ME 432 Fundamentals of Modern Photovoltaics

Discussion 29:
Contacts
30 October 2020
Fundamental concepts underlying PV conversion

input

solar spectrum → light absorption → carrier excitation & thermalization → charge transport → charge separation → charge collection → output

You Are Here

Courtesy: Yosuke Kanai, University of North Carolina
Learning Objectives: Contacts

• Describe the purpose of contacts, and the two main types of contacts used in the solar industry
• Describe what is meant by an ohmic and a Schottky contact, and the “work function”.
• Explain why we use large work function metals to make ohmic contacts to p-type semiconductors, and small work function metals to make ohmic contacts to n-type semiconductors
• Describe how contacts are typically incorporated into solar cells, and some common firing problems that can arise
• Describe how transparent conducting oxides work. That is, how are the both transparent and conducting at the same time?
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Contacts

- Purpose: extract electron and hole carrier from the interior of the solar cell, and deploy them into the external circuit
- Need to do this without allowing back-diffusion of carriers into the device
- Properties of a good contact: good conductor, inexpensive material, easy to manufacture, sturdy
- The best material to choose for a contact is very semiconductor specific. That is, silicon solar cells will use different contact materials than, e.g., CdTe cells.
- Two broad classifications of contacts: metals and transparent conducting oxides

**Metal Contacts**: optically opaque
- Usually less expensive, but does block sunlight

**Transparent Conducting Oxides**: optically transparent
- Can be more expensive, but doesn’t block the sun
- Can be fairly readily grown on top of thin-film cells
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What happens when we put a metal on a semiconductor?

In general, two types of behavior can be observed. The contact can either be ohmic or rectifying (Schottky barrier).

- **Ohmic contacts** – which freely allow current to flow in any direction, are most desirable.

- **Schottky barriers**, which act a lot like pn junctions, are to be avoided.
What happens when we put a metal on a semiconductor?

- The type of contact depends on the relative work functions between the semiconductor and the metal.
- The work function is, more or less, the energy required to completely remove an electron from a solid.
- It is equal to the difference between the Fermi energy and the vacuum level.

\[ E_{\text{work function}} = E_{\text{Fermi}} - E_{\text{vac}} \]
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Ohmic or Rectifying?

Whether the metal-semiconductor junction is ohmic or rectifying depends on the relative work functions of the semiconductor and metal:

<table>
<thead>
<tr>
<th></th>
<th>$\phi_m &gt; \phi_s$</th>
<th>$\phi_m &lt; \phi_s$</th>
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</thead>
<tbody>
<tr>
<td>p-type</td>
<td>Ohmic</td>
<td>Rectifying</td>
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<tr>
<td>semiconductor</td>
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<tr>
<td>n-type</td>
<td>Rectifying</td>
<td>Ohmic</td>
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<tr>
<td>semiconductor</td>
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</table>

- Thus, to achieve ohmic contacts on the n-type side of a solar cell, we need to use low work-function metals since we want $\phi_m < \phi_s$.
- By contrast, to achieve ohmic contacts on the p-type side of a solar cell, we need to use high work-function metals.
Example of Ohmic Contact

*p-type semiconductor with $\phi_m > \phi_s$*
Example of Ohmic Contact

*p-type semiconductor with $\phi_m > \phi_s$*

When the two are joined together, which way will the electrons flow?

- Recall that the Fermi energy represents the average energy of an electron.
- Electrons will flow from the semiconductor to the metal (high to low Fermi level) until the Fermi level equilibrates.
- Thus, electrons will diffuse from the semiconductor to the metal, resulting in a build-up of electrons at the metal surface, and a depletion of electrons at the semiconductor surface.
Example of Ohmic Contact

*p-type semiconductor with $\phi_m > \phi_s$*

- The flow will continue until the electric field that builds up across the junction creates a drift current that exactly cancels the diffusion current.
- The final band diagram is shown above. The bands in the semiconductor bend upwards to reflect that the interface region is even more depleted of electrons.
- Because the Fermi level is inside the VB near the junction, the semiconductor behaves like a metal near the junction. Current can flow in any direction.
Example of Ohmic Contact

*p-type semiconductor with \( \phi_m > \phi_s \)*

An ohmic contact has a linear IV relationship, and there is no barrier to current flow in either direction.
Example of Rectifying Contact

*n-type semiconductor with* $\phi_m > \phi_s$
Example of Rectifying Contact

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Example of Rectifying Contact

*n-type semiconductor with* $\phi_m > \phi_s$

- The flow will continue until the electric field that builds up across the junction creates a drift current that exactly cancels the diffusion current.
- The final band diagram is shown above. The bands in the semiconductor bend upwards to reflect that the interface region is even more depleted of electrons.
- Because the Fermi level is deep inside the gap near the junction, the junction region is poorly conducting.
Example of Rectifying Contact

*n-type semiconductor with $\phi_m > \phi_s$, no applied voltage*

- With no applied voltage, note that there is a barrier for electrons moving in either direction
Example of Rectifying Contact

