Solar panels' working principle and future development

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Introduction

Since the total energy on earth is limited, the energy shortage becomes the main problem for all humans. In order to address the shortage of energy, people come up with several ways to absorb the energy from environment. For examples， tidal energy, wind energy, solar energy…… Among these energies, solar energy seems to be the most abundant and direct energy source, but why don't people today use solar panel prevalently? This paper will explain this reason, and include the working principle of solar panels, solar panels' power, solar panels' efficiency and solar panels' future. The paper will also talk about the application of solar panel and its pros and cons.

Working principle

When sun light reaches the P-N junction on solar panels, the electrons in semiconductor gain the light energy and are released from their original orbits. Thus, electron-hole pairs appear. Because of the Potential Energy Barrier, electrons are forced to move to N field, and holes are forced to move to p field. As the result, there are more electrons in N field than in P field, and there are more holes in P field than in N field. Thus, the portion of potential difference between N and P field counteract with the Potential Energy Barrier from the electric field. [1]

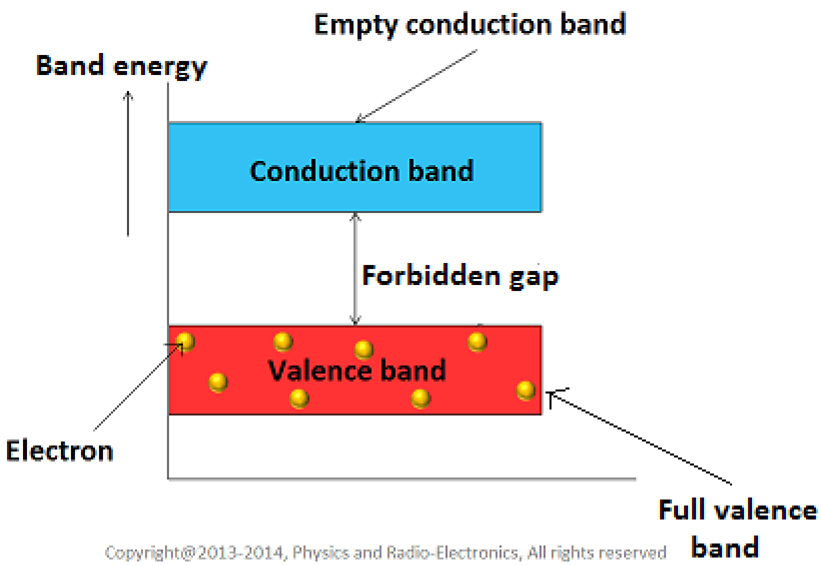
Intrinsic semiconductor: the element with low valence are tend to lose electrons because their outermost electrons tend to overcome the nuclear force and become free electrons. Because the energy of electrons becomes weaker as electrons become closer to nucleus. In the electric field, free electrons will move to a fixed direction, which form the electricity. However, for the element with high valence, such as inert gas, their outermost electrons have to overcome huge coulomb force to escape from their orbits, so the conductivity of their elementary substances is poor. For semiconductors, like Si and Ge, their valences are +4, their outermost electrons are bonded to their nucleus by the coulomb force whose magnitude is between coulomb force produced by the elements with low valence and high valence. Intrinsic semiconductors are made of pure semiconductors, and they are single crystal. In intrinsic semiconductors, covalent bonds are formed between adjacent atoms. The energy of covalent bond in crystal is huge. Thus, in indoor temperature, there are few valence electrons gain the energy to become free electrons. [1]

Electron-hole pairs: When valence electrons become free electrons, their original places form holes. Due to loss of electrons, the atoms are electropositive. The number of free electrons is equal to holes. When free electrons meet holes during their moving process, they will combine together and disappear. We assume that holes are electropositive, and in order to keep P, N regions are electrically neutral, we also assume that space charges are electronegative in P region and are electropositive in N region. [1]

