**Lecture-21**

# Basics of Solar Photovoltaics

## Photovoltaics (PV)

Photovoltaics (PV) comprise the technology to convert sunlight directly into electricity. The term "photo" means light and "voltaic," electricity. A photovoltaic (PV) cell, also known as "solar cell," is a semiconductor device that generates electricity when light falls on it . Although the French scientist Edmund Becquerel observed photovoltaic effect in 1839, it was not fully comprehensible until the development of quantum theory of light and solid state physics in early to middle 1900s. Since its first commercial use in powering orbital satellites of the US space programs in the 1950s, PV has made significant progress with total U.S. photovoltaic module and cell shipments reaching $131 million dollars in 1996. While most PV cells in use today are silicon-based, cells made of other semiconductor materials are expected to surpass silicon PV cells in performance and cost and become viable competitors in the PV marketplace. This paper surveys the major types of PV cell materials including silicon- and non-silicon-based materials, providing an overview of the advantages and limitations of each type of materials.

Photovoltaic and Photovoltaic Cells

When sunlight strikes a PV cell, the photons of the absorbed sunlight dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. It is this movement of electrons and holes that generates electricity. The physical process in which a PV cell converts sunlight into electricity is known as the photovoltaic effect. One single PV cell produces up to 2 watts of power, too small even for powering pocket calculators or wristwatches. To increase power output, many PV cells are connected together to f form modules, which are further assembled into larger units called arrays. This modular nature of Fundamentals of Photovoltaic Materials

PV enables designers to build PV systems with various power output for different types of applications. A complete PV system consists not only of PV modules, but also the "balance of system" (BOS) - the support structures, wiring, storage, conversion devices, etc. i.e. everything else in a PV system except the PV modules.

Two major types of PV systems are available in the marketplace today: flat plate and concentrators. As the most prevalent type of PV systems, flat plate systems build the PV modules on a rigid and flat surface to capture sunlight. Concentrator systems use lenses to concentrate sunlight on the PV cells and increase the cell power output. Comparing the two systems, flat plate systems are typically less complicated but employ a larger number of cells while the concentrator systems use smaller areas of cells but require more sophisticated and expensive tracking systems. Unable to focus diffuse sunlight, concentrator systems do not work under cloudy conditions. Types of PV cell materials PV cells are made of semiconductor materials. The major types of materials are crystalline and thin films, which vary from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production. The rest of the paper discusses the characteristics, advantages and limitations of these two major types of cell materials.

## Converting Photons to Electrons

The solar cells that you see on calculators and satellites are photovoltaic cells or modules (modules are simply a group of cells electrically connected and packaged in one frame). Photovoltaics, as the word implies (photo = light, voltaic = electricity), convert sunlight directly into electricity. Once used almost exclusively in space, photovoltaics are used more and more in less exotic ways. They could even power our houses.

Photovoltaic (PV) cells are made of special materials called semiconductors such as silicon, which is currently the most commonly used. In fact, Over 95% of the solar cells produced worldwide are composed of the semiconductor material silicon (Si). Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely. PV cells also all have one or more electric fields that act to force electrons freed by light absorption to flow in a certain direction. This flow of electrons is a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to use externally. For example, the current can power a calculator. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power (or wattage) that the solar cell can produce.

# 1. Crystalline Materials

## 1.1 Single-crystal silicon

Single-crystal silicon cells are the most common in the PV industry. The main technique for producing single-crystal silicon is the Czochralski (CZ) method. High-purity polycrystalline is melted in a quartz crucible. A single-crystal silicon seed is dipped into this molten mass of polycrystalline.

