2nd Asian Nations Joint Workshop on Photovoltaics

1. Date: Tuesday,14, November, 2017, 13:30 – 17:40
2. Conference room: Convention Hall 6, Lake Biwa Otsu Prince Hotel
   (same venue as PVSEC-27)

3. Program

Chairperson:	Makoto Konagai, Tokyo City University
Vice-chairperson	Donghwan Kim, Korea University
Vice-chairperson	Ying Zhao, Nankai University

Session-AN-1 Chair: Donghwan Kim

13:30-13:40 Opening Address
Makoto Konagai, Tokyo City University

13:40-14:00 Recent trends in innovative solar cell research in Europe
Arnulf Jäger-Waldau and Juan Lopez-Garcia
European Commission, Joint Research Centre

14:00-14:20 Materials and Process Informatics for SMART Silicon Ingot
Noritaka Usami[1], Yusuke Hayama[1], Tetsuya Matsumoto[2], Hiroaki Kudo[2], Tatsuya Yokoi[1], Katsuyuki Matsunaga[1], Kentaro Kutsukake[3], Yutaka Ohno[3]
[1]Graduate School of Engineering, Nagoya University, [2]Graduate School of Informatics, Nagoya University, [3]Institute for Materials Research, Tohoku University

14:20-14:40 Development Status and Prospect of High-Efficiency Crystalline Silicon Solar Cell Manufacturing in China
Zhiqiang Feng,
State Key Laboratory of PV Science and Technology,Trina Solar

14:40-15:00 Diamond like Nanocomposite (DLN) Coating as Promising Antireflective and Passivative Coating for Large Area Crystalline Silicon Solar Cell
Utpal Gangopadhyay, Meghnad Saha Institute of Technology

15:00-15:20 Recent Progress of Solar PV R&D in Thailand
Kobsak Sriprapha[1], Amornrat Limmanee[1], Taweewat Krajangsang[1], Songkiate Kittisontirak[1], Aswin Hongsingthong[1], Yaowanee Sangpongsanont[2], Manit Seapan[2], Dhirayut Chenvidhya[2], Surawut Chuangchote[2] and Jaran Sritharathikhun[1]
[1]Solar Energy Technology Laboratory (STL), NECTEC, NSTDA, [2]King Mongkut's University of Technology Tonburi (KMUTT)

15:20-15:40 break

Session-AN-2 Chair: Ying Zhao

15:40-16:00 Materials Science in Solution Process for Highly Efficient Perovskite Solar Cells
Atsushi Wakamiya, Institute for Chemical Research, Kyoto University

16:00-16:20 Materials engineering for efficient and stable halide perovskite solar cells
Jun Hong Noh[1,2],

[1]School of Civil, Environmental and Architectural Engineering, Korea University, [2]Division of Advanced Materials, Korea Research Institute of Chemical Technology

16:20-16:40 Low-cost and lightweight approaches for solar cells and their applications

Ching-Fuh Lin[1, 2, 3, 4*] , Subramani Thiyagu[1], Hong-Jhang Syu[1], Jia-Wei Wu[1], Yi Lai[1], and Po-Tsun Guo[1]
[1]Graduate Institute of Photonics and Optoelectronics, [2]Department of Electrical Engineering, [3]Graduate Institute of Electronics Engineering 4Innovative Photonics Advanced Research Center (i-PARC),National Taiwan University

16:40-17:00 Status and trends of thin-film on silicon tandem solar cell research in Singapore

Armin G. Aberle
Solar Energy Research Institute of Singapore (SERIS), National University of Singapore

17:00-17:20 Silicon-Based Multi-Junction Tandem Solar Cells

Xiaodan Zhang[a,b,c,d] * , Xin Yao[a,b,c,d], Shijie Zhu[a,b,c,d], Bofei Liu[a,b,c,d], Lisha Bai[a,b,c,d], Jia Fang [a,b,c,d], Tiantian Li [a,b,c,d], Changchun Wei[a,b], Qian Huang [a,b], Jian Ni [a,b], Dekun Zhang[a,b], Guofu Hou[a,b], Xinliang Chen[a,b], Shengzhi Xu[a,b], Huizhi Ren[a,b], Guangcai Wang[a,b], Yi Ding[a,b], Yuelong Li[a,b,c,d], Baozhang Li[a,b], Ying Zhao[a,b,c,d]
[a] Institute of Photoelectronic Thin Film Devices and Technology of Nankai University, [b] Key Laboratory of Photoelectronic Thin Film Devices and Technology of Tianjin, [c] Key Laboratory of Optical Information and Technology of Ministry of Education, [d] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin)