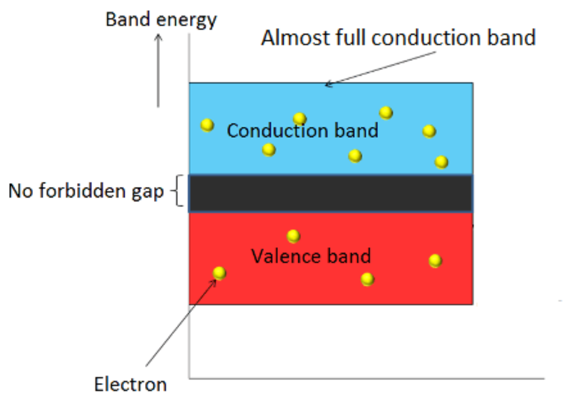
Valence band: The band of energy occupied by the valence electrons is called the valence band. [2]

Forbidden band: It is on Valence band, and it is the band of energy which can't be occupied by electrons. The width of Forbidden band is represented as Eg, whose value is affected by the temperature and material. For instance, when T=300K, Si's Eg=1.1eV

For insulators, there is no electron in conduction band, but the valence band is full of electrons because it shares electrons with adjacent atoms. Since electrons in the valence band are locked between atoms, they need huge energy to pass the forbidden gap to enter conduction band. The energy of frobidden gap is approximately 15 electron volt. [3]



For conductors, there is no forbidden gap, and valence band and conduction band overlap, which means electrons in valence band only need a little energy to move to conduction band. [3]



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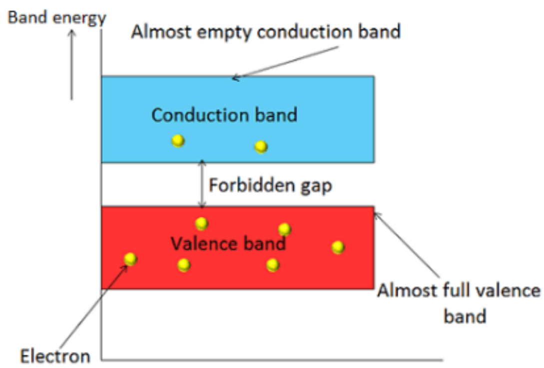
For semiconductors, the energy of forbidden gap is about 1 electron volt. In low temperature, electrons in valence band don't have enough energy to pass forbidden gap. However, in high temperature, some electrons have enough energy to enter conduction band and become free electrons. [3]



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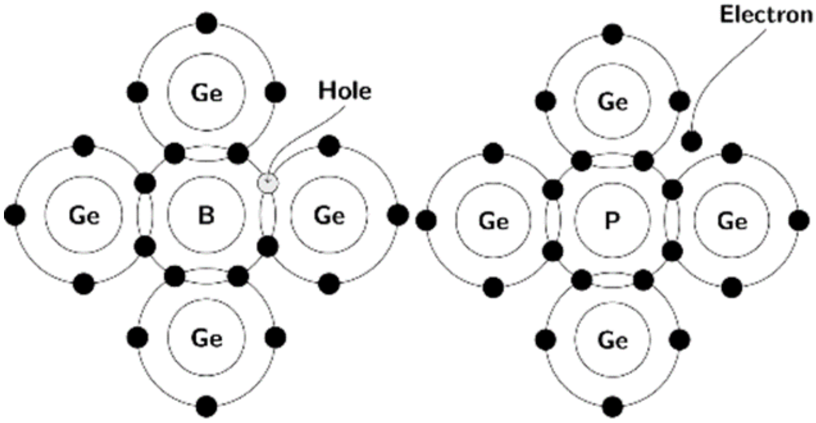
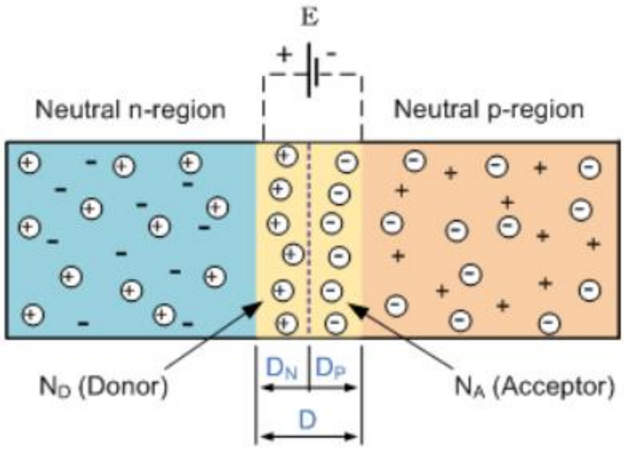
Impurity semiconductor: It is created by adding some specific elements to intrinsic semiconductor, which change the conductivity of the conductor.

