WET CHEMICAL ETCHING OF SOLARCELL FOR EDGE ISOLATION

A Thesis Submitted for the Partial Fulfillment for the Degree of Master of Science in Renewable Energy

Submitted By

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Certificate of Authentication

This is to certify that the Thesis Report entitled “Wet Chemical Etching of Solar Cell for Edge Isolation” submitted by Tanvir Hassan Mojumder for Partial Fulfillment for the Degree of Master of Science in Renewable Energy. His Class roll: 29, Exam rolls: 509, Session 2014-2015. His was prepared under my instruction and direct supervision.

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DECLARATION

I declare that this thesis is an original report of my research, has been written by Tanvir Hassan Mojumder Roll No. 29 Registration No. Ha 229, Session: 2013-14 department of Renewable Energy, Dhaka University and has not been submitted for any previous degree. This experimental work is almost entirely my own work; the collaborative contributions have been indicated clearly and acknowledged. Due references have been provided on all supporting literatures and resources.

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Certificate of Clearance

This is to certify that the Thesis Report entitled “Wet chemical etching for edge isolation” submitted by Masters student Tanvir Hassan Mojumder, Institute of Energy, University of Dhaka has performed and completed his research wholeheartedly at the Institute Of Electronics(IE),Bangladesh Atomic Energy Research Establishment (AERE).

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ABSTRACT

Solar Energy as an alternative for conventional resources is getting popular day by day. As fossil energy sources diminishing gradually and some of them have adverse effects on world climate. One of the most popular methods, now a day for harnessing solar energy is solar panel. Solar cell depends upon the photovoltaic effect for their operation.

The efficiency of solar cell depends upon how much energy input of solar energy is converted as output current. Solar cell efficiency also dependent upon some characteristic parameters such as short circuit current (Isc), open circuit voltage (Voc) and fill factor (FF).

Parasitic components affect these parameters. These resistive parameters are series and shunt resistances. Shunt in solar panel is a loss mechanism occurs due to defects. Volume shunts are material induced shunts can occur due to impurities, metal particles contamination or aluminum particle contamination while making grid fingers, are impossible to eradicate without destroying the cell. On the other hand, mostly occurred edge shunts due to crack, holes or scratches can be removed in many available techniques.

During the manufacturing of solar cell, a very important step called edge isolation process affects IV characteristics of solar cell, which is critical to the efficiency of itself. Deep and crack-free edge isolation to increase shunt resistance in the solar cell achieves higher efficiency and eliminates the source of fatigue cracks to extend lifespan of solar cells. There are many techniques available for removing shunts. In this paper, wet chemical etching method by HNA, is used for edge isolation process.

From the experiments results it is found that HNA etching improves the IV characteristics of solar cells and hence it improves the power curves. Efficiency of un-etched solar cells was 3.17% and 3.90%. After etching the solar cell efficiency increase up to 5.53% and 5.31% respectively. From these progressive results, it can be said that wet chemical etching has flawless demands for further study.

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CHAPTER 1

1.1 INTRODUCTION

The era we are living in, is obviously the best time in technical advancement for human civilization. This advancement is being propelled by the use of electricity in various sections of human daily routine. From daily chores at the kitchen to the humongous industrial purpose is being greatly favored by electricity. But from last few decades, generation of power from has become a great concern as conventional sources are diminishing. Scientists are trying to invent something new to back up the conventional source dependent power generation. It is undeniable that they made a huge advancement in harnessing solar energy.

The Sun is an average star. Sun produces energies and releases 95% of its output energy as light. The sun is responsible for all the energy available on Earth. Hydropower is made possible by evaporation-transpiration due to solar radiant heat. The wind caused by the sun's uneven heating of the earth's atmosphere. Fossil fuels are remnants of organic life previously nourished by the sun. Photovoltaic is the mean of harnessing solar energy directly from the sun. Photovoltaics are best known as an electricity generating method by using solar cells to convert energy from the sun into a flow of electrons. Photovoltaic devices are made of semiconductor materials that exhibit the photovoltaic effect.

Photovoltaics are the direct conversion of light into electricity. At atomic level, photovoltaic effect is a property, exhibited by some materials. Due to this property, material absorbs photons of light and release electrons.

Wet-chemical etching is a technique that utilizes liquid chemicals to remove material. In this way a thin/thick film can be patterned or completely removed. The technique involves immersion of a substrate in a pure or mixture of chemicals for a given amount of time. The time required is dependent on the composition and thickness of the layer to be etched, as well as the etchant and temperature to be used. Wet-chemical etching works very well when etching thin/thick films on substrates, but can be used also to etch the substrate itself. Different etchants are used for etching depending etching uniformity and isotropy or anisotropy. Wet chemical etching processes are isotropic. Isotropic process can be highly selective. Strong acids are used in etching process.

1.2 THESIS OUTLINE

This thesis is organized as follows:

Chapter 2 describes the renewable energy scenario worldwide and the importance of semiconductor in renewable energy sector. Theoretical analysis on possibilities related with solar cells.

Chapter 3 describes the procedure and instruments and equipment's involved with the experiments.

Chapter 4 provides the results and explanation regarding the experiments which are being followed during lab work.

Chapter 5 concludes the thesis work with the assumptions, findings and future scopes related to the field of study.

CHAPTER 2

2.1 LITERATURE REVIEW:

Human civilization has seen a gigantic increase in energy consumption during last 100 years. While in 1870 the energy use per inhabitant per year was around 5800kWh reached 20200kWh in 1970. With the course of time and labor provided by scientists has gifted us lots of means for the production of electricity. Some of them are fossil fuel dependent and some of them are renewable sources. This energy sources can be divided in two groups. First group includes all non-renewable sources can be called as depleting energy. Supply of power requirements are provided by depleting energy is 78%. Prediction about these non-renewable sources is that at the rate we are consuming these resources will be diminished within 320 years and the nuclear energy within 260 years. [1].

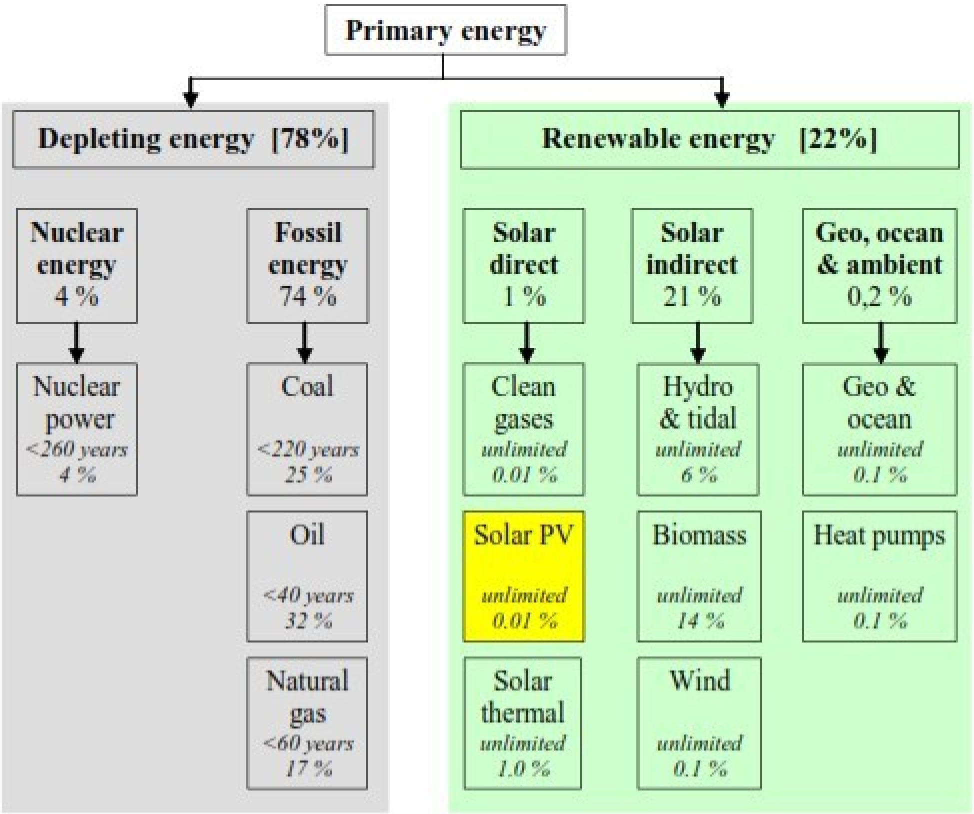

Figure 2.1: An Overview of energy Sources [1]

It is expected that the world population will grow and will reach 10 billion in 2050. In order to provide the growing population with high living standards, further economic development is essential. The further economic development requires more energy than we use today.

The extra energy has to come from additional sources than only the traditional ones.

Furthermore when we want to take the concept of sustainable development into account, we have to look for environmentally friendly energy sources. These sources are known as *renewable or sustainable energy* sources. The renewable energy sources form the second group of the primary energy sources and today they contribute with 22% to the total energy production. By renewable energy we understand energy that is obtained from the continuing flows of energy occurring in the natural environment, such as solar energy, hydropower and energy from biomass.

About one third of the primary energy is used to generate electric power. This form of energy has become very popular and is widely used for industrial and household applications. The electrical energy represents about 12% of all energy consumed worldwide

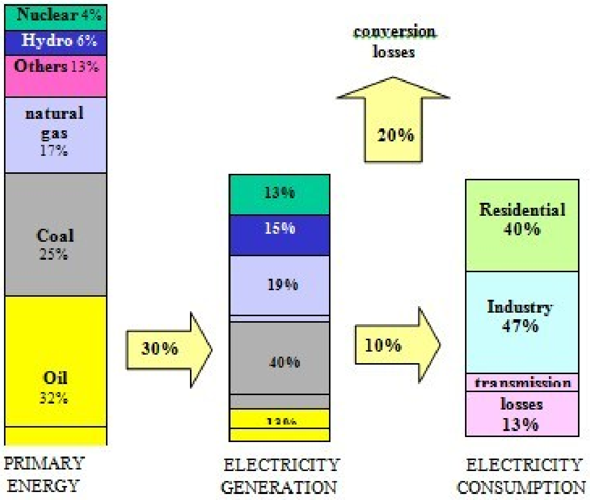

Figure 2.2: Primary energy use [1]

It has been recognized that a massive consumption of fossil fuels has a negative impact on the environment. Gases such as CO_2 and SO_X and NO_X are produced as the by- products during burning of the fossil fuels. Enormous quantities of these gases are emitted into the atmosphere, where they change the natural concentrations.

The ecological problems, such as the greenhouse effect and acid rains, are caused by the increase of these gases in the atmosphere. The greenhouse effect is linked to the increase of CO_2 in the atmosphere. The CO_2 molecules are transparent to solar radiation but are opaque to heat, which is the radiation in the infrared wavelength region. The concentration of CO_2 in the atmosphere has increased in the 20th century from 280 ppm to 350 ppm. Scientists expect that when this trend continues,the temperature will rise from 3 ºC to 5 ºC in 2030-2050. In order to avoid this situation, in which the climate change, known also as the global warning, can lead to undesired ecological changes a reduction in CO_2 emission is essential.

2.2 RENEWABLE ENERGY SOURCES:

Renewable energy sources are based on the continuing flows of energy that is considered inexhaustible from the point of view of human civilization. Solar radiation represents such an infinite source of energy for the Earth. The sun delivers 1.2×10^{14} kW energy on the Earth, which is about 10.000 times more than the present energy consumption.[1] The energy that the Earth receives from the sun in just one hour is equal to the total amount of energy consumed by humans in one year. The major advantages of using renewable energy sources over the traditional energy sources are reflected in a cleaner environment, creating employment opportunities, and security of energy supply. The use of renewable energy can reduce the emission of greenhouse gases and other pollutants. The expanded use of renewable sources of energy can have a positive impact on job creation in the technology manufacturing industries and also the agricultural sector, which supplies biomass fuel. Renewable energy can play an important role in increasing security of energy supply by providing domestic resources of energy and avoiding dependence on imported supplies of fossil fuels.

2.3 SEMICONDUCTOR:

Semiconductors are crystalline substances with exclusive electrical characteristics. Introduction of solid state devices made of silicon due to their wide range of variation in electrical properties, replaced vacuum tubes in many field of applications.

The first electrical revolution began in 1948 with the invention of the silicon transistor at Bell

Laboratoried by Bardeen,Brattain and Schockley. [2]

In 1953, Bell labs started a research project for devices to provide energy to the remote area of the world in the absence of grid power. The leading scientist Darryl Chappin suggested using solar cells. At that time, established method was photovoltaic effect in selenium got commercialized as a device for the measurement of light intensity in photography.Figure 2.3. is schematic diagram.

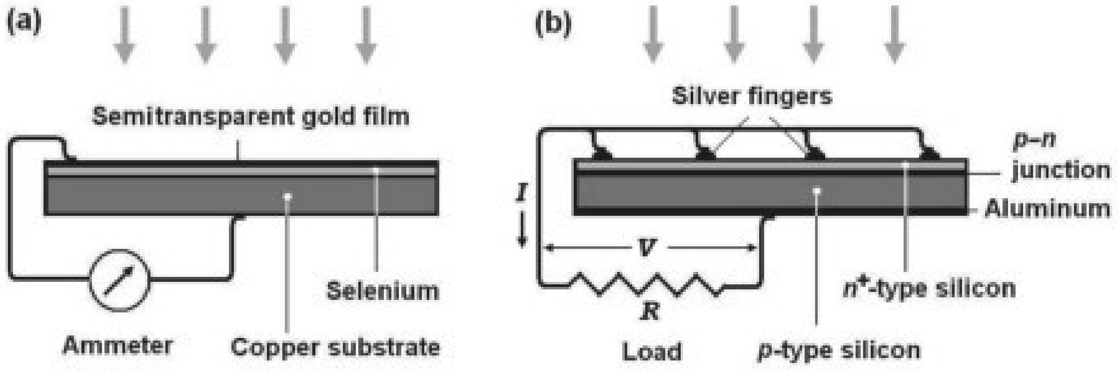

Figure 2.3: selenium solar cell [2]

In the seventh century BCE, humans used magnifying glasses to concentrate sunlight and hence to make fire. Later, the ancient Greeks and Romans used concentrating mirrors for the same purpose. In the 18th century the Swiss physicist Horace-Bénédict de Saussure build heat traps, which are a kind of miniature green houses. He constructed hot boxes, consisting of a glass box, within another bigger glass box, with a total number of up to five boxes. When exposed to direct solar irradiation, the temperature in the innermost box could rise up to values of 108°C; warm enough to boil water and cook food. These boxes can be considered as the World's first solar collectors. In 1839, the French phycisist Alexandre-Edmond Becquerel discovered the photovoltaic effect at an age of only 19 years. He observed this effect in an electrolytic cell, which was made out of two platinum electrodes, placed in an electrolyte.

An electrolyte is an electrically conducting solution; Becquerel used silver chloride dissolved in an acidic solution. Becquerel observed that the current of the cell was enhanced when his setup was irradiated with sunlight.

In the 1860s and 1870s, the French inventor Augustin Mouchot developed solar powered steam engines using the World's first parabolic trough solar collector that we will discuss in Chapter

20. Mouchot's motivation was his believe that the coal resources were limited. At that time, coal was the energy source for driving steam engines. However, as coal became cheaper, the French government decided that solar energy was too expensive and stopped funding Mouchet's research. In 1876, the British natural philosopher William Grylls Adams together with his student Richard Evans Day demonstrated the photovoltaic effect in a junction based on platinum and the semiconductor selenium, however with a very poor performance. Seven years later, the American inventor Charles Fritts managed to make a PV-device based on a gold-selenium junction. The energy conversion efficiency of that device was 1%. In 1887, the German physicist Heinrich Hertz discovered the photo-electric effect. In this effect, electrons are emitted from a material that has absorbed light with a wavelength shorter than a material-dependent threshold frequency. In 1905 Albert Einstein published a paper in which he explained the photoelectric effect with assuming that light energy is being carried with quantized packages of energy [21], which we nowadays call photons.

