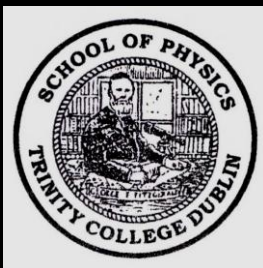
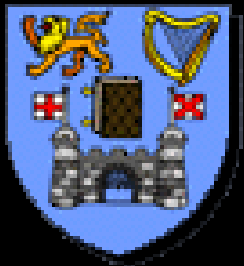


Semiconductor Devices - 2014

Lecture Course
Part of
SS Module PY4P03

Dr. P. Stamenov

School of Physics and CRANN, Trinity College,
Dublin 2, Ireland



Hilary Term, TCD
20th of Jan '14



M-S and p-n Junctions

- Minor current components
- The Schottky effect
- Abrupt p-n junction
- Charge, potential, field and bands...
- Graded p-n junction
- Charge, potential, field and bands...
- Epitaxial diodes
- Current components and IV-characteristics

Recombination in the Depleted Region

$$J_n = \frac{qn_i x_d}{2\tau_r} \exp\left(-\frac{E_g}{2kT}\right) \exp\left[\left(\frac{qV_a}{2kT}\right) - 1\right]$$

Recombination time
in the depleted region

$$pn = n_i^2 \exp(qV_a/kT)$$

Intrinsic carrier concentration

The product of the carrier concentrations is voltage activated. No bias – reverts to equilibrium case

- Simple modelling only in complete activation approximation (barrier height must be high enough)
- Distorts very significantly the experimental activation scales (temperature dependencies).
- When the junction structure is ‘bad’, with many recombination centres – this component can dominate the total current.

Hole Injection (Deep Recombination)

Hole current

$$J_p \propto \exp\left(-\frac{\Phi_p}{kT}\right)$$

Corresponding Barriers

Just a reminder

$$J_n \propto \exp\left(-\frac{\Phi_b}{kT}\right)$$

Barrier for the holes

$$\Phi_p = E_g - \zeta$$

$$\zeta = E_c - E_d$$

Donor states offset

$$\frac{J_p}{J_n} = \xi \propto \exp\left(-\frac{\Phi_p - \Phi_b}{kT}\right)$$

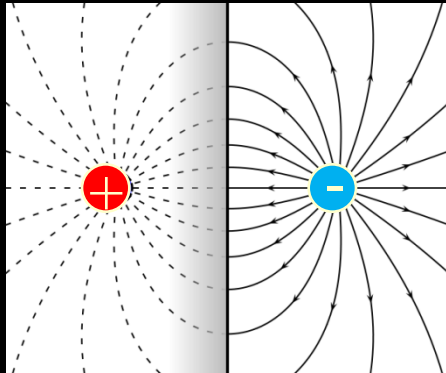
Minority Injection Ratio

Bias dependence (implicit via J)

$$\xi = \frac{\mu_p}{\mu_n} \left(\frac{n_i}{N_D}\right)^2 \frac{J}{J_S}$$

- Conventionally considered spurious (reverse gated JFET)
- Its analogue in p-n junctions is very important for the BJT principle of operation (will be discussed later in the course)

Schottky Effect – Barrier Lowering



M Ground S

$$\Delta\phi_b = \sqrt{\frac{q\mathcal{E}_{\max}}{2\pi\epsilon_s}}$$

Classical
Image Charge
Effect

$$\mathcal{E}_{\max} = \sqrt{\frac{2qN_d}{\epsilon_s} \left(V_{bi} - V_a - \frac{kT}{q} \right)}$$

