Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

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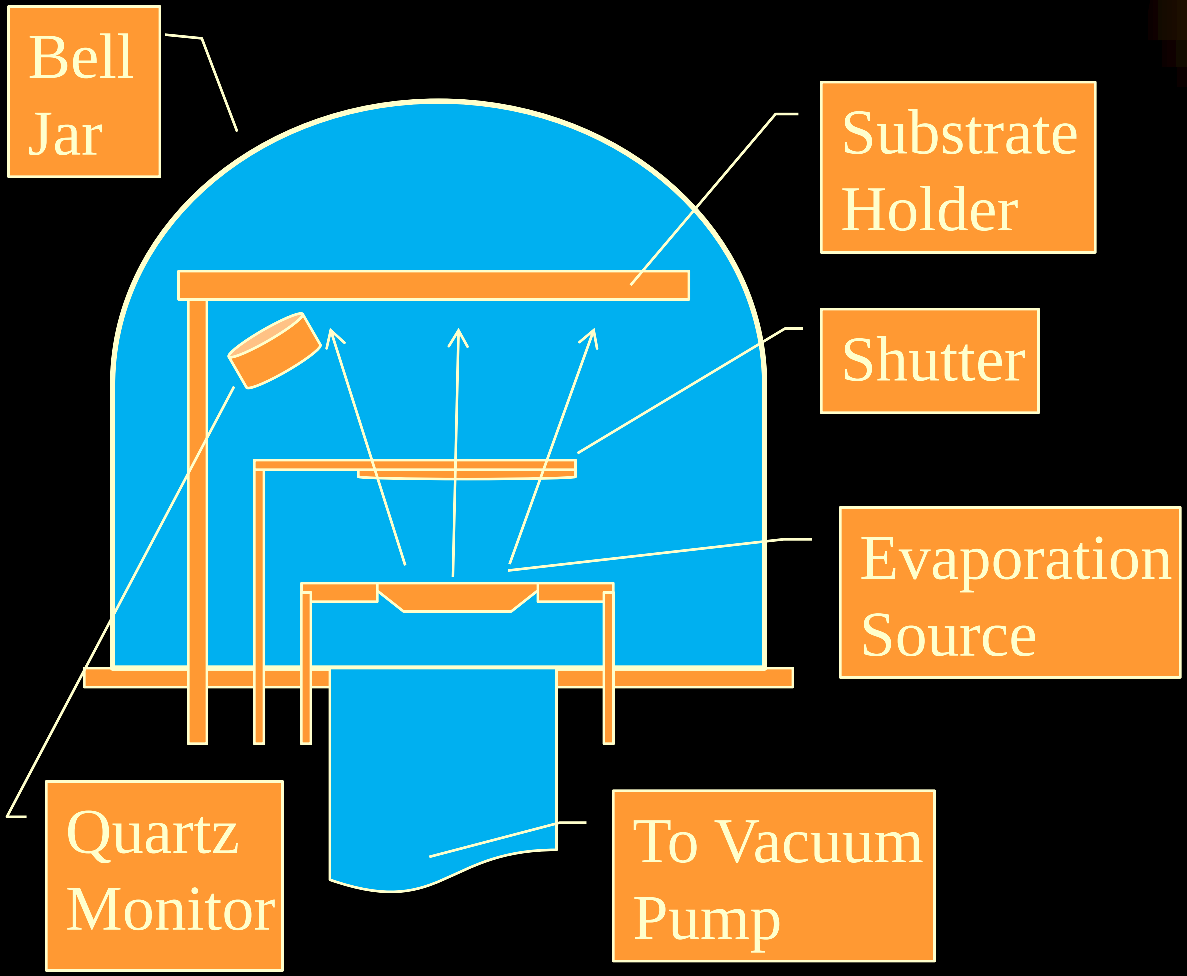
Metal-Semiconductor Contacts

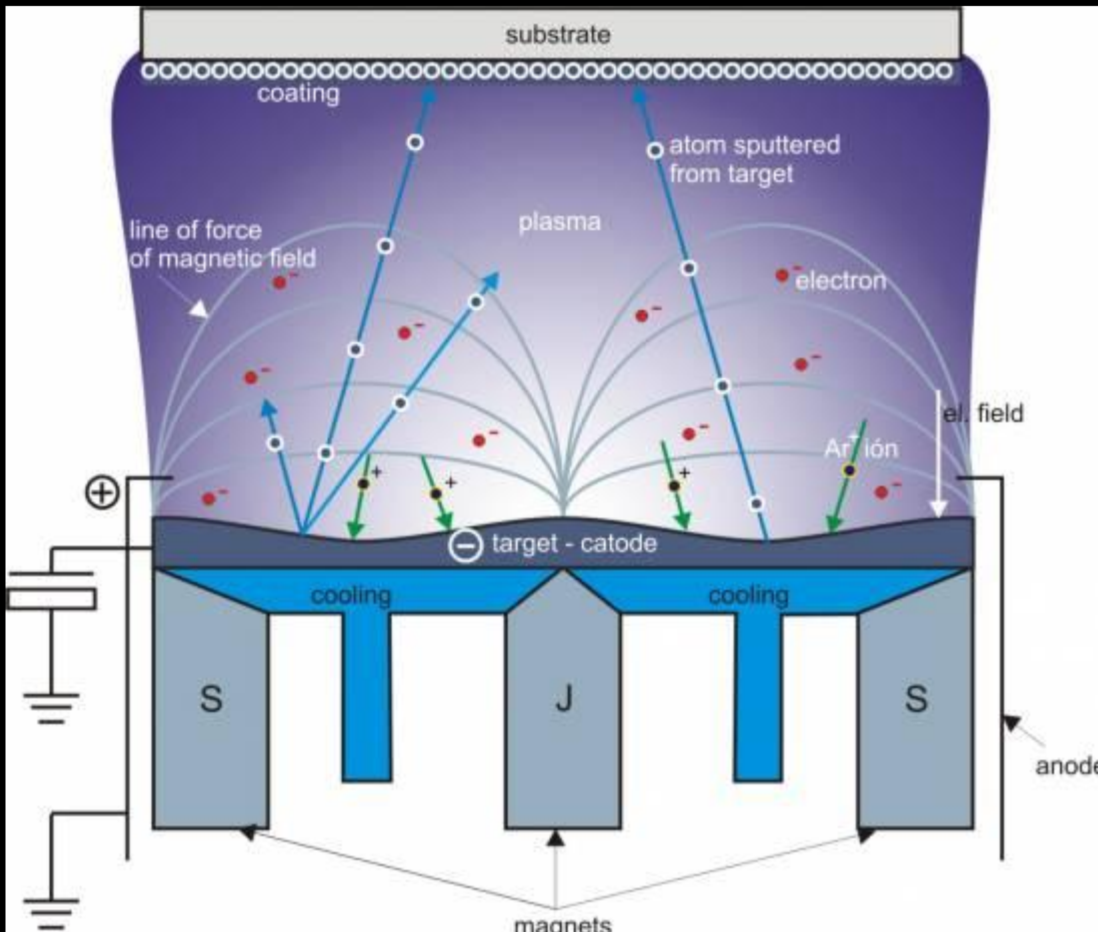
- How are they formed?
- Applications...
- What is the Physics of the barrier formation?
- Charge, potential, field and bands...
- Current models...
- IV-characteristics & temperature dependencies

