ECE 524 Advanced Analog IC Design

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Worcester Polytechnic Institute

Fall 2014

ECE524 Course Overview (I)

Week of	Module	Title	Reading
Sep 1	1	Semiconductor Physics Review	1.1,2
Sep 8	2	Bipolar Transistor	1.3
	3	IC manufacturing technology for BJT	2.1-7
Sep 15	4	SPICE modeling of BJT	1.4, A.2.1
	5	BJT Modeling for Amplifier Design	1.3,4
Sep 22	6	BJT Amplifiers (1 Transistor)	3.1-3
	7	BJT Amplifiers (2 Transistor)	3.4
		Quiz 1	
Sep 29	8	Differential Pair	3.5
Oct 6	9	Current Sources	4.1,2; A.4.1
	10	Active Loads	4.3
Oct 13	11	Output Stages	5.1-4
	12	Biasing	4.4
		Quiz 2	
Oct 20		OCTOBER BREAK	

ECE524 Course Overview (II)

Week of	Module	Title	Reading
Oct 27	13	Basic Op-Amp Design	6.1,2,8
Nov 3	14	Frequency response issues	7.1-5
Nov 10	15	Feedback	8.1-3
	16	Op-Amp Stability	9.1-4,6
Nov 17	17	MOSFET Op-Amp Design	1.5-9; 2.8-11; 3.3-5; 4.2,4; A.4.1; 6.3-7, 9.4,6
Quiz 3			
Nov 24	THANKSGIVING BREAK		
Dec 1	18	Fully Differential Op-amps	12.1-6
	19	Project Topics	TBD
Dec 8	20	Advanced / Optional Topics	TBD
Dec 15	21	Advanced / Optional Topics	TBD

Module 1: Semiconductor Physics Review

Topic	Reading
Bonding model, charge carriers	
Doping: p, n regions	
Fields review: E field, Capacitance	
Charge motion: Drift	
Charge motion: Diffusion	
PN junction: Equilibrium	
PN junction: Reverse Bias (capacitance)	1.1, 1.2
PN junction: Forward Bias (ideal diode equation)	

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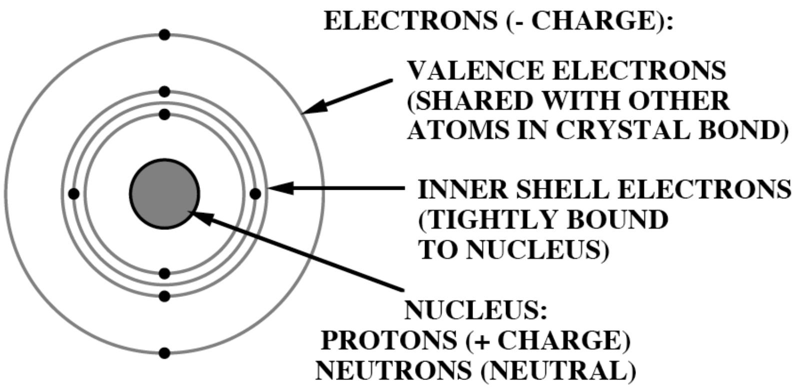
Chemistry Review

Model of atom (ridiculously oversimplified):



Periodic Table

METALS — NONMETALS

TRANSITION METALS

PERIODS	I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1 0	1.0079 H [1] 1																1.0079 H [1] 1	4.00260 He [2] 2
2 2	6.941 Li [3] 1	9.01218 Be [4] 2											10.81 B [5] 3	12.011 C [6] 4	14.0067 N [7] 5	15.9994 O [8] 6	18.9984 F [9] 7	20.179 Ne [10] 8
3 2, 8	22.9898 Na [11] 1	24.305 Mg [12] 2											26.9815 Al [13] 3	28.086 Si [14] 4	30.9738 P [15] 5	32.06 S [16] 6	35.453 Cl [17] 7	39.948 Ar [18] 8
4 2, 8	39.098 K [19] 8, 1	40.08 Ca [20] 8, 2	44.9559 Sc [21] 9, 2	47.90 Ti [22] 10, 2	50.9414 V [23] 11, 2	51.996 Cr [24] 13, 1	54.9380 Mn [25] 13, 2	55.847 Fe [26] 14, 2	58.9332 Co [27] 15, 2	58.71 Ni [28] 16, 2	63.546 Cu [29] 18, 1	65.38 Zn [30] 18, 2	69.72 Ga [31] 18, 3	72.59 Ge [32] 18, 4	74.9216 As [33] 18, 5	78.96 Se [34] 18, 6	79.904 Br [35] 18, 7	83.80 Kr [36] 18, 8
5 2, 8, 18	85.4678 Rb [37] 8, 1	87.62 Sr [38] 8, 2	88.9059 Y [39] 9, 2	91.22 Zr [40] 10, 2	92.9064 Nb [41] 12, 1	95.94 Mo [42] 13, 1	98.9062 Tc [43] 14, 1	101.07 Ru [44] 15, 1	102.9055 Rh [45] 16, 1	106.4 Pd [46] 18	107.868 Ag [47] 18, 1	112.40 Cd [48] 18, 2	114.82 In [49] 18, 3	118.69 Sn [50] 18, 4	121.75 Sb [51] 18, 5	127.60 Te [52] 18, 6	126.9045 I [53] 18, 7	131.30 Xe [54] 18, 8
6 2, 8, 18	132.9054 Cs [55] 18, 8, 1	137.34 Ba [56] 18, 8, 2	[57-71] *	178.49 Hf [72] 32, 10, 2	180.9479 Ta [73] 32, 11, 2	183.85 W [74] 32, 12, 2	186.2 Re [75] 32, 13, 2	190.2 Os [76] 32, 14, 2	192.22 Ir [77] 32, 15, 2	195.09 Pt [78] 32, 17, 1	196.9665 Au [79] 32, 18, 1	200.59 Hg [80] 32, 18, 2	204.37 Tl [81] 32, 18, 3	207.2 Pb [82] 32, 18, 4	208.9804 Bi [83] 32, 18, 5	(210) Po [84] 32, 18, 6	(210) At [85] 32, 18, 7	(222) Rn [86] 32, 18, 8
7 2,8,18,32	(223) Fr [87] 18, 8, 1	(226.0254 Ra [88] 18, 8, 2	(89-103) †	[104] 32, 10, 2	[105] 32, 11, 2	[106]	[107]	[108]										

