ME 210 Materials Science

SOLAR CELL MATERIALS

By

Serkan Çimen

Submitted to: Ercan Balıklıç

Fall 2005
Abstract:

When people discovered the fact that in the offing, they will consume all the fossil fuels -which they use now- between the years 2020 and 2060, finding new sources of energy has become a new challenge. One of the solutions of this problem is renewable energy sources such as solar energy. Researches on solar cell systems, which can convert solar energy to electricity, are mainly focused on the semiconductors since semiconductors are the main material used in solar cells (or photovoltaic cells). As a result it is convenient to discuss about the fundamentals of the semiconductor materials because it is necessary to develop the idea of solar cell. In fact, the current research on solar cells is mainly focused on developing the thin film solar cell technology. Some materials that are currently under investigation are GaAs, CdTe, CuInSe2, InP, Zn3P2, CdSe. They have the high efficiency but the drawback they all have is that they still have high costs. But there are several materials which have a lower efficiencies with reasonable market prices. A recent survey showed that the average prices are $5.30 per Watt in US and €5.78 per Watt in Europe. If these prices tend to decrease, it is obvious that the solar cell usage will be widespread in the future.

Introduction:

Energy will be one of the serious problems that people will be facing in future. What will the world’s energy demand be in future and how will people cover that demand? The electricity usage is growing worldwide. According to the anticipations of The International Energy Agency [1], the world’s electricity generating capacity will be nearly 5.8 million megawatts by the year 2020. However, petroleum industry's best analysts claim that the main source of this electricity - fossil fuels - are expected to be ran out from the years 2020 to 2060. On the other hand, the renewable energy is sustainable unlike fossils fuels. It will never run out. According to the World Commission on Environment and Development, sustainability is the concept of meeting "the needs of the present without compromising the ability of future generations to meet their own needs".

Also environment has begun to give the signs of the coming danger. The global warming is one of the main problems even today and the fossil fuel usage is responsible for that. The usage of fossil fuels increases the greenhouse gases - carbon dioxide, methane, nitrous oxide, hydrocarbons, and chlorofluorocarbons – which surround Earth’s surface letting the suns rays in and trapping them inside. According to the U.S. Environmental Protection Agency (EPA), carbon dioxide is responsible for one-half to two-thirds of our contribution to global warming. However, renewable energy can produce electricity without or with a little carbon dioxide. Another threatening problem about nature is contamination - air, water, and soil contamination - which grows out of the usage of fossil fuels. On the other hand, most renewable energy technologies produce little or no pollution [1].

Shortly, the renewable energy is an important field of research. The major research and development fields of renewable energy are solar, wind, biomass and geothermal. Without a doubt the most important subject is the solar energy, because of the lower costs and the easy applicability relative to others. The purpose of this paper is giving the basic concepts of solar energy and naming the emerging semiconductor materials and giving the recent researches focused on developing these materials. Also, the paper includes the prices of the current solar cell market and predictions about its future trends.
Theory:

The materials used in solar cells (or photovoltaic cells) are basically semiconductors. Semiconductors are materials which have intermediate electrical conductivity between conductors and insulators. At lower temperatures, semiconductors show insulator properties while at room temperature they have a mediocre conductivity which we cannot compare with conductors. The distinction between the conductor and semiconductor is that a semiconductor has a filled uppermost electron energy band while a conductor has partially filled. And a semiconductor differs from an insulator by the fact that a semiconductor has a band gap small enough to allow electrons to move to the conduction band at room temperatures [2].

Since they are the main materials used, the fundamental semiconductor physics must be known to understand how solar cells work.

As mentioned before, semiconductors are solids which have their valence band (the uppermost band of occupied electron energy states) fully filled (Figure 1). At room temperatures small but appreciable number of electrons cross to the conduction band. These excited electrons have enough energy to break the covalent bond between the neighboring atoms in the solid and free to move in other words, conduct electrical current. On the other hand, the covalent bonds which give their electrons form holes which are considered to move. (In fact, holes do not move but neighboring electron can move to fill the hole, forming a new hole where it comes. This way holes appear to move.) [2].

