50 Years of Solar Energy Research

EDITORS

Karin Hinzer
Matthew E. L. Jungwirth
Robert F. Hainsey

The content of this book reflects the work and thought of the authors and editors. Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Cover image generated by Microsoft Copilot.

SPIE.

Contents

Preface

Earth's solar resource is predictable and delivers more than 100,000,000 GW to water bodies and land. Solar thermal systems and photovoltaics are clean sources of energy, easily deployable, and made constant when combined with storage. Building on the demonstration of the photovoltaic effect in 1839 and the development of semiconductors in the 1950s, the first long-lived photovoltaic panels were deployed on satellites and space probes. The advent of widescale semiconductor manufacturing in the 1970s coupled with geopolitical events led to increased funding for research and development in alternative sources of energy. This prompted breakthroughs in photovoltaic technologies for terrestrial applications. Optics and photonics have been key to the development of high-efficiency, long-lived solar thermal and photovoltaic systems. This book highlights contributions to SPIE journals and proceedings over the last 50 years to bring this technology from lab bench to market.

Landmark papers. The papers are ordered chronologically to show technological evolution. The first paper on solar energy published by SPIE in 1974 was authored by Aden B. Meinel from the University of Arizona on 5 types of optical interfaces to increase optical-to-thermal energy transfer for concentrated solar collectors. Dr. Meinel envisions a future with large solar power farms capable of providing all electrical power requirements for the U.S. This paper was part of a proceedings collection for the SPIE Acquisition and Analysis of Pictorial Data conference. The first SPIE paper on concentrator optics was authored by E. L. Burgess from Sandia National Laboratories, in 1977. It reviews concentrator geometries and technologies and includes a cost analysis of concentrator photovoltaic systems from 1-sun to 1000-sun. The paper discusses silicon and gallium arsenide single-junction cells as well as 1- and 2-axis tracking systems. Early on, researchers explored thin film next-generation technologies other than silicon, as shown in the 1980 exhaustive review paper of S. K. Deb and W. L. Wallace. Light trapping has been used for decades to increase photovoltaic cell efficiency. The 1990 paper by M. T. Gale, B. J. Curits, H. Kiess, and R. Morf describes submicron grating structures for light trapping in very thin silicon photovoltaic cells to further increase device efficiencies. The 2009 paper authored by Rajendra Singh summarizes the reason for the technical and economic success of the silicon photovoltaic industry.

Thin films. Thin film technologies show high efficiencies, can use less material than purely silicon photovoltaics, can be integrated in multijunctions, and can be made flexible. Three papers in this collection discuss the rapidly emerging field of perovskite photovoltaics. The 2016 review paper by Zhaoning Song et al. is on organo-metal halide perovskites for photovoltaics; Yuxiong Zhou et al. (2019) describe methods for improving thermal and ambient stability, while Erkan Aydin et al. (2021) display results from the first outdoor tests

of perovskite/silicon tandem photovoltaic cells. Bülent M. Başol and Brian McCandless (2014) provide a review of cadmium telluride thin film technologies that include cell design, system performance, and life cycle profile. Louay Eldada (2011) describes copper indium gallium selenide (CIGS) photovoltaic module fabrication. From the same year, David C. Miller et al. describe the role of transmitted optical spectrum in concentrated photovoltaic systems for accelerated testing with multijunction gallium arsenide–based cells, while Alexander Slade et al. (2005) demonstrate early concentrated photovoltaic outdoor performance results. Masao Isomura et al. (1993) provide details on improved amorphous silicon photovoltaic cell performance by optimizing layers and fabrication steps. Ikerne Etxebarria et al. (2015) review polymer:fullerene photovoltaics that include multijunctions.

Emerging technologies. As solar thermal and photovoltaic technologies have matured, emerging concepts and new applications have been developed. These include work by Makoto Shimizu et al. (2015) on thermophotovoltaics to transform high-temperature heat into electricity, and the proposed uses of metamaterials to increase optical absorption (Patrick Rufangura and Cumali Sabah, 2018) and non-reciprocal photonic management in multijunction photovoltaic cells to increase efficiencies (Andrei Sergeev and Kimberly Sablon, 2022). The book concludes with a 2023 status report by Annick Anctil et al. on emerging photovoltaic cells & systems, sustainability, applications, and a survey regarding the needs and future evolution of photovoltaics.

In 2024, photovoltaics and solar energy will provide more than 6% of the world's electricity needs. The papers we have selected for this book cover essential aspects of deployed technologies as well as the technologies used for development of next-generation systems.

Karin Hinzer
Matthew E. L. Jungwirth
Robert F. Hainsey
July 2024

OPTICAL INTERFACES IN SOLAR ENERGY UTILIZATION

Aden B. Meinel
University of Arizona,
Helio Associates, Inc.
Tucson, Arizona

Solar energy is attracting considerable national attention as a potential new option in the search for energy alternatives for the future. The dream of the use of solar energy is not new. Since solar energy interest has grown and waned in the past one immediately wonders what might be new this time that would lead to success. Do the problems encountered in the past still hold today? If not, what is new that could make solar energy a practical reality? I would like to address this question in some detail under the title of this session: Optical Interfaces; since there obviously is a very important role for optical technology in solar energy, ranging from optical collectors to solid-state physics, but first, some background should be presented.

Many ways of using solar energy have been proposed, and each appears to have a good technological basis. A point we want to stress is that technological achievement is only the first step. The more important factors that will see many solar schemes fall by the wayside are the hard facts of economics and the realities of social asymilation of technological advances.

Scientists and engineers like to invent and talk about the revolutionary changes that will be forced upon us in "the world of the future". We would like to point out that society prefers evolutionary changes. When slow changes are possible, revolutionary changes are socially unacceptable, and many a revolutionary view of the future lies buried in past issues of popular magazines. It is only when evolutionary changes are forbidden that revolutionary changes spontaneously occur. In the energy field, we do not see that evolutionary changes are forbidden. We, therefore, urge that engineers adhere to the basic philosophy that changes that cause the lease change in the way people live and think will be the ones that have a chance for success.

Solar energy is a good idea, made irresistable since it has that quality which motivated the pioneers — of something you can acquire and use yourself. Solar energy is delivered to where you are and it is free. No one can lease or control sunshine. The problem is that you must first capture it, and this costs money and/or ingenuity. Capturing it is where we encounter the optical interface.

The sun is a prodigious source of energy. It is a fusion reactor, gravitationally contained, safely shielded from us by 93,000,000 miles and the beneficent depth of our terrestrial atmosphere. Its energy output arriving at the earth in one day is more than man has used since creation. It will last for billions of years into the future, without our yea or nay. We even hope to make small models of the sun work successfully in our laboratories and later in our terrestrial power plants, but unfortunately, that dream is still clouded by massive problems. So until the day that fusion power is successfully achieved, our only long range energy source will remain the sun. The question now is: can we use it in the decades immediately ahead?

The chief modes of using solar energy can be divided into two major groupings: biological and technological. Nature has been able to convert sunlight into useful forms of food, clothing, and for the hearth. The basic problem is that the efficiency of photosynthesis is not high, about 1% for the best crops during their peak growing seasons. When nature has millions of years to accumulate the remains of plant and animal life, one gets coal and oil. The question now is: can man accelerate the biological process and grow crops for energy in addition to food and fibre? The answer is probably yes, but a yes answer is in the shadow of a more ominous spectre, that of a world food shortage. The hard fact is that most of the world's arable land and water supply is already stressed to the limit to feed the world's population, so where will the additional land, water, and fertilizer come from to grow crops for burning and chemicals production? One ingeneous answer is to use the

Photovoltaic Energy Conversion Using Concentrated Sunlight

E. L. Burgess

Sandia Laboratories
Albuquerque, New Mexico 87115

Abstract

This paper describes a development program which uses sunlight concentration techniques to effect an immediate reduction in cost-per-unit power for photovoltaic systems in which solar cell cost dominates the total system cost. Current examples of concentrator solar cell technologies are single crystal silicon and gallium arsenide. Implementation of cost reductions by the use of sunlight concentration is not dependent on the development of low-cost, mass-production cell technologies but emphasizes high cell efficiency and low-cost concentrator systems.

Introduction

The photovoltaic cell or solar cell can be used to convert terrestrial sunlight directly into electrical energy. The relatively simple construction and absence of moving parts make these devices potentially attractive for electrical power generation in terrestrial applications ranging from individual residences to central power plants. The device technology is well developed, particularly single crystal silicon cells, as a result of extensive use in the space program. There are over 500 satellites in earth orbit which derive a significant amount of their electrical power requirements from silicon solar cells. Unfortunately, the cost of such cells today is prohibitive for practical, large-scale use in terrestrial applications. For example, an array which would produce one peak (solar noon) kilowatt of electrical power would cost approximately $20,000–$25,000.

