

### ③ Drift Currents

Apply a voltage across a material and charged particles will move in response to the electric field :  $[E] = V/m$   
 $\downarrow$   
 or drift

Drift Current Density :  $j = Qv$ ,  $[j] = A/m^2$

→ this density is in reference to a cross-sectional area

$Q$  = charge density :  $[Q] = C/cm^3$

$v$  = velocity of charge in an electric field :  $[v] = cm/s$

### ④ Mobility

→ positive charges drift in the direction of the electric field  $\vec{E}$

→ negative " " " opposite" " " " "

Note:  $\vec{E}$  is a vector quantity

For low drift velocities :  $\vec{V}_n = -\mu_n \vec{E}$  and  $\vec{V}_p = \mu_p \vec{E}$

where:  $\vec{V}_n$  = velocity of electrons in cm/s

$\vec{V}_p$  = " " holes " "

$\mu_n$  = electron mobility

$\mu_p$  = hole mobility

For intrinsic Si :  $\mu_n = 1350 \text{ cm}^2/\text{V}\cdot\text{s}$

$\mu_p = 500 \text{ cm}^2/\text{V}\cdot\text{s}$

note:  $\mu_n > \mu_p$ : electrons can move anywhere, holes can only move through the covalent bond structure

Velocity Saturation: as  $\vec{E}$  inc, the charge carrier velocity cannot increase  $\rightarrow \infty$ . For  $\vec{E} > \sim 3 \times 10^4 \text{ V}/\text{cm}$ , carrier velocity  $\rightarrow$  saturated drift velocity,  $V_{sat}$  : Si  $\rightarrow V_{sat} = \sim 10^7 \text{ cm/s} \Rightarrow$  this limits the freq response of solid state devices

### ⑤ Resistivity of Intrinsic Si

$$\begin{aligned} \text{e}^- \text{ current density} &= j_n^{\text{drift}} = Q_n v_n \quad \{ \text{1-dimensional model} \} \\ &= (-q_n)(-\mu_n E) \\ &= q n \mu_n E \end{aligned}$$

$$\text{drift} \quad [j_n^{\text{drift}}] = A/cm^2$$

$$\begin{aligned} \text{hole}^{\text{drift}} \text{ current density} &= j_p^{\text{drift}} = Q_p v_p \quad \{ \text{1-D model} \} \\ &= Q_p v_p \\ &= (+q_p)(+\mu_p E) \\ &= q p \mu_p E \\ &[j_p^{\text{drift}}] = A/cm^2 \end{aligned}$$

note:  $Q_n = -q_n \rightarrow$  electron charge density in  $C/cm^3$

$Q_p = +q_p \rightarrow$  hole charge density " "

$$\begin{aligned} \therefore \text{Total drift current density} &= j_T^{\text{drift}} \\ &= j_n + j_p \\ &= q(n\mu_n + p\mu_p)E \\ &= \sigma E \end{aligned}$$

$$\begin{aligned} \text{or: electrical conductivity} &= \sigma = q(n\mu_n + p\mu_p) \\ &[\sigma] = (\Omega^{-1} \cdot \text{cm})^{-1} \end{aligned}$$

$$\begin{aligned} \text{Resistivity} &= \rho = \frac{1}{\sigma} = \frac{E}{j_T^{\text{drift}}} \rightarrow \text{a version of Ohm's law: } R = \frac{V}{I} \\ &[\rho] = \Omega \cdot \text{cm} \end{aligned}$$

## 2) Impurities in Si

- Doping  $\rightarrow$  the introduction of controlled amounts of impurities to the intrinsic semiconductor material
- Doping can change the resistivity and the e<sup>-</sup>/hole properties of the material
- For Si : doping materials come from columns III + IV  
 $\rightarrow$  show Table 2.2

### a. Column IV Impurities

- Have 4 valence e<sup>-</sup>s in the outer shell  
 ex: P, As and Sb  $\rightarrow$  commonly used
- Show Fig. 2.6a
  - $\rightarrow$  1 Si atom replaced w/ 1 P atom
  - $\rightarrow$  P atom : 4 e<sup>-</sup>s in covalent bonds w/ Si atoms,  
 1 e<sup>-</sup> not " " " " "
  - $\rightarrow$  requires very little thermal energy to free that e<sup>-</sup> for conduction
  - $\rightarrow$  at room temp, each "donor" atom gives up 1 e<sup>-</sup> for conduction
  - $\rightarrow$  results in an  $\gamma$  fixed net +g charge in the crystal lattice immobile
  - $\rightarrow$  these impurities are called "donor impurities"

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

	IIIA	IVA	VIA	VA	VIA
5 <b>B</b> Boron	10.811 6 <b>C</b> Carbon	12.01115 7 <b>N</b> Nitrogen	14.0067 8 <b>O</b> Oxygen		
13 <b>Al</b> Aluminum	26.9815 14 <b>Si</b> Silicon	28.086 15 <b>P</b> Phosphorus	30.9738 16 <b>S</b> Sulfur		
30 <b>Zn</b> Zinc	65.37 31 <b>Ga</b> Gallium	69.72 32 <b>Ge</b> Germanium	72.59 33 <b>As</b> Arsenic	74.922 34 <b>Se</b> Selenium	
48 <b>Cd</b> Cadmium	112.40 49 <b>In</b> Indium	114.82 50 <b>Sn</b> Tin	118.69 51 <b>Sb</b> Antimony	121.75 52 <b>Te</b> Tellurium	
80 <b>Hg</b> Mercury	200.59 81 <b>Tl</b> Thallium	204.57 82 <b>Pb</b> Lead	207.19 83 <b>Bi</b> Bismuth	208.980 84 <b>Po</b> Polonium	(210)