*n-type semiconductor with $\phi_m > \phi_s$, no applied voltage*

- With no applied voltage, note that there is a barrier for electrons moving in either direction.
The applied bias, as drawn above, is called a forward or positive bias.
Because it opposes (and hence reduces) the electric field at the junction, the degree of band bending in the semiconductor is also reduced.
Example of Rectifying Contact

*n-type semiconductor with $\phi_m > \phi_s$, positively biased*

- The applied bias, as drawn above, is called a forward or positive bias.
- Because it opposes (and hence reduces) the electric field at the junction, the degree of band bending in the semiconductor is also reduced.
- Now the barrier for electrons flowing from the semiconductor to the metal is lower.
- With sufficient applied forward bias, the barrier disappear, and electrons can flow.
Example of Rectifying Contact

*n-type semiconductor with $\phi_m > \phi_s$, negatively biased*

- The applied bias, as drawn above, is called a reverse or negative bias.
- Because it aligns with (and hence increases) the electric field at the junction, the degree of band bending in the semiconductor is also increased.
Example of Rectifying Contact

*n-type semiconductor with $\phi_m > \phi_s$, negatively biased*

- The applied bias, as drawn above, is called a reverse or negative bias.
- Because it aligns with (and hence increases) the electric field at the junction, the degree of band bending in the semiconductor is also increased.
- The barrier for current flow increases, for electrons flowing in any direction.
Example of Rectifying Contact

**P-type semiconductor with** $\phi_m > \phi_s$

An ohmic contact has an IV curve that looks much like a pn junction. Can carry charge in one direction, but not the other.
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Contacts to Silicon Solar Cells

- Typically, the contacts are screen printed on to the front and back of the wafer, and then fired to improve the bonding to the wafer

**Front Contact:** silver metal lines are formed by screen printing a silver-loaded paste onto the semiconductor, and then firing the wafer to make good contact

The grid line spacing is determined as a tradeoff between (1) minimizing sunlight blocking, and (2) minimizing series resistances.
Silicon Solar Cells
Firing Metal Contacts

- Metal makes poor “contact” with the semiconductor
- Results in a large series resistance (carriers recombine as they try to cross from the semiconductor to the metal)

- Over-firing causes the metal to diffuse deep into the semiconductor and across the junction
- Results in a shunt: alternate pathway so carriers can avoid traveling through the depletion region
Silicon Solar Cells

- The rear side contacts are also screen-printed and fired.
- Two approaches are often employed:

  **Aluminum layer with Al/Ag strips to connect multiple cells together**
  
  *better, but more expensive*

  **Only Al/Ag grid (most typical for commercial cells)**
  
  *not as good, but cheaper*
Silicon Solar Cells

*Why the full aluminum rear contact is best: surface passivation through formation of a back surface field*

- Recall that the cell’s surfaces are often significant sources of recombination
- Recall also that Al is a p-type dopant in silicon
- The full aluminum layer has the advantage of contributing a **back surface field** (ultra-high p-doped region near the rear surface) that prevents minority carriers in the p-type region (electrons) from flowing towards the rear surface and promotes their flow towards the p-n junction
- So the net effect of the full Al layer is that it helps to passivate the rear surface
Buried Contact Solar Cells

A newer concept that demonstrates high efficiencies:
Buried Contact Solar Cells

- A high efficiency concept in which a laser is used to make a groove inside the silicon
- Copper is used instead of silver, and is plated into the grooves
- Allows for a large metal height-to-width aspect ratio, which enables a large volume of metal to be used for good charge extraction, without having a wide strip of metal on the surface

Compare: shading losses can be as high as 10-15% with screen printed cells, and as low as 2-3% with buried contacts

- Technology developed at UNSW in 1984, sold to a number of companies including BP Solar, Solarex, Samsung, ...
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Transparent Conducting Oxides

- We don’t have too many materials that both conduct electricity and are optically transparent (most transparent things are insulators, like glass or diamond or quartz).
- But, there are some. These tend to be metal oxides that normally would be insulating, but are either intentionally or naturally doped resulting in conductivity.
- Requirements for a TCO:
  - High transmittance (>80%), band gap greater than > 380 nm to avoid absorbing light.
  - Resistivities around $10^{-4}$ Ω-cm.
- To date, the industry standard is ITO (tin-doped indium oxide). It is expensive, since indium is rare ($800/kg), but is often used in our thin-film solar cells.
- Some alternatives are aluminum-doped zinc oxide (often used in CIGS), indium-doped cadmium oxide, antimony-doped tin oxide (sometimes used in CdTe).
- Can be growth as a thin film via metal-organic chemical vapor deposition.

Konarka, Organic Solar Cell
Transparent Conducting Oxides

*Electronic structure:*

- Large $E_g$ (transparent)
- Metal oxide (wide band gap semiconductor)
- Doping-induced defect states near the CB edge.
Transparent Conducting Oxides

Transparent Conducting Oxides

Sharp Corporation, solar panels for the Japanese market (6.8% efficient)