Metal Deposition - Evaporation



- Thermal, e-beam, laser, etc. versions
- Vacuum requirements $< 10^{-4}$ mBar
- Difficult for refractory metals and for low melting point ones
- Can lead to astaehiometrisation
- Very directional – coverage problems
- Poor deposition rate control apart from MBE
- Low energy process

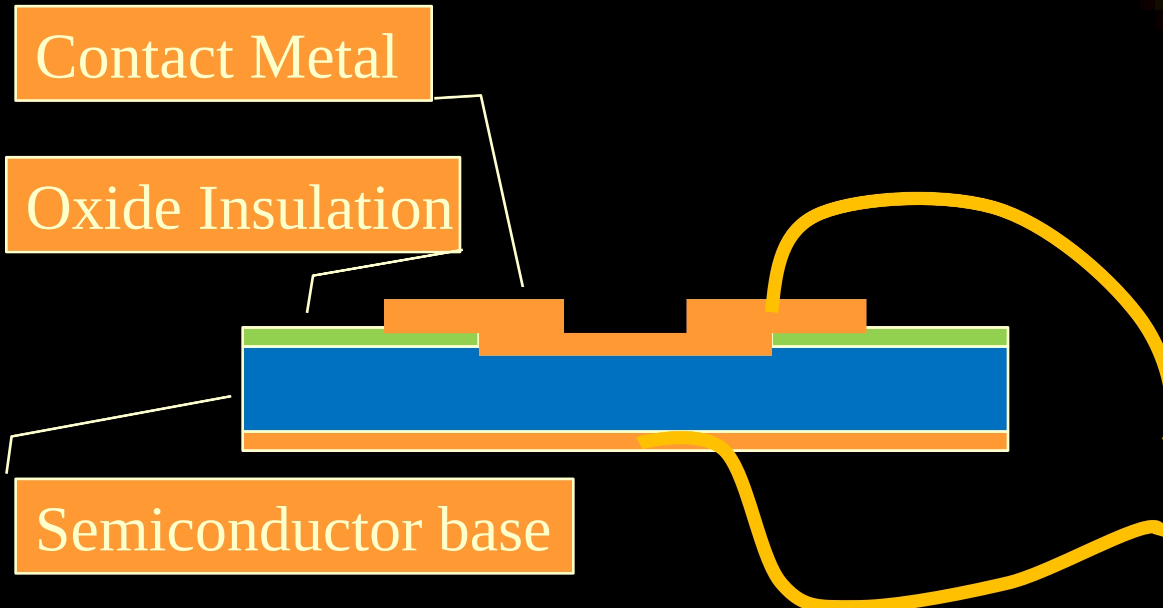
Metal Deposition - Sputtering



http://www.umms.sav.sk/index.php?ID=415

- DC, RF and Mixed versions
- Vacuum requirements < 10^{-2} mBar
- Easy for refractory metals
- Can lead to astaehiometrisation
- Not directional– no coverage problems
- Excellent rate control – no need to monitor
- Higher energy process
- Difficult for magnetic materials

