ECE 536
Integrated Optics and Optoelectronics

TuTh 11:00-12:20, 3020 ECEB  
Professor John Dallesasse  
2114 Micro and Nanotechnology Laboratory  
Tel: (217) 333-8416  
E-mail: jdallesa@illinois.edu  
Office Hours: Tuesday 1:00-2:00 pm
Upcoming Dates

• Revised Homework Schedule Posted
• Final Project Report Due 5/2
• Final Project Presentation Schedule (5/6):

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Comments on Abstracts

- Pay attention to who you attribute things to in your background section!
- Make sure you are operating at a graduate-school level in your analysis. Ask yourself “Would I submit this to a journal for publication as a mini-review?”
- Pay attention to formatting
- Pay attention to grammar
- As much as possible, make your figures “journal quality”
## Tentative Schedule [3]

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**Subject to Change**
Today’s Discussion

- Plasmonics
- Franz Keldysh Effect
- Polarization Rotation
- Assignments
- Topics for Next Lecture
Coupler Supermodes

Interference with Input

For a lossless coupler, $t^2 + \kappa^2 = 1$.

Roundtrip condition: $a_2 = ae^{i\theta}b_2$

$$a = e^{-\alpha L/2}$$

$$b_1 = ta_1 + i\kappa a_2 = ta_1 + i\kappa ae^{i\theta}b_2$$

For $a = t$, $b_1 = 0$
Plasmonics

§ 7.7
The goal is to develop waveguide structures with sub-wavelength dimensions. To form a surface plasmon polariton wave, the real part of the dielectric constant needs to change sign across the interface. Metals behave like plasma at optical frequencies, i.e.

$$\varepsilon_p(\omega) = \varepsilon_0(1 - \omega_p^2 / \omega^2)$$

Thus, the permittivity can be made negative by setting $\omega<\omega_p$. Negative feature: high loss.

$\omega_p$ is the plasma frequency.

A surface plasmon polariton wave involves both charge motion in the metal ("surface plasmon") and electromagnetic waves in the air or dielectric ("polariton").


Note: The book uses $z$ as the direction of propagation and $x$ as the direction perpendicular to the surface.
Surface Plasmon Mode for a Single Interface

To form a mode, that decays in both directions away from the surface but is guided along the $z$-direction, we need TM polarization:

$$\mathbf{H} = H_y \hat{y} = \hat{y} H_0 e^{ik_z z} \begin{cases} e^{-\alpha_1 x} & \text{for } x \geq 0 \\ e^{\alpha_2 x} & \text{for } x \leq 0 \end{cases}$$

The wave equation in each region results in:

$$-\alpha_1^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_1$$

$$-\alpha_2^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_p(\omega)$$

The electric field is obtained from Maxwell's equations $\mathbf{E} = \nabla \times \mathbf{H} / (-i\omega\varepsilon)$:

$$\mathbf{E} = \begin{cases} \frac{1}{i\omega \varepsilon_1} \left( \alpha_1 \hat{z} + \hat{x} k_z \right) H_0 e^{ik_z z} e^{-\alpha_1 x} & \text{for } x \geq 0 \\ \frac{1}{i\omega \varepsilon_p} \left( -\alpha_2 \hat{z} + \hat{x} k_z \right) H_0 e^{ik_z z} e^{\alpha_2 x} & \text{for } x \leq 0 \end{cases}$$
The tangential component for $E$, i.e. $E_z$ must be continuous:

$$\frac{\alpha_1}{\varepsilon_1} = -\frac{\alpha_2}{\varepsilon_p}$$

This explains why Re[$\varepsilon$] needs to change sign across the interface.

Overall, if $\varepsilon_p < -\varepsilon_1 < 0$, we obtain real solutions:

$$\alpha_1 = \omega \sqrt{\frac{-\mu_0 \varepsilon_1^2}{\varepsilon_1 + \varepsilon_p}}$$

$$\alpha_2 = \omega \sqrt{\frac{-\mu_0 \varepsilon_p^2}{\varepsilon_1 + \varepsilon_p}}$$

$$k_z = \omega \sqrt{\frac{\mu_0 \varepsilon_1 \varepsilon_p}{\varepsilon_1 + \varepsilon_p}}$$

The Poynting vector is given by:

$$P = \frac{1}{2} \text{Re}[E \times H] = \hat{z} \frac{k_z}{2\omega} |H_0|^2 \begin{cases} 
\frac{1}{\varepsilon_1} e^{-2\alpha_1 x} & \text{for } x \geq 0 \\
\frac{1}{\varepsilon_p} e^{2\alpha_2 x} & \text{for } x \leq 0 
\end{cases}$$
Surface Plasmon Mode for a Double Interface

Even and odd TM modes are guided:

\[ \mathbf{H}_{\text{even}} = \hat{y} e^{ikz} \begin{cases} C_0 e^{-\alpha_1(x-d/2)} & x \geq d/2 \\ C_1 \cosh \alpha_2 x & |x| \leq d/2 \\ C_0 e^{\alpha_1(x+d/2)} & x \leq -d/2 \end{cases} \]

The wave equation in each region results in:

\[ -\alpha_1^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_1 \]

\[ -\alpha_2^2 + k_z^2 = \omega^2 \mu_0 \varepsilon_p(\omega) \]

We need \( H_y \) and \( E_z \) to be continuous at \( x = \pm \frac{d}{2} \) [Use: \( \mathbf{E} = \nabla \times \mathbf{H} / (-i\omega\varepsilon) \)]

\[ C_0 = C_1 \cosh \alpha_2 \frac{d}{2} \text{ and } -\frac{\alpha_1}{\varepsilon_1} C_0 = C_1 \frac{\alpha_2}{\varepsilon_p} \sinh \alpha_2 \frac{d}{2}. \]

Dividing these two gives:

\[ \alpha_1 = -\frac{\varepsilon_1}{\varepsilon_p} \alpha_2 \tanh \alpha_2 \frac{d}{2} \quad \text{(boundary condition)} \]

\[ \alpha_2^2 - \alpha_1^2 = \omega^2 \mu_0 \left( \varepsilon_1 - \varepsilon_p \right) \quad \text{(wave equation)} \]
Surface Plasmon Mode for a Double Interface

Even and odd TM modes are guided:

\[
H_{\text{odd}} = \hat{y} e^{ikz} C_1 \begin{cases} 
\sinh \alpha_2 \frac{d}{2} e^{-\alpha_1 (x - \frac{d}{2})} & x \geq d / 2 \\
\sinh \alpha_2 x & |x| \leq d / 2 \\
-\sinh \alpha_2 \frac{d}{2} e^{\alpha_1 (x + \frac{d}{2})} & x \leq -d / 2
\end{cases}
\]

The same analysis yields:

\[
\alpha_1 = -\frac{\varepsilon_1}{\varepsilon_p} \alpha_2 \coth \alpha_2 \frac{d}{2} \quad \text{(boundary condition)}
\]

\[
\alpha_2^2 - \alpha_1^2 = \omega^2 \mu_0 (\varepsilon_1 - \varepsilon_p) \quad \text{(wave equation)}
\]
For both even and odd modes, we define:

\[ X = \alpha_2 \frac{d}{2}, \quad Y = \alpha_1 \frac{d}{2}, \quad R = \omega \sqrt{\mu_0 \left( \varepsilon_1 - \varepsilon_p \right)} \frac{d}{2}, \]

We need to solve:

\[ X^2 - Y^2 = R^2 \quad \text{(wave equation)} \]

\[
Y = \begin{cases} 
-\frac{\varepsilon_1}{\varepsilon_p} X \tanh X & \text{(even modes)} \\
-\frac{\varepsilon_1}{\varepsilon_p} X \coth X & \text{(odd modes)} 
\end{cases}
\]

Note: unlike the symmetric dielectric slab, there is only 1 even and 1 odd mode.
Franz-Keldysh Effect
Franz-Keldysh Effect: Physical Description