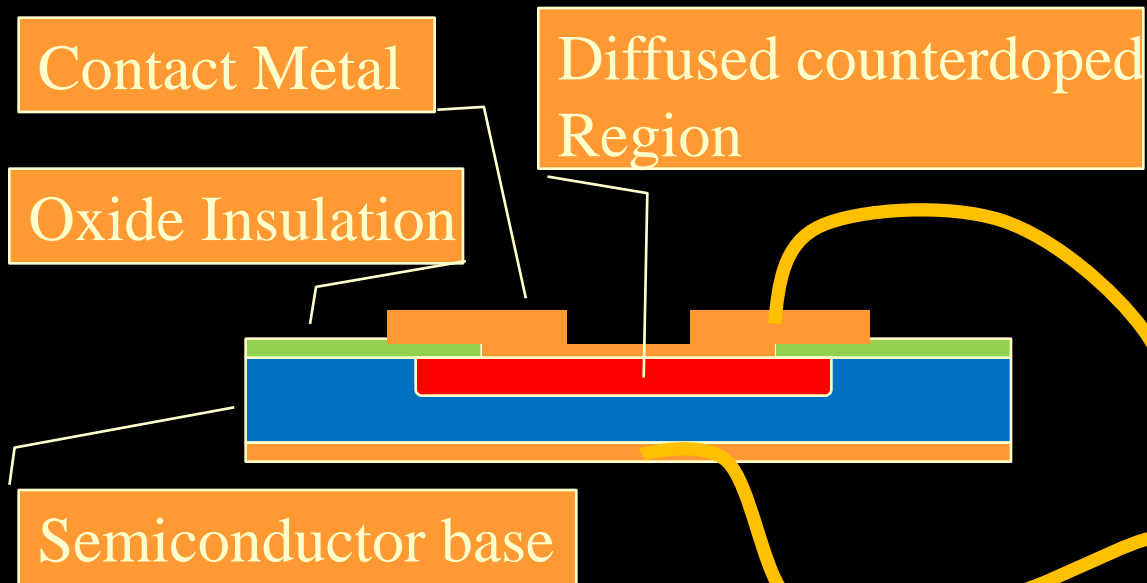
Maximal
depleted region
 E -field

$$V_{bi} = V(x_d) - V(0)$$

Actual
Build-in
Potential

- One should always measure lower barrier than expected (or otherwise suspect large recombination currents)
- Usually corrected for, based on calculations.