17:20-17:40 Progress in Perovskite/Si tandem solar cells

Donghwan Kim[1,2], Hae-Seok Lee[2], Yoonmook Kang[2], Soohyun Bae[1], Sang-Won Lee[1], Kyung Jin Cho[1], Jae Keun Hwang[1]
[1]Department of Materials Science and Engineering, Korea University, [2]KU-KIST GreenSchool,Graduate School of Energy and Environment, Korea University

Area: 2nd Asian Nations Joint Workshop on Photovoltaics

RECENT TRENDS IN INNOVATIVE SOLAR CELL RESEARCH IN EUROPE

Arnulf Jäger-Waldau and Juan Lopez-Garcia

European Commission, Joint Research Centre, Energy Efficiency and Renewables Unit, 21027 Ispra, Italy

The most established photovoltaic technologies are based on mono and multi-crystalline solar cells and have been used for decades in space and terrestrial application. At current, these Si-based technologies have the highest commercial conversion efficiencies with a well-established market and represent over 90% of the photovoltaic solar cells world production. The remaining share is taken by photovoltaic devices based on thin film solar cells, such as cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous and other thin-film silicon (a-Si, TF-Si). However, the single junction p-n crystalline Si PV modules are close to their theoretical maximum performance given by the Shockley–Queisser limit (33.7%) and new concepts (multi-junction, concentrators, etc) are required to exceed this barrier.

Innovative concepts are either based on thin-film technologies only or on a combination of crystalline silicon and thin-film technologies.

The first category includes: organic, dye-sensitized, and polymer-based solar cells, perovskite solar cells, copper zinc tin sulphide/selenide (kesterites), innovative III-V compounds (III-V and Intermediate band solar cells ISBC) and multi-junction or tandem architectures. All of these are based on thin film concepts and are manufactured with similar technologies. Low-cost manufacturing processes, roll-to-roll and flexible substrates are also includes in this category as a common concept.

The second category includes some innovative concepts to reduce cost and to approach the theoretical efficiency limit of silicon solar cells such as carrier-selective contacts (i.e. minority carrier mirrors or intrinsic thin film), or ultra-thin crystalline silicon absorber layers. To overcome this barrier, a cross cutting-technology with silicon solar cell as the base for innovative multi-junction or tandem solar cells (with top cell using, for example, perovskites, III-V materials, chalcogenide, Cu_2O or Si quantum dots) is investigated.

Area: Crystalline and Thin Film Silicon PV

MATERIALS AND PROCESS INFORMATICS FOR SMART SILICON INGOT

Noritaka Usami[1], Yusuke Hayama[1], Tetsuya Matsumoto[2], Hiroaki Kudo[2],
Tatsuya Yokoi[1], Katsuyuki Matsunaga[1], Kentaro Kutsukake[3], Yutaka Ohno[3]

[1]Graduate School of Engineering, Nagoya University, Japan
[2]Graduate School of Informatics, Nagoya University, Japan
[3]Institute for Materials Research, Tohoku University, Japan

Integration of experiments, computation, and theory with the aid of informatics is regarded as a promising approach to enable a paradigm shift in materials development to decrease the time and cost of the materials discovery to deployment process [1]. For example, cross-ministerial strategic innovation promotion program in Japan promotes such a multidisciplinary approach in research and development of structural materials for the future of Japanese aircraft industry [2]. This approach must be useful also in research and development of materials for photovoltaics.