There are two kinds of impurity semiconductor: N and P. N impurity semiconductor are composed of intrinsic semiconductor made of Si and 5-valence elements. Because a 5-valence atom has 5 outermost electrons, when it forms covalent bond with adjacent Si atoms, it still has one more electron. This electron becomes free electron. Losing electrons, atoms in N impurity conductor become cations. P impurity semiconductor is composed of 3-valence element and intrinsic semiconductor made of Si. Since 3-valence elements only have 3 outermost electrons, when the atom form covalent bond with adjacent Si atoms, holes are formed. [4]



(a) Hole Donation (b) Electron Donation

PN junction: when we connect P and N impurity semiconductor, the boundary where they connect is called PN junction.



Since there are lots of free electrons in N region and holes in P region, diffusion phenomenon appears. Free electrons move from N region toward P region, and holes move from P region toward N region. When free electrons and holes pass the boundary, they will meet, and 1 free electron combines with 1 hole.

Because the electrons entered P region combine with holes, anions appear in part of P region; because holes entered N region combine with electrons in N region, cations appear in part of N region. Then there is a region called space-charged region (D), which will create an electric field in the middle of the panel. As more and more free electrons fill holes, the space-charged region becomes wider and wider, and its electric field's strength also increases. Thus, free electrons return to N region won't move to P region anymore, and holes won't move to N region, which is called drift phenomenon. [5]

Characteristic of PN junction: unilateral conductivity.

When we connect battery cathode to P region, and connect battery anode to N region, we call it forward bias. In this situation, the electric field produced by battery in PN junction (from P region to N region) is in the reverse direction of the electric field produced by space-charged region (from N region to P region). Because of the electric field produced by battery, holes in P region move to space-charged region to neutralize a portion of negative space charges, and electrons in N region move to neutralize a portion of positive space charges. This phenomenon causes space-charge region becomes narrower. Thus, the electric field produced by space-charged region decreases, which helps the diffusion of majority carriers (holes and electrons). As the result, the semiconductor's conductivity is increased.

Corresponding to forward bias, there is a term called reverse bias, which means connecting battery cathode to N region and battery anode to P region.

In this case, battery helps to enlarge the area of space-charged region. As the result, the electric field of space-charged area enhances, which blocks the diffusion of electrons in N region, holes in P region and enhances the diffusion of minor holes in N region, minor electrons in P region. The diffusion of minority carriers creates an inverse current (from N region to P region). However, since there are few minority carriers in room temperature, we can ignore the inverse current. [6]

photovoltaic effect: When sun light reaches solar panel, due to the light energy, electrons in N region, space-charged region, P region gain enough energy to pass forbidden gap and enter conduction band. Numerous electron-hole pairs appear. The motion of these free elections and holes can be discussed in three categories: in P region, N region, and space-charged region. In P region, because of the diffusion effect, when free electrons move to the boundary of P region and space-charged region, free electrons will be dragged to N region due to the electric field in space-charged region. However, when holes diffuse to the boundary of P region and space-charged region, they will be repelled to P region due to the electric field.

