Digital Integrated Circuits – EECS 312

http://robertdick.org/eecs312/

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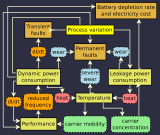
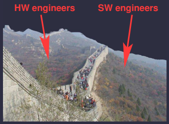
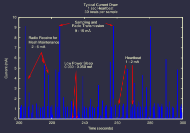
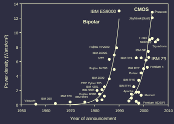


Battery depletion rate and electricity cost
Transient faults
Process variation
dI/dt
wear
Permanent faults
wear
Dynamic power consumption
severe wear
Leakage power consumption
dI/dt
reduced frequency
heat
Temperature
heat
Performance
carrier mobility
carrier concentration







Lecture plan

1. Most confusing points for the week
2. Diodes
3. Homework

Policy on confusing points

If it doesn't make sense, I will either

1. cover it in more detail right away,
2. indicate when it will be covered in detail, or
3. invite you to office hours.

Why and when does an NMOS-based consume more power than a CMOS inverter?

- If R is big, low→high output transition is slow.
- If R is slow, constant power consumption whenever input is high.

Derive and explain.

What is leakage power consumption? What is dynamic power consumption?

- Subthreshold leakage: not a perfect switch at V_t.
- Gate leakage.
- Dynamic power.

Derive and explain.

What is the difference between a source and drain?

- Source is the side the charge carriers for the MOSFET come from.
- Drain is the side to which the charge carriers go.
- Key question: *Which terminal has a higher voltage and which terminal has a lower voltage?*

Derive and explain.

Lecture plan

1. Most confusing points for the week
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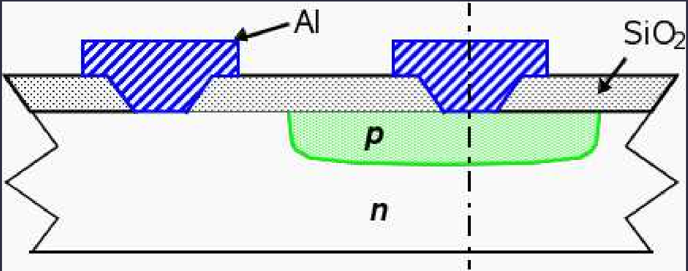
Why diodes?

- In the process of building MOSFETs, we accidentally make diodes.
    - Must understand their properties.
- What we learn about device physics here will help us understand MOSFETs in later lectures.

Diode physical structure



Step-by-step diode explanation

1. Dope regions with donors and acceptors.
2. N- and P-doped regions are in contact.
3. Diffusion according to diffusion equation.
4. Drift due to electrical field causes drift–diffusion effects to reach steady-state.
5. Left with built-in potential, and depletion region (without mobile charge carriers) near junction.
6. Reverse bias (making P voltage lower than N voltage) just makes depletion region bigger.
7. Forward bias at first reduces depletion region width, then allows mobile electrons and holes to combine at junction — sudden increase in current!
8. At extreme reverse bias, the few mobile carriers that get into the depletion region so fast that they collide with silicon atoms, generating electron-hole pairs, chain reaction fills depletion region with mobile carriers — sudden increase in current!

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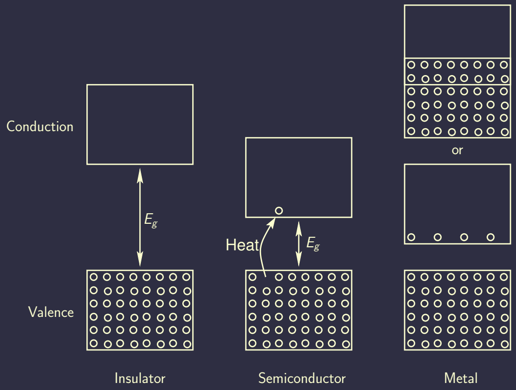
Material properties



- Electron mobility μ_n is a bit over twice that of hole μ_p.
- Units are $\frac{\text{cm}^2}{\text{Vs}}$.

Example dopants

- Example donor: As.
- Example acceptor: B.

What are the electrons and holes we have been discussing?

- We mean only electrons in the conduction band, not the valence band.
- We mean only holes in the valence band, not the conduction band.
- The conduction band is mostly empty for a semiconductor.
- The valence band is mostly full for a semiconductor.

