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PROGRESS OF PHOTOVOLTAIC SOLAR CELL TECHNOLOGY

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Solar electricity produced by photovoltaic solar cell is one of the most promising options yet identified for sustainable providing the world's future energy requirements. Recently, there has been a considerable increase in grid-connected photovoltaic power generating systems for private residential houses and buildings. This paper will review progress made in solar cell technology and photovoltaic system for houses and buildings. The new-structures, high-efficiency c-Si cell (called the HIT structure), process technology for large-volume production of a-Si cells and lower-cost thin-film technology integrated with roofing materials are discussed. The urban residential rooftop application of photovoltaic is expected to provide the major application of the coming decade and to provide the market growth needed to reduce prices. Finally, the prospects for future energy supply systems based on solar cells are introduced.

KEYWORDS

Photovoltaic, cost, thin-film, a-Si, c-Si, heterojunction, polycrystalline, spectrum splitting-cell, tandem-cell

1. INTRODUCTION

Since the late 1960, the world has been concerned about depletion of non-renewable energy resources and the pollution caused by their use. The consequences of fossil fuel burning on the CO_2 content of the atmosphere, and the so-called "greenhouse effect", are of great concern for the next generations. Increasing international resolve to reduce carbon dioxide emissions as a first step to reigning in the "greenhouse effect", combined with introduction photovoltaic renewable energy. This will be one of the main factors in accelerating the development of solar cells with decreasing cell costs.

Photovoltaic involves the direct conversion of sunlight in to electricity in thin layers of material known as semiconductors with properties intermediate between those of metals and insulators. Silicon photovoltaic solar cells started to be used mainly to generate small amounts of electricity in remote areas where there was no conventional source of electricity. Fig. 1 is a schematic of solar cell under illumination. Light entering the cell through the gaps between the top contact metal gives up its energy by temporarily releasing electrons from the covalent bonds holding the semiconductor together. The p-n junction within the cell ensures that the now mobile charge carriers of the same polarity all move off in the

same direction. The cell operates as a "quantum device", exchanging photons for electrons. Ideally, each photons of sufficient energy striking the cell, causes one electron to flow through the load. In practice, some of the incoming photons are reflected from the cell or get absorbed by the metal contacts (where they give up their energy as heat). Some of the electrons exited by the photons relax back to their bound state to their bound state reaching the cell contacts and thereby the load.

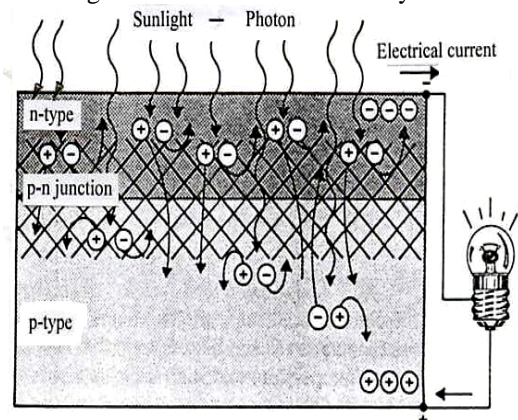


Fig. 1: Energy in the incoming sunlight is converted into electrical energy consumed by the load

2. SCREEN-PRINTING CELL TECHNOLOGY

The first step in processing a silicon wafer (less than a half-millimeter thick) in to a cell is to etch the wafer

surface with chemicals to remove damage from the slicing step. The surface of crystalline wafers is then etched again using a chemical that etches at different rates in different directions through the silicon crystal. This leaves features on the surface, with the silicon structure that remains determined by crystal directions that etch very slowly. The square-based pyramids apparent in Fig. 2 that are formed by this process are similar in shape, if not in size, to the great pyramids of Egypt. These pyramids are very effective in reducing reflection from the cell surface. Light reflected from the side of pyramid will be reflected downwards, getting a second chance to get coupled in.

The impurity required to give p-type properties (usually boron) and n-type properties (usually phosphorus). The all-important p-n junction is then formed. Next, the top and bottom contacts are applied using metal particles (usually silver) suspended in a paste with other additives.

