# Solar Cell Research Progress

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# SOLAR CELL RESEARCH PROGRESS

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# SOLAR CELL RESEARCH PROGRESS

# PREFACE

A solar cell or photovoltaic cell is a device that converts light energy into electrical energy. Sometimes the term solar cell is reserved for devices intended specifically to capture energy from sunlight, while the term photovoltaic cell is used when the light source is unspecified.

Fundamentally, the device needs to fulfill only two functions: photogeneration of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity (simply put, carrying electrons off through a metal contact into a wire or other circuit). This conversion is called the photovoltaic effect, and the field of research related to solar cells is known as photovoltaics.

Solar cells have many applications. They have long been used in situations where electrical power from the grid is unavailable, such as in remote area power systems, Earth-orbiting satellites and space probes, consumer systems, e.g. handheld calculators or wrist watches, remote radiotelephones and water pumping applications. More recently, they are starting to be used in assemblies of solar modules (photovoltaic arrays) connected to the electricity grid through an inverter, often in combination with a net metering arrangement.

This new book presents the lastest research in the field from around the globe.

Short Communication A - This paper presents a quality evaluation method on the coating shape of space solar cells by means of the Automatic Optical Inspection (AOI). In order to ensure that solar panels are working with high reliability in space missions, their quality must be controlled in the manufacture process. Although the current-voltage (I-V) characteristic of space solar cells is well-recognized in quality assessment, the further research on the quality of the coating shape based on automatic optical inspection (AOI) is also necessary for the total quality control. In this paper, the quality evaluation method on the coating shape of space solar cells is presented via image processing technology, and some essential conditions are given to judge whether the coating shape is qualified or not. If the shape-factor assessment is finished, the next I-V characteristic assessment will become more efficient. The experimental results show that the method can prevent more products from being input into a simulated vacuum-space condition to be tested, and decrease time consuming and unnecessary cost.

Short Communication B - Normal characterization of a solar cell or module is carried out with two illuminated IV curves, yielding series resistance, assuming very large shunt resistance. The authors have developed a new and simpler technique to determine series resistance, shunt resistance as well as dynamic resistance of a solar cell or module based on either one illuminated IV curve or one dark IV curve, taken into account finite series and finite shunt resistance. Applicability and accuracy of the techniques are shown through measurements with six mono-crystalline, polycrystalline and amorphous silicon modules. Three modules are small, less than 10Wp, the other three are large commercial modules of about 40 – 120 Wp. Comparison is made on the internal dynamic resistance $R_d$ , the external dynamic resistance $R_D$ ,the series resistance $R_s$ and the shunt resistance $R_{sh}$ determined from the proposed Single I-V Curve Method, the general Two I-V Curve Method and a commercial pulse solar simulator. The Single I-V Curve Methods yields results of comparable accuracy.

Short Communication C - Metal substrates have been applied as substrate material for efficient, flexible, nanoporous $TiO_2$ dye-sensitized solar cells (DSSCs) to improve the photochemical properties of the current plastic-based flexible DSSCs. Metal substrates have merits such as a low internal resistance and high sintering temperature. These merits enable the metal based cells to compete with glass substrate cells in electrical properties. Modules as well as individual cells with metal sheets have been successfully demonstrated as not only working electrodes but also counter electrodes. The characteristics and the current research direction of the DSSC based on metal substrates have been described.

Chapter 1 - Reduction of optical losses in both mono and multicrystalline silicon solar cells by surface texturing is one of the important issues of modern silicon photovoltaics.Texturing of the front surface of silicon solar cells has been modeled and analyzed with reference to the reduction in reflection co-efficient and increase in optical trapping. Significant enhancement in open circuit voltage and short circuit current has been achieved through such texturing of the front surface of mono-silicon solar cells. A proper optimization of texture angle appears to be important for the best performance of the solar cells. An alternative way of reducing the surface reflection and enhancement of the cell parameters is to produce to passive front surface porous silicon layer. An analysis of the characteristics of a porous silicon layer shows that the morphology of the layer is an important design parameter.