The electrons can be excited easily in semiconductors because of the fact that semiconductors have small band gap energies – less than 3eV – between the valence band and conduction band [2].

Semiconductors electrical properties can be changed in a controllable way by adding small amounts of impurities which are called dopants. There are two ways of doping by which a semiconductor becomes n-type or p-type [2].

In n-type doping, the purpose is exceeding the mobile or ‘carrier’ electrons in number. It is accomplished by adding group VB elements (e.g., phosphorus (P), arsenic (As), or antimony (Sb)) in the periodic table as impurity. Consider the case of silicon. Silicon (14) has four valence which are covalently bonded to neighboring silicon atoms in the lattice. If an atom with five valence electrons added into the lattice, some of the silicon form covalent bonds with them, resulting an extra electron which could not participate in bond formation. These extra electrons are weakly bounded to impurity atom and can easily be excited to the conduction band. Since excitation of these electrons does not result in the formation of a hole, electrons outnumber holes in such a material. In this case the electrons are the majority carriers and the holes are the minority carriers [2].

In p-type doping, the purpose is creating more carrier holes than carrier electrons. Think about the silicon again. This time a trivalent atom (such as boron) is added to the lattice and forms bond with the silicon in the lattice. But one electron is missing from one of the four covalent bonds for the original silicon lattice. The silicon which has not formed a bond in the
lattice forms covalent bonds with neighboring silicon atoms and creates a hole in the structure. When necessary impurity added, the number of holes exceeds the number of electrons. In this case the holes are the majority carriers, while electrons are the minority carriers [2].

While doping the semiconductor, it is important to add a very small level of impurities because even the small proportions have vast effects on the properties of the semiconductor. It is also important to attend not to destroy the semiconductors high degree of crystalline perfection because faults as dislocations, twins, and stacking faults are the major cause of the defective semiconductor devices. To achieve both, special methods have been developed to produce the initial semiconductor material. A technique called Czochralski process (Figure 2) is the most widespread. In this technique, a high purity semiconductor is melted down in a crucible. Then the impurity atoms are added into crucible to form p-type or n-type semiconductor. A seed crystal, mounted on a rod, is dipped into the molten semiconductor then it is pulled up while rotating at the same time. By changing the variables like temperature gradients, rate of pulling and speed of rotation, it is possible to obtain a large single crystal from the melt [2]. One other technique is Bridgman process which is basically a controlled freezing process. Bridgman process requires directional solidification of a melt starting from seed. The solidification can be horizontal or vertical and controlled by a moving temperature field. By these controlled solidification, a single crystal will propagate and grow [3].

So far, the fundamental physics of semiconductors is explained. But how a photon turns into electricity by the help of a semiconductor?

To give a satisfying answer to that question, p-n junctions have to be discussed first. In order to understand the concept of p-n junction, consider a piece of n-type semiconductor brought into contact with a piece of p-type semiconductor. That is not the way junctions are created. In practice, they are created by diffusing n-type of impurity into the p-type of wafer. In that situation, there will be a diffusion of electrons from the n-type side of the junction – since electrons have a high concentration at that side and have a low concentration at the other side – to the p-type of the material. Actually, these electrons which are obtained from impurities move to p-type side of the semiconductor leaving the positively charged nuclei of group VB elements behind or in other words leaving an excess positive charge on the n-type side. On the other hand, these electrons fill the holes on the p-type side of the junction and this accumulates a negative charge on the p-type side of the material. This imbalance of electrons on the both sides forms an electric field at the junction. This electric field has a dual effect. First, it opposes the further diffusion of electrons and second it obviously creates a dipole to determine the flow of the current as seen in Figure 3 [4].
When a photon hits the semiconductor, two things may occur. The first possibility, the photon can pass through the semiconductor and this possibility happens when the energy of the photon is lower than the bandgap of the semiconductor. The second possibility is that the photon may be absorbed by semiconductor and this possibility happens when the energy of photon is greater than the bandgap of the semiconductor. When the second possibility happens, the energy of the photon is given to an electron in the crystal lattice. This energy breaks the tightly bounded covalent bonds and excite the electron from valence band to the conduction band. And the missing electron in the covalent bond forms a hole. Thus, mobile electron-hole pairs are obtained. If this happens in the diffusion zone of the electric field at the junction between n-type and p-type semiconductor; the excited electrons and holes move according to the direction of the electric field (Figure 4). This electron-hole flow creates the current, and the electric field sets up the voltage [4].

