Extrinsic Semiconductors

Bill Knowlton

- Octet Rule – S/C Categories
- Doping
- Hydrogenic Model or Effective Mass Theory
- Free Carrier Statistics – find *n* and *p* for doped S/Cs

Semiconductors
Groups: IV, III-V, II-VI

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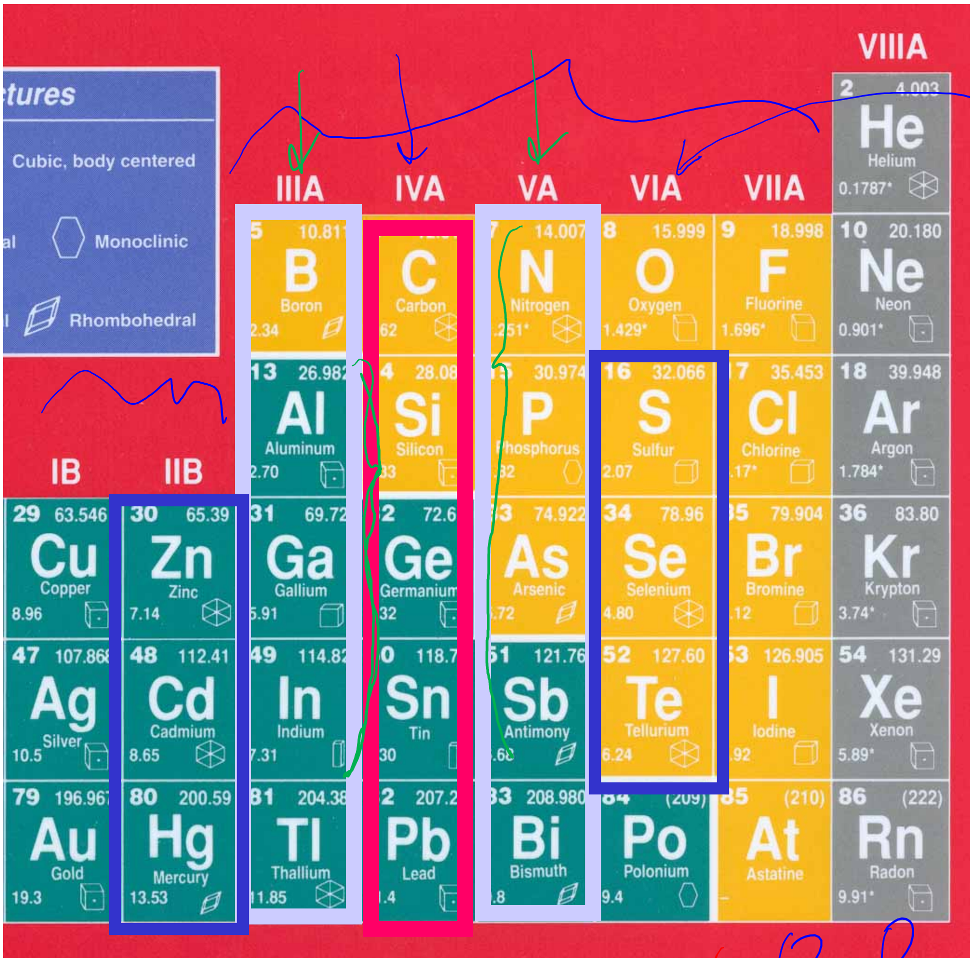
- **Octet Rule**: 2xIV & III+V & II+VI all add to 8!



IV Elemental S/c

III Al

V N small P As Sb bigger

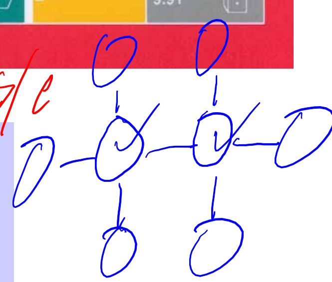
V_{AlN}

V_{AlSb}

Elemental

II-VI S/C

III-V S/c



IV IV

IV

II-VI

III-V

8 8 8

IV-IV = 8/2 = 4

$V_{AlN} < V_{AlSb}$

$E_{AlN} > E_{AlSb}$

$E_{gAlN} > E_{gAlSb}$

Semiconductors
Groups: IV, III-V, II-VI

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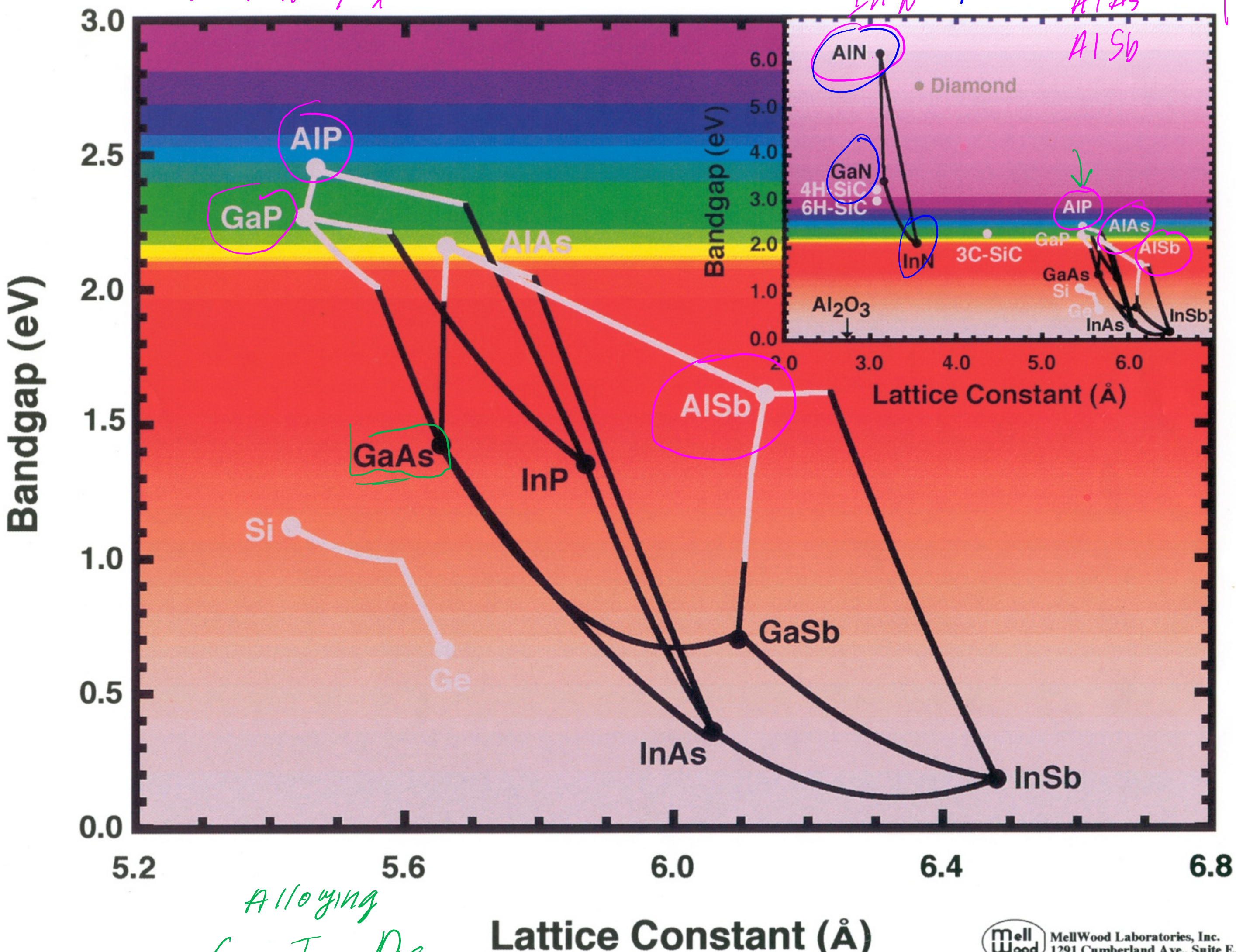
❑ Some Band Gaps and Lattice Constants

Alloying → E_g Bandgap Engineering

$Ga\,As_x\,P_{1-x}$

AlN, GaN, InN — E_g ↑

AlN, AlP, AlAs, AlSb — E_g ↑



Alloying

$Ga_x\,In_{1-x}\,As$

$X_{Ga} + X_{In} = 1$

Extrinsic S/C Prop.: Free Carrier Statistics

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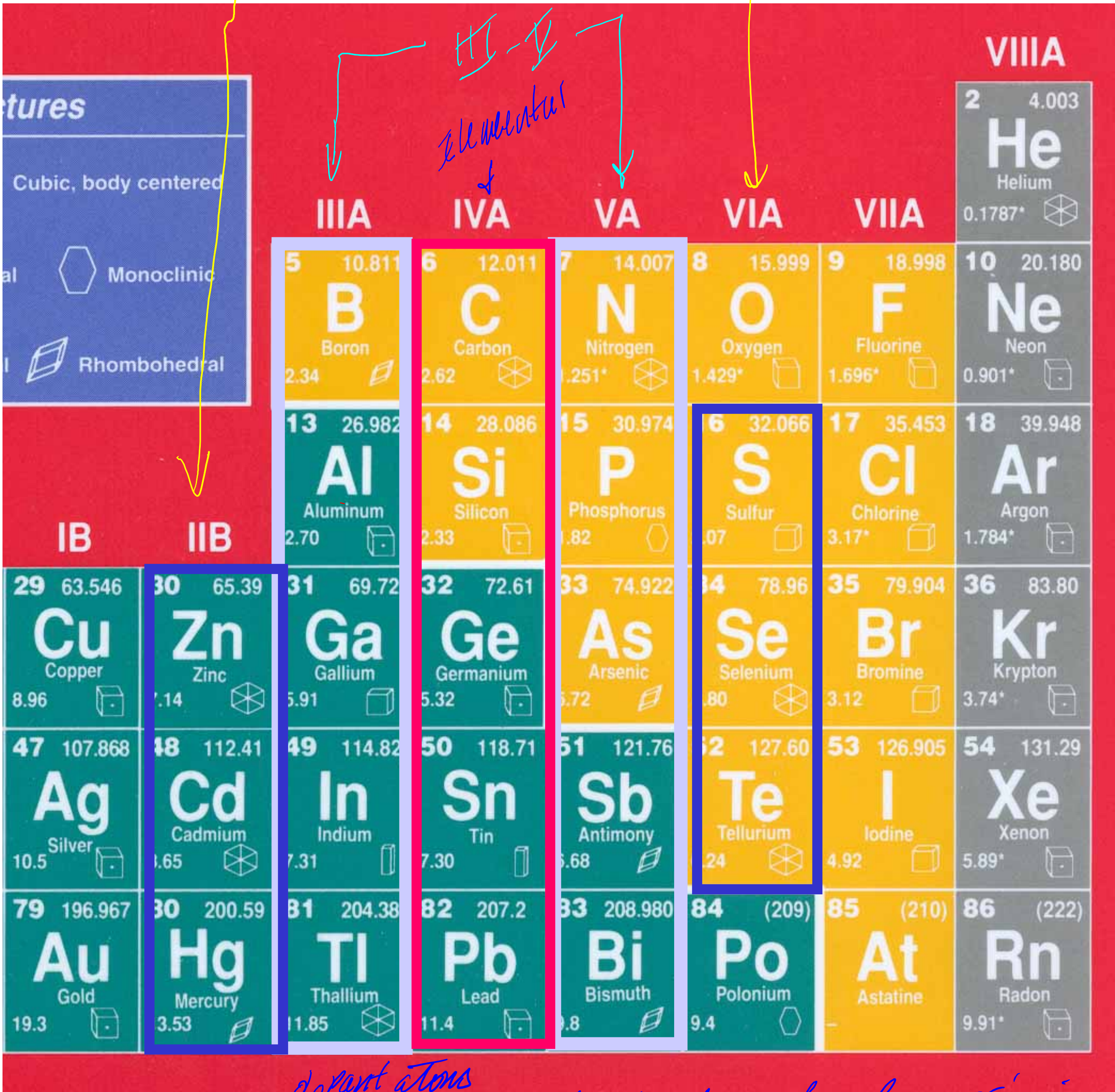
Donor and Acceptor Atoms for Group IV

