Lecture 3 - <u>Simple Heterostructures</u> - Outline

- **Energy band review**

  Energy levels in semiconductors:
  Zero reference, χ, E_g, E_c, E_v

  Homojunctions using bands - a review

- **Heterojunction band profiles**   **(the Depletion Approximation extended)**

  Abrupt junctions:
  1. Issues new to heterojunctions: $\Delta\chi$, ΔE_g, ΔE_c, ΔE_v
  2. Alignment options/types
  3. Type I heterojunctions:
     a. N-p: i. In equilibrium; ii. With applied bias
     b. P-n
     c. Iso-type: P-p, N-n

  Modulation doping:
  1. Motivation, concept
  2. Carrier concentrations

  Graded compositions:
  1. In bulk regions
  2. At heterojunctions (impact on spikes)

Energy band edge picture - review
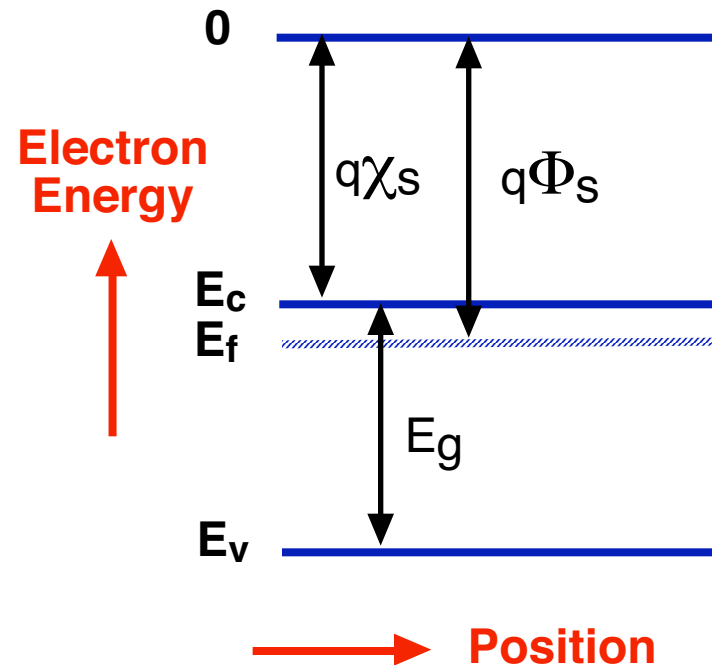
- ## Band edge energies

    The band edge energies relative to the vacuum reference level and to each other are a property of the semiconductor

    Electron affinity, χ: Conduction band edge to vacuum ref.