In 1918 the Polish chemist Jan Czochralski invented a method to grow high-quality crystalline materials. This technique nowadays is very important for growing monocrystalline silicon used for high-quality silicon solar cells. The development of the c-Si technology started in the second half of the 20th century.

In 1953, the American chemist Dan Trivich was the first one to perform theoretical calculations on the solar cell performance for materials with different bandgaps.

The real development of solar cells as we know them today, started at the Bell Laboratories in the United states. In 1954, their scientists Daryl M. Chapin, Calvin S. Fuller, and Gerald L. Pearson, made a silicon-based solar cell with an efficiency of about 6% [35]. In the same year, Reynolds et al. reported on the photovoltaic effect for cadmium sulfide (CdS), a II-VI semiconductor [22]. In the mid and late 1950s several companies and laboratories started to develop silicon-based solar cells in order to power satellites orbiting the Earth. Among these were RCA Corporation, Hoffman Electronics Corporation but also the Unites States Army Signal Corps. In these days, research on PV technology was mainly driven by supplying space applications with energy. For example, the American satellite Vanguard 1, which was launched by the U.S. Navy in

1958, was powered by solar cells from Hoffman Electronics. It was the fourth artificial Earth satellite and the first one to be powered with solar cells. It was operating until 1964 and still is orbiting Earth. In 1962 Bell Telephone Laboratories launched the first solar powered telecommunications satellite and in 1966 NASA launched the first Orbiting Astronomical Observatory, which was powered by a 1 kW photovoltaic solar array. In 1968, the Italian scientist Giovanni Francia built the first concentrated-solar power plant near Genoa, Italy. The plant was able to produce 1 MW with superheated steam at 100 bar and 500°C. In 1970, the Soviet physicist Zhores Alferov developed solar cells based on a gallium arsenide heterojunction. This was the first demonstrator of a solar cell based on III-V semiconductor materials. In 1976, Dave. E. Carlson and Chris R. Wronski developed the first thin-film photovoltaic devices based on amorphous silicon at RCA Laboratories. In 1978, the Japanese companies SHARP and Tokyo Electronic Application Laboratory bring the first solar powered calculators on the market.

Because of the oil crisis, induced by the OPEC oil embargo in 1973 and as a consequence a sharply rising oil price, the public interest in photovoltaic technology for terrestrial application was increasing in the 1970s. In that time, PV technology moved from a nichel technology for space application to a technology applicable for terrestrial applications. In the late 1970s and 1980s many companies started to develop PV modules and system for terrestrial applications.

In 1980 the first thin film solar cells based on a copper-sulfide/cadmium-sulfide junction was demonstrated with a conversion efficiency above 10% at the Univer- sity of Delaware. In 1985, crystalline silicon solar cells with efficiencies above 20% were demonstrated at the University of New South Wales in Australia.

From 1984 through 1991 the World's largest solar thermal energy generating facility in the world was built in the Mojave Desert in California. It consists of 9 plants with a combined capacity of 354 Megawatts. In 1991 the first high efficiency Dye-sensitized solar cell was published by the École polytechnique fédérale de Lausanne in Switzerland by Michael Grätzel and coworkers. The Dye-sensitized solar cell is a kind of photo-electrochemical system, in which a semiconductor material based on molecular sensitizers, is placed between a photo anode and an electrolyte.

In 1994, the U.S. National Renewable Energy Laboratory placed in Golden, Colorado, demonstrated a con- centrator solar cell based on III-V semiconductor materials. Their cell based on a indium-gallium- phosphide/gallium-arsenide tandem junction exceeded the 30% conversion limit. In 1999, the total global installed photovoltaic power passed 1 GWp . Starting from about 2000, environmental issues and economic issues started to become more and more important in the public discussion, which re-newed the public interest in solar energy. Since 2000, the PV market therefore transformed from a regional market to a global market, as discussed in Chapter 2. Germany took the lead with a progressive feed-in tar- iff policy, leading to a large national solar market and industry [23]. Since about 2008, the Chinese government has been heavily investing in their PV industry. As a result, China has been the dominant PV module manufacturer for several years now. In 2012 the world-wide solar energy capacity surpassed the magic barrier of 100 GWp [24]. Between 1999 and 2012, the installed PV capacity hence has grown with a factor 100. In other words, in the last 13 years, the average annual growth of the in- stalled PV capacity was about 40%. Fast growing factories in China push manufacturing costs down to about $1.25 per watt for silicon PV modules from 2011. The invention of 3D PV cells increased the efficiency by 30%. In recent year, University of New South Wales engineers established a new world record for diffuse radiation conversion to electricity with an efficiency increase up to 34.5%.[4]

A semiconductor is a solid material whose electrical resistivity is higher than conductor and lower than that of an insulator. There are some other essential characteristics of semiconductors which distinguish them from conductors and insulators.

i) The electrical resistance of semiconductor decreases with increase in temperature over a particular temperature range.

ii) The electrical conductivity of a semiconductor can be increased by a large value by doping with a small amount of suitable impurity.

2.4 ELECTRICAL CONDUCTION IN SEMICONDUCTOR:

Mostly used semiconductors are Germanium and Silicon for semiconducting devices. Both of them are tetravalent and there are four valence electrons. The crystal structure of Ge and Si is two interpenetrating face-centered cubic lattice also known as diamond structure. From two dimensional lattice diagram of Ge, it is observed that, in an unit cell, Ge atom is surrounded by four Ge atoms and all of them are in equidistant from that atom. Binding force between neighboring atoms arises due to formation of covalent bond by sharing of valence electrons between them. This unit cell structure is repeated all over the entire crystal lattice. Thus free electrons are not available in pure germanium crystal.[5]

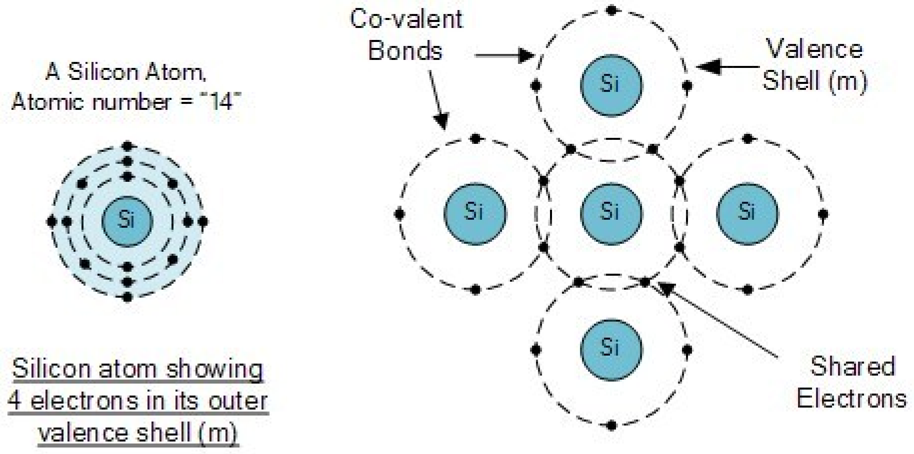

Figure 2.4: Silicon Cristal lattice

2.5 PV CELLS WORKING:

Photovoltaic cells are composed of thin layer of silicon wafer. An ultra-thin layer of N-type doped with phosphorus is placed on the top of a thicker layer of P-type silicon layer doped with boron. An electric field is created near the top surface of the cell where these two materials are in contact, named as P-N junction. At this junction, an interior electric field is built up which leads to the separation of the charge carriers that are released by light. Through metal contacts, an electric charge can be tapped. If the outer circuit is closed, meaning a consumer is connected, and then direct current flows. When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load.

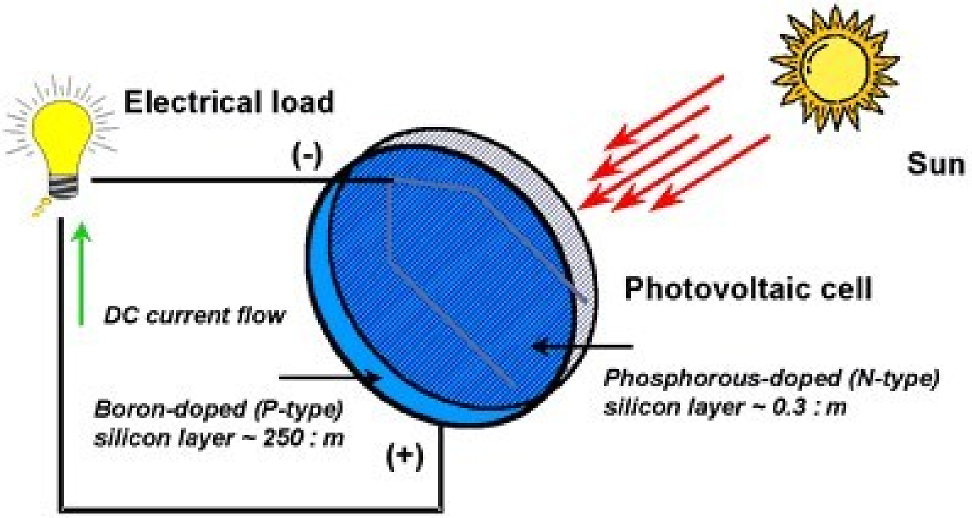

Figure 2.5: Solar cell working [5]

2.6 DIFFERENT CELL TYPES:

One can distinguish three cell types according to the type of crystal: mono crystalline, polycrystalline and amorphous. To produce a mono crystalline silicon cell, absolutely pure semiconducting material is necessary. Mono crystalline rods are extracted from melted silicon and then sawed into thin plates. This production process guarantees a relatively high level of efficiency.The production of polycrystalline cells is more cost-efficient. In this process, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects emerge. As a result of this crystal defect, the solar cell is less efficient. If a silicon film is deposited on glass or another substrate material, this is a so-called amorphous or thin layer cell. The layer thickness amounts to less than 1µm (thickness of a human hair: 50-100 µm), so the production costs are lower due to the low material costs. However, the efficiency of amorphous cells is much lower than that of the other two cell types. Because of this, they are primarily used in low power equipment (watches, pocket calculators) or as facade elements.

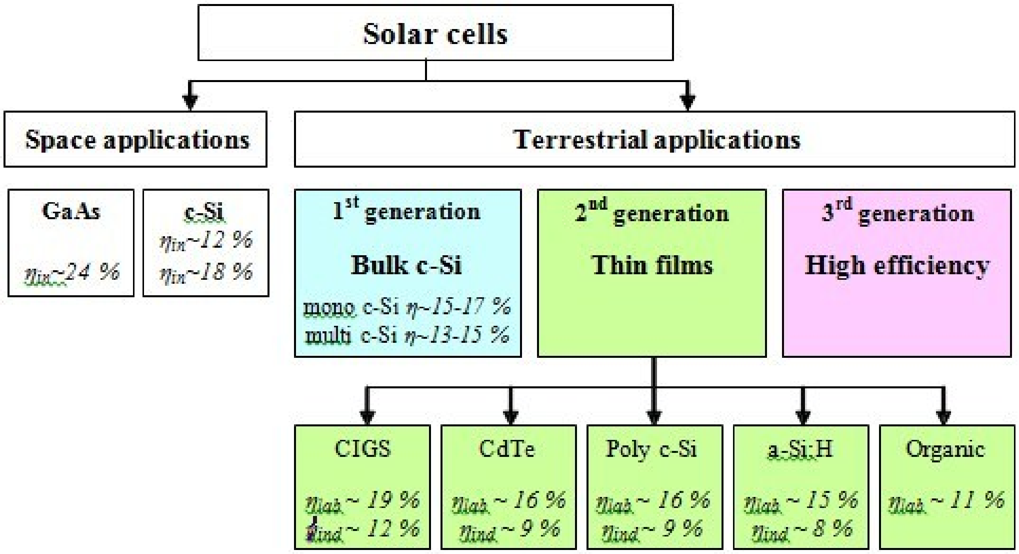

Figure2.6: Overview of Solar Cell Types and Application [1]

This resistance in solar cells occurs due to parasitic resistances. Parasitic resistances reduce the efficiency of the solar cell by dissipating power in the resistances. The most common parasitic resistances prevails in pv cells are series resistance and shunt resistances.

Reasons for the series resistance in a solar cell are:

- The movement of the current through the p-n materials of the solar cell;
- The contact resistance between the metal contact and the silicon;
- The resistance of the top layer and the bottom contacts

The series resistance reduces the fill factor but has no impact on the open circuit voltage or the short circuit current.

Reasons for the shunt resistance are:

- Crack between semiconductor layers;
- Aluminum particles at the cell surface;
- Shunts created during processing by residues of the emitter at the cell edge;
- Shunts below gridlines, known as shottkey type shunts.

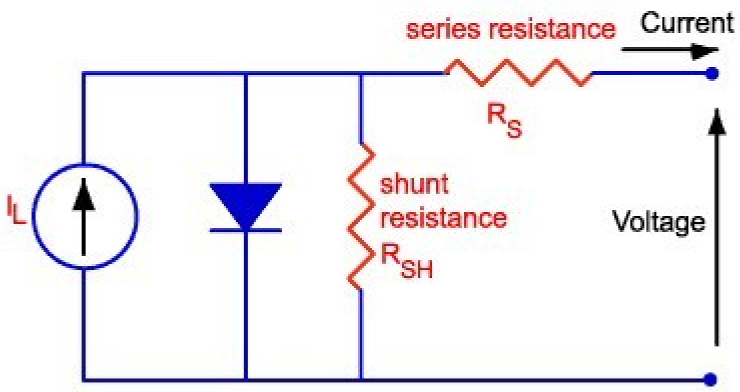

Figure 2.7: Schematic diagram of Series and Shunt Resistance

2.7 Si-based Solar Cell:

Solar cell, which is usually made of crystalline silicon, is an electrical device that can convert the energy of the light into electricity. Since the si-based solar cell is a semiconductor material that has special electrical properties, it allows the emission of electrons when light shines on the surface of the material, known as photovoltaic effect (PVeffect). After that, electrons flow out of the solar cell, and a current is formed. [6]

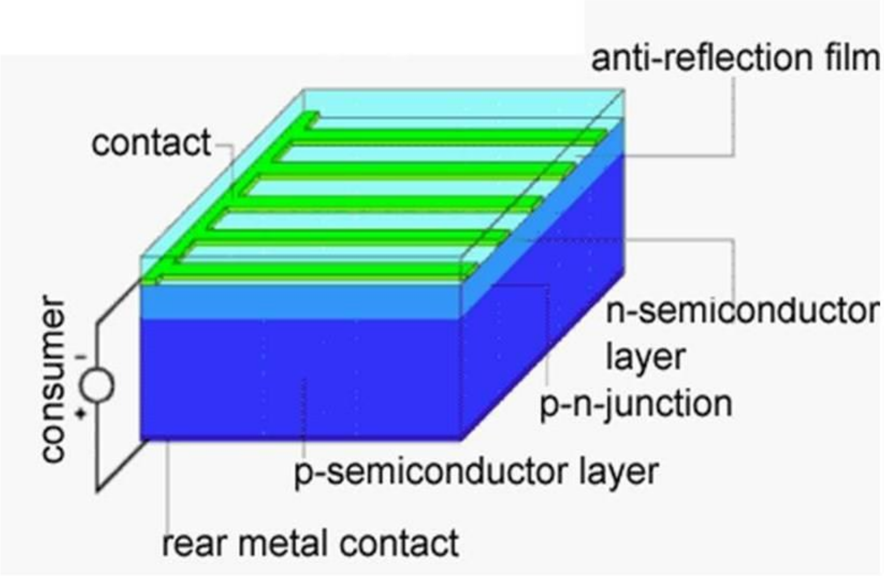

Figure 2.8 Model of a crystalline solar cell [10]

A Silicon-based solar cell consists of several different parts, as shown in Figure 2.8. How silicon makes a solar cell and how it converts light directly into electricity? First of all it starts with highly purified silicon. From the periodic table, it is known that a silicon atom totally has fourteen electrons, and the outer shell, however, is only half full with just four electrons. In order to stay in the stable state, a silicon atom will share electrons with four nearby atoms; each atom has four hands joined to four neighbors. That's what forms the crystalline structure. Since the electrons are unable to move freely in the crystalline structure due to the strong bonds between each atom, pure crystalline silicon is a poor conductor of electricity. A process called doping, which means adding impurities to the pure silicon, can improve its conductivity. As shown in Figure 2.9, boron, which only has three electrons in the outer shell, is doped into the silicon to form a free "hole" (missing electron).