Abrupt pn-Junction Diodes



Recipe

- ...
- Diffuse from a constant source
- Clean-up
- Deposit metal
- Contact

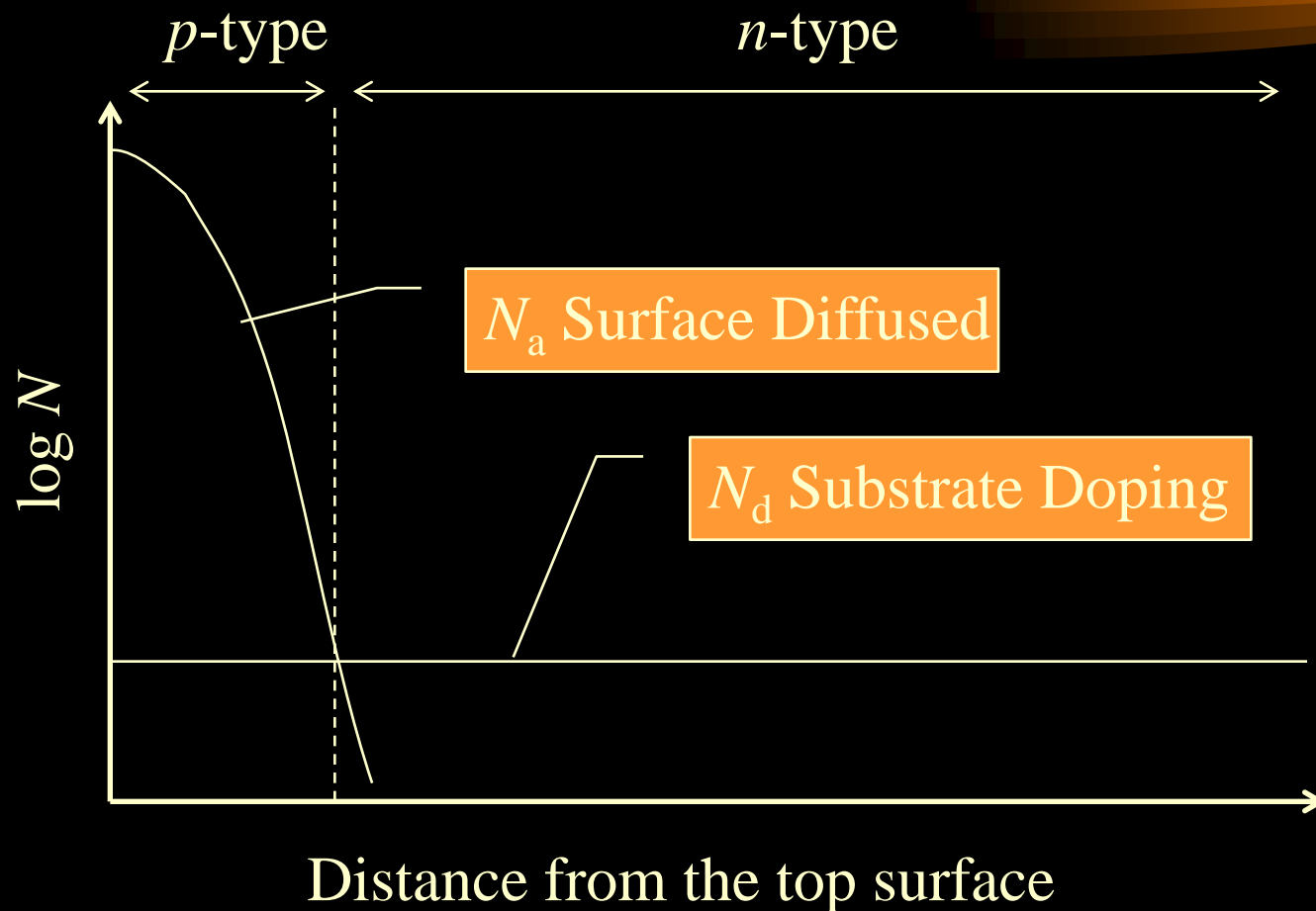
Features

- Building block
- Control of Capacitance
- Low forward drop