The paste is "screen printed" onto the cell surface in the desired pattern using a simple process similar to that used to print pattern onto T-shirts. A very thin layer of insulating material is sometimes added to the top cell surface as an antireflection coating. Such coating are always used for "multicrystalline" wafers, since the pyramidal-texturing approach is not effective for such wafers and this alternative approach is essential to control reflection. The screen-printed silver pastes are also quite expensive. After fabrication, the cells are soldered together and packaged under a sheet of glass into a weatherproof package known as a module. Generally, 36 cells are packaged into a module, since this is the required number to generate enough voltage to allow charging of a lead-acid battery.

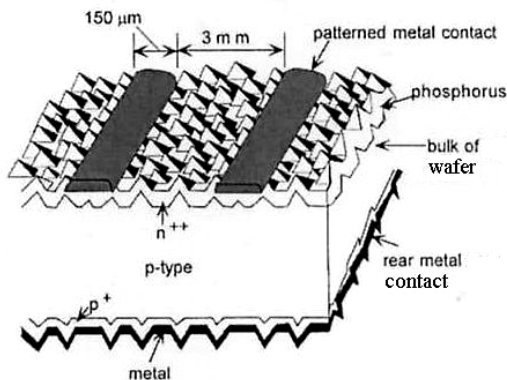


Fig. 2: Structure of a typical commercial cell with textured surface and screen-printed contacts

The most successful commercialization to date of an improved, higher performance sequence has involved the buried contact cell of Fig. 3. This cell offers 20-30% improvement in output with virtually no increase in cell processing costs [1]. The overall relative cost advantage of the technology is therefore close to its relative efficiency advantage. The improved performance comes from better quality surface regions that allow much better response to blue light, absorbed close to the surface, and much lower electrical resistance and optical losses due to the improved top contacting scheme.

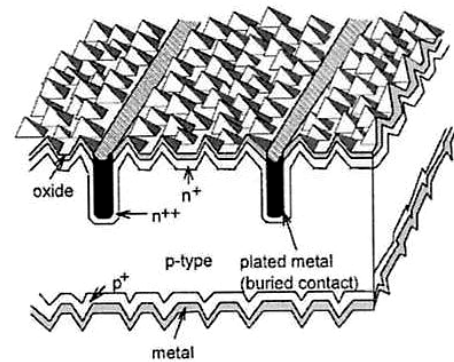


Fig. 3: Buried contact solar cell

The most important features of solar cells are their cost and conversion efficiency. In the past few years, we have seen improvements in conversion efficiency for various kinds of solar cells in both the research and the market stages. In market stage, Si-related solar cells such as c-Si (crystalline silicon), p-Si (polycrystalline) and a-Si (amorphous silicon) are shared almost all part. The conversion efficiency of these modules improved to 12-15% for c-Si based cells, 11-13% for poly-Si based cells, and 6-9% for a-Si based cells.

Recently, a new-structure c-Si cell (called the HIT structure) with 17.3% cell efficiency was developed. The HIT (Heterojunction with Intrinsic Thin-layer) solar cell is a hybrid composed of a thin single crystal silicon wafer sandwiched by layer of ultra-thin amorphous silicon as shown in Fig. 4.

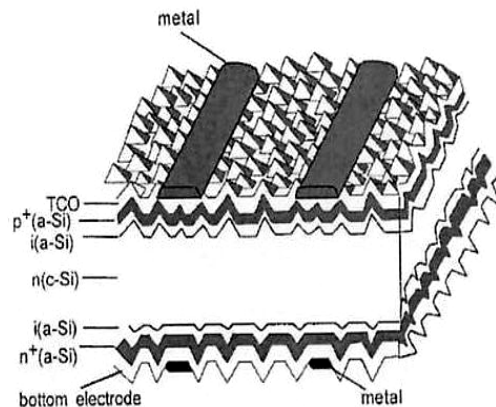


Fig. 4: Heterojunction with intrinsic thin layer (HIT) cell

This structure reduces energy loss and results in the world's highest conversion efficiency for a proto cell, 20.0% [2]. Because of its low temperature process, the HIT structure reduces thermal stress to the cell, and realizes very thin device ($\sim 250\mu\text{m}$) with a size of 100 cm^2 with no wrap. The HIT cell would be expected to give some of the improvements of the buried contact sequence in the areas mentioned. To achieve higher efficiency, the HIT power Double was developed, as shown in Fig. 5. The rear processing of the cell is improved compared to the buried contact sequence and the cell responds to light from both directions, a feature that can be used to advantage in some applications. This structure utilizes a symmetrical cell structure to generate electricity from both the front and back of the PV module. Optional simulations indicate that annual power output will be improved by 6% compared to previous HIT

modules when they are installed on concrete at a 30 degree pitch, facing south [2].

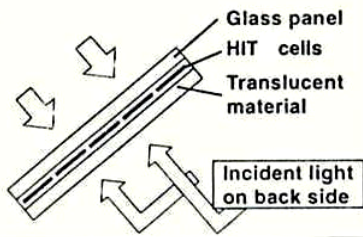


Fig. 5: HIT power Double

3. THIN-FILM SOLAR CELL TECHNOLOGY

For high-speed patterning, the laser patterning method is popular for fabricating integrated type thin-film modules.

In this approach (Fig. 6) thin layers of semiconductor material are deposited onto a supporting substrate, such as a large sheet of glass. Typically, less than a micron thickness of semiconductor material is required, 100-1000 times less than thickness of a silicon wafer. Reduced material use with associated reduced costs is a key advantage. Another is that the unit of production, instead of being a relatively small silicon wafer, becomes much larger, for example, as large as a conveniently handled sheet of glass might be. This reduces manufacturing costs.

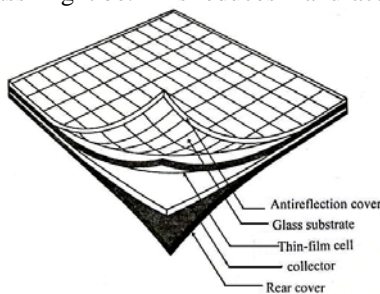


Fig. 6: Thin-film approach

Although this method has many advantages, the throughput is not sufficient for large-volume production of a-Si solar cells. Therefore, a new patterning method called plasma CVM (Chemical Vaporization Machining) was developed [3] as shown in Fig. 7. This method realizes a relatively short process time (within a few seconds per substrate using a multi-wire electrode) and has been successfully applied to the a-Si patterning of large-area integrated a-Si module [4].

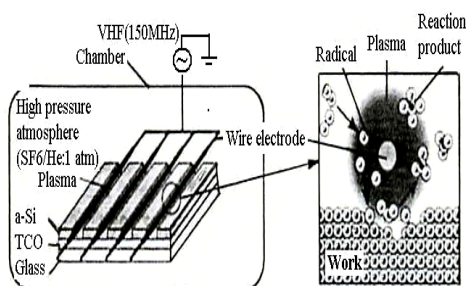


Fig. 7: Concept and apparatus of the CVM method

At present, solar cells made from five different thin-film technologies. Over the coming decade, one of these

is expected to establish its superiority and attract investment in major manufacturing facilities that will sustain the downward pressure on cell prices.

3.1 Amorphous silicon alloy cells

In amorphous silicon, the atoms are connected to neighbors in much the same way as in the crystalline material but accumulation of small deviations from perfection means that the perfect ordering over large distance no longer possible. Amorphous material has much lower electronic quality, as a consequence, and originally was not thought suitable for solar cells. However, producing amorphous silicon by decomposing the gas, silane (SiH_4), at low temperature, changed this opinion. It was found that hydrogen from the source was incorporated in to the cell in large quantities, improving the material quality (about 10%). Hydrogenated amorphous silicon cells very quickly found use in small consumer products such as solar calculators and digital watches. Since the amorphous silicon quality is much poorer than crystalline silicon, a different cell design approach is required. The most active part of a p-n junction solar cell is right at the junction between the p- and n-type region of the cell (Fig. 1). This is due to the presence of an electric field at this junction. With amorphous silicon cell design, the aim is to stretch out the extent of this junction region as far as possible so almost all the cell is junction. This is done by having the p- and n-type doped regions very thin, with an undoped region between them. The strength of the electric field established in this undoped region's width. The poorer the quality of amorphous silicon, the stronger electric field needs to be for the device to work well and hence thinner the device to be. For degraded material, it turns out that the cell needs to be thinner than the thickness required to absorb all the useable incident sunlight. The way around this is to stack several cells on top of one another so that light not absorbed by an upper one passes through to an underlying cell. By alloying with germanium, a material chemically similar to silicon but much scarcer, this is readily achieved. The best commercial amorphous silicon cells presently use three cells stacked on top of one another with progressively more germanium in the bottom two [5]. Each cell is very thin, only 100-200 nm thick. This ensures reasonable stability. However, the stabilized efficiency is quite poor, only 6-7% for the best commercial modules.

