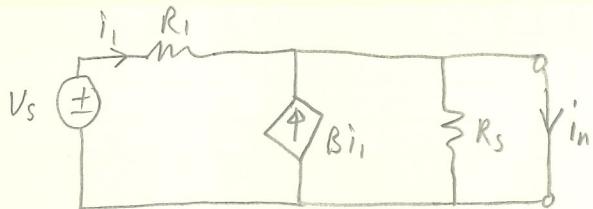


Finding i_n

→ short the output terminals and find the current flowing through the short

Solving for i_n

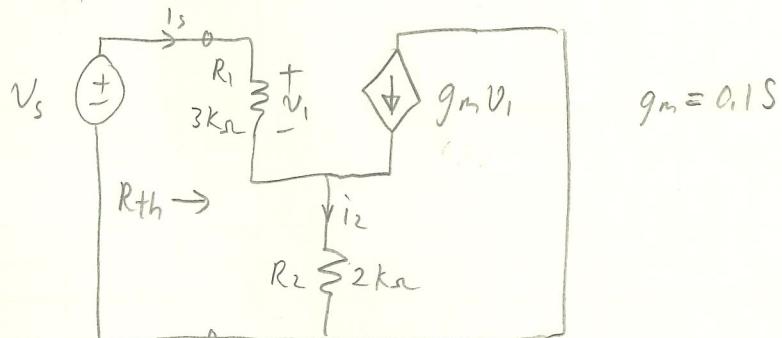
$$i_n = i_1 + \beta i_1 = i_1(1 + \beta)$$

$$i_1 = \frac{V_s}{R_1}$$

$$\therefore i_n = \frac{V_s(1 + \beta)}{R_1} = \frac{V_s 51}{20,000} = (2.55 \times 10^{-3}) V_s$$

Ex: Another Example

Find R_{th}



$$g_m = 0.1 S$$

$$KVL: V_s = i_s R_1 + i_2 R_2 = i_s R_1 + R_2(i_s + g_m V_1)$$

$$V_1 = i_s R_1$$

$$\therefore V_s = i_s(R_1 + R_2 + R_1 R_2 g_m) = i_s(605 k\Omega)$$

$$\text{solve for } R_{th} = \frac{V_s}{i_s} = 605 k\Omega$$

⑦ Device Tolerances

→ Passive and Active circuit devices have tolerances in their values due to manufacturing tolerances, temperature of operation, aging, etc..

→ We need to account for these tolerances in our circuit designs
Ex: 100Ω with a $\pm 10\%$ tolerance

$$\rightarrow 90\Omega \leq R \leq 110\Omega$$

Worst-Case Analysis

→ analysis of the circuit with the device values chosen over their tolerance range so that the desired variable (such as output voltage) is as large or as small as possible

Monte Carlo Analysis

→ A statistical analysis of the circuit through simulating the circuit many times while randomly picking device values over their tolerance range

⑧ Temperature Coefficients

circuit elements tend to vary in value over temperature.

$$\text{Ex: resistor: } R = R_0 (1 + \alpha_1 \Delta T + \alpha_2 \Delta T^2)$$

SPICE circuit analysis software can account for this by changing the temperature-of-operation parameter

Chapter 2 (p. 41) : Intro to Solid State Theory & Materials

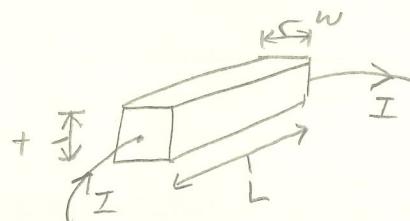
1) Electronic Materials

a) Resistivity is a material property

$$\rho \equiv \text{resistivity}, [\rho] = \Omega \cdot \text{cm}$$

$$\rightarrow \sigma \equiv \text{conductivity} \rightarrow \sigma = 1/\rho$$

Consider a rectangular conductor :



I flows along L and perpendicular to $t w$

$$\text{The resistance of the rectangular conductor} = R = \rho \frac{L}{w+t}$$

b. 3 types of electronic materials

$$\textcircled{1} \text{ Insulators} \rightarrow \rho > 10^5 \Omega \cdot \text{cm}$$

$$\textcircled{2} \text{ Conductors} \rightarrow \rho < 10^{-3} \Omega \cdot \text{cm}$$

$$\textcircled{3} \text{ Semiconductors} \rightarrow 10^{-3} \Omega \cdot \text{cm} < \rho < 10^5 \Omega \cdot \text{cm}$$

c. Solid State Devices are made from semiconductor materials

Examples: diodes, transistors, integrated circuits, LEDs, solar cells

d. Semiconductor Materials

\rightarrow refer to Table 2.2 in book/handout

\hookrightarrow portion of the Periodic Table

2 - Types : Elemental Semiconductors \rightarrow Si and Ge : column IV

Compound Semiconductors \rightarrow such as GaAs (Gallium Arsenide)