- Lower reverse bias leakage
- Minority carrier device



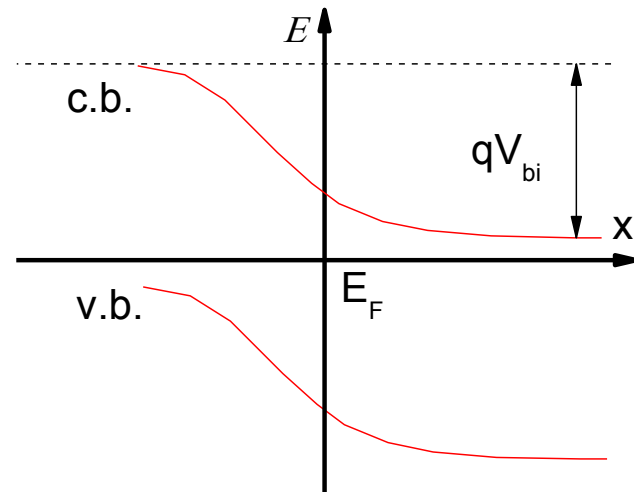
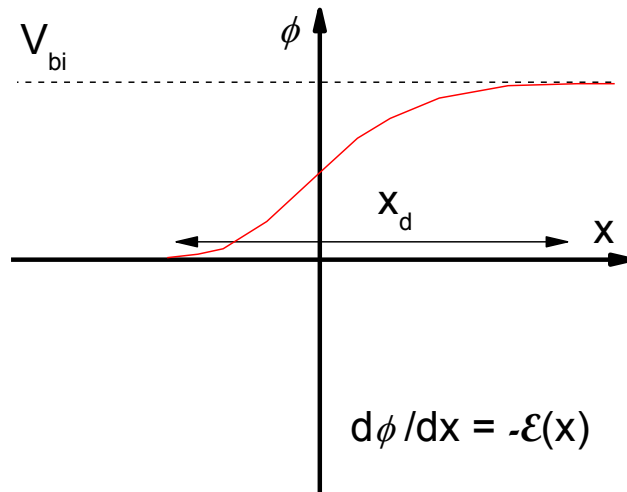
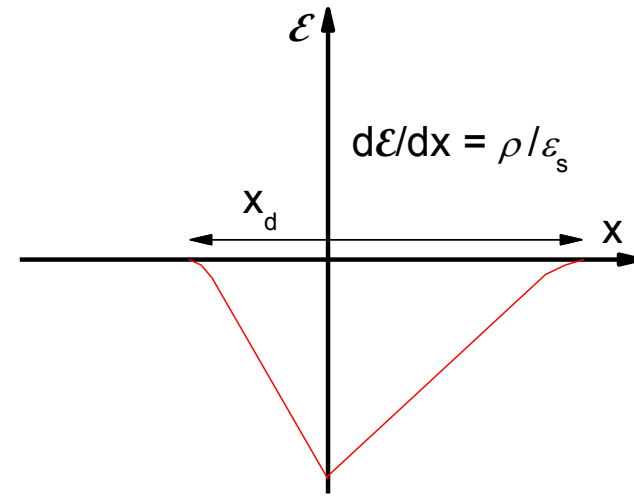
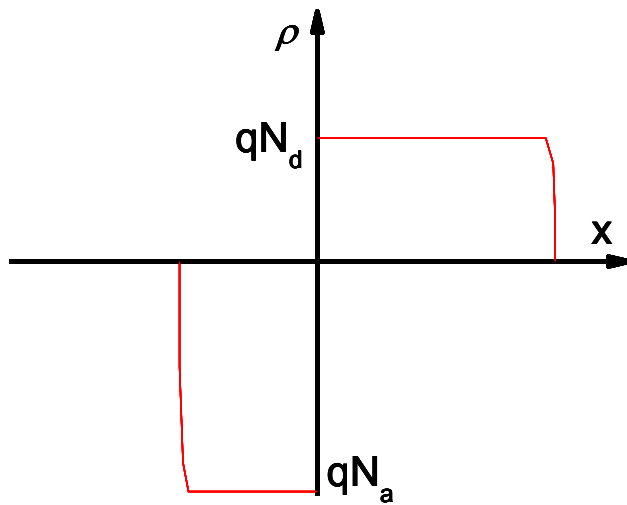
SMV14xx
Skyworks

Abrupt Junction via Diffusion

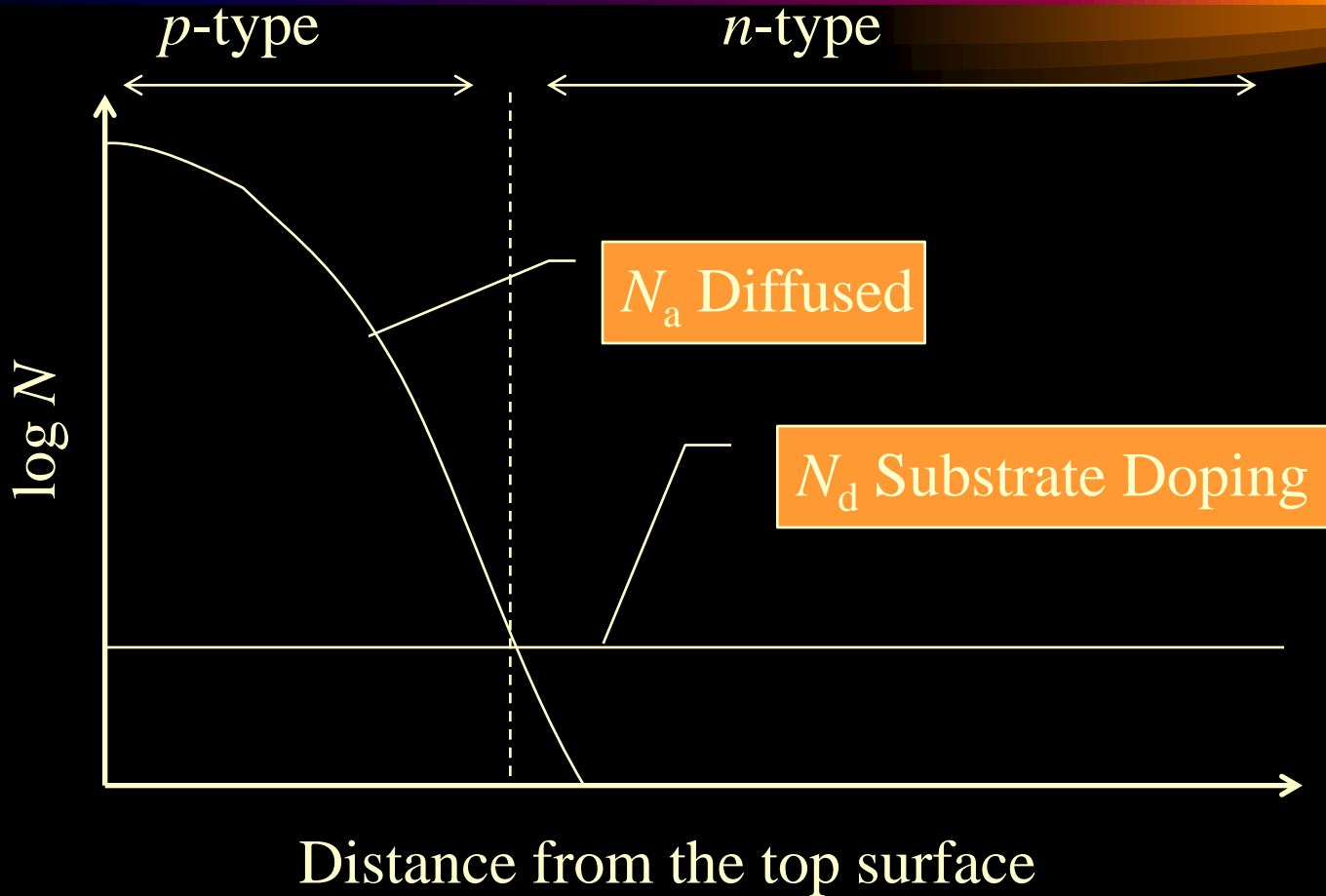


- Can be manufactured by counter-diffusing a surface region
- In a constant source diffusion N_a can be rather high while keeping the L_d short – an approximation of abrupt p^+n junction

Charge, Field, Potential and Bands

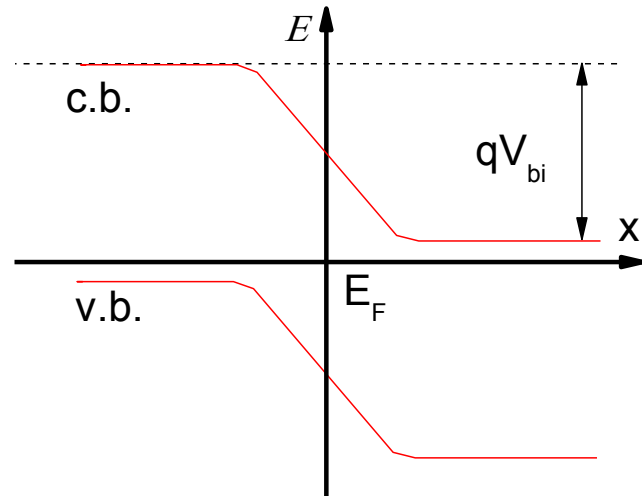
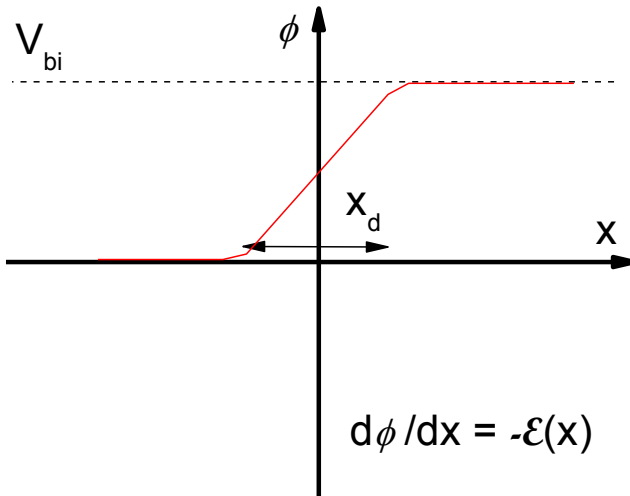
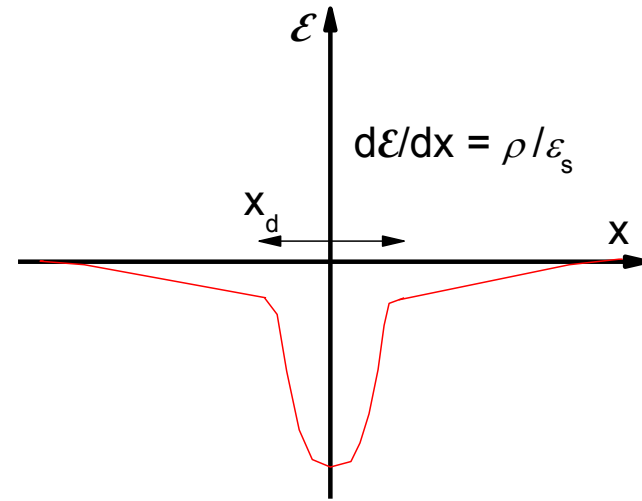
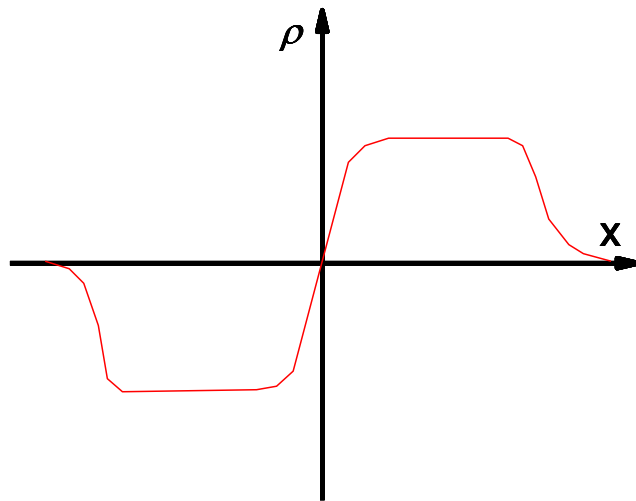