    Energy gap, E_g: Valence band edge to conduction band edge

    Electron Energy

    0

    $q\chi_S$ $q\Phi_S$

    E_c
    E_f

    E_g

    E_v

    Position

- ## Fermi level

    Depends additionally on the doping level

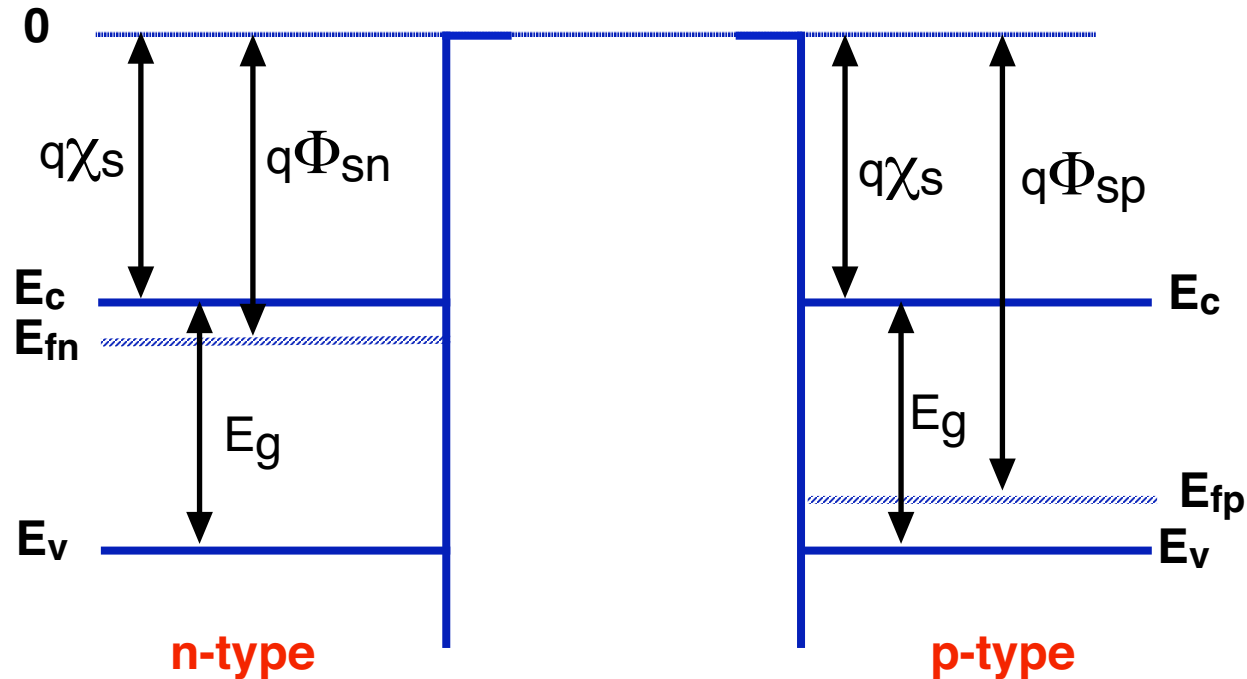 $n_o = N_c \exp[-q(E_c-E_f)/kT]$ **and thus** $E_c - E_f = (kT/q) \ln (N_c/n_o)$

    and/or

    $p_o = N_v \exp[-q(E_f-E_c)/kT]$ **and thus** $E_f - E_c = (kT/q) \ln (N_v/p_o)$

    Work function, Φ: Fermi level to vacuum ref.