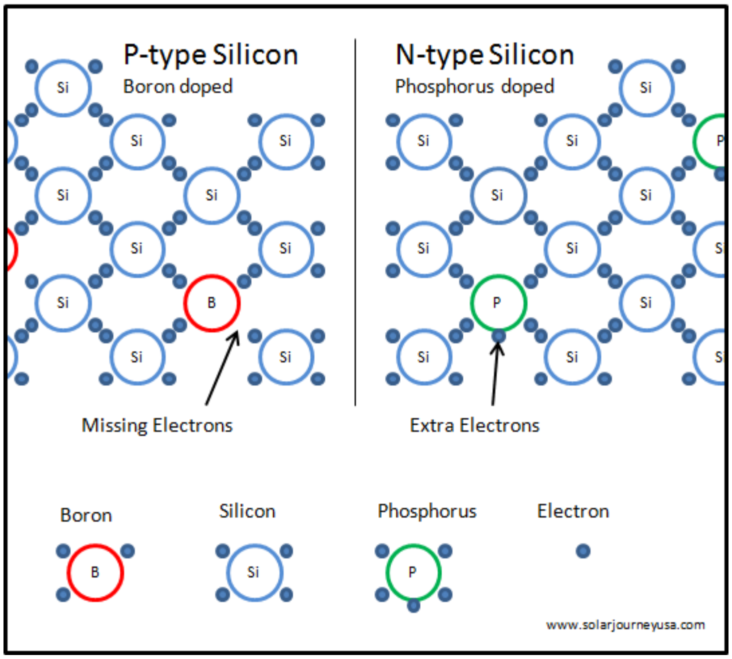

Figure 2.9 P-type and N-type Silicon Semiconductor [9]

This kind of doped silicon is called p-type silicon because one electron is missing, and it has free openings and carries the positive charge. On the other hand, phosphorous has five electrons in its outer shell, so it creates additional free electron when combing with silicon. Silicon doped with phosphorous is called n-type because of the prevalence of free electrons, relatively negative.

When the silicon wafers respectively are doped with boron (p-type) and phosphorous (n- type), they are electrically neutral. However, if the p-type and n-type silicon come into contact, P-N junction is formed. The electrons diffusing across the junction from n-type side into p-type side quickly recombine with some of the majority holes there, likewise holes moving from the p-type side to the n-type side, then forming electron-hole pairs. Figure 2.10 illustrates the diffusion. After the equilibrium of diffusion of electrons and holes is reached,

a “barrier” called depletion zone shown in Figure 2.10 appears, resisting the further transfer which makes it more difficult for electrons to move from n-type side into p-type side.

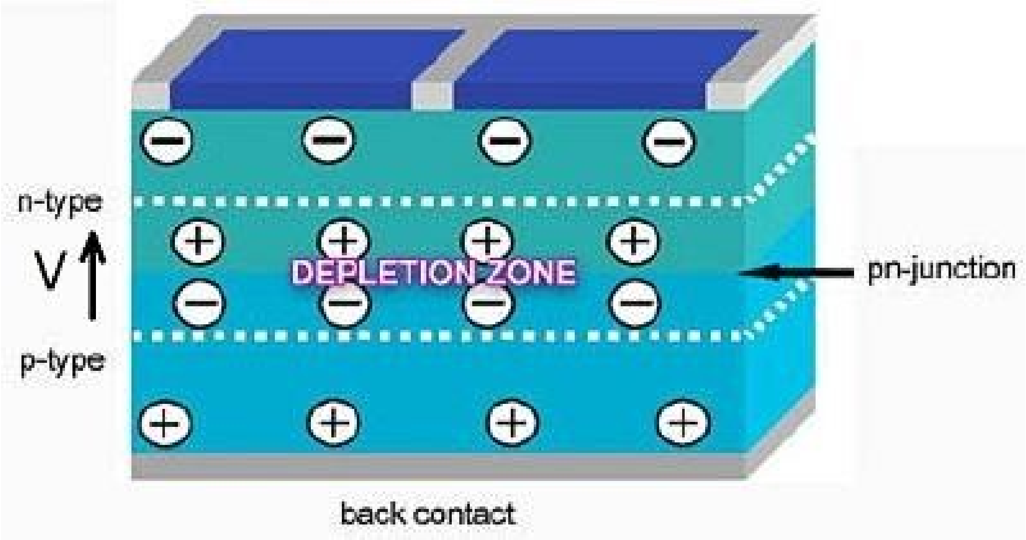

Figure 2.10 P-N Junctions and Depletion Zone [8]

Therefore, an electric field separates the two sides. As light, in the form of photons, with enough energy, are incident on the solar cell, electron-hole pairs are broken by them, each of them freeing exactly one electron. The electric field will send the electron to the n-side and the hole to the p-side. When an external current path is provided, like the consumer in Figure 2.8, electrons will flow through the path to the p-type side to unite with holes that the electric field sent there; a current is formed. In addition, the cell's electric field provides a voltage. With both current and voltage, the power is generated.

2.8 I-V Characteristic of Solar Cell:

In principle, a solar cell is a simple semiconductor device that converts light into electric energy, also called PV (Photovoltaic) cells. The conversion is accomplished by absorbing light, then ionizing crystal atoms creating free, negatively charged electrons and positively charged ions, and that is how current is formed. In addition, the p-n junction forms electric field providing voltage output. Therefore, one can use solar cells as a power source.

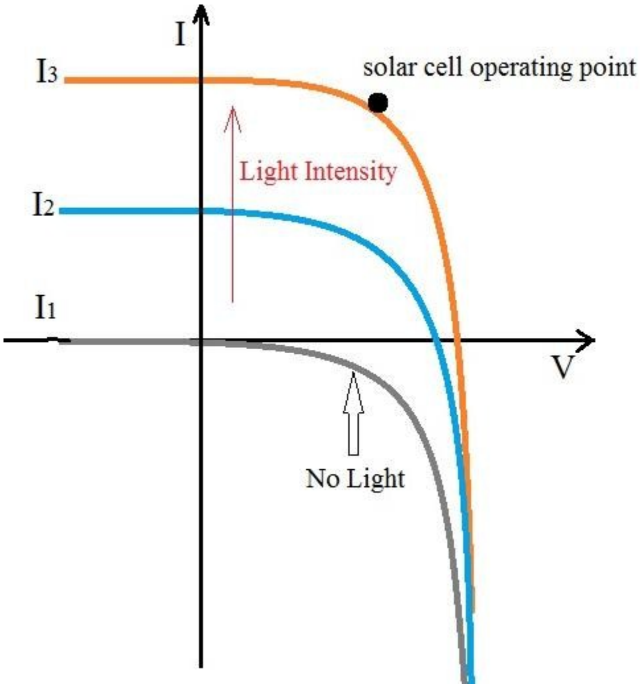

Figure 2.11 IV curve for solar cell and solar cell as current source parallel with diode

The performance of solar cell is determined by estimating the generated power output.
The solar cell has current-voltage characteristic curves representing the relationship between current and voltage produced by the solar cell, which are nonlinear and rectifying as shown in Figure2.11. I-V curves are plotted in a condition that the exposure of light is maintained at constant level at constant cell temperature.

In Figure 2.4, the x-axis and y-axis represent the voltage and current, respectively. It shows that the I-V curve will lift up when the intensity of incident light increases, but it is still the same as the curve in diode mode. The solar cell is usually operated in reverse bias mode. Solar cell acts as a diode when there is no current produced without light incident to it. Depending on both the intensity and wavelength of the incident light, solar cell can produce different current, which is proportional to the intensity of incident light. [7]

Let I_l be the current produced by the photoelectric effect and I_D be the diode current in an ideal cell. The total current I is calculated from the difference between I_l and I_D.

The equation (ibid) for the total current I is written as,

$I = I_l - I_D = I_l - I_0(e^{qV/kT} - 1)$

(2.1) Where I_0 – Saturation current of the diode

q – Elementary charge $1.6x10^{-19}$ Coulombs k –

Constant of value $1.38x10^{-23}$J/K

T –Cell temperature in Kelvin

V–Measured cell voltage which is either produced or applied

The above equation (ibid) can be expanded to,

$I = I_l - I_0(\exp^{[q(V+I.Rs)/n.k.T]} -1) - (V+I.R_s)/R_{sh}$

Where R_s – Series resistance

R_{sh} – Shunt resistance

n- Diode ideality factor. It is the measure of how closely a diode follows the ideal diode equation. Its value is between 1 and 2.

The equivalent circuit of the solar cell is shown in Figure 2.12.

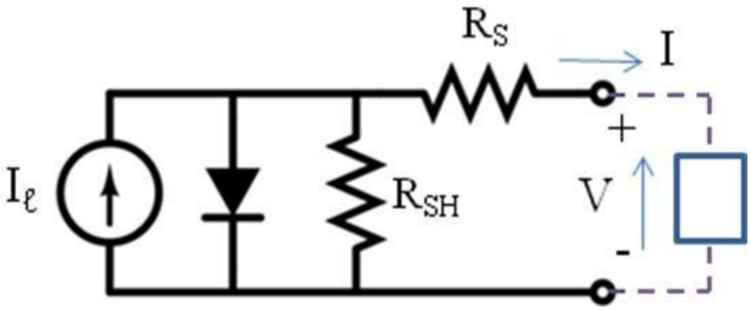

Figure 2.12 Equivalent circuits for the solar cell [7]

The load resistance is varied from zero to infinity and the I-V graph is plotted. I-V curve is shown in Figure 2.13. I_{SC} represents the short circuit current and V_{OC} represents the open circuit voltage.

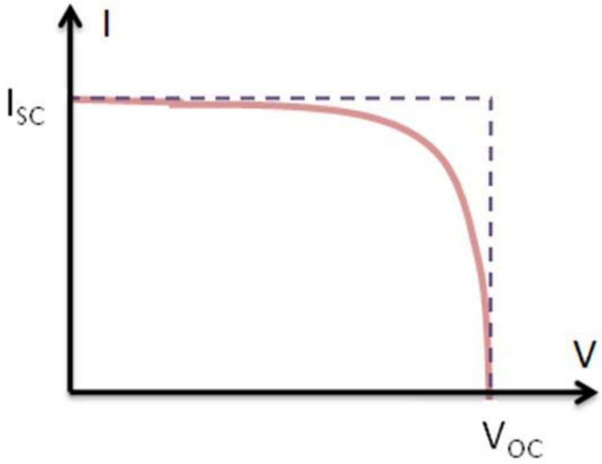

Figure 2.13 IV curve for Solar cell [2]

2.8.1 Fill Factor (FF):

Fill Factor is measured as the rectangular area of I-V curve. It is the measurement of quality of a solar cell. The Fill Factor can be calculated by comparing maximum power (P_{MAX}) to the theoretical power (P_T). Theoretical power can be assumed as power output at short circuit current and open circuit voltage.

$FF = P_{MAX} / P_T = (I_{MP}.V_{MP}) / (I_{SC}.V_{OC})$

(2.3) Where $I_{SC} = I_{MAX} = I_l$ for forward bias quadrant

$V_{OC} = V_{MAX}$ for forward bias quadrant

I_{MP} and V_{MP} = current and voltage at the maximum power point, respectively.

The Fill Factor represents the degree to which the voltage at the maximum power point matches with the open circuit voltage and to which the current at the maximum power point matches with the short circuit current.

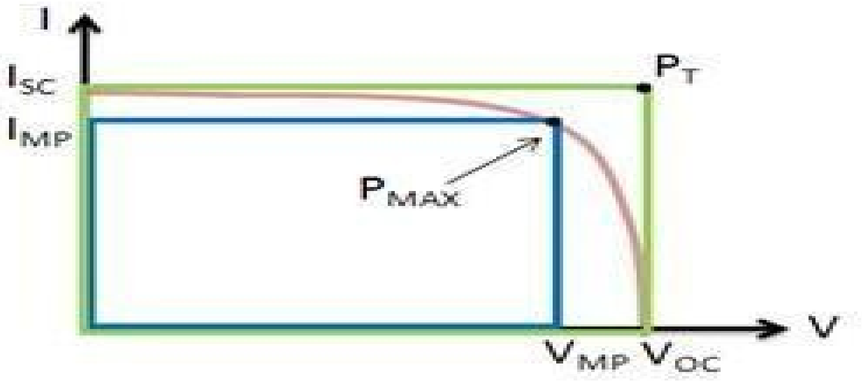

Figure 2.14 : Fill Factor [7]

The larger fill factor is desired as it approaches to the rectangular area of IV curve. Fill Factor is represented in percentage. Typically values of fill factors are between 0.5 and 0.82. The efficiency of the cell is decreased due to the loss of power across internal resistances. These resistances are represented as shunt resistances and series resistances in the equivalent circuit diagram of the solar cell. In an ideal situation, it is desired that the value of shunt resistance is infinite and the series resistance should have zero value. If the shunt resistance has infinite value, it will not provide an alternate path for current and if the series resistance has zero value, there will not be any voltage drop before the load.

2.8.2 Shunt Resistance (R_{SH}) and Series resistance (R_S)

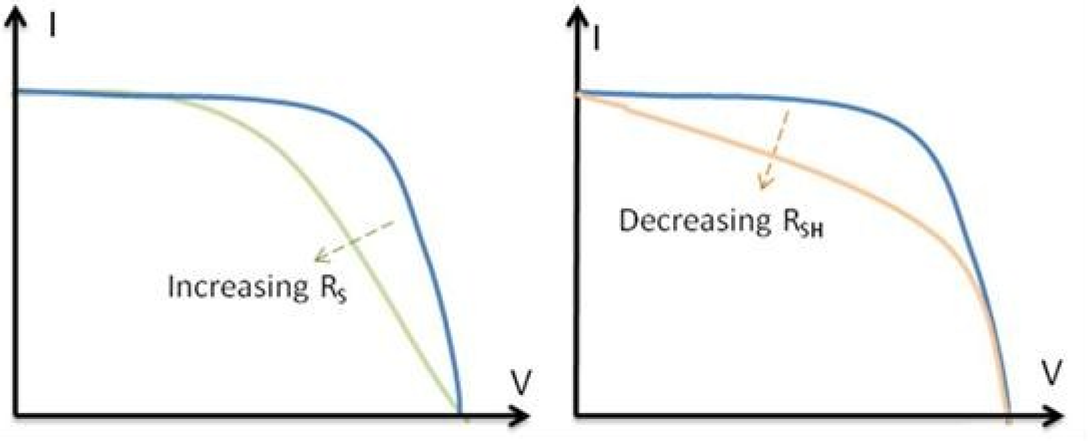

Figure 2.15 Effect of series and shunt resistances on IV curve [7]

Figure 2.8 shows the effect of resistances on the IV curve. Increasing the series resistance and decreasing shunt resistance will decrease the fill factor hence will decrease the efficiency of the solar cell. To achieve the maximum efficiency, the value of shunt resistance should tend to infinity and the value of the series resistance should tend to zero. Though infinite shunt resistance is desired for maximum power output of the solar cell, during the manufacturing process of the solar cell, an alternate conducting path is formed between p- type and n-type semiconductor layers resulting in decreased shunt resistances.