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Slowly from the melt, a single-crystal ingot is formed. The ingots are then sawed into thin wafers about 200-400 micrometers thick (1 micrometer = 1/1,000,000 meter). The thin wafers are then polished, doped, coated, interconnected and assembled into modules and arrays. A single-crystal silicon has a uniform molecular structure. Compared to non-crystalline materials, its high uniformity results in higher energy conversion efficiency is the ratio of electric power produced by the cell to the amount of available sunlight power i.e. power-out divided by power-in. The higher a PV cell’s conversion efficiency, the more electricity it generates for a given area of exposure to the sunlight. The conversion efficiency for single-silicon commercial modules ranges between 15-20%. Not only are they energy efficient, single-silicon modules are highly reliable for outdoor power applications. The average price for single-crystal modules is $3.97 per peak watt in 1996. (Renewable Energy Annual 1997). About half of the manufacturing cost comes from wafering, a time-consuming and costly batch process in which ingots are cut into thin wafers with a thickness no less than 200 micrometers thick. If the wafers are too thin, the entire wafer will break in wafering and subsequent processing. Due to this thickness requirement, a PV cell requires a significant amount of raw silicon and half of this expensive material is lost as sawdust in wafering.

### 1.2 Polycrystalline silicon

Consisting of small grains of single-crystal silicon, polycrystalline PV cells are less energy efficient than single-crystalline silicon PV cells. The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power output of the cell. The energy conversion efficiency for a commercial module made of polycrystalline silicon ranges between 10 to 14%. A common approach to produce polycrystalline silicon PV cells is to slice thin wafers from blocks of cast polycrystalline silicon. Another more advanced approach is the “ribbon growth” method in which silicon is grown directly as thin ribbons or sheets with the approach thickness for making PV cells. Since no sawing is needed, the manufacturing cost is lower. The most commercially developed ribbon growth approach is EFG (edge-defined film-fed growth). Compared to single-crystalline silicon, polycrystalline silicon material is stronger and can be cut into one-third the thickness of single-crystal material. It also has slightly lower wafer cost and less strict growth requirements. However, their lower manufacturing cost is offset by the lower cell efficiency. The average price for a polycrystalline module made from cast and ribbon is $3.92 per peak watt in 19962, slightly lower than that of a single-crystal module.

### 1.3 Gallium Arsenide (GaAs)

A compound semiconductor made of two elements: gallium (Ga) and arsenic (As), GaAs has a crystal structure similar to that of silicon. An advantage of GaAs is that it has high level of light absorptivity. To absorb the same amount of sunlight, GaAs requires only a layer of few micrometers thick while crystalline silicon requires a wafer of about 200-300 micrometers thick.3 Also, GaAs has a much higher energy conversion efficiency than crystal silicon, reaching about 25 to 30%.Its high resistance to heat makes it an ideal choice for concentrator systems in which cell temperatures are high. GaAs is also popular in space applications where strong resistance radiation damage and high cell efficiency are required. The biggest drawback of GaAs PV cells is the high cost of the single-crystal substrate that GaAs is grown on. Therefore it is most often used in concentrator systems where only a small area of GaAs cells is needed.

## 2 . Thin Film Materials

In a thin-film PV cell, a thin semiconductor layer of PV materials is deposited on low-cost supporting layer such as glass, metal or plastic foil. Since thin-film materials have higher light absorptivity than crystalline materials, the deposited layer of PV materials is extremely thin, from a few micrometers to even less than a micrometer (a single amorphous cell can be as thin as 0.3 micrometers). Thinner layers of material yield significant cost saving. Also, the deposition techniques in which PV materials are sprayed directly onto glass or metal substrate are cheaper. So the manufacturing process is faster, using up less energy and mass production is made easier than the ingot-growth approach of crystalline silicon. However, thin film PV cells suffer from poor cell conversion efficiency due to non-single crystal structure, requiring larger array areas and increasing area-related costs such as mountings. Constituting about 4% of total PV module shipments of US4, the PV industry sees great potentials of thin-film technology to achieve low-cost PV electricity. Materials used for thin film PV modules are as follows: the material, how much of the sunlight can be successfully converted into electricity is measured by the concept of energy conversion efficiency.

## 2 . 1 Amorphous Silicon (a-Si)

Used mostly in consumer electronic products which require lower power output and cost of production, amorphous silicon has been the dominant thin-film PV material since it was first discovered in 1974. Amorphous silicon is a non-crystalline form of silicon i.e. its silicon atoms are disordered in structure. A significant advantage of a-Si is its high light absorptivity, about 40 times higher than that of single-crystal silicon. Therefore only a thin layer of a-Si is sufficient for making PV cells (about 1 micrometer thick as compared to 200 or more micrometers thick for crystalline silicon cells). Also, a- Si can be deposited on various low-cost substrates, including steel, glass and plastic, and the manufacturing process requires lower temperatures and thus less energy. So the total material costs and manufacturing costs are lower per unit area as compared to those of crystalline silicon cells. Despite the promising economic advantages, a-Si still has two major roadblocks to overcome. One is the low cell energy conversion efficiency, ranging between 5-9%, and the other is the outdoor reliability problem in which the efficiency degrades within a few months of exposure to sunlight, losing about 10 to 15%. The average price for a a-Si module cost about $7 per watt in 1995.5

## 2 . 2 Cadmium Telluride (CdTe)

As a polycrystalline semiconductor compound made of cadmium and tellurium, CdTe has a high light absorptivity level -- only about a micrometer thick can absorb 90% of the solar spectrum. Another advantage is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing. The conversion efficiency for a CdTe commercial module is about 7%, similar to that of a-Si. The instability of cell and module performance is one of the major drawbacks of using CdTe for PV cells. Another disadvantage is that cadmium is a toxic substance. Although very little cadmium is used in CdTe modules, extra precautions have to be taken in manufacturing process.

## 2.3 Copper Indium Diselenide (CuInSe2, or CIS)

A polycrystalline semiconductor compound of copper, indium and selnium, CIS has been one of the major research areas in the thin film industry. The reason for it to receive so much attention is that CIS has the highest “research” energy conversion efficiency of 17.7% in 1996 is not only the best among all the existing thin film materials, but also came close to the 18% research efficiency of the polycrystalline silicon PV cells. (A prototype CIS power module has a conversion efficiency of 10%.) Being able to deliver such high energy conversion efficiency without suffering from the outdoor degradation problem, CIS has demonstrated that thin film PV cells are a viable and competitive choice for the solar industry in the future. CIS is also one of the most light-absorbent semiconductors of 0.5 micrometers can absorb 90% of the solar spectrum. CIS is an efficient but complex material. Its complexity makes it difficult to manufacture. Also, safety issues might be another concern in the manufacturing process as it involves hydrogen selenide, an extremely toxic gas. So far, CIS is not Fundamentals of Photovoltaic Materials commercially available yet although Siemens Solar has plans to commercialize CIS thin-film PV modules.

# Heat Transfer of Solar PV Panels

Because solar PV panels interact with their environment and their ref is so low, they passively absorb about 80% of the incoming solar irradiance as heat. This would not be such a problem if not for a 0.5% efficiency loss of the solar PV panels associated with a 1◦K increase of the cell temperature. Because the highest temperatures of solar PV panels recorded are about 70 ◦C, this efficiency loss can be very noticeable, especially true for yesterday’s PV arrays that have such a low efficiency to begin with. Therefore, heat transfer plays an important role in the actual output of PV arrays. The three modes of heat transfer are involved with the solar PV array. The main energy input is solar irradiance in the form of shortwave radiation. The solar panel undergoes heat removal by convection, radiation, and conduction. However, the heat conducted is negligible because of the small contact area between the solar array and the its structural framework. The heat removed from the panel is in the form of long wave radiation due to the much colder temperature of the panel compared to the Sun. A schematic of this heat transfer mechanism is shown. It is worth noting that some solar arrays have an anti-reflection coating to decrease reflection losses and increase actual solar irradiance incident on the panel

The temperature of each individual PV cell is a function of its materials, configuration, time of day, rotation of the Earth and environmental factors such as wind, temperature, cloud cover and humidity. To determine the temperature of the solar PV panel a comprehensive heat transfer analysis must be performed.

## Cooling Ducts

Brinkworth and Sandberg [2006] calculated the optimal length (L), the hydraulic diameter (Dh), and the width (H) of a cooling duct attached to the back of a solar PV panel which would reduce the most heat. They accomplished this by simultaneously solving the external and internal heat transfer equations. The external equation represents the heating of the surroundings from the front of the panel while the internal equation represents the heat transferred into the cooling duct. Their model was validated with measurements from a full-scale rig. Factors influence the temperature of the PV side of the duct are include radiation losses, and decreasing coefficients of heat transfer until the flow becomes fully developed.