Schottky Diodes



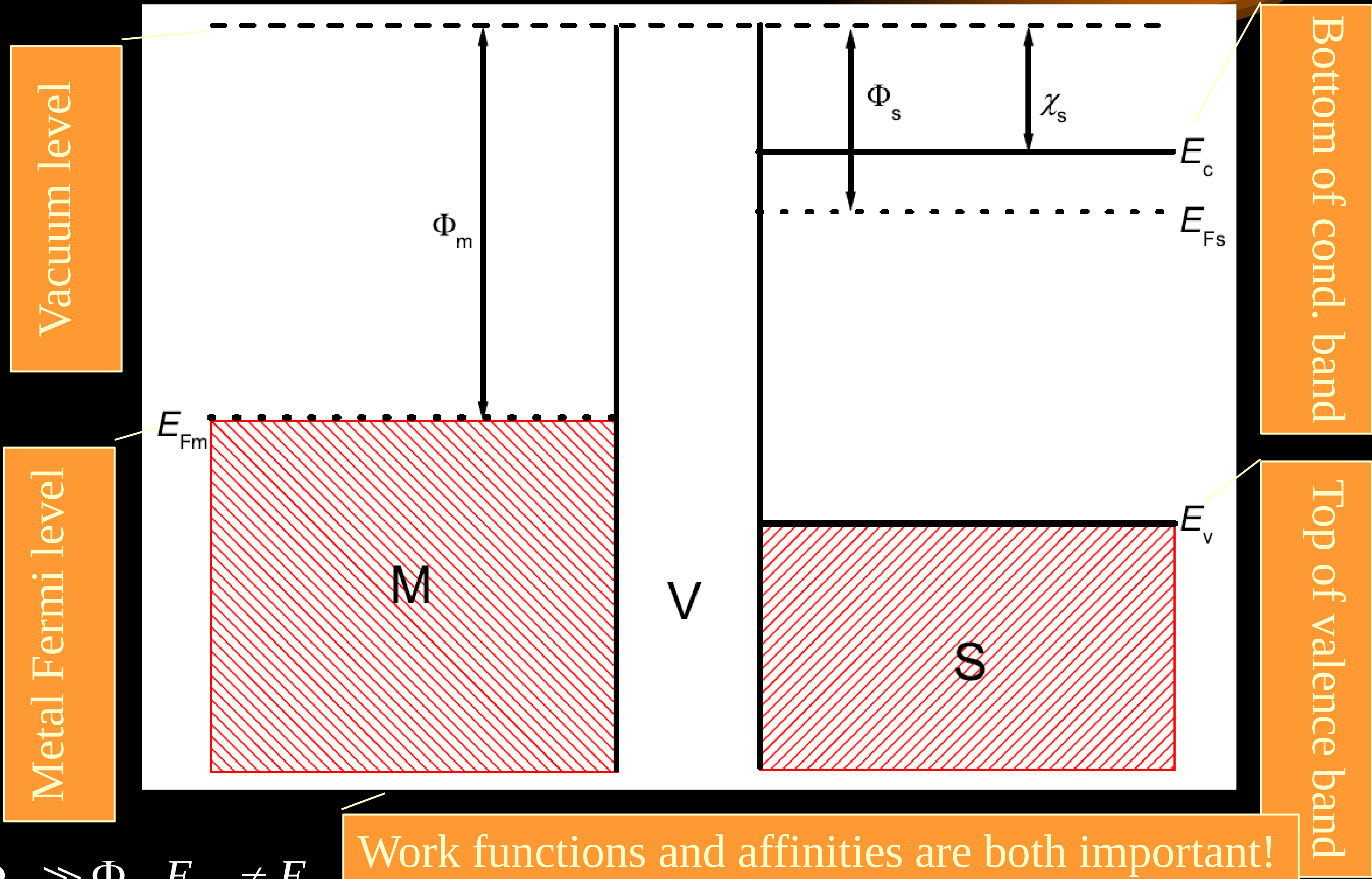
Recipe

- Mask an aperture
- Remove oxide
- Deposit metal
- Contact

Features

- Simple (...or not...)
- Important building block
- Fast
- Low forward drop
- Reverse bias breakdown not perfect
- Majority carrier device