Graded Junction via Diffusion



- Can be manufactured by counter-diffusing a surface region
- In a limited source diffusion N_a can be distributed within a smoother profile with a longer diffusion length.

Charge, Field, Potential and Bands



Epitaxial Growth Si-on-Si, CVD

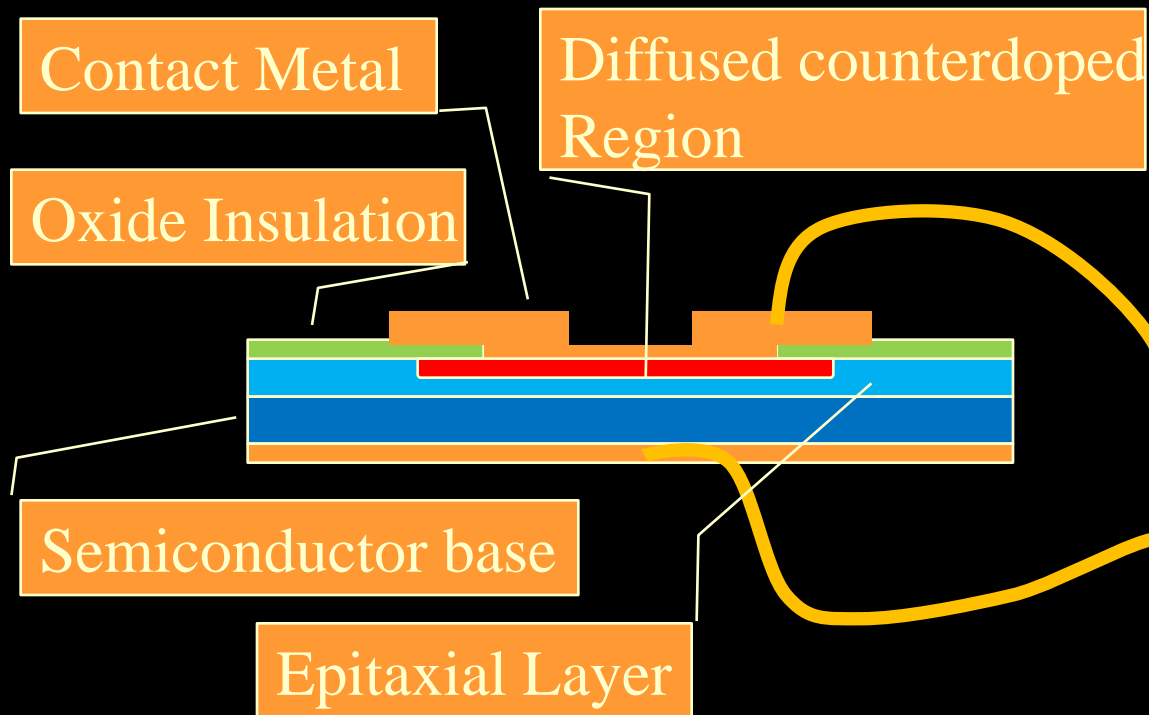
- There are a number of different methods that can achieve epitaxial growth – MBE CVD, LPE, PLD, however, the most popular for Si epilayers is the CVD (silane process).

