* Semiconductors contain mobile charge carriers
  - → electrons in the conduction band
  - → holes in the valence band
  - → thermally excited e-h pairs ($n = p = n_{intr}$) for an intrinsic semiconductor
  - → asymmetric population of electron and hole carriers for an extrinsic (doped) semiconductor
  - → doping with donor atoms controls the population of electron carriers
  - → doping with acceptor atoms controls the population of hole carriers

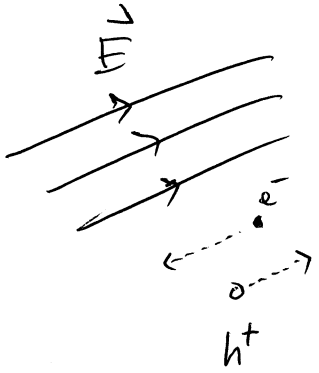
* Carriers are accelerated by an applied electric field
  - → motion is subject to scattering and dissipative processes
  - → velocity saturates; on average, there is a drift velocity

$$v_d = \mu E$$

(μ: "mobility"; E: applied field)

* mobility is a proportionality factor
  → having units $cm^2/V \cdot s$
  → dependent on temperature and impurity concentration
  → different values μ_n and μ_p for electrons and holes

* applied field sets up a current of electrons and holes
  → oppositely directed motion but constructive contributions to the net current



$$\vec{J} \sim n\vec{v}_{d,e}(-e) + p\vec{v}_{d,h}(+e)$$

$$\sim e(n\mu_n + p\mu_p)\vec{E}$$

→ resistivity is the proportionality constant between electric field and current density

$$\vec{E} = \rho\vec{J}$$

→ its reciprocal is the conductivity $\sigma = 1/\rho$:

$$\vec{J} = \sigma\vec{E}$$

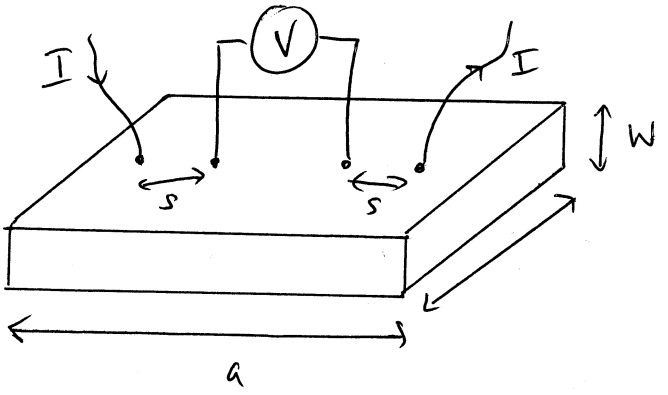
→ for semiconductors,

$$\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)}$$

→ in strongly n-type semiconductors, $n \gg p$ and hence

$$\rho \cong \frac{1}{e\mu_n n} \quad \text{or} \quad \sigma = e\mu_n n$$

* Four-point probe method to measure current



→ thin wafer with $W \ll a, d$

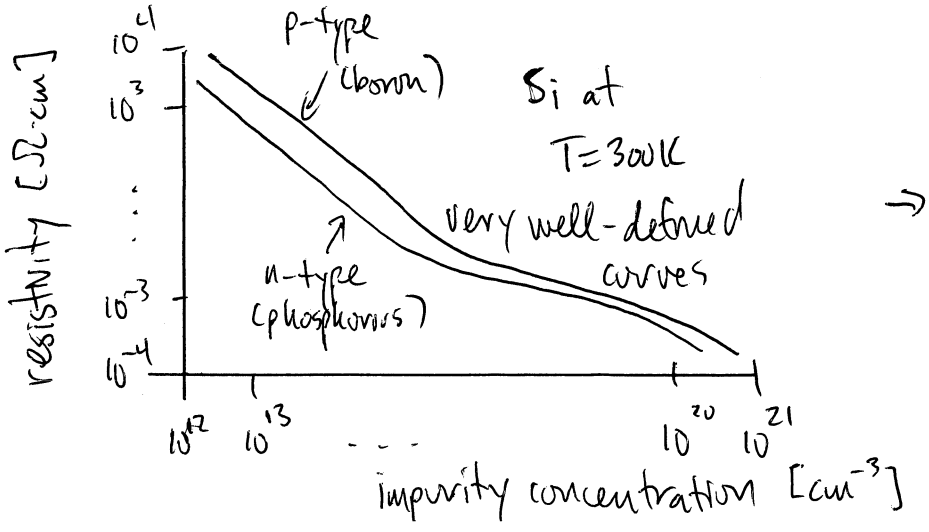
→ small constant current passed through two outer probes

