Lecture 1

• What are we Going to Cover?
• Course Overview.
• Course Logistics.
• Regulations.
• Effective Masses (Review of ECE614).
• Brillouin Zones (Review of ECE614).
• Constant Energy Surfaces (Review of ECE614).
What are we Going to Cover in this Course?

Device Physics Sequence

- ECE614 - Semiconductors.
- Last term – Fall term even years.
  - Energy bands [Schrödinger Equation to E vs. k].
  - Semiconductors in equilibrium [charge neutrality].
  - Semiconductors in non-equilibrium [continuity equations].
  - Transport [BTE, continuity equations].
Device Physics Sequence

• ECE615 - Semiconductor Devices I.
• This term – Winter term odd years.
• Two-Terminal Semiconductor Devices.
  • pn junctions.
  • Schottky barriers.
  • MOS (Metal-oxide-semiconductor) capacitors
  • Heterojunctions.

Device Physics Sequence

• ECE616 - Semiconductor Devices II.
• Next term – Spring term odd years.
• Three-Terminal Semiconductor Devices.
  • Bipolar junction transistors (BJTs).
  • Junction field-effect transistors (JFETs).
  • Metal semiconductor field-effect transistors (MESFETs).
  • Metal oxide semiconductor field-effect transistors (MOSFETs)
  • Heterojunction field-effect transistors (HFETs).
pn Junctions

- What happens when we put a p-doped semiconductor in contact with an n-doped semiconductor?

pn Junctions

- We cover this subject in extensive detail.
Metal Semiconductor Contacts

- What happens when we put a metal in contact with a semiconductor?

\[ E \]

\[ n\text{-Type} \quad p\text{-Type} \]

\[ \begin{align*}
E_F & \quad \phi_B \quad W \\
\text{Metal} & \quad \text{Semiconductor} & \quad \text{Metal} & \quad \text{Semiconductor}
\end{align*} \]

Emission mechanisms:

**Fig. 16** Five basic transport processes under forward bias. (1) Thermionic emission. (2) tunneling. (3) Recombination. (4) Diffusion of electrons. (5) Diffusion of holes.
MOS Capacitors

- Another important 2-terminal device.

![Diagram of MOS Capacitor]

MOS Capacitors

- Capacitance as a function of voltage will be explored extensively.
Heterojunctions

• The interface between two dissimilar semiconductors:

\[ \begin{align*}
E_C & \quad \Phi_1 \\
E_F \quad \chi_1 & \quad e^- \quad \xi \quad \Phi_2 \\
E_C & \quad \chi_2 \\
E_F & \quad E_{\text{VAC}}
\end{align*} \]

semiconductor 1 \quad + \quad semiconductor 2

Heterojunctions

• Again, we will be calculating band structure and IV characteristics.
Course Logistics

Instructor

- John Labram.
- Assistant Professor, Electrical Engineering and Computer Science.
- Office Location: 3103 Kelley Engineering Center.
- Office Hours: Monday 13:00 – 14:00.
- Email: john.labram@oregonstate.edu.
- Website: http://eecs.oregonstate.edu/people/Labram-John.
**Textbook**

- Physics of Semiconductor Devices.
- Simon M. Sze and Kwok K. Ng.
- [https://www.amazon.com/Physics-Semiconductor-Devices-Simon-Sze/dp/0471143235/](https://www.amazon.com/Physics-Semiconductor-Devices-Simon-Sze/dp/0471143235/)
- This is a very important book generally (it has received >50,000 times according to Google Scholar).
- I will assign reading from this book.
- But we are only interested in Part II (chapters 2-4).

**Lectures**

- The lectures are compulsory to attend.
- I will be teaching this slightly differently to my previous classes (ECE611, ECE613, ECE599-002).
- The teaching is designed to be more inline with the other classes in this series: ECE614, ECE615, ECE616.
- Predominantly PowerPoint based.
  - However I will be writing on the board (or bringing up equations onto the PowerPoint).
  - You will be expected to **make notes by hand** more in this class.
Lectures

• There will probably be more equations than my previous classes.
• The slides are designed to be self-contained and to provide enough information to complete all the homeworks / exams.
  • However the book will make things easier.
• Some lectures will contain examples, but the book and homeworks will serve as the best opportunity to practice.
• The slides will also be uploaded to the course website after every lecture.