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Diffusion equation

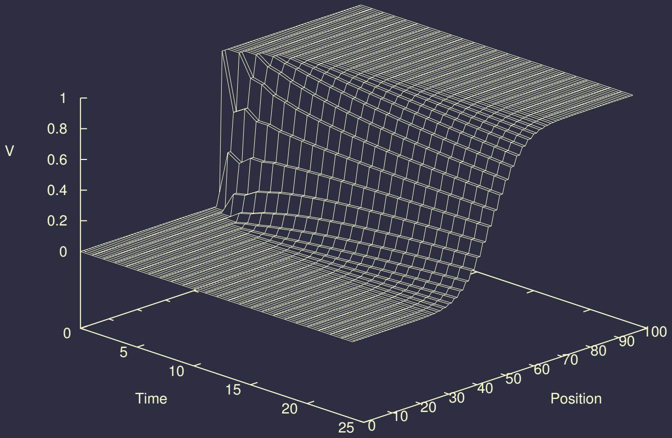
$$\frac{\partial \phi \left(\vec{r}, t\right)}{\partial t} = \nabla \cdot \left(D \left(\phi, \vec{r}\right) \nabla \phi \left(\vec{r}, t\right)\right)$$

- $\vec{r}$: location
- t: time
- $\phi(\vec{r}, t)$: density
- $D(\vec{r}, t)$: diffusion coefficient
- ∇: vector differential operator

If D is constant,

$$\frac{\partial \phi \left(\vec{r}, t\right)}{\partial t} = D \nabla^2 \phi \left(\vec{r}, t\right)$$

Diffusion example



Derive and explain.

Note: Python is awesome.

Step-by-step diode explanation

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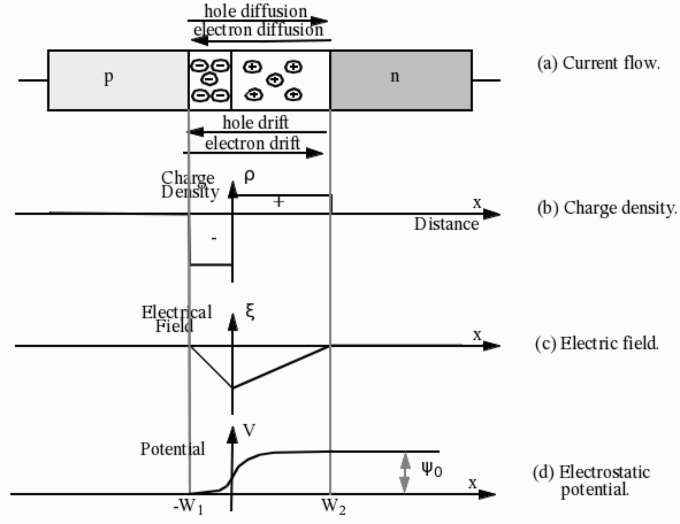
Junction depletion



Drift velocity

- The drift velocity $v_d = \mu\xi$, where μ is the mobility and ξ is the electric field.
- Net velocity must be small compared to particle random motion velocity for this to hold – more on this soon.

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Built-in potential

$$\Phi_0 = \Phi_T \ln\left[\frac{N_A N_D}{n_i^2}\right] \quad (1)$$

$$\Phi_T = \frac{kT}{q} \quad (2)$$

- n_i: intrinsic charge carrier concentration.
- N_x: acceptor and donor concentrations.
- k: Boltzmann constant
- T: temperature
- q: elementary charge

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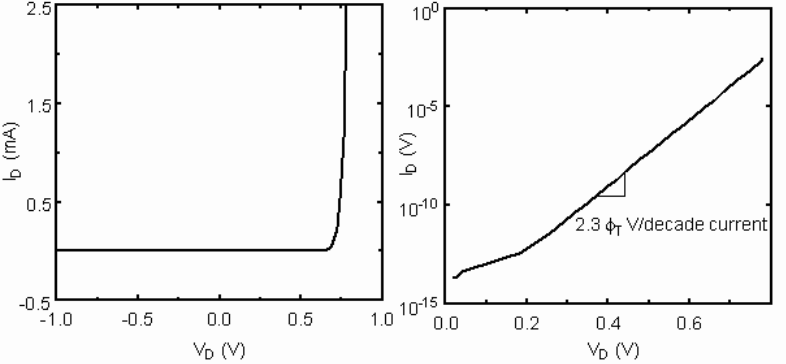
Diode operation



(a) On a linear scale.