In this presentation, we introduce our recent multidisciplinary approach to clarify and realize ideal microstructures of block-cast silicon ingot based on fundamental understanding of structural and electrical properties of grain boundaries and crystal defects with the aid of informatics. For this purpose, multiple photoluminescence images of as-sliced high-performance multicrystalline silicon wafers from the same ingot were taken with intentional partial introduction of reflection. This permits to obtain superimposed images of microstructures and crystal defects. By image processing, it is possible to track dislocation clusters and visualize their generation and annihilation. In addition, we can extract the sources of dislocations. Sparsely encoding basis functions learned from microstructure images could be utilized for independent component analysis of images around dislocations sources to characterize them. Grain boundaries to act as the source of dislocations will be investigated by atom probe tomography combined with transmission electron microscopy to clarify their atomistic structures and three-dimensional distribution of impurities [4]. Such advanced experiments could be utilized to optimize the simulated annealing algorithm to obtain stable grain boundary structures by simulation, and further computation of electrical properties of grain boundaries. All the data could be utilized to backcast ideal microstructures of block-cast silicon ingot by machine learning. Our recently developed crystal growth technique, seed manipulation for artificially controlled defect technique (SMART) [5], will be utilized to realize ideal silicon ingot in the future.

[1] “Materials Genome Initiative” https://www.mgi.gov/
[2] “SIP-SM^{4}I” http://www.jst.go.jp/sip/k03/sm4i/dl/jst_pamphlet_Japan.pdf
[3] Y. Hayama, T. Matsumoto, K. Kutsukake, I. Takahashi, H. Kudo, and N. Usami (to be presented at PVSEC-27).
[4] Y. Ohno *et al*., Appl. Phys. Lett. **110**, 062105 (2017).
[5] I. Takahashi, S. Joonwichien, T. Iwata, and N. Usami, Appl. Phys. Express **8**, 105501 (2015).

Development Status and Prospect of High-Efficiency Crystalline Silicon Solar Cell Manufacturing in China

Zhiqiang Feng

State Key Laboratory of PV Science and Technology, Trina Solar

No. 2 Trina Road, Trina PV Industrial Park, Xinbei District, Changzhou, Jiangsu Province, China 213031

Crystalline silicon photovoltaic (PV) cells are the most used technology of all types of solar cells, representing more than 90% of the world total PV cell production. The dominance of crystalline silicon PV technology is expected to continue in the foreseeable future. This report reviews the current status of crystalline silicon solar cell technology, both in laboratories and in the PV industry in China. PERC (Passivated emitter and rear cells) cells are now been widely used in the industry, reaching champion cell efficiencies of 22.6% for mono-Si and 21.6% for multi-Si. PERC production manufacturing lines reached cell efficiencies of 21.5% in average. In addition, new solar cell technologies with a very high energy conversion efficiency, like Interdigitated Back Contact (IBC), N-type PERT, Hetero-Junction (HJ), etc. have been developed with low cost industrial processes. As an example, the IBC solar cell developed at Trina Solar will be described in this report. The record-breaking n-type mono-crystalline silicon solar cell was fabricated on a large-sized phosphorous-doped Cz Silicon substrate with a low-cost industrial IBC process, featuring conventional tube doping technologies and fully screen-printed metallization. The 156×156 mm^2 solar cell reached a total-area efficiency of 24.13% as independently measured by JET in Japan. The IBC solar cell has a total measured area of 243.3cm^2 and was measured without any aperture. The champion cell presents the following characteristics: an open-circuit voltage V_{oc} of 702.7mV, a short-circuit current density J_{sc} of 42.1 mA/cm^2 and a fill factor FF of 81.47%. The report will also present a prospect of the different crystalline silicon solar cells both for technological and cost aspects.

Diamond like Nanocomposite (DLN) Coating as Promising Antireflective and Passivative Coating for Large Area Crystalline Silicon Solar Cell

Prof.(Dr.) Utpal Gangopadhyay
Meghnad Saha Institute of Technology
Nazirabad, P.O: Uchhepota Via Sonarpur (Behind NRI Complex)
Kolkata-700150, West Bengal, India
E-mail: utpal_ganguly@yahoo.com

Alternative sources of energy especially solar cell have become an alternative way to challenge the energy crisis. But, cost is the major limitation of solar cell. Researchers are trying to make it cost effective by different ways. Suitable anti-reflection as well as passivation coating has also a major role to enhance the efficiency of silicon based solar cell.

The reflection loss could be minimized by different ways like proper texturing on crystal- line silicon surface, using single and multi-layer dielectric coating as antireflective coating (ARC), using graded refractive index dielectric coating using plasmonic nanoparticle, nanostructured silicon, etc.