Course Website

• The course website can be found:
  • http://classes.engr.oregonstate.edu/eecs/winter2019/ece615/.
• Homeworks, solutions, lecture slides, and general information will be located here.
• It should be the first place you look for course information.
Schedule

- This is a preliminary schedule – is subject to change.

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Month</th>
<th>Lecture #</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tue</td>
<td>78</td>
<td>Jan</td>
<td>1</td>
<td>Introduction and Review of ECE614</td>
</tr>
<tr>
<td>Thur</td>
<td>10</td>
<td>Jan</td>
<td>2</td>
<td>pn junctions - Junction formation / electrostatics</td>
</tr>
<tr>
<td>Tue</td>
<td>15</td>
<td>Jan</td>
<td>3</td>
<td>pn junctions - Electrostatics / CV characteristics</td>
</tr>
<tr>
<td>Thur</td>
<td>17</td>
<td>Jan</td>
<td>4</td>
<td>pn junctions - Noise / ideal IV characteristics</td>
</tr>
<tr>
<td>Tue</td>
<td>22</td>
<td>Jan</td>
<td>5</td>
<td>pn junctions - Ideal / non-ideal characteristics</td>
</tr>
<tr>
<td>Thur</td>
<td>24</td>
<td>Jan</td>
<td>6</td>
<td>pn junctions - Non-ideal characteristics continued</td>
</tr>
<tr>
<td>Tue</td>
<td>29</td>
<td>Jan</td>
<td>7</td>
<td>pn junctions - Equivalent circuits / boundary conditions / surface recombination</td>
</tr>
<tr>
<td>Thur</td>
<td>31</td>
<td>Jan</td>
<td>8</td>
<td>pn junctions - Transient Analysis</td>
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<tr>
<td>Thur</td>
<td>2</td>
<td>Feb</td>
<td>-</td>
<td>No Lecture – Preparation for Midterm</td>
</tr>
<tr>
<td>Thur</td>
<td>7</td>
<td>Feb</td>
<td>-</td>
<td>Midterm Examination</td>
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<tr>
<td>Tue</td>
<td>12</td>
<td>Feb</td>
<td>9</td>
<td>Schottky Contacts - Metal Semiconductor Contacts</td>
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<tr>
<td>Thur</td>
<td>14</td>
<td>Feb</td>
<td>10</td>
<td>Schottky Contacts - Depletion Region Issues</td>
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<tr>
<td>Tue</td>
<td>19</td>
<td>Feb</td>
<td>11</td>
<td>Schottky Contacts - IV Characteristics</td>
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<tr>
<td>Thur</td>
<td>21</td>
<td>Feb</td>
<td>12</td>
<td>MOS Capacitors - Energy band diagrams</td>
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<tr>
<td>Tue</td>
<td>26</td>
<td>Nov</td>
<td>13</td>
<td>MOS Capacitors - Ideal electrostatics</td>
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<tr>
<td>Thur</td>
<td>28</td>
<td>Nov</td>
<td>14</td>
<td>MOS Capacitors - Non-ideal electrostatics</td>
</tr>
<tr>
<td>Tue</td>
<td>5</td>
<td>Mar</td>
<td>15</td>
<td>Heterojunctions - Classification / energy bands</td>
</tr>
<tr>
<td>Thur</td>
<td>7</td>
<td>Mar</td>
<td>16</td>
<td>Heterojunctions - electrostatics</td>
</tr>
<tr>
<td>Thur</td>
<td>12</td>
<td>Mar</td>
<td>17</td>
<td>Heterojunctions - IV Characteristics</td>
</tr>
<tr>
<td>Thur</td>
<td>14</td>
<td>Mar</td>
<td>-</td>
<td>No Lecture – Preparation for Final</td>
</tr>
<tr>
<td>Mon</td>
<td>18</td>
<td>Mar</td>
<td>-</td>
<td>Final Examination</td>
</tr>
</tbody>
</table>

Assessment

- The final grade will consist of the following contributions:

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Percentage of Final Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homework</td>
<td>40</td>
</tr>
<tr>
<td>Mid-Term Exam</td>
<td>30</td>
</tr>
<tr>
<td>Final Exam</td>
<td>30</td>
</tr>
</tbody>
</table>
Homework

- There will be a total of 4 homeworks.
- Each homework carries equal weight.
- The homeworks are designed to test your understanding of the concepts covered in the lectures.
  - Sometimes you will be expected to apply knowledge obtained in the lectures to new (previously unseen) situations.
- The homeworks overall contribute 40% of the course grade.
  - 10% each.

Homework

- Some homework will be analytical (answerable with pen and paper).
- Some will require simple computation.
  - E.g. I will provide some example data and expect you to carry out numerical integration or similar.
  - Everything you will be asked to do you will be able to do in Excel.
  - Although you can use a programming language if you prefer.
  - You may be expected to extract a parameter or plot a graph for example.
Homework

- Please hand in homework at the start of the lecture on the due date.
- Please make your name and OSU ID clearly visible.
- Please circle / make a box around the final answer.
- The solutions will be posted when the homeworks are returned.

Homework

- The homework schedule is as follows:

<table>
<thead>
<tr>
<th>Homework #</th>
<th>Set</th>
<th>Due</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thursday 01/17/19</td>
<td>Thursday 08:30 01/24/19</td>
</tr>
<tr>
<td>2</td>
<td>Thursday 01/24/19</td>
<td>Thursday 08:30 01/31/19</td>
</tr>
<tr>
<td>3</td>
<td>Tuesday 02/19/19</td>
<td>Tuesday 08:30 02/26/19</td>
</tr>
<tr>
<td>4</td>
<td>Tuesday 03/05/19</td>
<td>Tuesday 08:30 03/12/19</td>
</tr>
</tbody>
</table>

- Again, this is subject to change.
Examinations

- There will be two exams: one midterm and one final.
- They will carry equal weight to the final course grade: 30% each.
- The midterm will examine content covered in Lectures 1-8 (inclusive).
- The final exam will examine content covered in Lectures 9-17 (inclusive).
- The exams will consist of optional questions. For example, you may be expected to complete 2 out of 3 questions.

Exams

- The exams are designed to test your ability to apply knowledge acquired during the lectures to new situations.
- Both exams will be closed book and closed notes.
- Besides a small number of well-known equations, most equations will be provided at the start of the exam.
- All physical constants and parameters will also be provided.
- The dates and times of exams will be made known nearer the time.
Equations

- You will be given most equations. However, simple relationships you would be expected to know. E.g.

- Density:
  \[ n_{2D} = \frac{1}{A} \quad n_{3D} = \frac{1}{V} \]

- Area:
  \[ A = \pi r^2 \]

- Surface area of sphere:
  \[ A = 4\pi r^2 \]

Equations

- You will be given most equations. However, simple relationships you would be expected to know. E.g.

- Chain rule:
  \[ \frac{df}{dx} = \frac{df}{dg} \cdot \frac{dg}{dx} \]

- Standard derivatives:
  \[ \frac{d}{dx}(ae^{bx}) = a e^{bx} \quad \frac{d}{dx}(\ln(ax)) = \frac{1}{x} \]
  \[ \frac{d}{dx}(\sin(ax + b)) = -a \cos(ax + b) \]
  \[ \frac{d}{dx}(\cos(ax + b)) = -a \sin(ax + b) \]
Equations

- You will be given most equations. However, simple relationships you would be expected to know. E.g.

- Velocity:
  \[ v = \frac{x}{t} \]

- Current from charge:
  \[ I = \frac{Q}{t} \]

- Ohm’s Law:
  \[ V = IR \]

- Kinetic Energy:
  \[ E = \frac{1}{2}mv^2 \]

- Momentum:
  \[ p = mv \]

- Mass density:
  \[ \rho = \frac{m}{V} \]

Equations

- Limits of exponentials:
  \[ e^0 = 1 \]
  \[ e^{-\infty} = 0 \]
  \[ e^{\pm 1/\infty} = e^0 = 1 \]

- Unit conversions
  \[ 1\text{Å} = 10^{-10}\text{m} \]
  \[ 1\mu m = 10^{-6}\text{m} \]
  etc ...
Exam Style Example

- All constants will be provided.
- All relevant formulae will also be provided.
- Parameters will be labeled as clearly as possible.

Ideal Gas Law:

\[ P = \frac{n k T}{V} \]

- \( P \) is the gas pressure.
- \( n \) is the number density of gas molecules.
- \( k \) is the Boltzmann Constant.
- \( T \) is the gas temperature.