\hookrightarrow combinations of columns III and IV
or columns II and IV

TABLE 2.2
Portion of the Periodic Table, Including the Most
Important Semiconductor Elements (shaded)

	III A	IV A	V A	VI A
5 B	10.811 6 C	12.01115 Carbon	7 N	14.0067 Nitrogen
13 Al	26.9815 14 Si	28.086 Silicon	15 P	30.9738 Phosphorus
31 Zn	65.37 31 Ga	69.72 Gallium	32 As	72.59 Arsenic
49 Cd	112.40 49 In	114.82 Indium	50 Sn	118.69 Tin
81 Hg	200.59 81 Tl	204.37 Thallium	82 Pb	207.19 Lead
				83 Bi
				84 Bismuth
				(210) Po
				Polonium

Silicon (Si) \rightarrow most important semiconductor material

① Material Science

- atoms can bond together to be:
 - : amorphous [disordered structure]
 - as a solid : polycrystalline [many small crystallites]
 - : single crystal [one large crystal]

Si is in the IV column \rightarrow show full periodic chart handout
 It has 4 electrons (e^- 's) in its outer electron shell.

This shell wants 8 e^- 's

i: Si tends to covalently bond with 4 other Si atoms,
 where each Si atom shares electrons with 4 adjacent
 Si atoms to fill the outer electron shell

\hookrightarrow SHOW FIG 2.2 (handout)

ii: Si covalently bonds with 4 other Si atoms \rightarrow diamond crystal
 structure

$\left\{ \rightarrow$ a 3 sided pyramid with a Si atom in the middle

$\left\{ \rightarrow$ single crystal Si material \rightarrow forms a crystal lattice structure

\rightarrow SHOW FIG 2.1

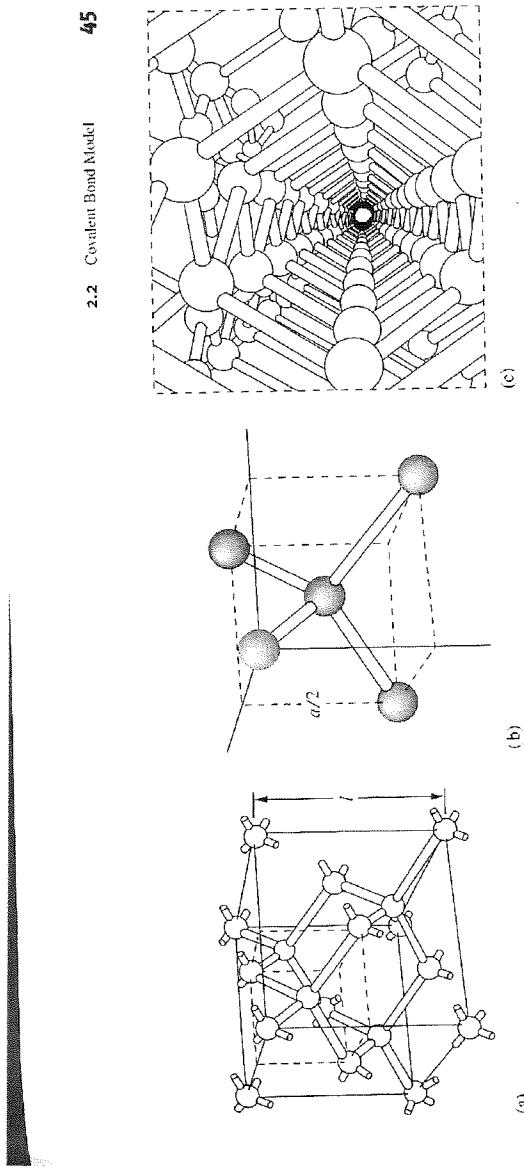


Figure 2.1 Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length $l = 0.543 \text{ nm}$. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis.
Source: (a) and (b) Adapted from Electrons and Holes in Semiconductors by William Shockley, © 1950 by Litton Educational Publishing, Inc. Adapted from The Architecture of Molecules by Linus Pauling © 1964 by W. H. Freeman and Company, used with permission.