- When a field is applied across a sample, band bending occurs.
- The allowed electron and hole wave functions (allowed state energies) penetrate into the forbidden band.
- A photon with a sub-bandgap energy can interact with the tails of the wave functions and be absorbed.
- This is photon-assisted tunneling: an electron in the valence band tunnels to the conduction band with the assistance of a sub-bandgap photon.
Consider the case of a uniform applied electric field:
\[ \mathbf{V}(\mathbf{r}) = e\mathbf{F} \cdot \mathbf{r} \]
Schrodinger's Equation can therefore be written:
\[
\left[ -\frac{\hbar^2}{2m^*_r} \nabla^2 + e\mathbf{F} \cdot \mathbf{r} \right] \phi(\mathbf{r}) = E\phi(\mathbf{r})
\]
In the case where the field is applied in the z-direction:
\[ \mathbf{F} = F\hat{z} \]
The wave function is a plane wave in x-y, so \( \phi \) can be written:
\[ \phi(\mathbf{r}) = \frac{e^{i(k_x x + i k_y y)}}{\sqrt{A}} \phi(z) \]
The z-dependent portion of the wave function is a solution to:
\[
\left[ -\frac{\hbar^2}{2m^*_r} \frac{d}{dz^2} + eFz \right] \phi(z) = E_z \phi(z)
\]
The total energy is:
\[ E = \frac{\hbar^2}{2m^*_r} \left( k_x^2 + k_y^2 \right) + E_z \]
The solutions to the wavefunction are Airy functions.
Schrödinger's Equation Solution: Uniform Field

To solve Schrödinger's equation in a uniform field, a coordinate transformation is applied:

\[ Z = \left( \frac{2m^*_r eF}{\hbar^2} \right)^{1/3} \left( z - \frac{E_z}{eF} \right) \]

Schrödinger's equation can thus be rewritten:

\[ \frac{d^2 \phi(Z)}{dZ^2} - Z\phi(Z) = 0 \]

The solution to this differential equation are Airy functions:

\[ Ai(Z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i \left( \frac{t^3}{3} + Zt \right)} dt \sim \frac{1}{2\sqrt{\pi}} Z^{-1/4} e^{-2Z^{3/2}/3} \quad (\text{approx. for large } Z) \]

\[ Bi(Z) = i \left( e^{2\pi i/3} \right)^2 Ai\left( e^{4\pi i/3} z \right) - i \left( e^{2\pi i/3} \right) Ai\left( e^{2\pi i/3} z \right) \sim \frac{1}{\sqrt{\pi}} Z^{-1/4} e^{+2Z^{3/2}/3} \quad (\text{approx. for large } Z) \]

The \( Bi(Z) \) solution is non-physical as the wave function needs to approach 0 for large \( Z \).

The energy spectrum is continuous because the potential is not bounded as \( z \to -\infty \).

Applying the normalization condition: \[ \int_{-\infty}^{\infty} \phi_{E_{z_1}}(z) \phi_{E_{z_2}}(z) dz = \delta(E_{z_1} - E_{z_2}), \]

The wave function is:

\[ \phi_{E_z}(z) = \left( \frac{2m^*_r}{\hbar^2} \right)^{1/3} \frac{1}{(eF)^{1/6}} Ai\left( \left( \frac{2m^*_r eF}{\hbar^2} \right)^{1/3} \left( z - \frac{E_z}{eF} \right) \right) \]
Franz-Keldysh Absorption Spectrum

The expression for the absorption spectrum (from Lecture 7) is given by:

$$\alpha(\hbar\omega) = C_o \frac{2}{V} \sum_{i,f} |\langle f | e^{i k_0 r} \hat{e} \cdot \mathbf{p} | i \rangle|^2 \delta \left( E_f - E_i - \hbar\omega \right) \left[ f \left( E_i \right) - f \left( E_f \right) \right],$$

where $C_o = \frac{\pi e^2}{n_r c \varepsilon_0 m_0^2 \omega}$.

For a two-particle Hamiltonian (i.e. electrons and holes), the coordinates are selected to be the center of mass $R = \frac{m_e^* \mathbf{r}_e + m_h^* \mathbf{r}_h}{m_e^* + m_h^*}$ and the separation $\mathbf{r} = \mathbf{r}_e - \mathbf{r}_h$ rather than the individual positions $\mathbf{r}_e$ and $\mathbf{r}_h$.

This transformation is useful when $V$ depends only on $\mathbf{r}$ such as for electrons and holes that are:

(a) free: $V(\mathbf{r}) = 0$

(b) in an electric field: $V(\mathbf{r}) = e \mathbf{F} \cdot \mathbf{r}$, or

(c) interacting via the Coulomb potential (exciton effect) $V(\mathbf{r}) = -\frac{e^2}{4\pi \varepsilon_s r}$.

In these cases, the absorption spectrum can be simplified as:

$$\alpha(\hbar\omega) = 2C_o |\hat{e} \cdot \mathbf{p}_{cv}|^2 \sum_n |\phi_n(0)|^2 \delta \left( E_n + E_g - \hbar\omega \right)$$
Since the quantum state $n$ is defined by $(k_x,k_y,E_z)$, we write:

$$\alpha(\hbar\omega) = 2 C_o |\hat{e} \cdot \mathbf{p}_{cv}|^2 \sum_n |\phi_n(0)|^2 \delta\left(E_n + E_g - \hbar\omega\right)$$

$$= 2 C_o |\hat{e} \cdot \mathbf{p}_{cv}|^2 \sum_{k_x} \sum_{k_y} \int |\phi_n(r = 0)|^2 \delta\left(\frac{\hbar^2}{2m^*_r} (k_x^2 + k_y^2) + E_z + E_g - \hbar\omega\right) dE_z$$

Using $\sum_{k_x,k_y} = 2 \int \frac{d^2k_t}{(2\pi)^2} = \frac{m^*_r}{\pi\hbar^2} \int dE_t$ where $E_t = \frac{\hbar^2(k_x^2 + k_y^2)}{2m^*_r} = \frac{\hbar^2k^2_t}{2m^*_r}$, we get:

$$\alpha(\hbar\omega) = C_o |\hat{e} \cdot \mathbf{p}_{cv}|^2 \frac{m^*_r}{\pi\hbar^2} \int dE_z \int_0^\infty |\phi_n(r = 0)|^2 \delta\left(E_t + E_z + E_g - \hbar\omega\right) dE_t$$

$$\alpha(\hbar\omega) = C_o |\hat{e} \cdot \mathbf{p}_{cv}|^2 \frac{m^*_r}{\pi\hbar^2} \int_{-\infty}^{\infty} \int_0^{\infty} |\phi_{E_z}(z = 0)|^2 dE_z$$
Franz-Keldysh Absorption Spectrum

\[ \alpha(\hbar \omega) = C_0 |\hat{e} \cdot \mathbf{p}_{cv}|^2 \frac{m^*_r}{\pi \hbar^2} \int_{-\infty}^{\hbar \omega - E_g} \left| \phi_{E_z}(z = 0) \right|^2 dE_z \]

With further work, it can be shown:

\[ \alpha(\hbar \omega) = C_0 |\hat{e} \cdot \mathbf{p}_{cv}|^2 \frac{1}{2\pi} \left( \frac{2m^*_r}{\hbar^2} \right)^{3/2} \sqrt{\hbar \theta_F} \left[ -\eta A i^2(\eta) + A i'^2(\eta) \right] \]

where: \( A i'(\eta) = \frac{dA i(\eta)}{d\eta} \), \( \hbar \theta_F = \left( \frac{\hbar^2 e^2 F^2}{2m^*_r} \right)^{1/3} \), \( \eta = \frac{E_g - \hbar \omega}{\hbar \theta_F} \)

Note that, in the limit as \( F \to 0 \), \( \alpha(\hbar \omega) \to C_0 |\hat{e} \cdot \mathbf{p}_{cv}|^2 \frac{1}{2\pi} \left( \frac{2m^*_r}{\hbar^2} \right)^{3/2} \sqrt{\hbar \omega - E_g} \)

The momentum matrix element can be found by fitting to absorption data curves both with and without an applied field.
Features of the Absorption Spectra that are Related to the Franz-Keldysh Effect
Exciton Effects
An electron-hole pair can interact through the Coulomb force to form an exciton:

\[ V(r) = \frac{-e^2}{4\pi \varepsilon_r r} \]

The wave function satisfies Shrodinger's Equation for a hydrogen-like potential:

\[
\left[ -\frac{\hbar^2}{2m^*_e} \nabla^2 - \frac{e^2}{4\pi \varepsilon_r r} \right] \phi(r) = E \phi(r)
\]

The absorption coefficients can be derived through Fermi's Golden Rule. Total absorption is the sum of contributions from bound states and continuum states.
Absorption Coefficients for 2-D and 3-D Cases

For 3D bulk GaAs,

\[ R_y \approx 4.2 \text{meV} \]

\[ a_0 \approx 12 \text{nm} \]

\[ \varepsilon = (\hbar \omega - E_g)/R_y, \quad A_0 = \frac{\pi e^2 |\varepsilon \cdot p_{cv}|^2}{n_r c \varepsilon_0 \omega m_0^*}, \quad a_0 = \frac{\hbar^2}{m_r^*} \left( \frac{4 \pi \varepsilon_0}{\varepsilon} \right), \quad R_y = \frac{m_r^* e^4}{2\hbar^2 (4 \pi \varepsilon_0)^2} \]