II-VI

III-V

Elementals



dopant atoms

n-Type: add an impurity in which the # of valence e⁻'s is one greater than the matrix atom that is replaced

IV → V provides one additional e⁻

Al P
↓ ↓
IV VI

dopant

p-Type: add an impurity in which # of valence e⁻'s is one less than the matrix atom it replaces

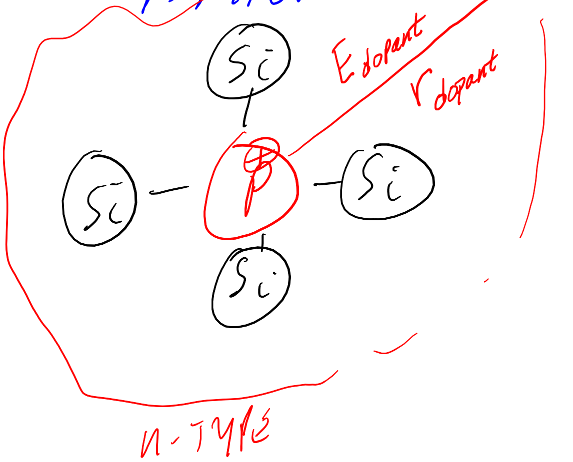
IV → III provides one less e⁻ or one more h⁺

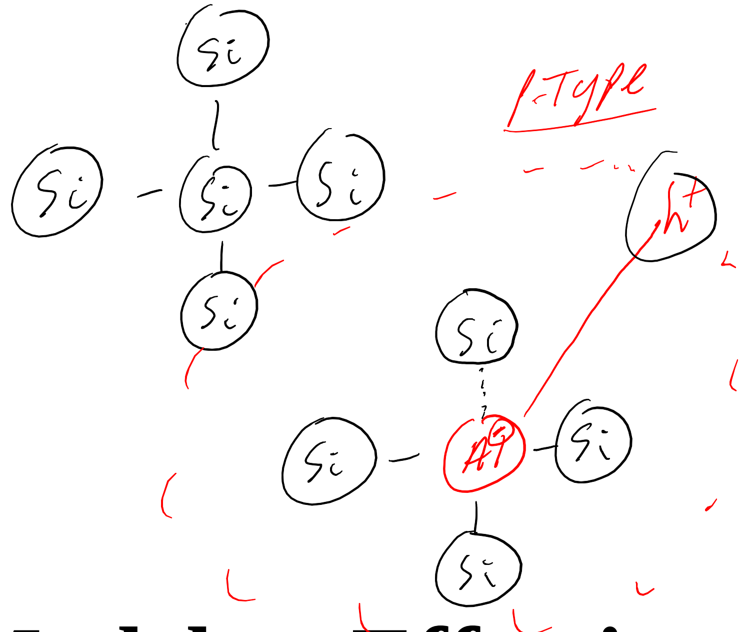
Al P
↓ ↓
II IV

II–V

n-type: III VI

p-type: I IV





Hydrogenic Model or Effective Mass Theory

Bohr Model → H

$$E_H = \frac{e^4}{2(4\pi\hbar)^2} \cdot \frac{m_0}{\varepsilon_0^2} = 13.6\,eV$$

$$r_H = \frac{4\pi\hbar^2}{e^2} \cdot \frac{\varepsilon_0}{m_0} \sim 0.5\,\text{Å}$$

$$\boxed{\begin{aligned} E_{dopant} &= E_H \frac{m^*}{\varepsilon_r^2} \\ r_{dopant} &= r_H \cdot \frac{\varepsilon_r}{m^*} \end{aligned}}$$

s/c & Not impurity

$$m_{eff} = m_0 \cdot m^*$$

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 K$$

HYDROGENIC

Guidelines

Extrinsic S/C Prop.: Effective Mass Model

- The model: Effective Mass Theory
  - a shallow impurity is compared to a hydrogen ~~model~~ atom embedded in a homogeneous medium with:
    - ↳ relative dielectric constant, ε.
    - ↳ an e^- or h^+ mass, which corresponds to the effective mass of the particular band extrema. Let's call this mass m^*.
  - We can estimate the binding energy between a shallow donor atom (or ion in this case) and it's 5^{th} valence e^- w/ the equation for the binding energy between a H^+ and its valence e^- modified by ε & m^*:

$$E = E_H \frac{m^*}{m_e}\frac{1}{\varepsilon^2} = \frac{e^4 m_e}{2(4\pi\varepsilon_o \hbar)^2}\frac{m_e^*}{m_e}\frac{1}{\varepsilon^2} = \boxed{13.6\,eV\,\frac{m_e^*}{m_e}\frac{1}{\varepsilon^2}}$$

$$E_{shallow-level} = E_H \frac{m_{eff}}{\varepsilon_r^2}$$

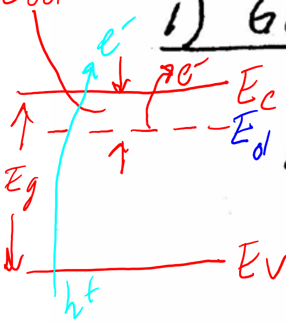
$$E_H = \frac{e^4 m_{eff}}{2\left(4\pi\varepsilon_o h^2\right)}$$

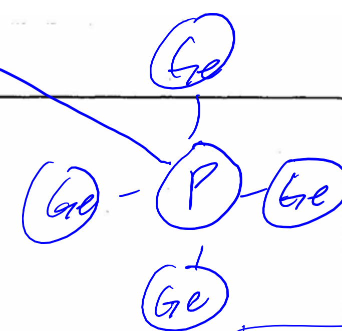
Extrinsic S/C Prop.: Effective Mass Model

EXAMPLES:

$E_{dopant} = E_{donor} = 11\,meV$

$E_{g_{Ge}} = 0.67\,eV$



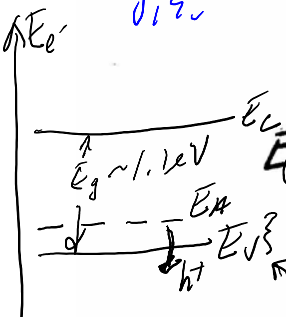


1) Ge: $\varepsilon_r = 16 \quad m_e^* \sim 0.2\,\cancel{m_e}$ (m_o)

$$E_{(\text{DONOR } e^-)} \sim \underbrace{13.6\,eV}_{E_H} \; \frac{0.2\,\cancel{m_e}}{\cancel{m_e}} \; \frac{1}{(16)^2} \sim 0.011\,eV = \boxed{11\,meV}$$

2) Si: $\varepsilon = 11.7 \quad m_e^* \simeq 0.33\,\cancel{m_e} \quad m_h^* \simeq 0.75\,\cancel{m_e}$

$E_g \sim 1.1\,eV$



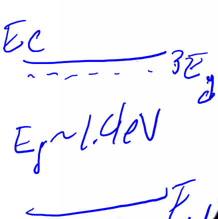
$$E_{\substack{\text{DONOR}\\ e^-}} \simeq 13.6\,eV \; \frac{0.33\,\cancel{m_e}}{\cancel{m_e}} \; \frac{1}{(11.7)^2} \simeq 0.033\,eV \simeq 33\,meV$$

(m_e^*, ε_r)

$$E_{\substack{\text{ACCEPTOR}\\ h^+}} \simeq 13.6\,eV \; \frac{0.75\,\cancel{m_e}}{\cancel{m_e}} \; \frac{1}{(11.7)^2} \simeq 0.075\,eV \simeq 75\,meV$$

(m_h^*, ε_r) ← p-type

3) GaAs: $\varepsilon = 13.2 \quad m_e^* \simeq 0.077\,\cancel{m_e} \quad m_h^* \simeq 0.36\,m_e$



$$E_{\substack{\text{DONOR}\\ e^-}} \simeq 13.6\,eV \; \frac{0.077\,\cancel{m_e}}{\cancel{m_e}} \; \frac{1}{(13.2)^2} \simeq 0.006\,eV \simeq 6\,meV$$

(ε_r)

$$E_{\substack{\text{ACCEPTOR}\\ h^+}} \simeq 13.6\,eV \; \frac{0.36\,m_e}{m_e} \; \frac{1}{(13.2)^2} \simeq 0.028\,eV \simeq 28\,meV$$

$E_{Ge:P} = 12\,meV$; $E_{Si:P} = 45\,meV$; $E_{GaAs:Si} = 58\,meV$

Extrinsic S/C Prop.: Effective Mass Model

- As you can see, Effective Mass Theory (EMT) works well. This is strongly related to the very large Bohr radii for e^-'s & h^+'s bound to shallow level impurity

- The Bohr Radius for e^-'s & h^+'s bound to shallow-level impurities can be approximated by modifying the eqn of the Bohr Radius for ~~a~~ the e^- of a hydrogen atom using m^* and ε.