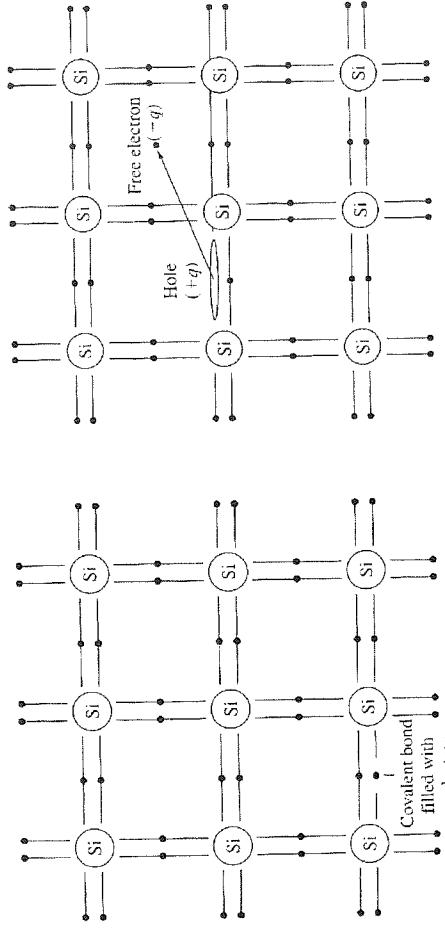
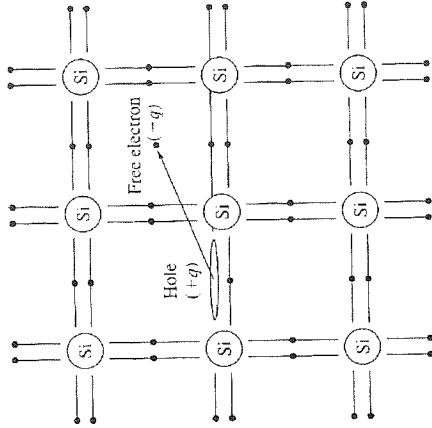


Figure 2.2 Two-dimensional silicon lattice with shared covalent bonds. At temperatures approaching absolute zero, 0 K, all bonds are filled, and the outer shells of the silicon atoms are completely full.

Figure 2.3 An electron-hole pair is generated whenever a covalent bond is broken.



Single crystal Si material \rightarrow at absolute zero: all e's are held in the covalent bonds \rightarrow Si = insulator
 \rightarrow no free e's for conduction

Inc Temp \rightarrow thermal energy added to the material

" " breaks some covalent bonds, freeing a few e's for conduction

SHOW FIG 2.3

Si = conducts electricity

\rightarrow where the free electron was bound is called a "hole"

\Rightarrow The density of these free e's is called the:

"Intrinsic Carrier Density" $\rightarrow n_i$

$$[n_i] = \text{cm}^{-3}$$

$$\rightarrow n_i^2 = B T^3 e^{-\left(\frac{E_g}{kT}\right)} \rightarrow [n_i^2] = \text{cm}^{-6}$$

B = a material dependent parameter $= 1.08 \times 10^{31} \text{ K cm}^{-3}$ for Si

T = absolute temperature in K $\{ K = ^\circ C + 273.15 \}$

K = Boltzmann's constant $= 8.62 \times 10^{-5} \text{ eV/K}$

E_g = semiconductor bandgap energy in eV

\rightarrow eV = "electron volts" \rightarrow a unit of energy

$$1 \text{ eV} \cong 1.602 \times 10^{-19} \text{ J}$$

E_g (the bandgap energy) is the minimum energy needed to break a covalent bond

WebElements™ periodic table

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Period																			
1	1 H																		
2	3 Li	4 Be																	
3	11 Na	12 Mg																	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	** Lr	103 Rf	104 Db	105 Sg	106 Bh	107 Hs	108 Mt	109 Ds	110 Rg	111 Uub	112 Uut	113 Uuq	114 Uup	115 Uuh	116 Uus	117 Uuo	
* Lanthanoids																			
* 57 La																			
** Actinoids																			
** Ac																			

<http://www.webelements.com/>

E_f for various semiconductor materials:

Si : $E_G = 1.12 \text{ eV}$

Ge : $E_G = 0.66 \text{ eV}$

GaAs : $E_G = 1.42 \text{ eV}$

$n_i \rightarrow$ intrinsic carrier density
 pure material : ex: pure Si

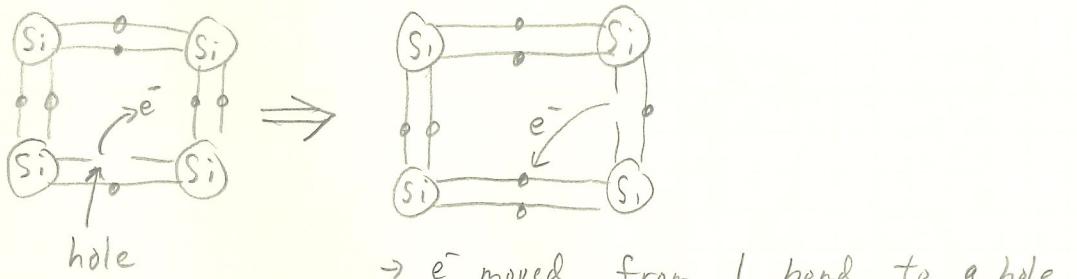
$n \rightarrow$ "density of conduction electrons" or "density of free electrons"
 for a material