* LANTHANIDE SERIES	138.9055 La [57] 18, 9, 2	140.12 Ce [58] 20, 8, 2	140.9077 Pr [59] 21, 8, 2	144.24 Nd [60] 22, 8, 2	(145) Pm [61] 23, 8, 2	150.4 Sm [62] 24, 8, 2	151.96 Eu [63] 25, 8, 2	157.25 Gd [64] 25, 9, 2	158.9254 Tb [65] 27, 8, 2	162.50 Dy [66] 28, 8, 2	164.9304 Ho [67] 29, 8, 2	167.26 Er [68] 30, 8, 2	168.9342 Tm [69] 31, 8, 2	173.04 Yb [70] 32, 8, 2	174.97 Lu [71] 32, 9, 2
† ACTINIDE SERIES	(227) Ac [89] 18, 9, 2	232.0381 Th [90] 18, 10, 2	231.0359 Pa [91] 20, 9, 2	238.029 U [92] 21, 9, 2	237.0482 Np [93] 23, 8, 2	(242) Pu [94] 24, 8, 2	(243) Am [95] 25, 8, 2	(245) Cm [96] 25, 9, 2	(245) Bk [97] 26, 9, 2	(248) Cf [98] 28, 8, 2	(253) Es [99] 29, 8, 2	(254) Fm [100] 30, 8, 2	(256) Md [101] 31, 8, 2	(253) No [102] 32, 8, 2	(257) Lr [103] 32, 9, 2

Source: General Chemistry, ISBN 0-669-63362-3

Types of Materials

Conductor

- Each atom: One or more valence e- not used in bond
- "Sea of electrons"
- Small applied V $\Rightarrow$ Lots of charge moving $\Rightarrow$ Large I $\Rightarrow$ Low resistance

Insulator

- All valence e- tightly bound
- Applied V $\Rightarrow$Little charge moving $\Rightarrow$ Small I $\Rightarrow$High resistance

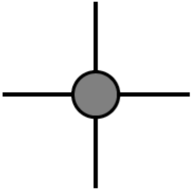
Semiconductor

- "In between"

Bonding Model

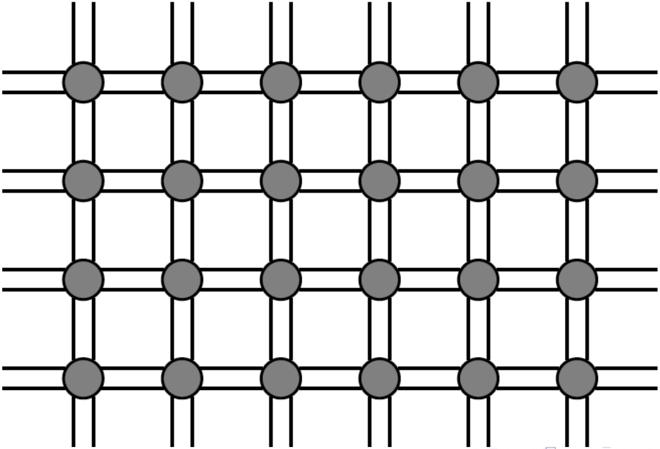
- **Lines represent valence electrons**
- **Silicon**

  4 valence electrons

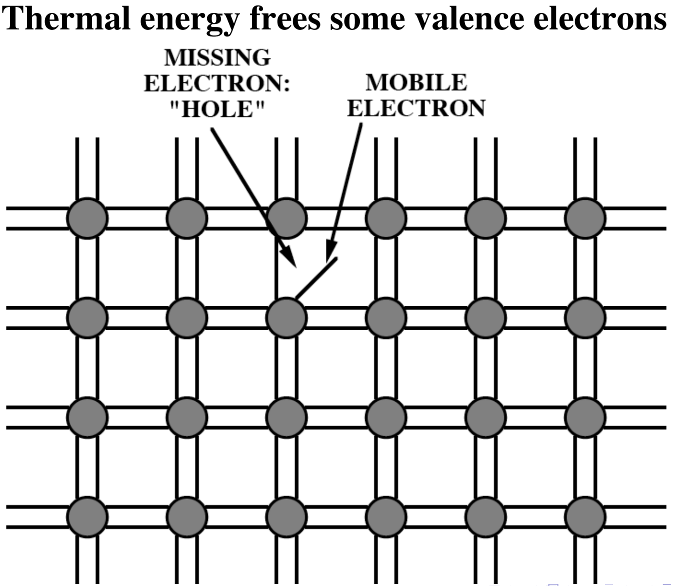


"Intrinsic" (pure) Silicon, T=0 K (Absolute zero)