→ voltage measured between two inner probes

→ sheet resistance is $R_s = \frac{V}{I} \cdot CF$

↑ upto some geometric correction factor that depends on a/d and d/s

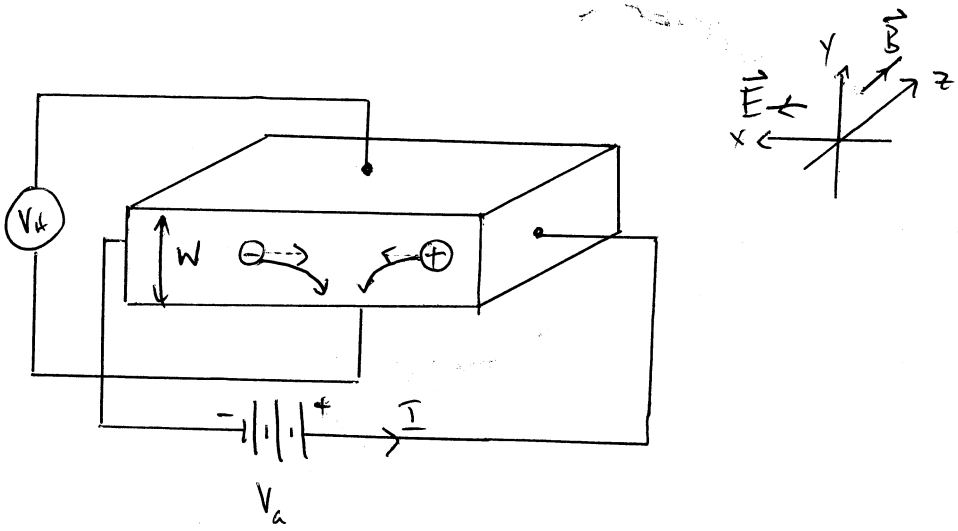
$$\left(\frac{1}{R_s} = \int_{\text{all paths}} \frac{1}{R} = \frac{1}{\rho} \int_{\text{all paths}} \frac{1}{\text{length}} \right)$$



$$CF \to \frac{\pi}{\log 2} = 4.54 \text{ as } \frac{d}{s} \to \infty$$

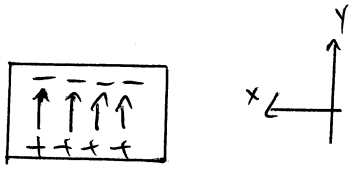
→ impurity concentration can be inferred if the resistivity is known (but not the same as carrier concentration!)

* Hall effect measures carrier concentration directly



→ applied voltage V_a sets up an x-directed electric field $\vec{E}$

→ Lorenz force $eV_x B_z$ accelerates holes in the negative y direction, so in a p-type sample holes (+ve charges) begin to pile up on the bottom edge

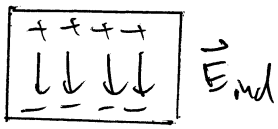


→ induces an electric field $\vec{E}_{ind}$ in the +ve y direction that exactly balances the Lorenz force

$$E_{ind} = \frac{V_y}{W} = R_H J_x B_z$$

↑ Hall resistance

→ the equivalent process occurs in n-type material but with negative charges piling up on the bottom



→ hence, the sign of the Hall resistance reveals the electron / hole nature of the carriers

→ in general,

$$R_H = r \cdot \frac{1}{e} \frac{p - b^2 n}{(p + bn)^2}$$

where $b = \mu_n / \mu_p$ and $r \equiv \langle \tau^2 \rangle / \langle \tau \rangle^2$ depends on the distribution of scattering times τ.

