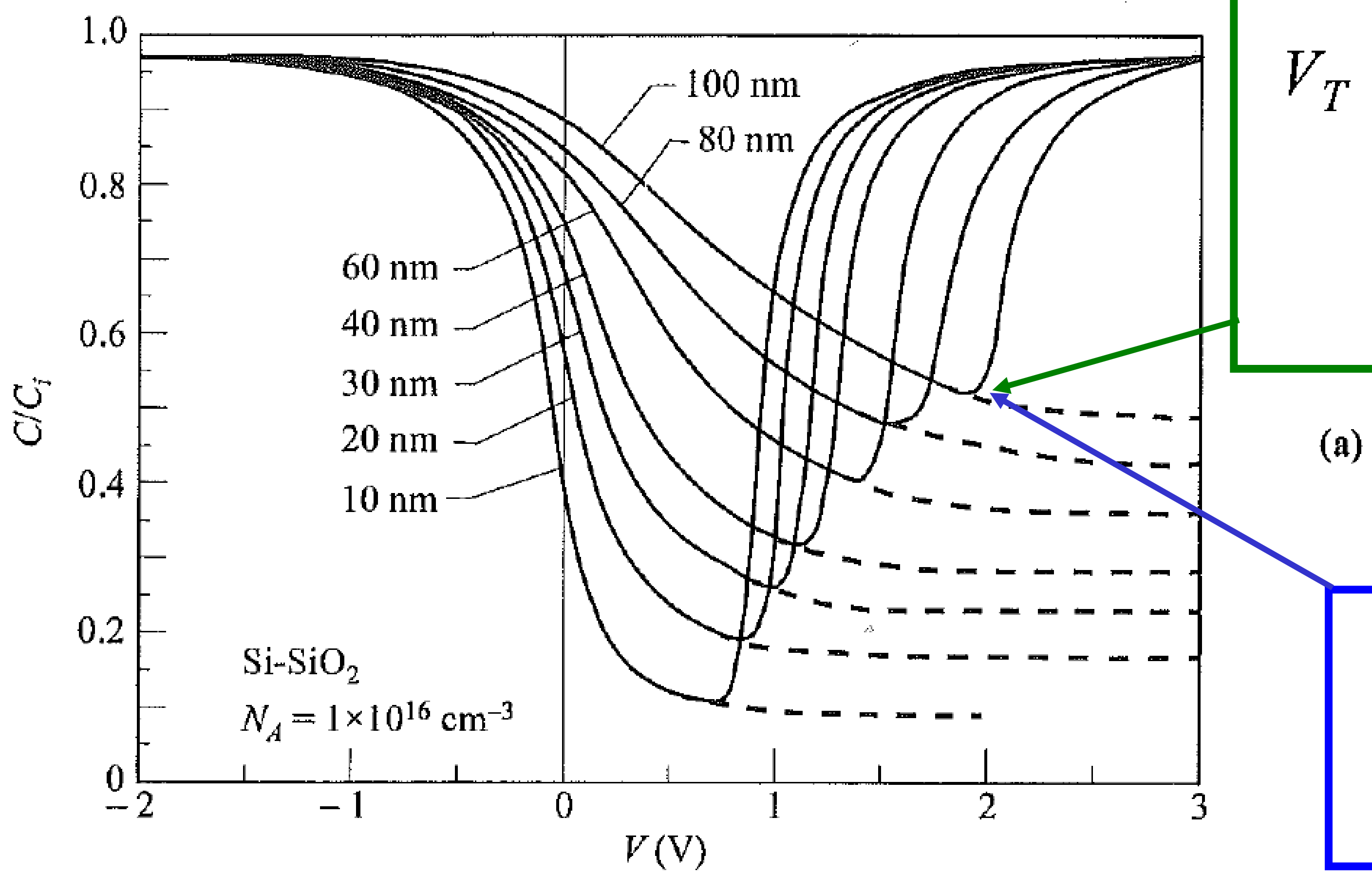


The calculation is similar as for a n$^+$p diode

$$w = \sqrt{\frac{2\varepsilon_s \psi_s}{qN_a}}$$

$$W_{Dm} \approx \sqrt{\frac{2\varepsilon_s \psi_s(\text{strong inv})}{qN_A}} \approx \sqrt{\frac{4\varepsilon_s kT \ln(N_A/n_i)}{q^2 N_A}}.$$

Ideal MOS C-V graphs for different oxide thickness



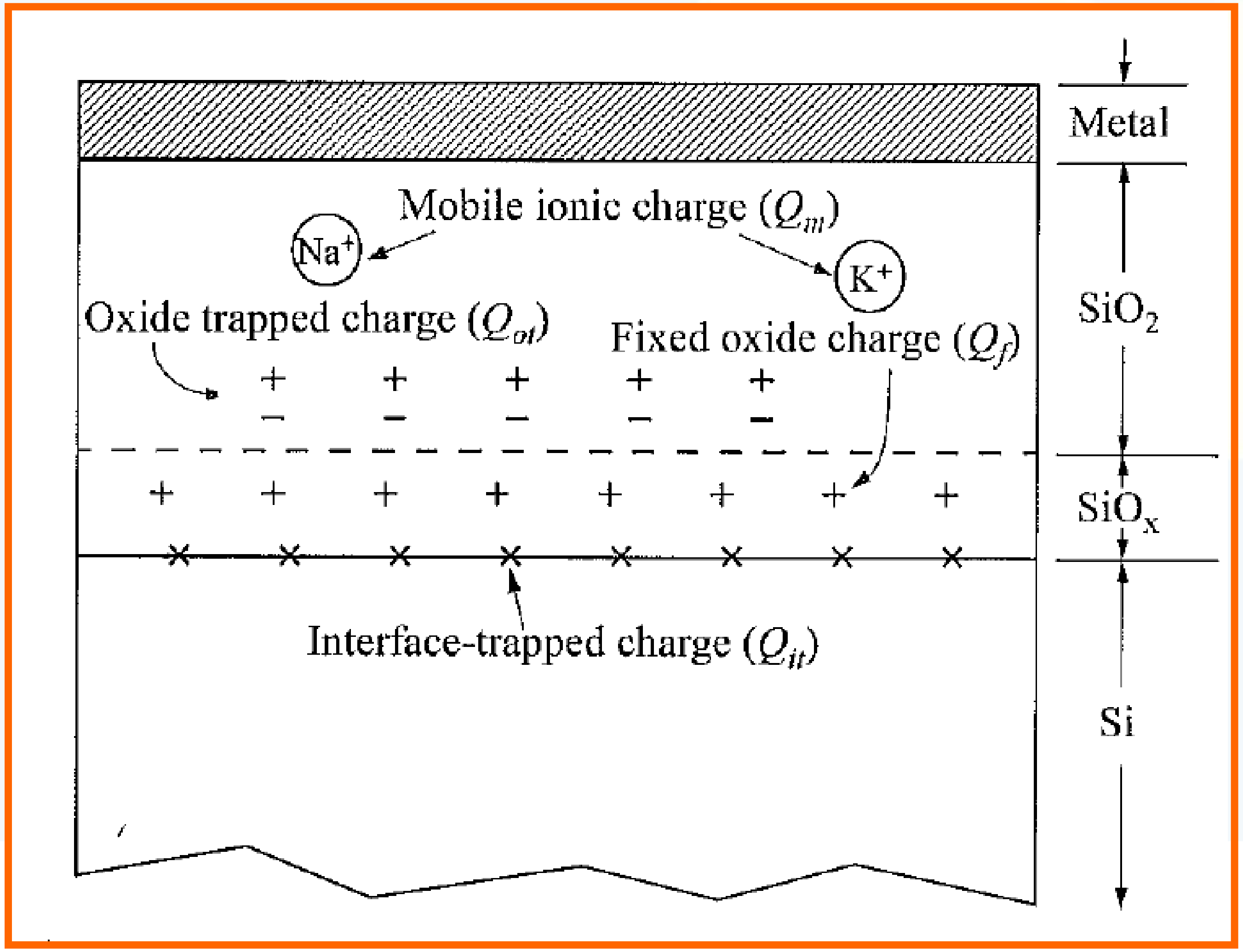
$$V_T = \frac{|Q_s|}{C_i} + 2\psi_{Bp}$$

$$= \frac{\sqrt{2\varepsilon_s q N_A (2\psi_{Bp})}}{C_i} + 2\psi_{Bp} .$$

$$C'_{\min} = \frac{\varepsilon_i \varepsilon_s}{\varepsilon_s d + \varepsilon_i W_{Dm}} .$$