The United States Energy Research and Development Administration (ERDA) has established a National Photovoltaic Conversion Program which has as its primary objective the development of low-cost reliable photovoltaic systems for widespread terrestrial applications. Two parallel strategies are being pursued in order to reach this objective. The first approach, and the one that has received the greatest emphasis to date, is to reduce the cost of solar arrays through methodical cost reduction of the various process steps and by large scale production. This program is called the Low-Cost Silicon Solar Array Program (LSSA) and is under the technical management of the Jet Propulsion Laboratory for ERDA.

The second approach, and the subject of this paper, is to increase the specific output power density of cells with concentrators. In a concentrator array, solar cell area is replaced with equivalent areas of lower cost reflective or refractive materials. The result is an immediate cost-per-unit power reduction to those solar cell technologies in which the cell cost dominates the total system cost. Sandia Laboratories has the technical management responsibility for the Concentrator Subsystems Development Task (CSD)* of the ERDA National Photovoltaics Conversion Program.

---

*The Concentrator Subsystem Development Task is one of two tasks of the Systems Definition Project of the ERDA Photovoltaic Program and is managed by Sandia Laboratories.

Some major cost and production goals of these two programs are shown in Table 1. In comparing these two approaches from the CSD point of view, one sees that not only does the CSD program offer an alternative to reaching the low-cost goal but the overall program is projected to be less expensive due to the lower production experience required to reach intermediate cost goals. Finally, the energy payback will be quicker for a concentrator array. This may be visualized by considering an array which concentrates sunlight by a factor of 100. If it requires, say 5 years, to pay back the energy used in making the silicon cells for a nonconcentrated array, it would require only 18 days plus the energy payback time for the concentrator materials for the 100X concentrator subsystem. The concentrator materials require, in general, much less energy to produce than silicon due to lower impurity requirements and lower process temperatures. These types of considerations are creating increased interest in the concentrator approach.

This paper describes a typical concentrator photovoltaic subsystem and the various types of concentrators which are being considered for photovoltaic applications. The energy intercepted by these different concentrator types is tabulated and used to analyze the effect of concentration ratio, cell cost and cell efficiency on energy cost. Finally, the concentrator subsystem development program established to reach the goals of this program is briefly described.

Concentrator Photovoltaic Subsystem

Figure 1 is a sketch of a concentrator photovoltaic subsystem which illustrates all of the components that are normally associated with the subsystem. The optical concentrator with an aperture area, A_O, intercepts the solar flux and concentrates it on the receiver placed at the focal position of the concentrator. The solar cells are mounted on the receiver and have a total area, A_c. Thus the geometrical concentration of the subsystem, CR, is the ratio, A_O/A_c. The actual concentration ratio, ACR, at the solar cell is given by

$$ACR = \eta_O A_O / A_c \tag{1}$$

where η_O is the total optical efficiency of the concentrator and includes reflection or transmission losses of the optics as well as optical aberrations. The structural supports include all the structure necessary to rigidly support the concentrator and receiver. The tracker consists of the mechanism required to rotate the array and keep it pointed toward the sun. Since the solar cells absorb more than 80% of the solar energy and convert only 10–20% to electrical energy, the excess energy appears as heat and must be removed to maintain the temperature of the cells at a relatively low level. The heat removal components perform this function.

There are many variations of a concentrator photovoltaic subsystem. Figure 1 illustrates reflective optics, two-axis tracking, and active cooling. Refractive optics, one-axis or no tracking, and passive cooling are also being considered. The remainder of the paper will discuss these various variations in more detail. Another variation to the basic concentrator subsystem is being investigated by Sandia Laboratories[1] and other research-

Status of nonsilicon photovoltaic solar cell research

S. K. Deb, W. L. Wallace
Photovoltaics Division, Solar Energy Research Institute
1617 Cole Boulevard, Golden, Colorado 80401

Abstract

The current status of non-silicon photovoltaic solar cells is discussed including the identification of current technical and economic issues and future research directions for potential high efficiency low cost technologies. This review covers such advanced materials as CdS/Cu_2S, $CdS/CuInSe_2$, and GaAs homojunction and heterojunction devices; such emerging materials as InP, Zn_3P_2 and CdTe; and liquid junction electrochemical photovoltaic cells. An attempt is made to compare the current relative status of these various technologies and to indicate their near term potential where possible.

1.0 Introduction

Nearly one hundred and forty years ago the photovoltaic effect was first discovered by Becquerel[1] with the detection of a photovoltage between illuminated AgCl and Pt electrodes immersed in an electrolyte. Since that time the first one hundred years of sporadic solar cell research was dominated almost exclusively by non-silicon materials. During this period extensive research was carried out on such materials as selenium, metal oxides and metal sulfides. With the advent of semiconductor technology, however, and the development of boron doped silicon by a diffusion process, the fabrication of the first stable photovoltaic cell based on silicon was accomplished by Chapin, Fuller and Pearson[2] in 1954. The enormous growth in solid state technology utilizing silicon has put that material in the unique position of currently being the most extensively studied candidate semiconductor material for photovoltaic applications. Reliable, high efficiency solar cells based on single crystal silicon are widely available today for space and terrestrial use and silicon has the added advantage of being one of the most abundant elements occurring in nature.

With such formidable technology behind silicon, it is reasonable to ask why non-silicon materials should be explored for solar cell applications. The answer is that silicon, in spite of its high technological development, has several disadvantages. First of all, silicon with a bandgap of 1.1 eV is not the optimum photovoltaic material based on theoretical conversion efficiency. As shown in Figure 1, which correlates the theoretical conversion efficiency (η) as a function of the energy gap (E_g), there are a number of materials which are potentially more efficient than silicon based on bandgap considerations alone. In addition, an efficient p-n junction photovoltaic device should satisfy the following two criteria: (i) the product of the minority carrier diffusion length (L) and the optical absorption coefficient (α) should observe the relationship $\alpha L \geq 3$; and (ii) the product of the optical absorption coefficient (α) and the semiconductor film thickness (t) should satisfy the condition $\alpha t \gg 1$. Silicon being an indirect bandgap semiconductor has low optical absorption coefficients and, therefore, cannot satisfy the first condition, $\alpha L \geq 3$, as easily as direct bandgap semiconductors. The implication is that for an indirect bandgap material more stringent requirements will necessarily be placed on crystalline perfection and grain size, as pointed out by Ghosh[3] in order to maximize the minority carrier diffusion length and optimize various other material parameters. Similarly, for indirect bandgap materials, satisfying the second requirement, $\alpha t \gg 1$, will necessitate the use of larger film thicknesses, which in turn implies less material economy and can lead to problems in maximizing carrier collection efficiencies and in device fabrication. Based upon these considerations, direct bandgap materials are in general more appropriate for solar energy conversion than indirect gap materials.

The projected cost of photovoltaic module and array systems and DOE cost goals are shown in Figure 2. It is expected that the price of silicon based systems will come down to approximately \$0.70/Wp (in 1980 dollars) by the year 1986. However, in order to bring the price level of photovoltaic cells down to the more practical level of approximately \$0.15/Wp, it will be necessary to develop thin film devices via relatively low cost mass production processes. Exemplifying the cost potential for non-silicon technologies is the cost analysis made by Westinghouse on the CdS/Cu_2S thin film solar cell, which indicates that this technology is capable of meeting the DOE price goals indicated in Figure 2[4].

The non-silicon materials that are currently most widely investigated for photovoltaic solar cell applications can be classified into the following categories:

Design and fabrication of submicron grating structures for light trapping in silicon solar cells

M.T. Gale, B.J. Curtis, H. Kiess and R. Morf

Paul Scherrer Institute c/o Laboratories RCA Ltd., Zürich, Switzerland

ABSTRACT

The application of submicron grating structure for light trapping in thin silicon solar cells has been investigated theoretically and experimentally. A gain in absorption corresponding to an increase in thickness of more than a factor of 4 for polarized light and about 3 for unpolarized light has been demonstrated.

INTRODUCTION

Thin crystalline or polycrystalline silicon solar cells are of great interest for improved efficiency energy conversion., The improvement results from the relaxed requirements on the diffusion length of minority carriers and the reduction of recombination losses, which scale with the volume of the cell [1,2]. The overall efficiency of such cells is, however, at the same time limited by incomplete absorption of light at longer wavelengths (near the silicon band gap) due to the finite cell thickness.

The application of submicron grating structures for light trapping in thinned silicon solar cells is being theoretically and experimentally investigated for overcoming this limitation. In contrast to coarse texturing, such structures are compatible with thin cells. Initial work has concentrated on the use of grating structures with a period of 310 nm [3,4]. In this paper we describe experimental techniques for the fabrication of the submicron structures and summarize the results obtained. More recent results for gratings with a period of 620 nm, with improved optical characteristics and less stringent fabrication tolerances, are also presented.