However, micro-texturing crystalline silicon substrate with appropriate ARC has become a well-established method in photovoltaic industry for reducing of reflection losses. Indeed, anti-reflection coatings are appropriate for decreasing not only light reflection but also transmit in a wider energy range, thus covering a broader range of the solar spectrum. Moreover, some of ARC films also have poor resistance to corrosive environments, leading to degradation of the solar cell performance with time. Usually silicon nitride (SiNx) AR coating is normally used on crystalline silicon solar cell in commercial scale. However, it is very difficult to achieve high broadband reflectance characteristics. Recently, few researchers also reported about the application of diamond- like carbon (DLC) as protective ARC for silicon solar cell. But DLC film has suffered from high internal stress, low thermal stability, low optical band gap, and high refractive index.

In this context Diamond like Nanocomposite (DLN) films, a modified DLC film, are of interest, since they have good properties due to its composition and structure: (i) excellent mechanical properties, (ii) corrosion resistant, (iii) high thermal stability, (iv) remarkable dielectric properties, (v) excellent optical properties, and (vi) easy deposition process by plasma assisted chemical vapour deposition (PACVD) technique. All these properties could be varied in wider range by changing the deposition parameters and post deposition treatment like annealing. So, the application of the DLN film as anti-reflective (AR) coating for large area crystalline silicon solar cell in industrial scale is one of the challenging area of research where no hazardous gases like ammonia and silane usually used for silicon nitride (SiN_x) AR coating in Industrial scale.

Area: PV Deployment; Industry, Market and Policy

RECENT PROGRESS OF SOLAR PV R&D IN THAILAND

Kobsak Sripapha[1], Amornrat Limmanee[1], Taweewat Krajangsang[1], Songkiate Kittisontirak[1], Aswin Hongsingthong[1], Yaowanee Sangpongsanont[2], Manit Seapan[2], Dhirayut Chenvidhya[2], Surawut Chuangchote[2] and Jaran Sritharathikhun[1]

[1]Solar Energy Technology Laboratory (STL), NECTEC, National Science and Technology Development Agency (NSTDA), Thailand, [2]King Mongkut's University of Technology Tonburi (KMUTT), Thailand,

Thailand has a great potential for using solar PV, since 64.5% of the country has an average solar radiation higher than 18 MJ/day (or 5 kWh/day). By Q3 2016, the cumulative installed capacity of solar PV is about 2.76 GW and will increase more since the government announced the Alternative Energy Development Plan 2015-2036 (AEDP 2015), which the use of renewable energy (RE) target will be 30% share in final energy consumption by 2036. For solar energy, the target is set to cumulative installed capacity of 6 GW by 2036.
The use of solar PV in Thailand was started in the 1980s for applications in rural areas such as schools, medical clinics, telecommunication stations and solar pumping. At the same period, the research and development on solar cell fabrication were initiated at Chulalongkorn University (CU) and King Monkut's Institute of Technology. In that time, both of them focused on crystalline silicon solar cell technology, after that CU was the pioneer in R&D in thin film silicon solar cell.
This article will provide a comprehensive review of the current progress of solar PV R&D in Thailand, starting from basic research to applied research. As shown in Table 1, in the area of basic research, some PV technologies such as HIT Solar cell, Thin film silicon solar cell, CIGS and Perovskite solar cells are interested. STL, NECTEC focus on fabrication of thin film silicon and HIT solar cells by using wide bandgap material in cell structure. The highest solar cell efficiency of 11% and 19.4% were obtained by a-Si:H/a-SiGeH tandem structure and HIT solar cells (cell area of 1 cm^2), respectively. For CIGS solar cell, only SPRL, CU pay attentions in this technology for a long time. The maximum cell efficiency of 15.8% was achieved (cell area of 1 cm^2) by flexible stainless steel foil substrate using NaF co-evaporation layer during deposition of CIGS process. In the case of perovskite solar cell, A group from KMUTT has developed perovskite/polymer tandem solar cell on a glass substrate. They also work on both glass and flexible substrates. Recently, the highest solar cell efficiency of 11.67% (cell area of 0.2 cm^2) was obtained.
There are many institutes, universities and private sectors are working in this area for the solar PV applications. Most of them are interested in solar PV system demonstration and assessment. NECTEC paid more attention on some topics such as improving PV performance, environmental effect, loss analysis, long term monitoring, PV system evaluation, PV hybrid system, developed software for PV output prediction. KMUTT has long term experiences on PV module reliability, they have investigated on PV module degradation after 13 years installing by using the accreditation laboratory PV modules testing according to IEC standard. They also focused on some topics such as improving the PV performance, PV system evaluation, PV floating. At present, the research topic concern in smart grid is interested by many researchers such as NECTEC, KMUTT, NU, UP, PEA, EGAT and MEA. A novel concept of DC microgrid was implemented and studied by Adicet. They have a small community, i.e. house, building, coffee shop, etc., and most of the electrical equipment i.e. lighting, air conditioner, television, refrigerator, etc., can be used DC in the range of 260 - 297 VDC which generated by the PV system. These appliances were modified in order to use with DC and AC systems. Finally, in case of PV components, i.e inverter, all of players are in the manufactures and they focus on improving the performance of their products.