To realize the structures in practice, several methods are available, but many of this method are either not cost effective or commercially non available. In order to achieve good uniformity of pyramidal textured structure of the silicon surface, a mixture of NaOH/KOH and isopropyl alcohol (IPA) is generally used for texturization of mono crystalline solar cells. However, due to high cost of IPA, there is always search for alternative source. This source should not only be cost effective but should also result in reduced interfacial energy between silicon and ionized electrolyte chemical solution to achieve sufficient wet-ability for the silicon surface in order to enhance pyramid nucleation. Different novel texturization techniques for monocrystalline silicon are descried in this chapter including solar cells performance.

For multicrystalline silicon (mc-Si) solar cells, the standard alkaline solution of NaOH/KOH does not produced textured surface of good quality so as to give satisfactory open circuit voltage and efficiency. This is because of grain boundary delineation with step formed between successive grains of different orientations. Different novel texturization techniques for multicrystalline silicon are also included in this chapter including solar cells performance.

Chapter 2 - Solar cell as a combination of a solar engine with a heat engine is described. The photon absorption is divided into processes with and without work production. The ideal solar and heat engines are Carnot cycles. The processes without work production are called photon reemissions. The photon reemissions take place as reversible and irreversible cyclic processes. The method for calculation of the relative contributions of the reversible and irreversible photon reemissions is proposed. Occuring together these processes made clear that it is impossible to achieve a very high efficiency of solar engine without the reversible photon reemission.

The radiation temperature and photon number are important parameters of the photon reemissions and solar engine. Thermodynamic functions of the sun photon number and temperature as independent variables are described. It is found that opposite to the fact that the chemical potential of thermal radiation is thought to be zero, the chemical potential of thermal radiation, as a partial derivative taken from these functions, has a temperature dependence. It is in respect with the thermodynamic postulates and laws.

Chapter 3 - The sequence of ground and excited states of atoms is presented as a thermodynamic process. The requirements to processes, under which the electron energy transitions with maximal work production are realized, are described. The number of such transitions increases from diamond to graphite and soot. On the example of silicon it is suggested that clusters with small number of atoms can be comparable with ideal absorber.

Electric properties of Cu-clusters in Ag-contact of Si-solar cells are investigated. The atomic copper clusters are obtained by copper deposition from water solutions. The crystalline clusters place in pores and on the surface of silver contact stripes. The illumination-dark alternation in the same experiment resulted to the unique results of specific resistance standard measurements for Cu/Ag-fingers. The dark current is found in silver contact; the current appears due to Cu-clustars in Ag-pores. This investigation was carried out in order to find an origin of electrical work in silicon solar cell differing from the illumination of the standard p-n-structure. The effect revealed experimentally will allow the solar cell to operate 24 h per day.

The paper is organized as follows: an introduction briefly describes the thermodynamic aspects of the problem to which our chapter is devoted; the first part describes the thermodynamics of solar energy conversion from the point of view of achieving maximum efficiency. The next part is devoted to the crystallography of the solar cell in order to show how the structure of the active element affects its efficiency, and the next part demonstrates unique experimental results obtained from very standard measurements of electric parameters of the active element.

Chapter 4 - Thin films polycrystalline solar cells are one of the most important researches for the photovoltaic industry today. Thin films solar cells based on CdTe and $CuInGaSe_2$ heterojunctions are the more important structure with CdS as "window" partner. Therefore, the investigation of thin films polycrystalline solar cells is very relevant today. In this regard, the authors summarize most of the work that they have done in the past for deposition, characterization of CdS and CdTe films and application of CdS/CdTe solar cells. In particular, they mention our research on Chemical Bath Deposited (CBD) CdS, Close Space Vapor Transport (CSVT) CdS and CdTe and Sputtering CdS and CdTe films and relate their morphological, structural, electrical and optical properties to the performance of solar cells; as well as the deposition and characterization of front and back contacts in these types of solar cells. The properties and level attained of the CdS/CdTe solar cells devices in the research groups and especially in our laboratories at the present and the future are presented and discussed.

Chapter 5 - Hitherto papers describing the surface photovoltage effect calculate mostly the voltage from the change in the surface band banding after illumination. Determination of this change is rather complex and can be obtained under simplified assumptions for thick samples with negligible recombination in the space charge regions (SCR). The authors approach is similar to that used for illuminated p-n junctions and Schottky diodes. It is shown that the space charge region and the bulk of the sample contribute to the photovoltage independently. It means that eventual recombination in the space charge region does not influence contribution from the bulk. If the space charge region contribution can be neglected, the excess electrons and holes are generated predominantly in the bulk, and the SCR serves for their separation only. The current and voltage can be simply calculated in such case solving diffusion equation in bulk of the sample. Thickness of the silicon wafers for solar cells is often comparable with the diffusion length, and, consequently, the SPV is formed at the upper and bottom surface. Using an auxiliary electrode contacting directly the bulk, separation of both contributions is possible. The signal from the bottom non-illuminated surface is controlled predominantly by diffusion of the photocarriers. That is why The authors used it for determination of the diffusion length.

The surface photovoltage (SPV) technique adapted to thin Si samples was used for monitoring of solar cell technology. The relatively short minority carrier diffusion length from 70 to 80 μm found in p-bulk of the cells results from the presence of a layer with structural defects near the surface. A diffusion length of about 300 μm was evaluated in the samples after removing the disturbed layer.

Effect of silicon nitride protection and antireflection coating on the minority carrier diffusion length in monocrystalline Si wafers represents another application. The Si wafers with plasma enhanced chemical vapour deposited and low pressure chemical vapour deposited nitride layers were compared. The value of the diffusion length and also ability of the SCR to sweep the minority carriers from the bulk were evaluated.

In order to evaluate diffusion length for thick sample the SPV signal is taken at the illuminated surface that is strongly influenced by its SCR as demonstrated on CdTe wafers. A model including recombination in the space charge region is presented to explain the SPV spectra. The contribution of the SCR is characterized by drift lengths of electrons and holes that play a similar role in the SCR as diffusion lengths of minority carriers in the bulk. The results are verified on samples with various resistivities.

Chapter 6 - Crystalline silicon solar cells have been the workhorse of the photovoltaic (PV) industry over the past decades. The dominant contributor to the cost of the solar cells is the cost of the silicon materials because the purity of the materials is quite high. It is well known that for any material, high purity implies high cost. The cost of electricity generated by solar cells can probably be greatly reduced if cells based on very low purity silicon can be made to operate with acceptably lower efficiencies. The major technical challenge will be finding a low-cost way to convert very low purity silicon (e.g., metallurgical grade silicon at a price of about $1/kg) into a material suitable for solar cell production.

An innovative silicon approach, silicon on defect layer (SODL), has been proposed to improve silicon materials. The experimental results achieved at Brookhaven and Sandia National Laboratories, USA, and the Chinese Academy of Sciences have demonstrated that the SODL approach leads to a novel superficial modification which offers a new opportunity to fabricate solar cells by using silicon materials with the lowest possible purity. If the SODL procedure is in combination with a plasma immersion ion implantation technique, there appears to be great potential for obtaining extremely inexpensive solar cells fabricated by using very low purity silicon. From a cost estimate, it is possible to achieve PV energy cost at a level of 7 cents/(kWh) which is comparable with the present cost of electricity generated by traditional energy resources such as fossil and petroleum fuels. Moreover, the SODL technique has the potential to extend its concept from silicon to other kinds of impure materials for solar cell fabrication.

In addition, a V-shaped module technique has been proposed to raise efficiencies for the above-mentioned low-purity-silicon solar cells and even numerous kinds of non-silicon solar cells.

Chapter 7 - In solar collector panels used for low-temperature applications such as heating of swimming pools, domestic water heating purposes in which the performance of an application essentially depends on its design and mainly on the optical and thermal stability of the material of which it is composed. Selective surfaces are already available; investigation on different deposition methods and materials still goes on at many labs. To improve the performance of these collectors considerable amount of work was undertaken to develop new, more efficient selective coatings with both high solar absorptance ($a > 0.9$) and low thermal emittance ($e < 0.1$) that are thermally stable, ideally in air, with improved durability and manufacturability and reduced cost. In this work, black Cu-Ni alloy coatings were deposited by electrodeposition using Hull cell since electroplating technique was industrially used for the production of selective black coatings as it offers a number of advantages. Plating parameters to optimize the optical properties of the solar selective coatings included the bath composition, current density, plating time, pH, thermal stability and substrate. Deposition of the coatings was made at room temp. The coatings obtained from optimized bath solution were coherent black and pore free, and exhibited good optical properties (solar absorptance $a = 0.94$ and thermal emittance $e = 0.08$) for solar energy conversion. The morphology and microstructure of the deposited coatings were characterized by scanning electron microscopy (SEM), X-ray diffraction studies, transmission electron microscopy (TEM). The coating may be promising for solar collector panels used in domestic water heaters.

Chapter 8 - The basic attention will be given to a new method of preparation of composites photosensitive in a wide spectral range which are based on polymers or $V_2O_5$ xerogel and polymethine dyes.

The high photosensitivity was observed in the composites with high concentration of polymethine dyes. The basic reason for widening the spectral region of photosensitivity for these composites is the formation of aggregates in them, for which the energy and efficiency of photogeneration of charge carriers are higher than those for quasi-isolated molecules of polymethine dyes.

The studied polymeric composites of polymethine dyes are multifunctional: they can be used as near-IR-radiation sensors (800-1400 nm) and plastic photovoltaic solar cells, as well as in the record of holograms.

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*Expert Commentary*

# FROM RANDOMLY DISTRIBUTED TO VERTICALLY ALIGNED BULK-HETEROJUNCTION SOLAR CELLS: A NEW ROUTE TO LOW COST PHOTOVOLTAICS?

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Solar cells based on organic materials are considered promising alternatives to their inorganic counterparts [1]. The advantages of organic materials are the easy tunability of their chemical properties, mechanical flexibility, low specific-weight and low-cost fabrication of large-area devices through easy solution-processing techniques [2].

Especially in the last decade, organic-based solar cells have attracted scientific and economic interest triggered by a rapid increase in power conversion efficiencies. This was achieved by the introduction of new materials, improved materials engineering and a more sophisticated device structure. Indeed an encouraging breakthrough in organic photovoltaics has been achieved with active layers obtained by blending an electron-donor (D) and an electron-acceptor material (A). The interpenetrating D/A network within these so-called "bulk-heterojunction" solar cells [3], Figure 1a, has to provide both an efficient exciton dissociation at the interface between the donor and the acceptor components, extended to the entire device volume, and separate pathways to the electrodes for the two types of charge carriers. Based on such interconnected networks of conjugated polymers, as electron-donors, with percolating buckminsterfullerene derivatives, as electron acceptors, power conversion efficiencies up to 5-6% have been achieved [4-5]. However, despite the progress made in this field, several issues must be addressed before organic materials can be considered for large-scale implementation in photovoltaics.

Morphology is a key factor for the efficiency of bulk-heterojunction solar cells [6], in which the donor and the acceptor phase form a randomly distributed bicontinuos network. Indeed, blend morphology has to enable both exciton dissociation at the distributed D/A interface and charge transport in the two different phases to avoid recombination. Currently, bulk-heterojunction cells rely on the accurate control of the blend morphology, through solvent and thermal annealing processes [4-5, 7-8]. However, the inherently disordered structure of the blends leads to both the reduction of carrier mobilities and the recombination between charges of opposite polarity.

The ideal morphology to balance exciton dissociation and charge transport requirements is a columnar segregated structure, perpendicular to the device electrodes, in which the size of the section of each donor or acceptor column is within an exciton diffusion length (a few tens of nm [9]). That vertically aligned D/A structure (Figure 1b) would provide an effective exciton dissociation, and, in the same time, would greatly reduce 'charge loss' by recombination, because of the independent and straight pathways to the appropriate electrodes provided for the two types of charge-carriers.

Some attempts have been made to self-organize ordered organic D/A bicontinuous architectures. To this purpose, D/A block-copolymers [10-11] as well as hydrogen-bonding interactions [12] have been proposed. However, the ideal vertically aligned D/A structure is hardly accessible through a full-organic approach and a few groups are moving toward vertically aligned architectures achieved through a hybrid approach. The vertically aligned hybrid architecture combines an inorganic semiconductor, nanostructured as a nanorod/nanofibril array or as a mesoporous layer, with an organic material. The inorganic nanostructure acts as a 'rigid' template for the subsequent infiltration, from solution, of the organic semiconductor, thus realizing the desired architecture for the active layer of solar cells. The optimum size for the horizontal domains of the nanostructured inorganics is determined by the exciton diffusion length of the organic component, in order to maximize the photogeneration process of free charge-carries.

Just a few attempts have been reported till now on hybrid solar cells, in which an organic material is deposited into a rigid nanostructured template. Nanoporous titania films [13-15] have been combined with p-type conjugated polymers, poly(3-hexylthiophene) and poly(2-methoxy-5-(2'-ethylhexoxy)-1,4-phenylenevinylene)- based polymers, acting as absorbers and electron-donor materials. Nanostructured rigid templates made of another high-bandgap n-type oxide, ZnO, have been recently proposed [16-18]. The nanostructured inorganics have been prepared using solution-based methods (sol-gel dip-coating, spin-coating, spray-pyrolysis deposition). The infiltration by the organic polymer has been improved by treating the inorganic nanostructures with an amphiphilic molecular layer [16] or by thermal annealing the hybrid devices [17]. These scarce and preliminary studies have shown the feasibility of this approach. However, the morphology of the investigated nanostructured inorganics was far from the ideal, resulting in a reduced charge-carrier photogeneration rate, thus in poor conversion efficiencies (not higher than 0.5 %).

The hybrid approach in obtaining vertically aligned D/A architectures could open new perspectives in the further development of low-cost organic-based photovoltaics. The challenges include the formation of nanostructured inorganic substrates with pore size comparable to exciton diffusion length and filling the organic materials into those pores. The skill lies in the nanostructuring of the inorganic component. The effort for obtaining the optimum morphology has to address the control of the shape (rods, fibrils, etc), size and density of the nanostructures. Another issue is the modification of the 'wettability' of the nanostructured substrates, in order to improve the infiltration by the organic materials.

It is worth noting that the technologies of bulk-heterojunction solar cells and of dye-sensitized solar cells [19] are converging. Indeed, while the former will take advantage from the nano-scale structural control achieved by the use of the inorganic semiconductor,

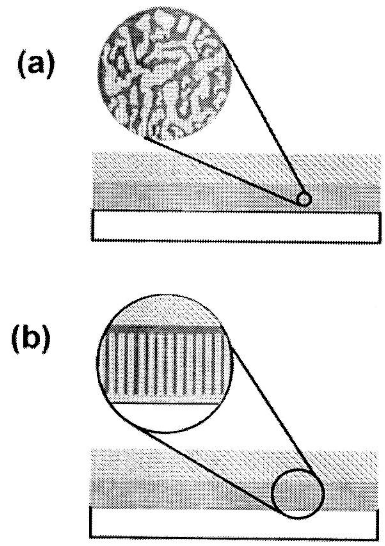


Figure 1. Schematic representation of (a) the randomly distributed bulk-heterojunction structure and of (b) the vertically aligned bulk-heterojunction structure.

the effort of the latter is in the direction of a full solid-state approach, through the replacement of the liquid electrolyte with a solid charge-transport material [20].

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*Short Communication A*

# EVALUATION ON COATING SHAPE OF SPACE SOLAR CELL BASED ON AUTOMATIC OPTICAL INSPECTION

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## ABSTRACT

This paper presents a quality evaluation method on the coating shape of space solar cells by means of the Automatic Optical Inspection (AOI). In order to ensure that solar panels are working with high reliability in space missions, their quality must be controlled in the manufacture process. Although the current-voltage (I-V) characteristic of space solar cells is well-recognized in quality assessment, the further research on the quality of the coating shape based on automatic optical inspection (AOI) is also necessary for the total quality control. In this paper, the quality evaluation method on the coating shape of space solar cells is presented via image processing technology, and some essential conditions are given to judge whether the coating shape is qualified or not. If the shape-factor assessment is finished, the next I-V characteristic assessment will become more efficient. The experimental results show that the method can prevent more products from being input into a simulated vacuum-space condition to be tested, and decrease time consuming and unnecessary cost.

**Keywords:** space solar cell array, automatic optical inspection, the quality of adhesive coating.

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# 1. INTRODUCTION

At present, most space missions adopt space panels as the electric power [1-2]. In the outer space environment, the intense space radiation and extremely high temperature variety can cause the property degradation of space panels. Thus, it is significant for space solar cells to possess the excellent performances of anti-irradiation and reliability. The adhesion quality between anti-irradiation coverglasses and solar cells, and between solar cells and solar panels must be well considered and evaluated.

The multiple-layer arrangement of a bonded solar panel assembly is illustrated in Figure 1.

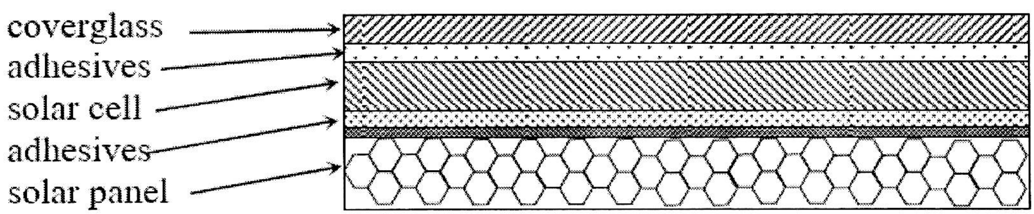


Figure 1. The structure of a bonded space panel, shown in a schematic vertical cut.

The assembly process usually has the following steps. First, a transparent coverglass with a single anti-reflective layer is bonded onto a thin-film space solar cell with silicone adhesive. The thickness of the attached silicone adhesive between them is required within 0.1 mm or less to ensure high photovoltaic conversion efficiency. After they are solidified, a series of solar cells are soldered together to a flexible cluster. Then, the next step is to bond the cluster onto a solar panel with another kind of silicone adhesive. Whether these bonding processes can provide high reliability or not is particularly important because they affect the photovoltaic power which plays a key role in overall space mission success [3]. In order to increase the security, the traditional bonding method is often conservative such as using superfluous adhesive. However, it brings some negative influences such as increasing the weight of spacecrafts and decreasing the photovoltaic conversion efficiency. To solve the quality problem of bonding space solar cells on the panel with the adhesive, it is essential to perform the quality evaluation.

The adhesive's shape has great influence on the bonding quality of space solar cells. An irregular shape may result in bad joining quality. Before assessing the photovoltaic conversion efficiency in a simulated space environment, we must conduct appearance evaluation on the adhesive's shape. If the adhesive shape is not qualified, it will have negative effect on the strength of joining. The adhesive joining with high quality can not only withstand repeated temperature cycle from -180 to +130°C, but also withstand the mechanical stress during the rocket launching. Manual work production has many disadvantages. The traditional unaided-eye testing methods result in a low evaluation efficiency [4-5], the manual manipulation requires engineers to be very highly technical, and the quality of surface bonding is hardly ensured due to the uncertainty of manual factors. Therefore, it is necessary to develop an auto-bonding robot for space solar panels with installation of an automatic optical inspection (AOI) system using the image processing technique.