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<th>Bound States</th>
<th>Continuum States</th>
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**Two-dimensional exciton:**

Zero linewidth

\[ A_0 \sum_{n=1}^{\infty} \frac{2}{n^2} \frac{1}{(n - \frac{1}{2})^2} R_y \delta \left( \varepsilon + \frac{1}{(n - \frac{1}{2})^2} \right) \]

\[ S_{2D}(\varepsilon) = \frac{2}{1 + \exp (-2\pi/\sqrt{\varepsilon})} \]

Finite linewidth

\[ A_0 \sum_{n=1}^{\infty} \frac{2}{n^2} \frac{1}{(n - \frac{1}{2})^2} R_y \left[ \frac{\gamma/\pi}{\varepsilon + \frac{1}{(n - \frac{1}{2})^2}} \right] + \gamma^2 \]

**Three-dimensional exciton:**

Zero linewidth

\[ A_0 \sum_{n=1}^{\infty} \left( \frac{2}{n^3} \right) \frac{1}{R_y} \delta \left( \varepsilon + \frac{1}{n^2} \right) \]

\[ S_{3D}(\varepsilon) = \frac{2\pi/\sqrt{\varepsilon}}{1 - e^{-2\pi/\sqrt{\varepsilon}}} \]

Finite linewidth

\[ A_0 \sum_{n=1}^{\infty} \left( \frac{2}{n^3} \right) \frac{1}{R_y} \left( \frac{\gamma/\pi}{(\varepsilon + \frac{1}{n^2})^2 + \gamma^2} \right) \]

\[ S_{3D}(\varepsilon) = \frac{\gamma \sqrt{\varepsilon}}{\pi} S_{3D}(\varepsilon') \quad \text{with} \quad \gamma = \frac{\hbar^2}{m_r^*} \left( \frac{4 \pi \varepsilon_0}{\varepsilon} \right) \]
Exciton Absorption for 2-D and 3-D

(a) 2D ($\gamma = 0$)

$\alpha(\hbar \omega)$

$1s$

With exciton effect

$2s$

Without exciton effect

$E_g$

$-4R_y$

$h\omega$

(b) 2D ($\gamma \neq 0$)

$\alpha(\hbar \omega)$

$h\omega$

$E_g - 4R_y$

$E_g$

(c) 3D ($\gamma = 0$)

$\alpha(\hbar \omega)$

$1s$

With exciton effect

Without exciton effect

$E_g$

$E_g - R_y$

$h\omega$

(d) 3D ($\gamma \neq 0$)

$\alpha(\hbar \omega)$

$h\omega$

$E_g - R_y$

$E_g$
Bulk and Quantum-Confined Absorption

(a) 
\[ \alpha (10^4 \text{cm}^{-1}) \]

Photon energy (eV)

(b) 
InGaAs/InAlAs
Undoped

100K
12K
300K

Absorbance-U

Energy (eV)
Assignments
Assignments

• Reading
  – Physics of Photonic Devices (S.L. Chuang)
    • Tues 3/26: §’s 8.2 C&C
    • Thurs 3/28: §’s 8.1, 8.2
    • Tues 4/2: N/A
    • Thurs 4/6: §’s 14.2, 14.3
    • Tues 4/9: §’s 14.4, 14.5, 14.6
    • Thurs 4/11: §’s 15.1, 2.4
    • Tues 4/16: §’s 15.2, 15.3
    • Thurs 4/18: §’s 15.4, 15.5
  – Diode Lasers and Photonic Integrated Circuits (Coldren & Corzine)
    • § 8.2.5
    • § ’s 3.6-3.7, 8.2.3-8.2.4
    • § ’s 6.6-6.8
    • Appendix 1, 2, 3, 9 (Supplemental)
Topics for Next Lecture
Agenda for Thursday, 4/11

• Continue VCSELs
• Laser Modulation
• Coupled Waveguides
Thank You for Listening!
Course Purpose & Objectives
Course Purpose

• Cover the theory and design of semiconductor devices used in optical communication systems and electronic-photonic integrated circuits
Course Objectives

