Lecture 12 - Carrier Flow *(cont.)*

March 2, 2007

Contents:

1. Transport in space-charge and high-resistivity regions
2. Carrier multiplication and avalanche breakdown

Reading assignment:

del Alamo, Ch. 5, §5.7

Seminar:

Matthias Passlack (Freescale Semiconductor) *High Mobility III-V MOSFET Technology.* March 6, 2007, 4-5 PM (reception at 3:30 PM).

Cite as: Jesús del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

Key questions

- What characterizes space-charge-region-type situations?
- How does impact ionization affect space-charge-region type situations?

1. Transport in space-charge and high-resistivity regions

In regions with very low carrier concentrations:

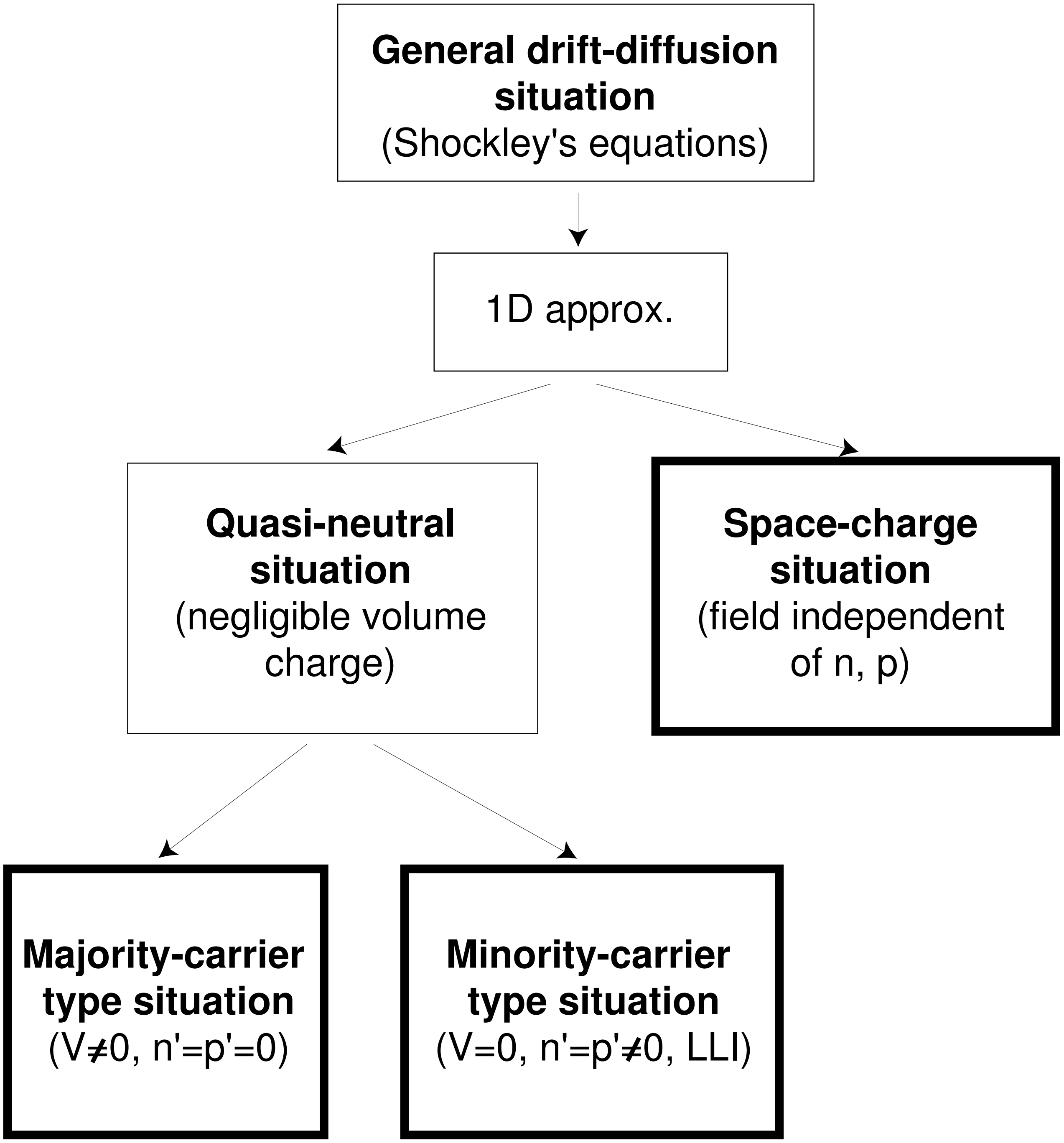
- *dielectric relaxation time long* → majority carriers take a long time to screen out charge perturbations
  i.e.: for $10^{12}\ cm^{-3}$ Si ($\rho \simeq 10^4\ \Omega \cdot cm$), $\tau_d \simeq 10\ ns$
- *Debye length long* → net charge can exist over substantial spatial extent
  i.e.: for $10^{12}\ cm^{-3}$ Si, $L_D \simeq 4\ \mu m$