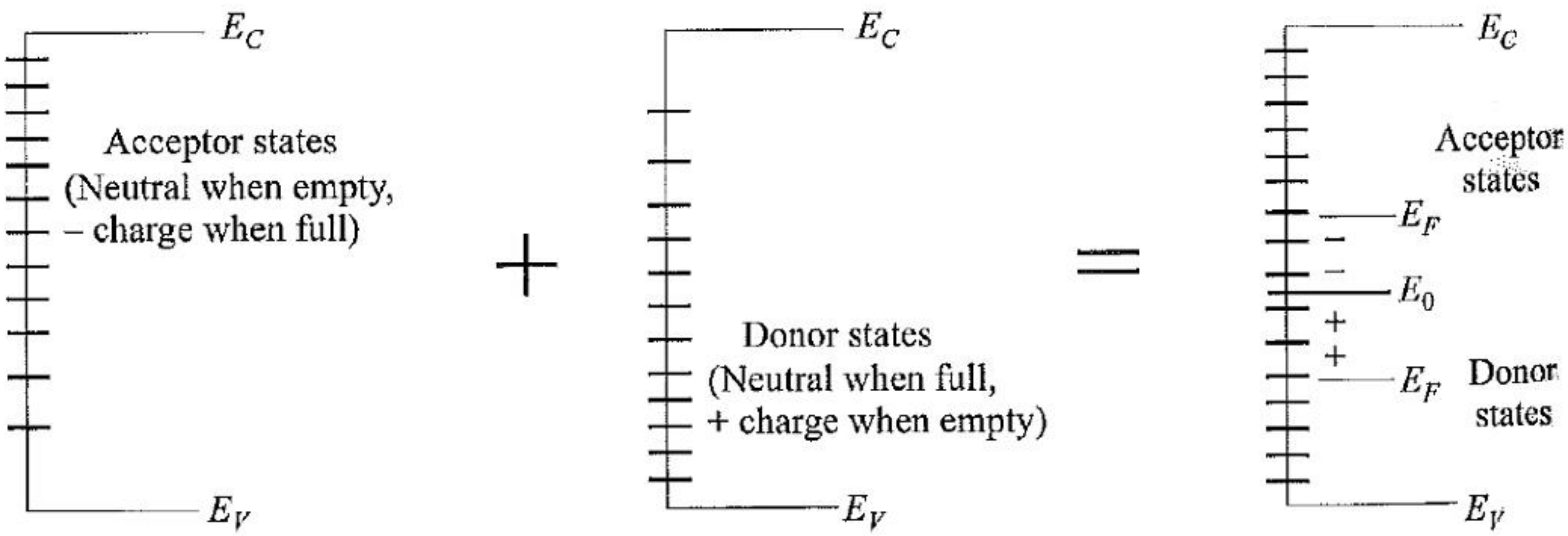
$$d \searrow \quad V_T \searrow \quad \Delta C/C_i \nearrow$$

Silicon MOS Capacitor, interface traps



- Mobile ions
- Oxide trapped charge
- Fixed oxide charge
- Interface trapped charge
    - ~10^{10} cm^{-2}, <100>, FGA

Interface trap system



$$
\begin{aligned}
Q_{it} &= -q\int_{E_0}^{E_F} D_{it}\,dE \qquad && E_F \text{ above } E_0, \\
&= +q\int_{E_F}^{E_0} D_{it}\,dE \qquad && E_F \text{ below } E_0.
\end{aligned}
$$

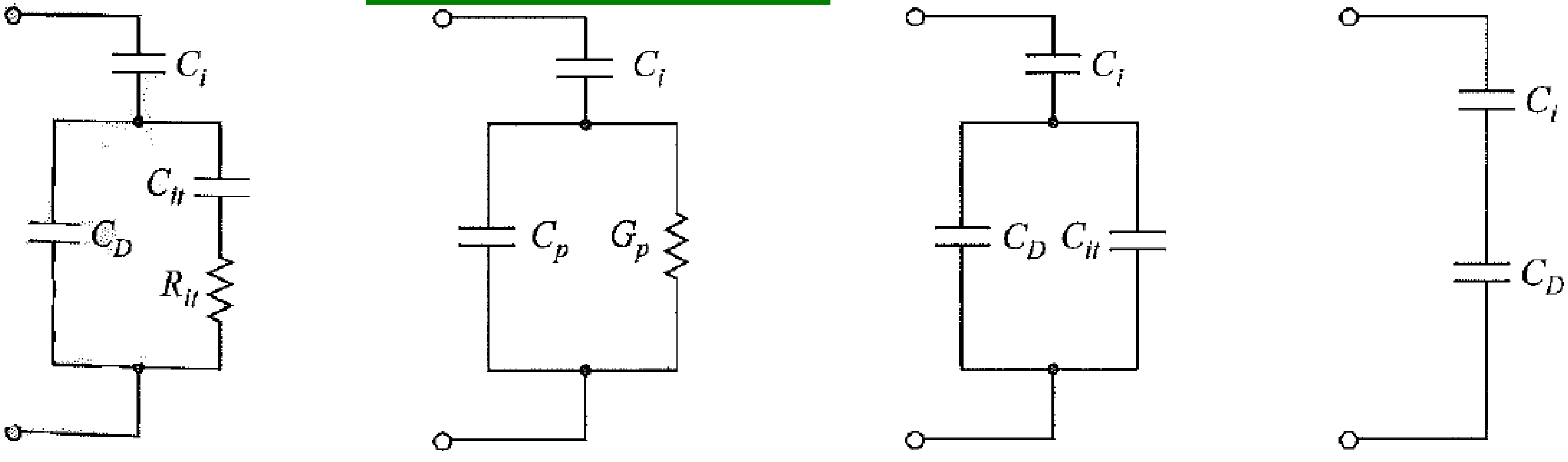
Equivalent circuits including interface-trap

$\tau_{it} = C_{it} R_{it}$

C_p *and* G_p frequency depended

Low f

High f

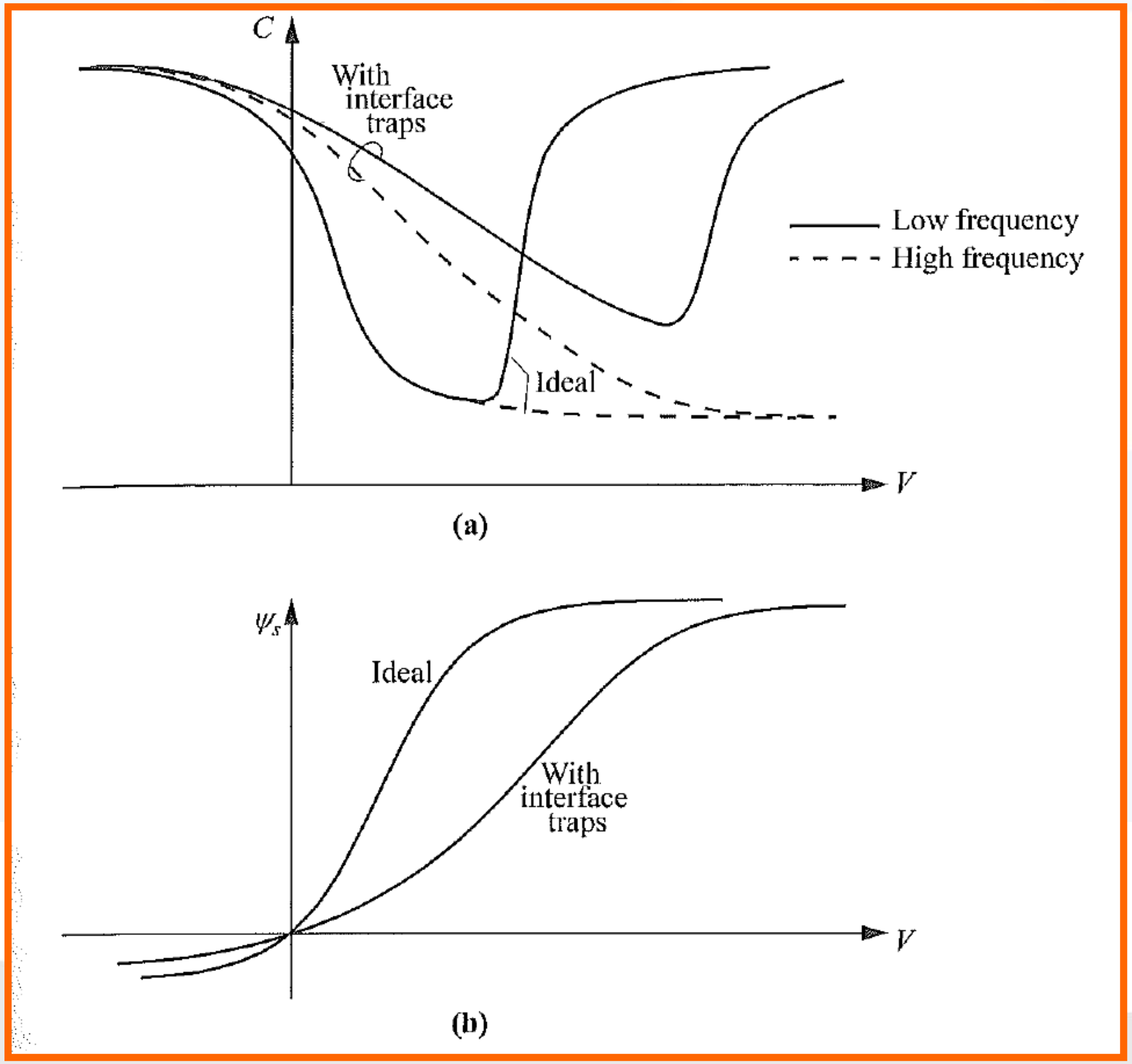


(a) (b) (c) (d)