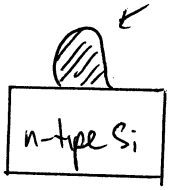
→ limits

$$R_H \sim \begin{cases} \frac{1}{p}\left(1 - b(2+b)\frac{n}{p} + O\left(\frac{n}{p}\right)^2\right) & \text{if } p \gg n \\ \frac{1}{n}\left(-1 + \frac{(1+2b)}{b^2}\frac{p}{n} + O\left(\frac{p}{n}\right)^2\right) & \text{if } n \gg p \end{cases}$$

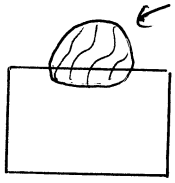
→ carrier concentration and carrier type can be obtained directly if one type dominates

* Basic fabrication technology

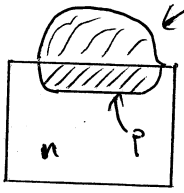
① Alloy method



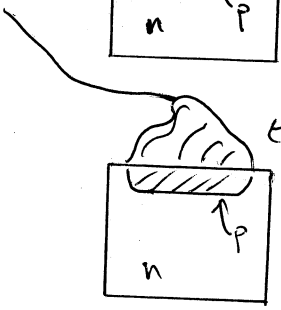
← pellet of Al placed on a <111>-oriented Si wafer
(III acceptor material)



← heat to eutectic temp (580°c for Al-Si)
small puddle of molten Al-Si mixture forms

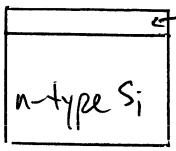


← cool so that the puddle solidifies
A recrystallized portion in the Si is now saturated with acceptor impurities

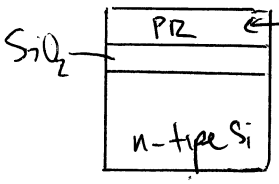


← add an ohmic contact to the Al button
rudimentary p-n junction

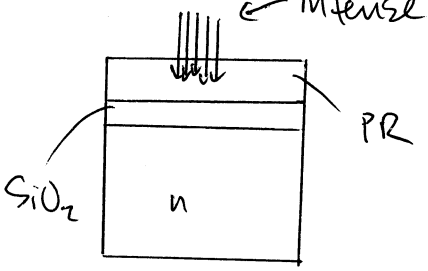
② Oxide masking



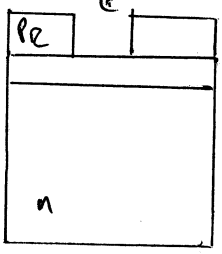
← SiO_2 insulator laid down in a thin top layer



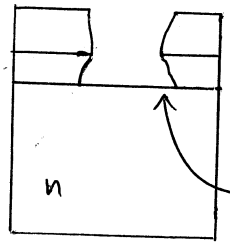
← apply a photoresist (polymethyl methacrylate PMMA, ...)
in a uniform layer by spin coating in a viscous solution and then baked to eliminate the solvent



← intense UV light (masked and focus using optical lithography techniques) causes some region of the PR to become soluble to an organic "developer" chemical

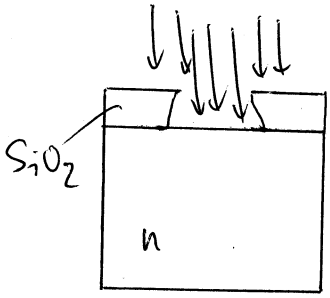


← after development, regions of the oxide layer are exposed; these can be etched out in a "wet" or "dry" process to reveal the substrate

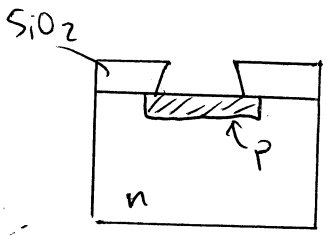


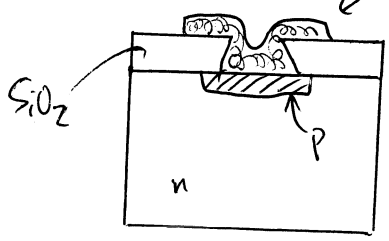
"wet" (liquid chemical agent) etching can cause undercutting, which may or may not be desirable

