

SYMPOSIUM ET02

TUTORIAL: High-Efficiency Crystalline Silicon Photovoltaics-Fabrication, Devices, and Testing
November 25 - November 25, 2018

* Invited Paper

TUTORIAL High-Efficiency Crystalline Silicon Photovoltaics—Fabrication, Devices and Testing

Sunday Afternoon, November 25, 2018
Hynes, Level 2, Room 201

Silicon and related thin films are applied widely in solar cells and other electronic devices. This tutorial will introduce the preparation methods, materials properties, fundamental Si surface chemistry, and device engineering. This will be followed by a review of the device physics of solar cells and the device output characteristics during testing. We shall also survey different monocrystalline Si solar cell architectures, with special emphasis on interdigitated back contact cells and the use of carrier-selective passivating contacts in advanced cell designs. Finally, we will discuss the physics of carrier lifetime and efficiency measurements in silicon solar cells and modules.

1:30 PM

Crystalline Si Growth, Surface Chemistry, and Passivation Sumit Agarwal; Colorado School of Mines

Overview of c-Si growth, converting SiO₂ to c-Si wafers; single and multi-crystalline Si; effect of oxygen in p-type Si solar cells; passivated of c-Si; H-terminated silicon surfaces; and structure and properties of the c-Si/SiO₂ and c-Si/Al₂O₃ interfaces.

2:15 PM

Device Physics of Solar Cells Ron Sinton; Sinton Instruments

Silicon solar cells are converging on high efficiency devices. For these the device physics is tremendously simplified, well described by a formalism first developed for high-efficiency n-type concentrator solar cells. This description, based on balancing photogeneration with recombination, gives simple insight into the operation of all modern solar cells, with extensions relevant to the interpretation of test data as well.

3:00 PM BREAK

3:30 PM

High-Efficiency Approaches for Monocrystalline Si Solar Cells Sumit Agarwal; Colorado School of Mines

Standard Al back surface field silicon solar cells; p-type PERC cells, light induced degradation and regeneration; methods for creating passivated contacts; interdigitated back contact Si solar cells; and HIT cells.

4:15 PM

Test and Measurement of Silicon Ingots, Wafers, Cells, and Modules Ron Sinton; Sinton Instruments

This section will focus on minority-carrier lifetime measurements as a tool for monitoring and optimizing device design and process optimization at each step in the production process. The difficulties in measuring the new generations of high-efficiency solar cells and modules will be discussed in detail.

SYMPOSIUM ET02

Silicon for Photovoltaics
November 26 - November 29, 2018

[Symposium Organizers](#)

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* Invited Paper

SESSION ET02.01: Poly-Silicon Contacts I

Session Chair: Stefaan De Wolf

Monday Morning, November 26, 2018

Hynes, Level 3, Room 311

8:30 AM *ET02.01.01

In-Depth Study of poly-Si / Oxide / c-Si Junctions and p+ poly-Si / n+ poly-Si Tunneling Junctions for Applications in Si Single Junction and Si-Based Tandem Cells Robby Peibst^{1,2}, Nils Folchert¹, Felix Haase¹, Christina Klamt^{1,3}, Yevgeniya Larionova¹, Jan Krügener², Agnes Merkle¹, Byungsul Min¹, Michael Rienacker¹, Udo Römer¹, Sören Schäfer¹, Dominic Tetzlaff², Tobias Wietler^{1,2} and Rolf Brendel^{1,3}; ¹Institute for Solar Energy Research Hamelin (ISFH), Emmerthal, Germany; ²Institute for Electronic Materials and Devices, Leibniz Universität Hannover, Hannover, Germany; ³Institute for Solid State Physics, Leibniz Universität Hannover, Hannover, Germany.

Passivating contacts based on a stack of polycrystalline (poly-) Si on a thin interfacial oxide (POLO) are attracting enormous research interest in crystalline (c-) Si photovoltaics. Its excellent passivation quality with emitter saturation current densities below 1 fA/cm², in combination with junction resistances in the sub-mΩcm² regime, result in a high carrier extraction selectivity S_{10} with an efficiency potential of an otherwise ideal Si single junction cell beyond 28 %. Three contributions of our group to this interesting research field will be reported: First, theoretical investigations of the current transport mechanism through these POLO junctions suggest a dominant contribution of pinhole-mediated current. These pinholes are experimentally verified post-priori with an excellent agreement between predicted and measured pinhole areal density. The temperature dependency of the junction resistance can be well described with our pinhole model. Second, we demonstrate the efficiency potential of the POLO-junctions on cell level. We so far achieved a record efficiency value for p-type Si material of 26.1%. On this back-junction back-contacted cell, the p+ type doped and n+ type doped poly-Si fingers are separated by a region of intrinsic poly-Si. Third, we combine an electron collecting n+ POLO junction on a p-type Si cell with a p+ type poly-Si layer to form a low-resistive tunneling junction as an interface of bottom and top cell for Si based tandem applications. The carrier lifetimes in the poly-Si of 42-54 ps, as experimentally determined by time-resolved photoluminescence, are used as input parameters for numerical Sentaurus simulations of our p+ poly-Si / n+ poly-Si tunneling junctions. These simulations reveal the importance of nonlocal band-to-band and especially trap-assisted tunneling for a low junction resistivity. Experimentally, a contact resistance of 7.4 mΩcm² for the entire (Al) / p+ poly-Si / n+ poly-Si / SiO_x / c-Si stack is determined, which is sufficiently low for a full area contact between bottom and top cell.