$$C_{LF} = \frac{C_i(C_D + C_{it})}{C_i + C_D + C_{it}},$$

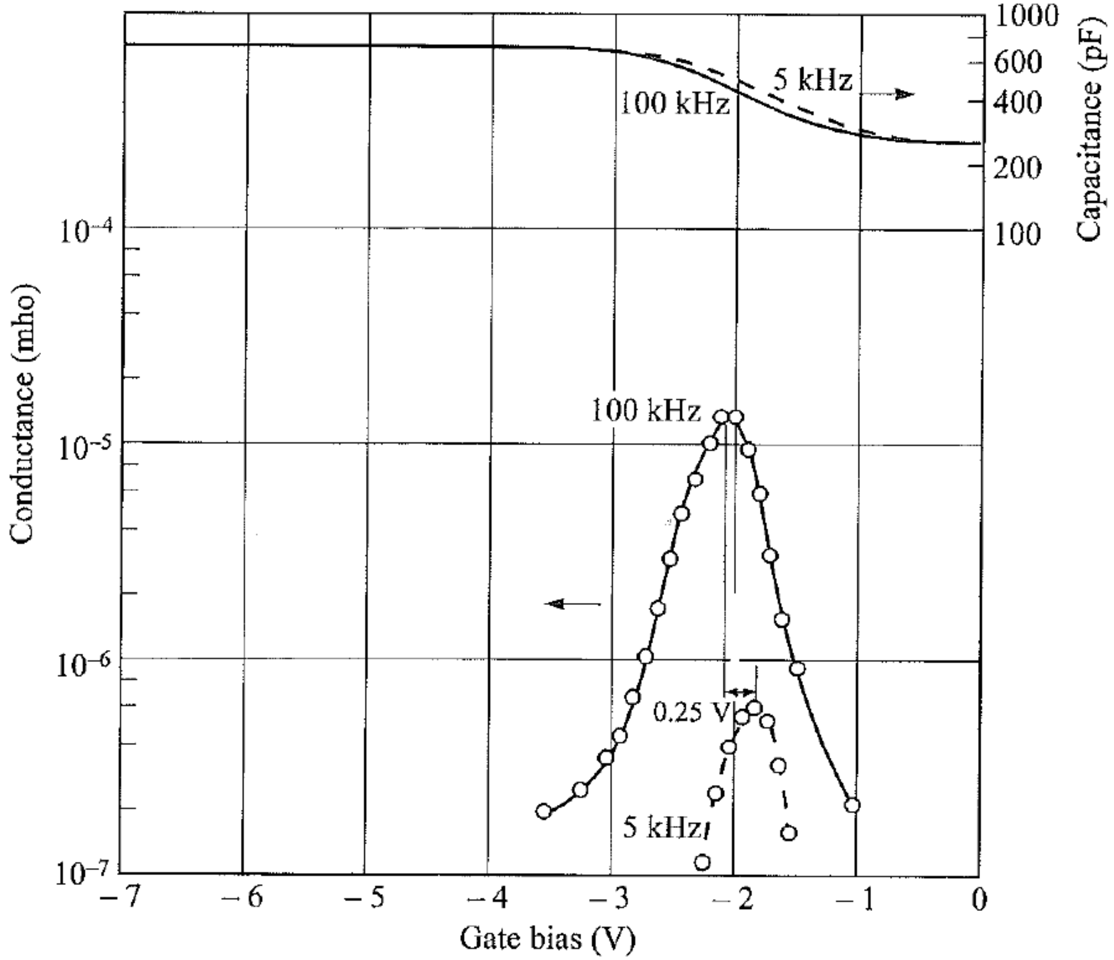
$$C_{HF} = \frac{C_i C_D}{C_i + C_D}.$$

Interface traps influence on C-V curves



- High f C method
- Low F C method
- High and low f C method
  - No theoretical calc needed, see eq 49
- Conductance method

Conductance method



$$\frac{G_p}{\omega} = \frac{\omega C_i^2 G_{in}}{G_{in}^2 + \omega^2 (C_i - C_{in})^2} = \frac{C_{it}\omega\tau_{it}}{1 + \omega^2 \tau_{it}^2}$$

$$D_{it} = C_{it}/q^2$$

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Properties for different orientation of silicon

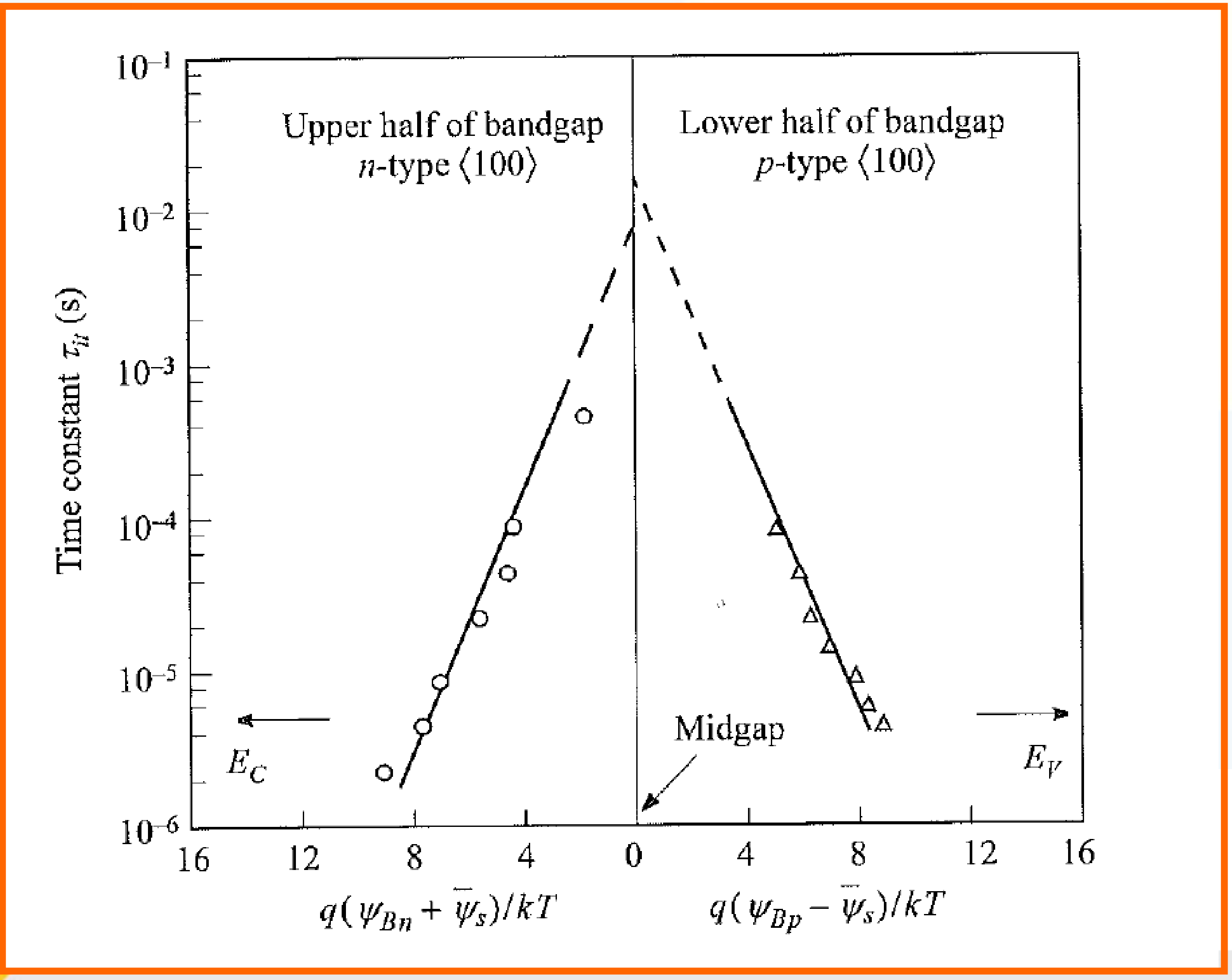
Orientation	Plane area of unit cell	Atoms in cell area	Available bonds in cell area	Atoms/cm^2	Available bonds/cm^2
$\langle 111 \rangle$	$\sqrt{3}a^2/2$	2	3	7.85×10^{14}	11.8×10^{14}
$\langle 110 \rangle$	$\sqrt{2}a^2$	4	4	9.6×10^{14}	9.6×10^{14}
$\langle 100 \rangle$	a^2	2	2	6.8×10^{14}	6.8×10^{14}

<100> ~5*10^{10} cm^{-2}

< 111> ~5*10^{11} cm^{-2}

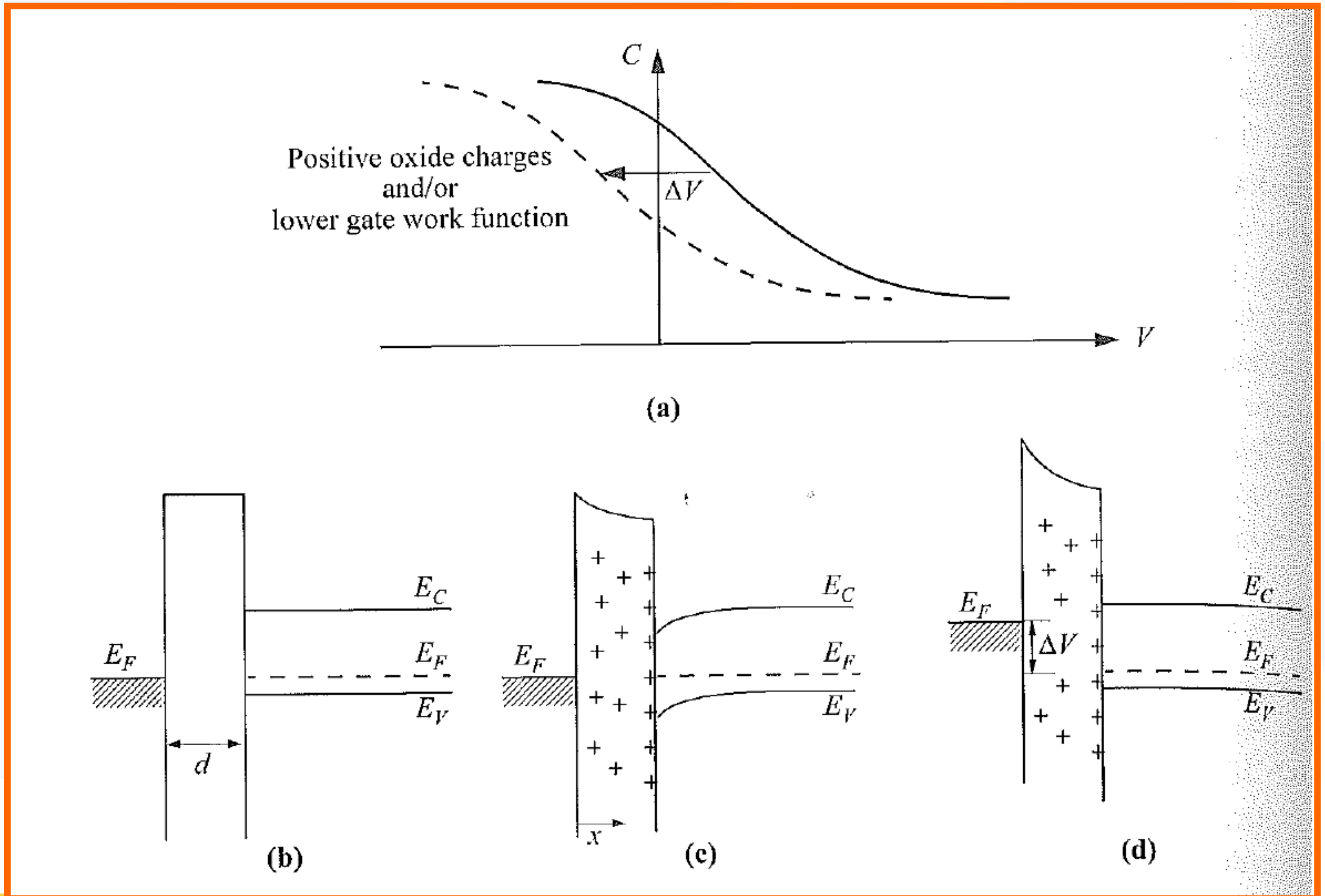
<111> ~3*10^{12} cm^{-2}, radiation damaged

Variation of trap time constant versus energy



Interface traps have a continuum distribution over the band gap, a measured value is therefore strongly depended on applied bias voltage

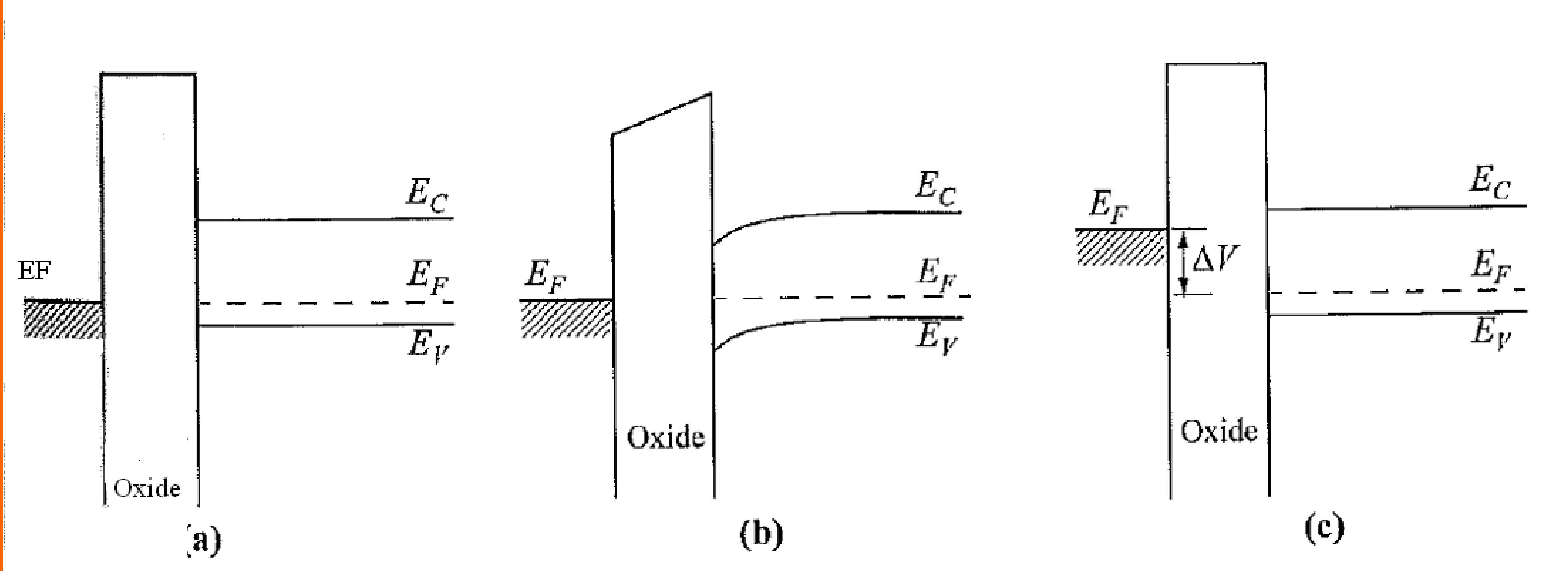
Oxide charge influence on flat band bias