<u>Homojunctions</u> - band picture, depletion approximation

- **Band picture**
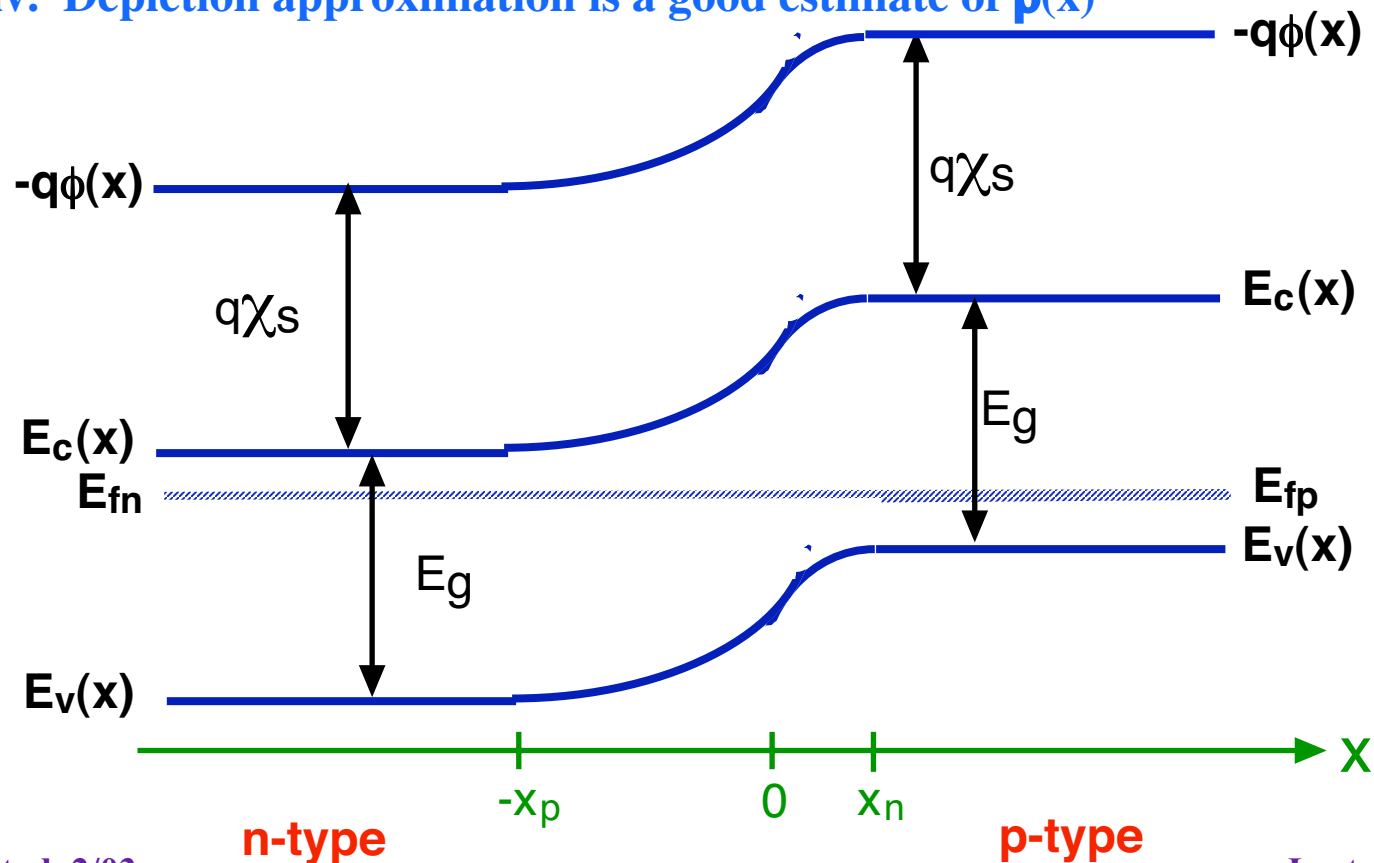 - a. <u>Isolated n- and p-type:</u>

  - i. **Have same vacuum ref.,**
  - ii. **Fermi levels differ**
  - iii. **Both materials neutral**