2.9 Types of Shunt:

The shunt is an undesired path with lower resistances for current flow, causing efficiency loss due to the emitter at the edge of the cells or the metal contacts. Shunted cells significantly reduce average efficiencies, result in modules with poor low light performance and reduce the total yield. [12] In solar cell, as the current generated by photons leaks though the shunts it decreases the current generated by solar cell thereby reducing the fill factor and the open circuit voltage. [11]

Shunt cans be defined as any local site where the local current exceeds the homogeneously flowing current. There are several types of shunt have been found in mono- and multi- crystalline solar cells. These shunts are different by the type of their I-V characteristics (linear or nonlinear) and by their physical origin. In general, shunt types can be either process-induced or caused by grown-in defects of the material. The most dominant type of shunt is linear edge shunt, which is process-induced, due to incompletely opened emitter at edge. The incompletely opened emitter is caused by improper edge isolation techniques, which is to isolate n-type layer and p-type cell electrically. [11] These shunts are accounted for 80% of the loss of power. The electrical isolation between p-type and n- type semiconductors can be achieved by creating a groove along the edges. [13] Another type of process-induced liner shunt occurs because of the cracks in the silicon wafers, so-called volume shunts, as shown in Figure 2.15.A Volume shunts are caused by material defects in the bulk. Volume shunts are accounted for 20% of the loss occurs due to shunts After the process of doping the n-type layer, it is possible that during adding the front metal contact or back metal coating, metal paste penetrates through the cracks, providing conduction between the p-n junction. [11] These shunts cannot be removed without destroying the solar cell; however, shunted regions isolation technique can reduce the impact of shunted regions in poor quality solar cells. The technique can increase the efficiency of a badly shunted solar cell from 9.6% to 13.3%. [12]

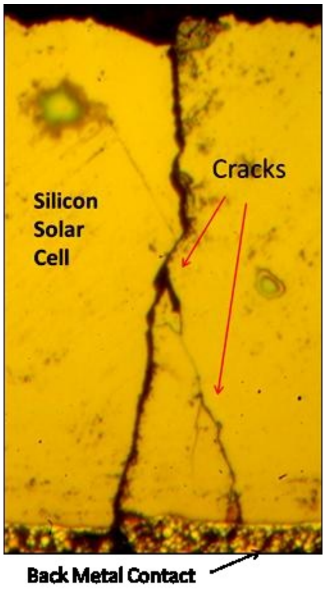

Figure 2.16 A commercial solar cell with a fatigue crack through the whole cell.

2.10 Quality and Efficiency of Si-based Solar Cell:

In solar cell manufacturing, quality is considered one of the most important things since the overall efficiency of the solar cell can be greatly or adversely affected by the differences in the manufacturing processes. Many researchers are concentrating on improving the efficiency of each solar cell over a longer lifetime and finding a new process to replace the conventional one. The efficiency of solar cells being used these days is between 14 and 18 Percent. [16] Efficiency of the solar cell is defined as the percentage of incident light absorbed by solar cell then converted into electricity. It is the ratio of output power of the solar cell to the input power of the incident light.

$$\eta = P_{out} / P_{in}$$

At the maximum power point, the solar cell operates at maximum efficiency.

$$\eta_{MAX} = P_{MAX} / P_{in}$$

The way to calculate the input power converted from incident light is the product of the light irradiance and the surface area of solar cell. Except for the intensity and wavelength of the light, there are other factors like natural resistance, temperature, reflection and electric resistance which affect the efficiency of the solar cell.

2.11 Improving efficiency:

There are several ways to improve efficiency of solar cell. First of all, the efficiency can be improved by changing the design of solar cell. When higher efficiencies are desired, adding a semiconductor of lower gap on the bottom as tandem solar cells can be beneficial. In this case, the photons not absorbed in the top cell can be absorbed at the second layer. Furthermore, different materials with better light absorptivity such as mono-crystalline photovoltaic or conductive polymers can convert light into electricity more efficiently. [15] Although the efficiency of solar cell can be increased by using different materials or design, the improvement is limited and the manufacturing cost is still high. Most current research therefore aims for increasing this efficiency or reducing solar cell cost in order to have higher price/performance ratio solar cell. There are innovations needed to replace the conventional manufacturing methods or to develop cheaper alternatives to expensive solar cell.

2.12 Edge Isolation:

The main purpose of edge isolation is to isolate p-type and n-type silicon electrically. Without proper edge isolation, an undesirable electric path will form to allow electrons liberated by sunlight to rejoin positive carriers (the holes) instead of flowing through the external circuit. Edge isolation is a very important part of all silicon-based solar cell production process, and it greatly affects the efficiency of the cells. The main purpose of edge isolation is to isolate p-type and n-type silicon electrically. Without proper edge isolation, an undesirable electric path (shunt) will form to allow electrons liberated by sunlight to rejoin positive carriers (the holes) instead of flowing through the external circuit. The edge isolation process is to remove the phosphorous diffusion (n-type layer) with a thickness 10 to 20 μm around the edge of the cell by creating narrow and continuous grooves through the boron diffusion (p-type layer) so that the front emitter is electrically isolated from the cell rear. To optimize the isolation grooves to ensure the maximum area for sunlight absorption, those groove must be as close as possible to the edges of the front surface and as narrow as possible.

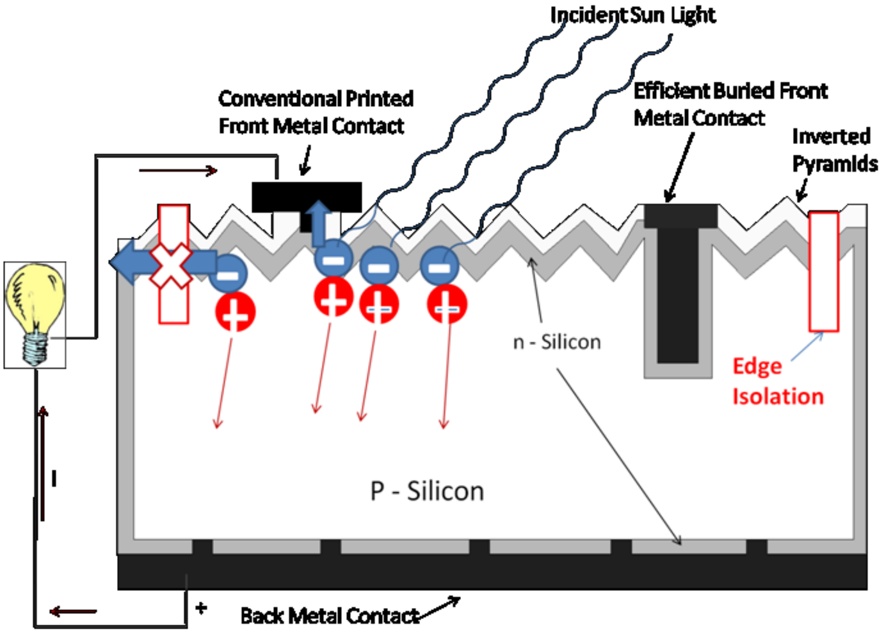

Figure 2.17 A functional Si-based solar cell panel with metal contacts and anti-reflection coating

By creating isolation grooves to isolate p-type and n-type silicon electrically, the edge shunt can be removed. Many different techniques to achieve edge isolation have been developed, including laser isolation, mechanical edge isolation, plasma edge isolation, and wet chemical etching.

2.13 DIFFERENT TECHNIQUES FOR EDGE ISOLATION

2.13.1 Laser Edge Isolation:

The laser edge isolation of solar cells is a new mechanical process to melt and evaporate material by scribing the cells with laser beam to remove edge shunts pathway. A laser- scribed thin groove through the n-type to p-type layer along the edges can make the front emitter electrically isolated. Typically, groove is 10 to 20 µm deep and less than 20 µm wide.

In most solar cell processes, edge isolation is an important step. To reduce the dominant cost within silicon-based solar cell manufacturing, wafers with larger size thinner than today's industry standard of 220 µm are considered dominant in the next generation. Since thinner and larger wafers are increasingly fragile and mechanically vulnerable, needless to say, the noncontact nature of laser edge isolation processes offers profound benefits versus any contact-based alternative. In addition, the laser processing is fast, easy to align and no chemicals or susceptible mechanics are needed compared to wet chemical etching and plasma edge isolation. The greener processing is one of the clear advantages of laser that can resonate with solar company mission statements and marketing campaigns. [14]

However, the laser technique is not perfect. Lower laser intensity leads to insufficient depth of the isolation grooves, resulting in lower shunt resistance that can damage the efficiency. On the other hand, there is a possibility that micro cracks can be formed during laser processing with 1064 nm wavelengths or when the grooves are too deep. Any micro crack can become crack fronts, leading to crack propagation and eventual total fractures and cell failure. In addition, internal shunts can be formed when micro cracks combing with metal paste during the metal contact coating. Micro cracks are the key limit factor since they greatly decrease the yield of production lines. There are needs to eliminate those disadvantages to make the laser processing better.

2.13.2 Plasma Etching Edge Isolation:

Plasma etching of wafer stacks to remove shunts is a very common technique in industry and has been the standard procedure for silicon-based solar cell for many years. In the process, the solar cells are stacked together and then are put into a vacuum chamber. The etching is done in a fluoride/oxide plasma environment. The waste gases produced by plasma etching are toxic and need to be filtered and washed before disposal into atmosphere. Typically material of thickness 2-5 µm is removed from the edges as the front n-doped area is electrically isolated from the back contact surface. [17]

The reasons why plasma edge isolation is so common in industry are because the coin stacking method ensures high throughput and low cost per wafer. This method also avoids handling of dangerous chemicals, produces less waste of silicon and ensures larger active area of solar cell. The waste silicon mass produced when processing 500 wafers sized $125\times125\text{mm}^2$ is less than 9g. However, this method is not in-line process; as the stacking of the wafers is required, careful handling of the wafers is required for stacking and reducing the wafer damages. Since the next-generation solar cell will be thinner and larger in order to potentially reduce the process cost, alternative methods need to be developed to replace the plasma etching edge isolation due to non-in line process and mechanically vulnerable property of silicon wafers.

2.13.3 Wet chemical Etching Edge Isolation:

In chemical etching process, the edge isolation is done chemically by removing the rear side emitter after the light emitter diffusion. The wafers travel through an etching bath which is filled up to a certain level to achieve that only one side of the wafers in is contact with the etching solution. The etching parameters (etching depth and speed) can be varied depending on the wafer transport velocity, etching bath concentration and temperature.

There is no loss in active cell area because this technique removes only 5 μm from the rear side. The waste silicon mass produced when processing 500 wafers sized 125×125mm²is 91g. [17] Compared to laser isolation, the process involves stacking of the wafers as plasma etching, so careful handling of the wafers is required for stacking and reducing the wafer damages. There is a new method is developed by RENA with InOxSide tool. This is in-line process hence the continuous production line is not interrupted. The main advantage of this process is that the front side of the wafer is not damaged as it does not come in contact with the etching chemical. Nevertheless, the most important thing is, the etching of the edges is carried out by the chemicals like KOH, which is hazardous to human body and the environment. Using solar cell is a concept that is eco-friendly and is considered as a green energy, so there is no point to involve toxic chemical that is harmful to the nature during the manufacturing process.

2.13.4 Conventional Mechanical Edge Isolation:

Conventional mechanical edge isolations include grinding the wafer edge with sandpaper, cutting the edge with a diamond dicing saw, and sawing grooves with a diamond dicing saw. Typically, thickness of the dicing saw is 0.1 μm. During the edge isolation process, material of thickness 1-2 mm is cut or grinded from the edges. After the edge isolation process, the active cell area is reduced by 3-6%, resulting in reduction of the short circuit current produced by the cell. Although those conventional methods can provide good shunt resistance, so they have better performance in terms of efficiency, a huge amount of silicon debris are generated during the process; this waste cannot be recycled. The waste silicon mass produced when processing 500 wafers sized 125×125mm²is 174.75g. Moreover, compared to other methods, conventional mechanical edge isolation results in a loss of active area. Due to the brittle in nature of silicon-based solar cell, the contact nature of grinding or cutting methods potentially damages the solar cells, leading to crack propagation and eventually total fractures.

We can summarize the different edge isolation techniques in the following table.

Edge Isolation Process	**Process Technique**	**Production Technique**	**Disadvantages**
Mechanical	Cutting off edges	In-Line	Waste of material
Chemical/Plasma Etching	Etching away n-type layer from sides	Stacking of wafer	Hazardous Environment
Laser	Scribing along the edges	In-line	Higher power induces cracks

Table 2.1 Comparison of different edge isolation techniques

CHAPTER 3

3.1 RESEARCH METHODOLOGY:

The majority of silicon solar cell production is currently based upon a very standardized process that is intended to make a p-n electrical junction on the entire front surface of the wafer and a full-area aluminum-based metallization on the back [18]. The fabrication process of our Si solar cell starts with a p-type monocrystalline silicon wafer with square shape 150×150 mm2 in size, 200 μm in thicknes.

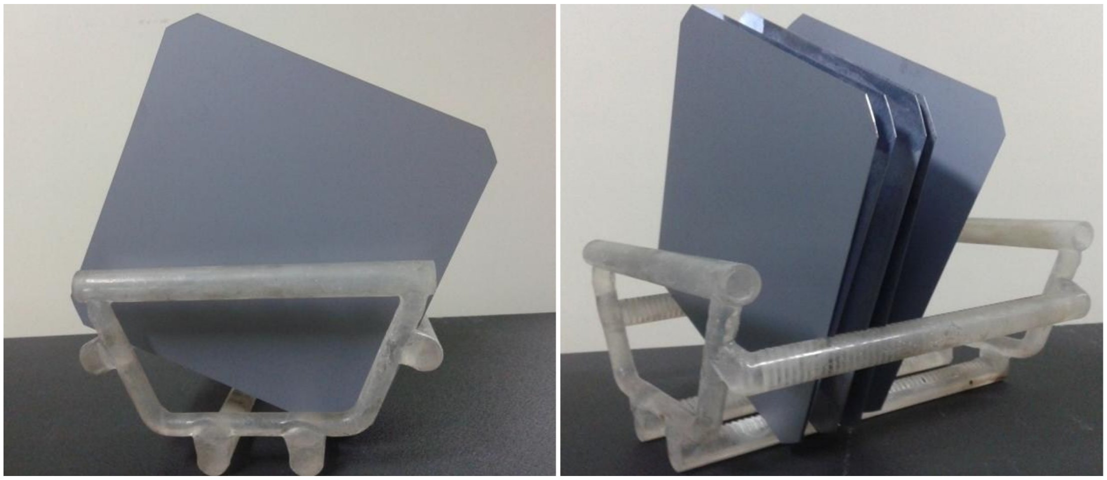

Figure3.1: Boron doped Silicon Solar Cell.