$$\Delta V_f = -\frac{Q_f}{C_i}.$$

$$\Delta V_m = -\frac{Q_m}{C_i}$$

work-function difference effect on flatband voltage

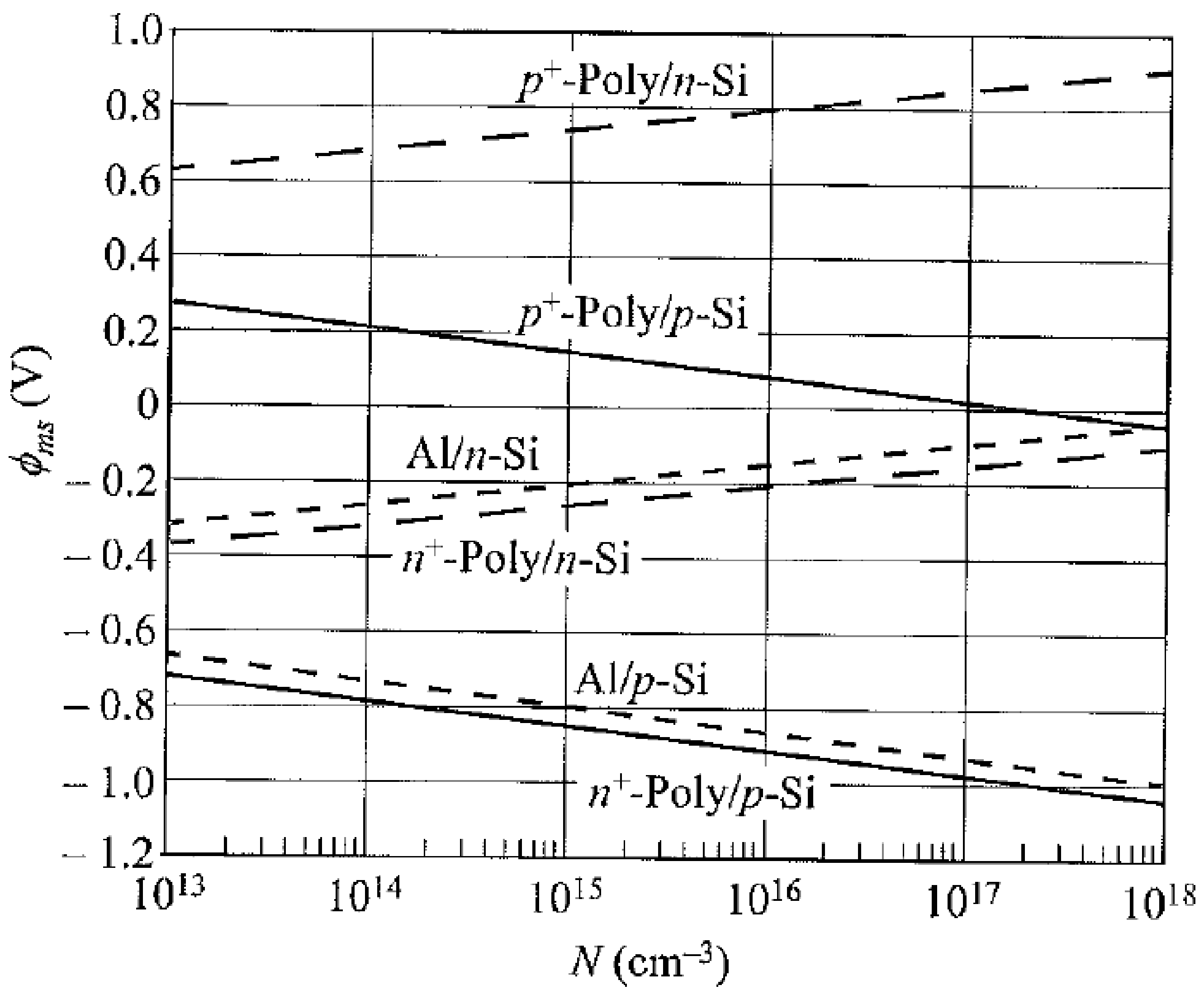


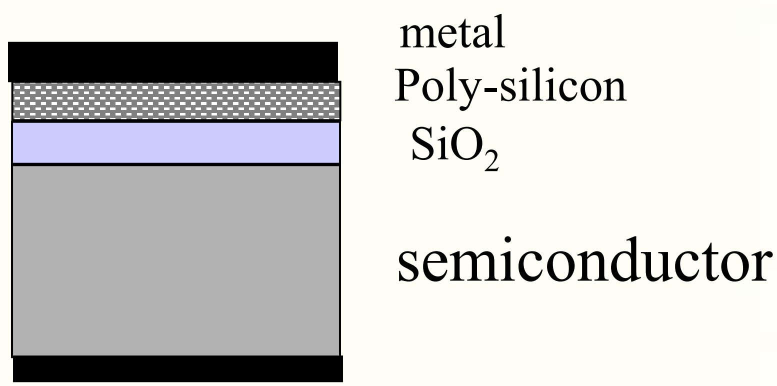
$$\phi_m < \phi_s$$

$$V_{FB} = \phi_{ms} - \frac{Q_f + Q_m + Q_{ot}}{C_i}.$$

$$\phi_{ms} \neq 0$$

Work function difference versus doping for poly silicon and Al





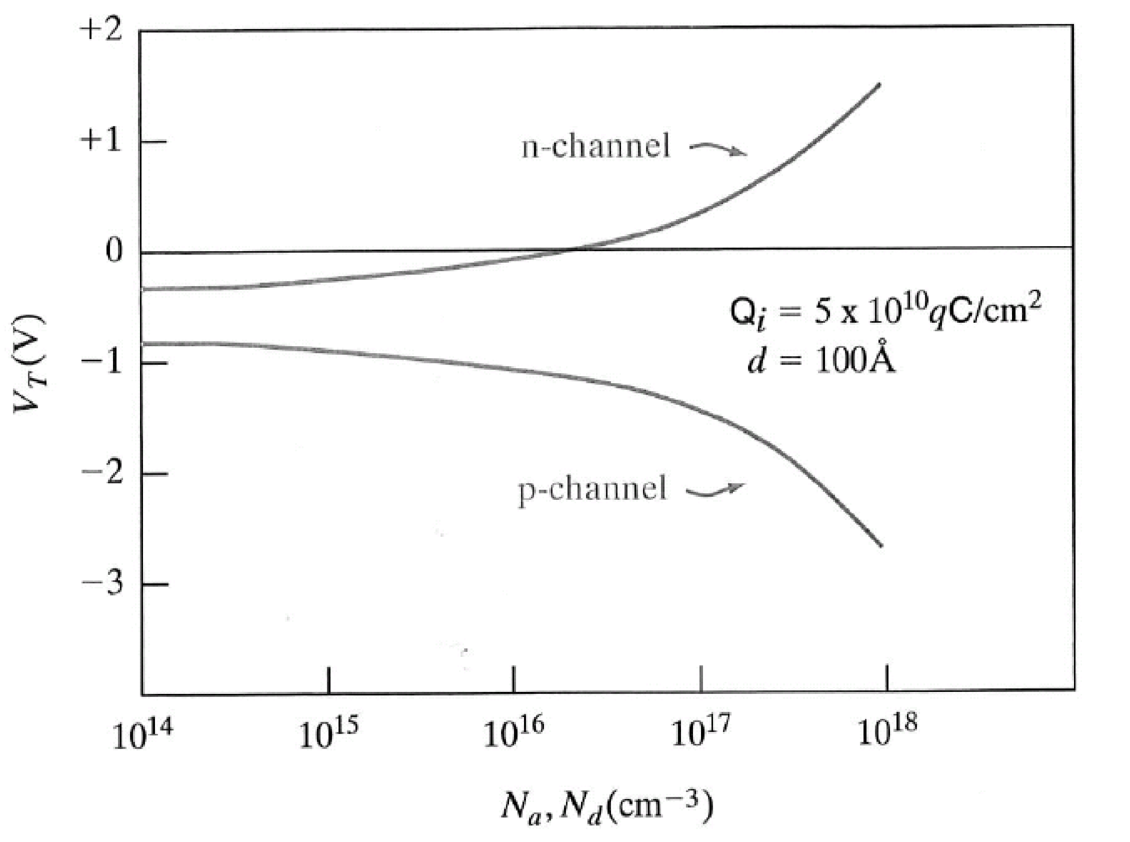
Real MOS Capacitance

Influence of material parameters on V_T

$$V_T = \Phi_{ms} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} + 2\phi_F$$

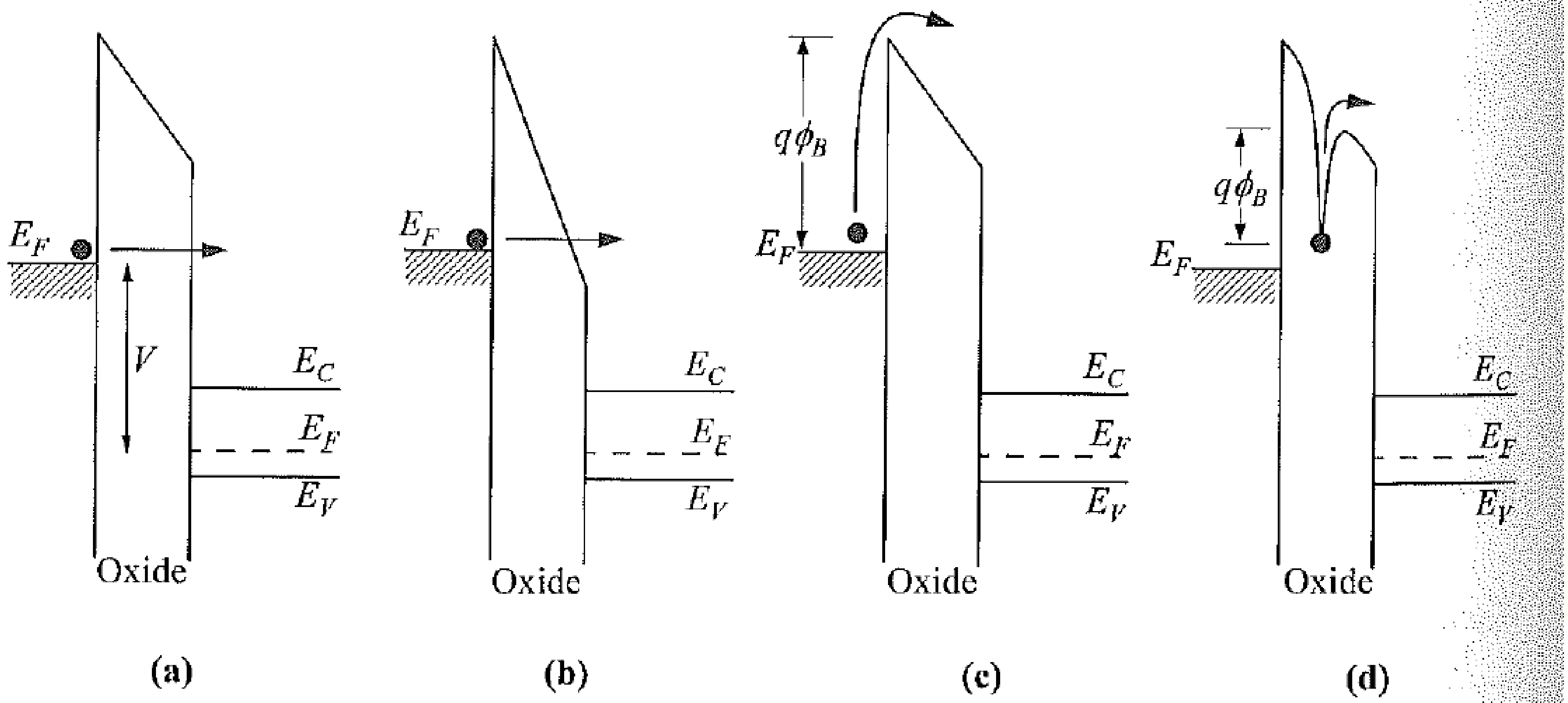
$$\phi_F = \psi_{Bp}$$

$V_T =$	Φ_{ms}	$-\frac{Q_i}{C_i}$	$-\frac{Q_d}{C_i}$	$+ 2\phi_F$
(a)	(−)	(−)	(+) n channel (−) p channel	(+) n channel (−) p channel



Carrier transport in MOS structure

Temperature and E-field dependence!