All valence electrons tightly bound



“Intrinsic” (pure) Silicon, T=300 K (Room temperature)



Charge carriers in semiconductor

- Electrons
  - Mobile electrons not in covalent bond
  - Concentration symbol: n carrier/cm^3
- Holes
  - Absence of an electron in valence band
  - Behaves like a mobile positive charge
  - Concentration symbol: p carrier/cm^3

Intrinsic semiconductor: $n = p$

- Pure material: hole, electron concentrations must be equal
- Mobile electrons, holes created in pairs
- Relatively poor conductor

Intrinsic carrier concentration

- Symbol: n_i carrier/cm^3
- Different for different semiconductors
- Silicon at T=300 K : n_i 1.0E+10 carrier/cm^3
- STRONGLY Temperature dependent!

Summary: Bonding model, charge carriers

- Charge carriers in semiconductor
  - Electrons n
  - Holes p
  - Concentration units: carriers / cm^3
  - Charge equal to electron charge $\pm q_e = 1.6\text{E-}19$ coul
- Intrinsic (pure) semiconductor
  - Hole, electron concentrations equal
  - $n = p = n_i$
- n_i STRONGLY Temperature dependent!

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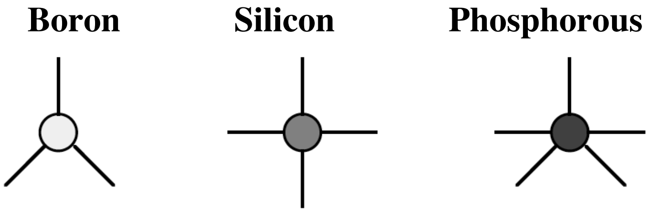
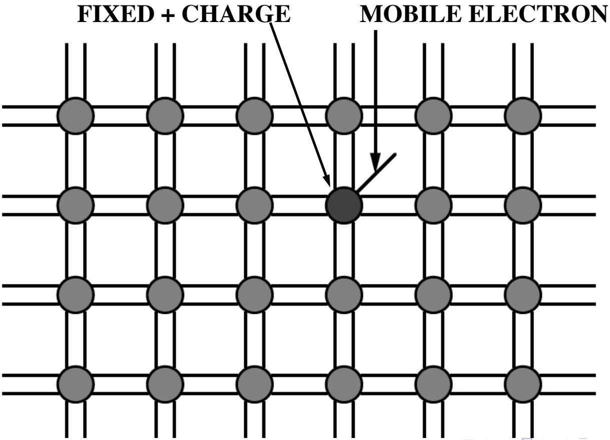
Doping

- Problem: Equal number of holes, electrons $n = p$ is boring
- "Doping": Intentional introduction of impurity atoms
- Purpose: Unbalance number of holes electrons $n \neq p$
- Use atoms from adjacent columns in periodic table



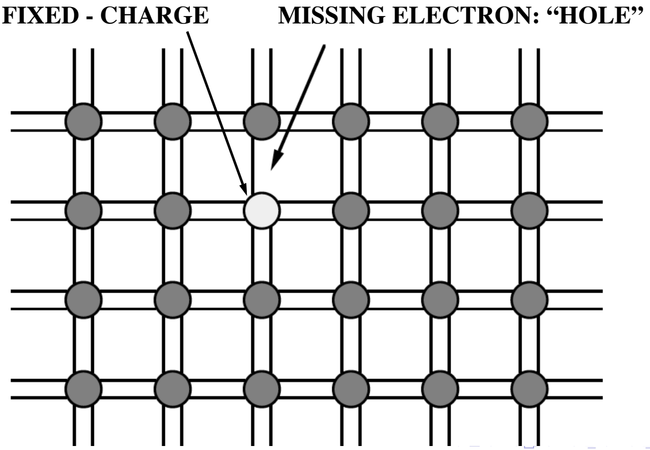
"Donor" impurity (Example: Phosphorous)

- **Donates extra electron: mobile**
- **Also extra proton: Fixed +positive charge**
- **More mobile negative charges: n-type**



"Acceptor" impurity (Example: Boron)

- **Vacancy ("hole") that can accept an electron**
- **Also missing proton: Fixed negative charge**
- **More mobile positive charges: p-type**



Terminology

Dopant atom concentration

- Donor: N_D atoms/cm^3
- Acceptor: N_A atoms/cm^3

CAUTION!