Schottky Junction – Before Formation

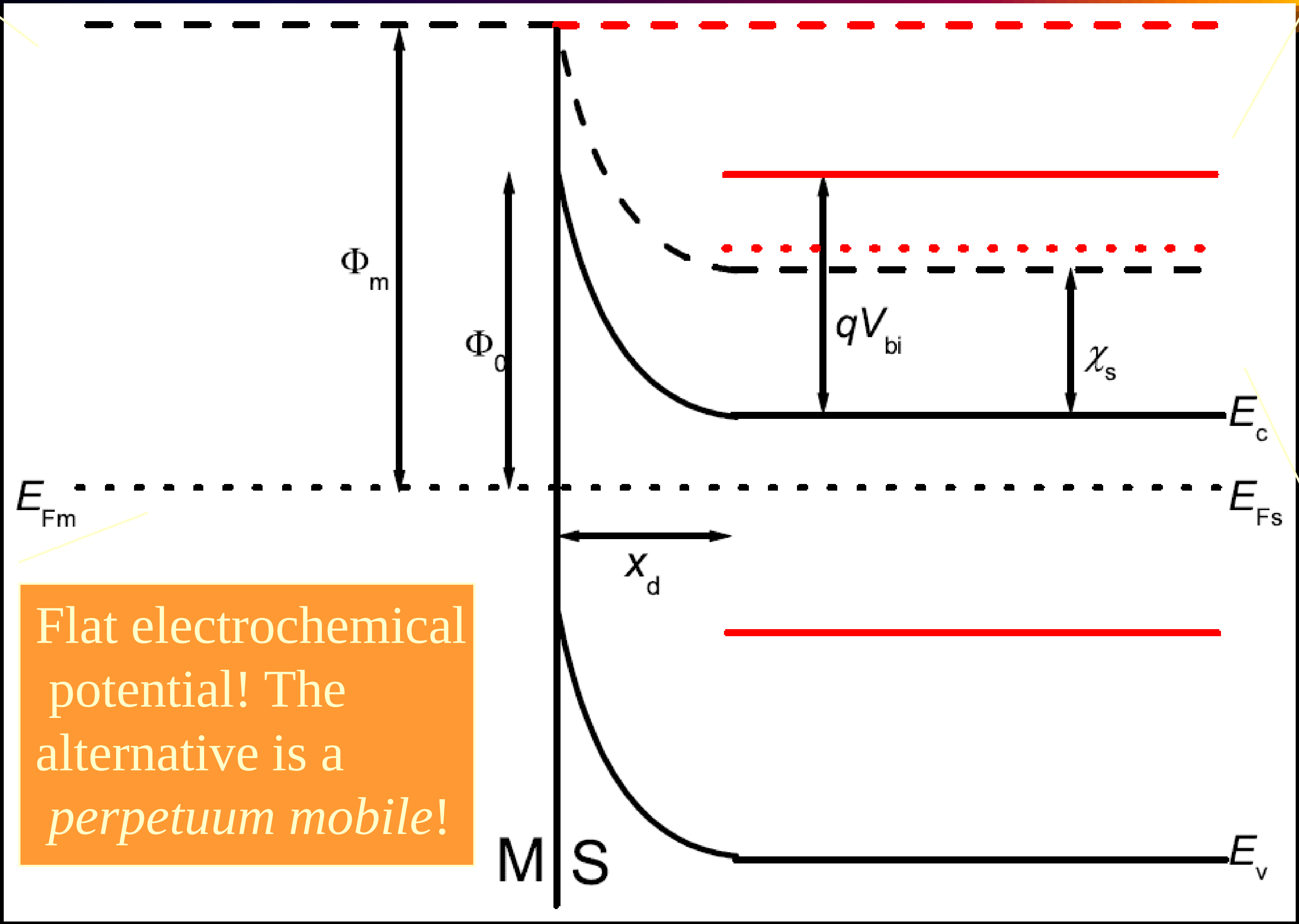


Work functions and affinities are both important!

$\Phi_m \gg \Phi_s \quad E_{Fm} \neq E_{Fs}$

Schottky Junction – In Equilibrium I

The bands have to bend to accommodate!



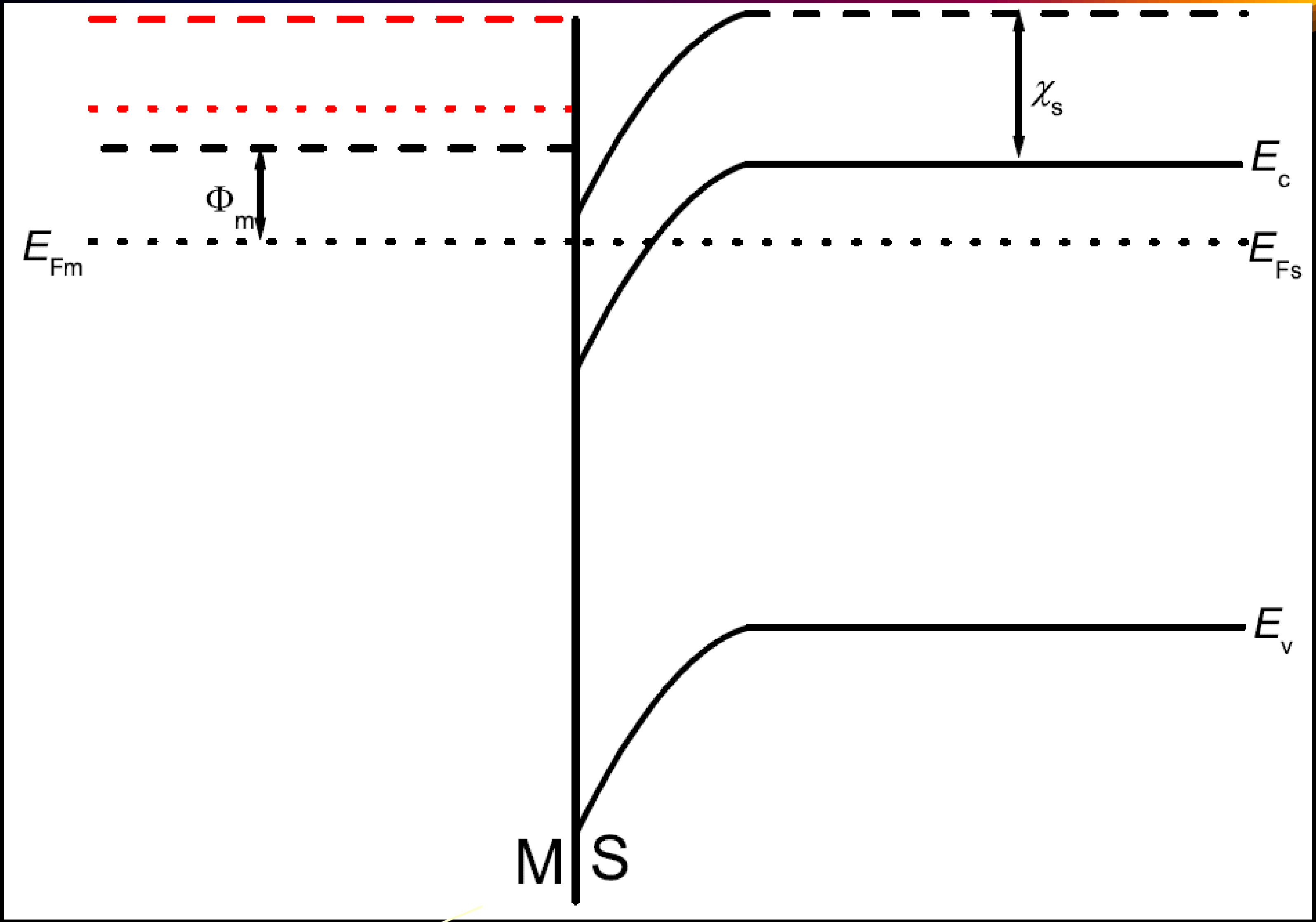
Before contact levels

Build-in potential

Flat electrochemical potential! The alternative is a *perpetuum mobile*!