2. LIGHT TRAPPING IN SOLAR CELLS

It has been long been recognized that the internal efficiency of crystalline Si solar cells can be significantly increased if their thickness is reduced from the conventional thickness of about 400 μm to below 100 μm. The gain in efficiency is estimated to be of the order of 1/5 relative to a thick cell, i.e. a 400 μm cell of 15% would have an efficiency of about 18% if thinned down by about a factor of ten. Theory implicitly assumes that the fraction of absorbed solar radiation remains unchanged, although in reality thin Si-cells transmit long wavelength light which would otherwise be absorbed and photoelectrically utilized by thick cells. (It is also assumed that the surface recombination velocity is so low such as not to adversely affect the efficiency - this aspect will not be treated here).

This paper is concerned with the problem of how to maximize the absorbed solar energy in thin cells by reducing the incomplete absorption at long wavelengths, close to the band gap of the silicon. We have suggested the use of metallized submicron structures to optimize the absorption of thin Si cells by light trapping [3], the basic design of the cell being illustrated in Fig. 1. Proposals for the use of coarse texturing of 5 to 10 μm dimensions in depth are not considered realistic for cells of 20 to 40 μm thickness, since they would result in excessive variations in the cell thickness. In contrast, the grating design presented here would not interfere with the cell thickness, even if it were in the micrometer range.

Correlation between Material Properties and Photovoltaic Performance
in Amorphous Silicon Solar Cells

Masao Isomura, Yoshihiro Hishikawa, Toshihiro Kinoshita, Shingo Okamoto,
Manabu Sasaki, Tsuyoshi Takahama, Takao Matsuyama, and Shinya Tsuda

Functional Materials Research Center, SANYO Electric Co., Ltd.
1-18-13 Hashiridani, Hirakata, Osaka 573, Japan

ABSTRACT

We have focused on the i-layer material in our efforts to improve in the conversion efficiency of a-Si:H solar cells. Reductions in the defect density has been also investigated from the viewpoints of extrinsic (impurities) and intrinsic effects. The main incorporated impurity in a-Si:H is oxygen, which affects the conversion efficiency of a-Si:H solar cells by increasing the defect density and its donorlike behavior. A unified relationship can be observed among the properties of intrinsic (pure) a-Si:H. The film deposition rate plays an essential role in controlling the properties. A lower or higher deposition rate results in a narrower or wider bandgap, respectively. Therefore, the properties of a-Si:H can be controlled independent of the substrate temperature in a certain range by varying the film deposition rate. The controllability of the a-Si:H properties can be improved by applying vibrational / rotational energy to SiH_4 molecules or related radicals by heating the source gas, and a-Si:H with the same properties as the best conventional one can be deposited at a lower substrate temperature and/or a higher film deposition rate. The highest conversion efficiency of 12% for an integrated a-Si solar cell submodule of 100 cm^2 has been achieved by combining the high-quality i-layer and other technologies.

1. INTRODUCTION

A-Si:H was first reported in 1969, using a glow discharge with silane gas (SiH_4).[1] It was confirmed that a-Si:H has good electrical properties with a high carrier mobility[2] and high photosensitivity with a low defect density.[3] The incorporated hydrogen terminates dangling bonds in a-Si:H. Significant progress in the development of a-Si:H technologies was made with the substitutional p-type or n-type doping of a-Si:H by adding diborane (B_2H_6) or phosphine (PH_3), respectively, to the deposition gas.[4] Since these reports, a-Si:H has received considerable attention as an electronic material and has been investigated intensively in several laboratories.

The device research of a-Si:H solar cells was started in 1976,[5] and the first a-Si:H solar cells were put onto the market by our group as a power source for hand-held calculators in 1980.[6] A-Si:H solar cells offer a great advantage as a low-cost energy source compared with crystalline materials. Subsequent research has enabled the development of several technologies, such as an a-SiC:H window layer,[7] a reduction in incorporated impurities,[8,9] and a laser patterning method.[10] The conversion efficiency has also been improved year by year. However, it still remains about half that of single-crystal solar cells, and further improvements in efficiency are of primary importance.

A-Si:H solar cells usually have a pin structure because the carrier diffusion length in a-Si:H is so short that the carrier diffusion does not enable sufficient photovoltaic properties. Photogenerated carriers in the intrinsic layer (i-layer) are separated toward the n- or p-layers by the electric field created by the built-in potential within the pin junction and thus a photovoltaic effect occurs. Therefore, the i-layer is the most important part of the a-Si:H solar cell. Defects in the i-layer, however, prevent the transport of photogenerated carriers. If the defect density is sufficiently reduced, the electric field in the intrinsic layer is uniformly spread with built-in potential, and most photogenerated electrons and holes are immediately separated to the n and p-layers, respectively, as shown in Fig. 1 (a). On the other hand, the electric field in the middle of the i-layer is weakened by the charged defects near the p/i and i/n interfaces if the defect density is not sufficiently reduced. In this region, photogenerated carriers cannot move quickly, and some of them recombine through the defects, as shown in Fig. 1 (b). This mainly causes a decrease in the fill factor (FF) and consequently obstructs the energy conversion.

The defects result from several sources, such as structural disorder, incorporated hydrogen, and impurities. Structural disorder and incorporated hydrogen are, however, important features of a-Si:H, and they give several advantages to a-Si:H. Therefore, it is important to optimaize the conditions, extracting only the good features from them as much as

High Efficiency Solar Cells for Concentrator Systems: Silicon or Multi-Junction?

Alexander Slade, Kenneth W. Stone, Robert Gordon and
Vahan Garboushian

Amonix Inc.
3425 Fujita Street, Torrance CA 90505 USA

ABSTRACT

Amonix has become the first company to begin production of high concentration silicon solar cells where volumes are over 10 MW/year. Higher volumes are available due to the method of manufacture; Amonix solely uses semiconductor foundries for solar cell production. In the previous years of system and cell field testing, this method of manufacturing enabled Amonix to maintain a very low overhead while incurring a high cost for the solar cell. However, recent simplifications to the solar cell processing sequence resulted in cost reduction and increased yield. This new process has been tested by producing small qualities in very short time periods, enabling a simulation of high volume production. Results have included over 90% wafer yield, up to 100% die yield and world record performance (η =27.3%). This reduction in silicon solar cell cost has increased the required efficiency for multi-junction concentrator solar cells to be competitive / advantageous.

Concentrator systems are emerging as a low-cost, high volume option for solar-generated electricity due to the very high utilization of the solar cell, leading to a much lower $/Watt cost of a photovoltaic system. Parallel to this is the onset of alternative solar cell technologies, such as the very high efficiency multi-junction solar cells developed at NREL over the last two decades. The relatively high cost of these type of solar cells has relegated their use to non-terrestrial applications. However, recent advancements in both multi-junction concentrator cell efficiency and their stability under high flux densities has made their large-scale terrestrial deployment significantly more viable. This paper presents Amonix's experience and testing results of both high-efficiency silicon rear-junction solar cells and multi-junction solar cells made for concentrated light operation.

Keywords: Concentrator Cells, High-Efficiency, Silicon Solar Cells, Multijunction Solar Cells

1. Introduction

Amonix Inc., having produced more GWh of high concentration photovoltaic generated power than anyone in the world, is ideally suited to benefit from this new concentrator solar cell technology. So far, the systems fabricated by Amonix (see figure 1) utilize silicon rear-junction, point-contact solar cells that are also produced by Amonix [1]. Exhaustive testing showed the cell to stable under prolonged exposure to UV radiation, diurnal temperature cycling, high current density and outdoor weathering; this stability of the silicon cell enabled Amonix to develop an

Why silicon is and will remain the dominant photovoltaic material

Rajendra Singh

Center for Silicon Nanoelectronics and Holcombe Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634-0915
rajendra.singh@ces.clemson.edu

Abstract. Rising demands of energy in emerging economies, coupled with the green house gas emissions related problems around the globe have provided a unique opportunity of exploiting the advantages offered by photovoltaic (PV) systems for green energy electricity generation. Similar to cell phones, power generated by PV systems can reach over two billion people worldwide who have no access to clean energy. Only silicon based PV devices meet the low-cost manufacturing criterion of clean energy conversion (abundance of raw material and no environmental health and safety issues). The use of larger size glass substrates and manufacturing techniques similar to the ones used by the liquid crystal display industry and the large scale manufacturing of amorphous silicon thin films based modules (~ GW per year manufacturing at a single location) can lead to installed PV system cost of \$3/Wp. This will open a huge market for grid connected PV systems and related markets. With further research and development, this approach can provide \$2/Wp installed PV system costs in the next few years. At this cost level, PV electricity generation is competitive with any other technology, and PV power generation can be a dominant electricity generation technology in the 21st century.

Keywords: Solar cells, photovoltaic system, silicon, manufacturing, nanostructures, clean energy, amorphous silicon, and thin film.

1 INTRODUCTION

Humans and other living creatures on Earth rely on solar energy as the key source of energy for their existence. The earth receives 174 pettawatt (1 PW = 10^{15}W) of solar radiations at the upper atmosphere [1]. From this amount 29% is reflected back to space 23% is absorbed by the atmosphere, and 48% (~ 87 PW) is received by the earth's surface [1]. In 2006, global energy consumption was about 16 terawatt (1 TW = 10^{12} W) [2], which is only 0.018% of the solar energy received by the earth. Since the invention of solar cells in 1954, photovoltaic (PV) systems have gained the reputation of a reliable power source for space and certain terrestrial applications. Mankind's dependence on fossil fuels has negatively impacted the environment and is responsible for global warming. Photovoltaics offer a unique opportunity to solve the 21st century's energy and environmental problems simultaneously, because solar energy is essentially unlimited and solar cells can convert it into electrical energy without any undesirable impact on the environment. Thus, photovoltaic (PV) technology is an ideal clean and reliable renewable source of electricity generation for space and terrestrial applications. Currently, wafer based silicon (single crystal, polycrystalline and multi-crystalline) solar cells and thin film solar cells based on amorphous silicon, CdTe, $CuInGaSe_2$ (CIGS) and III-V semiconductors dominate PV manufacturing for terrestrial applications [3]. For future generations of solar cells a number of approaches are being explored [4].

PV manufacturing based on semiconductor substrates has its origin in semiconductor manufacturing and most of the thin film PV manufacturing (use of large glass substrate) has its origin in liquid crystal display (LCD) manufacturing. Based on an examination of the fundamentals of materials, devices, systems and the experience of semiconductor

Analysis of transmitted optical spectrum enabling accelerated testing of multijunction concentrating photovoltaic designs

David C. Miller
Michael D. Kempe
Cheryl E. Kennedy
Sarah R. Kurtz
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
E-mail: david.miller@nrel.gov

Abstract. Concentrating photovoltaic (CPV) technology has recently gained interest based on its scalability and expected low levelized cost of electricity. The reliability of encapsulation materials used in CPV systems, however, is not well established. For example, the present qualification test for CPV modules includes only real-time ultraviolet (UV) exposure, i.e., methods for accelerated UV testing have not yet been developed. To better define the stress inherent to CPV systems, the UV and infrared spectra transmitted through representative optical systems were evaluated. Measurements of optical components are used to assess expected optical performance and quantify damaging optical exposure. Optical properties (transmittance, refractive index, reflectance, and absorptance) of candidate materials (including PMMA, soda-lime glass, borosilicate glass, and quartz refractors), components (including Ag- and Al-enabled reflectors), and encapsulants (including EVA, ionomer, PDMS, PPMS, polyolefin, and PVB) were identified. The activation spectrum was calculated for the representative optical systems using an assumed action spectrum to compare the expected damaging dose of UV radiation delivered to the cell encapsulation. The dose and flux analysis identifies the significance of IR relative to UV exposure for CPV systems. Because UV light is typically more highly attenuated, the UV dose within the encapsulation may not greatly exceed the unconcentrated global solar condition, but the thermal load scales nearly directly with the geometric concentration. Relative to a previous analysis for crystalline silicon cell technology, the analysis here is performed for III-V multijunction technology. Novel aspects here also include additional materials (such as TPU encapsulation) and additional components (transmission through silicone on glass lenses, antireflective coatings, and the front glass used with reflective systems, as well as reflection off of the cell). © *2011 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.3530092]

1 Introduction

Concentrating photovoltaic (CPV) technology has recently gained interest based on its scalability and expected low levelized cost of electricity. In some locations, power production may be improved by illuminating high-efficiency multijunction cells[1,54] using concentrating optics[2] that track the sun to harvest its direct (versus global) radiation. Figure 1 compares the cross-section for a traditional flat-panel photovoltaic (FP-PV) system to those that may be present in refractive and/or reflective CPV systems. The figure represents the essential optical components present, including the PV cell, but does not include heat sinks or mechanical components (such as module walls or opto-mechanical fixtures). FP-PV, Fig. 1(a), uses a glass superstrate (such as low-iron soda-lime glass) as well as encapsulation (such as ethylene-co-vinyl acetate "EVA," 33 wt %. vinyl acetate) to isolate the cell from the environment while providing mechanical and optical coupling. Refractive CPV systems, Fig. 1(b) and 1(c), use a lens (such as a faceted Fresnel lens[3]) to focus light, where the geometric concentration, C_g, may be approximated from the ratio of the area of the lens perpendicular to the incident light to the absorbing area at the PV cell. Reflective systems use a mirror either to redistribute, Fig. 1(d), or focus, Fig. 1(e), the solar flux onto a PV cell. A simple flat front glass may be used in reflective systems to facilitate cleaning and improve durability (e.g., against hail impact). A kaleidoscope homogenizer (indicated in Fig. 1 as a transmitting component) is a secondary optic using total internal reflectance to improve flux uniformity, compensate for misalignment, provide for manufacturing tolerance, reduce chromatic aberration, and compensate for focusing errors, while also providing additional optical concentration.

The photodegradation of materials used in CPV systems is not well established relative to the desired service life of 30 years. The present qualification test for CPV modules[4] includes only real-time ultraviolet (UV) exposure. Methods for accelerated optical testing have not been formally developed because of the difficulty of simulating the service exposure to highly concentrated sunlight in a reasonable time. More

Thin Film CIGS Photovoltaic Modules:
Monolithic Integration and Advanced Packaging
for High Performance, High Reliability and Low Cost

Louay Eldada

HelioVolt Corporation, 6301-8 E. Stassney Lane, Austin, TX, USA 78744

ABSTRACT

In recent years, thin-film photovoltaic companies started realizing their low manufacturing cost potential, and have been grabbing an increasingly larger market share. Copper Indium Gallium Selenide (CIGS) is the most promising thin-film PV material, having demonstrated the highest energy conversion efficiency in both cells and modules. However, most CIGS manufacturers still face the challenge of delivering a reliable and rapid manufacturing process that can scale effectively and deliver on the promise of this material system. HelioVolt has developed a reactive transfer process for CIGS absorber formation that has the benefits of good compositional control, and a fast high-quality CIGS reaction. The reactive transfer process is a two stage CIGS fabrication method. Precursor films are deposited onto substrates and reusable cover plates in the first stage, while in the second stage the CIGS layer is formed by rapid heating with Se confinement. HelioVolt also developed best-in-class packaging technologies that provide unparalleled environmental stability. High quality CIGS films with large grains were fabricated on the production line, and high-performance high-reliability monolithic modules with a form factor of 120 cm × 60 cm are being produced at high yield and low cost. With conversion efficiency levels around 14% for cells and 12% for modules, HelioVolt is commercializing the process on its first production line with 20 MW capacity, and is planning its next GW-scale factory.

Keywords: thin film photovoltaics, copper indium gallium selenide, CIGS, reactive transfer, monolithic photovoltaic modules, solar panels, packaging, reliability

1. INTRODUCTION

The interest in harnessing the Sun for energy through photovoltaic (PV) technologies has increased tremendously in recent years, as the importance of using renewable energy has moved to the forefront of social consciousness. With their cost advantage, thin-film PV technologies have been attracting especially high attention. Copper Indium Gallium Selenide (CIGS) is the most promising thin-film material, having exhibited the highest thin film energy conversion efficiency levels. Record efficiencies of 20.3% for cells [1] and 15.1% for modules [2] have been achieved. However, it has been challenging for CIGS manufacturers to deliver a reliable and rapid manufacturing process that can be scaled effectively. In this paper, we describe such a process developed by HelioVolt and scaled up on its first 20 MW capacity production line in Austin, Texas. The process is based on reactive transfer and has the benefits of high speed, high uniformity, and precise compositional control [3].