Boron doped solar cells are then put into $POCl_3$ diffusion Box for making a P-type layer on it. After the phosphorus doping, wet chemical etching is used on the edge to remove the short circuit between N and P layer. Grid fingers and back contact are then printed on the solar cell. Solar cells are put into RTA machine to make grids and back contact curing. Flash LIV characterization is used to simulate solar sufficiency measurement.

3.2 REQUIREMENTS:

3.2.1CHEMICALS:

Hydrofluoric Acid (HF) (48%): HF: liquid or vapors are extreme health hazards; cause severe burns and bone loss, which may not be immediately painful or visible. Significant exposure (100 mL) to HF can kill directly. Please use extreme caution; HF is very hazardous, both acutely and long term. It is Compatible with polymethylpentene (PMP), polyethylene (PE), and Teflon (PTFE).

Nitric Acid (68%):

Nitric acid causes acute burns to skin and eyes. It is a severe respiratory irritant. It gets hot when reacting with water, or any base. Nitric acid is Compatible with glass, HDPE, polymethylpentene (PMP), polyethylene (PE), and Teflon (PTFE).

Glacial Acetic Acid (>98%):

Acute burns to skin and eyes. Severe respiratory irritant .Can get very hot when reacting with water, or any base. It is Compatible with glass, HDPE, polymethylpentene (PMP), polyethylene (PE), and Teflon (PTFE).

Equipment:

Three polyethylene beakers or polymethylpentene screw cap jars, PTFEtweezers or stainless steel 4” wafer tweezers, PTFE wafer handling tools

3.2.2 HNA Preparation:

For etching 2mm at each side, it is important to have proper solution ratio with respect to the bowl size. For this experiment used ratio is 33ml of Acetic acid: 21ml of nitric acid: 12ml of hydrofluoric acid respectively.

3.2.3 Procedure:

This etch is intended to remove short circuit path at the edges. As HNA is an isotropic etchant. It will damage the cell if comes in contact in any other part of the cell other than its edge. For a short etch, solar cell is kept in HNA solution for 2 minutes at each side.

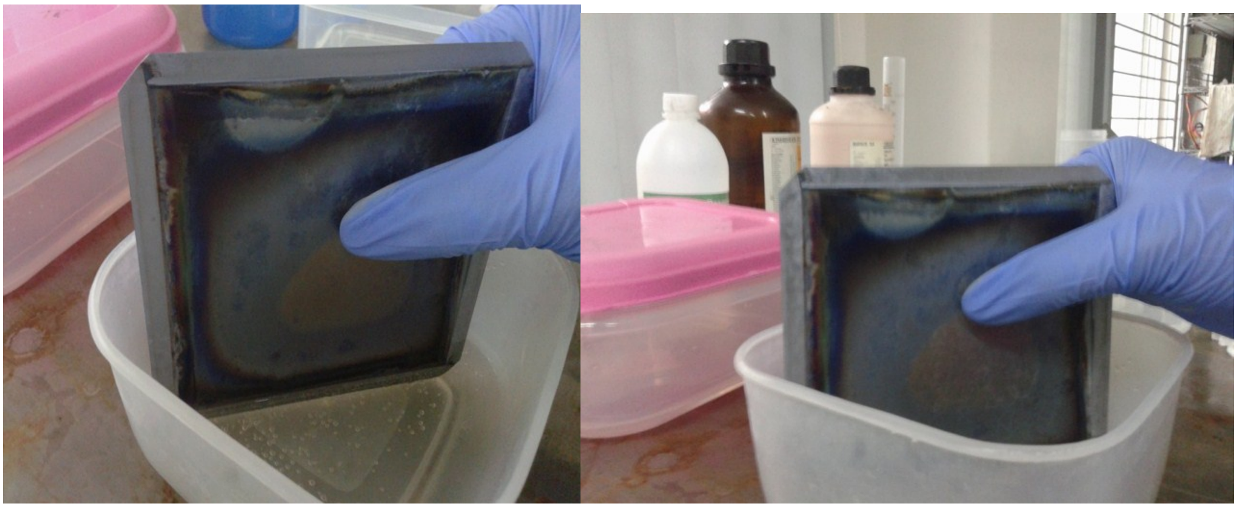

Figure 3.2: HNA Etching at BAE Lab

Steps:

- Experiment must be done under the fume hood chemical work bench.
- Place some soft tissue paper in the hood. Three polyethylene beakers are needed to pour the acids according to ratio (33:21:12).
- Graduated cylinders made of PTFE are used for measuring the right amount of acids.
- Cap the bottles and keep them away.
- A bowl of deionized water should be kept near for clean ups.
- For the mentioned ratio, etch rate is 3-5µm/min. so each side should be etched for 2 minutes.

Experiment should be conducted in procedure ventilated fume hood. Store the bottles of chemicals (sealed tightly) in the acid cabinet with secondary containment. Work area should contain an eye wash and safety shower.

Warning:

1. Hydrofluoric Acid (HF) is an extremely dangerous material. Because of the ability of HF to produce severe delayed tissue damage without necessarily producing pain, any contact with HF should receive immediate first aid and medical evaluation, even if the injury appears minor or no pain is felt. Nitric Acid and Glacial Acetic Acid are also strong, corrosive acids and will cause severe burns. Work carefully in the hood with full personal protective equipment. If HF or a mixture containing HF does get on your skin, rinse the affected area with water for 5 minutes and then apply calcium gluconate gel.

The calcium gluconate is on the metal shelves next to the phone. Have someone in the lab call Tufts EMS. In addition, HF attacks glass, so not glass containers should be used for this process.

2. HF attacks glass.it cannot be in a glass container. Polymethylpentene and polyethylene are fine to use. Polystyrene (plastic Petri dishes are often polystyrene!) is not considered compatible with long-term HF exposure

3.3 EQUIPMENTS:

Required instruments are:

1. SCREEN PRINTER
2. RTA
3. LIV MEASUREMENT SYSTEM

3.3.1 Screen Printer Process:

Screen printing process is most commonly used to form metal contacts on back and front surfaces of solar cells. Following diffusion, screen printed metallic contacts are formed to form electrical contacts to n and p doped regions. A thick, viscous metal solution or paste is forced through stainless screen grid onto the wafer in selected lithographically defined open regions in the screen. The metal lines on the front surface (n-type) are made of silver and on the back surface (p-type) are made of aluminum. Aluminum contact on the wafer backside also serves to form a heavily diffused p++ layer that reduces contact resistance and enhances back surface reflectance.

In monofacial solar cell, screen printers are used to form Ag and Al contacts to front and back solar cell surfaces. The printing process begins as a silicon wafer is placed onto the printing table. A very fine-mesh print screen mount within a frame, is placed over the wader; the screen blocks off certain areas and leaves other areas open, where the paste can go through. Figure 2.7shows the front contact screen which is normally used in basic screen printing. The distance between wafer and screen is carefully controlled (called the ‘snap-off’ distance). Screens used for front side printing typically have a much finer mesh size than do backside screens, due to the finer metal lines required on the front side. After a measured amount of paste is dispensed onto the screen, a squeegee distributes the paste over the screen to uniformly fill the screen openings.

Figure3.3: Screen Printer machine at BAEC

As the squeegee moves across the screen, it pushes the paste through the screen openings and onto the wafer surface. Back side screen printing done by using aluminum paste. This process must be tightly controlled for temperature, pressure, speed, and many other variables.

After each printing step the wafer goes to a drying furnace to solidify the paste. The wafer was then transferred to another printer for printing additional lines on either the front or back side of the wafer. Each solar cell has conductive lines on both front and back sides that are printed using screen masks and which have different functions.

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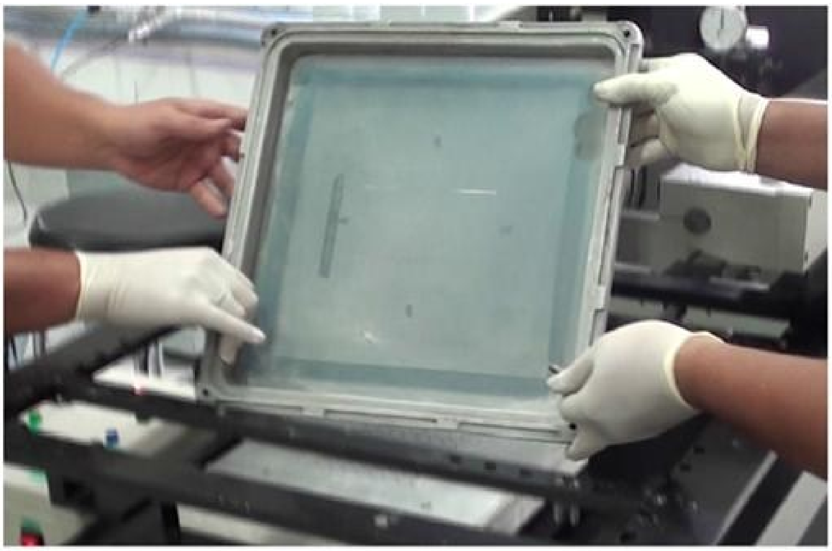


Figure 3.4: The print screen contains a pattern of open and closed spaces that allow paste to Wafer transfer.

The complete screen printed solar cell is shown in Figure 2.8. The silver lines on front side are much more narrow and delicate than those on the backside; some manufacturers perform the backside print steps first, and then flip the wafers over to print front side contact, minimizing the potential for damage during handling.

On the front side, which will face the sun, most crystalline silicon solar designs use a grid of very fine circuit lines (refer as ‘fingers’) that collect and conduct the light-induced electricity from the emitter to larger collecting lines, called ‘bus bars’. The grid finger lines, are as narrow as 80>m, are much smaller than the circuit lines on the backside. For standard cell, the printing requirements are ageless technically rigorous than on the front side. Instead of a grid of very thin circuit lines, the first backside print step deposits a uniform sheet of aluminum-based material that conducts electricity, and also reflects enraptured light back into cell. This layer also ‘passivity’s’ the solar cell, sealing off unwanted molecular pathways that can capture mobile electrons. A second backside print step creates the bus bars that interface with the outside electrical system.

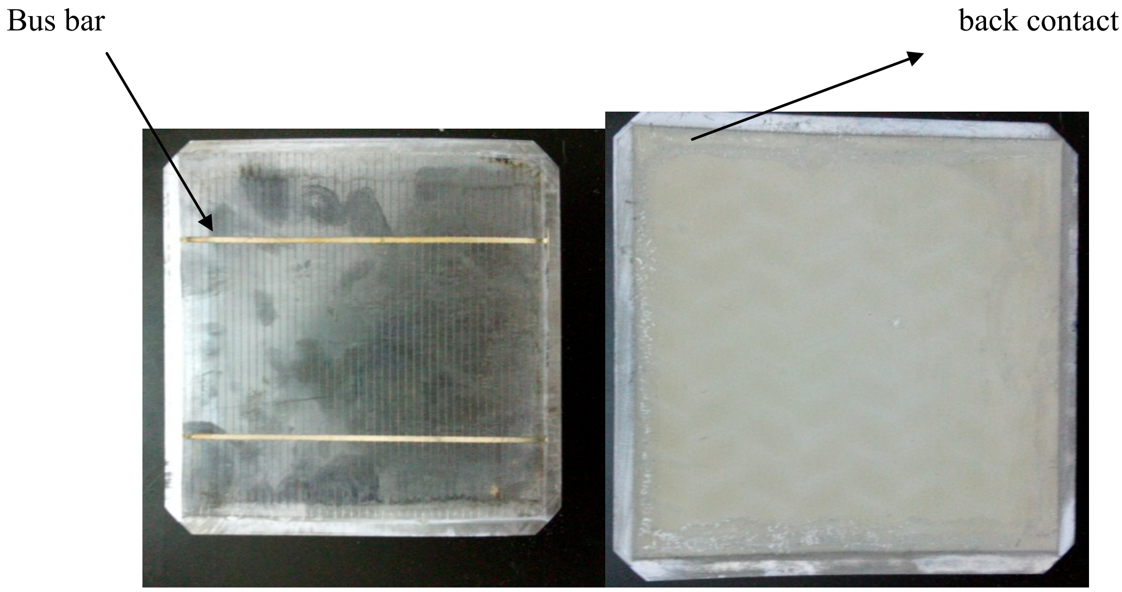


Figure 3.5: Silver on the front side and aluminum on the backside.

After screen printing, the silicon wafers are required to go through drying at relatively low temperature (around 120°C) for certain period. In our experiment, we placed the wafers after each time edge isolation, back and front side printing in a preheated oven at 120°C for 10 minutes so that the paste gets attached well to the wafer surface.

3.3.2 Rapid Thermal Annealing (RTA):

Rapid Thermal Processing (RTP) refers to a semiconductor manufacturing process which heats silicon wafers to high temperatures (over 1,000 °C) on a timescale of several seconds or less. During cooling, however, wafer temperatures must be brought down slowly to prevent dislocations and wafer breakage due to thermal shock. Such rapid heating rates are often attained by high intensity lamps or lasers [19]. The rapid thermal annealing (RTA) furnace was used to cure or fire screen printed contacts on silicon solar cells. It is one of the most sensitive steps of the solar cell fabrication [20].Rapid thermal annealing is important because its form low-resistance ohomic contacts and provides proper contact between the conductor and the semiconductor of solar cell.

3.3.3 Furnace Description:

Infrared (IR) heating is electromagnetic radiation emitted from the surface of IR lamps or emitters. Thermal radiation is generated when heat from the movement of charge particles within atoms is converted to electromagnetic radiation. In the furnace, radiant heating from IR lamps provides heat directly to objects without first heating the surrounding air. IR waves excite molecules within a substance (product) thus generating heat, but pass generally undisturbed through the surrounding atmosphere. Other substances such as glass, ceramics and some organic materials are also transparent to IR waves. Objects suspended in these media can, therefore, be heated directly by IR waves without directly heating the supporting media.

The RTC furnace is a compact, near-infrared, conveyor belt furnace for laboratory and general purpose thermal processing in the range of 100-980 ^{0}C in a controlled atmosphere, free of outside contamination. Process gas may be CDA, N2 or another inert gas. Dual gas furnaces may use Nitrogen and a second gas such as Forming Gas (pre-mixed N2/H2) or another type of reducing gas injected into the heating chamber. The RTC furnace transports product on a 150mm (6-inch) wide belt. Figure 2.9 shows a cross sectional drawing of a single wafer RTP furnace operated in atmosphere.

Figure 3.6: RTA furnace used in this work.

In our experiment, three temperature zones and one cooling zone annealing furnace with conveyer belt system was used in our co-firing process. The wafers were passed inside the RTA furnace through a moving belt with speed 60 inch per minute. While during the rapid thermal annealing process, the cell was then fired with the general temperature profile and in our experiment it was 500, 600 and 800 °C for three temperature zones respectively.

3.4 Light Current Voltage (LIV) Testing:

Solar cells are characterized by their ability to convert sunlight into electricity. The light (L) intensity current (I)-voltage (V) solar cell measurement is used to calculate sunlight- to-electricity conversion efficiency. This solar cell LIV measurement system determines fundamental device characteristics including short circuit current (Isc), open circuit voltage (Voc), fill factor (FF), series resistance (Rs), shunt resistance (RSHUNT), and maximum power (Pmax). Those collected results, can be used to determine the efficiency of solar cell. Incident intensity is controllable using absorptive metallic filters. System is independently calibrated with pre-qualified solar cells. LIV measurements using inexpensive, flash, xenon light source for illumination. LIV data acquisition is based on a custom-designed electronic interface integrated with high resolution, programmable voltage supply. Voltage across the solar cell is applied to measure the light generated photo-current. Spectral distribution of xenon high intensity plasma discharge lamp is light is closest to the solar spectra, and is industry standard. The flash LIV system is capable of measuring small (~ 10 cm^2) and large (up to ~15x15 cm^2) solar cells. The intensity variation is controllable in ~ 10 mW/cm^2 to 150 mW/cm^2 through simple absorptive metallic filters. Photo-generated photocurrent is measured across a one-ohm resistor. Figure 3.7 shows the LIV measurement system.