Solar cells and related materials		Solar PV application	
Research Topics	Institute/University	Research Topics	Institute/University/Agency
HIT	NECTEC	Environmental effects	NECTEC, NU, CU
Thin film Si	NECTEC	Improving pv performance	NECTEC, KMUTT
CIGS	CU	Loss analysis	NECTEC
Perovskite	NECTEC, KMUTT, CU, SU, MU, KU, etc.	Long term monitoring	NECTEC, KMUTT
		PV system evaluation	NECTEC, KMUTT, NU, UP, EGAT
		Software for PV output prediction	NECTEC
		PV floating	KMUTT, EGAT
		Smart grid	NECTEC, KMUTT, NU, UP, EGAT, PEA, MEA
		DC microgrid	Adicet

Table 1: Summary of solar PV R&D activities in Thailand.

Area: Asian Nations Joint Workshop on PV

Materials Science in Solution Process for Highly Efficient Perovskite Solar Cells

Atsushi Wakamiya[1]

[1]Institute for Chemical Research, Kyoto University, Japan

Perovskite solar cells have attracted much attention as cost-effective next generation printable photovoltaics. Their power conversion efficiencies (PCEs) have been substantially increased in a relatively short period, mainly due to improvements of the fabrication protocols for the perovskite layer as well as the development of new materials for charge collection layers. In this presentation, our approaches toward the development of high PCE cells in terms of materials science will be introduced.

Firstly, we demonstrated the importance of purity of the materials, especially PbI_2.[1] We developed the purified PbI_2 that can provide good performance in perovskite solar cells with high reproducibility. The purified PbI_2 using our method is commercially available from Tokyo Chemical Industry[2] and widely used all over the world as a standard material in the field of perovskite solar cells.[3] We also elucidated the working principle for perovskite solar cells by means of various spectroscopy collaboration with Prof. Kanemitsu group in our institute.[5–6]

Regarding the molecular design for organic semiconductors that are used as p-type charge collecting layer in perovskite solar cells, we have reported that the use of partially oxygen-bridged triarylamines as quasiplanar scaffolds for charge-transporting materials facilitates delocalized pi-conjugation and on-top pi-stacking in the solid state, which ensures high carrier mobilities in the pi-stacking direction.[7] We demonstrated that the two-dimensionally expanded and sheet-shaped system using four oxygen-bridged triarylamines and azulene-core can improve the performance of perovskite solar cells.[8]

In this presentation, we will report our recent progress on the development of new materials and the performance of our perovskite solar cells using these.

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Materials Engineering for Efficient and Stable Halide Perovskite Solar Cells

Jun Hong Noh[1,2]

(1) School of Civil, Environmental and Architectural Engineering, Korea University, Seoul 136-713, Republic of Korea
(2) Division of Advanced Materials, Korea Research Institute of Chemical Technology, 141 Gajeong-Ro, Yuseong-Gu, Daejeon 305-600, Republic of Korea.

e-mail: junhnoh@korea.ac.kr

Inorganic-organic hybrid halide materials such as methylammonium lead iodide ($MAPbI_3$) or formamidinium lead iodide ($FAPbI_3$) have emerged as an innovative photovoltaic semiconductor for the future photovoltaic systems which require low-cost fabrication process and high power conversion efficiency (PCE). Because the halides with perovskite crystal structure are not only possible to fabricate the solid-state solar cells through low-cost solution process at low temperature under 200 ^{o}C but they also have excellent material properties to utilize for high PCE such as tunable band gap, high absorption coefficient, low exciton binding energy, superior charge-transport. The perovskite solar cells have showed unprecedented progress in PCE reaching 22 % in last several years. This progress is attributed to developments in terms of device architecture, perovskite materials, and fabrication process based on material engineering. In particular, since it is difficult to form a desired perovskite film due to an unique self-assembly crystallization behavior of perovskite crystals, a key factor to achieve the high performance is how to make a high quality perovskite film with compact morphology and low trap density on n(p)-type semiconductor layers. In order to control such material factors of perovskite halide crystal films, we have introduced mediator which retards direct reaction between organic halide and inorganic halide and influences on crystal growth. We demonstrated that dimethyl sulfoxide (DMSO) is an excellent mediator for formation of high-quality halide thin film. The iodide management also was performed using I_3^- ions to reduce internal trap density in the halide film. In addition to PCE, recently, long-term stability of the perovskite solar cells is big challenge. The stability of PSC is not only related to halide materials themselves but also is dependent on n(p)-type oxide and organic semiconducting layers. In this talk, material engineering of perovskite halides and oxide semiconductors will be introduced for achieving efficient and stable perovskite solar cells by formation of high-quality perovskite halide crystal thin film and novel oxide semiconducting film.

Keywords: *perovskite, solar cells, formamidinium, hybrid, halide, stability*

Low-cost and lightweight approaches for solar cells and their applications

Ching-Fuh Lin[1, 2, 3, 4]* , Subramani Thiyagu[1], Hong-Jhang Syu[1], Jia-Wei Wu[1], Yi Lai[1], and Po-Tsun Guo[1]

*Director of i-PARC, Distinguished Professor, and IEEE Fellow
[1]Graduate Institute of Photonics and Optoelectronics
[2]Department of Electrical Engineering
[3]Graduate Institute of Electronics Engineering
[4]Innovative Photonics Advanced Research Center (i-PARC)
No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan, ROC. E-mail: lincf@ntu.edu.tw

Alternative energies become an important trend for future due to the depletion of fossil energies and the danger of nuclear power. Solar energy is one of the very attractive choices. So far, Si is the most popular material and dominate the solar industry. Nonetheless, the conventional Si-based solar cells needs high vacuum and high temperature processing procedures. Here new approaches to fabricate Si-based solar cells using solution process that could further lower the cost of solar-cell fabrication will be addressed. Conventionally n-type and p-type Si materials are formed for p-n junction that is needed in solar cells to separate electrons and holes created by sunlight. The n-type or p-type Si is usually made through thermal diffusion or ion-bombardment, so vacuum chamber and high-temperature process is required. Here we propose another way to form p-n junction. We deposit organic material of PEDOT on n-type Si using solution process to form heterojunction. Such approaches can be performed in air without high-vacuum condition, so the fabrication cost is expected to be much lower. To further improve the device performance, we also develop hole-blocking layers as well as electron-blocking layers to enhance the separation of electrons and holes, also through solution process. The interface issues involved in the new layer structure are also investigated. Moreover, some methods to reduce the wafer thickness are explored, making the Si solar cells flexible, so their application scope can be further extended, not limited to power plants only. Those details will be discussed in the presentation.

In addition to Si-organic hybrid solar cells, we also explore the perovskite solar cells using a newly designed chamber that is able to achieve sandwiched deposition, named sandwiched deposition technique (SDT). SDT can give us the joint advantages of solution process and the evaporation. The formation procedure and time of perovskite can be better manipulated through SDT. The details will also be discussed.