3.2 Thin-film, Polycrystalline Compound Semiconductors

Many semiconductor made from compounds can absorb light more strongly than the elemental semiconductors, silicon and germanium. This means compound semiconductor cells can be thin but still operate efficiently. Most compound semiconductors, when formed in polycrystalline form, have poor electronic properties due to highly deleterious activity at grain boundaries between individual crystalline grains in the material. A small number maintain good performance in polycrystalline form for reasons that are not usually well understood. These are the candidates for thin-film polycrystalline compound semiconductor solar cells. One

such semiconductor is the compound cadmium telluride (*CdTe*). Technically, it is an ideal material, giving properties suitable for making reasonable solar cells even with relatively crude material deposition approaches. The junction in these cells is again between p- and n-type material, but for latter, a different compound semiconductor, cadmium sulphide, gives best results [6].

Modules of this material are now commercially available in small volumes with efficiency up to 12% demonstrated in pilot production (laboratory 19%) [5,6].

3.3 Thin-film Polycrystalline Silicon cells

As previously, mentioned silicon is a weak absorber of sunlight compared to some compound semiconductors and even to hydrogenated amorphous silicon. Early attempts to develop thin-film solar cell based on the polycrystalline silicon did not give encouraging results since the silicon layers had to be quite thick to absorb most of the available light. Due to the optical properties of semiconductors, particularly their high refractive index, cells can trap light very effectively if the light direction is randomized, such as by striking a rough surface, once it is inside the cell. Optically a cell can appear about 50 times thicker than its actual thickness if this occurs. Such "light trapping" removes the weak absorption disadvantage of silicon. Work on polycrystalline thin-film solar cells is proceeding in two areas. A variety of "high temperature" approaches is being explored. There generally involve either high-temperature deposition of silicon onto a substrate or melting the silicon after deposition, to obtain large grain size in the final film. In this case, the silicon is deposited on to expansion-matched ceramic substrate. The final material consists of millimeter-sized grain and is similar in appearance to multicrystalline silicon wafers. Small area cell performance in the 16-17% range has been demonstrated [6]. The other type of approach is a "low temperature" approach, generally based on amorphous silicon technology. One approach is to deposit the silicon in amorphous form and then crystallize it by heating for prolonged periods at intermediate temperatures. This "solid-phase crystallization" approach has produced cells of quite reasonable performance [7]. Another approach has involved changing the amorphous silicon deposition conditions, to produce nanocrystalline phase of silicon. The potential of this approach was highlighted by early results with the "micromorph" solar cell. More recently, cell efficiency above 10% has been confirmed with this approach [8].

4. NANOCRYSTALLINE DYE CELLS

A completely different thin-film approach is based on the use of ruthenium-based organic dyes [9]. Dye molecule are coated onto a porous network to titanium dioxide particles and immersed in an electrolyte Fig. 8. In a process bearing some relationship to photosynthesis, light absorbed by the dye photo excites a electron into the titanium dioxide which completes the circuit through the external load and the electrolyte. Interestingly, the dye only absorbs a band of photon energies, rather than all photons of energy above the band gap, as is the case for normal cells. This gives rise to prospects for unique devices, such as transparent windows that convert the infrared wavelength while letting visible light through.

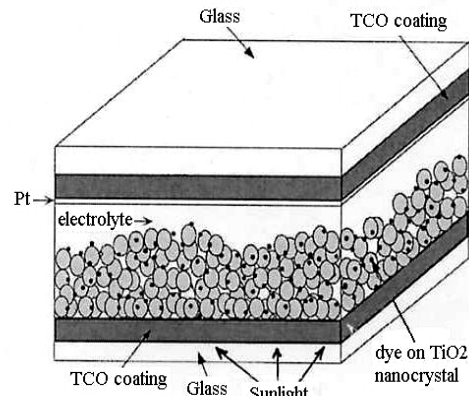


Fig. 8: Nanocrystalline dye sensitized solar cell

5. SPECTRUM SPLITTING CELLS

There will be evolutionary improvements in both first- and second-generation cell performance (silicon wafer-based and thin-film technologies), the efficiency of standard cells is restricted to less than 33% by quite fundamental consideration [10]. Basically, standard cells are quantum converters, ideally converting one sunlight photon to an electron in the load. This alone limits efficiency to about 44%. An additional loss arises since the cell can supply this current at a voltage somewhat less the potential corresponding to its energy band gap.