Mean Particle Velocity:

\[ \bar{v} = \frac{n k T}{m} \]

- \( \bar{v} \) is the mean particle velocity.
- \( n \) is the number density of gas molecules.
- \( k \) is the Boltzmann Constant.
- \( T \) is the gas temperature.
- \( m \) is the molecular mass.

Gases negligible rarefied case (Glenn):

\[ f_a = \frac{1}{12} \]

- \( f_a \) is the gas accommodation coefficient.
- \( n \) is the number density of gas molecules.
- \( \bar{v} \) is the mean particle velocity.

Exam Style Example

- Taken from 611, but style will be similar.
- Most constants will also be given.
Grading

- Hopefully I will not have to curve.
- But it depends on results.
- I may try to ~match grade distributions from previous years.
- But depends on performance, since this is a small class.

Regulations
Cheating and Student Conduct

- Academic dishonesty is defined as an intentional act of deception in one of the following areas:
  - **Cheating** - use or attempted use of unauthorized materials, information or study aids.
  - **Fabrication** - falsification or invention of any information.
  - **Assisting** - helping another commit an act of academic dishonesty.
  - **Tampering** - helping another commit an act of academic dishonesty.
  - **Plagiarism** - representing the words or ideas of another person as one's own.

When evidence of academic dishonesty comes to the instructor's attention, the instructor will document the incident, permit the accused student to provide an explanation, advise the student of possible penalties, and take action.

The instructor may impose any academic penalty up to and including an "F" grade in the course after consulting with his or her department chair and informing the student of the action taken.
Disruptive Behavior

- While the University is a place where the free exchange of ideas and concepts allows for debate and disagreement, all classroom behavior and discourse should reflect the values of respect and civility.
- Behaviors which are disruptive to the learning environment will not be tolerated.
- As your instructors, we are dedicated to establishing a learning environment that promotes diversity of race, culture, gender, sexual orientation, and physical disability.

Disruptive Behavior

- Anyone noticing discriminatory behavior in this class, or feeling discriminated against should bring it to the attention of the instructors or other University personnel as appropriate.
Effective Masses (Review of ECE614)

Wavevector

• Before we talk about effective mass, let us (very quickly) remind ourselves what the parameter $k$ is.
• According to quantum mechanics, we know that the energy and momentum of “particles” are determined by their “wave” properties.
  • Wave-particle duality.
    
    \[ E = \hbar \omega \]
    \[ p = \hbar k \]
  • So if the wavefunction describing the electron (or hole, or whatever) determines its energy and momentum.
Wavevector

- Normally we would describe a wave by an equation like this:

\[ \psi(r, t) = \psi_0 \exp(k \cdot r - \omega t + \phi) \]

- So we are just saying that \( k \) (or just \( k \) in one dimension) tells how many oscillations it completes per unit of space.

- It is related to the wavelength of the wave by:

\[ |k| = \frac{2\pi}{\lambda} \]

Effective Mass

- The effective mass approximation is designed to allow us to use the same equations we are familiar with when describing free particles in a vacuum.

- Classical Newtonian mechanics can be used to understand the motion of electrons (e\(^-\)) and holes (h\(^+\)) in semiconductors if we define an effective mass, \( m^* \) for these carriers.

- The convention is to quote effective mass as a dimensionless prefactor to the rest mass an electron in a vacuum. E.g.:

\[ m^* = 0.6m_e \]
Effective Mass

- If our particle has an effective mass of $m^*$, then we should be able to describe its motion using classical Newtonian mechanics. I.e. it should have a kinetic energy ($E$):

$$E = \frac{1}{2} m^* v_g^2$$

- Describing the particle classically, we can also say it has a momentum:

$$p = m^* v_g \quad \Rightarrow \quad v_g = \frac{p}{m^*}$$

$$E = \frac{1}{2} m^* \frac{p^2}{m^*^2} \quad \Rightarrow \quad E = \frac{1}{2} \frac{p^2}{m^*}$$

- From the de Broglie relationships we also know:

$$p = \hbar k \quad \Rightarrow \quad E = \frac{\hbar^2 k^2}{2 m^*}$$

- Differentiate twice:

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m^*} \quad \Rightarrow \quad \frac{d^2E}{dk^2} = \frac{\hbar^2}{m^*}$$
Effective Mass

• This is how we define the effective mass:
  \[ m^* = \frac{\hbar}{\frac{\partial^2 E}{\partial k^2}} \]

• Unless the band is perfectly parabolic, the effective mass is going to vary as a function of wavevector.