Status and trends of thin-film on silicon tandem solar cell research in Singapore

Armin G. Aberle

Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore

Abstract

Tandem solar cells consisting of a crystalline silicon bottom cell underneath a high-bandgap thin-film top cell are the most promising technology path towards 30% efficient flat-plate PV modules under 1-sun illumination. This contribution presents the status and trends of thin-film on silicon tandem solar cell research in Singapore. The research is conducted as a joint effort of three institutes from three different universities (SERIS at NUS, ERI@N at NTU and SMART at MIT), whereby SMART and ERI@N focus on the development of the thin-film top cells (III-V and perovskites, respectively), while SERIS develops the c-Si bottom cell as well as the cell integration and interconnection concepts for PV module fabrication. Cell efficiencies of close to 20% and 25%, respectively, have so far been achieved for perovskite on silicon and GaAs on silicon tandem solar cells.

Silicon-Based Multi-Junction Tandem Solar Cells

Xiaodan Zhang[a,b,c,d]* , Xin Yao[a,b,c,d], Shijie Zhu[a,b,c,d], Bofei Liu[a,b,c,d], Lisha Bai[a,b,c,d], Jia Fang [a,b,c,d], Tiantian Li [a,b,c,d], Changchun Wei[a,b], Qian Huang [a,b], Jian Ni [a,b], Dekun Zhang[a,b], Guofu Hou[a,b], Xinliang Chen[a,b], Shengzhi Xu[a,b], Huizhi Ren[a,b], Guangcai Wang[a,b], Yi Ding[a,b], Yuelong Li[a,b,c,d], Baozhang Li[a,b], Ying Zhao[a,b,c,d]

[a] *Institute of Photoelectronic Thin Film Devices and Technology of Nankai University, Tianjin 300071, P. R. China*

[b] *Key Laboratory of Photoelectronic Thin Film Devices and Technology of Tianjin, Tianjin 300071, P. R. China*

[c] *Key Laboratory of Optical Information and Technology of Ministry of Education, Tianjin 300071, P. R. China*

[d] *Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, China*

Abstract

Great concerns on increasing global energy demand and environmental sustainability have aroused tremendous research interests in developing clean and renewable energy, especially inexhaustible clean solar power, to compete with excessive used fossil fuels. Among numerous photovoltaic (PV) technology candidates with various materials and architecture systems to address the issues of providing affordable and clean solar energy, multi-junction solar cells (MJSC) become the first choice owing to their unique advantages, including high photovoltage, reduced carrier thermalization loss, and high efficiency potentials, which also enable their particular applications in household and industrial scales. MJSCs based on the earth-abundant element, silicon, can further open reliable pathways to achieve the goal. We herein report our latest progress in fabricating high-performing MJSCs.

After combining with the single-junction sub-cells and optimizing the current-matching, an outstanding initial efficiency of 10.3% (V_{oc}=1.96V), 11.63% (V_{oc}=1.75V), 13.65% (V_{oc}=1.39V), and 14.26% (V_{oc}=1.52V) were respectively achieved for double-junction a-Si:H/a-Si:H, a-Si:H/a-SiGe:H, a-Si:H/μc-Si:H, a-Si:H/SHJ solar cells. Further based on the optimized low-loss tunnel recombination junctions to connect the sub-cells, higher performance triple-junction and quadruple-junction MJSCs with an initial efficiency of 16.07% (V_{oc}=2.19V) and 15.03% (V_{oc}=3.02V) were achieved for a-Si:H/a-SiGe:H/μc-Si:H and a-SiC:H/a-Si:H/a-SiGe:H/μc-Si:H solar cells.

Besides the silicon MJSCs, new-type perovskite/SHJ tandem solar cells are also being developed. Two-terminal monolithic perovskite/silicon-heterojunction (SHJ) tandem solar cells hold great promise for further performance improvement of well-established silicon photovoltaics. However, monolithic tandem integration is challenging, with efficiency far below the simulation results of more than 30%. Key issues such as J_{SC}, V_{OC} and FF should be optimized to further improve the efficiency of tandem device.

Transparent electrode is important for the light utilization as from which light first passes before entering the perovskite and silicon absorber, the transmission is therefore vital for the J_{SC} of tandem device. It is clear that both sub-cells have to be optimized to produce the same current at maximum power point, as the tandem current will be limited by the sub-cell with the lower current, light management is therefore essential for a high J_{SC}. In conclusion, through the modification of transparent electrode and perovskite absorber, we obtain a high efficiency of 20.86%.