Homojunctions - band picture, depletion approximation

- ## Band picture, cont.
  - ### b. Electrically connected:
    - i. Charge shifts between sides
    - ii. Fermi levels shift until equal
    - iii. Vacuum ref. is now $-q\phi(x)$ where $\phi(x) = (q/\varepsilon)\iint\rho(x)\,dx\,dx$
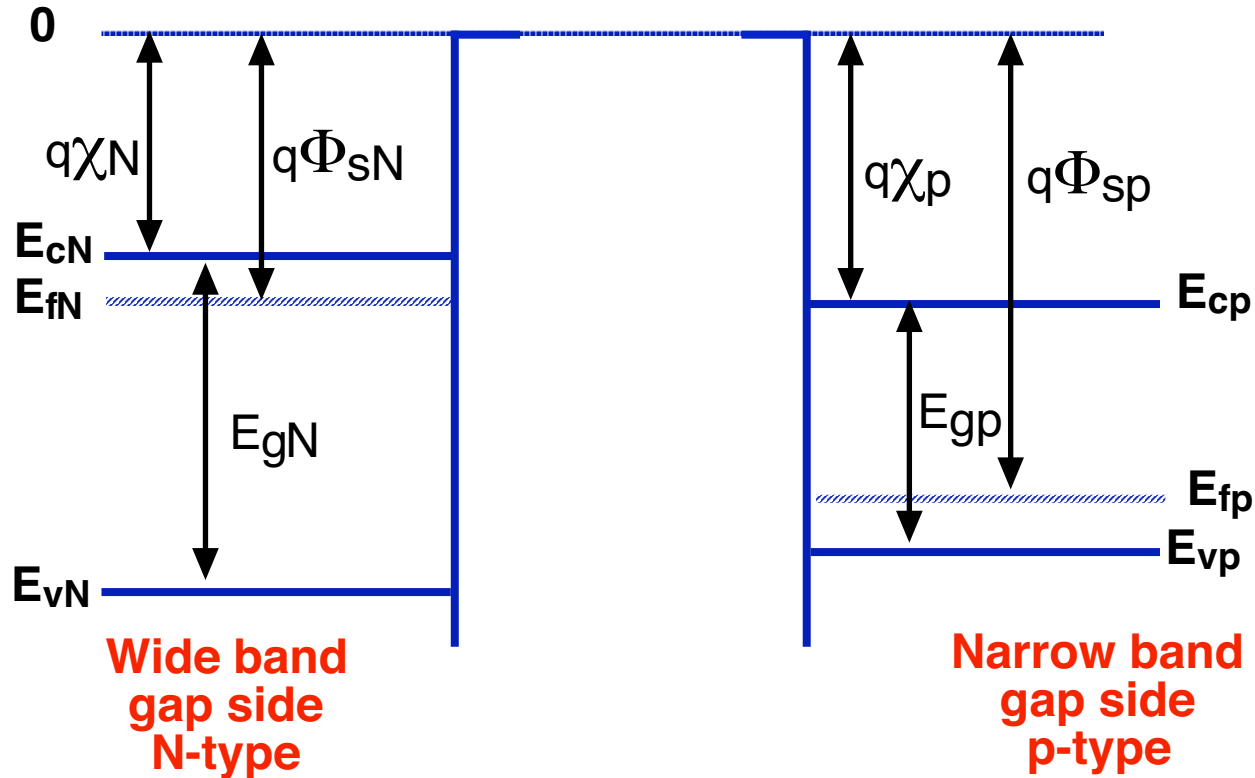   - iv. Depletion approximation is a good estimate of $\rho(x)$

Heterojunctions - band picture, depletion approximation

- **Band picture**
  - a. **Isolated N- and p-type:** (taking an N-p junction as the example)