$$r_{\substack{BOHR\\IMPURITY}} = r_{\substack{BOHR\\H-e^-}} \frac{m_e}{m^*}\varepsilon = \frac{4\pi\varepsilon_o h^2}{m_e e^2}\frac{\cancel{m_e}}{m^*}\varepsilon \simeq \boxed{0.5\,\text{Å}\,\frac{\cancel{m_e}}{m^*}\varepsilon}$$

$$r_{Bohr-shallow-level} = r_H \frac{\varepsilon_r}{m_{eff}}$$

$$r_H = \frac{4\pi\varepsilon_o h^2}{m_{eff} e^2}$$

Extrinsic S/C Prop.: Effective Mass Model

EXAMPLES:

1) Ge: $\varepsilon = 16 \quad m_e^* \sim 0.2 m_e$

$$r_{\substack{IMP.\\e^-}} \simeq 0.5Å \frac{\cancel{m_e}}{0.2 \cancel{m_e}} \underbrace{16}_{\varepsilon_r} \simeq \underline{40Å}$$

2) Si: $\varepsilon = 11.7 \quad m_e^* \simeq 0.33 m_e \quad m_h^* \simeq 0.75 m_e$

$$r_{\substack{IMP.\\e^-}} \simeq 0.5Å \frac{m_e}{0.33 m_e} 11.7 \simeq \underline{17.7Å}$$

$$r_{\substack{IMP.\\h^+}} \simeq 0.5Å \frac{m_e}{0.75 m_e} 11.7 \simeq \underline{8Å}$$

3) GaAs: $\varepsilon = 13.2 \quad m_e^* \simeq 0.077 \cancel{m_e} \quad m_h^* \simeq 0.36 m_e$

$$r_{\substack{IMP.\\e^-}} \simeq 0.5Å \frac{\cancel{m_e}}{0.077 \cancel{m_e}} 13.2 \sim \underline{86Å}$$

$$r_{\substack{IMP.\\e^-}} \simeq 0.5Å \frac{m_e}{0.36 m_e} 13.2 \sim \underline{18Å}$$

Extrinsic S/C Prop.: Effective Mass Model

- In a sphere of $r_{BOHR} \sim 85 Å$, over 10^5 lattice points are contained within.

- Such large Bohr radii of e^-_s & h^+_s of shallow-level impurities indicates how strongly delocalized in real space.

- That is, the wavefunctions of these e^-_s & h^+_s are spread over a very large volume relative to the volume of the impurity atom.

- The averaging over so many lattice points allows the use of an average dielectric constant, ε (b/c e^- "sees" a continuous medium).

- Such a large r_{BOHR}, giving rise to extended wavefunctions in real space, means that the wavefunction is strongly localized in k-space.

- This inverse relationship between real-space and k-space originates from where?

Dopant Energy Levels

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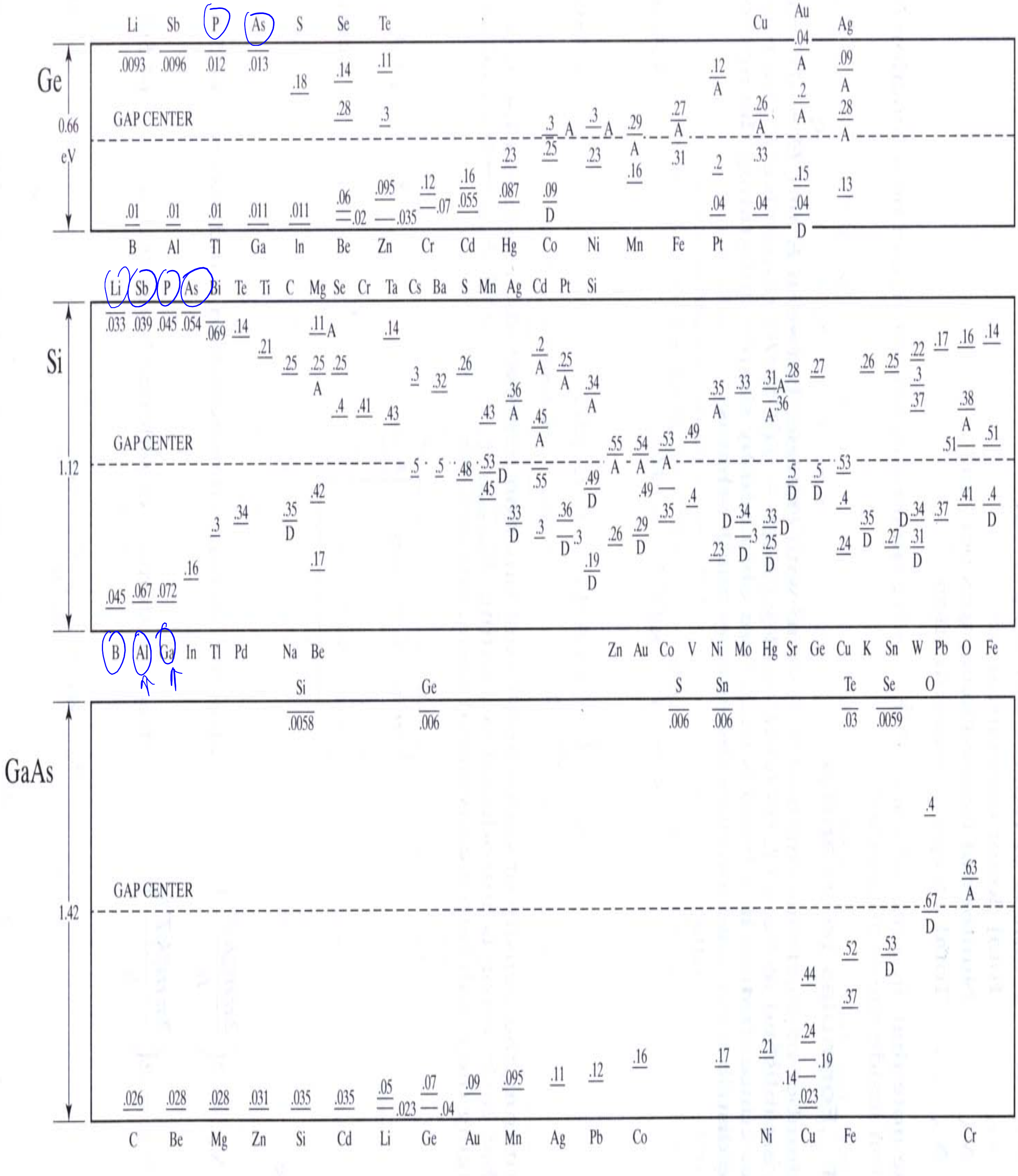

Figure 4.14 Measured ionization energies for the most commonly encountered impurities in Ge, Si, and GaAs. The levels above midgap are referenced to E_c and are donor-like or multiply charged donors, unless marked with an A which identifies an acceptor level. The levels below midgap are referenced to E_v and are acceptor-like or multiply charged acceptors, unless marked with a D for donor level. (From Sze.[3] Reprinted with permission.)

Pierret, Advanced Semiconductor Fundamentals (Pren. Hall, 2003).

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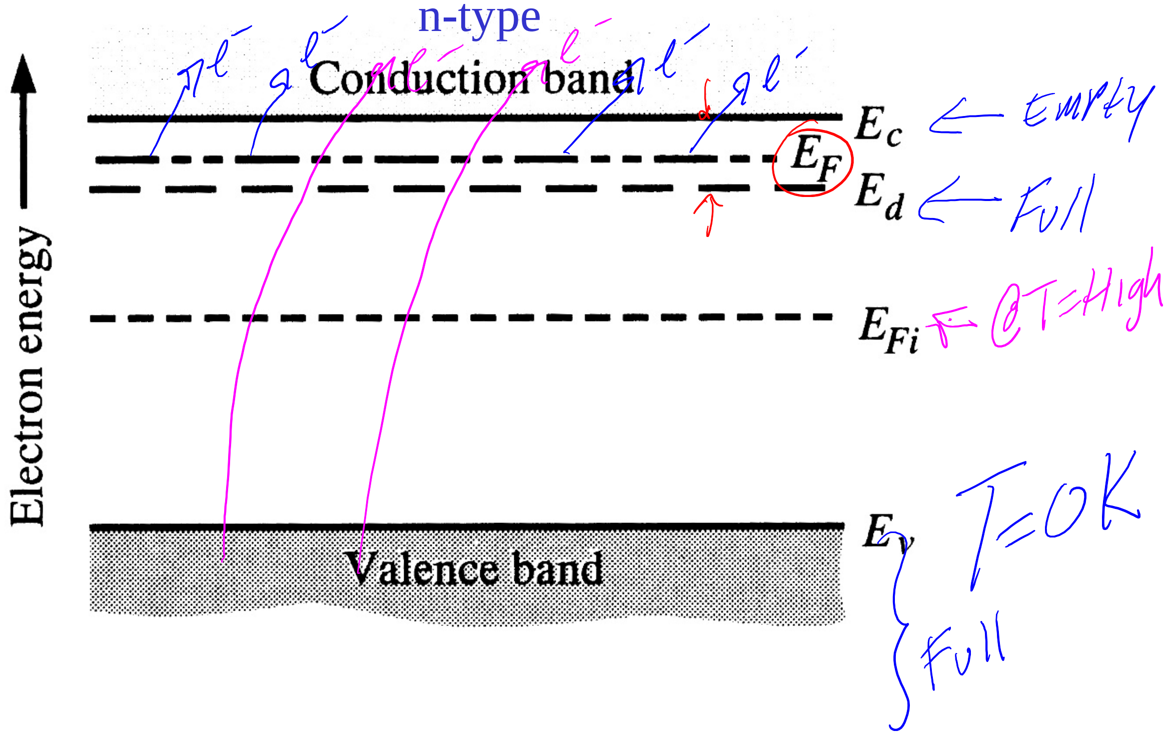
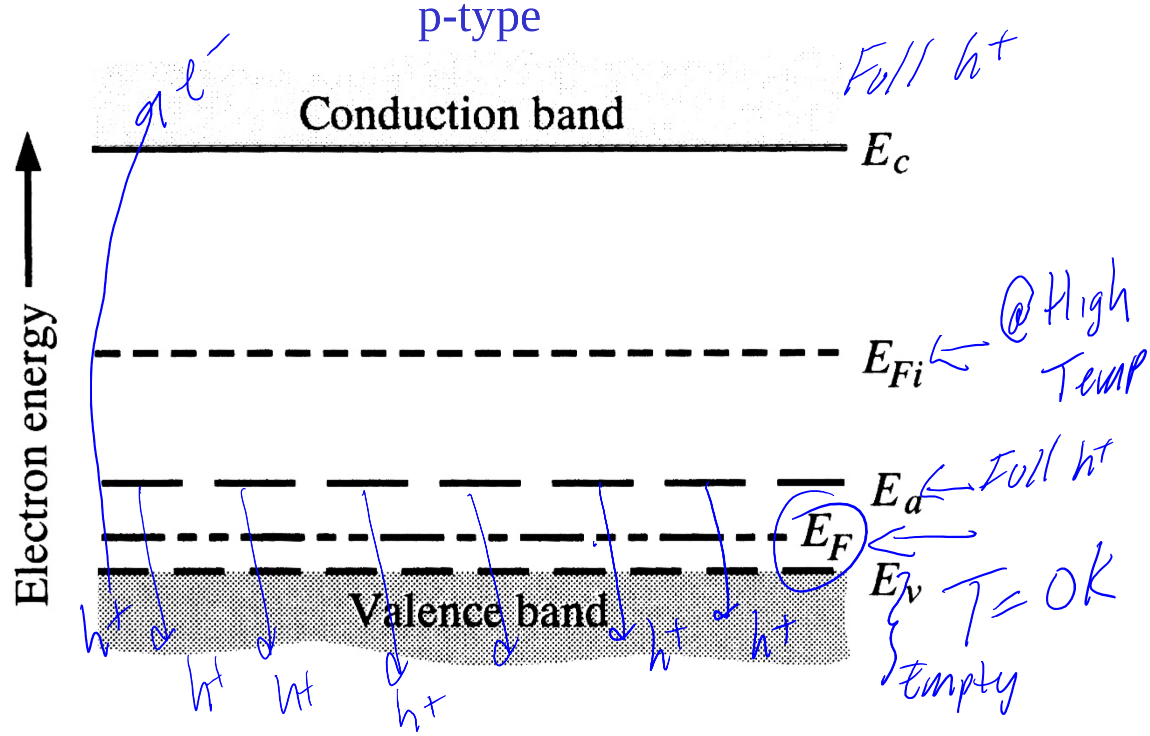
Extrinsic S/C Prop.: Doping