"dry" etching involves directed bombardment by a plasma of reactive gases



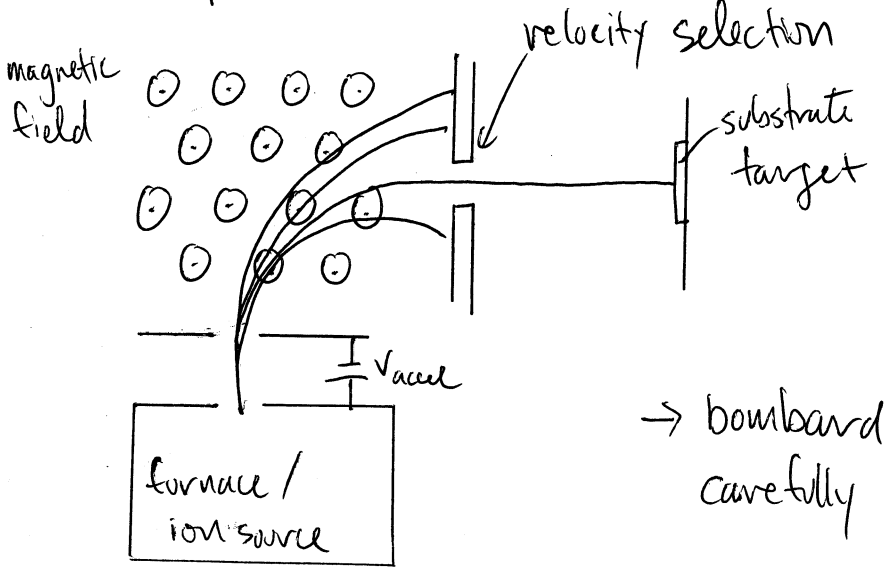
finally, remove all remaining photoresist; dope by diffusion or ion implantation





← additional deposition of metal + annealing if a contact is required

③ Ion implantation



→ beam of ions, electrostatically accelerated and then bent with a perpendicular applied field

→ bombard the substrate with a carefully calibrated "dose":

time × current = ion flux

→ energy of the beam controls the depth of implantation

< 1 keV	no penetration (ion deposition on surface)
1 – 10 keV	few nanometers
10 – 500 keV	10 nm – 1 micron
> 500 keV	structural damage to target

④ Epitaxy

→ deposition of a crystalline overlayer in registry with a crystalline substrate

→ can be grown from gas or liquid precursors, where substrate acts as a seed crystal

eg. vapour-phase growth

$$SiCl_4 + 2H_2 \rightarrow Si(solid) + 4HCl(gas)$$

proceeds at a rate ~ 1 μm/min @ 1200°C

$$Si(solid) + O_2(dry) \rightarrow SiO_2(solid)$$ slow rate

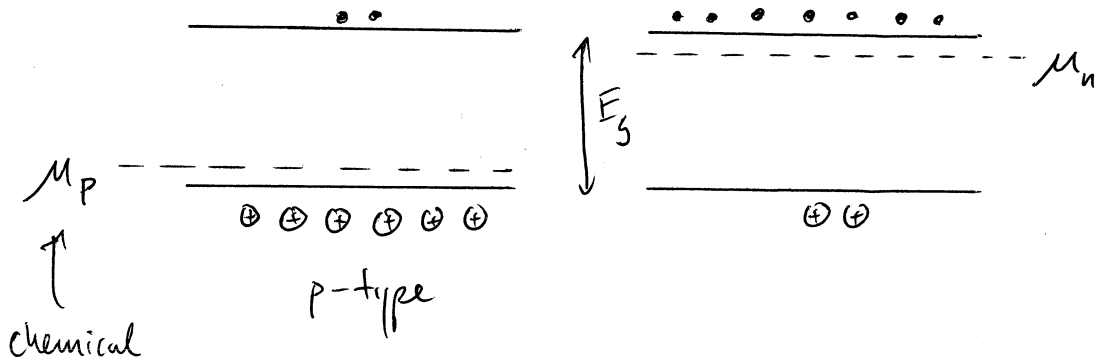
or $Si(solid) + 2H_2O(steam) \rightarrow SiO_2(solid) + 2H_2$ ~ 5-10 x faster

→ molecular beam epitaxy (MBE) requires ultrahigh vacuum and extremely slow deposition