- Entire semiconductor is electrically neutral
- Donor: Extra proton in nucleus relative to Si
- Acceptor: Missing proton in nucleus relative to Si
- Only *mobile* charge is unbalanced

"Majority carrier concentration"

- Assumption: Each dopant atom contributes one mobile carrier
- Donor doped: Electrons are majority carrier
  $n = N_D$
- Acceptor doped: Holes are majority carrier
  $p = N_A$
- Typical doping densities 1.0E+15 to 1E+22 atom/cm^3
  Much greater than n_i, "swamp out" intrinsic concentration
- NOTE: N_A, N_D NOT temperature dependent! Determined by introduction of impurity atoms in manufacturing process, then fixed over time.

What about concentration of "other" carrier?

Minority carrier concentration

Example: Donor doped region of semiconductor

- Donor: N_D atoms/cm^3
- Increases mobile electron concentration: $n \Uparrow$
- Some of extra mobile electrons "fill in" holes
- "Recombination"
- Decreases mobile hole concentration: $p \Downarrow$

"np product relationship": $np = n_i^2$

- For semiconductor at equilibrium
- (Other conditions apply; see ECE4904 / ECE569A,B)

Since $n = N_D$, applying $np = n_i^2$ gives

Example

Example: $N_D = 1.0E{+}15$ atom/cm^3; what are n, p?

Summary: Doping

- Intentionally unbalance n, p
- Donor: extra electron in valence band
- Acceptor: missing electron in valence band
- Majority carrier concentration
  Determined by doping
  NOT temperature dependent
- Minority carrier concentration
  Determined by np product relationship: $np = n_i^2$
  Temperature dependent through n_i

Dopant Type	Concen-tration	Type of Region	Mobile e^- concentration n	Mobile hole concentration p
Donors				
Acceptors				

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What is the Electric Field anyway?

- Vector
- Tells you force on a charge: $\overrightarrow{F} = Q\overrightarrow{E}$
- Direction positive charge would move
- Points from + to - charge
- Keep track of charge conservation:
  Every field line
  starts on a + and must end on a -
- Related to voltage: units [V/cm]

  $$E = -dV/dx$$

- Related to charge: Poisson's Equation (1-D)

  $$\frac{dE}{dx} = \frac{\rho}{\epsilon}$$

Poisson's Equation and Capacitance

Discretize $\frac{dE}{dx} = \frac{\rho}{\epsilon}$

Summary: Electric Field, Capacitance

E field

- Tells you direction positive charge would move
- Points from + to - charge
- Related to voltage: units [V/cm]
  $E = -dV/dx$
- Integral relationship:
- Related to charge: Poisson's Equation (1-D)
  $\frac{dE}{dx} = \frac{\rho}{\epsilon}$
- Integral relationship:

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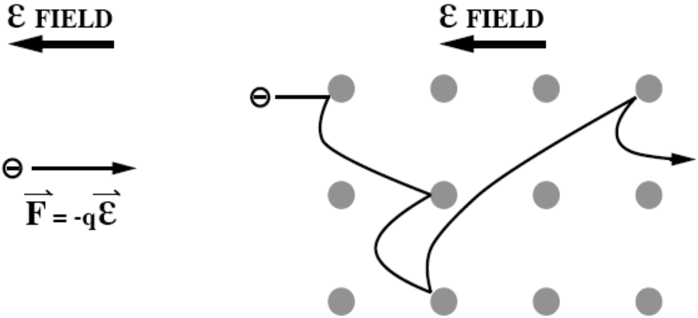
Drift: Motion of charge carriers due to electric field

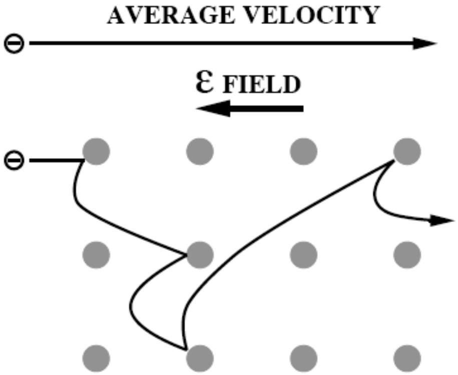
Free Space

Semiconductor Lattice

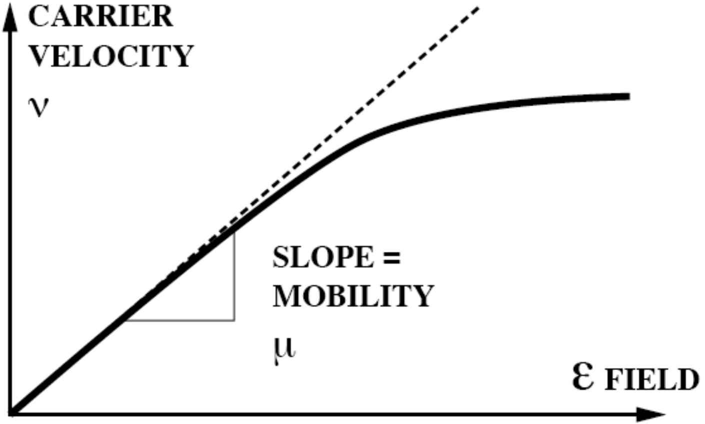


Mobility μ

Velocity with collisions "averaged out"