• So we are normally talking about the effective mass near the Gamma point \((k = 0)\).

Force and Velocity

• If our particle has an effective mass of \(m^*\), then should be able to relate the rate of change of momentum to force exerted \((F)\), using classical Newtonian mechanics:
  \[ F = m^* a = m^* \frac{\partial p}{\partial t} \]

• We also know the group velocity (velocity at which information is transmitted) is given by:
  \[ v_g = \frac{1}{\hbar} \frac{dE}{dk} \]
Effective Mass

- In reality, effective mass will depend on temperature and direction.

<table>
<thead>
<tr>
<th>Group</th>
<th>Material</th>
<th>Electron</th>
<th>Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>Si (4 K)</td>
<td>1.06</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Si (300 K)</td>
<td>1.09</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>Ge</td>
<td>0.55</td>
<td>0.37</td>
</tr>
<tr>
<td>III-V</td>
<td>GaAs</td>
<td>0.067</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>0.013</td>
<td>0.6</td>
</tr>
<tr>
<td>II-VI</td>
<td>ZnO</td>
<td>0.29</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>ZnSe</td>
<td>0.17</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Brillouin Zones
(Review of ECE614)
Brillouin Zones

- You may have seen diagrams such as the following in ECE614:

- This is First Brillouin zone for materials crystallizing in the diamond and zincblende lattices.

- It is basically the reciprocal space equivalent of Bravais lattice.

Brillouin Zones

- Depending on the model used, we describe charge carriers as a wave such as the following:

\[ \psi(r) = u(r) \exp(ik \cdot r) \]

- Normally it is informative to plot permitted energy vs \( k \):

\[ E \]

\[ k_x \]

Sze and Ng Fig 3.
Brillouin Zones

• However by reducing the graph to just one full wavelength we do not lose any information:

• We describe this region as the 1st Brillouin Zone.

Brillouin Zones

• An alternative picture is the extended zone scheme:

• The information is identical.
3D Brillouin Zones

• Because materials are 3D, we have to picture Brillouin Zones in 3 dimensions.

• Very few solids crystalize into the simple cubic structure.

• Most are more complex unfortunately:

\[ \alpha \neq 90^\circ \]
FCC Brillouin Zone

• The brillouin zone of diamond and zincblende lattices are the same as for face centred cubic:

[Diagram of FCC Brillouin Zone]

• By convention, Greek characters are used for points inside the first Brillouin zone, and Latin characters are used for points on the surface.
• $\Gamma$ is the zone the centre.
• $L$ is the zone end along the <111> direction.
• $X$ is the zone end along the <100> direction.
• Note that $L$ is shorter than $X$.
• Why?
Real Space Lattice

- Two interpenetrating fcc lattices, offset by 1/4a in each direction.
- All atoms are Si (despite colors).

Band Structure

- This is a very basic band structure in 1 dimension (e.g. $k_x$).
- To plot the possible energy in 3 dimensions we would need a 4-dimensional plot.
  - This is not possible...
  - The community has a way of dealing with this.
- We will just show results. See https://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/backbone/r2_1_5.html for more details.
General Band Structure

- We split the x-axis into different sections for different reciprocal directions.

Specific Band Structure

- Often a lot a symmetry exists, and we can get most of the information we need from 2 directions:
Different Semiconductors

- Three common semiconductors:

Constant Energy Surfaces
(Review of ECE614)
Constant Energy Surfaces

• One final way you can pictures band structures is via **constant energy surfaces**.

• See Figure 5 from Sze and Ng.

• What are we showing here?

Constant Energy Surfaces

• As the title suggests, we are just plotting a surface that has a constant particular energy in k-space.

• GaAs has its conduction band minimum is symmetric about Γ-point.
Constant Energy Surfaces

- Silicon has an indirect band gap.