At this point, it is important to say that the band gap also determines the strength (voltage) of the electric field. If the voltage is too low, it is obvious that there will be more free electrons. But since power is equal to voltage times current, they have to be balanced to have maximum power. The optimal band gap balancing these two effects is approximately 1.4 eV. That is why a material with a smaller band gap could not be used in solar cells [5].

Another important thing that deserves attention is that, most of the solar radiation reaching the Earth surface is greater than the band gap of the most semiconductors. The higher energy photons are absorbed by semiconductors but the difference between the band gap energy and the photon energy is not converted to electricity; it is converted to heat. Also, some of the solar radiation is not absorbed because of the surface reflections. And these accounts for the little efficiency (around 12 percent) of the solar cells [4].

One way to increase this efficiency is increasing the absorption level of the solar cell. Since the materials used in solar cell production are basically shiny materials, they are coated with an antireflective material. After all the solar cell gains the structure shown in Figure 5 [6].

**Figure 4 Operation of PV cell**

**Figure 5 Basic Structure of a generic silicon PV cell**

**Discussion:**

Although all semiconductor materials have the aspects above, certain materials have more suitable aspects for producing solar cells. Certain materials used in solar cell have stood out. Some of them are: GaAs, CdTe, CuInSe2, InP, Zn3P2, CdSe.
• **Gallium Arsenide (GaAs):**

GaAs have a band gap of 1.43 eV which is nearly ideal for solar cell production. It also has a high absorptivity so that it allows producing cell which are only a few microns thick. The other important feature of GaAs is that it is insensitive to heat so it does not create problems in the concentrator applications (focusing the light by lenses or mirrors) in which temperatures can get so high. GaAs is also very resistant to radiation so it can be used in space applications. Another outstanding feature of GaAs is that its alloys from aluminium, phosphorus, antimony, or indium has the above features which of all allows great flexibility in design. A cell made of GaAs can have different compositions in different layers, and this gives the designer the opportunity even to control the collection of electron and holes. This control increases the efficiency values to the theoretical results. To give an example, a common GaAs cell is a very thin layer of alluminimium gallium arsenide in which the electrons and holes are created very close to the p-n junction [7].

The greatest difficulty to use GaAs is the high cost of the GaAs material. Because of this reason they are used in concentrator systems which reach efficiencies between %25 and %30. Unfortunately, GaAs is commercially available only for space applications again because of its high cost. To decrease this high cost, certain fabricating methods (like using cheaper substrates or growing GaAs cells on a removable and reusable GaAs substrate) are being developed. By this methods, making low cost GaAs thin films similar to those of copper indium diselenide and cadmium telluride will be possible [7].

• **Cadmium Telluride (CdTe):**

CdTe is one of the most suitable semiconductors for solar cells because of its 1.4 eV band gap. The devices made of CdTe also includes a very thin layer of cadmium sulfide which passes most of the sunlight to the CdTe. This features allows high efficiency solar cells with low production costs [8].

Researches on CdTe tries to increase the efficiency by adding different type of oxides which will raise the absorption level of material. Also they are studying the mechanisms (such as grain boundaries) which can affect on the voltage. And they also test thin film modules in hot and humid climates to minimize the effect of moisture [8].

• **Copper Indium Diselenide (CuInSe₂ or CIS):**

NREL (National Renewable Energy Laboratory) currently holds the world-record conversion efficiency of 19.2% with CIS based thin film solar cell. Also, after almost two decades of research and development, CIS is currently available in market with the modules which reach 11% efficiency with appreciable costs [9].

