6.772/SMA5111 - Compound Semiconductors

Lecture 4 - Carrier flow in heterojunctions - Outline

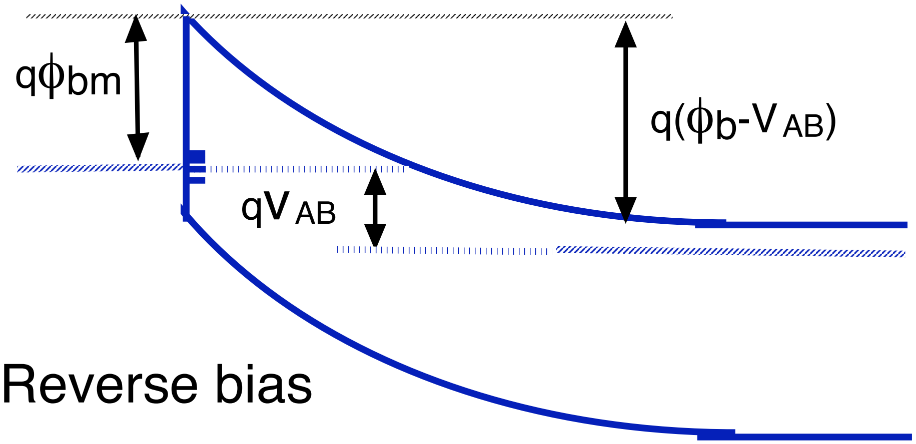
- **A look at current models for m-s junctions** (old business)
  - Thermionic emission vs. drift-diffusion vs. p-n junction
- **Conduction normal to heterojunctions** (current across HJs)
  - Current flow:
    - 1. Drift-diffusion
    - 2. Ballistic injection
  - Injection tailoring:
    - decoupling injection from doping
  - Band-edge spikes:
    - 1. Impact on conduction and evolution with bias:
      - a. Forward flow: i. Barriers to carrier flow; ii. Division of applied bias; iii. Evolution with bias
      - b. Reverse flow: i. impact on collection; ii. evolution with bias
    - 2. Elimination of spikes by composition grading (quasi-Fermi level discussion)
- **Conduction parallel to heterojunctions** (in-plane action)
  - Modulation doped structures:
    - Mobility vs. structure
  - Interface roughness

Applying bias to a metal-semiconductor junction, review

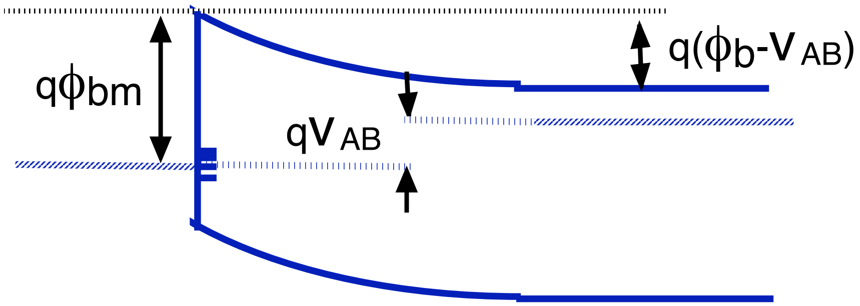
- **Currents**

Note: the barrier seen by electrons in the metal does not change with bias, whereas the barrier seen by those in the semiconductor does.

Thus the carrier flux (current) we focus on is that of majority carriers from the semiconductor flowing into the metal. Metal-semiconductor junctions are primarily majority carrier devices.



Reverse bias



Forward bias

(Minority carrier injection into the semiconductor can usually be neglected; more about this later)

M-S JUNCTION CURRENT MODELS:

General form of net barrier current: comparing models

$$i_d = A\,q\,R\,N_D\,e^{-q\phi_b/kT}\left(e^{qv_{AB}/kT}-1\right)$$

Thermionic emission model - ballistic injection over barrier

$$i_d/A = A^*T^2e^{-q\phi_{bm}/kT}\left(e^{qv_{AB}/kT}-1\right)$$

A^* : *Thermionic emission coefficient*

ϕ_{bm} : *Barrier in metal,* $= \phi_b + (kT/q)\ln(N_C/N_D)$

Substituting for ϕ_{bm} *and rearranging:*

$$i_d/A = q\,\frac{A^*T^2}{qN_C}\,N_D\,e^{-q\phi_b/kT}\left(e^{qv_{AB}/kT}-1\right)$$

from which we see $R_{TE} = A^*T^2/qN_C$

Drift-diffusion model - drift to and over barrier

$$i_d / A = q\,\mu_e\,\mathrm{E}_{pk}\,N_D e^{-q\phi_b / kT}\left(e^{qv_{AB}/kT} - 1\right)$$

where:

$$\mathrm{E}_{pk}: \quad \textit{Peak electric field}, = \mathrm{E}(0) = \sqrt{2q\left(\phi_b - v_{AB}\right)N_D / \varepsilon}$$

Comparing this to the standard form we see:

$$R_{DD} = \mu_e\,\mathrm{E}_{pk}, \quad \textit{which is the drift velocity at } x = 0!$$

Before comparing the thermionic emission and drift-diffusion expressions, we will look at the current through a p-n$^+$ junction diode.

P-n$^+$ Diode - diffusion away from the barrier

$$\frac{i_d}{A} \approx \frac{i_{de}}{A} = q\,\frac{D_e}{w_p}\,\frac{n_i^{\,2}}{N_{Ap}}\left(e^{qv_{AB}/kT} - 1\right)$$

$$\textit{The barrier at the junction is }\ \phi_b = \left(\frac{kT}{q}\right)\ln\left(\frac{N_{Dn}N_{Ap}}{n_i^{\,2}}\right)$$

$$\textit{from which we find: }\ n_i^{\,2}/N_{Ap} = N_D\, e^{-q\phi_b/kT}$$

$$\textit{and thus: }\quad \frac{i_d}{A} \approx q\,\frac{D_e}{w_p}\,N_D\, e^{-q\phi_b/kT}\left(e^{qv_{AB}/kT} - 1\right).$$

For this diode $R_{pn^+} = D_e/w_p$, *the diffusion velocity.*

Comparing the results -

Thermionic emission

$$R_{TE} = A^{*}T^{2} / qN_{C}, \textit{modeling from metal side}$$

Drift-diffusion

$$R_{DD} = \mu_{e}\,\mathrm{E}_{pk}, \ \textit{the drift velocity at } x = 0.$$

p-n^{+} diode

$$R_{p-n^{+}} = D_{e} / w_{p}, \textit{the diffusion velocity}.$$

Conduction normal to heterojunctions

Emitter efficiency expressions with and without spike, and comparison with homojunction result