• Discuss, at a graduate level, key topics in semiconductor physics
• Discuss, at a graduate level, key topics in electromagnetics as applied to photonic devices
• Provide an understanding of active photonic devices used in optical communication systems and photonic integrated circuits
• Provide an understanding of passive photonic devices used in optical communication systems and photonic integrated circuits
Overlap With ECE/PHYS Courses

Quantum Mechanics
(PHYS 486/487)

Semiconductor Physics
(ECE 488)

E&M
(ECE 452/520)

ECE 536
Course Schedule
# Tentative Schedule [1]

| JAN 15: Course Overview, Intro to Optoelectronics & Communication, Maxwell’s Equations | JAN 17: Semiconductor Electronics |
| JAN 22: Generation and Recombination in Semiconductors | JAN 24: Basic Quantum Mechanics and Square Wells |
| JAN 29: Time-Dependent Perturbation Theory, Fermi’s Golden Rule | JAN 31: Symmetric Optical Waveguides, Dispersion Relations |
| FEB 5: Optical Transitions Using Fermi’s Golden Rule | FEB 7: Interband Absorption and Gain of Bulk Semiconductors and Quantum Wells |

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<td>MAR 7</td>
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<td>APR 23</td>
<td>Lecture</td>
</tr>
<tr>
<td>APR 25</td>
<td>Lecture</td>
</tr>
<tr>
<td>April 30</td>
<td>Exam II</td>
</tr>
<tr>
<td>MAY 2</td>
<td>Reading Day (no class) Final Exam: Class Presentations</td>
</tr>
</tbody>
</table>

**Subject to Change**
Grading, Expectations, and Policies
## Determination of Grade

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homework</td>
<td>20%</td>
</tr>
<tr>
<td>Exam I</td>
<td>25%</td>
</tr>
<tr>
<td>Exam II</td>
<td>25%</td>
</tr>
<tr>
<td>Class Participation &amp; Term Project Presentation</td>
<td>15%</td>
</tr>
<tr>
<td>Term Project Report</td>
<td>15%</td>
</tr>
</tbody>
</table>
Homework

• Assigned per posted class schedule on Thursdays, due 1 week later

• TA is Fu-Chen Hsiao, 3211 MNTL
  – Office hours Wednesday from 10-11am, 4034 ECEB
  – TA: good first contact for questions on homework

• Do not copy solutions from others in class or from other sources
Term Project

• Collaborative presentation: teams of 2
• Individual paper
• Details and a list of topics will be provided in early February
Expectations

• Diligence
  – Attend class & participate

• Honesty
  – No cheating on exams or homework
  – Original work on term project
  – Accurate/legitimate representation of any issues affecting homework/exams/project

• Mutual Respect

• Maturity
  – Graduate-level class
Policies

• Where applicable, general university policies on academic affairs will be used

• Any issues involving homework, exams, semester project, etc. should be disclosed and discussed as soon as the issue is known
Text Errata
Text Errata

• Text errata provided by Professor Chuang will be posted on the class website
  – I will include additional errata in the lecture slides

• Handout: inside book cover

• Additional errata:
  – Equation 3.2.18 “=“ should be “>”
    • $|z| > L/2$
  – Equation 3.2.23 “=“ should be “<“
    • $|z| < L/2$
  – Equation 3.2.23: “L/2” not “L2” in exponent
1) Equation 1.3.1 should be:
\[ a(\text{A}_x\text{B}_{1-x}\text{C}) = xa(\text{AC}) + (1-x)a(\text{BC}) \]
where \(a(\text{AC})\) is the lattice constant of the binary compound \(\text{AC}\) and...

2) Equation 1.3.2 should be:
\[ E_g(\text{A}_x\text{B}_{1-x}\text{C}) = xE_g(\text{AC}) + (1-x)E_g(\text{BC}) - bx(1-x) \]

3) Other printing errors in book - see errata posted on website
Errata

• Equation 3.6.15 should be:

\[ a_m^{(0)}(t = 0) = 0 \quad \text{not} \quad a_m^{(0)}(t) = 0 \]
Correction: Typo in Book

- Pg. 41, top of page, between equations 2.3.3 and 2.3.4
- Current Text is: “0 = Bn_o p_o = e_r”
- Should Be: “0 = Bn_o p_o - e_r”

The consequence of this is that $Bn_o p_o = e_r$ in equilibrium where there is no optical generation or electrical injection of carriers.
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