Materials Concepts for Solar Cells: Overview

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The following topics may be covered in the 5-week short course following Dittrich (2014); Nelson (2003); Würfel and Würfel (2016).

I. Basic Characteristics of a Solar Cell

The photovoltaic energy conversion is a one-step process, which generates energy from light. As observed from the photoelectric effect, photons are quantized. The sun emits a spectrum of photons with a peak near 1.4 eV and a flux of $1360\,\mathrm{J\,s^{-1}\,m^{-2}}$. The solar cell generates a photocurrent and also a photovoltage that can be used to power electronics. It is characterized by a current-voltage graph, or I-V curve, which has 3 characteristic points, called the short-circuit current I_{SC}, open-circuit voltage V_{OC} and the fill factor FF. These parameters depend on the chosen materials and geometry of the solar cell, as well as the sun's spectrum and the ambient temperature T.

II. Photocurrent Generation

The absorbing material of a solar cell has to be a semiconductor with a characteristic energy gap E_G. The open-circuit voltage V_{OC} cannot exceed the potential E_G/q from the gap. Certain photons can be converted into an electron-hole pair, which reside in the conduction and valence band respectively. The best solar cell efficiencies η_{ult} are achieved for energy gaps in the range from 0.7 eV to 1.6 eV achieving around 30% conversion efficiencies. On the other hand, for wide-gap semiconductors ($E_G > 2.5\,\mathrm{eV}$), η_{ult} is always below 10%. The reason being that not all photons can be absorbed. The absorption is limited by the optical properties of the material, such as the transmission and reflection. Enhancements can be made through choice of surface roughness, choice of bottom absorption layer interface, and addition of anti-reflection layers.

III. Carrier Lifetime and Recombination Rates

Recombination is the annihilation of free electrons and holes. Even after the photon has generated an electron-hole pair, defects and impurities in the material lead to recombination, which reduces the efficiency of the solar cell. The characteristic time τ for the recombination process to occur is referred to as the carrier lifetime. The recombination rate increases with decreasing lifetime of the minority charge carriers. From the lifetime and the diffusion coefficient D, the diffusion length L can be computed, which needs to be compared to the absorber layer thickness to build useful solar cells. Typical diffusion coefficients are $15\,\mathrm{cm^2\,s^{-1}}$ for crystalline Silicon. Therefore, the lifetime in c-Si based solar cells is around $100\,\mu\mathrm{s}$. Given these values, the number of photo-generated charge carriers (Δn) can be estimated to be about $10^{15}\,\mathrm{cm^{-3}}$ for high-efficiency solar cells under ambient conditions.

IV. Charge Separation across pn-Junctions

Charge separation occurs at the interface of a pn-junction. This interface introduces a strong electric field gradient that is characterized by typical diode behavior. Near the pn-junction, the so-called space charge region, the drift directions of holes and electrons are opposite. Countering this perfect separation is the diffusion of minority carriers. After the photons generated the electron-hole pair, it needs to be quickly driven towards the charge-selective contacts before recombination occurs. The charge-selective contacts are characterized with the diode saturation current density I_0, which depends on the squared density of intrinsic (thermal) charge carriers n_i.

V. Nano-composite Solar Cells

Even though crystalline Silicon and GaAS solar cells stand out in regards to their performances towards efficiency, they also come with some disadvantages, such as large minimum absorption layer thickness, poor mechanical properties, and so on. New materials, summarized as nano-composites, include lead selenide (PbSe), conjugated organic molecules, such as zinc phthalocyanine, quantum dots, and dye molecules. The architecture is enriched through nanoparticles or nanowires that contribute to the performance of such solar cells. The absorber thickness - on the order of 100 nm - is much thinner than traditional solar cells, thereby decreasing the material cost. Processing temperatures of organic-based solar cells are much lower, thereby decreasing the energy cost during fabrication. Currently, promising materials include PbS and $CH_3HH_3PBI_3$. Research towards improving the stability and discovery of new materials in this group is on-going.

References

Dittrich, T. (2014). *Materials Concepts for Solar Cells*. ICP, New Jersey.

Nelson, J. (2003). *Physics of Solar Cells, The*. ICP, London : River Edge, NJ, 1 edition edition.

Würfel, P. and Würfel, U. (2016). *Physics of Solar Cells: From Basic Principles to Advanced Concepts*. Wiley-VCH, Weinheim, 3 edition edition.