Figure 3.7: LIV measurement systems.

For each value of voltage, current is measured at the peak pulse and averaged over a large number of pulses. The voltage and current are plotted to characterize solar cell LIV response. Figure 3.8 (left) shows the basic schematic for the electronic data acquisition and Fig. 3.8 (right) shows the picture of the electronic circuit board.

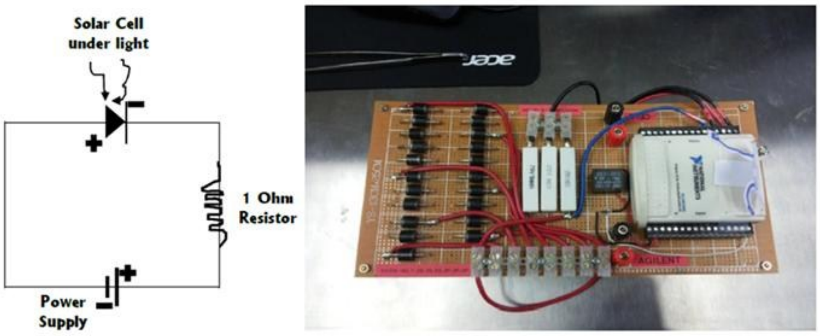


Figure 3.8: Solar cell LIV measurement schematic (left) and electronic hardware interface (right)

CHAPTER 4

4.1 RESULTS:

This experiment is intended to find a low cost process for removing short circuit between P and N layer in solar cells. Normally after $POCL_3$ diffusion boron doped cell gets covered with P-type material. In this paper, wet chemical etching using HNA is applied on the edges to remove short path for photo generated current leakage.

4.2 ETCH RATE:

Sample 1		Sample 2	
Weight before etching	Weight after etching	Weight before etching	Weight after etching
6.5gm.	6.2gm	6.85gm	6.11gm

Table 4.1: Weight before and after etching.

Solar cells available at BAE have thickness is about 200µm.
Each side is etched for 2 minutes in the HNA solution. So the total procedure takes about 8 minutes.
From these information etch rate can be determined.

For sample 01:
Per gram thickness: 200/6.5 = 30.76µm
Thickness lost due to etching of 0.1gm from four side = 30.76*0.3 = 9.228µm.
So the etch Rate: 9.228/8 =1.15µm/min

For sample 02:
Per gram thickness = 200/6.85 = 29.197µm
Thickness lost due to etching of 0.74gm from four side = 29.197*0.74 = 21.605µm
So the etch rate = 21.605/8 = 2.7µm/min

4.3 DETERMINATION OF EDGE ISOLATION:

	Sample 01				Sample 02			
Edges	P+	N-	P-	N+	P+	N-	P-	N+
1	120mv		-110mv		128mv		-90mv	
2	140mv		-89mv		150mv		-56mv	
3	127mv		-76mv		90mv		-73mv	
4	145mv		-87mv		190mv		-104mv	

Table4.2: voltage difference between P and N layers.

From the table 4.2, we see the voltage difference between the two layers of solar cell. These voltage differences are the clear indication that the P and N layers of cell are isolated electrically.

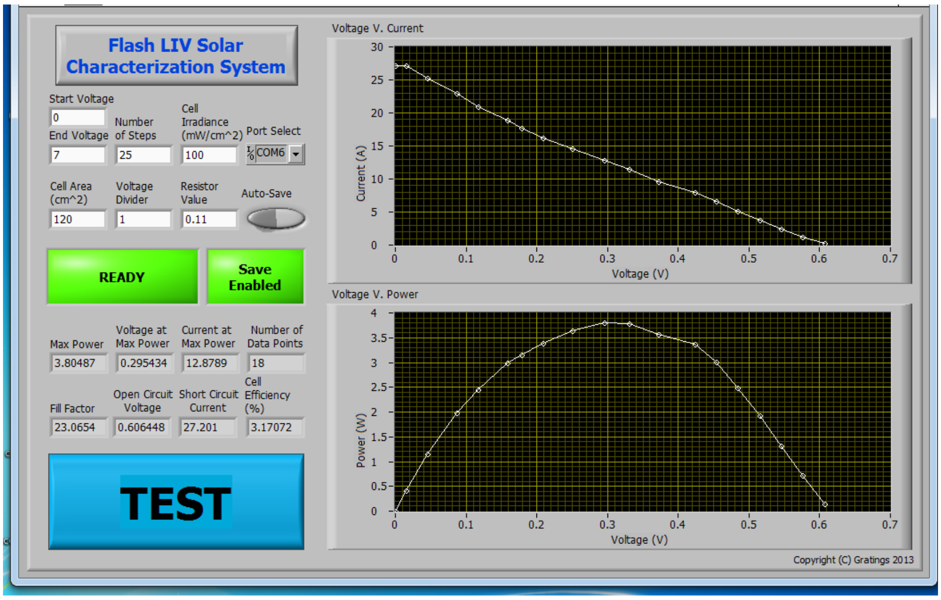
4.4 PERFORMANCE STUDY OF SOLAR CELL:

Solar cells are characterized by their ability to convert sunlight into electricity. The light intensity (L), current (I) and voltage (V) test, which is known as LIV test, is a series of measurements performed on a completed solar cell to study their operating characteristics. The LIV test identifies the characteristics such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), fill factor (FF) and power maximum (P_{max}). These values can be used to determine the efficiency of solar cell. Solar cells are tested using Xenon-arc lamps; a xenon spectrum is much closed to sunlight spectrum. Data acquisition based on programmable current-voltage source power supplies capable of handling current up to ~ 8 mA which is used in conjunction with a proprietary data acquisition system.

4.4.1 PERFORMANCE BEFORE ETCHING:

4.4.1.1Sample 1 before etching:

The measured LIV data are shown in Figure no 4.1, where light illumination of 150mW/cm^2, the active surface area is 120 cm^2, cell thickness 200µm.



Start Voltage: 0

End Voltage: 7

Number of Steps: 25

Cell Irradiance (mW/cm^2): 100

Port Select: COM6

Cell Area (cm^2): 120

Voltage Divider: 1

Resistor Value: 0.11

Auto-Save

Max Power: 3.80487

Voltage at Max Power: 0.295434

Current at Max Power: 12.8789

Number of Data Points: 18

Fill Factor: 23.0654

Open Circuit Voltage: 0.606448

Short Circuit Current: 27.201

Cell Efficiency (%): 3.17072

Figure 4.1: Sample 1 solar cell LIV output before etching

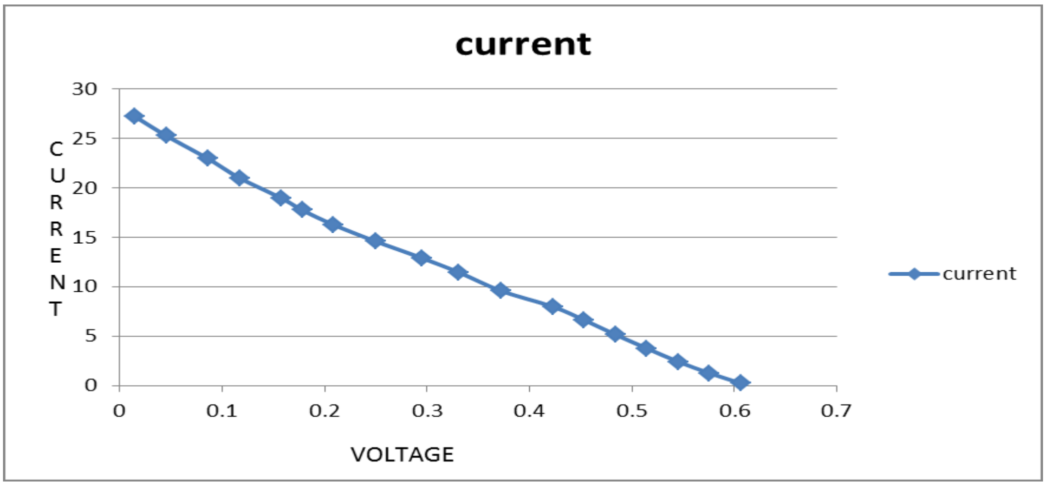


Figure 4.2: Sample 1 Solar cell I-V curve before Etching

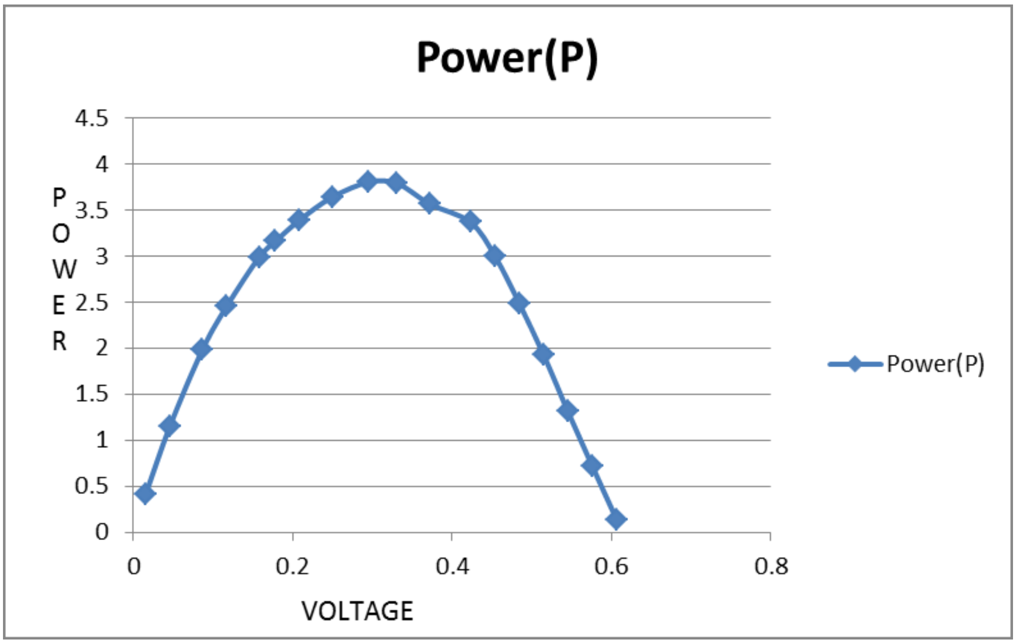


Figure 4.3: Sample 1 Solar Cell P_{max}-V curve before Etching

The software provides I-V curve of un-etched solar cell. From the LIV data, the following results of fabricated monocrystalline silicon solar cell are found, which are, Maximum power (P_{max}) is 3.80487 mW, Voltage at maximum power (V_{max}) is 0.295434 V, Current at maximum power (I_{max}) is 12.8789 mA, Open circuit voltage (V_{oc}) is 0.606448 V, and Short circuit current is (I_{sc}) is 27.201 mA.

Fill factor (FF): The fill factor is calculated using the Equation

$$FF = V_m I_m / V_{oc} I_{sc} = (0.295434V*12.8789mA)/\ (0.606448V)*(27.200mA)$$

$$= 0.230745$$

So the value of FF is 0.23

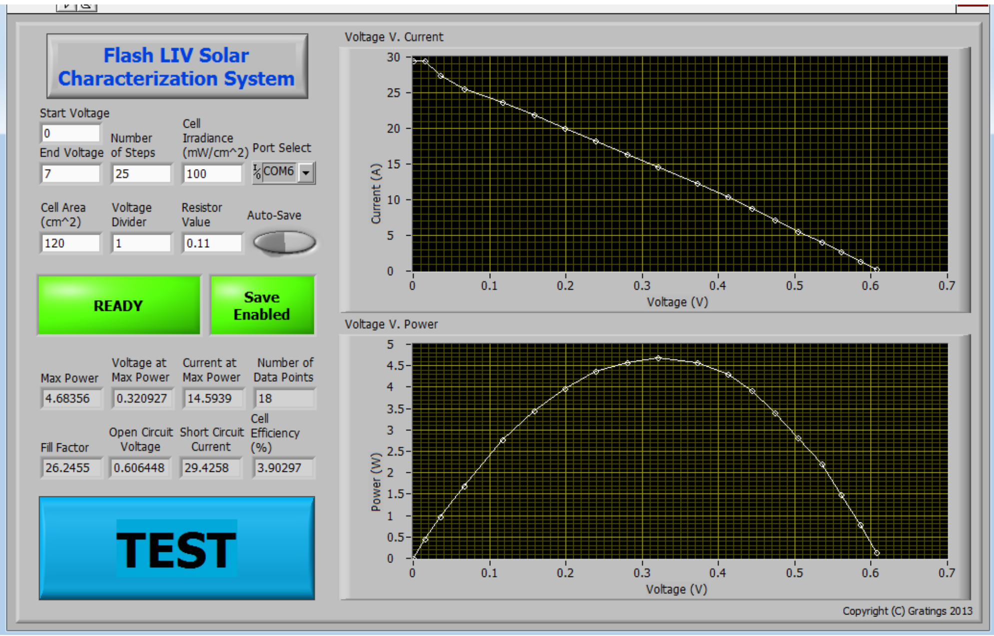
Efficiency (η): The efficiency of solar cell is calculated using the Equation,

$$\eta = P_{out}/P_{in.}$$
$$= [V_{oc}*I_{sc}*FF/P_{in}]$$
$$= [\{0.606448V*27.201mA*0.23\}/100mw]$$
$$= 3.8$$

In the current study the value of efficiency is 3.8%

4.4.1.2 Sample 2 before etching:

The measured LIV data are shown in Figure no: 4.4, where light illumination of 150mW/cm^2, the active surface area is 120 cm^2, cell thickness 200μm.