2. THIN FILM PHOTOVOLTAICS

A new generation of solar electric products has emerged recently from the lab into the global market. Much innovation centers around thin-film solar technologies that use approximately 1% of the active and expensive photovoltaic material to convert photons from the sun into electrons. Through a combination of cost advantages and new product applications, thin-film solar power generation is serving as a paradigm shift toward distributed electricity generation at cost parity with other forms of energy. CIGS has long been the most promising thin-film photovoltaic material, used for its high conversion efficiencies in advanced spacecraft applications, but has not had a reliable and rapid manufacturing process that could scale effectively and provide significant amounts of electricity at the point of use. HelioVolt's reactive transfer process is one such robust manufacturing process, enabling the rapid printing of microscale CIGS films with

Brief review of cadmium telluride-based photovoltaic technologies

Bülent M. Başol[a],* and Brian McCandless[b]

[a]Encore Solar, 6541 Via Del Oro, Suite B, San Jose, California 95119
[b]University of Delaware, Institute of Energy Conversion, 451 Wyoming Road, Newark, Delaware 19716

Abstract. Cadmium telluride (CdTe) is the most commercially successful thin-film photovoltaic technology. Development of CdTe as a solar cell material dates back to the early 1980s when ~10% efficient devices were demonstrated. Implementation of better quality glass, more transparent conductive oxides, introduction of a high-resistivity transparent film under the CdS junction-partner, higher deposition temperatures, and improved Cl-treatment, doping, and contacting approaches yielded >16% efficient cells in the early 2000s. Around the same time period, use of a photoresist plug monolithic integration process facilitated the demonstration of the first 11% efficient module. The most dramatic advancements in CdTe device efficiencies were made during the 2013 to 2014 time frame when small-area cell conversion efficiency was raised to 20% range and a champion module efficiency of 17% was reported. CdTe technology is attractive in terms of its limited life-cycle greenhouse gas and heavy metal emissions, small carbon footprint, and short energy payback times. Limited Te availability is a challenge for the growth of this technology unless Te utilization rates are greatly enhanced along with device efficiencies. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JPE.4.040996]

1 Introduction

For decades, the case for thin-film photovoltaics (PV) has been its low-cost potential. It was argued that inexpensive, large-area deposition methods could be developed to yield high-efficiency devices, and monolithic integration methods would lower the cost of module fabrication. Having achieved many of these targets, cadmium telluride (CdTe) is today the most commercially successful thin-film PV technology with a market share of ~5 to 6%. CdTe, with its near-ideal bandgap of ~1.5 eV and high optical absorption coefficients, was recognized to be a promising thin-film solar cell material back in 1950s.[1] But, it took researchers nearly three decades of R&D work to translate this potential into the first encouraging results when ~10% efficient devices were reported during the 1980–1985 period by groups using a variety of film growth techniques, such as screen printing,[2] close-space sublimation (CSS),[3] and electrodeposition (ED).[4] Then, yet another three decades of R&D effort was needed for the CdTe cell efficiency to reach the present 20.4% level[5] and for the CdTe module to become a strong competitor in the global PV market.

CdTe solar cells can be fabricated in superstrate or substrate configurations. As shown in Fig. 1(a), devices with the superstrate configuration are processed by forming a transparent-conductive-oxide (TCO)/junction-partner/CdTe/back-contact stack on a transparent sheet, i.e., superstrate, through which light enters the device. In the substrate configuration of Fig. 1(b), the deposition sequence is reversed and the stack is formed on a substrate, which does not have to be transparent. The highest-efficiency devices and commercialized modules have typically been fabricated using the superstrate configuration.

---

*Address all correspondence to: Bülent Başol, bbasol@Encore-Solar.com

High-efficiency solar-thermophotovoltaic system equipped with a monolithic planar selective absorber/emitter

Makoto Shimizu,* Asaka Kohiyama, and Hiroo Yugami
Tohoku University, Graduate School of Engineering, Aoba 6-6-01 Aramaki Aoba-ku,
Sendai 980-8579, Japan

Abstract. We demonstrate a high-efficiency solar-thermophotovoltaic system (STPV) using a monolithic, planar, and spectrally selective absorber/emitter. A complete STPV system using gallium antimonide (GaSb) cells was designed and fabricated to conduct power generation tests. To produce a high-efficiency STPV, it is important to match the thermal radiation spectrum with the sensitive region of the GaSb cells. Therefore, to reach high temperatures with low incident power, a planar absorber/emitter is incorporated for controlling the thermal radiation spectrum. This multilayer coating consists of thin-film tungsten sandwiched by yttria-stabilized zirconia. The system efficiency is estimated to be 16% when accounting for the optical properties of the fabricated absorber/emitter. Power generation tests using a high-concentration solar simulator show that the absorber/emitter temperature peaks at 1640 K with an incident power density of 45 W/cm^2, which can be easily obtained by low-cost optics such as Fresnel lenses. The conversion efficiency became 23%, exceeding the Shockley–Queisser limit for GaSb, with a bandgap of 0.67 eV. Furthermore, a total system efficiency of 8% was obtained with the view factor between the emitter and the cell assumed to be 1. © *2015 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JPE.5.053099]

1 Introduction

Solar-thermophotovoltaics (STPVs) generation systems are a type of a photovoltaic (PV) generation system first reported by Swanson in 1979[1] and expanded upon in later research.[2–7] In these systems, a solar absorber is heated by solar radiation, which in turn heats an emitter to radiate thermal energy; this thermal radiation is then converted to electricity within a PV cell.

STPVs have some advantages over conventional PV systems. For instance, it is possible to control the thermal radiation spectrum of an emitter to optimize electron excitation in the inherent sensitive region. Using such spectral matching in a single-junction PV cell, a PV conversion efficiency comparable to that of a triple-junction PV-cell system can be obtained. Furthermore, in these systems, the power generation density can be as high as several W/cm^2, and unlike a multijunction cell, the generation efficiency is not sensitive to seasonal solar-spectrum fluctuations.

Theoretically, an STPV can achieve an efficiency of 85% in terms of Carnot efficiency. Then, by considering PV conversion losses due to a monochromatic radiation emitter, system efficiencies may become as high as 45%.[8,9] General studies on STPV have been performed by several groups in recent years. In 2000, Sai et al. reported an STPV composed of a dish-type solar concentrator, a gallium antimonide (GaSb) TPV cell, a graphite-cavity absorber, and an $Al_2O_3/Er_3Al_5O_{12}$ eutectic composite spectrally selective emitter.[10] However, its system efficiency was quite low (0.02% at 1480 K under 25,000 suns). In 2014, Lenert et al. constructed

Polymer:fullerene solar cells: materials, processing issues, and cell layouts to reach power conversion efficiency over 10%, a review

Ikerne Etxebarria, Jon Ajuria, and Roberto Pacios*
IK4-IKERLAN, Goiru Kalea, 20500 Arrasate, Spain
CIC microGUNE, 20500 Arrasate, Spain

Abstract. In spite of the impressive development achieved by organic photovoltaics throughout the last decades, especially in terms of reported power conversion efficiencies, there are still important technological and fundamental obstacles to circumvent before they can be implemented into reliable and long-lasting applications. Regarding device processing, the synthesis of highly soluble polymeric semiconductors first, and then fullerene derivatives, was initially considered as an important breakthrough that would definitely change the fabrication of photovoltaics once and for all. The potential and the expectation raised by this technology is such that it is very difficult to keep track of the most significant progresses being now published in different and even monographic journals. In this paper, we review the development of polymeric solar cells from its origin to the most efficient devices published to date. We separate these achievements into three different categories traditionally followed by the scientific community to push devices over 10% power conversion efficiency: active materials, strategies—fabrication/processing procedures—that can mainly modify the active film morphology, and all the different cell layout/architectures that have been used in order to extract as high a photocurrent as possible from the Sun. The synthesis of new donors, the use of additives and postprocessing techniques, buffer interlayers, inverted and tandem designs are some of the most important aspects that are reviewed in detail in this paper. All have equally contributed to develop this technology and bring it at the doors of commercialization. © *2015 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JPE.5.057214]

1 Introduction

An abundance of raw materials, simplicity in device fabrication, and easy integration into different applications, thanks to their lightweight, semitransparency, flexibility, and color tunability, have made organic photovoltaics (OPV) an attractive source of green energy. Nowadays research on this technology is focused on understanding the physics behind the technology and on achieving an efficiency as high as possible.

Nelson calculated the limiting efficiency for an ideal single solar cell as a function of the semiconductor bandgap, obtaining a limiting efficiency of ∼33% at a bandgap of 1.4 eV (885 nm).[1] In principle, all the assumptions made for this model are also perfectly valid for organic semiconductors. However, more accurate models explicitly developed for polymer: fullerene bulk heterojunction (BHJ) solar cells and that take into account their detailed working mechanisms predict maximum efficiencies of ∼15% (Ref. 2) and 21% (Ref. 3) for single and tandem cells, respectively. The main reasons why ideal performances are not achieved are incomplete absorption of the incident light, nonradiative recombination of photogenerated carriers, i.e., excited charges that are trapped at defect sites and recombine before being collected leading to transport losses, and voltage drop due to nonideal series and/or parallel resistance

---

Pathways toward high-performance perovskite solar cells: review of recent advances in organo-metal halide perovskites for photovoltaic applications

Zhaoning Song, Suneth C. Watthage, Adam B. Phillips, and Michael J. Heben*

University of Toledo, Wright Center for Photovoltaics Innovation and Commercialization, Department of Physics and Astronomy, 2600 Dorr Street, Toledo, Ohio 43606, United States

Abstract. Organo-metal halide perovskite–based solar cells have been the focus of intense research over the past five years, and power conversion efficiencies have rapidly been improved from 3.8 to >21%. This article reviews major advances in perovskite solar cells that have contributed to the recent efficiency enhancements, including the evolution of device architecture, the development of material deposition processes, and the advanced device engineering techniques aiming to improve control over morphology, crystallinity, composition, and the interface properties of the perovskite thin films. The challenges and future directions for perovskite solar cell research and development are also discussed. © *2016 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JPE.6.022001]

1 Introduction

In 1954, the first practical photovoltaic (PV) device based on crystalline silicon was demonstrated at Bell Laboratories.[1] After many decades of progress, crystalline silicon technology dominates the global PV market with a 55% and 36% market share for polycrystalline- and monocrystalline-silicon modules in 2014, respectively.[2] The remaining 9% of the market was split between a variety of other established and emerging PV technologies, including polycrystalline thin films, amorphous semiconductors, dye-sensitized solar cells (DSSCs), organics, and quantum dot solar cells.[3] To gain market share from crystal silicon solar cells, alternative technologies have to provide a desirable combination of high power conversion efficiency (PCE), low manufacturing costs, and excellent stability. Recent research suggests that organo-metal halide perovskites (OMHPs), with methylammonium lead iodide ($CH_3NH_3PbI_3$ or $MAPbI_3$) being the prototypical example, have the potential to meet these conditions and become competitive in the marketplace. As a result of intensive research efforts across the globe over the past three years,[4–13] perovskite-based solar cell PCEs are now comparable to or better than most other PV technologies, and the simple device processing promises lower manufacturing costs, suggesting the potential to challenge the prevailing silicon technology in the foreseeable future.[14]

The term perovskite refers to the crystal structure of calcium titanate ($CaTiO_3$), which was discovered by the German mineralogist Gustav Rose in 1839 and named in honor of the Russian mineralogist Lev Perovski.[15] In the field of optoelectronics, OMHPs are a group of materials with the formula AMX_3, where A is an organic cation ($CH_3NH_3^+$ or $NH_2CH_3NH_2^+$), M is a divalent metal cation (Pb^{2+} or Sn^{2+}), and X is a monovalent halide anion (I^-, Br^-, or Cl^-). Figure 1 shows the crystal structure and a single crystal of $MAPbI_3$. In a unit cell of the OHMP

Perfect metamaterial absorber for applications in sustainable and high-efficiency solar cells

Patrick Rufangura[a,b] and Cumali Sabah[c,d,*]

[a]Middle East Technical University—Northern Cyprus Campus, Sustainable Environment and Energy Systems, Kalkanli, Guzelyurt, TRNC/Mersin 10, Turkey
[b]University of Technology Sydney, School of Electrical and Data Engineering, Faculty of Engineering and Information Technology, Ultimo, New South Wales, Australia
[c]Middle East Technical University—Northern Cyprus Campus, Department of Electrical and Electronics Engineering, Kalkanli, Guzelyurt, TRNC/Mersin 10, Turkey
[d]Middle East Technical University—Northern Cyprus Campus, Kalkanli Technology Valley, Kalkanli, Guzelyurt, TRNC/Mersin 10, Turkey

Abstract. The current state of energy is characterized by complex challenges in production processes and environmental issues. With the world population continuing to multiply faster and the globalization process, additional energy production is needed to meet future demands. Solar energy is one of the best sustainable energy resources, which is expected to play a vital role in this scenario. One of the best techniques to harvest this resource is through solar photovoltaic technology, which produces electricity directly from solar radiation. But, one of the problems still persisting is its low efficiency. To harness this technology, this problem needs to be addressed. Metamaterial (MTM) technology has enabled the creation of advanced devices for various applications. Solar cell technology is one of the fields to benefit from this technology. MTM perfect absorber can be used in solar cells to improve their absorption. Multiple-bands MTM absorber for next generation high-efficiency solar cells is proposed. The design gives a nearly perfect absorption (99.94%) with a bandwidth of 23.4% in visible spectrum. In addition, the geometric flexibility of a proposed design causes its absorption rate to be insensitive of polarization angles and angles of incident electromagnetic radiations. © *2018 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JNP.12.026002]

Keywords: metamaterial; perfect absorber; solar cell.

1 Introduction

The contemporary energy sector is characterized by complex challenges in production processes, economic, geopolitical, and environmental issues. These challenges are available in both industrialized and developing countries but at different levels.[1,2] Nonetheless, the world population continues to multiply faster, which implies that the future energy production needs to be increased to meet the demand. Another concern is the globalization process that is taking place in the present century, where large additional energy supplies are needed to foster the process. In the meantime, predictions on the world's most relied energy production resources, "fossil fuel", shows a decline of this resource for future centuries.[1–5] With these uncertainties, the only remaining hope is the renewable energy resources and their technological advancement,[6] success in nuclear energy technology (prospective deployment of advanced nuclear reactor systems),[7] and on ability to develop hybrid systems that combine the two resources (nuclear-renewable energy systems).[8,9] Solar energy is one of the best sustainable energy resources, which is expected to play a vital role in the future energy production, and can be

---

Review on methods for improving the thermal and ambient stability of perovskite solar cells

Yuxiong Zhou,[a,†] Jinghua Hu,[a,†] Yuxia Wu,[b] Rongbang Qing,[a] Chengming Zhang,[a] Xiaoying Xu,[a,*] and Minlin Jiang[b,*]

[a]Wuhan University of Technology, Department of Physics, Wuhan, Hubei, China
[b]Nanchang University, Institute of Advanced Study, Nanchang, Jiangxi, China

Abstract. Perovskite solar cells (PSCs) are solar cells that are efficient, low cost, and simple to fabricate. Over the last 9 years, researchers have conducted in-depth research on PSCs to increase their photoelectric conversion efficiency from 3.8% to 24.2%. PSCs have the potential to replace traditional energy sources in the future. However, the stability of these cells is poor, which limits their practical applications, because the perovskite material is susceptible to degradation by environmental factors, such as moisture, heat, and oxygen. In our review, some studies related to improving the stability of PSCs are summarized. Strategies that have been developed to improve the stability of PSCs are reviewed from the aspects of the electron transport, perovskite, and hole transport layers (HTLs). These strategies include doping the electron transport layer (ETL), using dopant-free HTL, grain passivation, employing double layers or graded hybrid structure of ETL or HTL, two-dimensional perovskites, and so on. We provide a reference for future studies on the stability of PSCs. © *2019 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JPE.9.040901]

Keywords: perovskite solar cells; stability; review.

1 Introduction

Fossil energy cannot meet future demands, on account of the depletion of the necessary resources and the accompanying environmental problems. Therefore, researchers have exerted efforts to convert clean solar energy into electricity via the photovoltaic effect. Over the last few years, Si, CdTe, CuInGa/Se, and other light-absorbing materials have been employed to fabricate solar cells. However, the effects of these materials are not ideal. Then, researchers found a new light-absorbing material, the perovskite material.

The molecular formula of perovskite is ABX_3 [Fig. 1(a)]; here, A is a monovalent cation, B is a divalent metal cation, and X is a halogen anion. Kojima et al.[1] fabricated perovskite solar cells (PSCs) for the first time by using the perovskite material $CH_3NH_3PbI_3$ ($MAPbI_3$) as a light-absorbing material in dye-sensitized solar cells; the power conversion efficiency (PCE) of these cells was 3.8%. The excellent photovoltaic performance of PSCs attracted the attention of researchers worldwide. Indeed, in just a few years, the conversion efficiency of these cells has been rapidly improved from 3.8% to 24.2%,[2] which indicates that PSCs with a layered structure may become a new energy source in the future. Figure 1(b) shows a schematic of a planar heterojunction PSC.

Despite their many benefits, however, PSCs present serious stability problems and have a short effective life, mainly because the perovskite material is susceptible to environmental factors, such as oxygen, moisture, thermal stress,[3,4] light, and applied electric fields.[5] These factors lead to material degradation, resulting in a short cell life.[6] Furthermore, a large number of defect states are observed in PSCs, and these states can not only affect the photoelectric performance of a PSC but also damage its stability.

Lessons learned from the first outdoor test of perovskite/silicon tandem solar cells

Erkan Aydin*[a], Thomas G. Allen[a], Michele De Bastiani[a], Lujia Xu[a], Esma Ugur[a], Ahmed Ali Ahmed[a], Michael Salvador[a], Emmanuel Van Kerschaver[a], Stefaan De Wolf[a]

[a]King Abdullah University of Science and Technology (KAUST), KAUST Solar Center (KSC), Physical Sciences and Engineering Division (PSE), Thuwal 23955-6900, Kingdom of Saudi Arabia,

ABSTRACT

Perovskite/silicon tandem solar cells promise power conversion efficiencies (PCE) beyond the thermodynamic limit of single-junction devices. This potential has been unveiled via several champion devices, however, their actual outdoor performance is yet to be investigated. Here, we fabricate 25 %-efficient two-terminal (2T) monolithic perovskite/silicon tandem solar cells and test them outdoors to reveal the characteristics of these devices specifically in hot and sunny climates, which are the ideal locations to operate such efficient photovoltaic devices. In this article, we summarize our observation on the perovskite/silicon tandem solar cells under actual operational conditions and discuss the lessons we take from our interpretations.

Keywords: perovskites, silicon, tandem solar cells, textured tandems, outdoor test, temperature-dependent performance, bandgap

1. INTRODUCTION

The field of perovskite/silicon tandem solar cells is a rapidly evolving research area since these tandem cells promise to achieve PCEs beyond the physical limits of their individual single-junction sub cells. The facile perovskite fabrication process, and its versatility in terms of bandgap engineering (the perovskite bandgap can be easily 'tuned' by manipulating its composition) means that an optimal tandem configuration can be achieved in an economically feasible way compared to other approaches that use expensive III/V materials. Indeed, as well as several research groups, already a number of companies have focused on the development of perovskite/silicon tandems.[1-6] However, the actual outdoor performance of such solar cells was yet to be studied and understood. Critically, outdoor tests are a crucial step to understand the real performance of the solar cells before the market entrance.

Coupling silicon solar cells with the with the ideal band gap (E_g ~1.73 eV) top cell (either perovskite or any other absorber materials) pushes the radiative-efficiency limit of such devices to ~44% under standard test conditions (STC). However, for monolithic, 2T tandems, this requires perfect current matching between perovskite top cell and c-Si bottom cell. For this, the perovskite E_g should be ideal (~1.73) eV at STC, [7-9] which is significantly larger than those typically used for record single-junction perovskite devices (~1.50 − 1.60 eV). [10-12] Typically, to widen the E_g of metal halide perovskites, the Br:I halide ratio in the precursor (and thus crystallized film) is increased.[13] However, beyond a Br:I ratio of ~1:4 (corresponding to an E_g of ~1.68 eV), segregated I-rich and Br-rich domains occur upon illumination, thus hindering device performance.[14],[15, 16] This issue remains still as an open question although several mitigation strategies have been offered.[16, 17]

Meanwhile, although the solar cells are characterized at STC, the devices may show different behaviors at actual operational conditions, specifically due to the heating effect originated from the parasitic and sub bandgap absorption.[18] Quite generally, the E_g of semiconductors depends on temperature: with increasing temperature, it narrows for c-Si, but interestingly increases for perovskites.[19, 20] This is relevant for photovoltaics (PV), as outdoor field-testing conditions (FTC) often imply elevated operating temperatures of PV modules well above 25 °C, especially for high solar irradiation and space-constrained roof-top applications (due to heat-trapping effects).[21] Therefore, what may be an ideal perovskite E_g for tandems at STC, is likely not an ideal E_g under actual FTC: Firstly, due to the red-shift of the c-Si E_g with temperature, the required perovskite E_g for current matching will already be lower than 1.73 eV. Secondly, due to the blue-shift of the perovskite E_g with temperature, its optimal E_g measured at STC will be even lower than that at FTC, impacting the design guidelines for efficient tandems.

Nonreciprocal photonic management for photovoltaic conversion: design and fundamental efficiency limits

Andrei Sergeev[a,*] and Kimberly Sablon[b,c]†
[a]U.S. Army Research Laboratory, Adelphi, Maryland, United States
[b]Army Futures Command, Austin, Texas, United States
[c]Texas A&M University, Bush Combat Development Complex, Bryan, Texas, United States

Abstract. Significant progress in the development of nonreciprocal optical components with broken Kirchhoff symmetry paves the way for increasing the photovoltaic (PV) conversion efficiency beyond the Shockley–Queisser limit due to reuse of emitted photons. Recent papers have analyzed the PV converter with several or an infinite number of multijunction cells, in which the cells are coupled via nonreciprocal filters (optical diodes) in such a way that the light emitted by one cell is absorbed by another cell. We proposed and investigated a single cell converter with nonreciprocal external photon recycling, which provided reabsorption and reuse of the emitting light by the same cell. We considered properties of photons in the sunbeam in terms of ergodicity, disorder, energy availability, information entropy, and coherence, and established fundamental limitations imposed by endoreversible thermodynamics on conversion efficiency at maximal power output. Our results show that the nonreciprocal converter with an ideal multijunction cell can approach the Carnot efficiency, whereas operating exactly at the Carnot limit requires an infinite number of photon recycling processes. This requirement resolves the famous thermodynamic paradox of the optical diode because any small dissipation in the cell or optical system enhanced by infinite recycling will stabilize the converter operation below the Carnot limit. We generalized endoreversible thermodynamics to photonic distributions with nonzero chemical potential and derived the limiting efficiency of the nonreciprocal single-junction PV converter. The performance of this converter with available GaAs solar cells was evaluated. © *The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JPE.12.032207]

Keywords: photovoltaic conversion; efficiency limits; nonreciprocal photonics.

1 Introduction

Recent progress in nonreciprocal optics[1] raises a set of principal questions about limiting efficiencies of photovoltaic (PV) converters with nonreciprocal photonic management. Fundamental limit imposed by thermodynamic laws on PV conversion efficiency is a critical issue for basic science and numerous applications, such as PV conversion of solar light, thermal radiation, and laser light. In this work, we consider perspectives for integration of PVs with nonreciprocal photonics. We propose and investigate an architecture of a PV converter and calculate limiting efficiencies on the base of endoreversible thermodynamics, which will be generalized to photonic systems with nonzero chemical potential.

Maximal efficiencies of traditional PV devices are given by the Shockley–Queisser (SQ) limit.[2] The SQ limit is established by the balance between the absorbed photon flux, $\dot{N}_{ab}$, and the emitted photon flux, $\dot{N}_{em}$, which is proportional to the flux emitted in thermodynamic equilibrium, $\dot{N}_{em}^{eq}(T)$. In the absence of nonradiative recombination, the balance of incoming and outcoming fluxes is described by two parameters. Spectral characteristics of the incoming flux and the cell absorption are taken into account by the average photon energy per a photon

---

Status report on emerging photovoltaics

Annick Anctil,[a] Meghan N. Beattie,[b] Christopher Case,[c] Aditya Chaudhary,[d]
Benjamin D. Chrysler,[e] Michael G. Debije,[f] Stephanie Essig,[d] David K. Ferry,[g]
Vivian E. Ferry,[h] Marina Freitag,[i] Isaac Gould,[j] Karin Hinzer,[b] Harald Hoppe,[k,l]
Olle Inganäs,[m,n] Lethy Krishnan Jagadamma,[o] Min Hun Jee,[p] Raymond K. Kostuk,[q,r]
Daniel Kirk,[c] Stephan Kube,[s] Minyoung Lim,[p] Joseph M. Luther,[t,u] Lorelle Mansfield,[t]
Michael D. McGehee,[u,v] Duong Nguyen Minh,[t] Preeti Nain,[a] Matthew O. Reese,[t]
Angèle Reinders,[w] Ifor D. W. Samuel,[x,*] Wilfried van Sark,[y] Hele Savin,[z]
Ian R. Sellers,[aa] Sean E. Shaheen,[u,ab,ac,*] Zheng Tang,[ad] Fatima Toor,[ae,*]
Ville Vähänissi,[z] Ella Wassweiler,[af] Emily L. Warren,[t] Vincent R. Whiteside,[ag]
Han Young Woo,[p] Gang Xiong,[af] and Xitong Zhu[w]