Mobility μ: Units, typical values

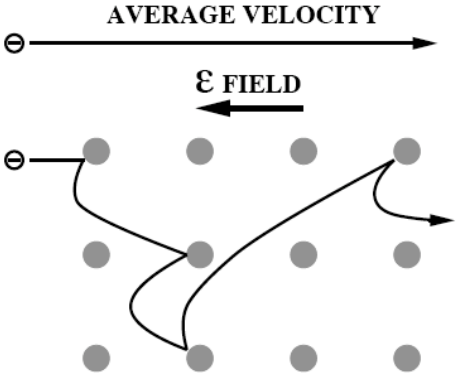


Terminology / Material Parameters

- Mean free time τ_m
  Average time between collisions
- Mean free path x_m
  Average distance between collisions
- Thermal velocity $v_t = \frac{x_m}{\tau_m}$
  Average velocity due to random thermal motion
- Thermal equilibrium
  Average energy in each independent mode of energy stoarge $= kT/2$
  - k Boltzmann's constant: 1.38E-23 J/K
  - T Absolute temperature in Kelvins
- m^* Carrier effective mass

Relating Mobility μ to Material Parameters

Velocity with collisions "averaged out"



Mobility: Typical values

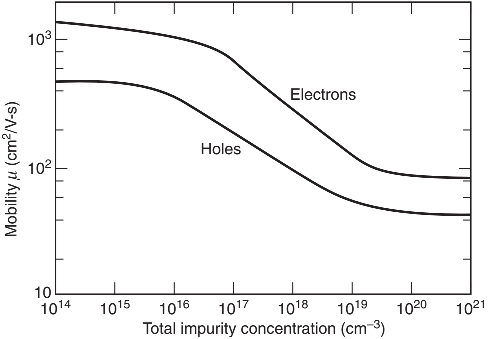


Figure 2.1 Hole and electron mobility as a function of doping in silicon.[3]

Summary: Mobility

- For charge carriers in a material
- Micro level:
  Random thermal collisions
  Carrier accelerated by field between collisions
- Macro level:
  Average velocity due to electric field
- Mobility μ [$\mathrm{cm}^2/V \cdot sec$]
- Drift velocity $v = \mu E$

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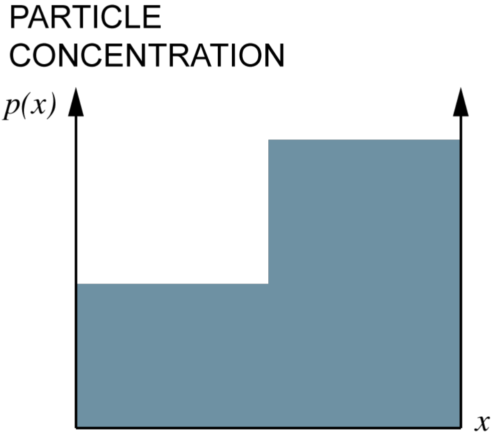
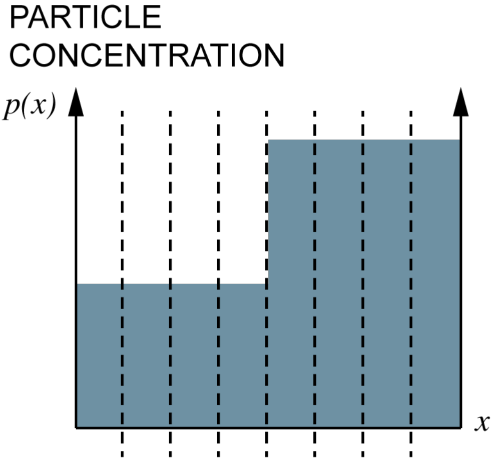
Diffusion: Net motion of particles due to concentration gradient



Terminology / Material Parameters

- Diffusion coefficient D

Diffusion: Net motion of particles due to concentration gradient



Summary: Diffusion

- For any particles (charged or not)
- Micro level:
  Random thermal collisions
- Macro level:
  Random motion smooths out concentration gradient
  Effect of diffusion is a net flow of particles opposite to gradient
- Diffusion coefficient D [cm^2/sec]
- Particle flow per unit cross sectional area

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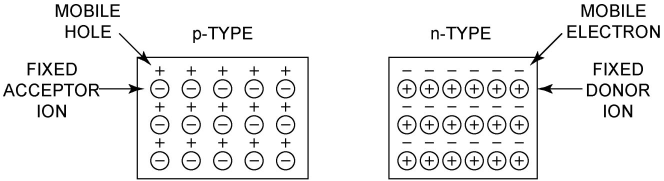
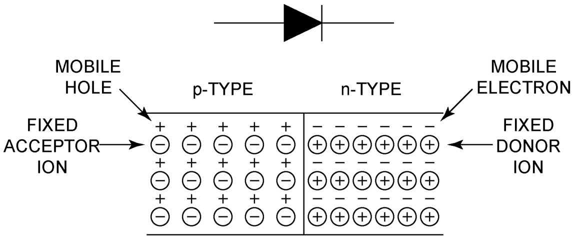
PN Junction

Thought experiment:
Take isolated p-type, n-type regions and bring together



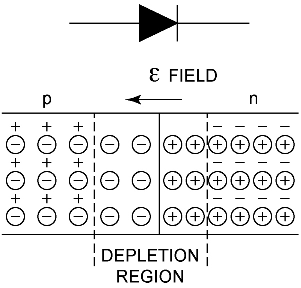
PN Junction

Applied voltage $V_A = 0$ at time t=0.