1. In space-charge region, free electrons are pushed to N region, and holes are pushed to P region due to the electric field.
2. In N region, when free electrons diffuse to the boundary of the space-charge region and N region, electrons will return to N field; on the contrary, holes will enter P region due to the electric field in space-charge region.

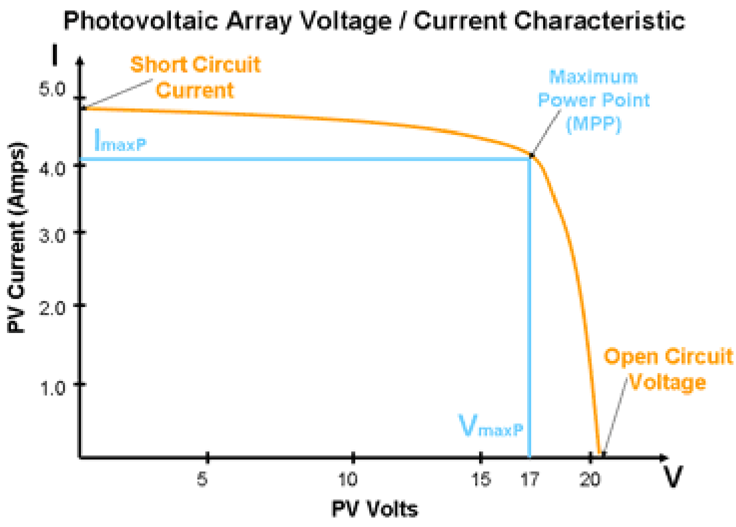
Since there are huge number of free electrons in N region and holes in P region, N is electronegative relative to P region, and there is an electrodynamic potential between N and P region (a portion the electric field created by light energy counteract the electric field created by space-charge field). Then, the solar panel is like a cell which can provide voltage in a circuit. Because all of P, N and space-charged region can provide free electrons and holes, free electrons have to cross the space-charged region to enter N region before meet a hole so that they can contribute to the electric field created by light. As the result, people have to consider free electrons' motion, diffusion, drift phenomenon. [1]

Solar panel's power

Before talking about the power of solar panels, we first introduce two terms:

Open-circuit voltage: When we connect a voltmeter to P side and N side, we can measure the open-circuit voltage. For the solar panel made of Silicon, the open-circuit voltage is about 0.5V.

Short – circuit current: if we connect P side and N side use a ampere meter, we measure the short-circuit current. The short-circuit current is proportional to light energy received by the solar panel. The freer electrons are produced, the larger the short-circuit current the solar panel can provide.



The area enclosed by the blue rectangle represents the maximum power the solar panel can produce when it receives sun light. When load's resistance is infinite large, the voltage is open-circuit voltage (U_{oc}). When the load's resistance is zero, the current is short-circuit current (I_{sc}). As the resistance of load increase to reach a specific value (Rm), the power of solar panel can reach the maximum-power point (MPP). The corresponding current is optimal current (I_m), the voltage is optimal voltage (U_m). Pm is maximum power. [7]

Fill factor (FF): It is the product of short-circuit current and open-circuit voltage ($U_{oc}\times I_{sc}$), which can measure the efficiency of solar panels.

$$\mathrm{FF} = \frac{P_m}{U_{oc}I_{sc}} = \frac{U_m I_m}{U_{oc}I_{sc}}$$

P_m is the maximum power the solar panel can generate.

When other conditions are same, the larger the FF is, the more power the solar panel can produce. [7][1]

Solar panel's efficiency

$$\eta = \frac{P_m}{A_t P_{in}} = \frac{I_m U_m}{A_t P_{in}} = \frac{(FF) I_{sc} U_{oc}}{A_t P_{in}}$$

$$P_{in} = \int_0^{\infty} \Phi(\lambda) \frac{hc}{\lambda} d\lambda$$

Φ is the intensity of light, and its unit is lumen (LM); h is Planck constant; λ is wavelength of light; c is speed of light.