[a]Michigan State University, Department of Civil and Environmental Engineering, East Lansing, Michigan, United States
[b]University of Ottawa, School of Electrical Engineering and Computer Science, SUNLAB, Ottawa, Ontario, Canada
[c]Oxford Photovoltaics Ltd., Kidlington, United Kingdom
[d]University of Stuttgart, Institute for Photovoltaics (IPV), Stuttgart, Germany
[e]Amazon Lab, Sunnyvale, California, United States
[f]Eindhoven University of Technology, Department of Chemical Engineering and Chemistry, Eindhoven, The Netherlands
[g]Arizona State University, School of Electrical, Computer & Energy Engineering, Tempe, Arizona, United States
[h]University of Minnesota, Department of Chemical Engineering and Materials Science, Minneapolis, Minnesota, United States
[i]Newcastle University, School of Natural and Environmental Sciences, Newcastle upon Tyne, United Kingdom
[j]University of Colorado, Department of Materials Science and Engineering, Boulder, Colorado, United States
[k]Friedrich Schiller University Jena, Laboratory of Organic and Macromolecular Chemistry (IOMC), Jena, Germany
[l]Friedrich Schiller University Jena, Center for Energy and Environmental Chemistry Jena (CEEC Jena), Jena, Germany
[m]Linköping University, Department of Biomolecular and Organic Electronics, Linköping, Sweden
[n]Linköping University, Department of Physics, Chemistry and Biology, Linköping, Sweden
[o]University of St Andrews, School of Physics and Astronomy, St Andrews, United Kingdom
[p]Korea University, Department of Chemistry, Seoul, Republic of Korea
[q]University of Arizona, Electrical and Computer Engineering Department, Tucson, Arizona, United States
[r]University of Arizona, The Wyant College of Optical Sciences, Tucson, Arizona, United States
[s]Heliatek GmbH, Dresden, Germany
[t]National Renewable Energy Laboratory, Golden, Colorado, United States
[u]Renewable and Sustainable Energy Institute (RASEI), Boulder, Colorado, United States
[v]University of Colorado, College of Engineering and Applied Science, Materials Science and Engineering Program, Department of Chemical and Biological Engineering, Boulder, Colorado, United States
[w]Eindhoven University of Technology, Energy Technology Group, Eindhoven, The Netherlands
[x]University of St Andrews, School of Physics and Astronomy, Organic Semiconductor Centre, St Andrews, United Kingdom
[y]Utrecht University, Copernicus Institute of Sustainable Development, Utrecht, The Netherlands
[z]Aalto University, Department of Electronics and Nanoengineering, Espoo, Finland
[aa]University at Buffalo, Department of Electrical Engineering, Buffalo, New York, United States
[ab]University of Colorado Boulder, Department of Electrical, Computer and Energy Engineering, Boulder, Colorado, United States
[ac]University of Colorado Boulder, Department of Physics, Boulder, Colorado, United States
[ad]Donghua University, Center for Advanced Low-dimension Materials, State Key Laboratory for Modification of Chemical Fibers and Polymer Materials, Shanghai, China
[ae]University of Iowa, Department of Electrical and Computer Engineering, Iowa City, Iowa, United States
[af]First Solar, California Technology Center, Santa Clara, California, United States
[ag]University of Oklahoma, Department of Physics and Astronomy, Norman, Oklahoma, United States

*Address all correspondence to Ifor D. W. Samuel, idws@st-andrews.ac.uk; Sean E. Shaheen, sean.shaheen@colorado.edu; Fatima Toor, fatima-toor@uiowa.edu

ABSTRACT. This report provides a snapshot of emerging photovoltaic (PV) technologies. It consists of concise contributions from experts in a wide range of fields including silicon, thin film, III-V, perovskite, organic, and dye-sensitized PVs. Strategies for exceeding the detailed balance limit and for light managing are presented, followed by a section detailing key applications and commercialization pathways. A section on sustainability then discusses the need for minimization of the environmental footprint in PV manufacturing and recycling. The report concludes with a perspective based on broad survey questions presented to the contributing authors regarding the needs and future evolution of PV.

1 Introduction

The field of photovoltaic (PV) solar power generation has grown to become a significant component of the global energy landscape, with ~4.5% of the world's electricity being generated and ~240 GW of new installations in 2022.[1,2] However, further acceleration of PV and other renewable energy sources is urgently required to mitigate the impacts of global greenhouse gas emissions. A recent analysis has concluded that PV needs to grow at ~25% annually with a target of 75 TW of global installations by 2050, a ~75x increase from current installed capacity.[3] While the existing PV landscape is largely dominated by silicon (crystalline and polycrystalline) and CdTe, achieving these long-term goals can be greatly aided by the development of new materials, device concepts, and light management strategies that enable higher efficiencies and more scalable and sustainable manufacturing.

This article is intended to provide a snapshot of the current status of emerging PV approaches that show potential in helping to achieve the above goals. It is intended to be a convenient resource for people within and outside the field, including new researchers, students, technology managers, and program managers, who can play a role in accelerating the global effort. The article is structured in sections covering silicon (Sec. 2), thin film (Sec. 3), III-V (Sec. 4), perovskite (Sec. 5), organic (Sec. 6), and dye-sensitized solar cells (Sec. 7). Each section provides background, a technology status update, and challenges towards commercialization/scalability. Subsequent sections provide an overview of the applications and commercialization of emerging PV (Sec. 8), strategies for exceeding the detailed balance limit (Sec. 9), and concepts in light management (Sec. 10). A final section describes sustainability and environmental impact issues that apply to all the above technologies (Sec. 11). The article concludes with a perspectives section (Sec. 12) that first discusses common themes that appear throughout the article, and then also presents and draws conclusions from a survey of emerging PV, which was completed anonymously by contributing authors.

2 Silicon Photovoltaics

2.1 Bifacial Silicon PV

Section Author: Fatima Toor (University of Iowa)

In recent years, bifacial silicon (Si) photovoltaics (PV) technology has been growing in commercial PV systems because it results in higher performance yield and lower levelized cost of energy (LCOE) compared with conventional monofacial PV technology.[4] Figure 1 illustrates the difference between monofacial and bifacial solar cell architectures. While traditional monofacial Si cells have an aluminum (Al)-based back surface field (BSF) that covers the entire backside of the cell precluding any light absorption on the backside, bifacial Si cells have point contacts that allow for backside light collection and absorption in the cells.

Author Index

Karin Hinzer received her BSc, MSc, and PhD degrees in Physics from the University of Ottawa, Ottawa, Ontario, Canada, in 1996, 1998, and 2002, respectively. She is the Vice-Dean, Research of the Faculty of Engineering and a Professor at the School of Electrical Engineering and Computer Science, with a cross-appointment in the Department of Physics at the University of Ottawa. She is also the University Research Chair in Photonic Devices for Energy. Professor Hinzer has made pioneering contributions to the experimental physics of quantum dots, marked by two landmark papers in *Science*. She gained extensive experience in the design and fabrication of group III–V semiconductor devices while at the National Research Council Canada, Nortel Networks, and then Bookham (now Lumentum). Cost-reduction strategies and liaison with remote fabrication facilities strongly feature in her industry experience.

In 2007, Professor Hinzer joined the University of Ottawa, where she founded the SUNLAB, the premier Canadian modeling and characterization laboratory for next-generation optoelectronic devices and photovoltaic systems. Her research involves developing new ways to harness the sun's energy. From 2007 to 2017, she was the Tier II Canada Research Chair in Photonic Nanostructures and Integrated Devices. Professor Hinzer has received several awards, including the Inaugural Canadian Energy Award in 2010 with industry partner Morgan Solar for the development of more efficient solar panels; the Ontario Ministry of Research and Innovation Early Researcher Award in 2015 for her contributions to the fields of photonic devices and photovoltaic systems; and the University of Ottawa Young Researcher Award in 2016. She is a senior member of IEEE. She is also the Principal Investigator of a Natural Sciences and Engineering Research Council of Canada Collaborative Research and Training Experience Program, "Training in Optoelectronics for Power: From Science and Engineering to Technology" (NSERC CREATE TOP-SET, 2017–2024), a multidisciplinary program that has trained more than 170 students and postdoctoral fellows.

Professor Hinzer is an editor of the *IEEE Journal of Photovoltaics*. She has published more than 220 refereed papers and trained more than 200 highly qualified personnel. Her laboratory has spun off three Canadian companies in the energy sector. Her research interests include new materials, high-efficiency light sources and light detectors, solar cells, solar modules, new electrical grid architectures, and power converters.

Matthew E. L. Jungwirth is the Manager of Technical Content & Scientific Publishing at SPIE. He earned his PhD in Optical Sciences from the University of Arizona, where he studied adaptive optical zoom using deformable carbon fiber mirrors. He has 12 years of industrial experience specializing in optical and optical system design working for Sandia National Laboratories, Honeywell International, and Cyber-Optics. Additionally, he has 18 patents and 15 publications covering a diverse array of topics such as barcode sensing, quantum information processing, structured light illumination, and real-time alignment techniques. He is an SPIE Fellow.

Robert F. Hainsey is the Director of Science and Technology at SPIE, where he oversees development of the Society's technical conferences and industry programs. Previously, he was Senior Director of Central Research and Development at Electro Scientific Industries, a supplier of laser-based micromachining equipment for the consumer electronics market. He began his career at Intel Corporation, where he led the advanced technology transistor patterning team. He holds 12 patents and has 20 publications in areas including semiconductor processing, laser–material interactions, and laser system architectures. He has a PhD in Physics from Carnegie Mellon University.