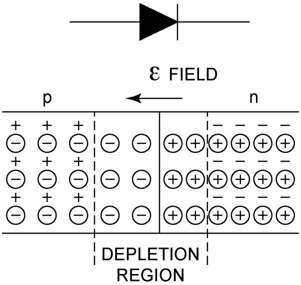
PN Junction

Applied voltage $V_A = 0$ equilibrium as time $t \to \infty$



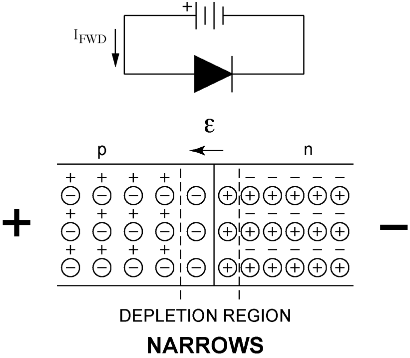
PN Junction Current Components

Carrier motion: drift and diffusion for both holes and electrons



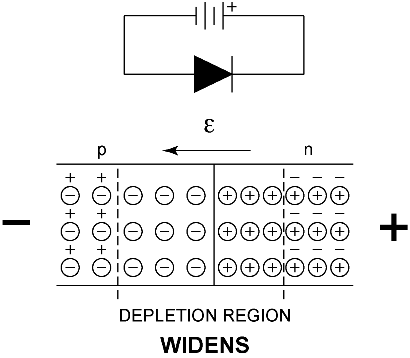
PN Junction Forward Bias (preview)

$V_A > 0$ Applied V_A "overpowers" internal E field

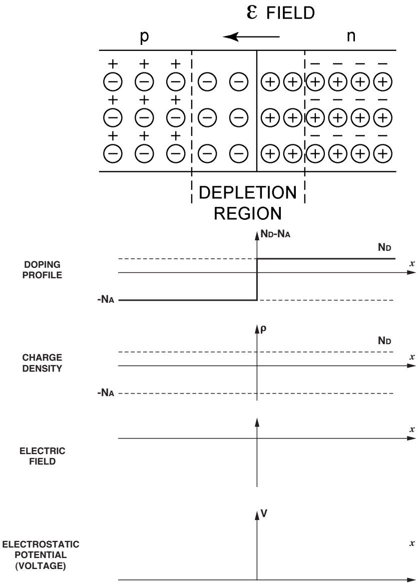


PN Junction Reverse Bias (preview)

$V_A < 0$ Applied V_A "reinforces" internal E field
"Pulls" mobile carriers further apart



PN Junction: Electrostatics at equilibrium



PN Junction: Electrostatics at equilibrium

"Built-in" potential:

For zero applied bias, there exists a voltage ψ_0 across the junction called the *built-in potential*. This potential opposes the diffusion of mobile holes and electrons across the junction in equilibrium and has a value[1]

$$\psi_0 = V_T \ln \frac{N_A N_D}{n_i^2} \tag{1.1}$$

where

$$V_T = \frac{kT}{q} \simeq 26\ \text{mV} \quad \text{at} \quad 300^\circ\text{K}$$

Example: $N_A = 1E + 15atom/cm^3, N_D = 1E + 16atom/cm^3$

Summary: PN Junction at Equilibrium

- Depletion region
  Depleted of mobile carriers near junction
  Fixed charges (of other sign) “uncovered”
- Macro level: Zero net current
- Micro level:
  Drift, diffusion current balance for holes and electrons
- Built-in potential ψ_0
  Voltage across junction that opposes diffusion

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PN Junction: Electrostatics, V_R reverse bias applied

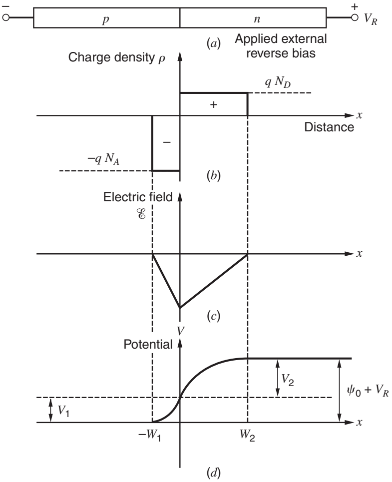


Figure 1.1 The abrupt junction under reverse bias V_R. (*a*) Schematic. (*b*) Charge density. (*c*) Electric field. (*d*) Electrostatic potential.

