Lecture 13
Solar Cells
Schroder: Chapter 4.4

Last Time
• We studied the basics of diodes.

```
E / V
I

normal case

r_s-dominated

metal (ohmic)

semiconductor (p-type)

n^+

metal (ohmic)
```

ECE / ChE 613 – Electronic Materials Characterization
Spring 2020 - John Labram
Announcements

Midterm Exam:
• I will return your exams (and solutions) on Wednesday May 6th.

Homework 3/5:
• Will be posted online on Friday May 8th.
• Homework 3 will cover Lectures 12-15 (inclusive).
• Due Friday May 15th at the start of the lecture (09:00am).
• I will return it one week later Friday May 22nd.

Lecture 13

• Basics of Solar Power Conversion
• Carrier Generation.
• Carrier Extraction.
• Device Characterization.
Basics of Solar Power Conversion

Photoelectric Effect

- The photoelectric effect was first experimentally discovered in 1839 by Becquerel.
- He found that if you shine light on one of these electrodes, you could generate a voltage.
Photoelectric Effect

- However it wasn’t until 1905 and Albert Einstein, when the effect was fully understood.

- Light was described as *quanta*, with an energy that depends on the wavelength / frequency of light:

\[ E = hf \]

- Metals have a property called work function \( \phi \) (units of voltage).

- If \( E > e\phi \), electrons can be emitted.

Work Function

- Consider the band picture of a metal:

<table>
<thead>
<tr>
<th>Metal</th>
<th>( \phi ) (eV)</th>
<th>( \lambda ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>4.26-4.74</td>
<td>262-291</td>
</tr>
<tr>
<td>Au</td>
<td>5.10-5.47</td>
<td>226-243</td>
</tr>
<tr>
<td>Al</td>
<td>4.06-4.26</td>
<td>291-305</td>
</tr>
<tr>
<td>Ca</td>
<td>2.87</td>
<td>432</td>
</tr>
<tr>
<td>Cu</td>
<td>4.53-5.10</td>
<td>243-274</td>
</tr>
<tr>
<td>Pd</td>
<td>4.25</td>
<td>292</td>
</tr>
</tbody>
</table>
Solar Spectrum

• What light do we receive from the sun?

Illuminating Semiconductors

• Consider the band picture:

  - Carriers are excited across the band gap:
    \[ E_G = E_{CBM} - E_{VBM} \]

  - Conduction Band Minimum
  - Valence Band Maximum

  \[ h\nu > E_G \]
Charge Generation

- Charge generation in semiconductors is a complex topic (beyond the scope of this lecture).
- We can broadly describe the absorption properties via quantum efficiency:
  - External Quantum Efficiency (EQE):
    \[
    EQE = \frac{\text{Electron – Hole Pairs Created}}{\text{Photons Incident}}
    \]
  - Internal Quantum Efficiency (IQE):
    \[
    IQE = \frac{\text{Electron – Hole Pairs Created}}{\text{Photons Absorbed}}
    \]
**Charge Generation**

- Absorption if characterized through optical spectroscopy.
  
  ![Diagram of direct and indirect band gaps](image)
  
  - **Direct band gap semiconductors** e.g. GaAs, CdTe, just require a photon.
  
  - **Indirect band gap semiconductors** e.g. Si, CIGS, also require a phonon for absorption to occur.

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**Excitons**

- In some materials (e.g. Si, GaAs, perovskites) free carriers are generated directly in material.

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Excitons

- However often free carrier pairs are not generated directly.

- Instead what is termed an exciton is created.
  - A quasi-particle that exists only in solids.
  - Electron and hole remain bound.
  - They are better described by a single wavefunction.

Excitons

- The physical description is as follows:
  - Light generates an electron and hole.
  - They separate (conservation of momentum).
  - Positively charged hole distorts electrons in lattice.
  - This provides screening / repulsion to free electron.
  - Equilibrium occurs with a binding energy ($E_B$).
  - Thermal energy ($k_B T$) required to collapse charges.
Thermalization

- To excite carriers in a semiconductor, the energy of incoming photons needs to be equal to, or in excess of, the band gap.

• What happens to this excess energy?

- The behaviour of carriers depends on the material properties.
- But generally carriers “thermalize” very quickly (~ps) in solar materials.
- Scattering events:
  • Ionized Impurity.
  • Phonons.
  • Band-to-band impact ionization.
Thermalization

- So energy above the band gap is normally wasted as heat.

- Every photon above band gap will provide same energy as one at band-gap.