$\Phi_m \gg \Phi_s$ $E_{Fm} = E_{Fs}$ $qV_{bi} = \Phi_m - \Phi_s$ $\Phi_0 = \Phi_m - \chi_s$

Schottky Junction – In Equilibrium II



$\Phi_m \ll \Phi_s$ $\quad E_{Fm} = E_{Fs}$

There are not too many examples of these…

Notes on Barrier Formation

- Mott-Schottky Model – noninteracting interface

$$\Phi_0 = \Phi_m - \chi_s \qquad \varsigma \equiv \frac{d\Phi_0}{d\Phi_m} = 1$$

- Bardeen Model - (Gap States)

$$\Phi_0 \approx \varsigma(\Phi_m - \chi_s) + (1-\varsigma)\Phi_g \qquad \varsigma = \frac{1}{1+\frac{q^2 D_g x_g}{\varepsilon_g}} \sim 0.1$$

Screening distance

Interface Index

- Heine Model (Metal-induced States)

$$\varsigma = \frac{1}{1+q^2 D_g(E_{Fm})\left(\frac{x_g}{\varepsilon_s}+\frac{\lambda_T}{\varepsilon_0}\right)}$$

Interface Capacitance

- Generalized Models

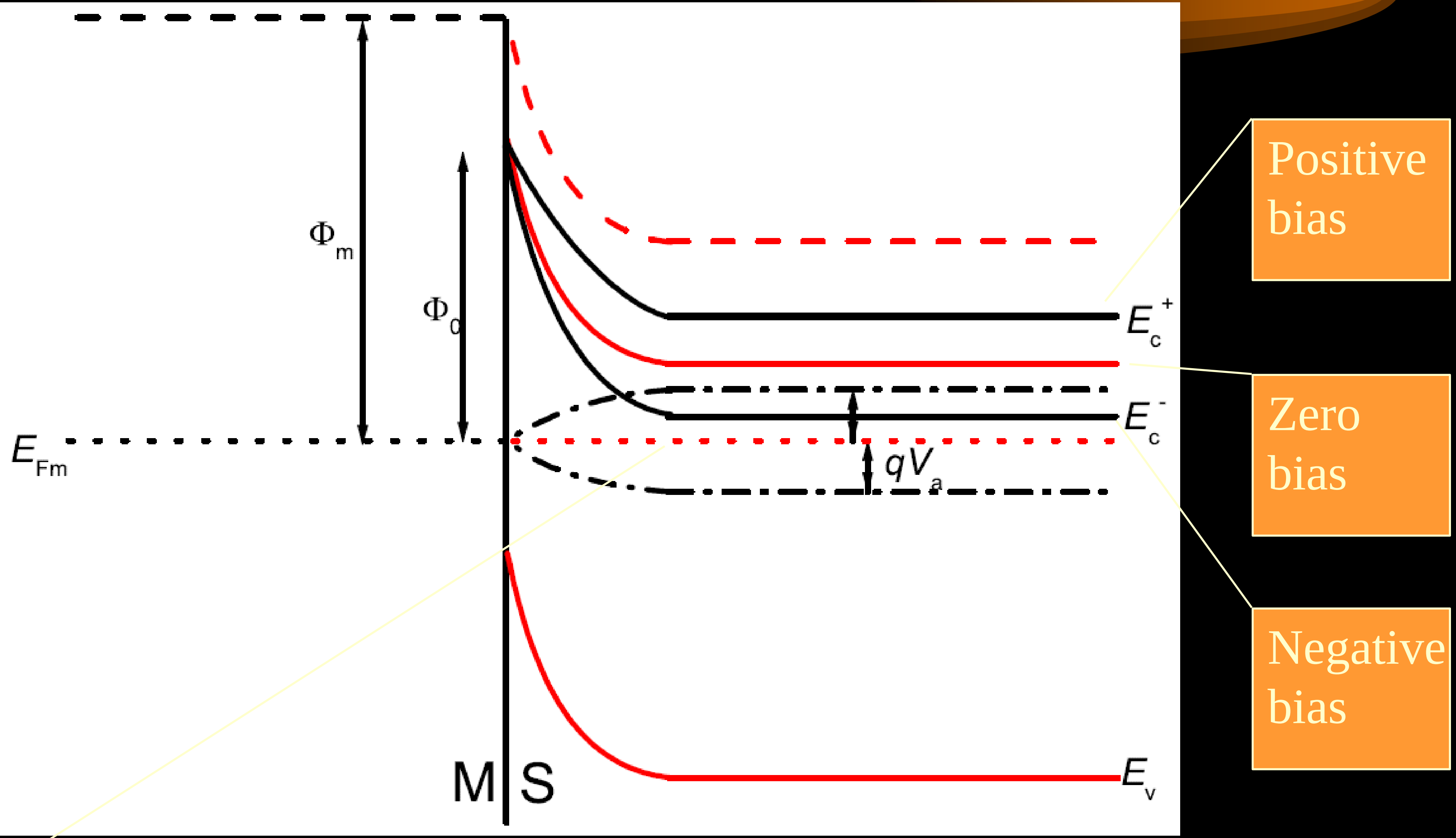
Nat. oxide thickness

$$\varsigma = \frac{1}{1+q^2 D_s \varpi} - (E_g + \chi_s - \Phi_b - \Phi_m)\frac{q^2 D_s \lambda_s}{\varepsilon_s(1+q^2 D_s \varpi)} \qquad \varpi = \frac{\lambda_T}{\varepsilon_m} + \frac{\delta}{\varepsilon_{ox}}$$