Silicon-Based Multi-Junction Tandem Solar Cells

Xiaodan Zhang[a,b,c,d]* , Xin Yao[a,b,c,d], Shijie Zhu[a,b,c,d], Bofei Liu[a,b,c,d], Lisha Bai[a,b,c,d], Jia Fang [a,b,c,d], Tiantian Li [a,b,c,d], Changchun Wei[a,b], Qian Huang [a,b], Jian Ni [a,b], Dekun Zhang[a,b], Guofu Hou[a,b], Xinliang Chen[a,b], Shengzhi Xu[a,b], Huizhi Ren[a,b], Guangcai Wang[a,b], Yi Ding[a,b], Yuelong Li[a,b,c,d], Baozhang Li[a,b], Ying Zhao[a,b,c,d]

[a] *Institute of Photoelectronic Thin Film Devices and Technology of Nankai University, Tianjin 300071, P. R. China*

[b] *Key Laboratory of Photoelectronic Thin Film Devices and Technology of Tianjin, Tianjin 300071, P. R. China*

[c] *Key Laboratory of Optical Information and Technology of Ministry of Education, Tianjin 300071, P. R. China*

[d] *Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, China*

Abstract

Among numerous photovoltaic (PV) technology candidates with various materials and architecture systems to address the issues of providing affordable and clean solar energy, multi-junction solar cells (MJSC) become the first choice owing to their unique advantages, including high photovoltage, reduced carrier thermalization loss, and high efficiency potentials, which also enable their particular applications in household and industrial scales. MJSCs based on the earth-abundant element, silicon, can further open reliable pathways to achieve the goal. We herein report our latest progress in fabricating high-performing MJSCs.

Based on the optimized low-loss tunnel recombination junctions to connect the sub-cells, higher performance triple-junction and quadruple-junction MJSCs with an initial efficiency of 16.07% (V_{oc}=2.19V) and 15.03% (V_{oc}=3.02V) were achieved for a-Si:H/a-SiGe:H/μc-Si:H and a-SiC:H/a-Si:H/a-SiGe:H/μc-Si:H solar cells, respectively.

Besides the silicon MJSCs, new-type perovskite/SHJ tandem solar cells are also being developed. Two-terminal monolithic perovskite/silicon-heterojunction (SHJ) tandem solar cells hold great promise for further performance improvement of well-established silicon photovoltaics. Transparent electrode is important for the light utilization as from which light first passes before entering the perovskite and silicon absorber, the transmission is therefore vital for the J_{SC} of tandem device. It is clear that both sub-cells have to be optimized to produce the same current at maximum power point, as the tandem current will be limited by the sub-cell with the lower current, light management is therefore essential for a high J_{SC}. In conclusion, through the modification of transparent electrode and perovskite absorber, we obtain a high efficiency of 20.86%.

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PROGRESS IN PEROVSKITE/SILICON TANDEM SOLAR CELL

Donghwan Kim[1,2,*], Hae-Seok Lee[2], Yoonmook Kang[2], Soohyun Bae[1], Sang-Won Lee[1], Kyung Jin Cho[1], Jae Keun Hwang[1]

[1]Department of Materials Science and Engineering, Korea University, Seoul, Korea
[2]KU-KIST GreenSchool,Graduate School of Energy and Environment, Korea University, Seoul, Korea

Efficiency of silicon solar cells, which account for approximately 90% of the PV market, have reached 26.6% with the heterojunction back contact structure. The theoretical efficiency limit lies at around 30%. The tandem structure is an option for overcoming the efficiency limit. The organic-inorganic hybrid perovskite solar cell is a candidate as the top cell in the tandem structure with Si solar cell. The perovskite solar cell has demonstrated an efficiency over 22% with relatively a simple structure and a simple coating method. Perovskite material had a tunable bandgap, which is a necessary characteristics for the top cell. Efficiency of 23.6% is reported by Si/perovskite monolithic tandem structure. To further increase the efficiency, several parameters should be optimized including the photon trapping, the tunnel junction, the transparent contact materials, and the top cell's bandgap. In this presentation, we overview the trend of perovskite / silicon tandem solar cell technology and discuss future prospects.