Wide band gap side N-type
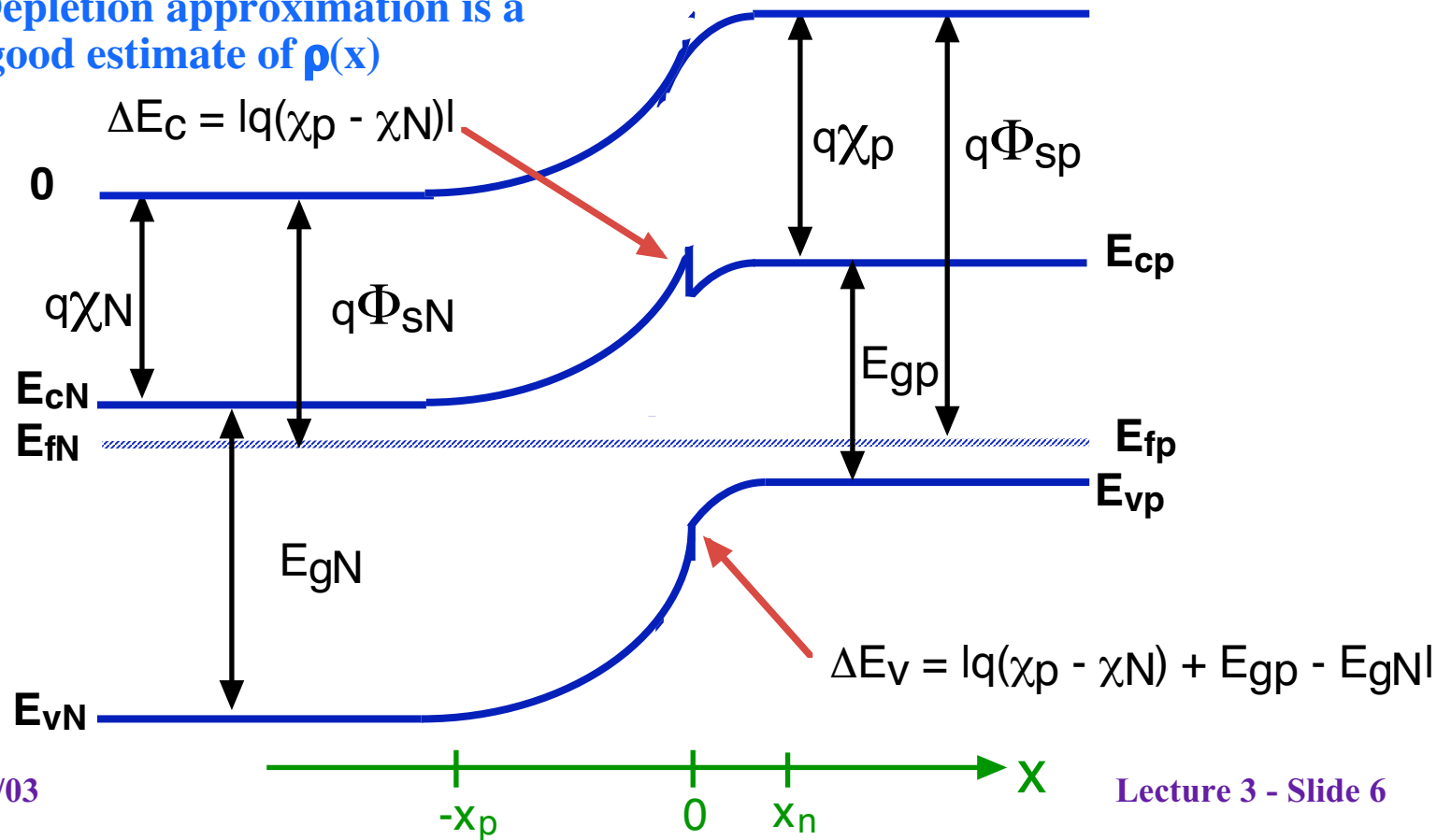
Narrow band gap side p-type

Similar to homojunction except that now the two materials have different electron affinities, energy gaps, dielectric constants, and effective masses.

Heterojunctions - band picture, depletion approximation

- ## Band picture, cont.

  b. **Electrically connected:**

  i. Charge shifts between sides

  ii. Fermi levels shift until equal

  iii. Vacuum ref. is now $-q\phi(x)$ where $\phi(x) = (q/\varepsilon)\iint\rho(x)\,dx\,dx$

  iv. $E_c(x)$ is $-q\phi(x) - \chi(x)$ and $E_v(x) = -q\phi(x) - [\chi(x) + E_g(x)]$

  v. Depletion approximation is a good estimate of $\rho(x)$

$\Delta E_C = |q(\chi_p - \chi_N)|$

$q\chi_p$ $q\Phi_{sp}$

0

$q\chi_N$ $q\Phi_{sN}$

E_{cp}

E_{gp}

$\mathbf{E_{cN}}$

$\mathbf{E_{fN}}$ E_{fp}

E_{vp}

E_{gN}

$\Delta E_V = |q(\chi_p - \chi_N) + E_{gp} - E_{gN}|$

$\mathbf{E_{vN}}$

$-x_p$ 0 x_n X

Heterojunctions - band picture, depletion approximation

- **Band picture, cont.**

    c. **Useful Observations:**

    i. **The final electrostatic potential profile, $\phi(x)$, is primarily a consequence of the doping levels.**

    ii. **The band-edge profiles, $E_c(x)$ and $E_v(x)$, are additionally a consequence of the electron affinity and energy gap profiles, $\chi(x)$ and $E_g(x)$, respectively.**

    iii. **In an abrupt heterojunction there are frequently discontinuities in the conduction and valence band edges at the junction.**