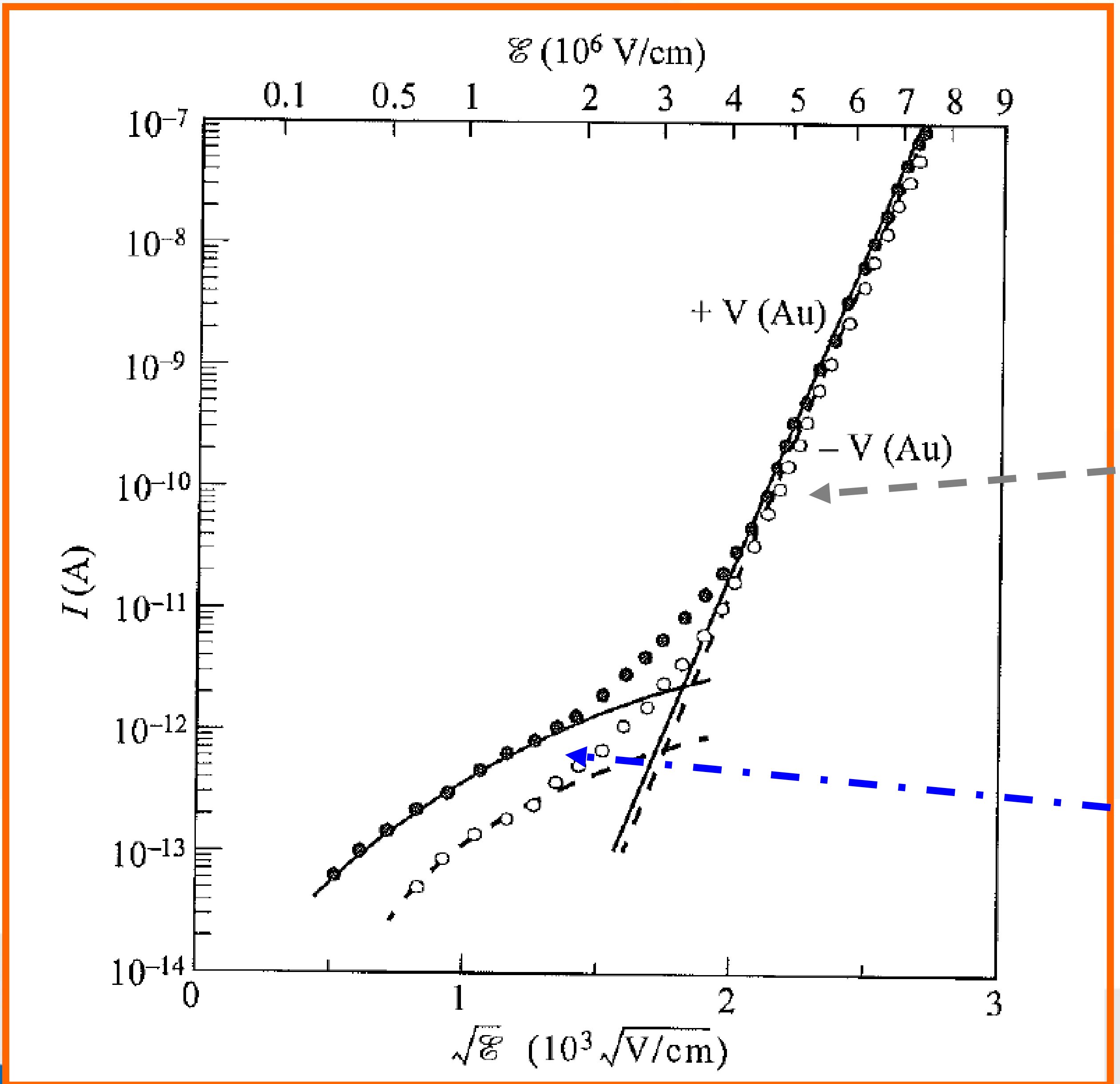
Direct tunneling

Fowler-Nordheim tunneling

Thermionic emission

Frenkel-Poole emission, trapped electron in conduction band (SiO2)

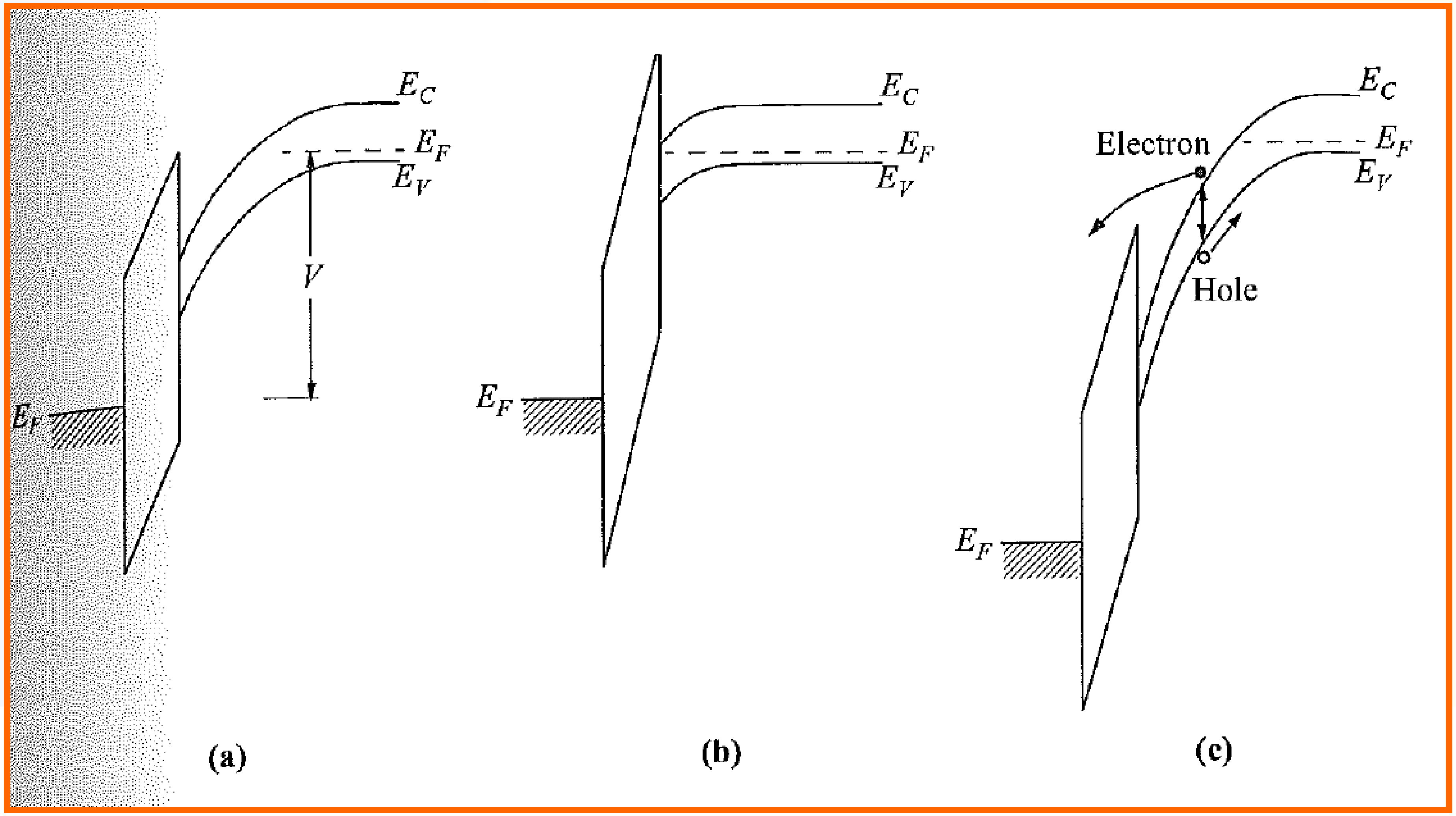
Current-voltage characteristics of Au-Si_3N_4-Si capacitor at room temperature