### b. Column III Impurities

- have 3  $e^-$ 's in the outer shell
- ex: B is commonly used
- Show Fig 2.6 b
  - 1 Si atom replaced w/ 1 B atom
  - results in a vacancy in the bond structure
  - easy for nearby  $e^-$  to move into this vacancy, creating another vacancy in the bond structure
  - this mobile vacancy is a hole, that moves through the lattice
  - holes are "considered" to be particles with a +g charge
  - each impurity atom that accepts an  $e^-$  in the hole becomes negatively ionized
  - results in an immobile fixed net -g charge in the crystal lattice
  - these impurities are called "acceptor impurities"

### c. $e^-$ & hole concentration in doped semiconductors

① in doped semi's :  $n \neq p$

if  $n > p \rightarrow$  material called "n-type"  $\rightarrow$  Donor material

if  $p > n \rightarrow$  material called "p-type"  $\rightarrow$  Acceptor material

② carrier w/ larger population  $\rightarrow$  called the "majority carrier"

" " smaller " "  $\rightarrow$  " " " " "minority carrier"

$N_D \rightarrow$  donor impurity concentration,  $[N_D] = \text{atoms/cm}^3$

$N_A \rightarrow$  acceptor " "  $[N_A] = \text{atoms/cm}^3$

Charge Neutrality  $\rightarrow$  the semiconductor material must remain charge neutral

$$\therefore \sum (\text{pos. + neg. charge}) = 0$$

Ionized donors + holes  $\rightarrow$  represent pos. charge

Ionized acceptor +  $e^-$ 's  $\rightarrow$  represent neg. charge

$$\therefore p(N_D + p - N_A - n) = 0$$

$$\text{also: } pn = n_i^2$$

③ n-type material:  $N_D > N_A$

$$n^2 - (N_D - N_A)n - n_i^2 = 0$$

$$\text{solving: } n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2}$$

$$\text{usually: } (N_D - N_A) \gg 2n_i$$

$$\therefore n \approx (N_D - N_A)$$

④ p-type material:  $N_A > N_D$

$$p^2 - (N_A - N_D)p - n_i^2 = 0$$

$$\text{solving for } p: p = \frac{(N_A - N_D) \pm \sqrt{(N_A - N_D)^2 + 4n_i^2}}{2}$$

$$\text{usually: } (N_A - N_D) \gg 2n_i$$

$$\therefore p \approx (N_A - N_D)$$

⑤ Doping impurity densities

Range:  $10^{14}$  to  $10^{21}$  atoms/cm<sup>3</sup>

$\therefore N_A$  or  $N_D \gg$  Si intrinsic carrier concentration at room temp.

Majority carriers  $\rightarrow$  important for some applications

Minority carriers  $\rightarrow$  " " other "

## ⑥ Mobility + Resistivity of Doped Semiconductors

Impurities disrupt the Si lattice and result in regions of localized charge

- i: electrons & holes scatter as they move through material
- i: doping reduces the mobility, but greatly increases the density of majority carriers

i: For n-type material:  $\mu_{nn} \gg \mu_{pp}$

$$\sigma \approx q\mu_{nn} = q\mu_n(N_D - N_A)$$

For p-type material:  $\mu_{pp} \gg \mu_{nn}$

$$\sigma \approx q\mu_{pp} \approx q\mu_p(N_A - N_D)$$

## ⑦ Diffusion Currents

Doping may not be uniform through a semiconductor material

$\rightarrow$  creates gradients in  $e^-$  & hole concentration

$\rightarrow$  free carriers tend to diffuse from regions of high concentrations to regions of low concentrations

1-D model of diffusion current densities:

$$j_p^{\text{diff}} = (+q)D_p \left( -\frac{\partial p}{\partial x} \right) = -qD_p \frac{\partial p}{\partial x}$$

$$j_n^{\text{diff}} = (-q)D_n \left( -\frac{\partial n}{\partial x} \right) = +qD_n \frac{\partial n}{\partial x}$$

$D_p \equiv$  hole diffusivity  $\rightarrow [D_p] = \text{cm}^2/\text{s}$

$D_n \equiv e^-$  diffusivity  $\rightarrow [D_n] = \text{cm}^2/\text{s}$

$\Rightarrow$  relation between mobility and diffusivity:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} \Rightarrow \text{Einstein's relationship}$$

$\frac{kT}{q} = V_T \equiv$  thermal voltage  $\approx 0.025V$  at room temp.

We will encounter  $V_T$  later

### ⑧ Total Current in Doped Semiconductors

$\Rightarrow$  combination of drift and diffusion currents:

$$\begin{aligned} j_n^T &= q\mu_n n E + qD_n \frac{\partial n}{\partial x} \\ &= q\mu_n n \left( E + V_T \left( \frac{1}{n} \right) \frac{\partial n}{\partial x} \right) \end{aligned}$$

$$\begin{aligned} j_p^T &= q\mu_p p E - qD_p \frac{\partial p}{\partial x} \\ &= q\mu_p p \left( E - V_T \left( \frac{1}{p} \right) \frac{\partial p}{\partial x} \right) \end{aligned}$$

### Results

Column IV impurities: P: 5 valence  $e^-$ 's  $\rightarrow$  gives up 1  $e^-$   $\rightarrow$  fixed +g charge in crystal lattice: called "Donor Impurities":  $N_D$   
 $\rightarrow$  n-type material

Column III impurities: B: 3 valence  $e^-$ 's  $\rightarrow$  vacancy in bond structure  $\rightarrow e^-$  fills it  $\rightarrow$  fixed -g charge in crystal lattice: called "acceptor impurities":  $N_A$   
 $\rightarrow$  p-type material