- Extrinsic States

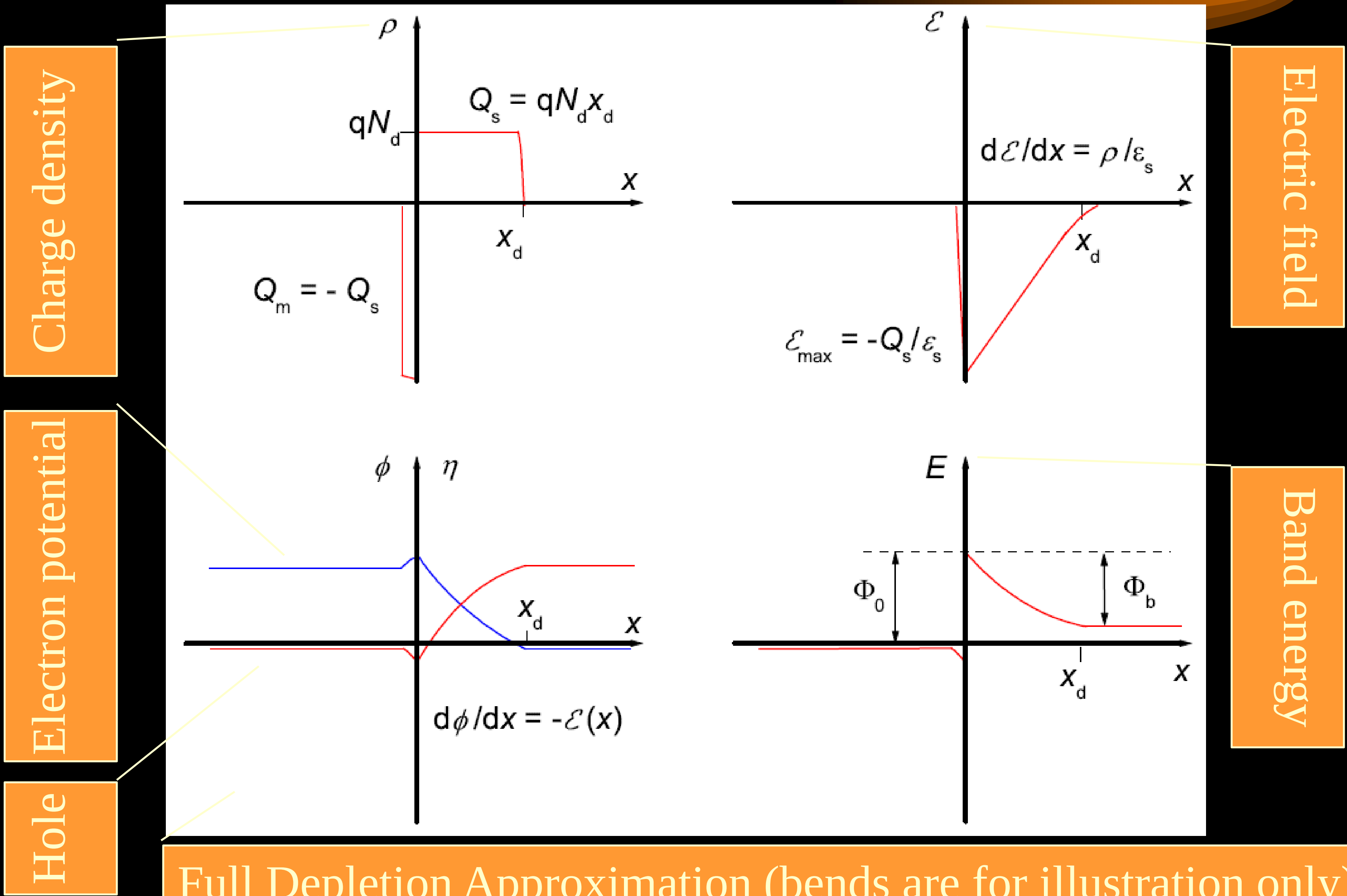
Thomas-Fermi screening length

Schottky Junction – Under Bias



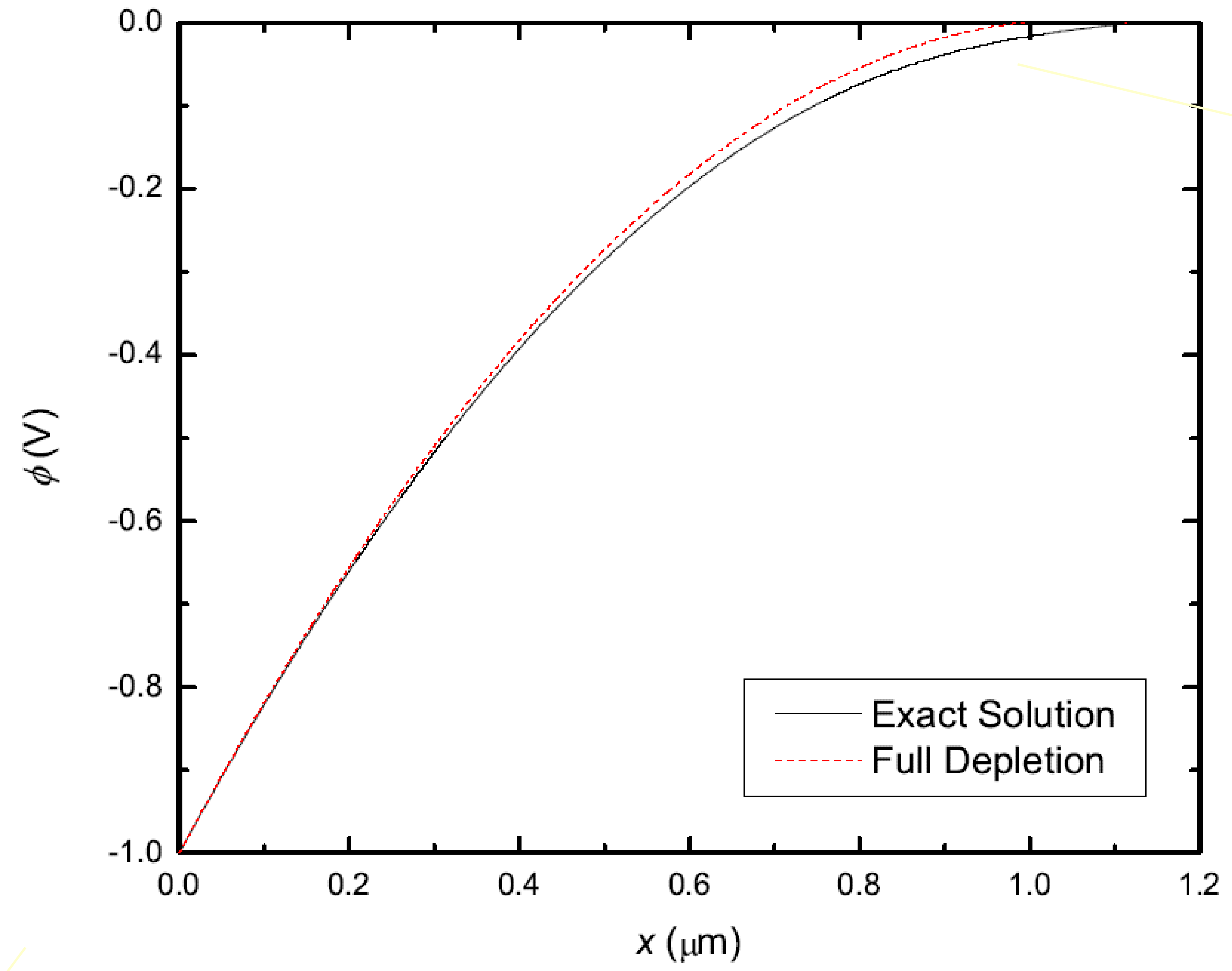
All within a rigid band approximation for the shifts in depth on S side.