PN Junction: Electrostatics, V_R reverse bias applied

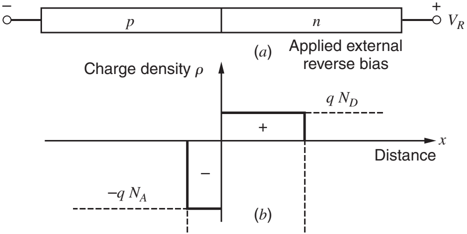
Extent of Depletion Region (step junction):

$$W_1 = \left[\frac{2\epsilon(\psi_0 + V_R)}{qN_A\left(1 + \frac{N_A}{N_D}\right)} \right]^{1/2} \tag{1.14}$$

$$W_2 = \left[\frac{2\epsilon(\psi_0 + V_R)}{qN_D\left(1 + \frac{N_D}{N_A}\right)} \right]^{1/2} \tag{1.15}$$

Example: $N_A = 1E + 15atom/cm^3, N_D = 1E + 16atom/cm^3$

PN Junction: Capacitance



For step junction

Use of (1.17) and (1.18) in (1.16) gives

$$C_j = A\left[\frac{q\epsilon N_A N_D}{2(N_A + N_D)}\right]^{1/2}\frac{1}{\sqrt{\psi_0 + V_R}} \tag{1.19}$$

PN Junction Capacitance: General

Equations 1.20 and 1.21 were derived using the assumption of constant doping in the *p*-type and *n*-type regions. However, many practical diffused junctions more closely approach a *graded* doping profile as shown in Fig. 1.2. In this case, a similar calculation yields

$$C_j = \frac{C_{j0}}{\sqrt[3]{1 - \frac{V_D}{\psi_0}}} \tag{1.22}$$

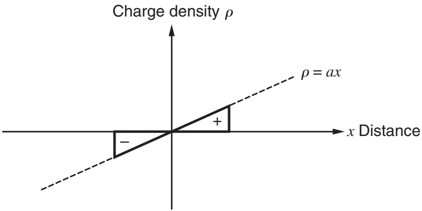
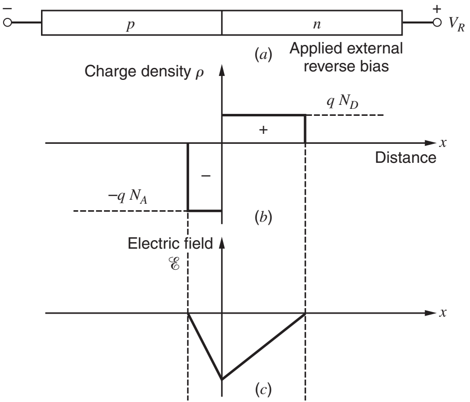


Figure 1.2 Charge density versus distance in a graded junction.

PN Junction: Maximum Field at junction

2 **Chapter 1 ■ Models for Integrated-Circuit Active Devices**



PN Junction: Reverse breakdown

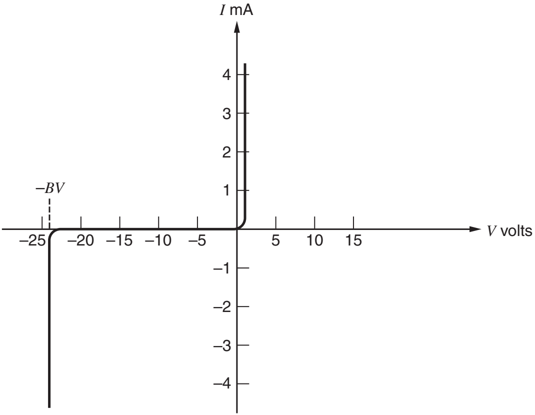


Figure 1.4 Typical *I-V* characteristic of a junction diode showing avalanche breakdown.

Summary: PN Junction in Reverse Bias

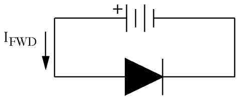
- Depletion region
  Separation of +, - charges: Acts as capacitance
  Junction capacitance depends on applied voltage
- DC current behavior
  Applied voltage reinforces built-in ψ_0
  "Turns off" diffusion current
  Small reverse current (nA to pA) flows due to drift
- Maximum value of E field at junction E_{max}
- Breakdown voltage
  When maximum field E_{max} exceeds critical value E_{crit}
  of semiconductor material
  Large reverse current flows

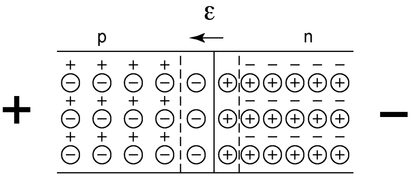
Module 1: Semiconductor Physics Review

Topic	Reading
Bonding model, charge carriers	
Doping: p, n regions	
Fields review: E field, Capacitance	
Charge motion: Drift	
Charge motion: Diffusion	
PN junction: Equilibrium	
PN junction: Reverse Bias (capacitance)	1.1, 1.2
PN junction: Forward Bias (ideal diode equation)	

PN Junction Forward Bias $V_A > 0$

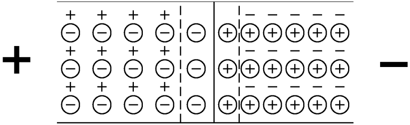
Applied V_A "overpowers" internal E field which opposed diffusion
$\Rightarrow$ Current components: Diffusion dominates





PN Junction Forward Bias $V_A > 0$

"Law of the Junction": Applied V_A changes minority carrier concentration at edge of depletion region by factor $(e^{(V_A/V_T)} - 1)$