\rightarrow for a pure material (ie intrinsic material) : $n = n_i$

\rightarrow Intrinsic Carrier Density varies with temperature

SHOW FIG 2.4

② Holes and Electrons



e^- 's \rightarrow charge carrier : $g = -1.602 \times 10^{-19} \text{ C}$

hole \rightarrow another type of charge carrier : $g = +1.602 \times 10^{-19} \text{ C}$

$\rightarrow p \equiv$ hole density , $[p] = \text{holes/cm}^3$

for intrinsic Si : $n = n_i = p$: when in Thermal Equilibrium - no other applied stimulus
 and $n_i^2 = pn \equiv$ product of the e^- and hole concentrations

such as a voltage
 or light

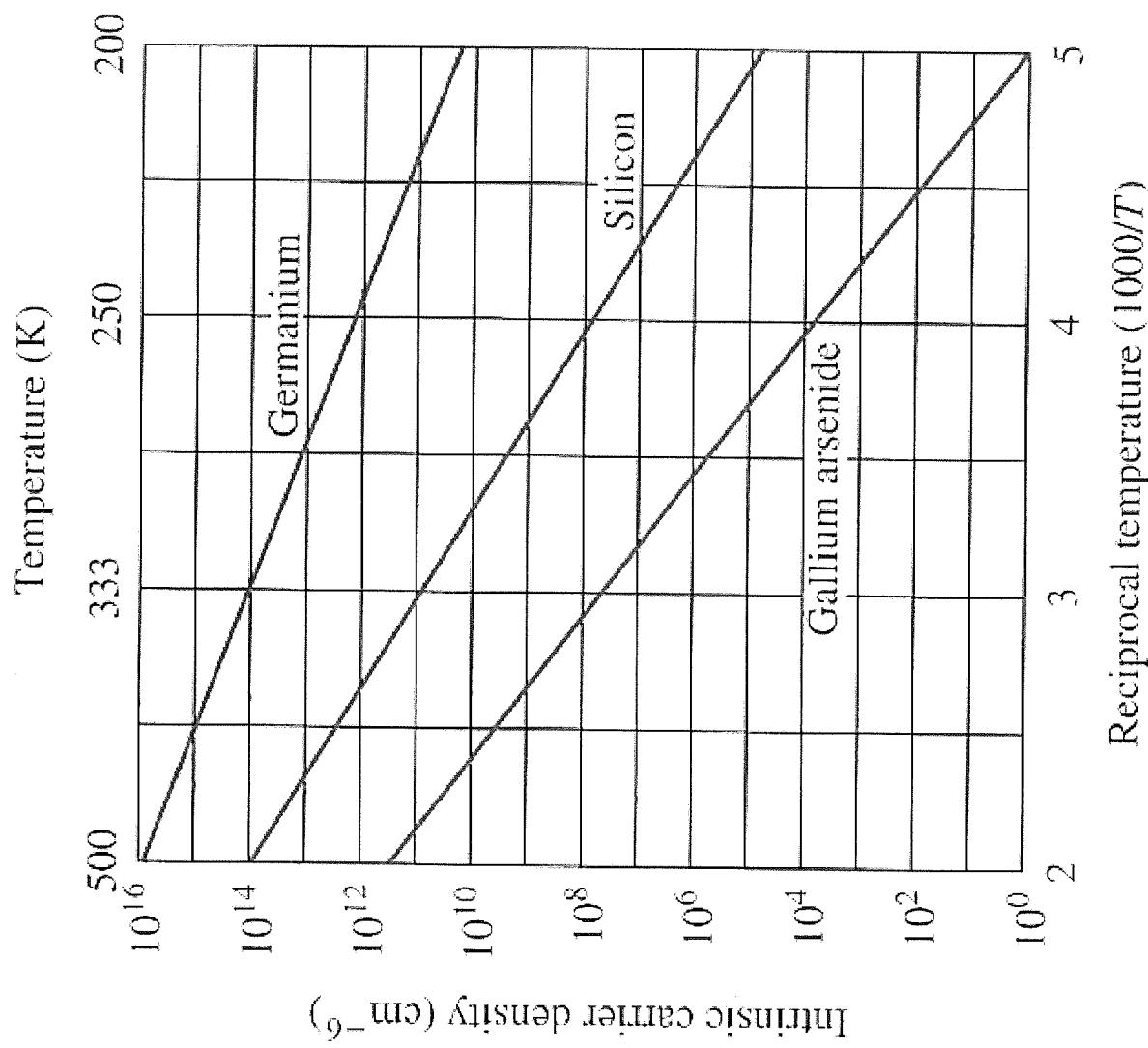


Figure 2.4 Intrinsic carrier density versus temperature from Eq. (2.1).