(b) On a logarithmic scale (forward bias).

$$I_D = I_S\left(e^{V_D/\phi_T} - 1\right)$$

Diode current

$$I_D = I_S \left(e^{\frac{V_D}{\phi_T}} - 1 \right)$$

- I_D: diode current
- V_D: diode voltage
- I_S: saturation current constant
- $\phi_T = \frac{kT}{q}$: thermal voltage
  - k: Boltzmann constant
  - T: temperature
  - q: elementary charge

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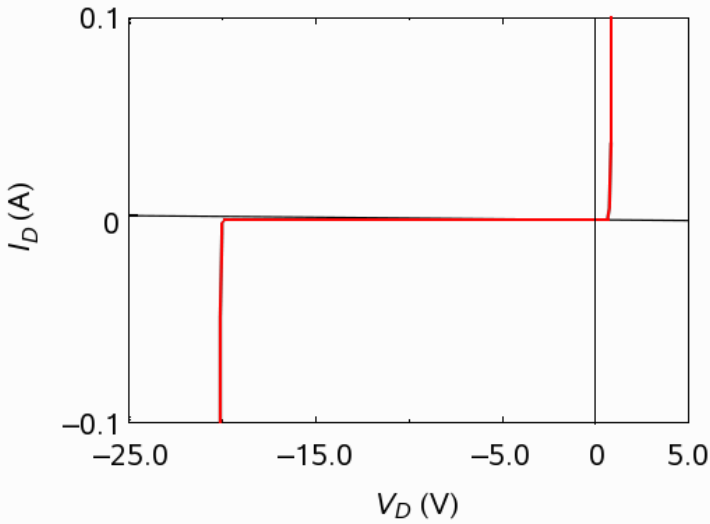
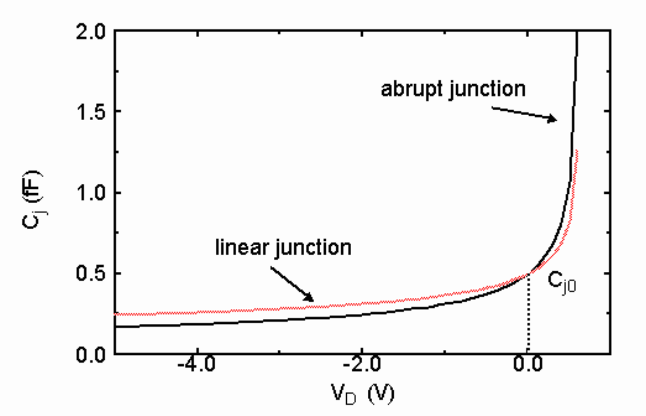
Avalanche breakdown



Diode capacitance



$$C_J = \frac{C_{J0}}{(1 - V_D/\Phi_0)^m}$$

$m = 0.5$ for abrupt junctions, $m = 0.33$ for linear junctions

Diffusion capacitance

$$C_{J0} = A_D \sqrt{\frac{\epsilon_{Si} q}{2} \frac{N_A N_D}{N_A + N_D} \frac{1}{\phi_0}}$$

- A_D: area of diode
- ϵ_{Si}: permittivity of silicon
- N_X: carrier density
- $\phi_0 = \phi_T \ln \frac{N_A N_D}{{n_i}^2}$
  - $\phi_T = \frac{kT}{q}$
  - n_i: intrinsic carrier concentration

Summary of basic device physics and diodes

- What are the electrons, holes, dopants, and acceptors we have been talking about?
- What are diffusion and drift?
- What is “built-in” potential?
- Avalanche breakdown?
- Intrinsic carriers?

Upcoming topics

- Transistor static behavior.
- Fabrication.
- Transistor dynamic behavior.
- Interconnect.

Lecture plan

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Homework assignment and announcement

- 12 September: Section 3.3.2 in J. Rabaey, A. Chandrakasan, and B. Nikolic. *Digital Integrated Circuits: A Design Perspective*. Prentice-Hall, second edition, 2003.
- 17 September: Laboratory assignment one.