Carrier Extraction
Extracting Carriers

- Creating charge carriers is not enough – we need to be able to extract them before they recombine.

\[ \text{Anode} \quad \text{Cathode} \]

- The average time carriers live for is parameterised by the lifetime \( \tau \).
- In reality, there are several processes, each of which depend on the carrier density in a different way:

  - Monomolecular
  - Bimolecular
  - Auger
Extracting Carriers

- The average time carriers live for is parameterised by the lifetime $\tau$.
- The rate of change of carrier density can be described by:

$$\frac{dn}{dt} = nk_1 + n^2k_2 + n^3k_3$$

Carriers also need to be able to make it to the electrodes before they recombine (i.e. in time $\tau$):
Extracting Carriers

- To determine how far carriers can move before recombination we need to know their “velocity”.

- In reality, we use velocity normalised for electric field strength, i.e. mobility:

\[ \mu = \frac{v}{E} \]

- With a knowledge of carrier lifetime and mobility we can evaluate the diffusion length:

\[ L = \sqrt{\frac{k_B T}{e \mu \tau}} \]

- This quantifies the average distance that carrier can travel before they recombine.
- Informs on how thick we can make our cells.
Example

• Diffusion length in silicon with phosphorus concentration:

![Graph showing diffusion length vs. donor density](image)

Del Alamo and Swanson, Sol. State. Electron. 30 (1987) 1127

Device Characterization
IV Characteristics

- A solar cell is just a diode.
- The circuit is typically modelled by the following circuit:

\[ I = I_{ph} - I_0 \left[ \exp \left( \frac{eV + IR_S}{n k_B T} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \]

- Photogenerated Current
- Applied Bias
- Load Resistor
- Shunt Resistor
- Cell
- Series Resistor

\( I_0 = \) Dark Current
\( n = \) Ideality factor (~1)
\( k_B = \) Boltzmann Constant
\( e = \) Fundamental unit of charge
\( T = \) Temperature
IV Characteristics

- An ideal solar cell would have:
  - $R_{SH} = \infty$
  - $R_S = 0$
  - Giving:

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{eV}{nk_BT} \right) - 1 \right]$$

Short-Circuit Current

- The short-circuit current is defined as the current that flows when $V=0$, and is labelled $I_{SC}$.
Short-Circuit Current

- The short circuit current is dependent on how quickly we generate carriers in the cell, and how well we can extract them.
- It can be approximated by:

$$J_{SC} = e G (L_e + L_h)$$

- The short circuit current is a property of the solar cell material and design.

Exercise

- Using the equation for current in a solar cell (below), evaluate the short-circuit current when $R_S = 0$ and $R_{SH} = \infty$

$$I = I_{ph} - I_0 \left( \exp \left( \frac{eV + IR_S}{nk_BT} \right) - 1 \right) - \frac{V + IR_S}{R_{SH}}$$
Open-Circuit Voltage

- The voltage that occurs when the current from the solar cell is zero.

\[
V_{oc} = \frac{n k_B T}{e} \left[ \frac{I_{ph}}{I_0} - \frac{V_{oc}}{R_{SH} I_0} + 1 \right]
\]

- The open circuit voltage is due to internal field in the device (e.g. band offsets).
Exercise

- Using the equation for current in a solar cell (below), evaluate the open-circuit voltage when \( R_S = 0 \) and \( R_{SH} = \infty \)

\[
I = I_{ph} - I_0 \left[ \exp \left( \frac{eV + IR_S}{nk_BT} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}}
\]

Fill Factor

- The solar cell is operated when the power \((IV)\) is a maximum.
- We define this as the maximum power point \((I_{mp} \text{ and } V_{mp} \text{ respectively})\).
Fill Factor

- The voltage at which the maximum power occurs as can be evaluated from the turning point in power vs voltage:

\[
\frac{d(IV)}{dV} = 0
\]

- In the case that \( R_S = 0 \) and \( R_{SH} = \infty \), this can be shown to be:

\[
V_{mp} = V_{oc} - \frac{n k_B T}{e} \ln \left[ \frac{e V_{mp}}{n k_B T} + 1 \right]
\]

Fill Factor

- The so-called fill-factor (\( FF \)) is a parameter used in the determination of solar cell efficiency:

\[
FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}
\]

- Typically this is evaluated numerically from measured data:
Fill Factor

- It can also be interpreted visually as the “squareness” of the current-voltage characteristics.

Solar Cell Efficiency

- Despite being difficult to evaluate from first-principles, $FF$, $V_{oc}$ and $I_{sc}$ are all reasonably easy to evaluate from real solar cell data.

- With a knowledge of the incident optical power density $P$, we can then evaluate the efficiency of the solar cell:

\[ \eta = \frac{V_{oc}I_{sc}FF}{P} \]

- The power density depends on location, but typically we consider “1 sun” as $P = 100 \text{ mW/cm}^2$. 

Next Time

- We will study the basic operation of conventional capacitors and metal-oxide-semiconductor (MOS) capacitors.