Transport physics quite different from QN regions.

Key approximation: $\mathcal{E}$ *independent of* n, p:

- $\mathcal{E}$ imposed from outside (*i.e.* high resistivity region under bias), or
- $\mathcal{E}$ set by spatial distribution of dopants (*depletion region*)

Overview of simplified carrier flow formulations



General drift-diffusion situation
(Shockley's equations)

1D approx.

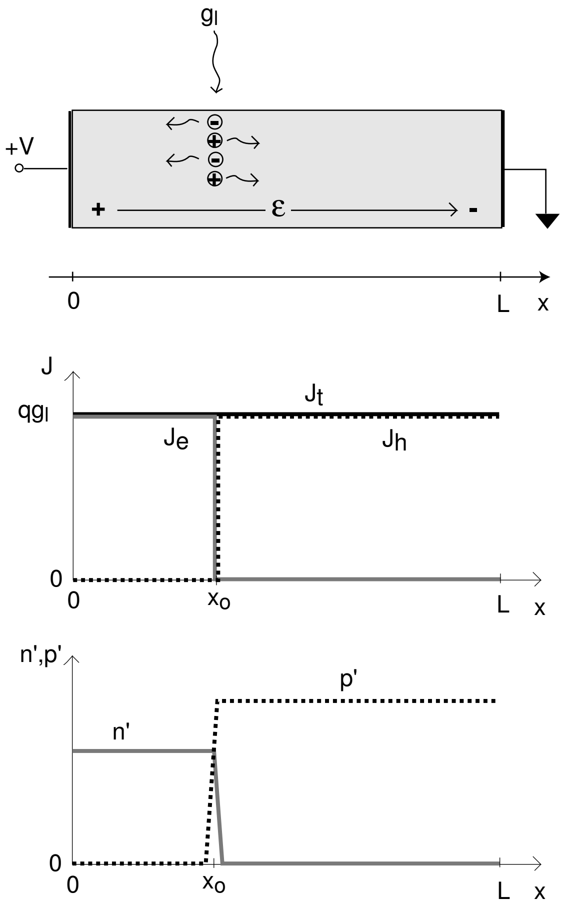
Quasi-neutral situation
(negligible volume charge)

Space-charge situation
(field independent of n, p)

Majority-carrier type situation
($V \neq 0$, $n' = p' = 0$)

Minority-carrier type situation
($V = 0$, $n' = p' \neq 0$, LLI)

Example: Drift in a high-resistivity region under external electric field



Electric field separates photogenerated carriers:

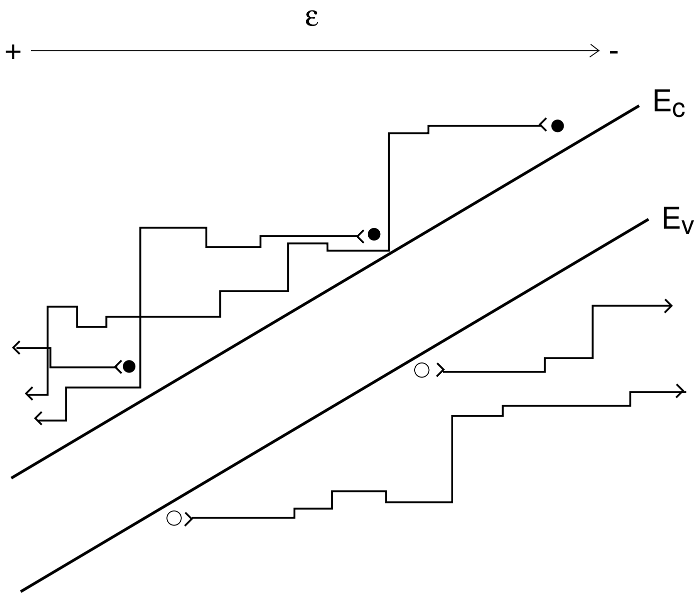
$$J_e = qg_l \qquad \text{for } x < x_o$$