Charge, Field, Potential and Bands



Full Depletion Approximation (bends are for illustration only)

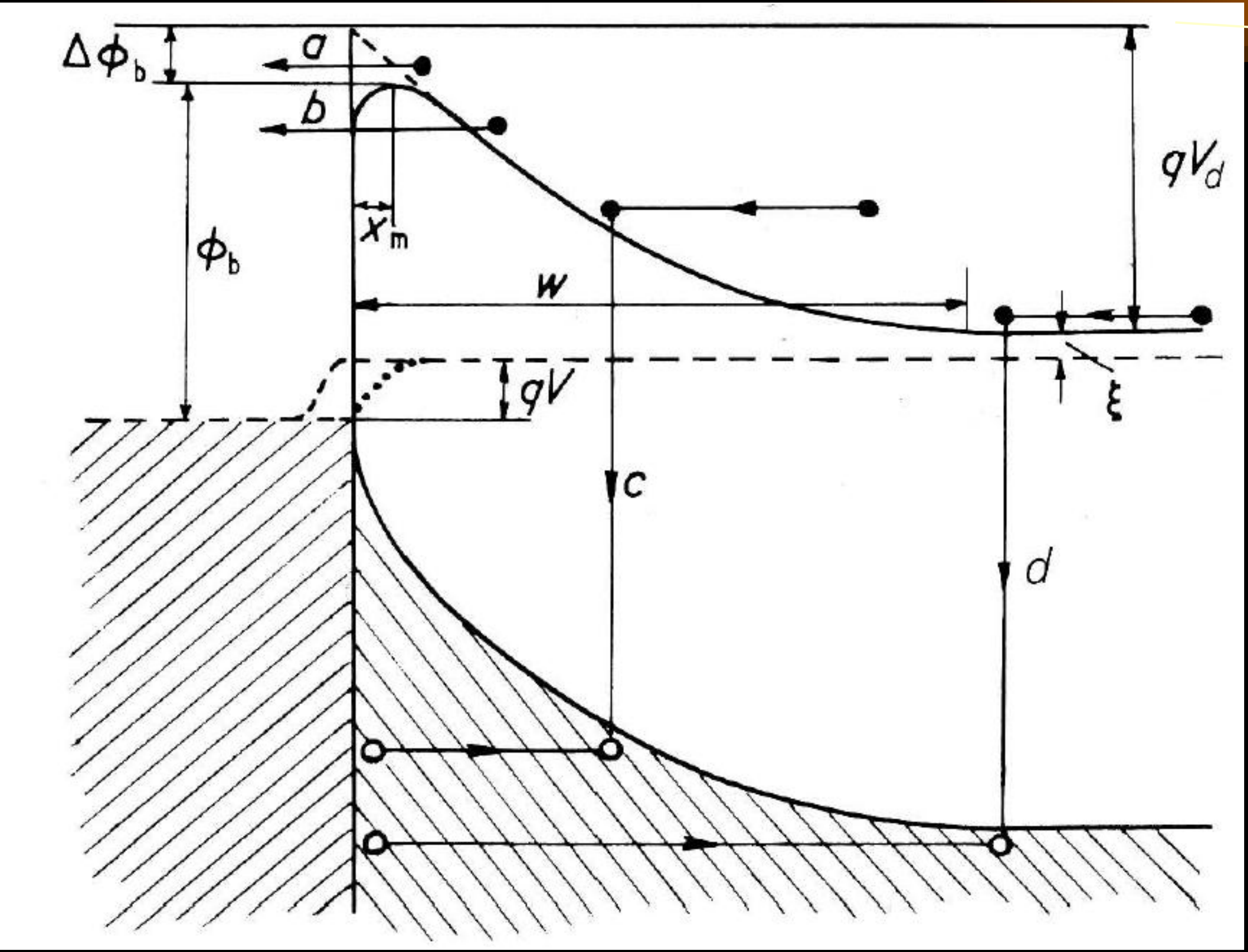
Full Depletion Approximation



Only at the very edge of the depleted region is there an appreciatable difference between the FDA and the exact solution.

The Full Depletion Approximation is quite valid for a typical SC at RT.