- The *main* reactions are as follows:



- The decomposition of SiCl_4 carried by H_2 over the silicon wafers results in epilayer growth at temperatures $> 1200^\circ\text{C}$.
- Silane is rather pyrophoric – especially when mixed with nitrogen. It irritates the eyes and is rather toxic – with lethal concentrations below 1 %.
- Doping is achieved by admixing gases such as PH_3 and AsH_3 – also extremely toxic.

Epitaxial Diode



Recipe

- ...
- Grow an epilayer
- Oxidize
- Diffuse from a constant source

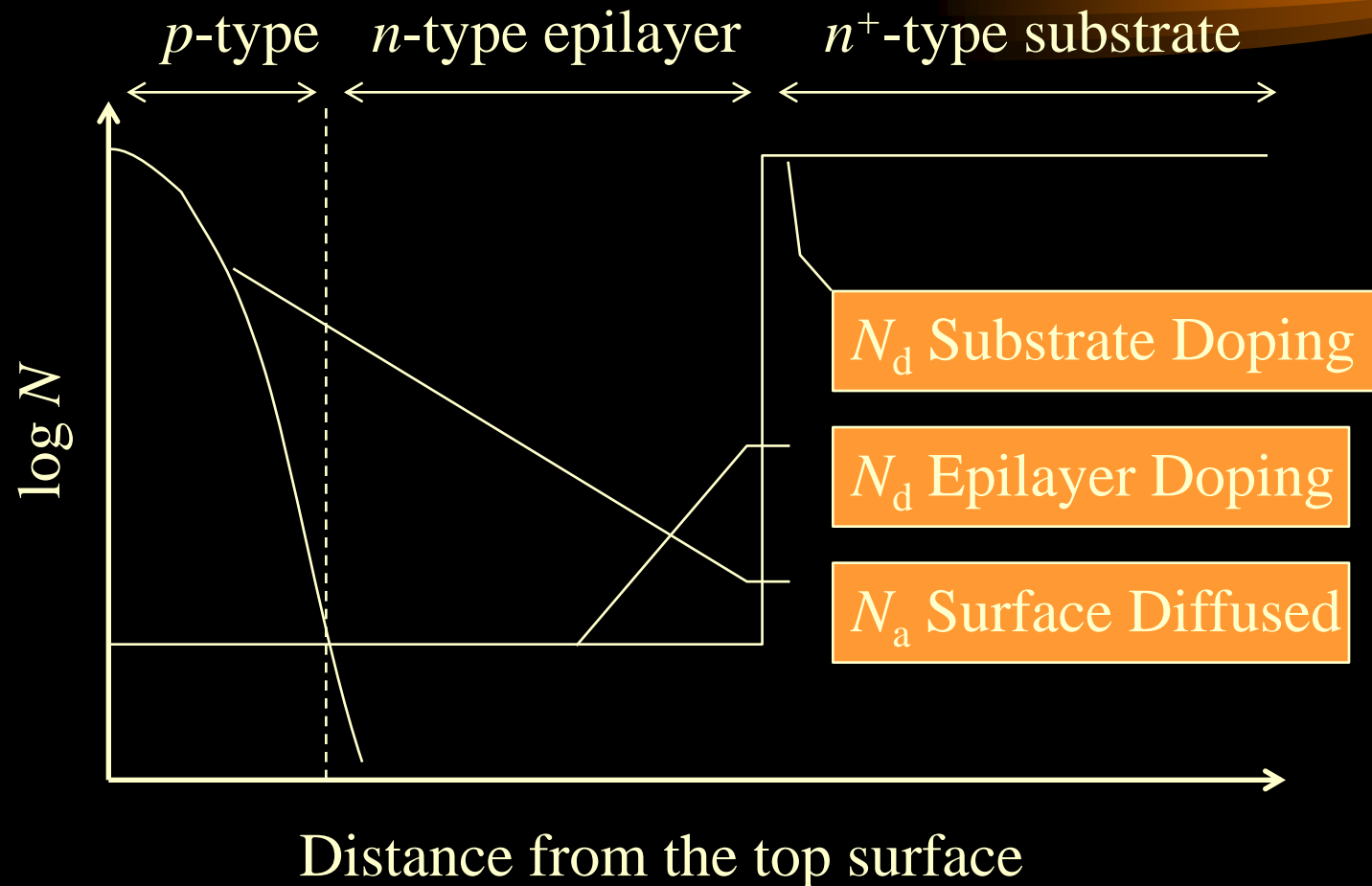
• ...