$$J_h = qg_l \qquad \text{for } x > x_o$$

$$J_t = qg_l \qquad everywhere$$

3. Carrier multiplication and avalanche breakdown

If $\mathcal{E}$ high, impact ionization may take place → *carrier multiplication*



If $\mathcal{E}$ high enough, *carrier avalanche* possible → **avalanche breakdown**

- Dominant breakdown mechanism in semiconductor devices → imposes limit to maximum voltage
- Noisy

Cite as: Jesús del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

Impact ionization → new generation mechanism:

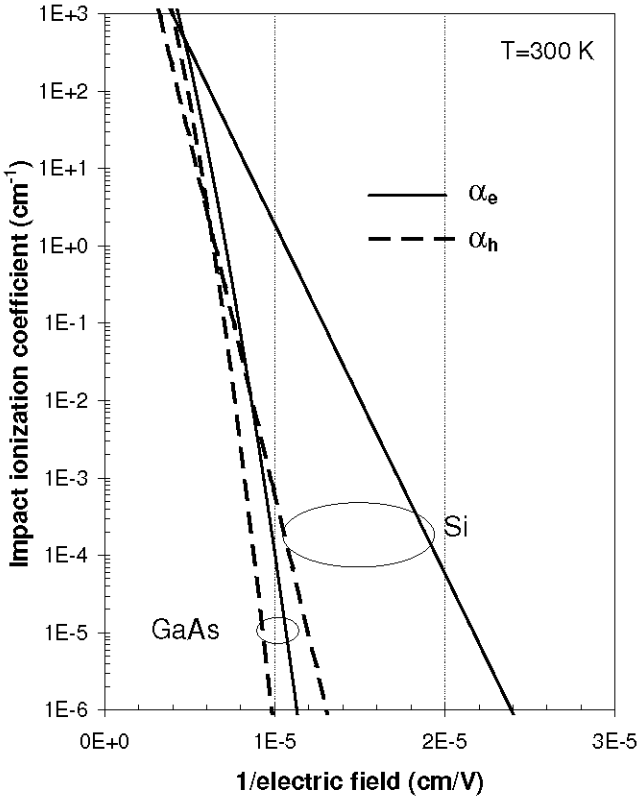
$$G_{ii} = \alpha_e |F_e(drift)| + \alpha_h |F_h(drift)|$$

$$\alpha_e \equiv electron\ impact\ ionization\ rate\ (cm^{-1})$$
$$\alpha_h \equiv hole\ impact\ ionization\ rate\ (cm^{-1})$$

$\alpha \equiv$ average number of ionizations per unit length per carrier

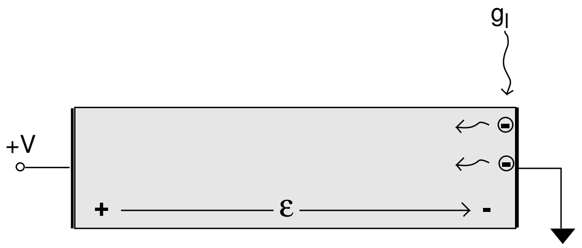
$1/\alpha \equiv$ mean distance between II events per flowing carrier

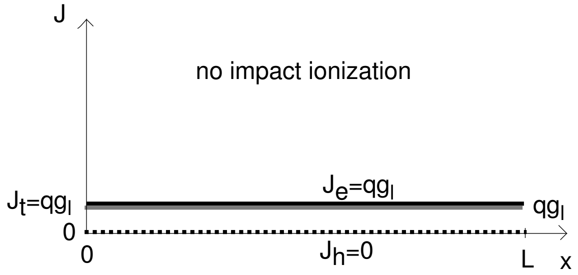
α is strongly dependent on $\mathcal{E}$:

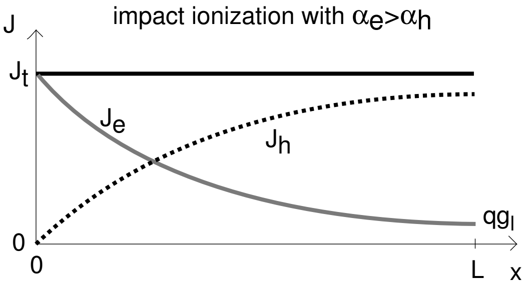


Example: carrier multiplication in a high-resistivity region with uniform electric field

High-resistivity uniformly-doped sample under $\mathcal{E}$:







$$J_t = qg_lM \geq qg_l$$

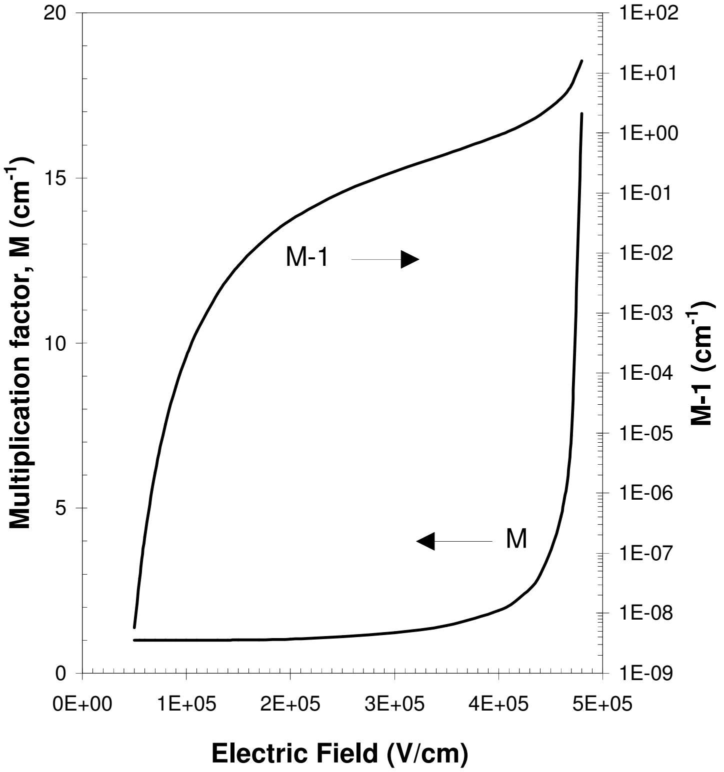
$M \equiv$ *Multiplication coefficient* [n.u.]

Two limits to M:

- if $\mathcal{E}$ small, $M \rightarrow 1$
- for high enough $\mathcal{E}$, M diverges: avalanche breakdown

Cite as: Jesús del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007.
MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].

Calculation for 1 μm long Si sample:



For example above:

- *critical breakdown field*: $\mathcal{E}_b = 4.9 \times 10^5\ V/cm$
- *Breakdown voltage*: $BV = 49\ V$

Key conclusions

- In a quasi-neutral, charge redistribution takes place in scale of *dielectric relaxation time.*
- Majority-carrier type situations can be considered quasi-static.
- Minority-carrier type situations show substantial memory.
- Time constants in minority-carrier type situations:
  - carrier lifetime
  - transit time $\propto L^2/D$
  - whichever one is smallest dominates
- SCR/high-resistivity regions:
  - electric field independent of carrier concentrations
  - behavior of electrons and holes independent of each other and of the background carrier concentrations
- Carrier multiplication can lead to avalanche breakdown at high fields → limit to maximum voltage: **breakdown voltage**.
- Order of magnitude of key parameters in Si at $300K$:
  - Dielectric relaxation time: $\tau_d < 1\ ps$ (for typical doping levels).

Self study

- Simplification of Shockley's equations for space-charge and high-resistivity regions
- Comparison between SCR and QNR transport.