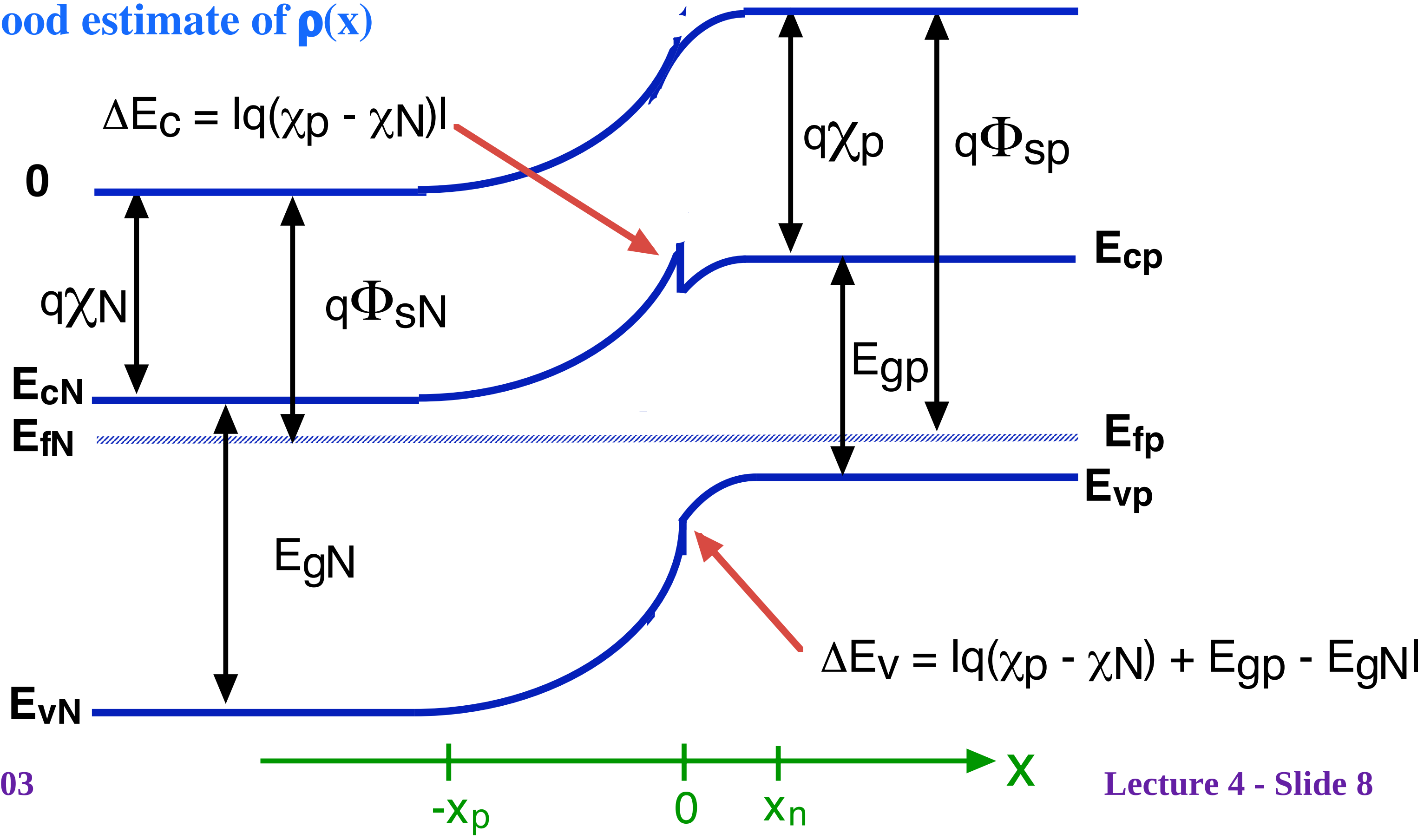
Grading composition to eliminate spikes:

WHITE BOARD

Quasi-Fermi levels and built-in effective fields due to band-edge slopes $\partial E_c/\partial x$ for electrons, $\partial E_v/\partial x$ for holes

Heterojunctions - band picture, depletion approximation

- Electrically connected:
  1. Charge shifts between sides
  2. Fermi levels shift until equal
  3. Vacuum ref. is now $-q\phi(x)$ where $\phi(x) = (q/\varepsilon)\iint \rho(x)\,dx\,dx$
  4. $E_c(x)$ is $-q\phi(x) - \chi(x)$ and $E_v(x) = -q\phi(x) - [\chi(x) + E_g(x)]$
  5. Depletion approximation is a good estimate of $\rho(x)$



Conduction parallel to heterojunctions

- Modulation doped structures
    - N-n heterojunctions and accumulated electrons
    - Modulation doped structure with surface pinning and HJ

WHITE BOARD

Back to foils

- Carrier scattering and mobilities in accumulated two-dimensional electron gas

Modulation doping - two-dimensional electron gases

- Components of mobility

GaAs

(Image deleted)

See Fig 1-9-2 in: Shur, M.S. Physics of Semiconductor Devices

Englewood Cliffs, N.J., Prentice-Hall, 1990.

Sample doping

A: 5×10^{13} cm^{-3}

B: 10^{15} cm^{-3}

C: 5×10^{15} cm^{-3}

Modulation doping - two-dimensional electron gases

- **Bulk mobilities in GaAs as a function of doping level**

  (at room temperature)

(Image deleted)
See Ch2 Fig19 in: Sze, S.M. Physics of Semiconductor Device
2nd ed. New York: Wiley, 1981.

Modulation doping - two-dimensional electron gases

- **Improvement of TEG mobility with time**

(Image deleted)

See Fig 60 in: Weisbuch, C. and Vinter, B., Quantum Semiconductor Structures: Fundamentals and Applications Boston: Academic Press, 1991.