* p-n junction

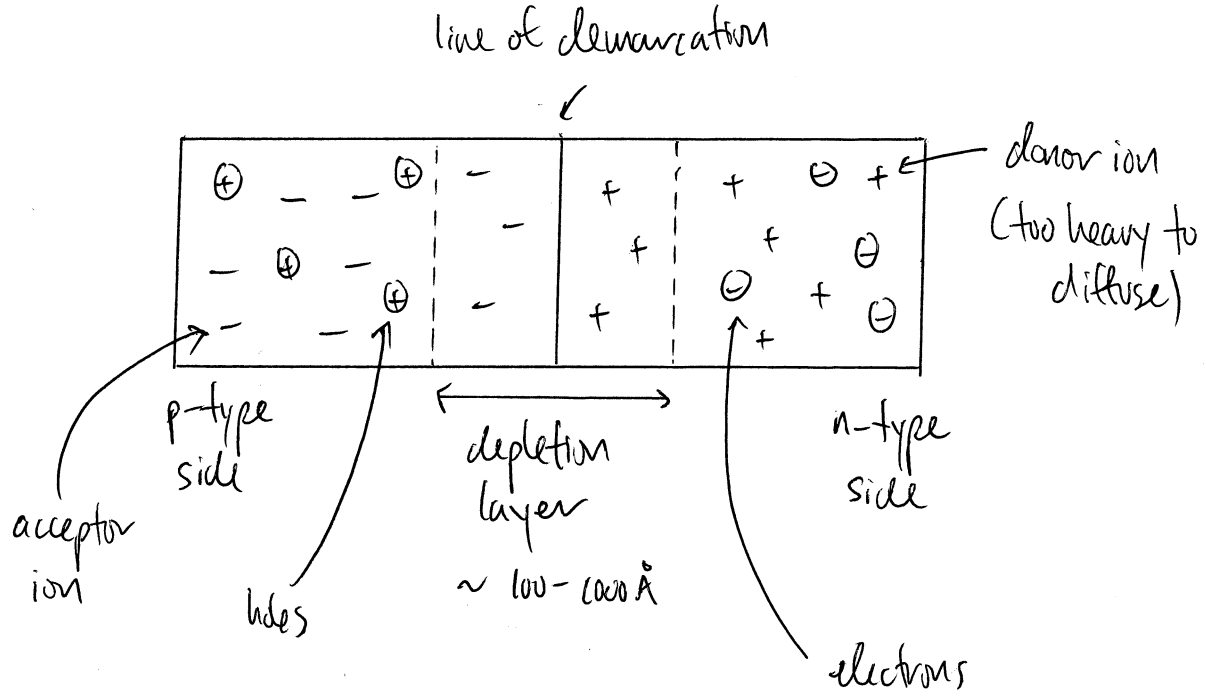
→ interface between acceptor-doped and donor-doped regions

→ must be atomically contiguous (generally not sufficient to put two cleaved crystal faces in contact)



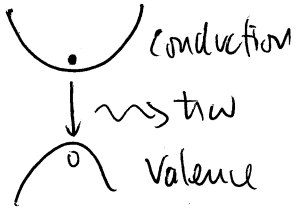
chemical potential (not the mobility!)

→ chemical potential must smoothly interpolate between the two bulk values

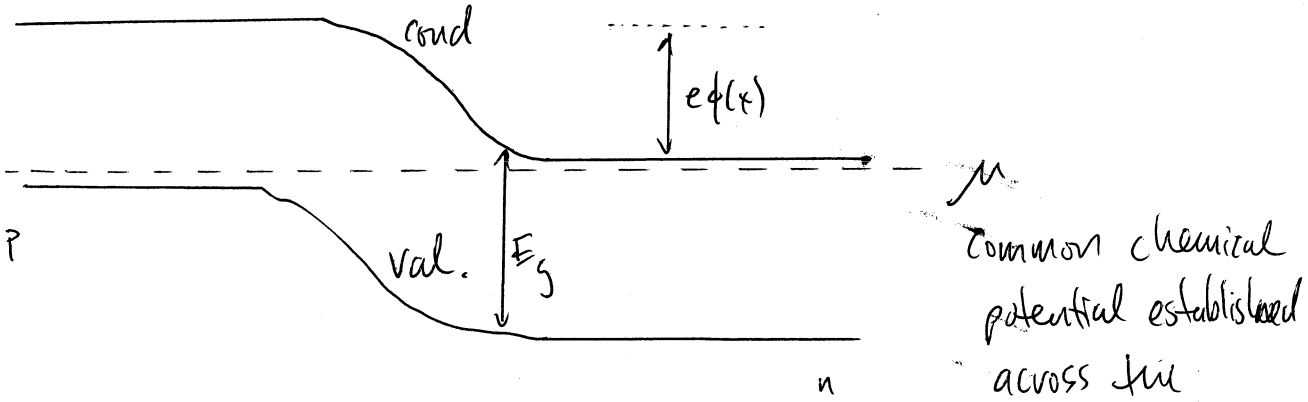


→ electrons from the n-type side diffuse into the p-type side and recombine with holes:

process of mutual annihilation



→ and vice versa: holes move into the n region and recombine with electrons



→ band bending described by the electrostatic potential $\phi(x)$

* spatial dependence is slowly varying enough that we can assume local equilibrium