Doping

n-type



p-type



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Extrinsic S/C Prop.:

Doping & Temp Effects on Fermi Energy Level

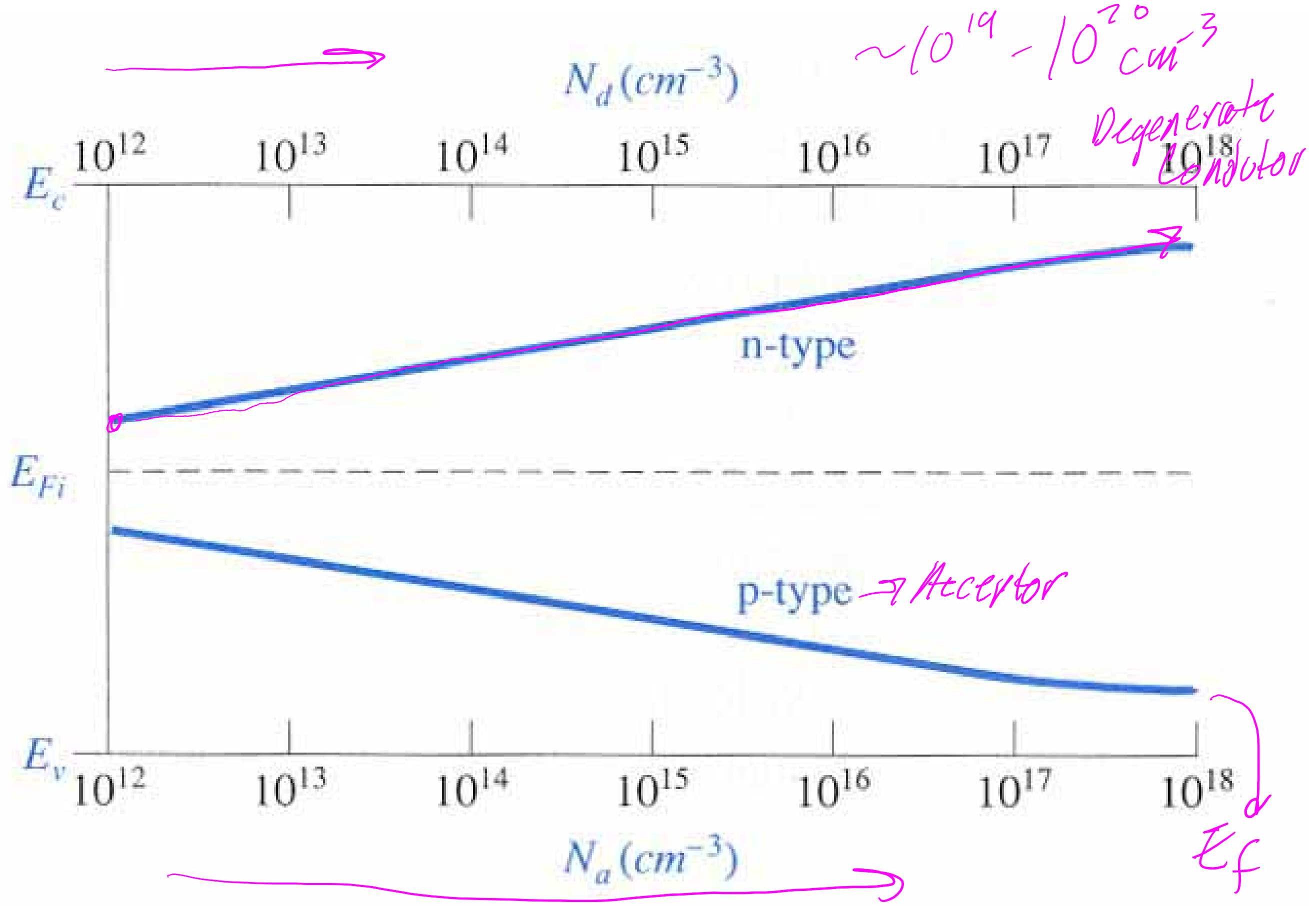

Figure 3.18 Position of Fermi level as a function of donor concentration (n-type) and acceptor concentration (p-type)

$$E_i = \frac{E_g}{2} + \frac{3}{4} kT \ln \frac{m_{eff,h^+}}{m_{eff,e^-}}$$

As $N \uparrow$,
$E_f \rightarrow$ band edge

Neamen, *Semiconductor Physics and Devices: Basic Principles*, 3rd Ed (McGraw Hill, 2004)

Extrinsic S/C Prop.:

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Doping & Temp Effects on Fermi Energy Level

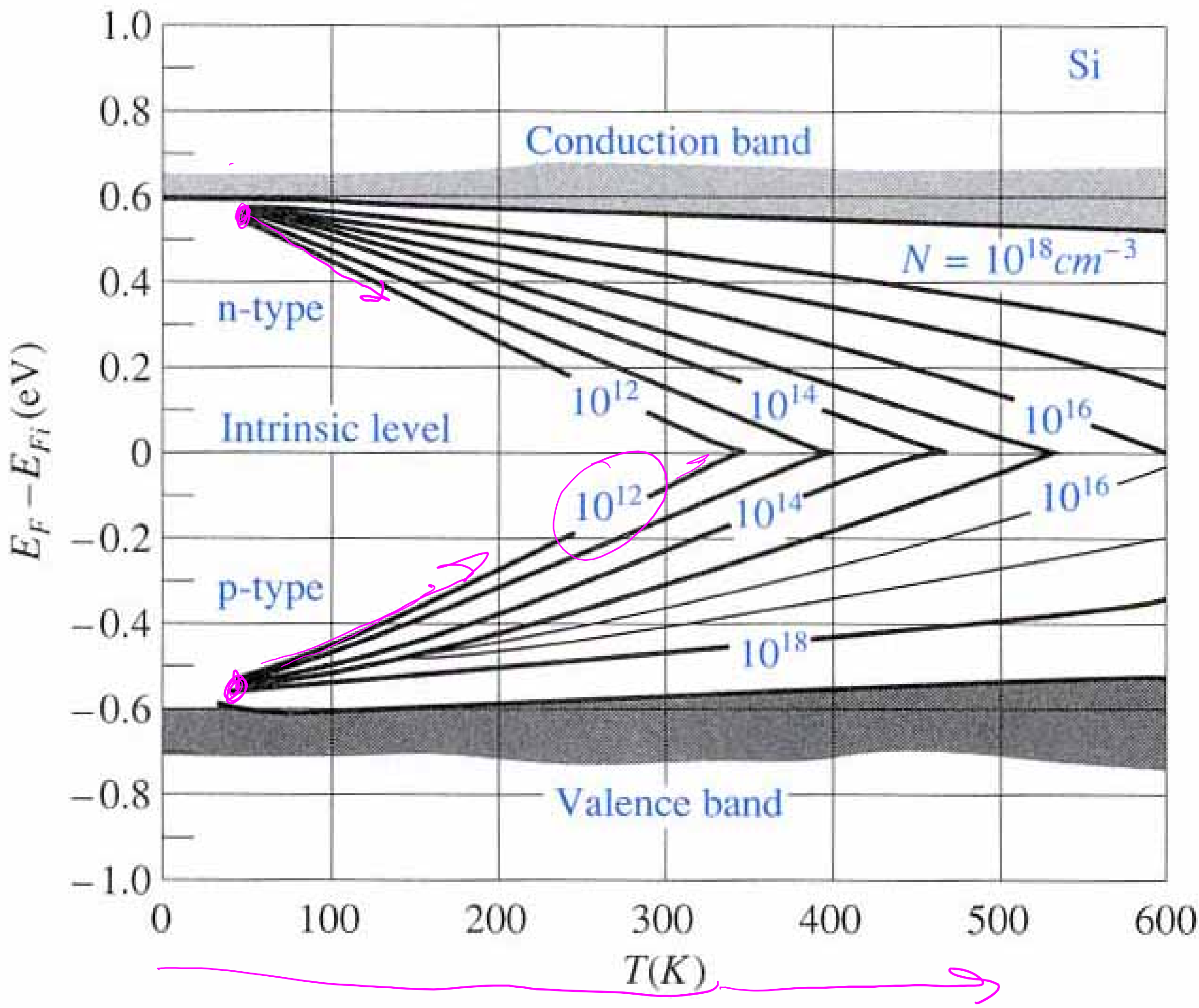


Figure 3.19 Position of Fermi level as a function of temperature for various doping concentrations (From Sze [11])

$$\boxed{E_i = \frac{E_g}{2} + \frac{3}{4} kT \ln \frac{m_{eff,h^+}}{m_{eff,e^-}}}$$