However, the thermodynamic limit on the conversion of sunlight into electricity is a more impressive 93%. Is it possible for solar cell to come closer to this limit?

One idea that is well established is based on splitting sunlight into different wavelength bands and sending to cell of band gap optimized for each band Fig. 9(a).

Fortunately, this splitting can be achieved more simply merely by staking cells on top of one another (Fig. 9(b)), with the highest band gap cells uppermost. In the limit of an infinite number of such cells, the limit on conversion efficiency is increased to 70%, and further to 87% if focused sunlight is used [10] (the diffuse component of sunlight would have to be wasted in latter case, giving a lower effective efficiency in practice).

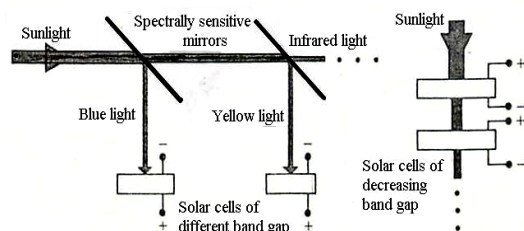


Fig. 9: Multigap-cell concepts:

(a) spectrum-splitting cell; (b) tandem-cell

6. PHOTOVOLTAIC POWER GENERATING SYSTEM FOR HOUSE AND BUILDING

The solar cell production volume has increased rapidly in recent years, as shown in Fig. 10. Therefore, the global production volume was 160 MW in 1998 [11].

The interest of general public in photovoltaic power generation is increasing and as a result, the number of

application for the subsidy system this year doubled those of last year. Fig. 11 shows the annual installation figures for home photovoltaic power generating systems and total capacity. The application of photovoltaic power generating systems to buildings and houses is a very important element in promoting their widespread use. By increasing the number of photovoltaic power generating systems installed in houses and buildings, an independent market for these systems will be established and spread rapidly in early 21st century.

In order to reduce the cost of photovoltaic power generating systems for private houses and buildings, research on photovoltaic modules integrated with roofing materials is being conducted. Many types of photovoltaic modules integrated with roofing materials have been promoted. These modules, which employ a glass surface, are already on the market. In addition, the development of the next generation of modules, with lower cost improved functions, as well as improved design (exchangeable photovoltaic shingles).

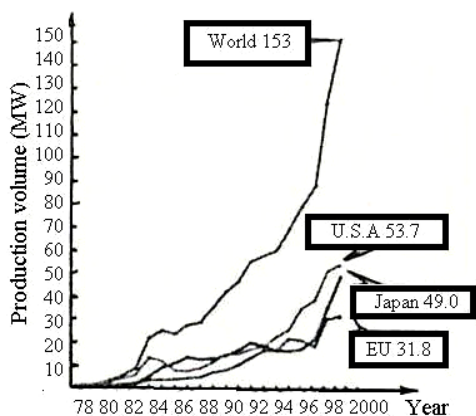


Fig. 10: Progress in global production volume

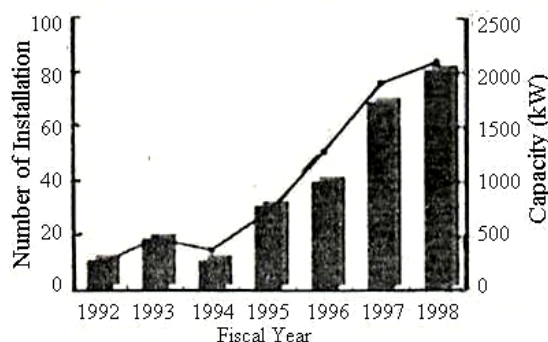


Fig. 11: Annual installation figures for PV power generating system and total capacity

7. CONCLUSION

Solar cells are today's most prominent candidate as a new clean energy source. In order to resolve the environmental problems facing us today and to live comfortable lives in the 21st century, we must build a global photovoltaic power generating system using solar cells. For this purpose, the application of solar cells to houses and buildings is of primary importance at the first step.

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