- The shape will depend on the energy we choose to cut through.
Constant Energy Surfaces

- There are three main situations to consider in terms of e\(^{-}\) and h\(^{+}\) motion in \(k\)-space:
  - For the \(\Gamma\)-conduction band (CB), \(m^{*}\) is scalar, the constant energy surface is a sphere, and the electron dynamic problem is fairly simple.
  - For \(L\) or \(X\) CBs, the constant energy surfaces are ellipsoids of revolution such that \(m^{*}\) is a tensor.
  - Energy bands are characterized by two kinds of effective masses:
    - \(m_{l}^{*}\) = longitudinal (// to the symmetry direction; large \(m^{*}\))
    - \(m_{t}^{*}\) = transverse (\(\perp\) to the symmetry direction, small \(m^{*}\))
Hole States

- There are three main situations to consider in terms of e⁻ and h⁺ motion in \( k \)-space:
  - For valence bands (VBs), the top of the band is degenerate and characterized by three \( m^* \)'s:
    - \( m_{lh}^* \) = light hole effective mass.
    - \( m_{hh}^* \) = heavy hole effective mass.
    - \( m_{soh}^* \) = split-off hole effective mass.

What \( m^* \) do we Use?

- At first glance, 2(b) and 2(c) appear to imply non-isotropic carrier dynamics described by tensors.
- However, the cubic symmetry of all of the semiconductors in which we are likely to be interested allows us to avoid this complication by using a single, appropriately averaged \( m^* \) to characterize the average curvature of the energy bands.
- Note that the method of obtaining the appropriate average depends on what type of physical process the carriers are participating in.
There are Two Types of $m^*$

- Density of States (DOS) $m^*$ :
  
  $$m^*_{de} = \left[ m_i^* m_t^* M_C^2 \right]^{1/3}$$
  $$m^*_{dh} = \left[ m_i^* \frac{3}{2} + m_{hh}^* \frac{3}{2} \right]^{1/3}$$

- The parameter $M_C$ is the conduction band (CB) multiplicity factor (i.e., the number of equivalent minima in the CB).
  
  - For the $\Gamma$-conduction band $M_C = 1$.
  - The X band has six ellipsoids of revolution along the <100> axis.

Density of States $m^*$

- The $X$ band has six ellipsoids of revolution along the <100> axis:
  
  - For a CB minimum along the $X$-axis, $M_C = 6$.
  - Si is an example since its CB minima is located at 0.85 $\Gamma X$.
  
  - However, if the band is located at the $X$ point, $M_C = 3$. Since these points are at the Brillouin zone boundary and separated by one reciprocal lattice vector, they are equivalent.
Density of States $m^*$

- Similarly, the $L$ band has eight ellipsoids of revolution along the $<111>$ axis:
  - Thus $M_C = 8$ for a CB minimum along the $L$ axis.
  - However, if the minimum is located at the $L$ point (usually the case, Ge is an example), $M_C = 4$. (Since these points are at the Brillouin zone boundary and are separated by one reciprocal lattice vector, they are equivalent.)

Density of States $m^*$

- Use density of states $m^*$ for semiconductor statistics (i.e. equilibrium) such as:
  - Carrier concentrations.
  - Screening radius.
  - Chemical potential.
### Conductivity $m^*$

- The other type of effective mass is the conductivity effective mass:
  
  $$m_{\sigma e}^* = \left[ \frac{1}{3} \left( \frac{1}{m_l^*} + \frac{2}{m_t^*} \right) \right]^{-1}$$
  
  $$m_{\sigma h}^* = \frac{m_{th}^* \frac{3}{2} + m_{hh}^* \frac{3}{2}}{m_{th}^* \frac{13}{2} + m_{hh}^* \frac{1}{2}}$$

- Use $m_\sigma^*$ for transport issues (non-equilibrium):
  - Mobility.
  - Inertial mass.
  - Conductivity.
  - Optical
  - Calculation of ionization energy of impurities

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### Summary

- Semi-classical Newtonian mechanics may be used to describe the motion of charge carriers in a crystal if $m$ in $F = ma$ is replaced by an effective mass $m^*$.
  - I.e. This means that e$^-$ and h$^+$ will respond to external fields in a crystal almost as if they were in a vacuum, but with different $m^*$.
  - Lots of quantum mechanics is buried in the $m^*$ term, which depends on the quantitative characteristics of the band structure:

  $$m^* = \frac{\hbar}{\frac{\partial^2 E}{\partial k^2}}$$
Summary

• Density of states $m_d^*$'s are used in equilibrium situations.
• Conductivity $m_\sigma^*$'s are used in non-equilibrium situations

Next Time...

• pn Junction formation:

• Reading: Sze & Ng Chapter 2.
  • p79–83.