Researches on CIS focuses on increasing the efficiencies of CIS based solar cells by investigating the chemistry and physics of the junction formation and by exploring the ways to allow more of the high energy part of the solar spectrum to reach the absorber layer. They also try to reduce the cost by decreasing the manufacturing complexity and by improving the module packing [9].

• **Indium Phosphate (InP):**

InP is a radiation resistant solar cell material which has also relatively low cost in comparison with the other radiation resistant solar cell materials. It also has a high conversion efficiency which is around 19% percent. Through its features, it is used as the basic material in the NASA’s cell development programs and also in some military
applications. It is also available in market because of the fact that it provides long life reliable photovoltaic power for commercial systems [10].

- **Zinc Phosphide (Zn$_3$P$_2$):**
  
  Zinc phosphide has a band gap of 1.41 eV which is very suitable for solar cell production. Also it has high absorption region in thin single crystals so it has a high absorption coefficient and this leads to a high conversion efficiency [11].

  The greatest drawback of zinc phosphide is that it is a poisonous material which is also being used as a rodenticide. It is shown that it has no secondary poisoning which means the animals that feed on rodents are not affected. But still there is a risk of poisoning the other animals (such as it has shown that birds affected most) [12].

- **Cadmium Selenide (CdSe):**

  Cadmium Selenide is being used in developing of the thin film solar cells of inorganic nanocrystals. It is achieved to build a thin film solar cell which has a thickness of 200 nanometers with a reasonable price, but it has only 3% conversion efficiency. However, researchers are very hopeful about these new nano solar cells. One of the research workers, Ilan Gur who carries out researchs in Berkeley university as a material science engineer says that with improvement the nanocrystal approach could become "a general strategy to cheaply produce solar cells" [13].

As seen from the above materials, the main problem is obtaining a high efficiency solar cell with low prices. A survey conducted by Solarbuzz website [14] shows us the precise prices for the solar cells. They have gathered information from the major solar cell brands. According to that survey, the average price for solar cells is $5.30 per Watt in US and €5.78 per Watt in Europe. The lowest retail price for a multicrystalline silicon module is $3.89/Wp from a US dealer. The lowest price for a monocrystalline module is $4.07/Wp (€3.46/Wp), also from a US-based dealer. The lowest thin film module price is $3.67/Wp (€3.12/Wp) per Watt from a German dealer. The survey also showed a disappointing result which is that the prices which were tending to decrease in 2004 increased little in 2005.

**Conclusion:**

Energy will be one of the main problems the world will encounter in the future. The world energy demand is increasing rapidly, and the basic energy sources of us, fossil fuels, are consuming with the same rapid trend. Also, if the fossil fuels were not consuming, still we may not be able to continue using them because the fossil fuels contaminates the Earth and cause the global warming which is also known as green house effect. But the question is that what can be the alternative energy sources, and the answer is simple: renewable energy sources especially the solar energy.

The solar cells are produced by semiconductor materials. Semiconductors are materials which has a conductivity between conductors and insulators. In order to understand the structure of solar cell, the basic features of the semiconductor materials should be known. But the main idea is that; with a little amount of impurity atoms semiconductors can create excess electrons and excess holes which we say n-type and p-type respectively. At the junction of this two types there is a electron-hole imbalance and at that regions an electric field is created.

When light comes and hits the semiconductor light is absorbed and the energy of this light excites an electron. The electrons which are close to the electric field at the junction
moves according to field and the flow of electrons create an electric current. This is the basic idea how a solar cell works.

Some of the materials used in solar cells are GaAs, CdTe, CuInSe2, InP, Zn3P2, CdSe. They differ from each other in terms of conversion efficiency, cost and some other features(such as radiation resistance, being poisonous etc.). But the main common point is that although they are trying to develop the solar cells, the efficiencies and the costs are not satisfactory. That is why recent research is focused on that matter.

To conclude, as solar cell technology develops, solar cells will find a stable place in the market. The widespread of solar cells may solve our energy demand problem not only for now but also in future.

References: