"Study of the efficiency of different types of solar cells"

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A project submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Electronics and Telecommunications Engineering.

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Declaration

This report on the basis of our thesis paper and its enhancement of studies throughout our thesis work is submitted to follow the terms and conditions of the department of Electronics and Communications Engineering .This report is the requirement for the successive competition of B.Sc. Engineering in Electronics and Communications Engineering.

We state that the report along with its literature that has been demonstrated in this report papers, is our own work with the masterly guidance and fruitful assistance of our supervisor for the finalization of our report successfully.

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Approval

This project report "Study of the efficiency of different types of solar cells" submitted by Rajib Chandra Sutradhar, ID: 2011-1-55-017 & Nusrat Jahan Afrad **,** ID**:** 2011-1-55-009 to department of Electronics & Communications Engineering, East West University has been accepted as satisfactory for the partial fulfillment of the requirements for the degree of Bachelor of Science in Electronics & Communications Engineering and approved as to it's style and contents.

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Study of the efficiency of different types of solar cell

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ABSTRACT

Solar energy, radiant light and heat from the sun, have been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar energy technologies include solar heating, solar photovoltaics, concentrated solar power and solar architecture, which can make considerable contributions to solving some of the most urgent problems the world now faces. The International Energy Agency projected that solar power could provide "a third of the global final energy demand after 2060, while CO_2 emissions would be reduced to very low levels."

Nowadays the world energy demands around500 exajoule. In 2050, the demand will be around 1000 exajoule. From fossil fuel we may have got almost 85%. Rest of the world demand may be mitigated from alternative energy sources like Solar, Coal, Oil, Natural Gas, Biomass, Geothermal, and even the wind and hydropower. Most of the power generated nowadays is produced using fossil fuels, which emit tons of carbon dioxide and other pollution every second. More importantly, fossil fuel will eventually run out. In order to make the development of our civilization sustainable people are looking for new source of substitute clean energy. Of them solar energy is the potential alternative cause less harm to our environment, carbon emission in the environment is zero, low initial cost, solar systems performance more efficient, economical and stable. Moreover, solar cells are a promising renewable, carbon-free electric energy resource to address the fossil fuel shortage and global warming.

In this work,we tried to make a brief review and present status of solar cell conversion efficiency, material usually used for fabrication and different solar cell technology on the most promising routes to realize cheap and efficient solar cells. It is found that the a:Si solar cells have a highest efficiency of approximately 25% in laboratory and 15% in industry, compound semiconductor solar cells have an efficiency of 28.8% (GaAs) and thin film solar cells have an efficiency of 19.6% (CdTe), and HIT solar cells have an efficiency of 22.3%.

Chapter 1
Introduction

1.1 Introduction

A solar cell in an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, so this cell is also called photovoltaic cell or (PV) cell. This cell is made of some semiconductor material used in electronics and computer chips. Solar cell is a device that can utilize the ultimate energy from the sun.

Not only is the efficiency of the cell important, but also its ability to perform well over a long period of time under real atmospheric conditions. In this paper we will discuss about solar cell history, classification, efficiency, different structures, a review of the features of solar cells. But in chapter one giver below about history &classification.

1.1.1 History of Solar Cells

Solar technology is not new. Its history spans from the 7th Century B.C. to today. Researchers started concentrating the sun's heat with glass and mirrors to light fires. Nowadays, we have everything from solar-powered buildings to solar powered vehicles. From the nice review [1],we can learn more about the milestones in the historical development of solar technology, century by century, and year by year and we can also glimpse the future.

First Invention of Solar Cell- The photovoltaic effect was discovered in 1939 by Alexandre-Edmond Becquerel, who was a French physicist. This was "the beginning" of the solar cell technology. Becquerel's experiment was done by illuminating two electrodes with different types of light. The electrodes were coated by light sensitive materials, AgCl or AgBr, and carried out in a black box surrounded by an acid solution. The electricity increased when the light intensity increased.

1873 – The photo conductivity of an element, selenium, was discovered by Willoughby Smith, who was an English electrical engineer.

1876 – Selenium produces electrical current when it is exposed to sun light. William Grylls Adams and Richard Evans Day proved that it is possible to convert solar energy into electricity directly, without any moving parts or heat. The solar cell was very inefficient, and it couldn't be used to run any electrical equipment.

1883 – A description of the first solar cells made from selenium wafer was made by Charles Fritts.

1894 – Charles Fritts constructed what was probably the first true solar cell. He coated a semiconductor material (selenium) with an extremely thin layer of gold. The efficiency was only about 1%, so it couldn't be used as energy supply, but were later used as light sensors.

1904 – A German physicist, Wilhelm Ludwig Franz Hallwachs, discovered that a combination of copper and cuprous oxide was photosensitive.

1905 – Albert Einstein published his paper about the photoelectric effect. There he claimed that light consists of "packets" or quanta of energy, which we now call photons. This energy varies only with its frequency (electromagnetic waves, or the "color of the light"). This theory was very simple, but revolutionary, and it explained very well the absorption of the photons regarding to the frequency of the light.

1914 – Goldman and Brodsky noted that it existed a barrier layer in photovoltaic devices.

1916 – Robert Andrews Millikan provided experimental proof of the photoelectric effect. He was an American experimental physicist who later won the Nobel Prize for his work on the photoelectric effect and for his measurement of the charge of the electron.

1918 – Jan Czochralski, a Polish chemist, developed a way to grow single-crystal silicon. This increased the efficiency of the silicon-based cells considerably.

1923 – Albert Einstein received the Nobel Prize for his theories explaining the photoelectric effect, which he published 18 years earlier.

1930s – Walter Schottky, Neville Mott and some others developed a theory of metal-semiconductor barrier layers.

1932 – Audobert and Stora discover the photovoltaic effect in cadmium sulfide (CdS).

1950s – Bell Labs produce solar cells for space activities.

1951 – A grown p-n junction enabled the production of a single-crystal cell of germanium.

1953 – Dr. Dan Trivich of Wayne State University makes the first theoretical calculations of the efficiencies of various materials of different band-gap widths based on the spectrum of the sun

1954 – Three researchers,Gerald Pearson, Daryl Chapin and Calvin Fuller, at Bell Laboratories discovered a silicon solar cell, which was the first material to directly convert enough sunlight into electricity to run electrical devices. The efficiency of the silicon solar cell, which Bell Labs produced, were 4%, which later increased to 11%. The cells were made by hand and cost $1000 per watt.

1954 – A cadmium sulphide p-n junction was produced with an efficiency of 6%

1958 – Hoffman Electronics achieved 9% efficient PV cells.

1958 – The first PV-powered satellite, Vanguard I, was launched. The solar panel had an area of 100cm² and delivered an effect of approximately 0.1W. The satellite power system operated for 8 years, and is the world's oldest satellite still in orbit (2007).

1958 – Ted Mandelkorn of U.S. Signal Corps Laboratories fabricates n-on-p (negative layer on positive layer) silicon photovoltaic cells,

1959 – Hoffman Electronics achieved 10% efficient commercially available PV cells and demonstrated the use of a grid contact to significantly reduce series resistance.

1959 – Explorer-6 was launched with a PV array of 9600 cells, each only 1 cm x 2 cm.

1960 – Hoffman Electronics achieved 14% efficient PV cells.

1962 – The Telstar communications satellite, launched by Bell Labs, is initial powered(14W) by solar cells.

1963 – A Japanese electronic manufacturer, Sharp Corporation, produces a viable photovoltaic module of silicon solar cells.

1970 – First highly effective GaAsheterostructure solar cells are created by ZhoresAlferov (a Russian physicist) and his team in the USSR.

1972 – The Institute of Energy Conversion is established at the University of Delaware to perform research and development on thin-film photovoltaic and solar thermal systems, becoming the world's first laboratory dedicated to photovoltaic research and development.

1976 – David Carlson and Christopher Wronski of RCA Laboratories produced the first amorphous silicon photovoltaic cells, which could be less expensive to manufacture than crystalline silicon devices. The efficiency was of 1.1%.

1980 – At the University of Delaware, the first thin-film solar cell exceeds 10% efficiency. It's made of copper sulfide (Cu_2S) and cadmium sulfide(CdS).

1981 – Paul MacCready builds the first solar-powered aircraft, the Solar Challenger, and flies it from France to England across the English Channel. The aircraft had over 16,000 solar cells mounted on its wings, which produced a power of 3kW.

1982 – Hans Tholstrup, an Australian, drives the first solar-powered car, the Quiet Achiever, 4,000km between Sydney and Perth in 20 days. That was 10 days faster than the first gasoline-powered car to do so. The maximum speed was 72 km/h, and the average speed was 24 km/h.

1984 – The IEEE Morris N. Liebmann Memorial Award was presented to Drs. David E. Carlson and Christopher R. Wronski at the 17th Photovoltaic Specialists Conference, "for crucial contributions to the use of amorphous silicon in low-cost, high-performance photovoltaic solar cells."

1985 – The University of South Wales breaks the 20% efficiency barrier for silicon solar cells under one sun conditions.

1989 – Reflective solar concentrators are first used with solar cells.

1991 – Efficient Photo electrochemical cells (PEC) are developed. Each cell consists of a semiconducting photo anode and a metal cathode immersed in an electrolyte. The Dye-sensitized solar cell (DSC), also called Grätzel cells, is invented. It was a new class of low-class DSC.

1992 – University of South Florida develops a 15.9% efficient thin-film photovoltaic cell made of cadmium telluride, breaking the 15% barrier for the first time for this technology.

1994 – The National Renewable Energy Laboratory develops a solar cell, made from gallium indium phosphide and gallium arsenide that becomes the first one to exceed 30% conversion efficiency.

1996 – Renewable Energy Corporation (REC), a Norwegian solar energy company established.

1996 – EPFL, the Swiss Federal Institute of Technology in Lausanne, achieves 11% efficiency with the DSCs.

1999 – Spectrolab, Inc. and the National Renewable Energy Laboratory develops a photovoltaic solar cell that converts 32.3 percent of the sunlight that hits it into electricity. The high conversion efficiency was achieved by combining three layers of photovoltaic materials into a single solar cell. The cell performed most efficiently when it received sunlight concentrated to 50 times normal. To use such cells in practical applications, the cell is mounted in a device that uses lenses or mirrors to concentrate sunlight onto the cell. Such "concentrator" systems are mounted on tracking systems that keep them pointed toward the sun.

1999 – The National Renewable Energy Laboratory achieves a new efficiency record for thin-film photovoltaic solar cells. The new measurement is of 18.8 percent efficiency.

2000 – Two new thin-film solar modules, developed by BP Solarex, break previous performance records. The company's 0.5-square-meter module achieves 10.8 % conversion efficiency—the highest in the world for thin-film modules of its kind. And its 0.9-square-meter module achieved 10.6% conversion efficiency and a power output of 91.5 watts — the highest power output for any thin-film module in the world.

2001 – TerraSun LLC developed a method of using holographic films to concentrate sunlight onto a solar cell.

2007 – The University of Delaware achieves a 42.8% efficiency solar cell technology.

1.1.2 Types of Solar Cells

Silicon-based solar cells

P-n junction is the simplest device [2] to create current in a particular direction upon illumination and is the key part of many optoelectronic devices. p-type or n-type silicon can be obtained through a doping process with different dopants, boron or phosphorous .The solar cells based on single-crystal silicon have been characterized by high efficiency levels (up to 25% in laboratory and 15% in industry).

Group III-V Technologies

Photovoltaic technologies based on group III and V elements in the periodic table show very high efficiencies under either normal or concentrated sunlight. Although expensive, their cost can be compensated for by using concentrators, which increase the energy conversion efficiency under higher illumination [3]. Concentrators focus light from a large area to a small area, thereby increasing illumination to many times the terrestrial sunlight. The most important solar cells in this category are gallium arsenide (GaAs) and indium phosphide (InP).

Dye-sensitized

Dye-sensitized solar cells [4-7], DSSCs or dye cells, arethe most promising alternative to conventional solar cellsconceived in recent years. They also function by a muchdifferent mechanism than conventional solar cells, a mechanismthat emphasizes interfacial processes rather than thebulk processes that mostly control silicon p–n junctionsand other conventional cells. Conventional photovoltaic(PV) cells are minority carrier devices with planar inter-faces/junctions in which both electrons and holes coexistin the same chemical phase: their efficiency is thereforedetermined by the ability of photogenerated minority carriers(say, electrons in a p-type material) to escape from thatside of the device before recombining with the majoritycarriers [8].

Cadmium Telluride (CdTe) solar cell

As a polycrystalline semiconductor compound made of cadmium and tellurium, CdTe has [9] a high light absorptivity level; only about a micrometer thick can absorb 90% of the solar spectrum. Another advantage is that it is relatively easy and cheap to manufacture by processes such as high-rate evaporation, spraying or screen printing. The conversion efficiency for a CdTe commercial module is about 7%, similar to that of a-Si. The instability of cell and module performance is one of the major drawbacks of using CdTe for PV cells. Another disadvantage is that cadmium is a toxic substance. Although very little cadmium is used in CdTe modules, extra precautions have to be taken in manufacturing process.

Organic solar cells

Organic (polymer-based) solar cells are flexible and their production costs are only about a third of the price of silicon cell. They are disposable and can be designed on a molecular level. Current research is focusing on the improvement in efficiency and development of high quality protective coatings to minimize the environment effects.

Thin Film Materials

In a thin-film PV cell [9], a thin semiconductor layer of PV materials is deposited on low-costsupporting layer such as glass, metal or plastic foil. Since thin-film materials have higherlight absorptivity than crystalline materials, the deposited layer of PV materials is extremelythin, from a few micrometers to even less than a micrometer (a single amorphous cell can be as thin as 0.3 micrometers). Thinner layers of material yield significant cost saving.Also, the deposition techniques in which PV materials are sprayed directly onto glass or metal substrate are cheaper. So the manufacturing process is faster, using up less energyand mass production is made easier than the ingot-growth approach of crystalline silicon.However, thin film PV cells suffer from poor cell conversion efficiency due to non-singlecrystalstructure, requiring larger array areas and increasing area-related costs such asmountings. Constituting about 4% of total PV module shipments of US4, the PV industry sees great potentials of thin-film technology to achieve low-cost PV electricity.

Polycrystalline silicon

Consisting of small grains of single-crystal silicon, polycrystalline PV cells [9]are lessenergy efficient than single-crystalline silicon PV cells. The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power output of the cell. The energy conversion efficiency for a commercial module made ofpolycrystalline silicon ranges between 10 to 14%. A common approach to produce polycrystalline silicon PV cells is to slice thinwafers from blocks of cast polycrystalline silicon. Another more advancedapproach is the "ribbon growth" method in which silicon is grown directly as thinribbons or sheets with the approach thickness for making PV cells. Since nosawing is needed, the manufacturing cost is lower. The most commerciallydeveloped ribbon growth approach is EFG (edge-defined film-fed growth).

1.1.3 Why Solar Energy is One of the Key Solutions to World Energy Demand

The sun is the most plentiful energy source for the earth. All wind, fossil fuel, hydro and biomass energy have their origins in sunlight. Solar energy falls on the surface of the earth at a rate of 120 petawatts, (1 petawatt = 10^{15} watt).This means all the solar energy received from the sun in one days can satisfied the whole world's demand for more than 20 years.

We are able to calculate the potential for each renewable energy source based on today's technology [11]. (Figure 1) Future advances in technology will lead to higher potential for each energy source. However, the worldwide demand for energy is expected to keep increasing at 5 percent each year[10] .Solar energy is the only choice that can satisfy such a huge and steadily increasing demand
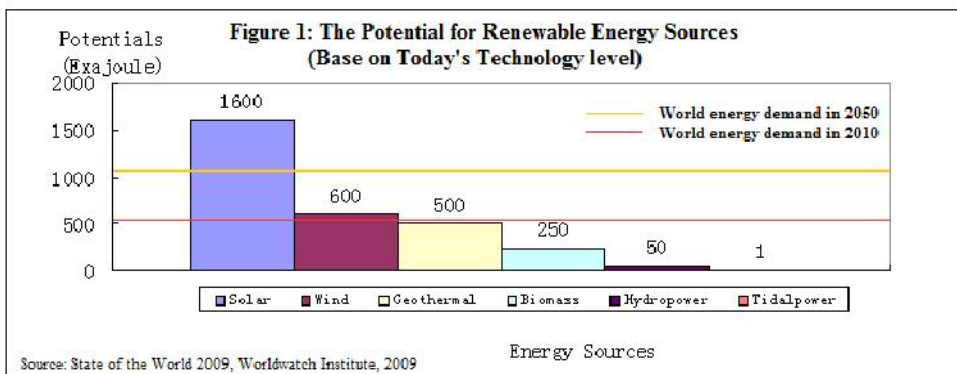

Fig 1(a): The Potential for Renewable Energy Source

There are several applications for solar energy, for instance: electricity generation, photochemical, solar propulsion, solar desalination, and room temperate control. The collection of solar energy and its transfer to electricity energy will have wide application and deep impact on our society, so it has attracted the attention of the researchers.

Figure 2: Word Energy Demand and Forecast
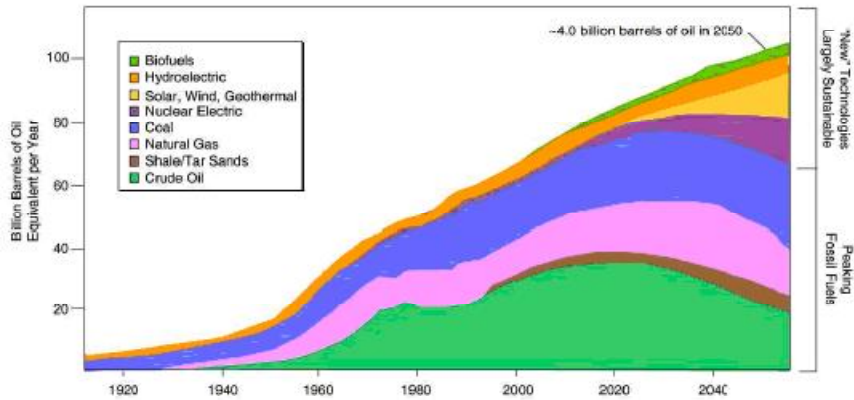
Sources: Lynn Orr, *Changing the World's Energy Systems*, Stanford University Global Climate & Energy Project (after John Edwards, American Association of Petroleum Geologists); SRI Consulting.

Fig 1(b): Future demand with present perspective

According to 2010 Energy Balance for World Report provided by International Energy Agency (IEA), about 30 percent of the total energy produced is consumed by electricity generation sectors with an efficiency rate of 42.6 percent.

Electricity is high grade energy. This means it can be easily transferred into other forms like mechanical energy or heat. If we are able to generate economic and plentiful electricity energy, together with the easy transportation electricity energy transmission, the electric power will increase it shares in demand sectors dramatically.

1.1.4 Environmental Aspects

Solar energy is clean and renewable. It doesn't emit carbon dioxide during operation. The major material of photovoltaic panel which is the most commonly used today is silicon. Silicon is abundant and environmentally safe. However, the application of solar energy technologies can be dangerous under several conditions. Multi-junction photovoltic cells (III–V), which can achieve relatively higher energy converting efficiency than commonly used silicon cells, are

usually made with poisonous materials like gallium arsenide (GaAs) or cadmium telluride (CdTe), can cause harm to the environment if leaked.

If these drawbacks are avoided, we are able to conclude that solar energy is clean and safe.

1.1.5 Advantage and Drawback of Different Solar Technology

There are several kinds of solar techniques that are currently available. However, each of them is based on quite different concepts and science and each has its unique advantages. For some Technology discussed below:

- **Solar thermoelectricity**

Advantages
- A simple system that can be deployed on roof tops.

- Able to work in harsh environments.

- Quiet in operation.

- Capable of virtually endless shelf life.

- The thermoelectric part has simple structure without any moving parts.

- Extremely reliable.

- Driven by low grade heat energy.

Drawbacks

- The efficiency of the thermoelectric materials is still very low, the recently achieved figure of merit is only 1.3~2.0.

- Like most of the other solar technologies with concentration requirements, this system is unable to collect diffuse irradiation and must rely on direct radiation only.

- In order to have sufficient output, high temperatures are needed to make it work efficiently (~200o C based on Carnot or thermal efficiency), which lead to higher concentration ratio of the collector (10~100 suns) and more precise tracking systems. Higher concentration collector will increase capital cost and maintenance cost.

- Thermoelectric material like Bismuth telluride is toxic and expensive.

- ☐ Cooling systems are required to decrease the temperature of the cold side in order to increase to total efficiency.

- **Dye Sensitized Solar Cell (DSSC)**

Advantages

➢ DSSCs use low-cost materials; are simple to manufacture, and are technically attractive.

➢ DSSCs can be replacements for existing technologies in "low density" applications like rooftop solar collectors, where mechanical reliability and light weight of the glass-less collector are important factors.

➢ The process of injecting an electron directly into the TiO_2 is qualitatively different to that occurring in a traditional cell, where the electron is "promoted" within the original crystal.

➢ As a result of these favorable "differential kinetics" (the reaction rate), DSSCs work even in low-light conditions, allowing them to work under cloudy skies and non-direct sunlight when traditional designs would suffer a "cutout" at some lower limit of illumination, when charge carrier mobility is low and recombination becomes a major issue. The cutoff is so low that this technology is being considered for indoor use, collecting energy for small devices from the lights in the house.

➢ DSSCs are normally built with only a thin layer of conductive plastic on the front layer, allowing them to radiate away heat much easier, and therefore operate at lower internal temperatures.

Drawbacks

➤ Current efficiency is still relatively low compare with traditional semiconductor solar cells.

➤ Dyes will degrade when exposed to ultraviolet radiation that limits the lifetime and stability of the cells adding a barrier layer will increase the cost and may lower the efficiency.

➤ Generally, DSSC technology uses liquid electrolyte that has temperature stability problems. At low temperatures, the electrolyte can freeze, stopping power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem.

➤ The electrolyte solution contains volatile organic solvents and must be carefully sealed. This, along with the fact that the solvents permeate plastics, precludes large-scale outdoor application and integration into flexible structures.

- **Concentrated Photovoltaic (CPV)**

Advantages

➤ Despite the energy lost during the concentrating process, CPV can achieve the highest efficiency among all kinds of solar technologies.

➤ Unlike traditional, more conventional flat panel systems, CPV systems are often much less expensive to produce, because of the reduced use of semi-conductor material compared with flat-plate silicon. This reduces risk for the investor and allows more rapid adjustment of plans based on changing markets.

Drawbacks

> Like most concentration systems, CPV is unable to collect diffuse irradiation... Some researchers suggest equipping the CPV unit with a tracking system. However CPV can collected more energy than non-concentrated PV techniques due to superior performance during morning and late afternoon time. Although the energy consumption by a tracking system is minimal, the moving parts of the tracking system make it less reliable and increases both manufacturing and maintenance costs.

> Even a small cloud may drop the production to zero. Unlike concentrated solar power, the storage system that can mitigate this problem above is expensive since it is much easier to store heat than electric energy. This kind of instability will not be preferable when connected to the grid.

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Chapter2

Review of Efficiency of Solar Cell

2.1 Introduction

Since January 1993, Progress in Photovoltaic has published six monthly listings of the highest confirmed efficiencies for a range of photovoltaic cell and module technologies [1–3]. By providing guidelines for inclusion of results into our given tables, this not only provides an authoritative summary of the current state-of-the-art but also encourages researchers to seek independent confirmation of results and to report results on a standardized basis. In Version 33 of module Tables-1 [2], results were updated to the new internationally accepted reference spectrum where this was possible.

The most important criterion for inclusion of results into the Tables is that they must have been independently measured by a recognized test centre listed elsewhere [1]. A distinction is made between three different eligible Definitions of cell area: total area, aperture area and designated illumination area, as also defined elsewhere [1]. 'Active area' efficiencies are not included. There are also certain minimum values of the area sought for the different device types (above 0.05 cm2 for a concentrator cell, 1 cm^2 for a one-sun cell and 800 cm^2 for a module). Results are reported for cells and modules made from different semiconductors and for sub-categories within each semiconductor grouping (e.g. crystalline, polycrystalline and thin film). From Version 36 onwards, spectral response information is included when available in the form of a plot of the external quantum efficiency (EQE) versus wavelength, either as absolute values or normalized to the peak measured value.

2.1.1 Review of Efficiency

Here we show Table ,Graph for Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global) with different materials.We shall also showconfirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).For modulewhich based on different kind of materials with help of different version. From the analysis of literature (Table & Graph from 2001 to 2014), it is found that the efficiency has been increasing or saturating.

Table 1(a): Confirmed terrestrial cell and sub module efficiencies (for silicon) measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
Si (crystalline)	**25.6±0.5**	**143.7(da)**	**0.740**	**41.8**	**82.7**	**AIST(2/14)**
Si (Multi-crystalline)	**20.4±0.5**	**1.002(ap)**	**0.664**	**38.0**	**80.9**	**NREL(5/04)**
Si (Thin film transfer)	**20.1±0.4**	**242.6(ap)**	**0.682**	**38.1**	**77.4**	**NREL(10/12)**
Si (Thin film mini module)	**10.5±0.3**	**94(ap)**	**0.492**	**29.7**	**72.1**	**FHG-ISE(8/07)**

For Silicon, from the latest version we get different efficiency for different material. Silicon Crystalline's efficiency is highest than others. From ref.[4], we saw thatAIST (2/14) testcentre get highest efficiency of 25.6% with Fill Factor of 82.7% for crystalline silicon. Designated illumination area is 143.7 cm^2.Thin film minimodule's efficiency is lowest among them,which is 10.5% with fill factor of 72.1%. Aperture area is 94.0 cm^2.Here we show all information from latest efficiency [4] which was published in April, 2014.
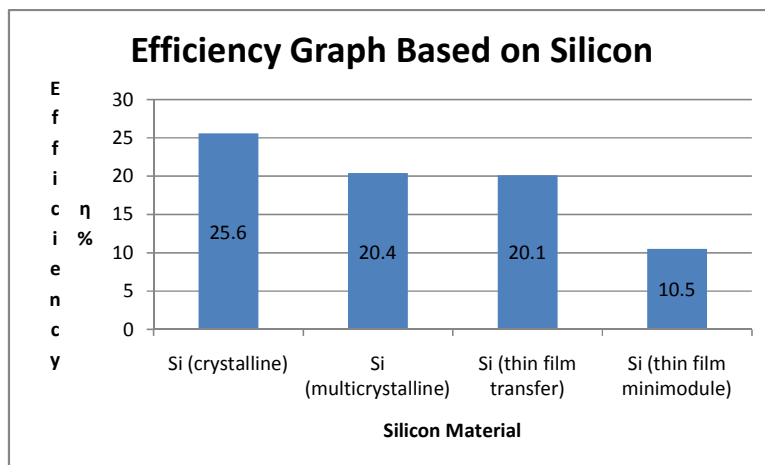

Fig 1 (a): Efficiency graph

Table 1(b): Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global). For III-V cells:

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
GaAs(Thin film)	28.8±0.9	0.9927(ap)	1.122	29.86	86.5	**NREL(5/12)**
GaAs(Multicrystalline)	18.4±0.5	4.011(t)	0.994	23.2	79.7	**NREL(11/95)**
InP(Crystalline)	22.1±0.7	4.02(t)	0.878	29.5	85.4	**NREL(4/90)**

Under III–V Cells Sub materials are **GaAs (thin** film) GaAs (multicrystalline) InP (crystalline) .Among all materials **GaAs** 's (thin film) efficiency is 28.8 ± 0.9 which is highest [5] and GaAs's (multicrystalline) lowest efficiency .GaAs (crystalline) is taken from version (27) [6] Measurement purpose here take aperture area for GaAs**(thin** film) , total area for both GaAs (multicrystalline) and InP (crystalline).All materials are tested in NREL test center .In table we mentioned all essential document for all material under III–V Cells .
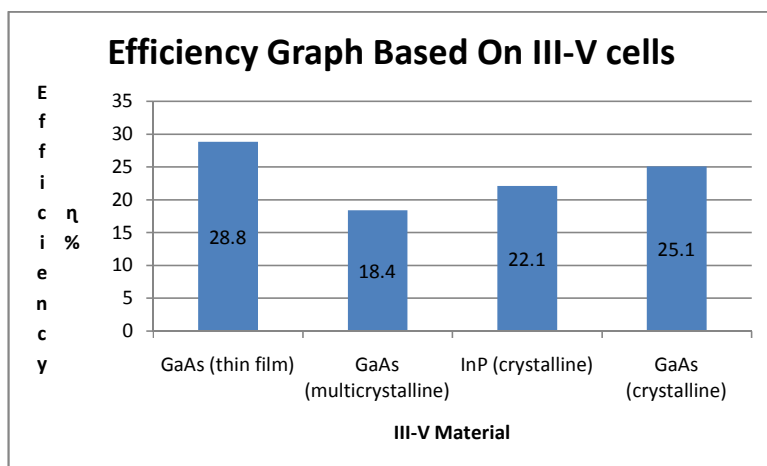

Fig 1(b): Efficiency graph of III-V cells

Table 1(c): Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).For amorphous/microcrystalline Si.

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
Si(amorphous)	10.1±0.3	1.036	0.866	16.75	67.8	NREL(7/09)
Si(micro-crystalline)	11.0±0.3	1.045	0.542	27.44	73.8	AIST(1/14)

Here they work with only two material   one is Si (amorphous) and another is   Si (microcrystalline) under Amorphous .Si (microcrystalline) have highest efficiency 11.0±0.3m [7] and Si (microcrystalline) have lowest efficiency 10.1 ± 0.3k [8].Si (microcrystalline) tested by AIST (1/14) and Si (amorphous) tested by NREL (7/09). Designated illumination area used for Si (microcrystalline) which is 1.045 ,with 73.8 fill factor. Aperture area is used for Si (amorphous) which is 1.036 with fill factor 67.8.
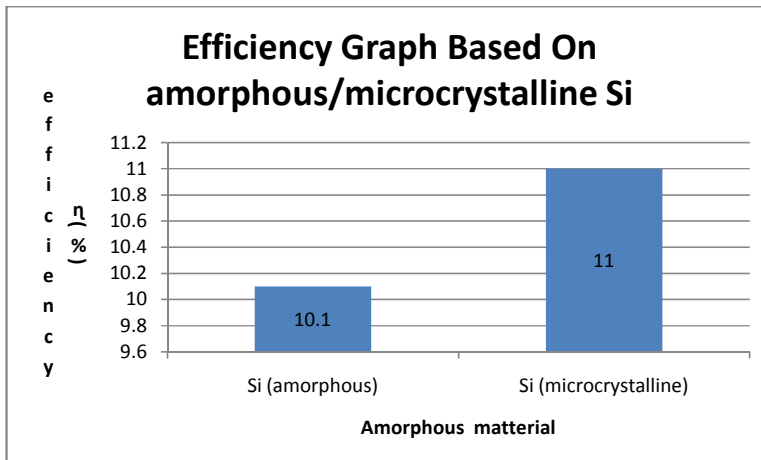

Fig 1(c): Efficiency graph of amorphous Si

Table 1(d): Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global). For thin film chalcoogenide

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
ClGs (cell)	20.5±0.6	0.9882(ap)	0.752	35.3	77.2	NREL(3/14)
ClGs (minimodule)	18.7±0.6	15.892(da)	0.701	35.29	75.6	FhG-ISE(9/13)
CdTe (cell)	19.9±0.4	1.0055(ap)	0.8573	28.59	80.0	New port(6/13)

In version (44) [9],[10],[11] they tested in their test Centre with three materials CIGS (cell) , CIGS (minimodule), CdTe (cell) under thin flimchalcogenide. Among those materials CIGS (cell) have highest efficiency 20.5±0.6 [9].For this material they used aperture area0.9882 (ap), Voc (V)0.752 and got fill factor 77.2. NRELtest it .CIGS (minimodule) have lowest efficiency 18.7 ± 0.6[10].Designated illumination area used for CIGS (minimodule which is 892 (da).FraunhoferInstitutfürSolareEnergiesysteme center worked with CIGS (minimodule) in (9/13).
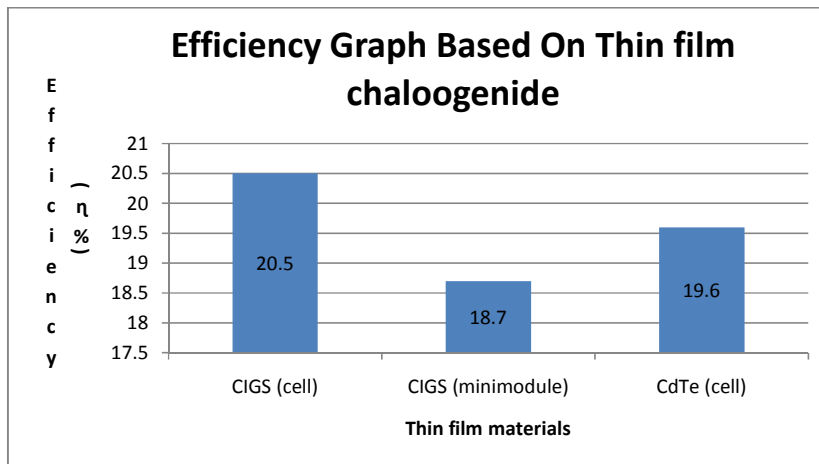

Fig 1(d): Efficiency graph of thin film chaloogenid

Table 1(e): Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).Table: Dye sensitized

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
Dye sensitized	11.9±0.4	1.005 (da)	0.744	22.47	71.2	AIST (9/12)
Dye sensitized (minimodule)	29.9±0.4	17.11(ap)	0.719	19.4	71.4	AIST ()8/10
Dye sensitized (submodule)	8.8±0.3	398.8 (da)	0.697	18.42	68.7	AIST (9/12)

Dye sensitised (minimodule) have high efficiency 29.9 ± 0.4n [12] and Lowest efficiency for Dye (submodule) is 8.8 ± 0.3n [13].Under **Dye sensitized all materials are tested by** AIST. For highest efficiency used aperture area and for rest two used Designated illumination area.
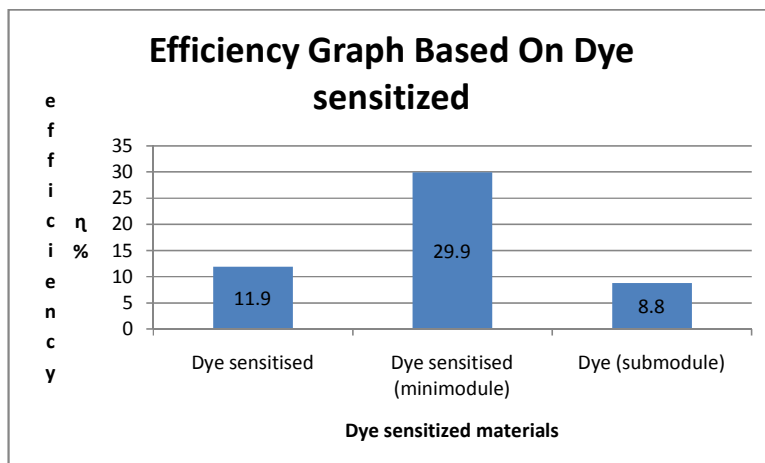

Fig 1(e): Efficiency graph of Dye-sensitized materials

Table 1(f): Confirmed terrestrial cell and sub module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global). Table: Multijunction device.

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
InGaP/GaAs/InGaAs	**37.9±1.2**	**1.047 (ap)**	**3.065**	**14.27**	**86.2**	**AIST (2/13)**
a-Si/nc-Si/nc-Si (thin film)	**13.4±0.4**	**1.006(ap)**	**1.963**	**9.52**	**71.9**	**AIST (7/12)**
a-Si/nc-Si (thin film cell)	**12.3±0.3**	**0.962(ap)**	**1.365**	**12.93**	**69.4**	**AIST (7/11)**
a-Si/nc-Si	**11.8±0.6**	**40.26(ap)**	**1.428**	**12.27**	**67.5**	**AIST (4/14)**

Four material are exist here, Among them InGaP/GaAs/InGaAs have highest efficiency 37.9±1.2 [14] and lowest efficiency 11.8±0.6s [15] for a-Si/nc-Si (thin film minimodule). InGaP/GaAs/InGaAs used aperture area 1.047, with fill factor 86.7. AIST test centre got highest efficiency for InGaP/GaAs/InGaAs. a-Si/nc-Si (thin film minimodule) used aperture area which is 40.26 with fill factor 67.5. FraunhoferInstitutfür Solar Energiesysteme center worked with a-Si/nc-Si (thin film minimodule) in (4/14).
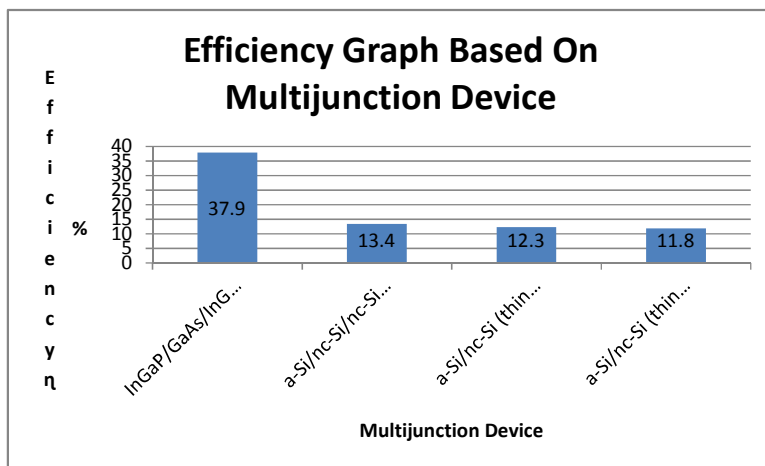

Fig 1(f): Efficiency graph of multijunction device

Table 1(g): Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000W/m^2) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).**For module:**

Classification	Effi(%)	Area(cm^2)	V_{oc}(v)	J_{sc}(mA/cm^2)	F.F(%)	Test centre(data)
Si(crystalline)	22.9±0.6	778(da)	5.60	3.97	80.3	Sandia(9/96)
Si(Multi-crystalline)	18.5±0.4	14661(ap)	38.97	9.149[g]	76.2	FhG-ISE (1/12)
Si (large crystalline)	22.4±0.6	15775(ap)	69.57	6.341[f]	80.1	NREL (8/12)
Si (thin film polycrystalline)	8.2±0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)e
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255h	84.2	NREL (11/12)
CdTe (thin film)	17.5±0.7	7021(ap)	103.1	1.553i	76.6	NREL (2/14)
CIGS (thin film)	15.7 ± 0.5	9703 (ap)	28.24	7.254j	72.5	NREL (11/10)
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)e
a-Si/nc-Si (tandem)	11.6±0.5k	14250 (t)	198.5	1.254i	66.2	ESTI (12/13)

For different material efficiencies are showed here. Sandia ,NREL ,FhG-ISE, ESTI test center tested those efficiency. Sandia test centre get highest efficiency 22.9 ± 0.6 [16] for Si (crystalline) .For module lowest efficiency is 8.2 ± 0.2 [17] using Si (thin film polycrystalline).
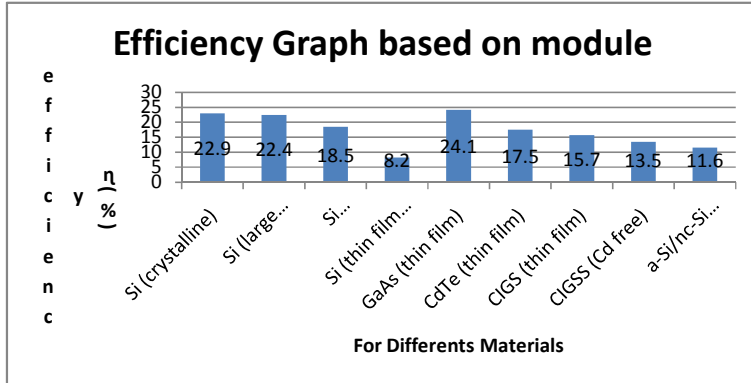
Fig 1(g): Efficiency graph of different materials for module

Table 1(h): Confirmed terrestrial cell and sub module efficiencies table of si(crystalline) for different years:

MATERIALS	YEAR	EFFICIENCY
Si(crystalline)	2001	24.7±0.5
Si(crystalline)	2002	24.7±0.5
Si(crystalline)	2003	24.7±0.5
Si(crystalline)	2004	24.7±0.5
Si(crystalline)	2005	24.7±0.5
Si(crystalline)	2006	24.7±0.5
Si(crystalline)	2010	25.0±0.5
Si(crystalline)	2011	25.0±0.5

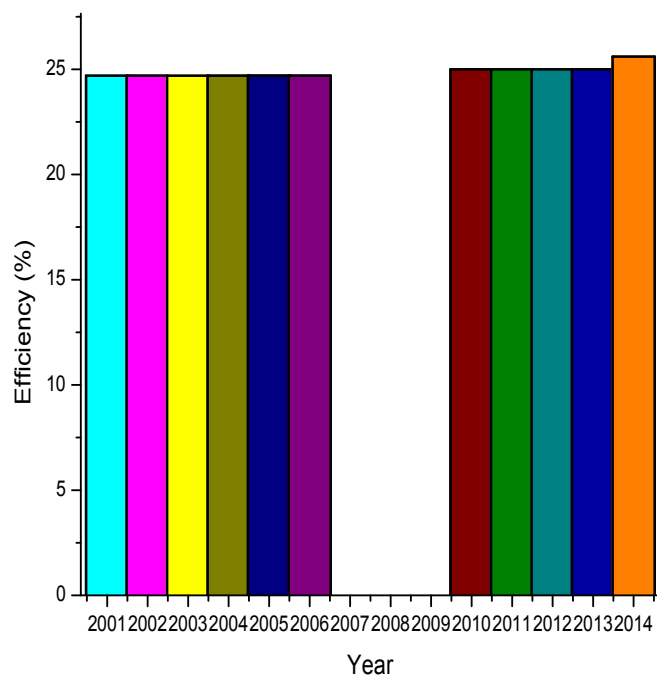| Si(crystalline)	2012	25.0±0.5
Si(crystalline)	2013	25.0±0.5
Si(crystalline)	2014	25.6±0.5

Fig 1(h): Efficiency graph for different year based on Si (crystalline)

Table 1(i): Confirmed terrestrial cell and sub module efficiencies table of III-V cells for different years:

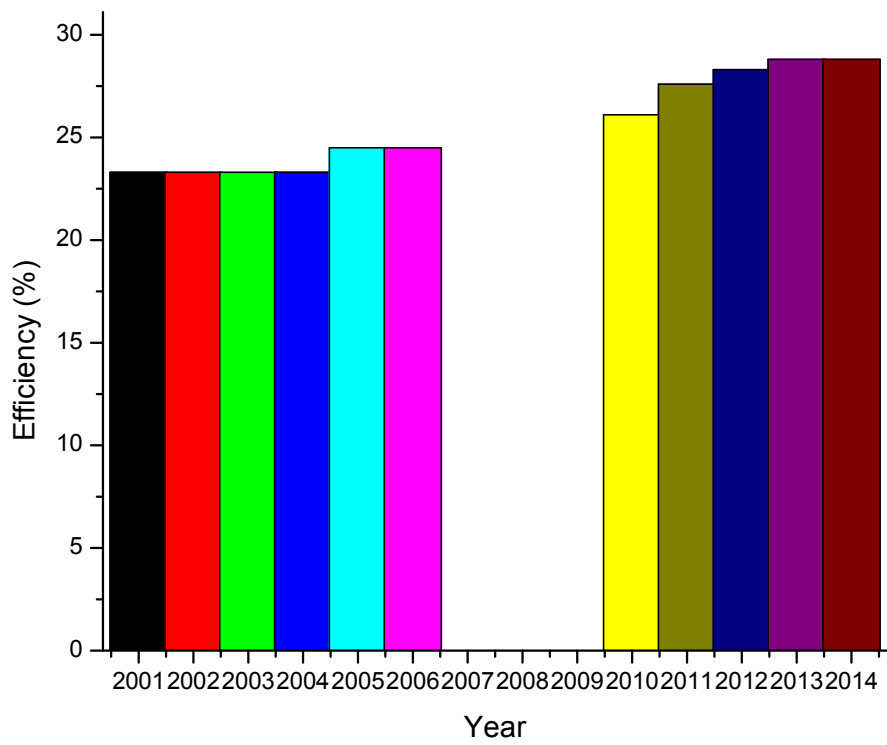| MATERIALS	YEAR	EFFICIENCY
GaAs (thinfilm)	2001	23.3±0.7
GaAs (thinfilm)	2002	23.3±0.7
GaAs (thinfilm)	2003	23.3±0.7
GaAs (thinfilm)	2004	23.3±0.7
GaAs (thinfilm)	2005	24.5±0.5
GaAs (thinfilm)	2006	24.5±0.5
GaAs (thinfilm)	2010	26.1±0.8
GaAs (thinfilm)	2011	27.6±0.8
GaAs (thinfilm)	2012	28.3±0.9
GaAs (thinfilm)	2013	28.8±0.9
GaAs (thinfilm)	2014	28.8±0.9

Fig 1(i): Efficiency graph for different year based on III-V cells

Table 1(j): Confirmed terrestrial cell and sub module efficiencies table of Thin film (chalcologenid) cdTe cells for different years:

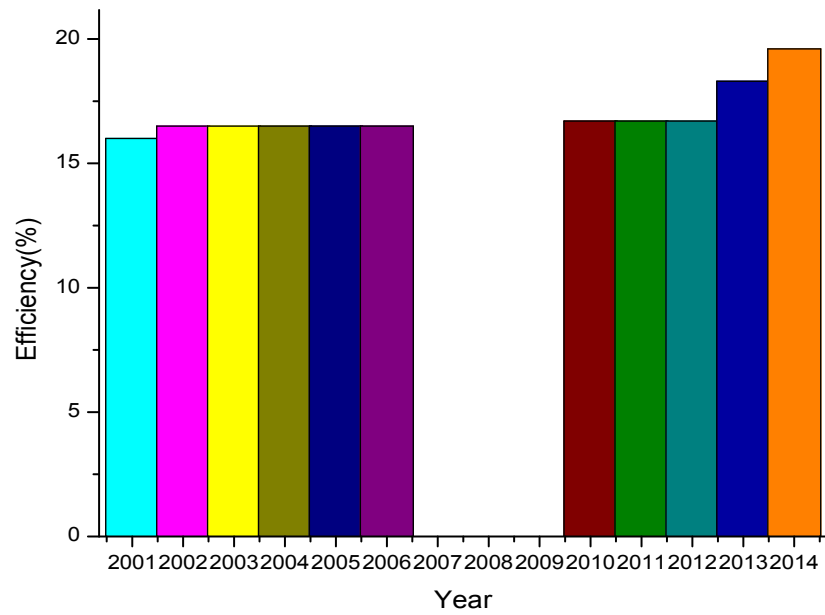| MATERIALS	YEAR	EFFICIENCY
CdTe (cell)	2001	16.0±0.2
CdTe (cell)	2002	16.0±0.2
CdTe (cell)	2003	16.0±0.2
CdTe (cell)	2004	16.0±0.2
CdTe (cell)	2005	16.0±0.2
CdTe (cell)	2006	16.0±0.2
CdTe (cell)	2010	16.7±0.5
CdTe (cell)	2011	16.7±0.5
CdTe (cell)	2012	16.7±0.5
CdTe (cell)	2013	18.3±0.5
CdTe (cell)	2014	19.6±0.4

Fig 1(j): Efficiency graph for different year based on III-V cells

Table 1(k): Confirmed terrestrial module efficiencies table of Si (crystalline) cells for different years:

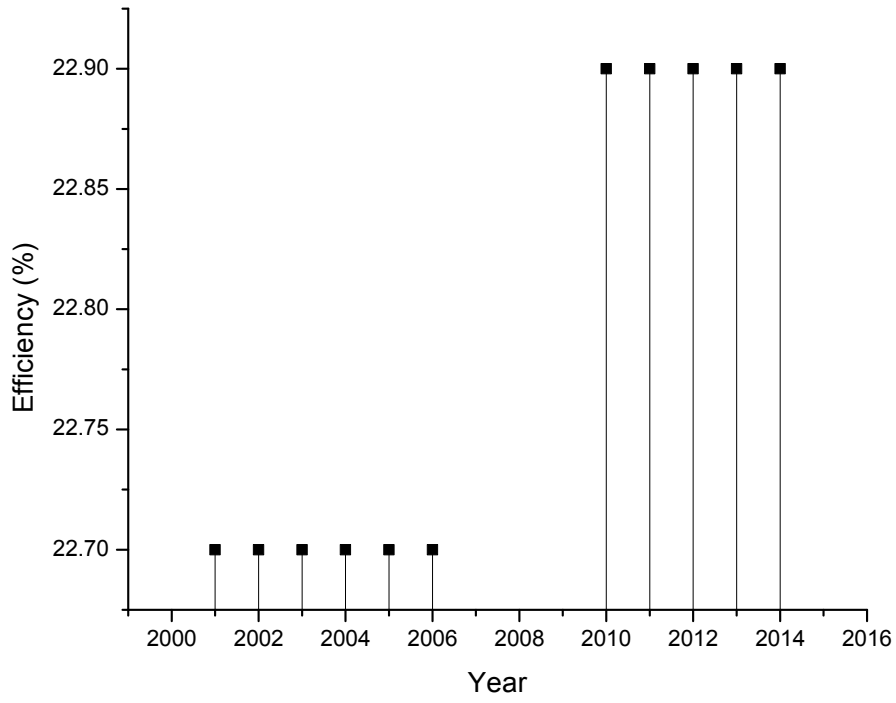| MATERIALS	YEAR	EFFICIENCY
Si(crystalline)	2001	22.7±0.6
Si(crystalline)	2002	22.7±0.6
Si(crystalline)	2003	22.7±0.6
Si(crystalline)	2004	22.7±0.6
Si(crystalline)	2005	22.7±0.6
Si(crystalline)	2006	22.7±0.6
Si(crystalline)	2010	22.9±0.6
Si(crystalline)	2011	22.9±0.6
Si(crystalline)	2012	22.9±0.6
Si(crystalline)	2013	22.9±0.6
Si(crystalline)	2014	22.9±0.6

Fig 1(k): Efficiency graph for different year based on Si (crystalline)

Table 1(l): Confirmed terrestrial module efficiencies table of Thin film (chalcogenide) CdTe cells for different years:

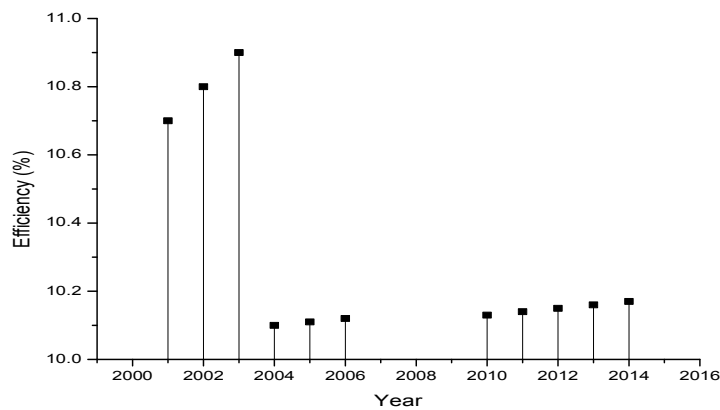| MATERIALS	YEAR	EFFICIENCY
CdTe (cell)	2001	10.7±0.5
CdTe (cell)	2002	10.7±0.5
CdTe (cell)	2003	10.7±0.5
CdTe (cell)	2004	10.7±0.5
CdTe (cell)	2005	10.7±0.5
CdTe (cell)	2006	10.7±0.5
CdTe (cell)	2010	10.9±0.5
CdTe (cell)	2011	10.9±0.5
CdTe (cell)	2012	12.8±0.4
CdTe (cell)	2013	15.3±0.5
CdTe (cell)	2014	17.5±0.7

Fig 1(l): Efficiency graph for different year based on Thin film (chalcogenide) CdTe cells.

Table 1(m): Confirmed terrestrial module efficiencies table of Thin film (chalcogenide) CdTe cells for different years:

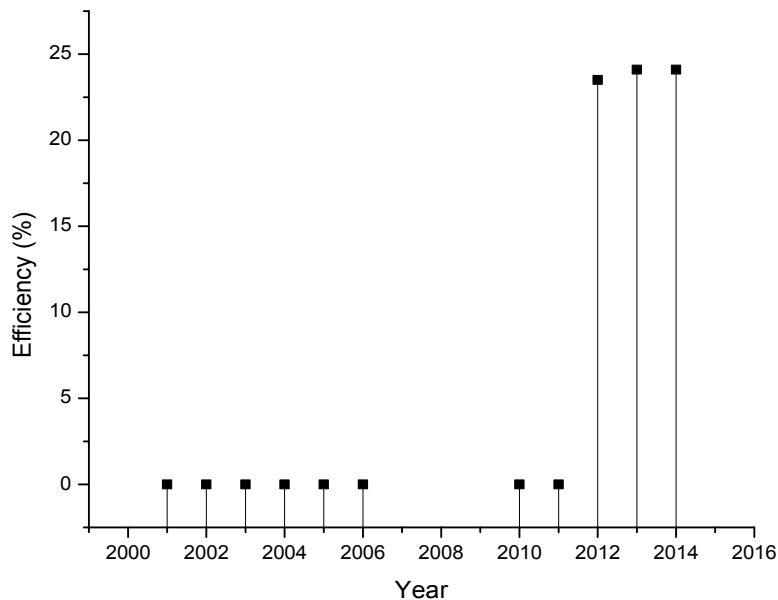| MATERIALS	YEAR	Efficiency
GaAs (thinfilm)	2001	0
GaAs (thinfilm)	2002	0
GaAs (thinfilm)	2003	0
GaAs (thinfilm)	2004	0
GaAs (thinfilm)	2005	0
GaAs (thinfilm)	2006	0
GaAs (thinfilm)	2010	0
GaAs (thinfilm)	2011	0
GaAs (thinfilm)	2012	23.5±0.7
GaAs (thinfilm)	2013	24.1±1.0
GaAs (thinfilm)	2014	24.1±1.0

Fig 1(n): Efficiency graph for different year based on III-V cells GaAs(thin film)

Reference:

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Chapter 3

Heterojunction with Intrinsic Thin Film Solar Cell

3.1 Introduction

Nowadays, photovoltaic power appears to be one of the major technologies for tackling our global environmental concerns. The world production volume of solar cell modules reached a level of more than 2500MW per year in 2006. To fulfill these needs, Sanyo has decided to increase the production capacity of heterojunction with intrinsic thin layer (HIT) solar cells [1] annually from 165MW in 2006 to 600MW in 2010. Our R&D policy for HIT solar cells is chiefly aimed at improving cost-performance. Specifically, the following four points are being focused upon:

 a) Improve conversion efficiency;

 b) Effectively use thinner substrates;

 c) Improve the temperature coefficient of efficiency;

d) Develop a bifacial module

Some of the above points are related to special features of the HIT solar cell, such as its ability to use thinner substrates and its symmetrical device structure. We have recently succeeded in raising the maximum conversion efficiency for a practical sized standard HIT solar cell to 23.0%, measured at National Institute of Advanced Industrial Science and Technology (AIST) Japan[2], which was achieved by optimizing a variety of processes at AIST laboratory[2]. Now, we have set our new target for conversion efficiency to 25.0%. In order to further expand the use of solar modules, it is necessary to thoroughly reduce the power-generating cost. With this goal, technologies for higher conversion efficiency and a thinner c-Si wafer are both important.

3.1.1 HIT solar cell

HIT solar cell is a unique high- efficiency silicon solar cell with a symmetrical structure, which results from amorphous silicon (a-Si:H) and crystalline silicon (c-Si) solar cell technologies. HIT solar cell is based on Sanyo's technologies for forming high-quality a-Si:H films and a-Si:H solar cells with low- plasma and low-thermal-damage processes. The HIT solar cell also provides high performance.

In one side an intrinsic a-Si:H layer followed by a p-type a-Si:H layer is deposited on a randomly textured n-type CZ c-Si wafer to form a p/nheterojunction. On the other side of the c-Si, intrinsic and n-type a-Si:H layers are deposited to obtain a back surface field (BSF) structure.

On both sides of the doped a-Si:H layers, transparent conducting oxide (TCO) layers are formed and finally, metal grid electrodes are formed using a screen-printing method. By inserting the high-quality intrinsic a-Si:H layer, the defects on the c-Si surface can be effectively passivated, and a high V_{oc} can be obtained.

3.1.2 HIT solar cell structure

The structure of the HIT solar cell is shown in Fig.1 An intrinsic amorphous-Si layer, a doped amorphous-Si layer, and a TCO layer are deposited on both sides of a crystalline-Si substrate. Grid electrodes are also fabricated on both sides of the doped amorphous-Si layer. Therefore, the HIT solar cell has a symmetrical structure, and does not use high-hardness alloy metals as electrodes. As a result, it achieves a stress-free cell structure, which is well suited to thinner-substrate solar cells.
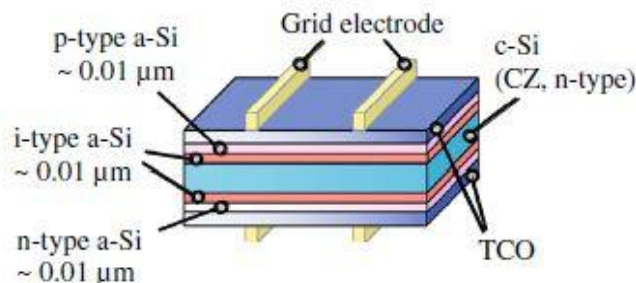

Fig.1: HIT solar cell structure

The HIT solar cell uses high-quality and very-thin amorphous silicon (a-Si) layers to form the Heterojunction. In addition, a high-quality intrinsic a-Si layer can effectively passivate the surface dangling bonds of the crystalline silicon substrate. As a result, this cell has achieved a high V_{oc} of more than 700 mV[3]. Further, all of the process temperatures for HIT solar cells are below 200 1C, which allows it to preserve the initial high-level quality of the crystalline silicon substrate. We have improved the a-Si/c-Si hetero-interface structure of the HIT solar cell through

further process optimization, to reach a V_{oc} of more than 720 mV[4]. The higher Voc offers not only a high conversion efficiency but also a better temperature coefficient, which is comparable to amorphous silicon solar cells Fig. 2. Of course, a better temperature coefficient of conversion efficiency improves the output power under high temperature operating conditions.
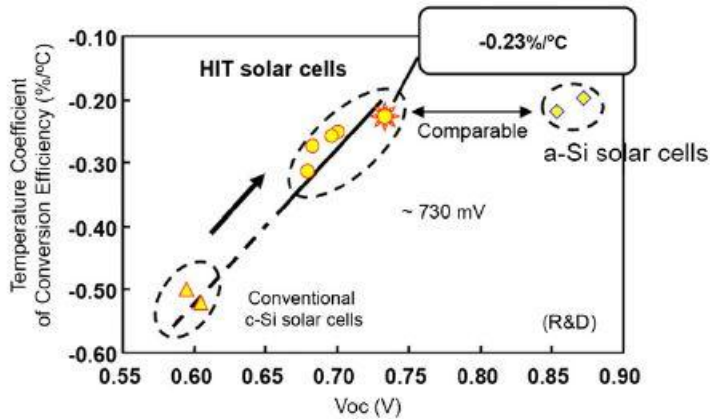

Fig.2: Temperature coefficient of the conversion efficiency of HIT solar cells

3.1.3 Approach for high-efficiency HIT

To obtain higher efficiency with the HIT structure, following three aspects are very important:

(i)   Improving the a-Si:H/c-Si heterojunction;
(ii)   Improving the grid electrode,
(iii)   Reducing absorption in the a-Si:H and TCO layers.

3.1.4 Improving the a-Si:H/c-Si heterojunction

The high V_{oc} of the HIT solar cell is achieved primarily by the effective passivation of defects on the c-Si surface with high- quality intrinsic a-Si:H. In the p-a-Si:H/n-c-Si heterojunction without intrinsic a-Si:H layers, tunneling is caused by the many localized states in the doped layer. As a result, a high V_{oc} cannot be achieved[5]. By inserting the high-quality intrinsic layer, tunneling can be suppressed and excellent interface properties can be obtained. Moreover, by inserting an intrinsic a-Si:H layer into the backside n+-a-Si:H/n-c-Si interface, the interface recombination velocity in the BSF structure can be decreased, allowing for a high $V_{oc.}$ Therefore, in order to attain a higher V_{oc}, it is very important to have high-quality intrinsic a-Si:H layers and excellent a-Si:H/c-Si interfaces. It is essential to develop a fabrication process with the following technologies:

(1) a clean c-Si surface before a-Si:H deposition;

(2) deposition of a high-quality intrinsic a-Si:H layer;

(3) lower plasma and/or thermal damage to the c-Si surface during a-Si:H, TCO, and conductive electrode fabrication.

3.1.5 Improving the grid electrode

For a higher I_{sc} and FF, the grid electrode requires lower resistance and finer lines for a larger aperture, simultaneously. Since the grid electrode of HIT solar cells is made of resin-bonded silver (Ag) paste, which has high resistivity in itself, the aspect ratio must be as high as possible. Fig 3(a) shows a conventional grid electrode fabricated by the screen-printing method. The conventional grid electrode has a spreading area that causes optical loss. In order to lower the optical loss and the resistance loss, it is necessary to eliminate this spreading area and improve the height, as shown in Fig. 3(b).
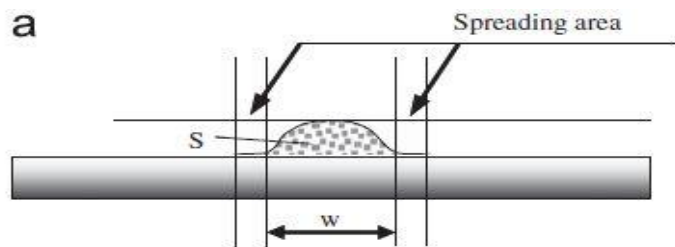

Fig.3 (a) Schematic diagrams of a conventional grid electrode with a larger spreading area.
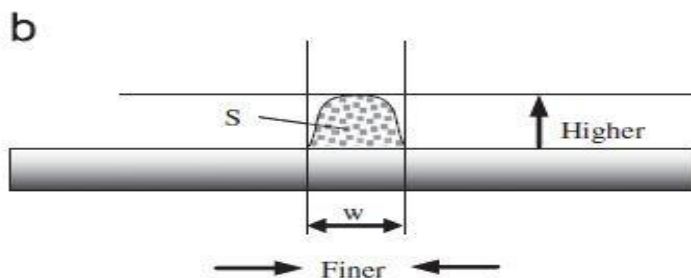

Fig.3 (b) Schematic diagrams of (b) an ideal grid electrode without a spreading area
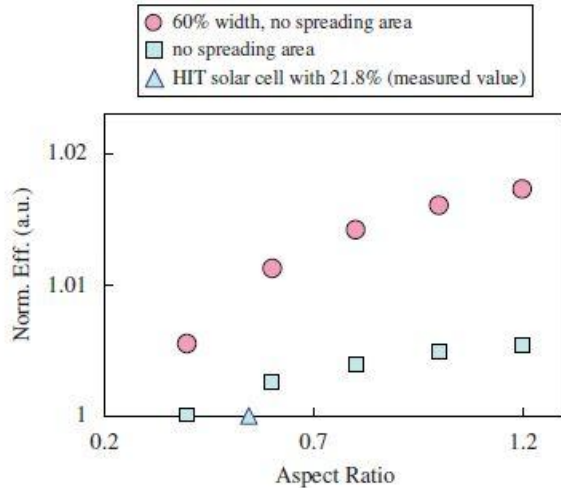
Fig.3 (c) Simulated relationship between grid electrode improvement and conversion efficiency relative to a 21.8% HIT solar cell

Fig. 3 (c) shows a simulated relationship between an improved aspect ratio for the grid electrode and the normalized conversion efficiency of HIT solar cells relative to a HIT solar cell with 21.8% efficiency. Considering the cross-sectional shape of the grid electrode, the aspect ratio was calculated using the following equation: $A = S/w^2$, where S and w denote the cross-section and the line's width excluding the spreading area, respectively, as shown in Fig.3 (a) and Fig.3.(b) In Fig.2, the triangle represents the HIT solar cell with 21.8% efficiency using a conventional grid electrode with spreading area. The squares represent HIT solar cells using a grid electrode without a spreading area. The circles show HIT solar cells using a finer (60% width) grid electrode without a spreading area. By improving the aspect ratio of the grid electrode to a level exceeding 1.0 with the finer grid electrode, we can enhance the efficiency by about 1.6% compared to that of the 21.8% HIT solar cell. To achieve this performance, we need to optimize the following factors:

(1) The viscosity and rheology of the silver paste;

 (2) The process parameters in the screen printing

3.1.6 Reducing absorption in the a-Si:H and TCO layers

For a higher I_{sc}, optical losses such as absorption in the a-Si:H and TCO layers must be reduced. These optical losses are mainly caused by the optical absorption of a-Si:H and the free carrier absorption of TCO. Therefore, to reduce the optical losses, we need to develop the following layers:

(1) high-quality wide-gap alloys such as a-SiC:H;

(2) high-quality TCO with high carrier mobility.

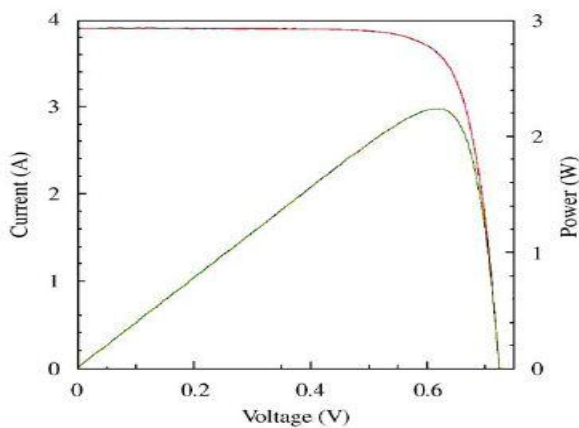### 3.1.7 Twenty-two percent efficiency HIT solar cell

Fig.4: Illuminated I–V characteristics of the HIT solar cell with the world's highest confirmed conversion efficiency of 22.3%.

As a result of our progressive studies, we have achieved a new record of 22.3% efficiency (Voc: 0.725V, Isc: 3.909A,FF:0.791 ,total area: 100.5cm2confirmed by AIST) as shown in Fig. 4 [2].The Voc, Isc, and FF have been simultaneously improved compared to a 21.8% HIT solar cell.

3.1.8. Characteristics of P/nheterojunction solar cells

P/n heterojunction solar cells incorporating amorphous silicon (a-Si) and crystalline silicon (c-Si) have recently received much attention because of the following characteristics:

1. **Low temperature process:**
    Conventional c-Si solar cells are mainly fabricated by a thermal diffusion process at a high temperature of up to 1000°C. In contrast, a temperature of less than 200°C is necessary for heterojunction cells. Therefore, it is possible to create polycrystalline silicon (poly-Si) solar cells on inexpensive substrates.

2. **Shallow junction:**

It is easy to fabricate shallow junctions, which have an advantage in a spectral response at a short-wavelength region.

3. **Same process (glow discharge method) as that for top a-Si solar cells:**

This is an advantage for a-Si / c-Si tandem type (stacked) solar cells[6].

Up to now, various researchers have been working on a-Si/ c-Si p/nheterojunction solar cells. Hamakawa*et al.* developed a tandem solar cell containing both a-Si and poly-Si, which was called the "Honey-moon Cell"[6]. Their bottom cell (poly-Si cell) has an n-type poly-Si/ p-type microcrystalline silicon (pc-Si) heterojunction structure. A conversion efficiency of more than 20% has been achieved with the tandem ce11[7].

Morikawaet at [8] studied the characteristics of pcSi/poly-Si p/nheterojunction solar cells. They found that pc-Si deposition after fabricating a thin layer of silicon oxide (SiO$_2$) improved solar cell characteristics such as the open circuit voltage (V_{oc}).

Mimura and Hatanaka [9] and Matsuura *et al* [10] investigated junction properties of a-Si/ c-Si heterojunctions, but they made no reference to their application in solar cells.

In spite of above R&Ds, the conversion efficiencies of heterojunction solar cells are lower than those of conventional homojunction cells; maximum efficiencies of conventional cells are about 24%.[6] The authors have investigated their junction properties and succeeded in improving the conversion efficiency by developing a new-structure solar cell called the ACJ-HIT. This paper describes the development of the ACJ-HIT solar cell and the improvement of its conversion efficiency.

3.1.9 Removing the insufficient junction in HIT solar cell using ACJ technology

As mentioned above, the p/nheterojunction has a large backward current density and insufficient junction properties. Therefore, in order to improve the junction properties, we have developed "Artificially Constructed Junction (ACJ)" technology. An ACJ is a junction with a "designed" impurity profile which was artificially constructed by using a deposition of a plurality of thin-layers, although there were some inter diffusions of dopants in the conventional junction.
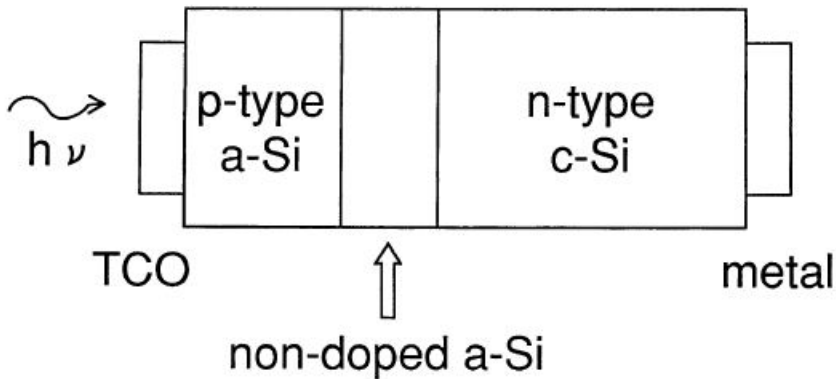
Fig.5 Structure of ACJ-HIT solar cell

By using the ACJ technology, we have developed a new structure solar cell in which the a-Si thin i-layer is inserted into the p/nheterojunction,We call this structure HIT that is Heterojunction with Intrinsic Thin-layer.

3.1.9 Improvement in ACJ-HIT solar cell conversion efficiency

To achieve higher conversion efficiency, textured substrate and back surface field (BSF) technologies were applied to ACJ-HIT solar cells and the a-Si layer deposition conditions were optimized.

Textured substrates have been used for various kinds of solar cells because of their optical confinement effects [11]. We therefore applied textured substrate to the ACJ-HIT solar cell, but difficulties were encountered in the fabrication of a uniform a-Si layer on the textured c-Si and insufficient cleaning of the c-Si surface before a-Si film growth. To improve uniformity, we optimized the deposition conditions and as a result the decrease in deposition rate and optimization of silane gas dilution were found to be effective. Effective cleaning of the c-Si was achieved by hydrogen plasma treatment before the deposition of a-Si layers. As a result, Isc was improved by about 20% by using the textured c-Si. It was also con- firmed that the superiority of ACJ-HIT to the p/nheterojunction was retained as in the case of flat c-Si.

In addition to the textured substrate, BSF structures using n-type a-Si were applied. As a result, a high conversion efficiency of 18.1% was obtained. This is the highest ever value for solar cells in which the junctions were fabricated at a low temperature (<200°C).

3.2.0Stability

Since ACJ-HIT solar cells have a non-doped a-Si layer, they are liable to light induced degradation. The output characteristics of the ACJ-HIT solar cells were unchanged after 10 hours' irradiation, which indicates that the ACJ-HIT solar cells are stable under light irradiation.

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Chapter4

Review of Thin-film Silicon Solar Cells

4.1 Review of Thin-film Silicon Solar Cells

Because silicon (Si) is an indirect band gap material, it is generally perceived that the thickness of Si required to absorb usable sunlight should be larger than (α bandedge)$^{-1}$, where α bandedge is the absorption coefficient for wavelength (λ) of light corresponding to the near-bandedge. Using this simple rule of thumb, on the basis of absorption due to a single pass of light, and using the mid-point of the bandedge $\lambda=1.05\mu m$ one gets $\alpha^{-1} \sim 700\ \mu m$. This is quite a large thickness for a Si wafer and is not desirable for commercial production of solar cells for two reasons: the wafer cost can be very high and its effectiveness for collection of photogenerated carriers will be small because it is difficult to have a minority-carrier diffusion length (MCDL) comparable to such a large wafer thickness. Thus, for practical reasons, wafer thickness must be less than this value. The physics and modeling capabilities for analyses of solar cell structures have taken two decades to develop and have been responsible for the majority of the improvements in Si solar cell efficiency.

As an introduction, it is necessary to have a general understanding of the requirements for a thin-film Si solar cell and the problems that emerge when the thickness of a Si solar cell is reduced. Clearly just reducing the cell thickness will result in reduced absorption, and thus, a reduced photocurrent.

Many basic concepts of thin-film Si solar cells were suggested decades ago [1, 2]. It was apparent then that thinner cells would require a means of enhancing optical absorption. As early as 1975, it was proposed that enhanced optical absorption accompanying light-trapping can help lower the cell thickness required for efficient generation of photocurrent to a few microns. The proposed approach used a prismatic configuration to deflect light into a thin film at oblique incidence, so that the light would be total internally multireflected within the thin cell. This approach is similar to launching guided waves in integrated optics. Although this approach did not flourish because of evident drawbacks, other cell configurations that would support the use of very thin Si films for solar cell applications were later suggested [3, 4]. Some simple (approximate) calculations showed that cell efficiencies approaching 10% could be obtained with polycrystalline Si films of 10-μm thickness with 1-μm grain size [3]. These calculations only considered bulk recombination arising from grain boundaries (GBs) in polycrystalline Si and planar cell structures. Although the possibility of the thin-film Si solar cell was envisioned long ago, a practical realization has begun only recently. The path to TF-Si cells has awaited some understanding of how to improve optical losses through enhanced absorption and the recognition and mitigation of electronic losses because of carrier recombination at interfaces.

Initial theoretical analysis based on thermodynamic considerations [5] suggested that rough surfaces and an asymmetric cell structure would effectively enhance optical absorption in the cell. Surface texturing, which was initially introduced to reduce surface reflectance for broadband illumination, also resulted in an increase in the optical path of light transmitted into a Si wafer [6–10]. Following the initial success, texture etching became a standard process step for fabricating Si solar cells, both in the laboratory and commercially. Figure(1) shows calculated short-circuit current density (J_{SC}) values as a function of thickness for different texture structures including planar, standard chemical texture, pyramids, inverted pyramids, and perpendicular slats.
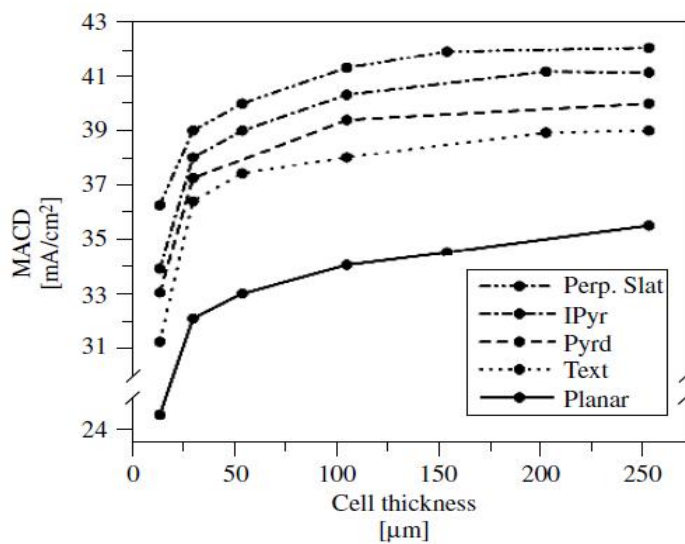

Fig: 1. Calculated MACD for Si solar cells with different texture shapes: perpendicular slats, inverted pyramids, uniformly textured pyramids, chemically textured random pyramids and planar.

4.1.1 Single-crystal Films Using Single-crystal Si Substrates

This approach involves separating a single-crystal thin film from a single-crystal substrate. Three techniques are currently being followed.

One approach consists of generating a porous-Si layer on a single-crystal substrate, which is then followed by epitaxial growth of a thin film. The thin film is then separated from the substrate by chemically etching the porous-Si interface. The best efficiency attained by such cells is about 12.5%.

The second approach that has been suggested is similar to the "smart cut" method used in the microelectronics field for wafer-bonding [11, 12]. It involves implanting a Si wafer with hydrogen and creating a defect interface below the surface, followed by a separation of the surface layer. This technique has been used successfully to separate thin (<1 μm) layers of Si, but may not be cost-effective for making the 10-μm-thick, separable layers needed for solar cells. For the hydrogen atoms to penetrate such a thick layer required for PV applications, requires a very high-energy implant. No singlejunction cells have been made using this approach. Recently, however, this approach has been used for making stacked multijunction solar cells that use GaAs-based and Si-based devices.

The third technique, called *epilift*, consists of depositing an epilayer on a patterned single-crystal wafer through a mask with openings along <110>directions [13]. The masking layer is exposed in a mesh pattern; the lines are 2 to 20 μm wide and spaced 50 to 100 μm apart. The growth faces have an (111) orientation and the layer has a diamond cross-section giving it an antireflection texture.

4.1.2 Multicrystalline-Si Substrates

Thin Si films can be deposited on a multicrystalline Si (mc-Si) substrate by an epitaxial process. The general objective is to use a low-cost, large-grain, cast-Si wafer, such as a metallurgical grade feedstock, as the substrate and to deposit a high-quality thin layer on it. The epitaxially grown layer would be low in impurity content, as well as in crystallographic defects [14, 15]. There is interest in the use of liquid-phase epitaxy, as well as other vapor-phase deposition techniques for high-growth-rate. Some of the issues in this method include impurity contamination from the low-cost substrate, different growth rates of different grains, and prevention of substrate defects from propagating into the film.

One of the major problems in this method is that the solar cell is not amenable to efficient light-trapping designs because the backside becomes a Si–Si interface with little or no discontinuity in the refractive index for high reflectance from this interface.

4.1.3 Non-Si Substrates

The cost advantages of thin-film Si are likely to be realized if the support for the thin film consists of a low-cost substrate. Clearly, in this case, it is not possible to directly deposit a crystalline or mc-Si film. Use of a non-Si substrate has gained some prominence because of the recent success in depositing μc-Si on glass substrates at reasonably low temperatures. However, there are a number of challenges in making such a device. These challenges are related to both the design and the fabrication process (es) of the device. A major issue in the device design is identifying method(s) for efficient light-trapping that are compatible with a low-cost cell design. Theoretical calculations show that film thicknesses of about 10 μm are sufficient to yield photocurrent densities of $35mA/cm^2$ in fairly simple thin film device structures [16]. Other issues of device design are related to the carrier-collection approaches, such as the nature of junction(s), electrode geometry, and electronic and optical reflectors. Finally, all of these aspects must be achieved compatible with low-cost methods of cell fabrication.

A recent advance in Si-based thin-film technology has led to a new realm of thin filmμc-Si solar cells. The Kaneka group has developed a cell configuration called SurfaceTexture and enhanced Absorption with a back Reflector (STAR) [17, 18].

4.1.4 Design concepts of TF-SI solar cells

Like any other emerging technology, the fabrication of TF-Si solar cells has, to date, followed empirical optical and electronic designs. The optical design aims at a high degree of light-trapping, such that the effective optical thickness of the absorber is similar to that of a much thicker wafer-based cell. It is generally known that one or more interfaces must be rough or textured to produce effective light-trapping. The electronic design of a TF-Si cell, particularly one using small-grain Si, is very difficult because such a structure has three dimensional nonuniformity. The material quality of a TF-Si cell should be such that the volume recombination is significantly lower than its thick-cell counterpart. In a thin-Si cell, the carrier recombination is expected to arise primarily from impurities, grain boundaries, and interfaces. Impurity effects can be minimized by the use of Al gettering, whereas a large ratio of grain size/Si thickness can minimize shunting effects of grain boundaries. A more difficult task is that of interface passivation, particularly if the Si film is in contact with a substrate material that may be conducting.
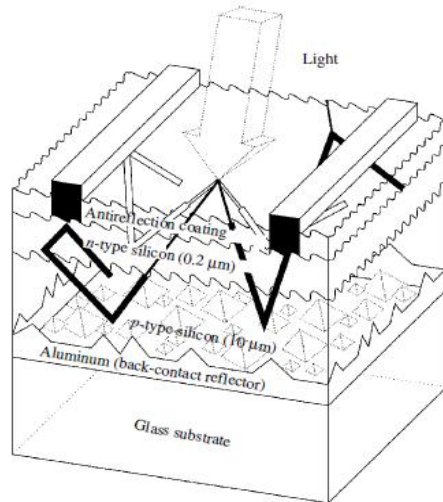
Fig: 2. A schematic of the proposed thin silicon solar cell

Qualitatively, one can identify various built-in features of the cell structure that potentially can make it a high-efficiency design. These include the following:

1. An interfacial texture to promote light-trapping. Some details on the nature of the texture, such as shape, height, and location(s) of the texture, are determined in the next section.
2. The use of a backside optical reflector to enhance light-trapping.
3. A large grain-size-to-film-thickness ratio compatible with high V_{oc} and *FF*. Large grain size is obtained by solid-phase grain growth using photo excitation (e.g. IR (infrared) lamps, lasers, RTA).
4. A built-in impurity-gettering mechanism that can improve the material quality of the deposited Si. It is common for thick Si wafer-based solar cell processing to require advanced techniques, such as impurity gettering and hydrogen passivation. The proposed structure offers a simple means of using Al gettering. As discussed in the next section, phosphorous diffusion and Al alloying are very effective impurity-gettering methods.

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Chapter 5
Review of III-V Semiconductor Compound Solar Cells

5.1 Introduction

The energy conversion efficiency of a solar cell is defined as the ratio of the electric power generated by the solar cell to the incident sunlight energy into the solar cell per time. The current world consumption of electric energy is around 12–13 TW and the earth receives more solar energy in one hour than the energy used globally in one year, considering the solar constant 1.7×10^5 TW at the top of the earth's atmosphere [1]. However the solar energy incidence, around 1 kW/m^2, is quite dilute and thus a vast area of energy converters would be required to meet the world's energy consumption. Therefore high efficiency solar energy conversion is crucial. Solar cells, also called photovoltaics, are devices that convert sunlight energy into electricity by the photovoltaic effect discovered by the French scientist Henri Becquerel in 1839. Electron–hole pairs are generated by the energy of the incident photons overcoming the energy bandgap of the photovoltaic material to make a current flow according to the built-in potential slope in the material. Solar cells have been recognized as an important alternative power source especially since the oil crises in the 1970s. Solar cells are also promising as a carbon-free energy source to suppress the global warming.

Currently in laboratories the highest reported cell efficiencies are around 40%, while the energy conversion efficiencies for thermal power generation can exceed 50%. This fact however does not mean that thermal generation is superior since its resources such as fossil fuels are limited, while solar energy is essentially unlimited. The incident energy flux spectrum of sunlight for reported solar cell efficiencies is standardized as some specifically defined spectra such as Air Mass 0 (AM0), Air Mass 1.5 Global and Direct (AM1.5G and AM1.5D) [2–4].

In this paper, we focus on solar cells made of III-V semiconductor compounds since these types of solar cells have exhibited the leading energy conversion efficiencies, rather than the other materials represented by silicon [5]. Besides the potential for high efficiency, III-V semiconductor compound materials have advantages including the bandgaptunability by elemental compositions, higher photon absorption by the direct bandgap energies, higher resistivity against high-energy rays in space, and smaller efficiency degradation by heat than Si solar cells. The energy conversion efficiencies of III-V solar cells have been steadily increasing year-to-year and are approaching 40% for the laboratory-scale cells, as seen in Figure 2 [6]. A lot of efforts have been made to date to improve the cell performance further for the purpose of the development of space activities and as a solution for the upcoming energy crisis and global environmental issues. In this paper, key factors recently being studied intensively for performance enhancement of III-V semiconductor compound solar cells were selected for review.
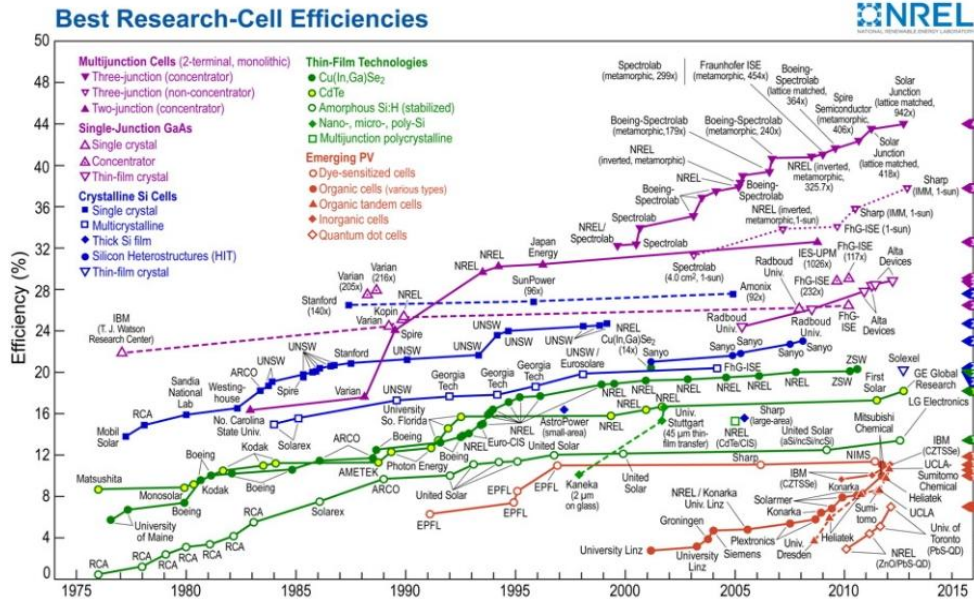
Fig 1: Best research-cell efficiency for year (1975-2015)

5.1.1 Developments of Multijunction III-V Solar Cells

One of the major factors of energy loss in a solar cell is the gap between the photon energy and the bandgap energy E_g of the photovoltaic material. No absorption would occur if the photon energy was smaller than the bandgap energy and merely the part equal to the bandgap energy out of the photon energy could be extracted as electric power leaving the other part wasted as heat if larger. Multistacking of photovoltaic materials of different bandgap energies is therefore commonly used for high efficiency III-V solar cells to reduce this energy loss and absorb the photon energy from the sunlight spectrum more widely and efficiently, taking advantage of the tunability of bandgap energies and lattice constants with the compositions of III-V semiconductor compounds, called multijunction or tandem cells. For instance, Figure 2 shows an energy utilization spectrum for a series-connected AlInGaP (1.9 eV) / GaAs (1.4 eV) / Ge (0.66 eV) triple-junction solar cell calculated as 50.1% efficient with Shockley and Queisser's *detailed balance limit* scheme under 1,000 sun concentration (41.4% under AM1.5G, 1 sun), exhibiting significantly higher efficiency represented by the spectral coverage relative to single-junction solar cells.
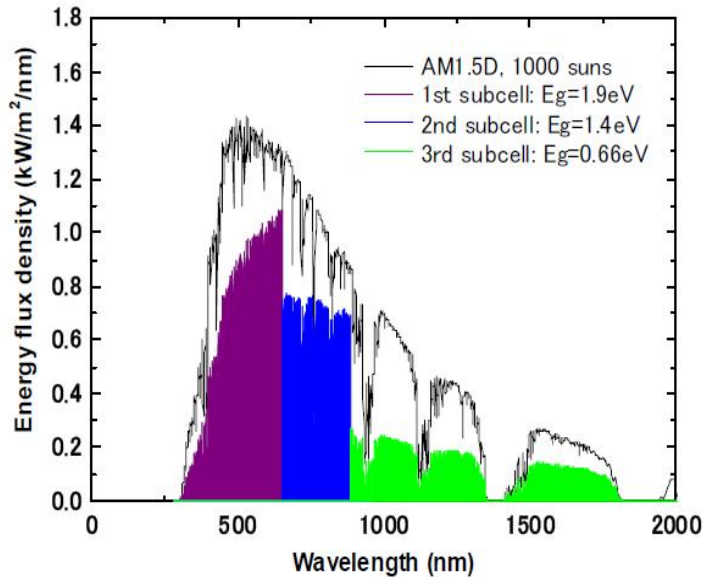
Fig 2: Solar irradiation spectrum of AM1.5D, 1,000 suns and energy utilization spectrum by a series-connected AlInGaP (1.9 eV) / GaAs (1.4 eV) / Ge (0.66 eV) triplejunction solar cell calculated with the "detailed balance limit" scheme with current-match restriction. Calculated energy conversion efficiency $\eta = 50.1\%$ ($\eta = 41.4\%$ under AM1.5G, 1 sun).

For multijunction cells, series-connected or two-terminal monolithic structures are generally favored and used rather than expensive and impractical three- or four-terminal structures [7]. A schematic cross-sectional diagram of a monolithic 3J solar cell structure is shown in Figure 3. Multijunction solar cells have been layered by epitaxial growth generally with metalorganic chemical vapor deposition (MOCVD) requiring lattice matching among the stacked semiconductor materials [8-11]. Figures 4 [12] show the relation between the lattice constants and the bandgap energies for commonly used III-V semiconductor compounds.

One of the most common and highest efficiency two 2J cells consists of a combination of In0.49Ga0.51P and GaAs with the same lattice constant of 5.64 Å and the bandgap energy of 1.86 eV and 1.42 eV, respectively [13-15]. This InGaP/GaAs cell has the highest efficiency of 30.3% under AM1.5G solar spectrum with 1-sun intensity (100 mW cm^{-2}) among monolithic 2J cells [9,23], while 4-terminal configuration allowed the highest 2J efficiency of 32.6% under AM1.5D spectrum at 100 suns for a lattice-mismatched GaAs/GaSb stack (GaSb: 6.09 Å, 0.70 eV) [16]. Quite recently, a 32.6% efficient monolithic InGaP/GaAs 2J cell under AM1.5D at 1000 suns has been also reported [17].
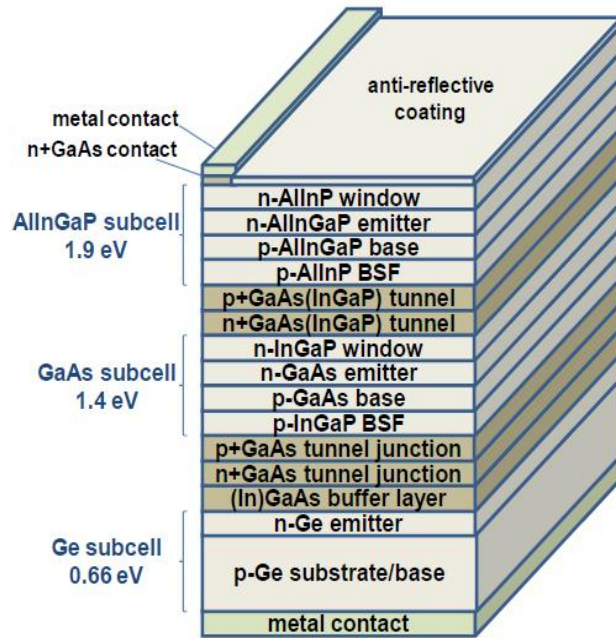
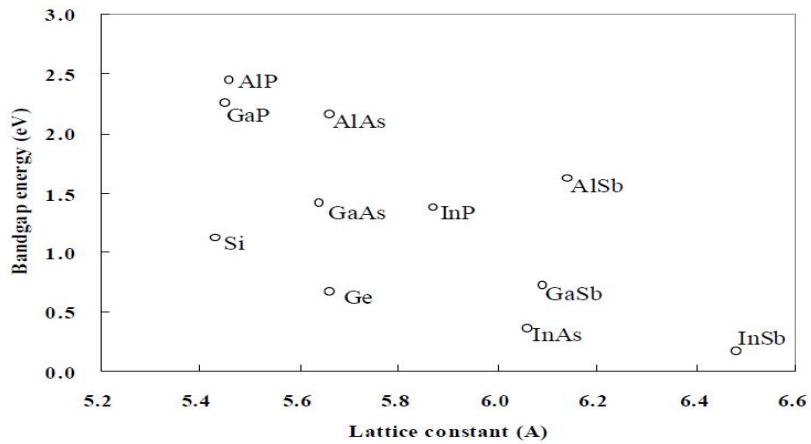Fig 3: Cross-sectional schematic of a triple-junction cell structure.

Fig 4 : Bandgap energies plotted as a function of the lattice constant of semiconductors.

5.1.2 Utilization of Higher Energy Photons

The most crucial loss mechanism for solar cell efficiency is the energy mismatch between the photons and the bandgap of photovoltaic materials, some concepts to utilize the photons with energy higher and lower than the semiconductor bandgap will be discussed in utilization of higher and lower energy photons.

One method to utilize higher energy photons is multiple carrier excitation from one photon by impact ionization, schematically depicted in Figure 5, the inverse process of Auger recombination [18,19]. This nonlinear phenomenon is more commonly called "multiple exciton generation" or "carrier multiplication". In semiconductor quantum dots (QDs), also called "nanocrystals", the carrier cooling rate can be significantly reduced due to the discrete character of the carrier density of states. Also, the impact ionization rate is greatly enhanced because of the moderated momentum-match condition and enhanced Coulomb interaction between excitons due both to the three-dimensional carrier confinement. Multiple carrier excitation can thus be quite efficient in quantum-confined semiconductor QDs, while it is inefficient in bulk semiconductors due to the much faster carrier recombination rate than the impact ionization rate [20]. Currently quantum efficiency enhancement using this multiple carrier excitation process is intensively studied with PbSe, PbS and CdSe QDs using high energy incident optical beam. Surprisingly a quantum efficiency (QE) of 300% [21], excitation of three electron-hole pairs from each incident photon, has been demonstrated with PbSe QDs followed by the even more striking news of a 700% QE in 2006 [22]. They verified generation of more-than-one exciton pairs from each incident photon in QDs through detection of exciton population evolution by time-transient absorption measurements in the time scale of biexciton decay lifetime [19,23,24]. Multiple exciton generation has been observed also in InAs [25,26] and Si [27] QDs.
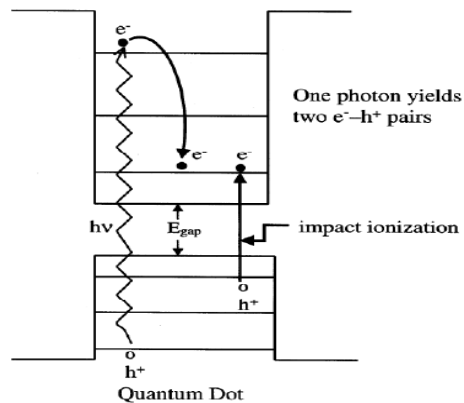

Fig5: Schematic energy diagram for impact ionization generating two carrier pairs from each incident photon (reprinted from [18]; © 2002, with permission from Elsevier.)

5.1.3 Utilization of Lower Energy Photons

An emerging idea is to utilize the photons with lower energy than the bandgap of photovoltaic materials, which would be wasted as heat in conventional solar cells, by up-converting the lowerenergy photons into higher energy photons. Two IR photons absorbed by a vitroceramic doped with certain rare earths, for instance, could emit one visible photon [28]. Sub-bandgap photons can be utilized by putting such an up-converting material in front of a solar cell or behind a solar cell with a reflector behind the up-converter. This concept was proven for a GaAs cell with a rare-earth-doped vitroceramic up-converter, as depicted in Figure 6 , showing power output from IR incident light [29]. The upper limit of cell efficiency with an up-converter was estimated to be 48% and 63% under 1 sun and 46,200 suns, the geometrical concentration limit, respectively [30].
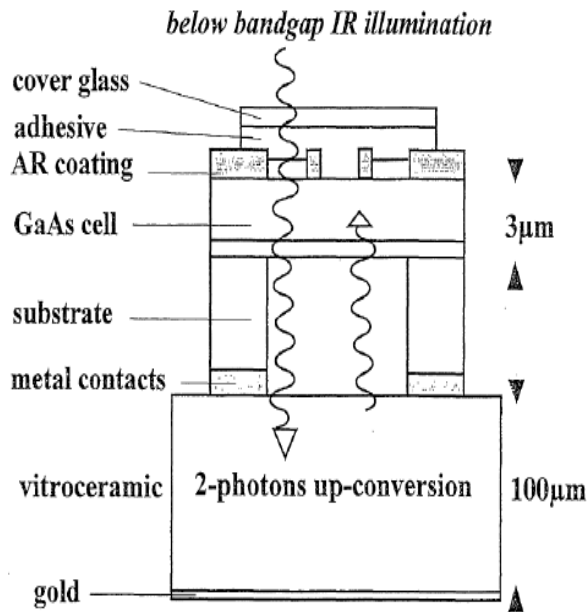

Fig 6: Cross-sectional schematic of the experimental coupling of a substrate-free GaAs solar cell to a vitroceramic doped with Er^{3+} and Yb^{3+} (reprinted from [56]; © 1996, with permission from The Japan Society of Applied Physics.)

Another idea to utilize lower-energy incident photons is to add intermediate bands inside the semiconductor photovoltaic material itself rather than an external up-converter described above. Insertion of impurity levels in the bandgap of photovoltaic materials to excite carriers by photons with energies lower than the bandgap is proposed [31,32]. Quantum well (QW) or quantum dot (QD) structures can also enable photons of lower energy than the bandgap of the original photovoltaic material to be absorbed by QWs/QDs with narrower bandgap incorporated in the original material [18,33–35]. The carriers or excitons generated in the QWs/QDs can thermally escape onto the conduction band for electrons or valence band for holes to contribute to the total photocurrent enhancement ideally maintaining the photovoltage of the original material, Photocurrent enhancement for a GaAs solar cell with InGaAs/GaAs multi-quantum wells (MQWs) relative to a GaAs cell without MQW in the IR region was observed [36]. The efficiency limit for such solar cells with intermediate bands was estimated as 63% under 46000 suns [37], inevitably equal to the value in [30].

5.1.4 PlasmonicNanometallic Structures for Light Absorption Enhancement

Metal nanoparticles are known to exhibit distinctive optical characteristics, such as surface enhanced Raman scattering (SERS) and second harmonic generation (SHG), relative to the bulk form of metals [38–40]. Representatives of the use of metal nanoparticles are biomolecular manipulation, labeling and detection with SERS [41,42]. Other optoelectronic fields inspired by metal nanoparticles are also emerging, such as multiphoton absorption and fluorescence excitation for microscopy, microfabrication and optical data storage [43,44].

These characteristics highly rely on the surface plasmon absorption, an enhanced absorption of light or electromagnetic fields by coupling between the incident photons and collective oscillation of free electrons at the metal surface [45,46]. It was theoretically suggested that electromagnetic energy can be guided along periodic chain arrays of closely spaced metal nanoparticles that convert the optical mode into non-radiating surface plasmons [47]. Such plasmonic devices exploit light localization in the dipole-dipole coupling, or collective dipole plasmon oscillations of electrons, in neighboring nanoscale metal particles at the plasmon frequency. Plasmon waveguides consisting of closely spaced Ag nanoparticles with diameters around 30 nm have been experimentally observed to guide electromagnetic energy over distances of several hundred nanometers via near-field particle interactions [48]. Furthermore it has been suggested that light can be routed efficiently around sharp corners of nanoparticle chain arrays [49]. Such plasmon waveguide technologies can potentially be utilized for construction of all-optical nanoscale network [50-52].

Solar cell structures have been suffering from such a trade-off on the thickness of the active photovoltaic layers as follows. Thinner photovoltaic layers will have less light absorption while thicker layers will have more bulk carrier recombination, as schematically depicted in Figure 8.

Both of these two factors would be losses for the solar cell electrical output converted from the incident sunlight energy. Therefore the thickness of the active photovoltaic layer is usually optimized to maximize the energy conversion efficiency through that trade-off. Metallic nanostructures can excite surface plasmons and can dramatically increase the optical path length in thin active photovoltaic layers to enhance overall photoabsorption. In this Section, I describe two schemes to utilize surface plasmons for solar cell applications.
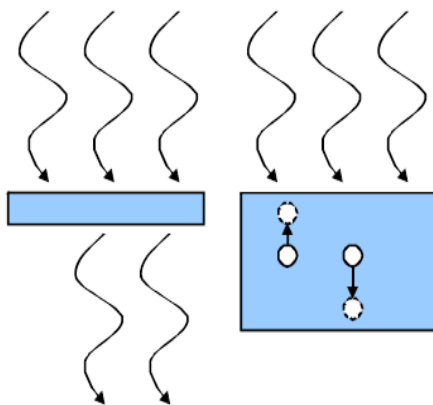

Fig 7: Schematic for the trade-off issue in photovoltaic layer thickness. Thinner photovoltaic layers will have less light absorption (left) while thicker layers will have more bulk carrier recombination (right).

The very same trade-off between the absorption length and the carrier diffusion length exists of course also in III-V semiconductor compound solar cells. A couple of groups have experimentally studied optically-thin GaAs solar cells with arrays of sub wavelength-size metal particles on top and observed enhancement in photocurrent particularly in near-IR region and even in overall cell efficiencies [53–55].

Some types of conventional solar cells such as silicon solar cells also have metallic back reflectors to increase optical path, while III-V semiconductor compound solar cells such as GaAs cells have thin photovoltaic active layers on top of thick substrate. However, the Plasmon induced absorption enhancement by metallic back structures observed in this study would occur significantly only for strongly absorbing or direct bandgap semiconductors accounting for the energy dissipation in metals.
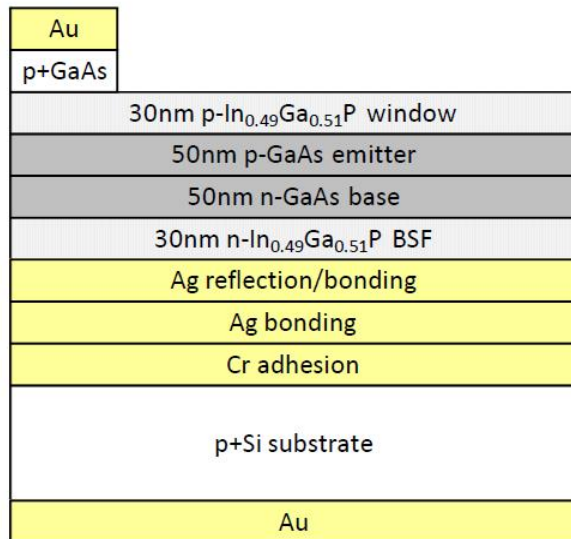
Fig 8: Schematic cross-sectional diagram of the waveguide-like GaAs solar cell with metal back layer.

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Chapter 6

Conclusions

Solar energy is the energy of tomorrow, because all renewable energy in the world is in one way or another driven by solar energy. Energy from the sun, also known as solar radiation and short-wave radiation. Solar energy includes ultra-violet radiation, visible radiation, and infra-red radiation. The sun sends more energy to the earth every day then humans currently consume. The problem is that we are unable to capture more than a small percentage of this energy.

Solar energy is very useful, particularly in a time when we are concerned about greenhouse gas emissions from other energy sources.

There are many advantages worth considering when it comes to solar energy and everything that it offers. There are many advantages that solar energy has over oil energy. Not only does solar energy benefit your pocketbook, but it also benefits the environment as well. However, there are two sides to everything, and there is a list of solar power disadvantages to accompany the list of advantages

Advantage: Solar energy is a completely renewable resource. This means that even when we cannot make use of the sun's power because of nighttime or cloudy and stormy days, we can always rely on the sun showing up the very next day as a constant and consistent power source.Oil, which is what most people currently use to power their homes, is not a renewable resource. This means that as soon as the oil is gone, it is gone forever and we will no longer have power or energy.Solar cells make absolutely no noise at all. They do not make a single peep while extracting useful energy from the sun. On the other hand, the giant machines utilized for pumping oil are extremely noisy and therefore very impractical.Solar energy creates absolutely no pollution. This is perhaps the most important advantage that makes solar energy so much more practical than oil. Oil burning releases harmful greenhouses gases, carcinogens and carbon dioxide into our precious air.Very little maintenance is required to keep solar cells running. There are no moving parts in a solar cell, which makes it impossible to really hurt them. Solar cells tend to last a good long time with only an annual cleaning to worry about.Solar panels and solar lighting may seem quite expensive when you first purchase it, but in the long run you will find yourself saving quite a great deal of money. After all, it does not cost anything to harness the power of the sun. Unfortunately, paying for oil is an expensive prospect and the cost is still rising consistently. Why pay for expensive energy when you can harness it freely? Solar powered panels and products are typically extremely easy to install. Wires, cords and power sources are not needed at all, making this an easy prospect to employ.Solar power technology is improving consistently over time, as people begin to understand all of the benefits offered by this incredible technology. As our oil reserves decline, it is important for us to turn to alternative sources for energy.

Today has seen remarkable development of solar cells. The next generation of microelectronics is aiming for applications of "electronics everywhere.

In this paper we tried to find out highest efficiency using different materials. We used here silicon, III-V cells, amorphous Si, thin film chaloogenid, Dye-sensitized materials, multijunction device and also give here different year based efficiency graph to find maximum efficiency.

This report is intended to provide a brief summary for those who are interested in solar energy technologies and as a reference for those who want to invest or work in this f