→ make the replacement

$$E_c \to E_c - e\phi(x)$$

$$E_v \to E_v - e\phi(x)$$

in our usual equations

→ the carrier concentrations become position-dependent

$$n(x) = D_c e^{-\beta(E_c - e\phi(x) - \mu)} \equiv D_c e^{-\beta(E_c - \mu_e(x))}$$

$$p(x) = D_v e^{-\beta(E_v - e\phi(x) - \mu)} \equiv D_v e^{-\beta(E_v - \mu_e(x))}$$

↑ the electrochemical potential $\mu_e = \mu + e\phi$

→ must recover bulk values at the extremes $x \to \pm\infty$

$$N_D = n(\infty) \quad \text{and} \quad N_A = p(-\infty)$$

hence

$$\mu_e(\infty) - \mu_e(-\infty) \equiv e\Delta\phi = E_g + k_B T \log\left(\frac{N_D N_A}{D_c D_v}\right)$$

where $\Delta\phi = \phi(\infty) - \phi(-\infty)$

* Determine ϕ self-consistently from Poisson's equation:

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{4\pi \rho(x)}{\epsilon}$$

ϵ ↖ dielectric in the semiconductor

where the total charge density is

$$\rho(x) = N_D(x) - n(x) - N_A(x) + p(x)$$

↖ ↗ basically step functions $N_D(x) = N_D \theta(x)$

$N_A(x) = N_A \theta(-x)$

→ solutions of the form

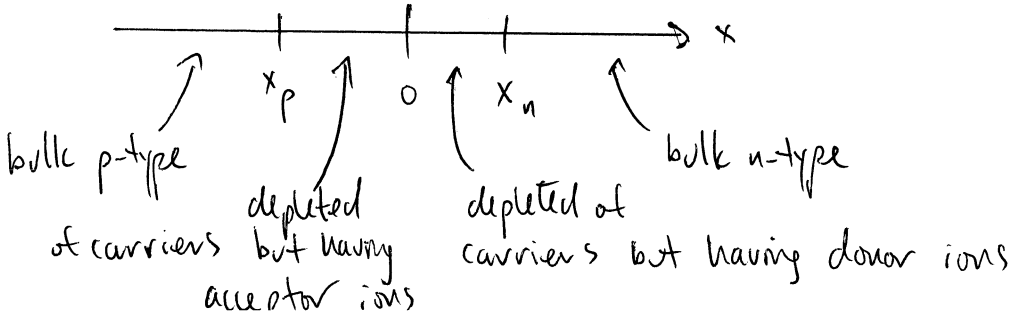
$$n(x) = N_D e^{-e\beta[\phi(\infty) - \phi(x)]}$$

$$p(x) = N_A e^{+e\beta[\phi(-\infty) - \phi(x)]}$$

with $\rho(x) \approx 0$ outside the depletion layer

and $\rho(x) = e[N_D(x) - N_A(x)]$ inside

→ defines four regions



→ $\phi''(x) = \text{const}$ gives quadratic behaviour in the depletion layer:

$$\phi(x) = \begin{cases} \phi(-\infty) & x < x_p \\ \phi(-\infty) + \left(\frac{2\pi e}{\epsilon}\right)(x - x_p)^2 & 0 > x > x_p \\ \phi(\infty) - \left(\frac{2\pi e}{\epsilon}\right)(x - x_n)^2 & 0 < x < x_n \\ \phi(\infty) & x > x_n \end{cases}$$

→ impose continuity

$$\phi(0^+) = \phi(0^-) = \phi(\infty) - \frac{2\pi N_D}{\epsilon} x_n^2 = \phi(-\infty) + \frac{2\pi N_A}{\epsilon} x_p^2$$

$$\text{or} \quad \Delta\phi = \frac{2\pi \left(N_A x_p^2 + N_D x_n^2\right)}{\epsilon}$$

→ impose smoothness

$$\phi'(0^+) = \phi'(0^-) = N_D x_n = -N_A x_p$$

hence. $$x_{n,p} = \pm \left[\frac{\epsilon \left(N_A / N_D\right)^{\pm 1} \Delta\phi}{2\pi e \left(N_A + N_D\right)} \right]^{1/2}$$