Features

- Building block
- Low series resistance
- Low forward drop
- Lower reverse bias leakage
- Minority carrier device

- Avoids the necessity for a very thin base
- The epitaxial (greek: *επιταξία*) layer needs only be several micrometer thick
- The secondary junction formed (say nn^+) is normally perfectly ohmic

Abrupt Junction in an Epilayer



- Can be readily manufactured, provided epitaxy is available
- Since the diffusion of the pn -junction is executed after the epitaxial growth – the nn^+ transition is actually rather smooth

Static, Zero-bias Considerations

Poisson's Equation

$$\frac{\partial^2 \phi(x)}{\partial x^2} = \frac{\rho(x)}{\epsilon_s} = \frac{q}{\epsilon_s} (p - n + ax)$$

Postulate of constant gradient

Parabolic dependence

$$\mathcal{E}(x) = -\frac{qa}{\epsilon_s} \frac{x_d^2 - x^2}{2}$$

Electric Field Profile

$$V_{bi} = \frac{qax_d^3}{12\epsilon_s} \simeq \frac{k_B T}{q} \ln \left(\frac{ax_d}{2n_i} \right)^2$$

Build-in Field Magnitude

Note that the power law is not the same as in the case of Schottky diodes

$$C_j = \left[\frac{qa\epsilon_s^2}{12(V_{bi} \pm V_a)} \right]^{\frac{1}{3}}$$

Associated Capacitance

Static, Biased Considerations

Quasi-equilibrium potential

$$n = n_i \exp \left[\frac{q(\psi - \phi_n)}{k_B T} \right]$$

$$p = n_i \exp \left[\frac{q(\phi_p - \psi)}{k_B T} \right]$$

Treat as definitions

$$n_i^2 \neq np$$

Remember !!!

$$\phi_n = \psi - \frac{k_B T}{q} \ln \left(\frac{n}{n_i} \right)$$

$$\phi_p = \psi + \frac{k_B T}{q} \ln \left(\frac{p}{n_i} \right)$$

The potentials for electrons and holes

$$pn = n_i^2 \exp \left[\frac{q(\phi_p - \phi_n)}{k_B T} \right]$$

pn -product under bias

Current Components

$$\mathbf{J}_n = q\mu_n \left(n\mathcal{E} + \frac{k_B T}{q} \nabla n \right) = -q\mu_n n \nabla \phi_n$$

Electrons

$$\mathbf{J}_p = -q\mu_p p \nabla \phi_p$$

Holes

$$\mu_n \mathcal{E} \frac{\partial n_n}{\partial x} + \mu_n n_n \frac{\partial \mathcal{E}}{\partial x} + D_n \frac{\partial^2 n_n}{\partial x^2} = U$$

$$-\mu_p \mathcal{E} \frac{\partial p_n}{\partial x} + \mu_p p_n \frac{\partial \mathcal{E}}{\partial x} + D_p \frac{\partial^2 p_n}{\partial x^2} = U$$

Continuity

At the edge
of the depleted
region

$$V_a = \phi_p - \phi_n$$

Applied Bias

$$n_p = \frac{n_i^2}{p_p} \exp \left(\frac{qV_a}{k_B T} \right) \Big|_{-x_p} = n_{p0} \exp \left(\frac{V_a}{V_t} \right)$$

$$p_n = p_{n0} \exp \left(\frac{V_a}{V_t} \right)$$

The same for holes

Thanks and Acknowledgements



Thank You Very Much for Your Attention!