Start Voltage 0
End Voltage 7
Number of Steps 25
Cell Irradiance (mW/cm^2) 100
Port Select COM6
Cell Area (cm^2) 120
Voltage Divider 1
Resistor Value 0.11
Max Power 4.68356
Voltage at Max Power 0.320927
Current at Max Power 14.5939
Number of Data Points 18
Fill Factor 26.2455
Open Circuit Voltage 0.606448
Short Circuit Current 29.4258
Cell Efficiency (%) 3.90297

Figure 4.4: Sample 2 Solar cell LIV output before etching

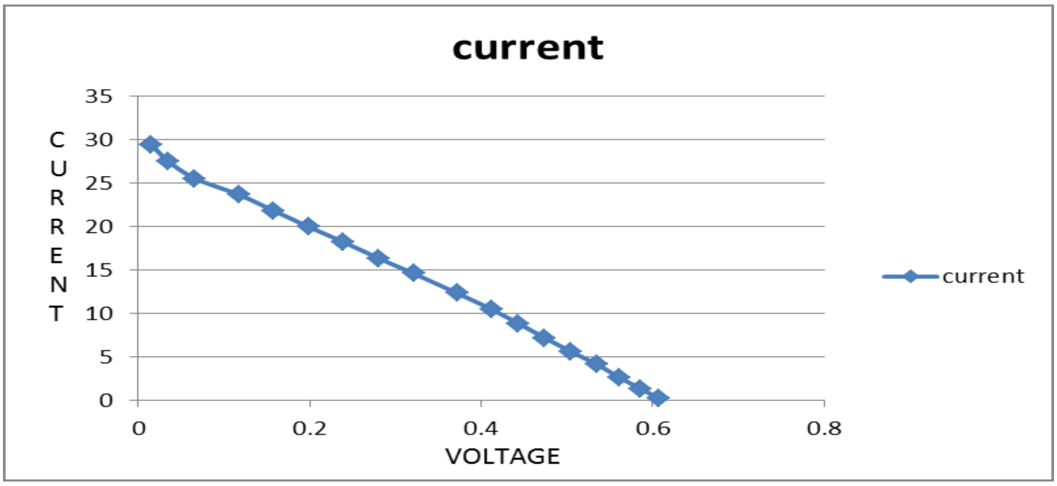


Figure 4.5: Sample 2 Solar Cell I-V curve before Etching

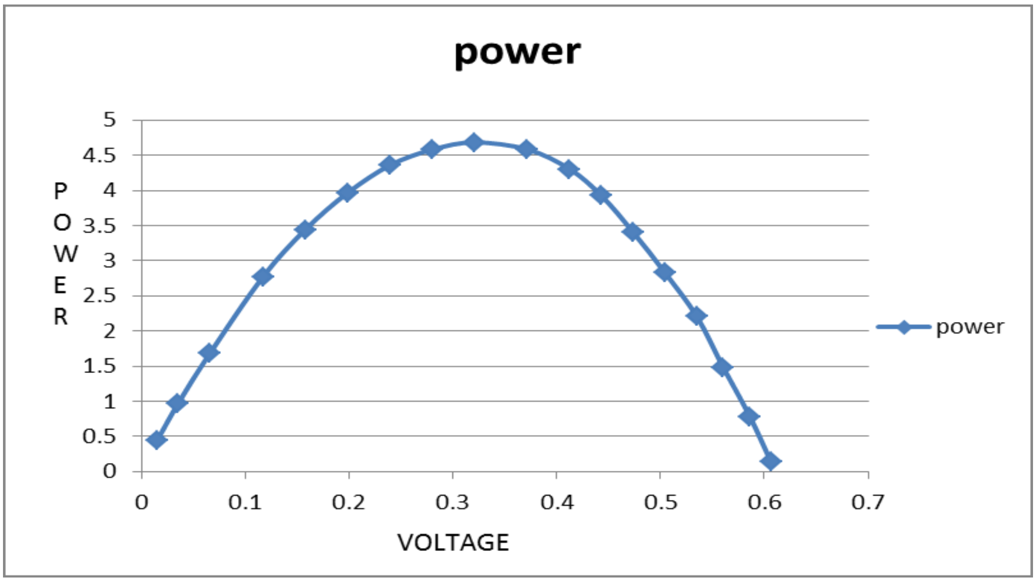


Figure 4.6: Sample 2 Solar Cell P_{max}-V Curve before etching

The software provides I-V curve of un-etched solar cell. From the LIV data, the following results of fabricated monocrystalline silicon solar cell are found, which are, Maximum power (P_{max}) is 4.68356 mW, Voltage at maximum power (V_{max}) is 0.320927 V, Current at maximum power (I_{max}) is 14.5939 mA, Open circuit voltage (V_{oc}) is 0.606448 V, and Short circuit current is (I_{sc}) is 29.4258 mA.

Fill factor (FF): The fill factor is calculated using the Equation

$FF = V_m I_m / V_{oc} I_{sc} = (0.320927V*14.5939mA)/ (0.606448V)*(29.4258mA)$

$=0.26241$

So the value of FF is 0.26

Efficiency (η): The efficiency of solar cell is calculated using the Equation,

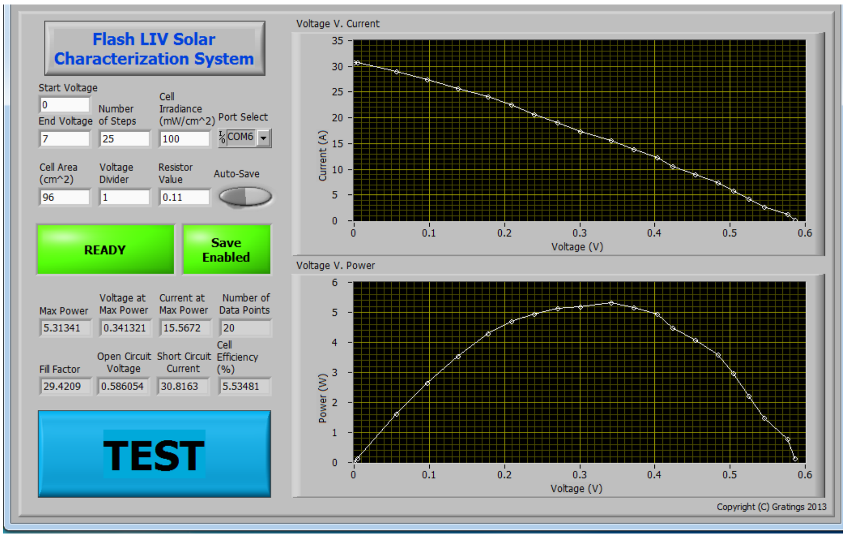
$$\eta = P_{out}/P_{in.}$$
$$= [V_{oc}*I_{sc}*FF/P_{in}]$$
$$= [\{0.606448V*29.4258mA*0.26\}/100mw]*100\%$$
$$= 4.6\%$$

In the current study the value of efficiency is 4.6%

4.5 PERFORMANCE AFTER ETCHING:

4.5.1 Sample 1 after etching:

The measured LIV data are shown in Figure no: 4.7, where light illumination of 150mW/cm^2, the active surface area is 96 cm^2, cell thickness 200µm.



Flash LIV Solar Characterization System

Start Voltage	0
End Voltage	7
Number of Steps	25
Cell Irradiance (mW/cm^2)	100
Port Select	COM6
Cell Area (cm^2)	96
Voltage Divider	1
Resistor Value	0.11
Max Power	5.31341
Voltage at Max Power	0.341321
Current at Max Power	15.5672
Number of Data Points	20
Fill Factor	29.4209
Open Circuit Voltage	0.586054
Short Circuit Current	30.8163
Cell Efficiency (%)	5.53481

Figure 4.7: Sample 1 Solar Cell LIV output after etching

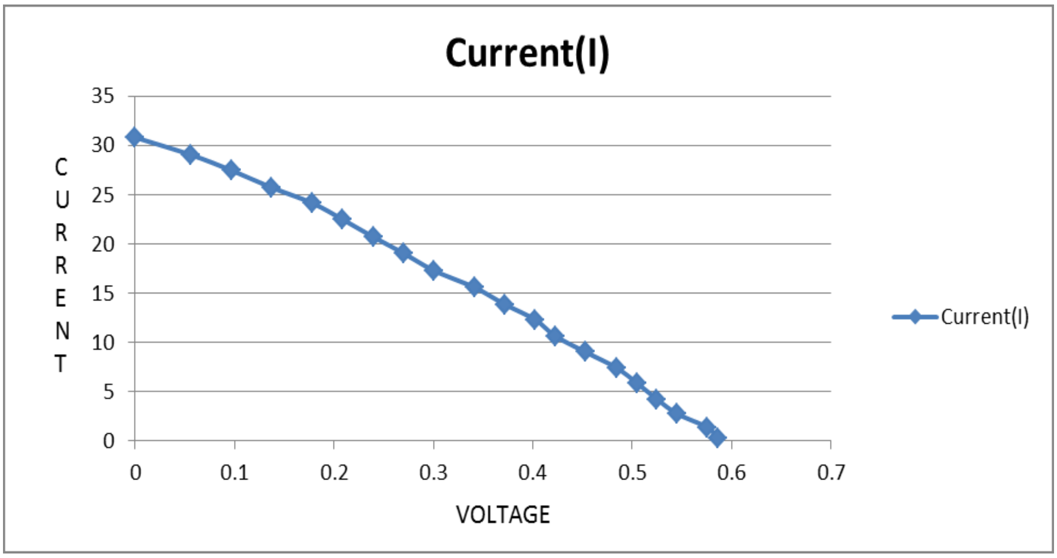


Figure 4.8: Sample 1 Solar Cell I-V Curve After etching

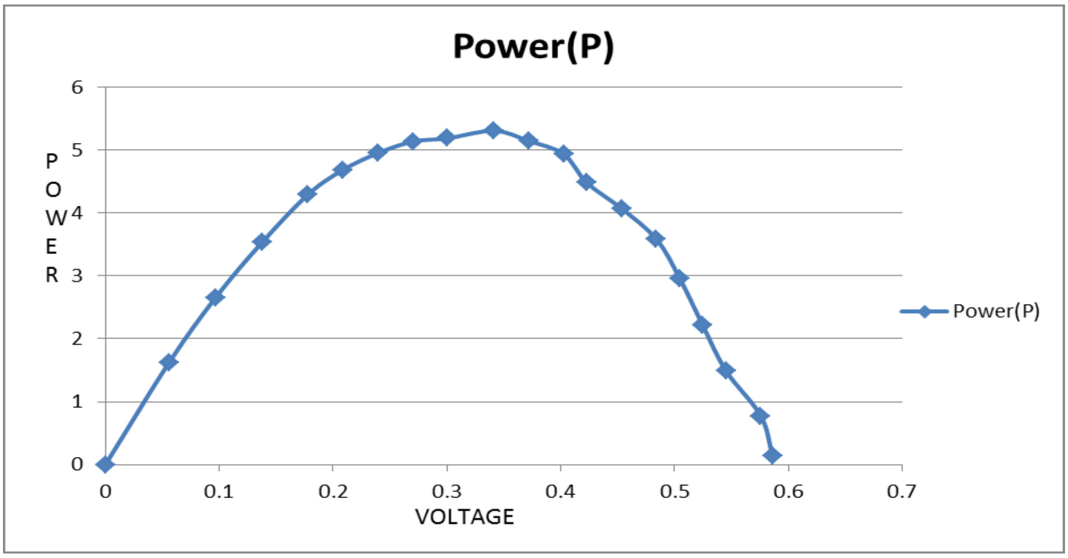


Figure 4.9: Sample 1 Solar Cell P_{max}-V curve after etching

The software provides I-V curve of un-etched solar cell. From the LIV data, the following results of fabricated monocrystalline silicon solar cell are found, which are, Maximum power (P_{max}) is 5.31341 mW, Voltage at maximum power (V_{max}) is 0.341321 V, Current at maximum power (I_{max}) is 15.5672 mA, Open circuit voltage (V_{oc}) is 0.586054 V, and Short circuit current is (I_{sc}) is 30.8163 mA.

Fill factor (FF): The fill factor is calculated using the Equation

$FF = V_m I_m / V_{oc} I_{sc} = (0.341321V*15.5672mA)/ (0.58654V)*(30.8163mA)$

$=0.29405$

So the value of FF is 0.29

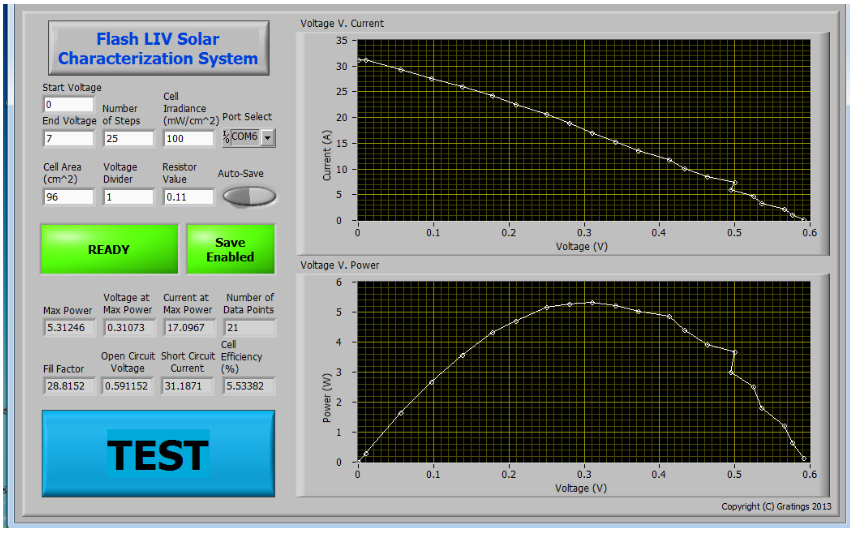
Efficiency (η): The efficiency of solar cell is calculated using the Equation,

$$\eta = P_{out}/P_{in.}$$
$$= [V_{oc}*I_{sc}*FF/P_{in}]$$
$$= [\{0.586054V*30.8163mA*0.29\}/100mw]*100\%$$
$$= 5.31\%$$

In the current study the value of efficiency is 5.31%.

4.5.2 Sample 2 after etching:

The measured LIV data are shown in Figure 4.10, where light illumination of 150mW/cm^2, the active surface area is 96 cm^2, cell thickness 200µm.


Flash LIV Solar Characterization System

Start Voltage: 0
End Voltage: 7
Number of Steps: 25
Cell Irradiance (mW/cm^2): 100
Port Select: COM6
Cell Area (cm^2): 96
Voltage Divider: 1
Resistor Value: 0.11
Auto-Save

Max Power: 5.31246
Voltage at Max Power: 0.31073
Current at Max Power: 17.0967
Number of Data Points: 21
Fill Factor: 28.8152
Open Circuit Voltage: 0.591152
Short Circuit Current: 31.1871
Cell Efficiency (%): 5.53382

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Figure 4.10: Sample 2 Solar cell LIV output after etching