Ideal Diode Equation

$$I_D = qA\left(\frac{n_i^2}{N_A}\frac{D_n}{L_n} + \frac{n_i^2}{N_D}\frac{D_p}{L_p}\right)\left[e^{(V_A/V_T)} - 1\right]$$

Summary: PN Junction in Forward Bias

- DC current behavior
  Applied voltage subtracts from built-in ψ_0
  Allows diffusion current to flow
  "Law of the Junction":
  $\Rightarrow$ Exponential increase in current
- Diffusion current dominates: driven by concentration gradient
  Preview: carrier motion in base region of bipolar transistor
- Ideal diode equation
  Note parts of equation due to
  - Junction geometry (cross-sectional area A)
  - Semiconductor material properties (n_i, N, D, L)
  - Applied voltage (V_A)

Module 2: Bipolar Transistor

Topic	Reading
Construction	1.3
Active Region operation (DC)	
Large signal model equations	
Charge control model	
Saturation, cutoff operating regions	
β vs. operating condition	

Module 3: IC manufacturing technology for BJT

Topic	Reading
Passive Components: Resistors	2.1-7
Passive Components: Capacitors	
Passive Components : Inductors	
BJT Parasitics	
Integrated vs. Discrete Design	

Module 4: SPICE modeling of BJT

Topic	Reading
DC parameters	A.2.1, 1.4.7
AC parameters	
Parasitic parameters	
Modeling example: CA3096	

Module 5: BJT Modeling for Amplifier Design

Topic	Reading
Large signal (DC) models	1.3
2-port amplifier model	1.4
Small signal (ac, incremental) modeling	
Hybrid pi model	
f_T frequency domain figure of merit	
T model	
Use of models: DC bias, small signal gain, bandwidth	

Module 6: BJT Amplifiers (1T)

Topic	Reading
Common Emitter	3.1-3
Common Emitter with Degeneration	
Emitter Follower	
Common Base	
Summary of 1T BJT amplifiers	
Preview: Opportunities for Improvement	

Module 7: BJT Amplifiers (2T)

Topic	Reading
Darlington	3.4
Cascode	

Module 8: Differential Pair

Topic	Reading
Motivation and configuration (op-amp input stage)	3.5
DC transfer characteristic	
Half-circuit analysis	
Differential mode behavior	
Common mode behavior	
Differential Pair with Emitter Degneration	
Mismatch in Differential Pair: Offset voltage	
CM-to-DM conversion	
Preview: Opportunities for Improvement	

Module 9. Current Sources

Topic	Reading
Motivation	
Simple Current Mirror	
Current Mirror with Beta helper	4.1, 4.2
Degeneration	
Cascode	A.4.1
Wilson	
Summary of current sources	

Module 10. Active Loads

Topic	Reading
Motivation	4.3
Common-Emitter with Current Source Load	
Differential Pair with Mirror Load	
Summary of active load techniques	

Module 11. Output Stages

Topic	Reading
Motivation	5.1-4
Emitter Follower	
DC Transfer Characteristics	
Efficiency Considerations	
Push-pull output stage	
DC Transfer Characteristic / Dead Zone distortion	
Class AB output	
Overload Protection	

Module 12. Biasing

Topic	Reading
Widlar source	4.4
Supply Insensitive Biasing	
Bandgap voltage reference	

Module 13. Basic Op-Amp Design (single-ended output)

Topic	Reading
Motivation	6.1, 6.2, 6.8
Op-Amp nonidealities	
Basic BJT Op-amp and design evolution	
Increase gain of input differential stage	
Current Source Biasing	
Use of active load	
Push pull, class AB output stage	
Stage-to-stage coupling, buffering	
Systematic Offset issues	
Basic Op-Amp design Summary	

Module 14. Frequency response issues

Topic	Reading
Transfer function; pole-zero review	7.1-5
Common Emitter Amplifier	
Miller effect	
Emitter follower frequency response	
Common Base frequency response	
Cascode frequency response	
Differential Amplifier frequency response	
Frequency response summary	

Module 15. Feedback

Topic	Reading
Advantages of Negative Feedback	8.1-3
Feedback Configurations	

Module 16. Op-Amp Stability

Topic	Reading
Gain-Bandwidth relationship	9.1-4, 9.6
Stability Criteria	
Phase Margin	
Op-Amp Compensation	
Dominant Pole / Miller Integrator Compensation	
Slew Rate Limiting	
Example Design: Stability of 3-stage BJT Op-Amp	
Stability Summary	

Module 17. MOSFET Op-Amp Design

Topic	Reading
MOS Construction	2.8-11
MOS Operation	1.5-9
MOS Modeling	
MOS-BJT Comparison	3.3-5, 4.2, 4.4, A.4.1
MOS Op-amp design example	6.3-7
Compensation for MOS Op-amp	9.4, 9.6
MOS Op-amp Summary	

Module 18. Fully Differential Op-amps

Topic	Reading
Differential mode operation	12.1-6
Need for Common Mode Feedback (CMFB)	
CMFB Techniques	
Design Example	
Fully Differential Op-amp Summary	

Module 19. Advanced / Optional Topics

Topic	Reading
Noise	11.1-9
Current Feedback Op-Amp	
Analog Multiplier	10.1, 10.2
Gilbert Cell	
Student requested	