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
- cover it in more detail right away,
- indicate when it will be covered in detail, or
- invite you to office hours.
Why and when does an NMOS-based consume more power than a CMOS inverter?

- If $R$ is big, $\text{low} \rightarrow \text{high}$ 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.
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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
Dop 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!
Step-by-step diode explanation

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Material properties

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

\[
\frac{\partial \phi(\vec{r}, t)}{\partial t} = \nabla \cdot (D(\phi, \vec{r}) \nabla \phi(\vec{r}, t))
\]

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

If \(D\) is constant,

\[
\frac{\partial \phi(\vec{r}, t)}{\partial t} = D \nabla^2 \phi(\vec{r}, t)
\]
Diffusion example

Derive and explain.

Note: Python is awesome.
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Junction depletion

(a) Current flow.

(b) Charge density.

(c) Electric field.

(d) Electrostatic potential.
Drift velocity

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

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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
Step-by-step diode explanation

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Diode operation

\[ I_D = I_S \left( e^{V_D/\phi T} - 1 \right) \]

(a) On a linear scale.

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

2.3 \( \phi_T \) V/decade current
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
Step-by-step diode explanation

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Most confusing points for the week

Diodes

Homework

Avalanche breakdown

![Graph showing avalanche breakdown](image-url)
Diode capacitance

\[ C_J = \frac{C_{J_0}}{(1 - V_D/\Phi_0)^m} \]

- \( m = 0.5 \) 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
- **\( \epsilon_{Si} \):** 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
Most confusing points for the week

Diodes

Homework

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.
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Homework assignment and announcement

- 17 September: Laboratory assignment one.