As $T \uparrow$,
$E_f \rightarrow$ mid gap

Dopant Energy Levels

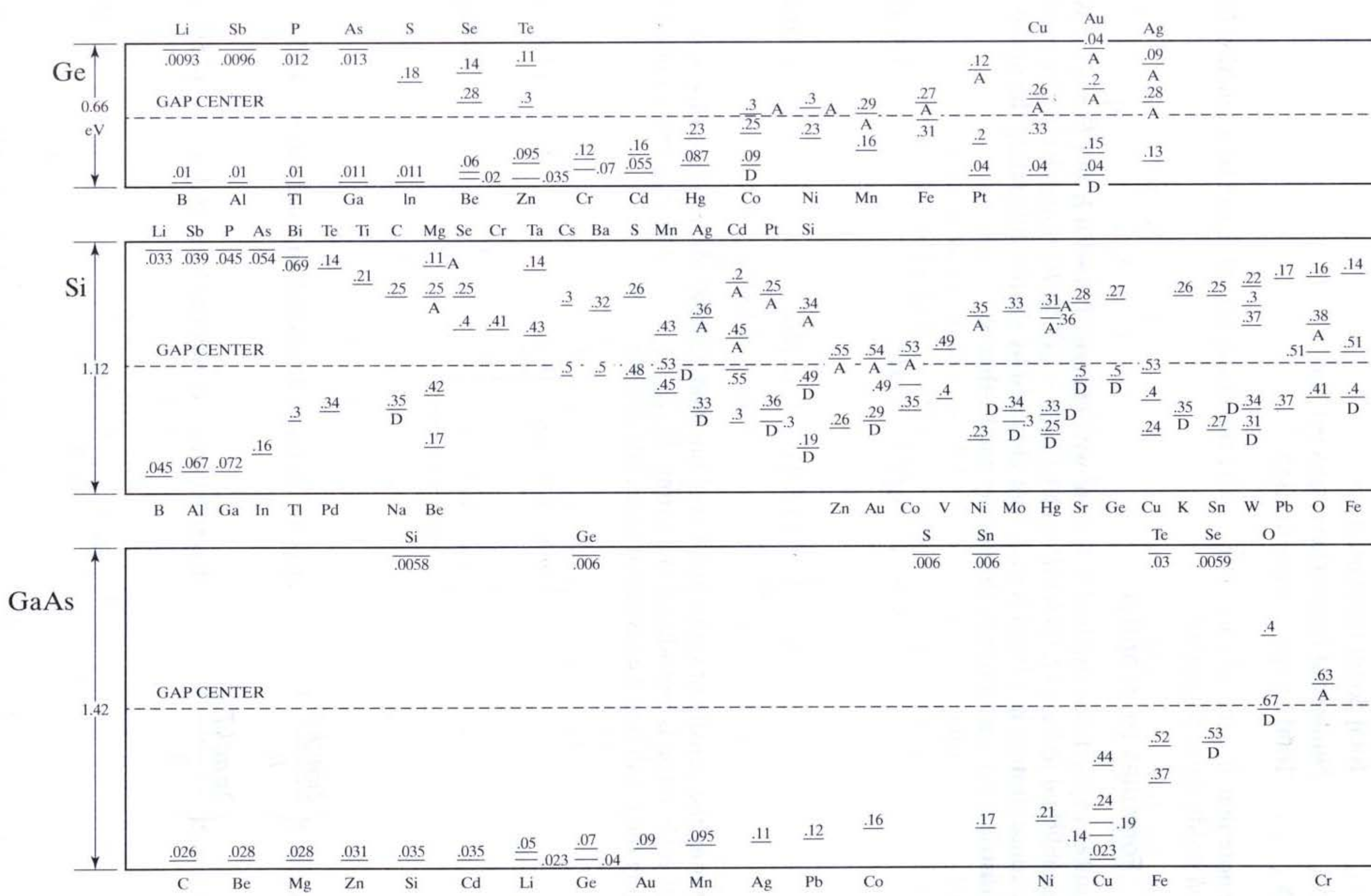


Figure 4.14 Measured ionization energies for the most commonly encountered impurities in Ge, Si, and GaAs. The levels above midgap are referenced to E_c and are donor-like or multiply charged donors, unless marked with an A which identifies an acceptor level. The levels below midgap are referenced to E_v and are acceptor-like or multiply charged acceptors, unless marked with a D for donor level. (From Sze.[3] Reprinted with permission.)

Pierret, Advanced Semiconductor Fundamentals (Pren. Hall, 2003).

Dopant Energy Levels

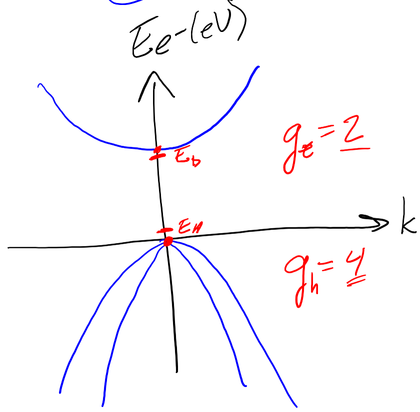
Table 5.1 Selected typical properties of Ge, Si and GaAs at 300 K. Effective mass related to conductivity (labeled a) is different than that for density of states (labeled b).

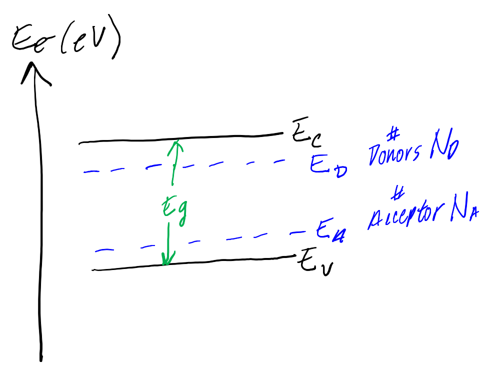
	E_g (eV)	χ (eV)	N_c (cm^{-3})	N_v (cm^{-3})	n_i (cm^{-3})	μ_e ($cm^2\ V^{-1}\ s^{-1}$)	μ_h ($cm^2\ V^{-1}\ s^{-1}$)	m_e^*/m_e	m_h^*/m_e	ε_r
Ge	0.66	4.13	1.04×10^{19}	6.0×10^{18}	2.4×10^{13}	3900	1900	0.12 a 0.56 b	0.23 a 0.40 b	16
Si	1.10	4.01	2.8×10^{19}	1.04×10^{19}	1.45×10^{10}	1350	450	0.26 a 1.08 b	0.38 a 0.56 b	11.9
GaAs	1.42	4.07	4.7×10^{17}	7×10^{18}	1.8×10^{6}	8500	400	0.067 a,b	0.40 a 0.50 b	13.1

Note: Effective mass related to conductivity (labeled a) is different for density of states (labeled b).
From Principles of Electronic Materials and Devices, Second Edition, S.O. Kasap (© McGraw-Hill, 2002)
http://Materials.Usask.Ca

Extrinsic Free Carrier Statistics

Find n and p for doped S/Cs





Extrinsic S/C Prop.: Free Carrier Statistics

- Free Carrier Statistics:
  - ✓ Previously, we determined the eqns:
    - o $n = f(T)$
    - o $p = f(T)$
  - ✓ Carrier concentrations as a function of temperature in intrinsic S/C's.
  - ✓ We found that:

$$n_i^2 = N_c N_v e^{-E_g/kT}$$

  - ✓ Since we have been discussing impurities in S/Cs (extrinsic S/Cs), we would like to find *n* and *p* for the extrinsic case.
  - ✓ That is, we want to determine how many free e⁻'s and h⁺'s exist near their respective band edges a a function of:
    - o Impurity concentration $n = f(N_{A,D}, T)$
    - o Temperature
  - ✓ Called "Free Carrier Statistics", this is again performed using:
    - o Statistical Mechanics ✓ $f_{FD}(E)$
    - o Quantum Mechanics ✓ $g(E)$

Extrinsic S/C Prop.: Free Carrier Statistics

❑ Let's define our extrinsic S/C system:

- ✓ One type of donor (when I say "donor" or "acceptor", I mean shallow-level donor or acceptor):
  - o The donor has energy, E_D
  - o The donor concentration, N_D

- ✓ One type of acceptor
  - o The acceptor has energy, E_A
  - o The acceptor concentration, N_A

- ✓ The position of the Fermi energy level, E_f, will be determined self-consistently by the:
  - o *Temperature*, T
  - o *Impurity concentrations*, N_D & N_A
  - o *Band gap energy*, E_g

- ✓ One additional factor to introduce: Degeneracy, g, in k-space:
  - o Donors:
    - $g = 2$, (spin ½) $m_j = \pm½$ (2 spin states)
  - o Acceptors:
    - $g = 4$, (spin 3/2) $m_j = \pm3/2$ (4 spin states)
      - » m_j is the total angular momentum

Extrinsic S/C Prop.: Free Carrier Statistics

Derive $\underline{n}$ $\therefore$ $\underline{N_D > N_A}$

- We now can ask: "What is the probability that a donor level at energy E_D with degeneracy g is occupied?"

- In order to answer this question, we need to use a distribution statistics of e^-'s & h^+'s

- What distribution function would you suggest?

Extrinsic S/C Prop.: Free Carrier Statistics

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- The Fermi-Dirac distribution function is (w/degeneracy g):

$$F(E) = \frac{1}{1 + g e^{(E - E_f)/kT}}$$

- The probability for occupancy of a donor level at energy E_D is:

$E = E_D$

$$F(E_D) = \frac{1}{1 + g_D e^{(E_D - E_f)/kT}}$$

- The fraction of donor levels, N^*, which are occupied by e⁻s is:

$$N^* = N_D \cdot F(E_D) = \frac{N_D}{1 + g_D e^{(E_D - E_f)/kT}}$$

- Let's choose a specific case in which:

$$N_D > N_A$$

n-Type

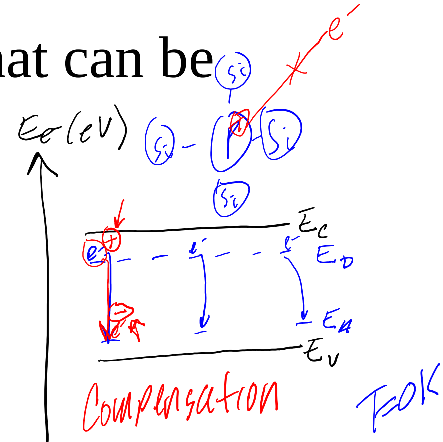
- What "type" of extrinsic S/C do we have?

Extrinsic S/C Prop.: Free Carrier Statistics

- The maximum number of e⁻'s that can be promoted to the CB is:

majority dopants minority dopants

$$N = N_D - N_A$$



- There are N_A e⁻'s compensated by acceptors.

- Since the acceptor states lie very close to the VB, the compensated e⁻'s in the acceptor states need nearly the E_g to be promoted to the CB.

- Therefore, they can be safely neglected at low temperatures: $T <$ room temperature

- Let: n = number or concentration of e⁻'s in CB

e⁻ In E_D # e⁻ In E_c

- Thus: $N = N_D - N_A = N^* + n$

  ✓ Where N^* is concentration of donor states occupied by e⁻'s

Extrinsic S/C Prop.: Free Carrier Statistics

- Since: $$N^* = N_D \cdot F(E_D)$$

- Substituting N^* in the previous equation:

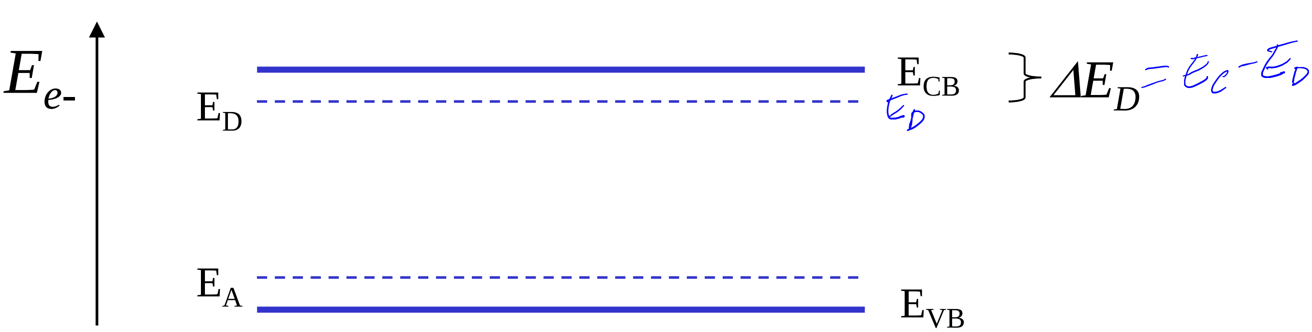
$$N = \frac{N_D}{1 + g_D e^{(E_D - E_f)/kT}} + n$$

$$= \frac{N_D}{1 + g_D e^{E_D/kT} e^{-E_f/kT}} + n$$

- Thus:

$$\frac{N - n}{N_D} = \frac{1}{1 + g_D e^{E_D/kT} e^{-E_f/kT}}$$

- Let's draw the energy band diagram when the S/C is compensated and define certain energy levels.



Extrinsic S/C Prop.: Free Carrier Statistics

- Continuing with our previous equation and taking the reciprocal of both sides, we have:

$$\frac{N_D}{N-n} = 1 + g_D e^{E_D/kT} e^{-E_f/kT}$$

$$\frac{N_D}{N-n} - 1 = g_D e^{E_D/kT} e^{-E_f/kT}$$

$$\frac{N_D - N + n}{N-n} = g_D e^{E_D/kT} e^{-E_f/kT} \qquad \text{(i)}$$

- From our earlier determination of the number of e$^-$'s in the CB, we found that:

$$\underline{n} = N_C e^{-(E_c - E_f)/kT}$$

· Intrinsic Case
· Solve For E_f → Substitute

- Where we assumed the *Boltzmann Approximation*.
- Thus, we are assuming that the S/C is nondegenerate.

Extrinsic S/C Prop.: Free Carrier Statistics

- Solving for E_f, we have:

$$E_f = E_c + kT\ln\left(\frac{n}{N_C}\right)$$

- Substituting E_f into equation. (i), we obtain:

$$n\cdot\frac{N_D - N + n}{N - n} = g_D e^{-\overbrace{(E_C - E_D)}^{\Delta E_D}/kT}\,\frac{N_C}{n}\cdot n$$

$$Let: \quad \Delta E_D = E_C - E_D \;\; \& \;\; \Theta = N_C g_D e^{-\Delta E_D/kT}$$

$$So: \quad \frac{n\left(N_D - N + n\right)}{N - n} = \Theta \quad \text{(ii)}$$

LHS = RHS → Arrhenius Behavior

- With some algebra, we obtain a quadratic equation in n:

$$n^2 + \left(N_D + \Theta - N\right)n - N\Theta = 0$$

Extrinsic S/C Prop.: Free Carrier Statistics

- To determine the number of e⁻'s in CB, solve for *n*.
- Using the Quadratic equation, solve for *n*:

$$n = \frac{1}{2}\left\{-\left(N_D + \Theta - N\right) \pm \sqrt{\left(N_D + \Theta - N\right)^2 + 4\Theta N}\right\}$$

$$= \frac{1}{2}\left\{-\left(N_D + \Theta - N\right) \pm \left(N_D + \Theta - N\right)\sqrt{1 + \frac{4\Theta N}{\left(N_D + \Theta - N\right)^2}}\right\}$$

$$= \frac{1}{2}\left(N_D + \Theta - N\right)\left\{\pm\sqrt{1 + \frac{4\Theta N}{\left(N_D + \Theta - N\right)^2}} - 1\right\}$$

- Since $n \geq 0$, we take only the positive solution.

$N = N_D - N_A$

✓

$$n = \frac{1}{2}\left(N_D + \Theta - N\right)\left\{\sqrt{1 + \frac{4\Theta N}{\left(N_D + \Theta - N\right)^2}} - 1\right\}$$

$$Where: \quad \Theta = N_C g_D e^{-\Delta E_D / kT}$$

$T^{3/2}$

ARRHENIUS

- This last expression is good to within several *kT* of the CB b/c the *Boltzmann Approximation* was used. $n = \frac{1}{2}(\Theta + N_A)\left[\sqrt{1 + \frac{4\Theta(N_D - N_A)}{(\Theta + N_A)^2}} - 1\right]$ (iii)

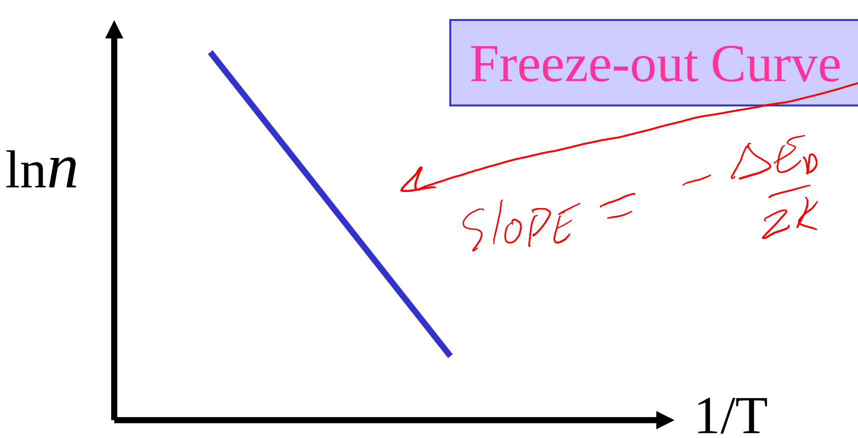
Extrinsic S/C Prop.: Free Carrier Statistics

We can use equation (ii) to examine several *Cases*:

- **Case 1:** $N_A = 0$ therefore $N = N_D$.
  - ✓ @ low T, $n << N_D$.
  - ✓ n = concentration of CB e⁻'s, a.k.a. the free carrier concentration

$$\boxed{n \approx \sqrt{g_D N_D N_C e^{-\Delta E_D / kT}} = \left(g_D N_D N_C\right)^{1/2} e^{-\Delta E_D / 2kT}}$$

✓Plot of ln(n) vs 1/T

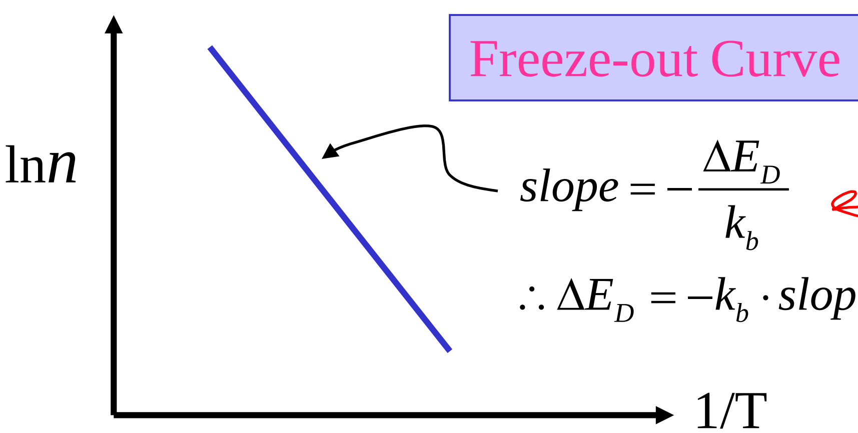


Extrinsic S/C Prop.: Free Carrier Statistics

- Case 2: $N_A \neq 0$. T~low, thus $n << N_A < N_D$

$$\underbrace{\boxed{n \approx g_D N_C \frac{N_D - N_A}{N_A} e^{-\Delta E_D / kT}}}$$

✓ Plot of ln(n) vs 1/T



$$slope = -\frac{\Delta E_D}{k_b}$$

$$\therefore \Delta E_D = -k_b \cdot slope$$

slope $= \cancel{2} \cdot \frac{\Delta E_D}{\cancel{2} k}$

✓ This region is also known as the "***Full-slope regime***".

Full-slope regime

Extrinsic S/C Prop.: Free Carrier Statistics

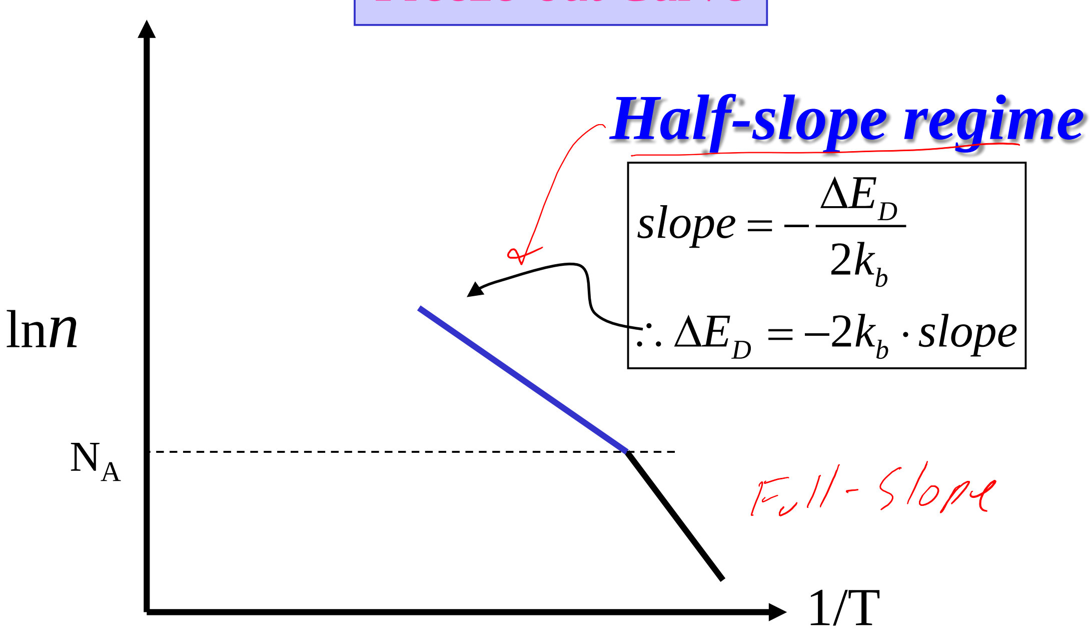
- Case 3: Increase T such that $N_A << n < N_D$

$$\boxed{n \approx \left(g_D N_C N_D\right)^{1/2} e^{-\Delta E_D / 2kT}}$$

✓ Similar to case 1, we find that the slope is $E_D/2k$ or "half-slope".

✓ Hence, the region in blue below is known as the "***half-slope regime***".

Freeze-out Curve



$$slope = -\frac{\Delta E_D}{2k_b}$$

$$\therefore \Delta E_D = -2k_b \cdot slope$$

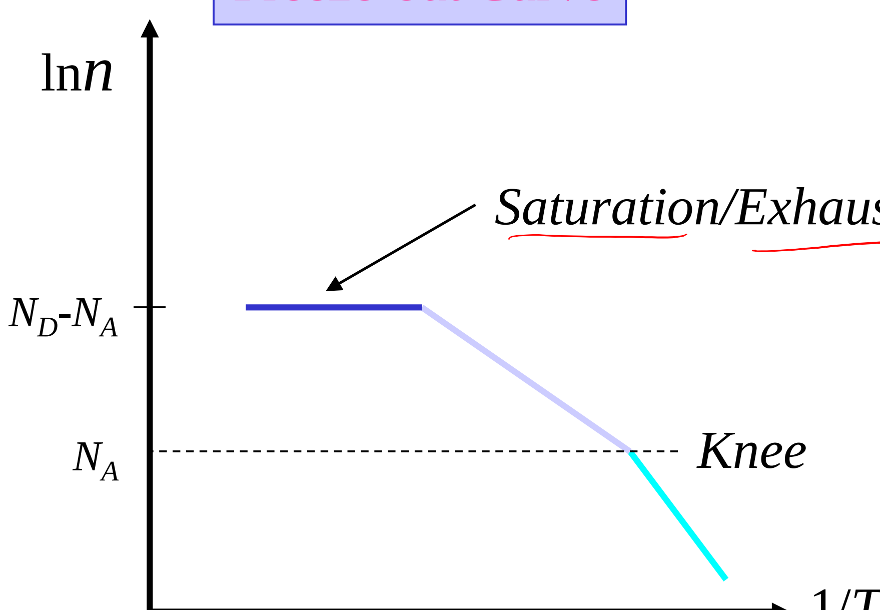
Extrinsic S/C Prop.: Free Carrier Statistics

Case 4:

- ✓ As T continues to increase, a region is attained in which the free e^- concentration, n, remains constant.
- ✓ This is known as the
  - o Exhaustion regime
  - o Saturation regime
- ✓ In this condition, n is given by:

$$\boxed{n = N_D - N_A}$$

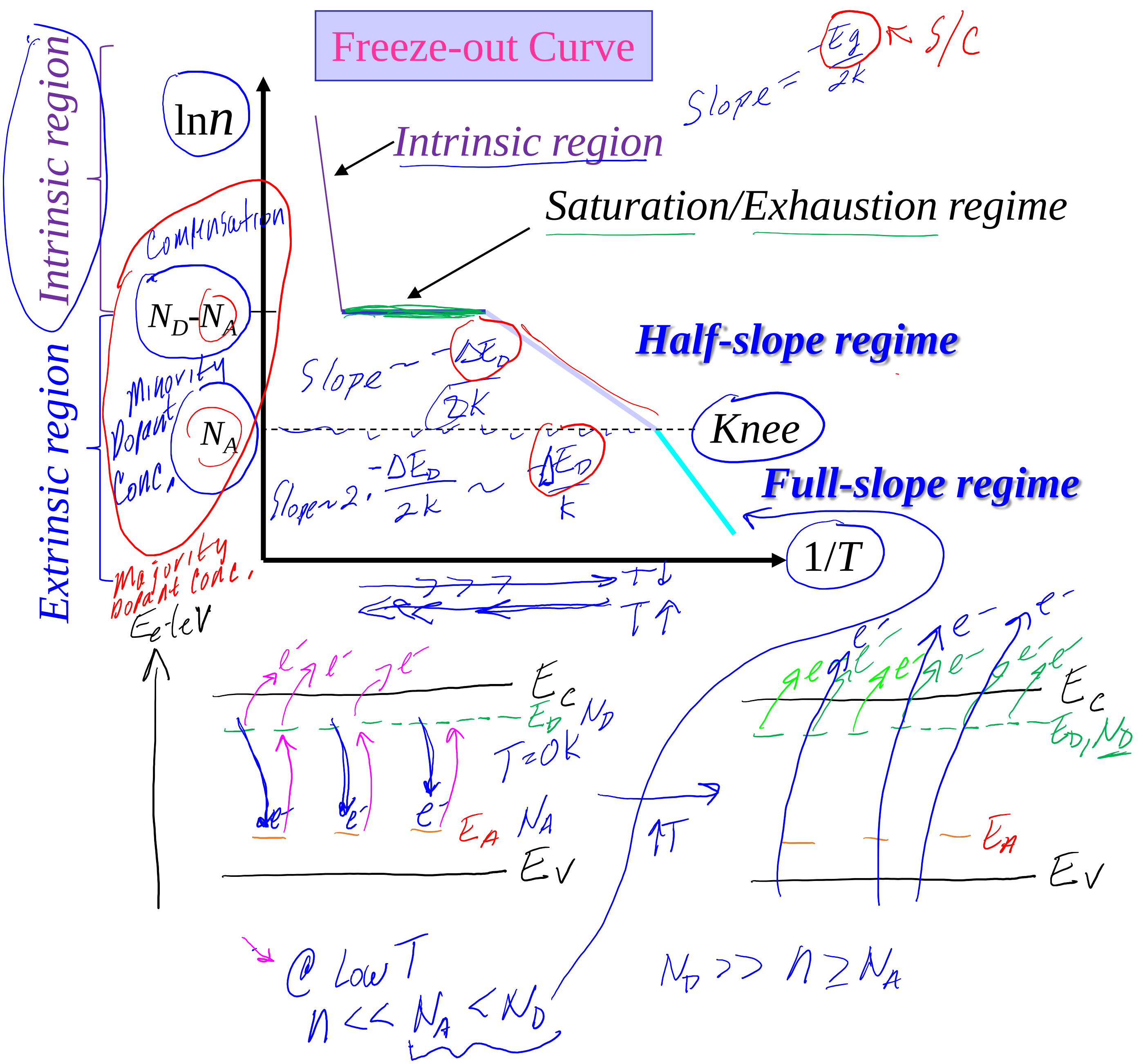
Freeze-out Curve



- ✓ Question: What happens at higher temps beyond the saturation regime?

Extrinsic S/C Prop.: Free Carrier Statistics

- Putting it all together:



Extrinsic S/C Prop.: Free Carrier Statistics

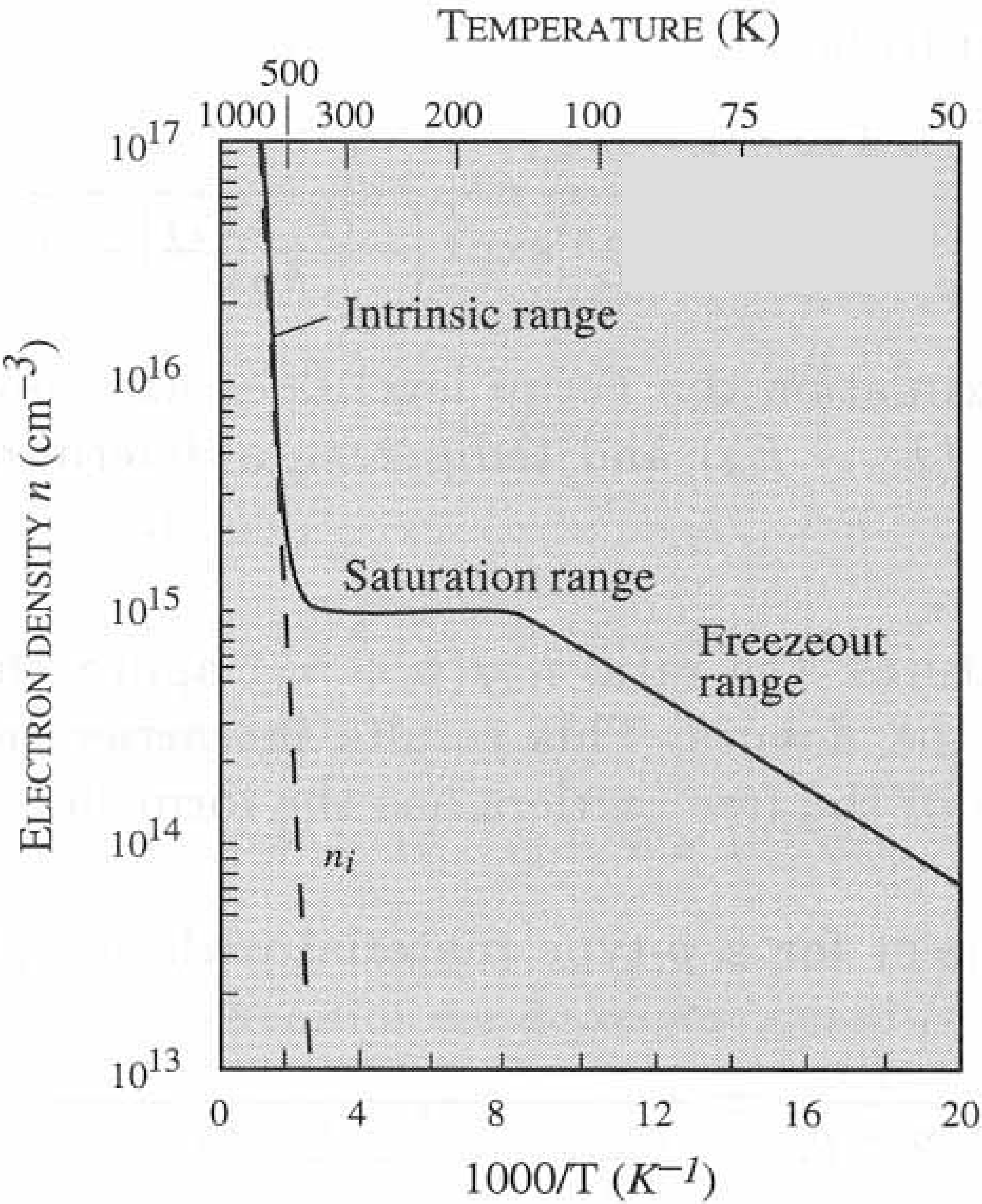
- Fermi Energy Level of a Doped S/C as a Function of Temperature
  - ✓ Assume equilibrium
  - ✓ At temperatures sufficiently high for the S/C to be intrinsic, E_f lies near mid-gap.
  - ✓ As T decreases E_f moves either toward the:
    - o CB for n-type
    - o VB for p-type
  - ✓ E_f coincides with the majority dopant energy level at the T for which 50% of the majority dopants are frozen out (i.e., neutral).