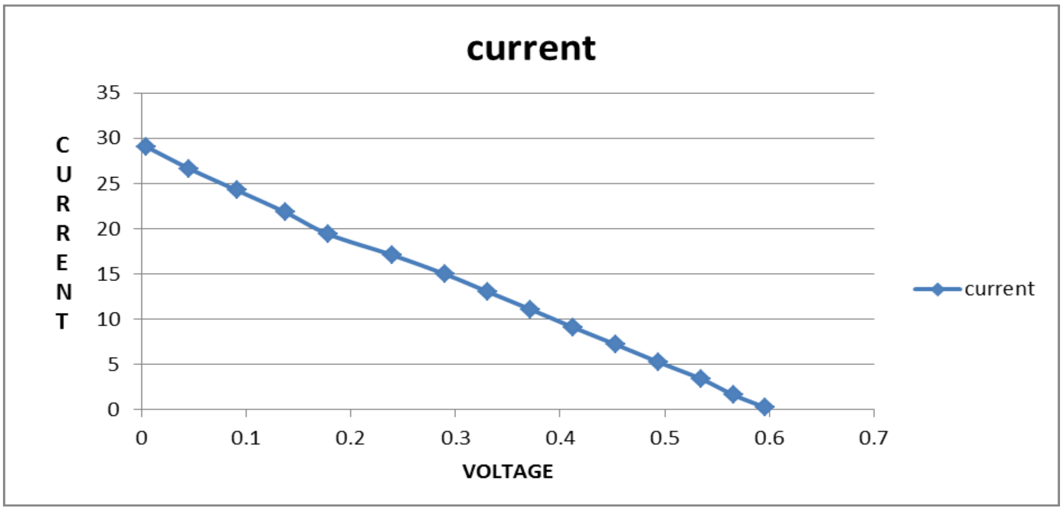

Figure 4.11: Sample 2 Solar cell I-V curve after etching

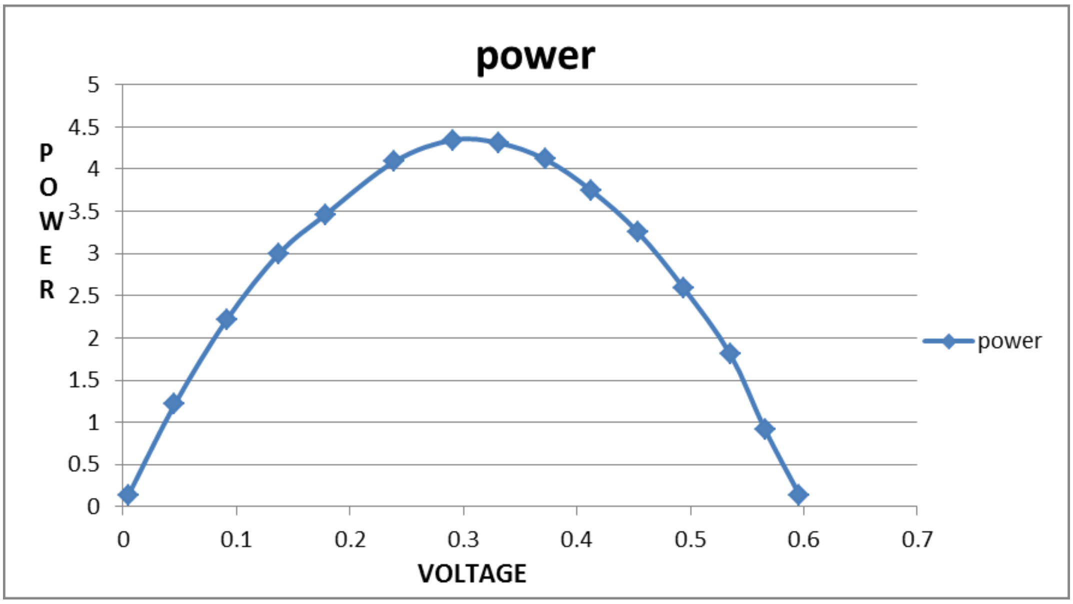

Figure 4.12: Sample 2 Solar cell P_{max}-V Curve after etching

The software provides I-V curve of un-etched solar cell. From the LIV data, the following results of fabricated monocrystalline silicon solar cell are found, which are, Maximum power (P_{max}) is 5.31246 mW, Voltage at maximum power (V_{max}) is 0.31073 V, Current at maximum power (I_{max}) is 17.0967 mA, Open circuit voltage (V_{oc}) is 0.591152 V, and Short circuit current is (I_{sc}) is 31.1871 mA.

Fill factor (FF): The fill factor is calculated using the Equation

$$FF = V_m I_m / V_{oc} I_{sc} = (0.31073V*17.0967\text{ mA})/(0.591152V)*(31.1871\text{ mA})$$

$$=0.28825$$

So the value of FF is 0.29

Efficiency (η): The efficiency of solar cell is calculated using the Equation,

$$\eta = P_{out}/P_{in.}$$
$$= [V_{oc}*I_{sc}*FF/P_{in}]$$
$$= [\{0.591152\text{ V} *31.1871\text{ mA}*0.29\}/100\text{mw}]*100\%$$
$$= 5.34\%$$

In the current study the value of efficiency is 5.3%

4.6 Graphical comparison etched and un-etched sample 1 solar cell:

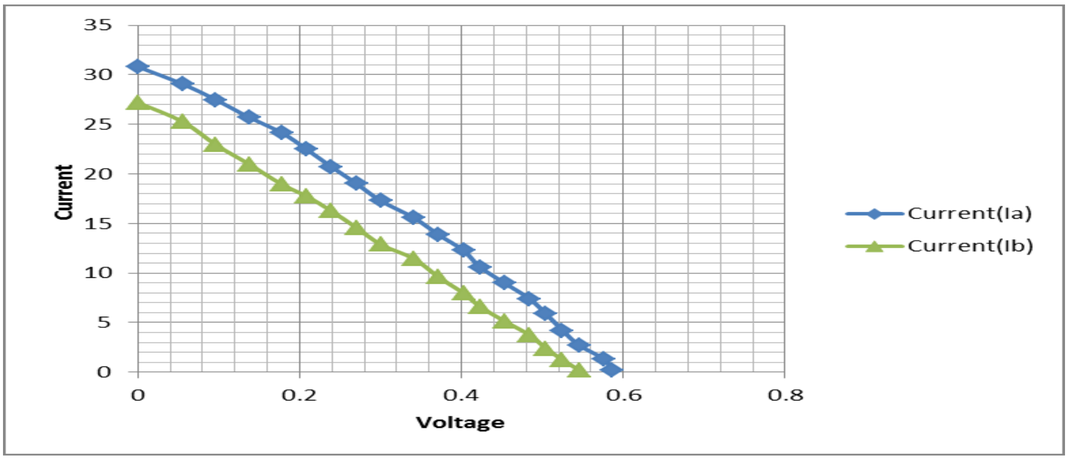

Figure 4.13: I-V curve Comparison before and after etching for Sample 1

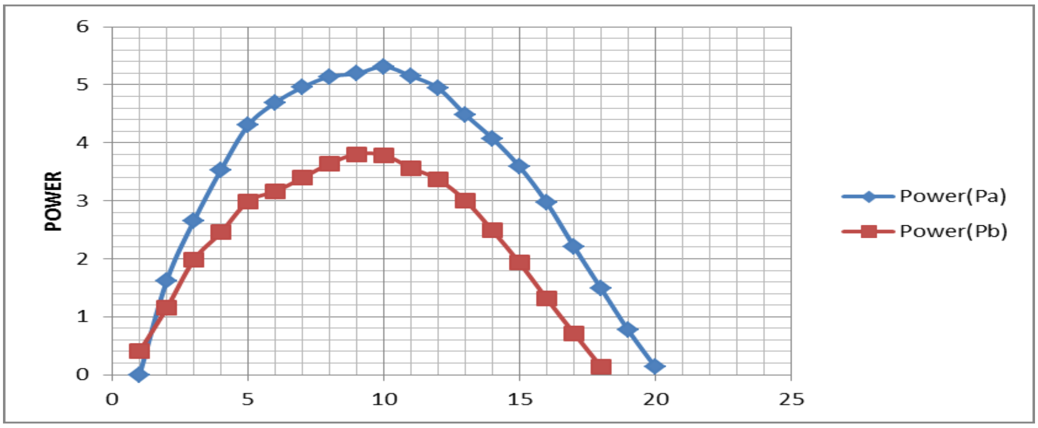

Figure 4.14: P_{max} curve comparison before and after etching for sample 1

From graphical comparison of I-V curves of solar cell, before and after etching. The measured I-V curves for un-etched cell has lower current than the cell that is etched. Moreover Voc and Isc of cell also get improved. Fill factor of solar cell also improved.

From the comparison of power curves, we can see that, cells total power output also improved after etching.

4.7 Graphical comparison etched and un-etched sample 2 solar cell:

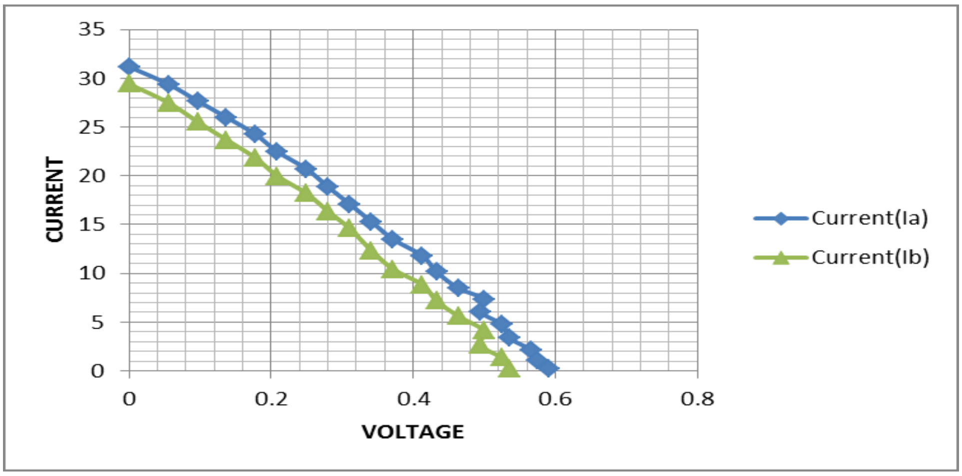

Figure 4.15: I-V curve Comparison before and after etching for Sample 2

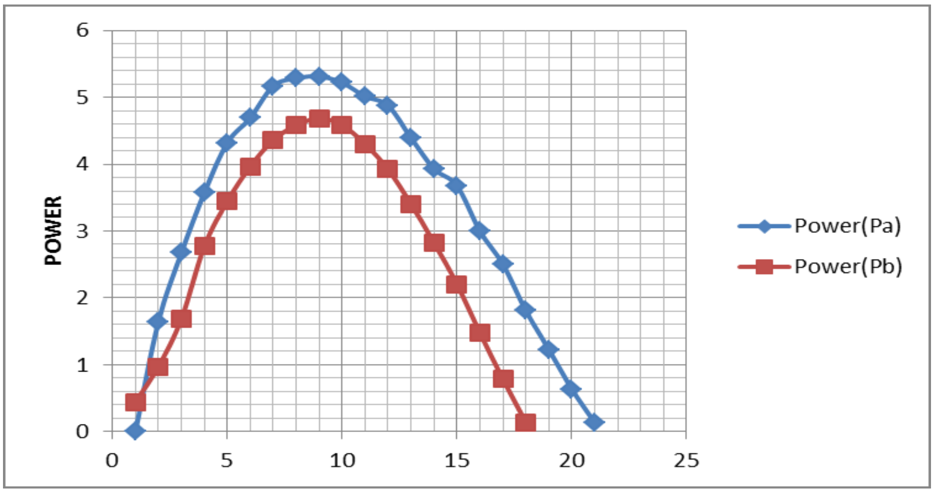

Figure 4.16: Pmax Curve Comparison before and after etching for Sample 2

From graphical comparison of I-V curves of solar cell, before and after etching. The measured I-V curves for un-etched cell has lower current than the cell that is etched. Moreover Voc and Isc of cell also get improved. Fill factor of solar cell also improved.

From the comparison of power curves, we can see that, cells total power output also improved after etching.

4.8 Discussion:

The objectives of this research are to study the HNA solution etching property for solar cell’s edge isolation and to investigate the suitability of HNA for edge isolation for crack free isolation.

Experimental procedures are less costly in comparison to other etching techniques like laser scribing, plasma etching as unlike other techniques; HNA etching doesn’t require costly and high power consuming devices. With wet chemical etching procedure, cracks during edge isolation can be avoided. By using HNA as wet chemical etchant, different parameters such as etching rate, process speed can be predicted.

Chapter 5

Conclusion

Wet etching technique has been applied in this research at BAEC for increasing efficiency of solar cell for the first time in Bangladesh. The objective of this research is to study the procedure of edge isolation using wet chemical etching, which will be more cost effective than other available etching methods in Bangladesh.

In this research, it has been found that if edges of the solar cell are etched with wet chemical solution, it improvise the IV characteristics of solar cells and power curve. There are different procedure and recipes available for wet chemical etching. HNA, a mixture of acetic acid, nitric acid and hydrofluoric acids mixed in a ratio of 33.22:12, has been used due to cost effectiveness and availability. In order to assess the performance of solar cells, a simulation software LIV measurement system has been used.

Experimental procedures were carried out to examine the theoretical analysis. In conclusion, it has been found that the etching procedure substantially increase the efficiency of solar cell. After etching, the cell efficiencies are 5.53% and 5.31%, which are 2.36% and 1.41% more than un-etched cell efficiencies. Simulation and related calculation verified the above results. This research result will contribute in further improvement of mono-crystalline solar cell efficiency. With further study, there are scopes for chemical etching to achieve more popularity than other methods if it is possible to do the experiments in sophisticated way

FUTURE SCOPE:

In this research, it is mainly focused on the wet chemical etching by HNA, a solution consists of hydrofluoric acid, nitric acid and acetic acid. Experiments are done to observe the HNA etched solar cell behavior before etching and after etching. There are other wet chemical etchants available like KOH, TMAH, which can be used for edge isolation.

Moreover, due to lack of available instruments and equipment's experiments couldn't be done more accurately.

In the future, different ratio of HNA can be used to find better etching rate. Other chemical etchants can be used to observe that if it is possible to improvise further.

Appendices

Appendix A: LIV measurement data of a typical monofacial solar cell using LabVIEWSoftware

Sample 01 Solar Cell :Before Etching		
Voltage(V_B)	Current(I_B)	Power(P_B)
0.015011	27.20098	0.408319
0.045603	25.25429	1.151665
0.086392	22.9368	1.981545
0.116983	20.99012	2.455488
0.157772	18.95073	2.989891
0.178166	17.74563	3.161672
0.208758	16.26244	3.394911
0.249547	14.59385	3.641845
0.295434	12.87891	3.804867
0.331124	11.44207	3.788744
0.371913	9.58808	3.56593
0.422899	7.965839	3.368744
0.45349	6.621697	3.002875
0.484082	5.138505	2.487457
0.514673	3.748013	1.929003
0.545265	2.403871	1.310747
0.575857	1.245127	0.717015
0.606448	0.225433	0.136714

Sample 02 Solar Cell: Before Etching		
Voltage(V_B)	Current(I_B)	Power(P_B)
0.015011	29.42577	0.441716
0.035406	27.47908	0.972912
0.065997	25.53239	1.685064
0.116983	23.6784	2.769972
0.157772	21.82441	3.443277
0.198561	19.97042	3.965339
0.239349	18.20913	4.358344
0.280138	16.35514	4.581698
0.320927	14.59385	4.683559
0.371913	12.32271	4.582975
0.412702	10.42238	4.301331
0.443293	8.846484	3.921586
0.473885	7.177894	3.401494
0.504476	5.602003	2.826077
0.535068	4.118811	2.203843
0.560561	2.635619	1.477425
0.586054	1.337827	0.784038
0.606448	0.225433	0.136714

Sample 01 Solar cell: After Etching		
Voltage(V_A)	Current(I_A)	Power(P_A)
0	30.81626	0
0.0558	29.05497	1.621266
0.096589	27.479078	2.654168
0.137377	25.717788	3.533044
0.178166	24.141897	4.30127
0.208758	22.473307	4.691478
0.239349	20.712017	4.957408
0.269941	19.043426	5.1406
0.300532	17.282136	5.193843
0.341321	15.567196	5.313415
0.371913	13.852256	5.151831
0.402504	12.276365	4.941291
0.422899	10.607774	4.486015
0.45349	8.985533	4.074852
0.484082	7.409642	3.586874
0.504476	5.880101	2.966371
0.524871	4.211511	2.210498
0.545265	2.728319	1.487657
0.575857	1.337827	0.770396
0.586054	0.225433	0.132116

Sample 2 Solar Cell: after Etching		
Voltage(V_A)	Current(I_A)	Power(P_A)
0	31.187057	0
0.0558	29.379418	1.63937
0.096589	27.664477	2.672076
0.137377	25.995887	3.571249
0.178166	24.234597	4.317786
0.208758	22.473307	4.691478
0.249547	20.712017	5.168612
0.280138	18.858027	5.282852
0.31073	17.096737	5.312464
0.341321	15.289098	5.218494
0.371913	13.481458	5.013927
0.412702	11.812867	4.875189
0.433096	10.144277	4.393445
0.463688	8.475686	3.93007
0.499378	7.363293	3.677064
0.494279	6.0655	2.99805
0.524871	4.767707	2.50243
0.535068	3.377215	1.807039
0.565659	2.172122	1.228681
0.575857	1.106078	0.636942
0.591152	0.225433	0.133265

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