Main Current Components



a) Thermionic emission
b) Tunnelling
c) Recomb. in dep. region
d) Deep recombination

After: Rhoderick and Williams (1988) *Metal-Semiconductor Contacts*

The Schottky Model – Diffusion I

$$J_n = q(\mu_n n \mathcal{E} + D_n \frac{\mathrm{d}n}{\mathrm{d}x})$$

Continuity Drift-Diffusion Equation

Einstein's Relation

$$D_n = \frac{kT\mu_\mathrm{n}}{q}$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = -\frac{\rho}{\epsilon_s} = -\frac{q}{\epsilon_s}\left(p - n + N_\mathrm{d}^+ - N_\mathrm{a}^-\right)$$

1D – Poisson Equation

Depleted Region Width

$$x_\mathrm{d} = \sqrt{\frac{2\epsilon_\mathrm{s}(\phi_\mathrm{i} - V_\mathrm{a})}{qN_\mathrm{d}}}$$

The Schottky Model – Diffusion II

Barrier height (V)

$$\phi_b = \frac{\Phi_m - \chi_s}{q}$$

Donor activation corrected barrier

$$\phi_i = \phi_b - \frac{kT}{q} \ln \frac{N_c}{N_d}$$

Deposited charge

Barriers for the electrons and the holes

$$q\phi_{b_n} = (\Phi_M - \chi_c)$$

$$q\phi_{b_p} = E_g - (\Phi_M - \chi_s)$$

$$Q_s = \sqrt{2q\epsilon_s N_d (\phi_i - V_a)}$$

$$C_j = \frac{\epsilon_s}{x_d} = \sqrt{\frac{q\epsilon_s N_d}{2(\phi_i - V_a)}}$$

Total current

Junction capacitance

$$J_n = \frac{q^2 D_n N_c}{kT} \sqrt{\frac{2q(\phi_b - V_a) N_d}{\epsilon_s}} \exp\left(-\frac{q\phi_b}{kT}\right) \left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$$

The Bethe Model - Emission

$$J_{\mathrm{n}} = \int_{E_{\mathrm{c}}(x=+\infty)}^{q\phi_{\mathrm{n}}} q v_x \frac{\mathrm{d}n}{\mathrm{d}E} \mathrm{d}E$$

Thermionic Emission

$$A^{\star} = \frac{q N_{\mathrm{c}} \overline{v}}{4} = \frac{4\pi m^{\star} q k^2}{h^3}$$

Richardson's Constant

$$A^{\star}_{\mathrm{Si}\{111\}} = 258 \ \mathrm{Acm}^{-2}\mathrm{K}^{-2}$$

$$m^{\star}_{\mathrm{c}} = \sqrt{l^2 m_y m_z + m^2 m_z m_x + n^2 m_x m_y}$$

Projected Effective Mass

Total current

$$J_{\mathrm{n}} = \frac{4\pi q m^{\star}_{\mathrm{c}} k^2}{h^3} T^2 \exp\left(-\frac{q\phi_{\mathrm{b}}}{kT}\right)\left[\exp\left(\frac{qV_{\mathrm{a}}}{kT}\right) - 1\right]$$

The Sze Model – Diffusion + Emission

$$v_{\mathrm{r}} = \frac{\int_0^{\infty} v_{\mathrm{x}} \exp\left(-\frac{m^\star v_{\mathrm{x}}^2}{2kT}\right) \mathrm{d}v_{\mathrm{x}}}{\int_{-\infty}^{\infty} \exp\left(-\frac{m^\star v_{\mathrm{x}}^2}{2kT}\right) \mathrm{d}v_{\mathrm{x}}} = \sqrt{\frac{kT}{2\pi m^\star}} \approx v_{\mathrm{R}}$$

Recomb. Velocity

$$v_{\mathrm{r}} = \frac{\int_0^{\infty} v_{\mathrm{x}} \exp\left(-\frac{m^\star (v_{\mathrm{x}} - v_{\mathrm{d}})^2}{2kT}\right) \mathrm{d}v_{\mathrm{x}}}{\int_{-\infty}^{\infty} \exp\left(-\frac{m^\star (v_{\mathrm{x}} - v_{\mathrm{d}})^2}{2kT}\right) \mathrm{d}v_{\mathrm{x}}}$$

Correct Recomb. Velocity

Drift-Diffusion Velocity

$$v_{\mathrm{d}}^{-1} = \int_{x_{\mathrm{m}}}^{x_{\mathrm{d}}} \frac{q}{\mu_{\mathrm{n}} kT} \exp\left(-\frac{q\phi_{\mathrm{b}} - E_{\mathrm{c}}(x)}{kT}\right) \mathrm{d}x \approx \frac{L_{\mathrm{D}}^2}{D_{\mathrm{n}} x_{\mathrm{d}}} \left(1 - \mathrm{e}^{-\frac{x_{\mathrm{d}}^2}{L_{\mathrm{D}}^2}}\right)$$

Total current

$$J_{\mathrm{n}} = \frac{q N_{\mathrm{c}} v_{\mathrm{r}}}{1 + v_{\mathrm{r}}/v_{\mathrm{d}}} \exp\left(-\frac{q\phi_{\mathrm{b}}}{kT}\right) \left[\exp\left(\frac{qV_{\mathrm{a}}}{kT}\right) - 1\right]$$

Tunnelling Current

$$-\frac{\hbar^2}{2m^\star}\frac{\mathrm{d}^2\Psi}{\mathrm{d}^2x}+q\phi(x)\Psi=E\Psi$$

Schrodinger's Equation

Need only factor in the part of the DOS with significant tunnelling probability

$$v_\mathrm{R}=\sqrt{\frac{kT}{2\pi m_\mathrm{c}^\star}}$$

Recombination Richardson Velocity

Total tunnelling current (Note the weak temperature dependence)

$$J_\mathrm{n}\approx qv_\mathrm{R}n\exp\left(-\frac{4}{3}\frac{\sqrt{2m_\mathrm{c}^\star}}{\hbar}\sqrt{q\phi_\mathrm{b}}x_\mathrm{d}\right)\exp\left[\left(\frac{qV_\mathrm{a}}{kT}\right)-1\right]$$

Thanks and Acknowledgements

Thank You Very Much for Your Attention!