In order to maximum the solar panel's efficiency, producer have to consider both Uoc and Isc to ensure that the product of U_{oc}, I_{sc}, and FF is as large as possible. [1]

Since now photovoltaic modules only can produce electricity from a range of frequencies of light, and sun light covers the entire solar range, much of the incident sunlight energy is wasted. Currently the best achieved sunlight conversion rate (solar module efficiency) is around 21.5% in new commercial products. If solar panels can receive monochromatic light, they will have far higher efficiencies. Splitting the light into different wavelength ranges and directing the beams onto different cells tuned to those ranges can raise efficiency by 50%. [8]

Solar panels' future

Some people say solar energy will be prevalent in future：

In the last decade, solar energy has experienced a rapid growth and not only did the number of installed solar units increase, solar energy has become a major player in the US economy. Since 2010, the number of people working in the solar industry has doubled. In 2015, some 210 000-people worked in the solar energy business. In the last 10 years, the prices have dropped over 60%, making the investment even more profitable. Back in 2015, MIT published an extensive, 365-page study on the future of solar energy. According to the study, “Solar electricity generation is one of very few low-carbon energy technologies with the potential to grow to very large scale.” The researchers at MIT believe that the solar energy has the potential to generate multi-terawatt scale power. In comparison, today’s largest solar farm has a 550-megawatt capacity. This is a clear sign of the growth potential of solar energy. [9]

Some people consider the disadvantages of solar energy and confirm the future of solar energy:

Even though sunlight energizes virtually all processes on Earth, the amount of solar energy falling on one square meter of ground is actually pretty small. The average amount of sunlight reaching the surface of the Earth is about 300 Watts per square meter (about 10 sq. ft.). the solar energy technology is relatively expensive compared to, say, coal-fired power plants. Electricity costs in the United States average 7 cents per kilowatt-hour. A currently advertised inexpensive 3 kilowatt (peak) solar system bought in California, after a hefty state rebate and tax incentive, will cost $6,552. Running at an average of 30% of peak capacity (no sun at night, cloudiness, etc.), this system will take ten years before it costs less than buying all electricity from utilities. Most people would rather pay less now, rather than invest in something where the payoff is years down the road. First-time home buyers are usually trying to buy as large and as nice a house as possible for what they can afford in a monthly payment. Barring a massive change in public sentiment, it will probably take government regulation to force higher efficiency standards on the building industry, since the public is unlikely to voluntarily make such an investment. Despite the competitive disadvantage that solar energy technologies have right now, the availability of "free" sunlight will remain a driving force behind the development of new ideas that can make solar power more affordable in the future. As economies of scale are achieved in the manufacture of solar collection devices (both thermal and electric), and as petroleum prices gradually rise, solar energy will become more cost competitive. [10]

Some people think solar energy will never be prevalent:

Advocates of solar energy have argued for years that the industry only needs subsidies to gain the economies of scale that would make it cost competitive. We think that day may never arrive. When is solar going to become cost competitive without subsidies? In three to five years? Try never. But if it did, society would have to pay out trillions of dollars to get there. But should governments provide massive subsidies to support solar energy in places where electric power can be generated at a much lower cost? I think not. Much of the money is likely to be wasted. Germany, for example, has subsidized the solar industry to the tune of $50 billion, yet it only gets 6% of its electricity from solar power. The marginal tax dollar would find a better home in the research labs of universities, where fundamental technological breakthroughs are more likely to yield a big increase in efficiency and corresponding decline in price. [11]

Conclusion

From the working principle of solar panel, we can understand how solar panels convert solar energy to electricity and their efficiencies. Knowing their low efficiencies, we can predict the future direction of development of solar panels. Since the efficiencies of solar panels are relatively lower than petroleum, and cost of solar panels are also higher than petroleum, people haven't adopted solar energy prevalently. However, there are some improvements in solar panels to boost the efficiencies to convert solar energy to electricity. Besides this, there are more and more people purchase solar panels and attend the manufacture of solar panels, which lowers the price. The future of solar energy is still unpredictable.

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