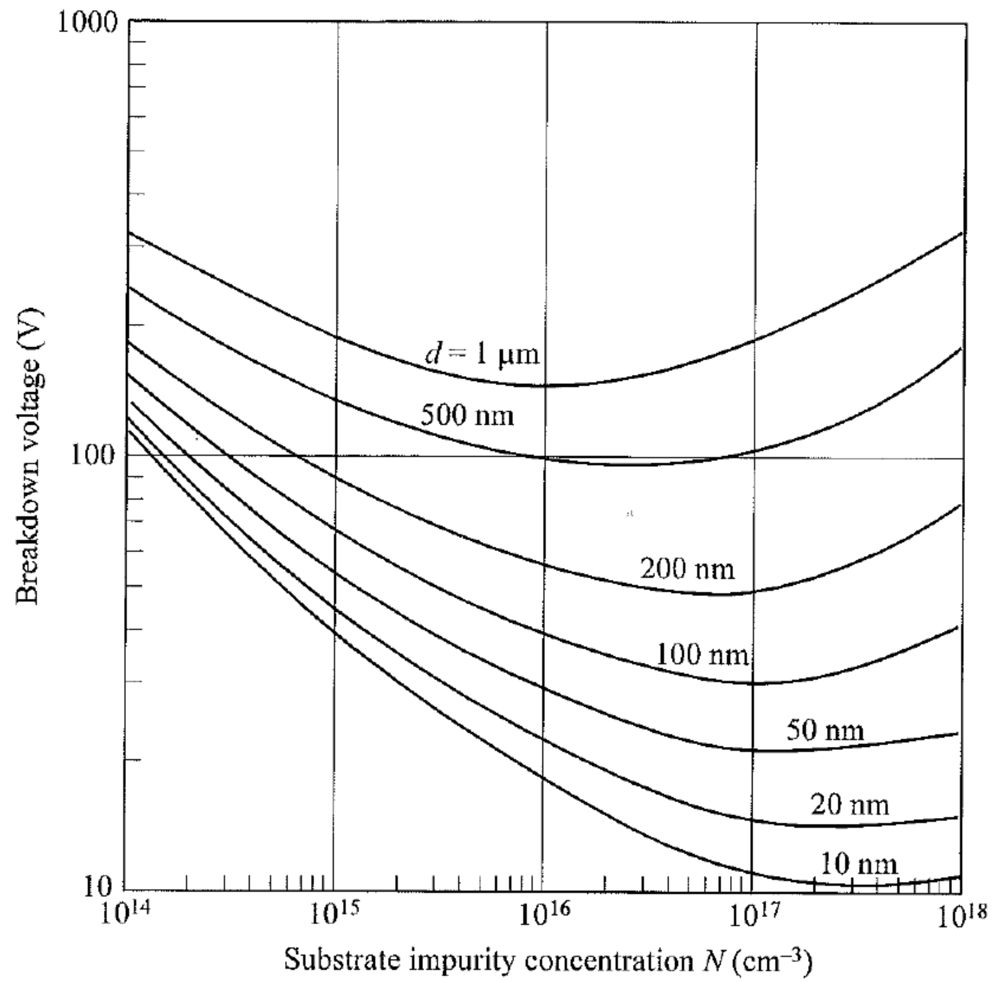
Frenkel –Poole emission

Ohmic

Avalanche injection of electrons into the oxide (c)

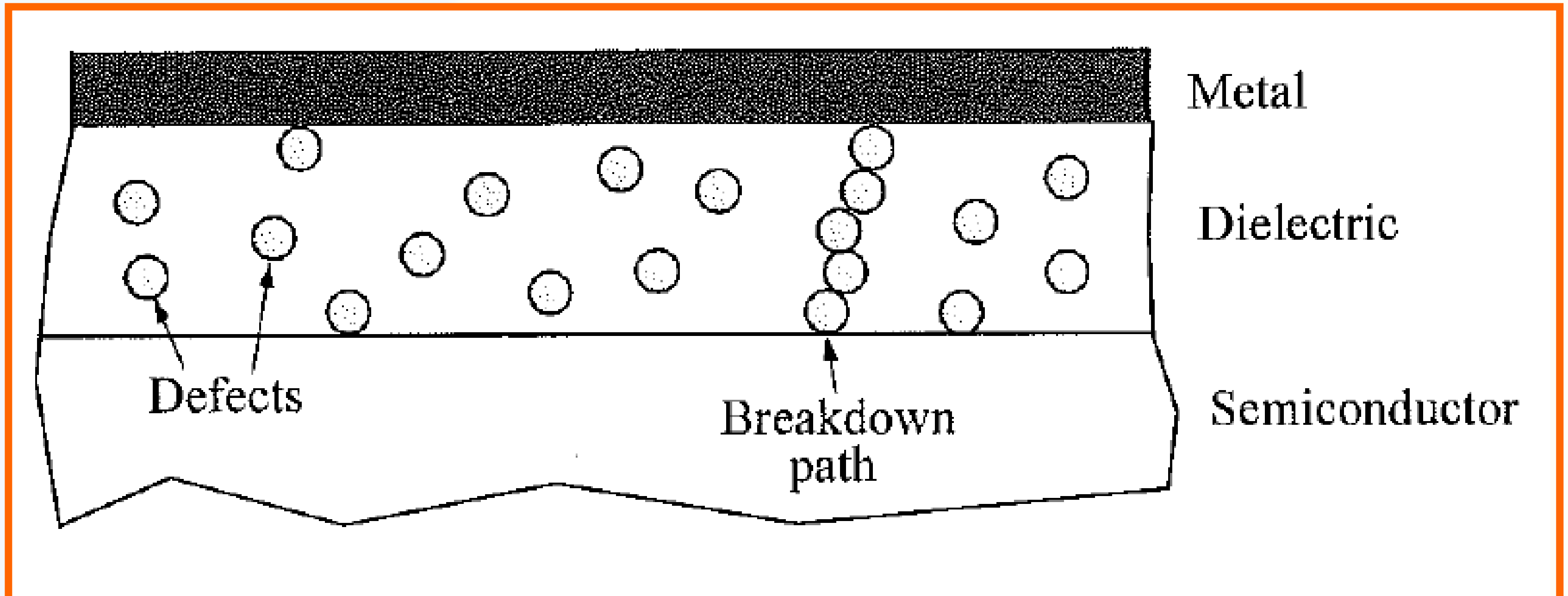


Breakdown voltage of MOS capacitor



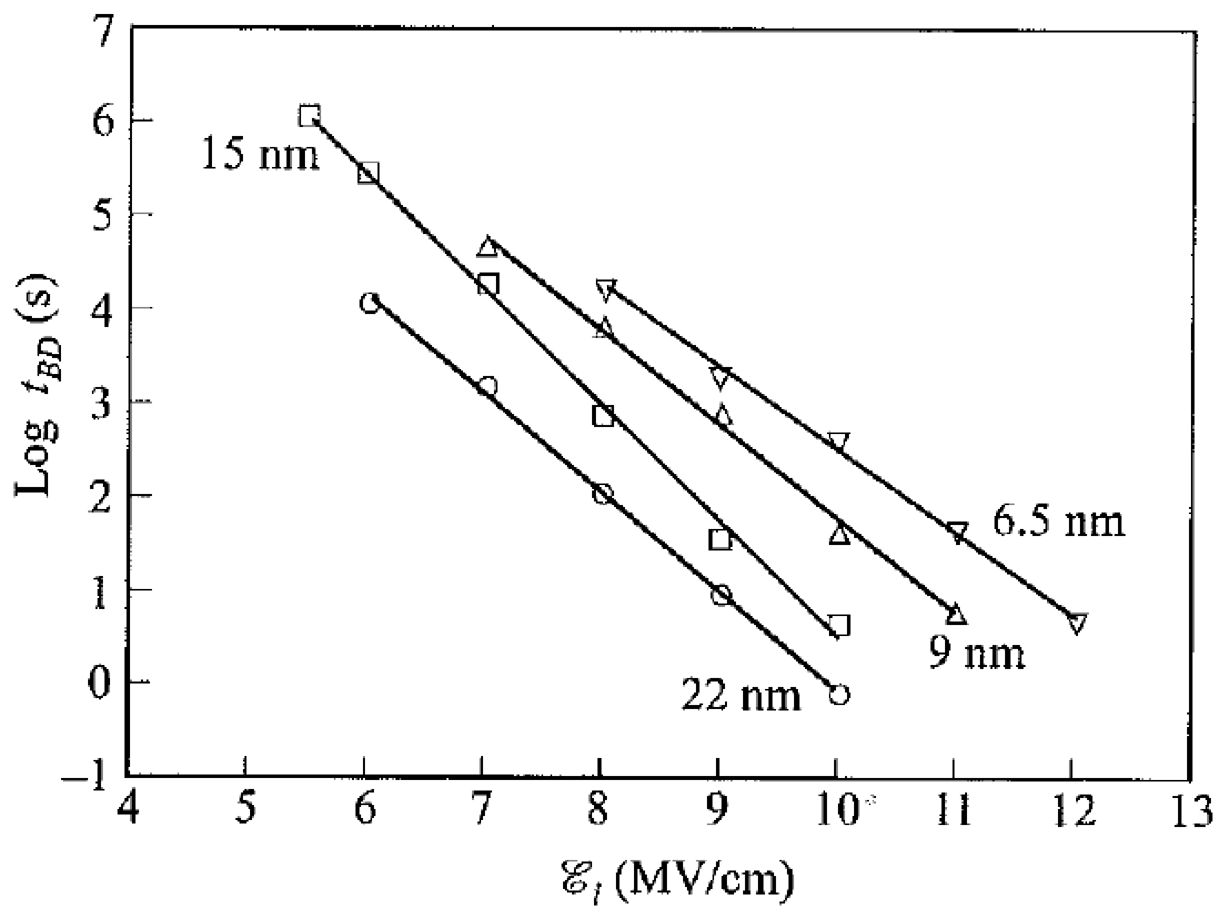
Hot carrier injection cause a change in the components characteristic

Dielectric breakdown



Occur when a chain of defects forms between metal and semiconductor

Time to breakdown versus oxide field



DE-detector

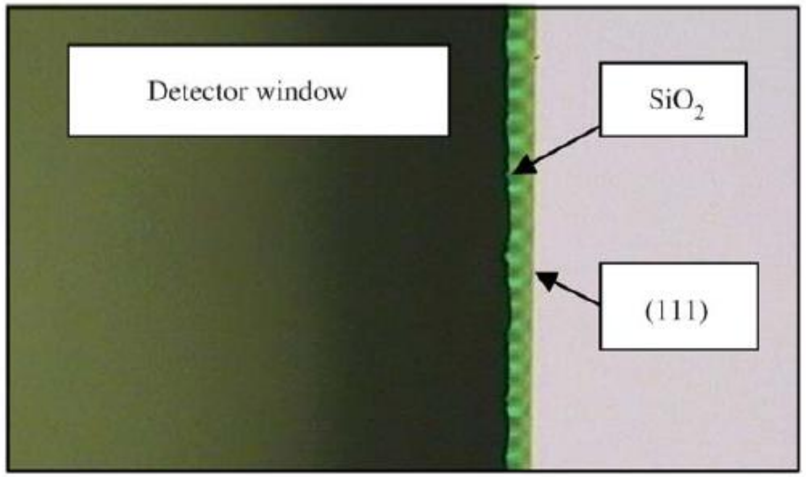


Fig. 1. Overhanging silicon dioxide edge in the detector window.

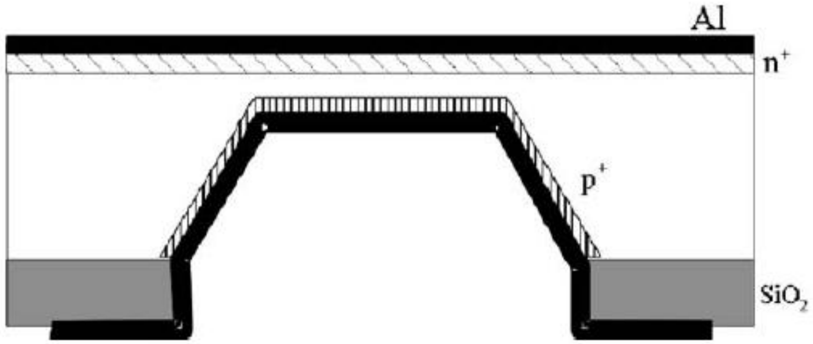


Fig. 2. Schematic sketch of the detector structure.

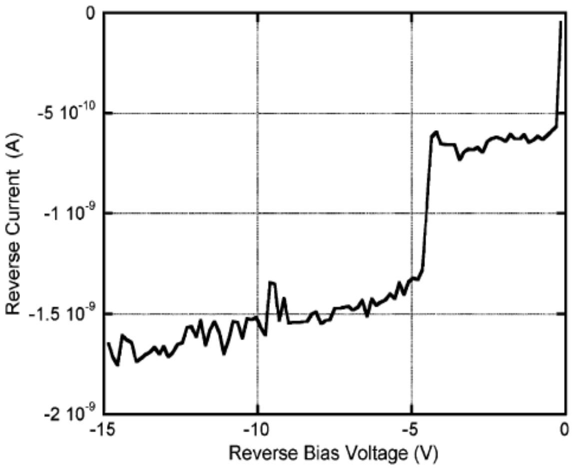


Fig. 4. *IV*-characterization of an 8.8 µm ΔE detector.

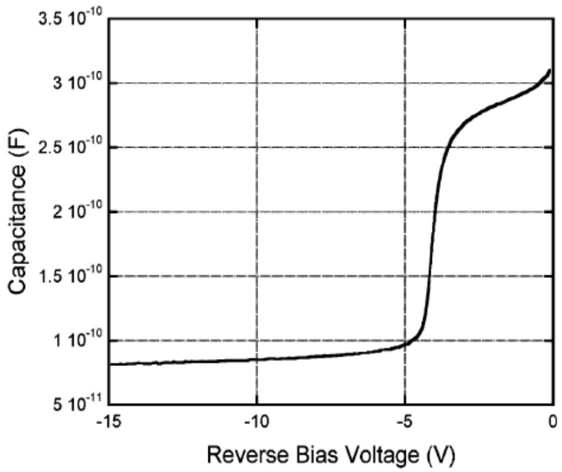


Fig. 5. *CV*-characterization of an 8.8 µm ΔE detector.

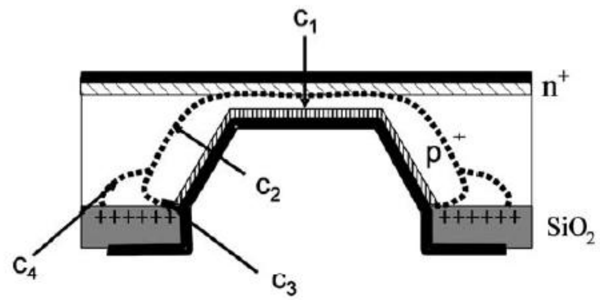


Fig. 6. Distributed capacitances in the ΔE detector. C_1 is detector window capacitance, C_2 side wall capacitance, C_3 edge capacitance, and C_4 metal oxide semiconductor capacitance.

An example, from "Streetman"

EXAMPLE 6–1 An n^+-polysilicon-gate n-channel MOS transistor is made on a p-type Si substrate with $N_a = 5 \times 10^{15}\,\text{cm}^{-3}$. The SiO_2 thickness is 100 Å in the gate region, and the effective interface charge Q_i is $4 \times 10^{10}\, q\text{C/cm}^2$. Find C_i and C_{min} on the C–V characteristics, and find W_m, V_{FB}, and V_T.

SOLUTION

$$\phi_F = \frac{kT}{q}\ln\frac{N_a}{n_i} = 0.0259\ln\frac{5\times 10^{15}}{1.5\times 10^{10}} = 0.329\text{ eV}$$

$$W_m = 2\left[\frac{\epsilon_s\phi_F}{qN_a}\right]^{1/2} = 2\left[\frac{11.8\times 8.85\times 10^{-14}\times 0.329}{1.6\times 10^{-19}\times 5\times 10^{15}}\right]^{1/2}$$
$$= 4.15\times 10^{-5}\text{cm} = \mathbf{0.415\ \mu m}$$

From Fig. 6-17, $\Phi_{ms} \approx -0.95$ V, and we have

$$Q_i = 4\times 10^{10}\times 1.6\times 10^{-19} = 6.4\times 10^{-9}\text{ C/cm}^2$$

$$C_i = \frac{\epsilon_i}{d} = \frac{3.9\times 8.85\times 10^{-14}}{0.1\times 10^{-5}} = 3.45\times 10^{-7}\text{ F/cm}^2$$

$$V_{FB} = \Phi_{ms} - Q_i/C_i = -0.95 - 6.4\times 10^{-9}/3.45\times 10^{-7} = \mathbf{-0.969\ V}$$

$$Q_d = -qN_aW_m = -1.6\times 10^{-19}\times 5\times 10^{15}\times 4.15\times 10^{-5}$$
$$= -3.32\times 10^{-8}\text{C/cm}^2$$

$$V_T = V_{FB} - \frac{Q_d}{C_i} + 2\phi_F = -0.969 + \frac{3.32\times 10^{-8}}{3.45\times 10^{-7}} + 0.658 = \mathbf{-0.215\ V}$$

$$C_d = \frac{\epsilon_s}{W_m} = \frac{11.8\times 8.85\times 10^{-14}}{4.15\times 10^{-5}} = 2.5\times 10^{-8}\text{ F/cm}$$

$$C_{min} = \frac{C_iC_d}{C_i + C_d} = \frac{3.45\times 10^{-7}\times 2.5\times 10^{-8}}{3.45\times 10^{-7} + 2.5\times 10^{-8}} = \mathbf{2.33\times 10^{-8}\ F/cm^2}$$