$$\boxed{\begin{gathered}\therefore N_D = N_D^o - N_D^+ \\ N_D^o = N_D^+\end{gathered}}$$

  - ✓ For *uncompensated* S/C (ideal case), E_f would approach a position close to the mid-point between the dopant level and a band edge (CB or VB).
  - ✓ For compensated S/Cs, a fraction of the majority dopants remain ionized at the lowest T and E_f will be very close to the majority dopant energy level.

Extrinsic S/C Prop.: Free Carrier Statistics

- In-class Exercise:
  - ✓ Determine if n- or p-type?
  - ✓ $|N_D - N_A|$?
  - ✓ Minority dopant concentration?
  - ✓ Full slope or half slope?
  - ✓ E_g? What is the S/C material?
  - ✓ E_D or E_A? What is the dopant?
  - ✓ Show where intrinsic region and extrinsic region and saturation regimes are.



Extrinsic S/C Prop.: Free Carrier Statistics

- Freezeout Curve

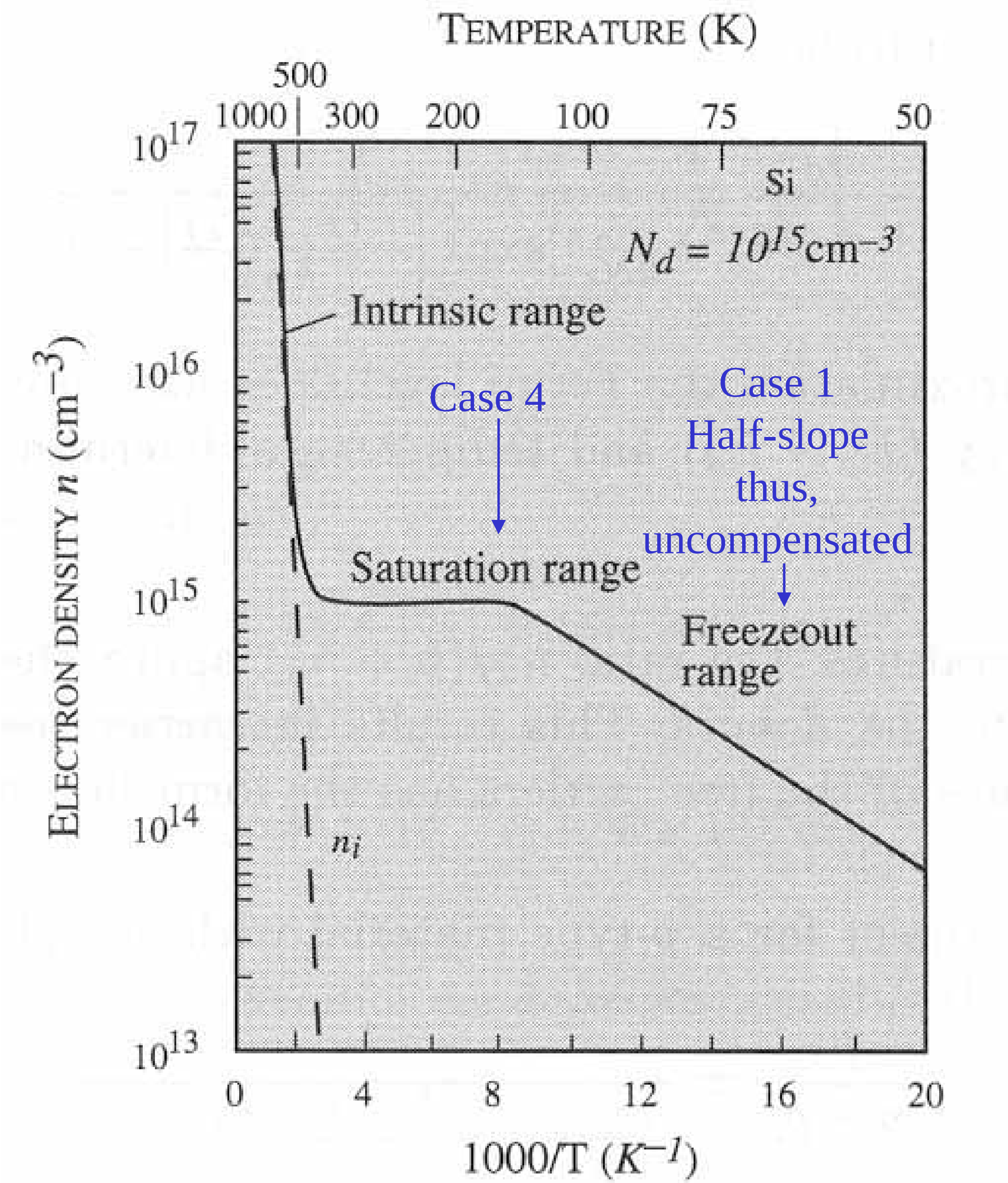


Figure 2.15: Electron density as a function of temperature for a Si sample with donor impurity concentration of 10^{15} cm^{-3}. It is preferable to operate devices in the saturation region where the free carrier density is approximately equal to the dopant density.

Singh, *Semiconductor Devices: Basic Principles* (2000)

Extrinsic S/C Prop.: Free Carrier Statistics

- Freezeout Curve

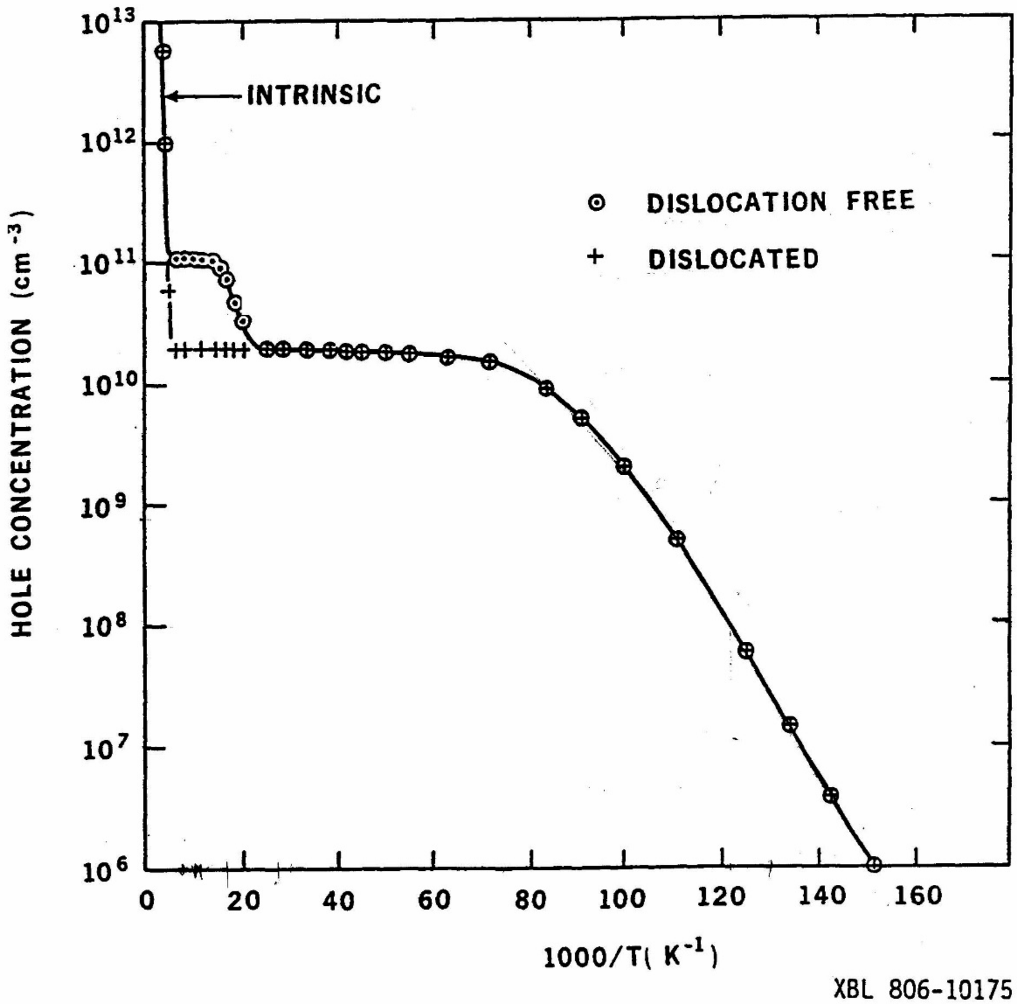


Fig. 21. Arrhenius plots of the free hole concentrations of a dislocation-free and a dislocated piece of single crystal high-purity Ge grown in a H_2 atmosphere.

McCluskey & Haller, *Dopants & Defects in Semiconductors* (CRC Press, 2012) fig. 4.13, p. 120
After: Haller, Hansen, & Goulding, **Adv. Phys**. (1981)