9:00 AM *ET02.01.02

Overview on the Amorphous/Crystalline Silicon Heterojunction Development at CEA-INES—From R&D Activities Up to Ready-to-Market Technology Delfina Muñoz; France, CEA-INES, Le Bourget du Lac, France.

In this work, an overview of the amorphous/crystalline heterojunction (SHJ) activity performed at CEA-INES during the last 15 years will be presented. First, the ramping-up of R&D developments allowed us to unlock the path to > 21% efficiencies in 2011. These results were obtained through a core understanding of the technology to overcome its main limitations and drawbacks, from the silicon material up to metallization. Back then, this placed CEA-INES as one of the main European actors in the SHJ development. Then (2012-2016), these developments were taken to the next level through the startup of the first pilot-line (1200wph) that brought the devices to a mature SHJ product using industrial deposition equipment. This second step got us familiar with production constraints and associated issues such as defectivity, silicon material impact, and reproducibility or tack-time constraints. A milestone was an R&D record bifacial cell >23% with median efficiencies around 21% in production, along with >300W on 60-cells modules thanks to associated module development. The third phase (2016-present) based on the new generation of MeyerBurger tools (2400wph) is ongoing, demonstrating the potential of the technology in a ready-to-market approach. Median efficiencies >21.5% in a 4-busbar and >22.5% in a busbarless technology on bifacial devices are demonstrated. R&D record cells surpassing 23.5% efficiency are also systematically obtained (up to 23.8%) using R&D processes on top quality Cz wafers. Bifacial GG modules over 380W on a 72-cells are demonstrated and transfer is ongoing towards ENEL and others. A record-breaking 410W module was also recently achieved on a GBS configuration coupling the SwartWire technology and top efficiency SHJ cells form the production line (>23.4%). Bankability studies demonstrate also the economic potential of the technology. Moreover, intense R&D activities are focusing on new paths to further boost the efficiency, in the field of materials, integration, processes and new architectures thanks to the know-how developed at CEA in the field of organic, perovskite, microelectronics and materials and thanks to efficient interactions with the main R&D actors in the SHJ community, through collaborative projects.

9:30 AM ET02.01.03

Optimization of the Ultrathin SiO_x Passivation Layer and n⁺-poly-Si Electron Selective Layers in TOPCon c-Si Solar Cells Zhi Zhang^{1,2}, Yuheng Zeng¹, Yuqing Huang^{1,3}, Mingdun Liao¹, Pingqi Gao¹, Chunhui Shou⁴, Jie Yang⁵, Xinyu Zhang⁵, Baojie Yan¹ and Jichun Ye¹; ¹Ningbo Materials Institute of Technology and Engineering, Ningbo, China; ²School of Materials Science and Engineering, University Science and Technology, Kunming, China; ³Materials Physics Department, Zhejiang Normal University, Jinhua, China; ⁴Zhejiang Energy Group R&D, Hangzhou, China; ⁵Zhejiang Jinko Solar Co. Ltd., Haining City, China.

Carrier selective tunnel oxide passivated contact (TOPCon) c-Si solar cell has attracted a great attention as one of potential technologies for high efficiency c-Si module production beyond the passivated emitter rear contact solar cell (PERC) structure. Currently, the highest TOPCon solar cell efficiencies have

reached 25.7% and 24.4% with N-type and P-Type c-Si wafers, respectively [1,2], demonstrating the potential in efficiency improvement of solar panels. In this contribution, we will report our recent progresses in the research and development of high efficiency TOPCon solar cells, including the fabrication and optimization of SiO₂ passivation layer, P-doped poly-Si contact layer, Al₂O₃/SiN_x:H emitter passivation, and metallization, with the focus on the post-crystallization treatment effect on the passivation quality and improvement of TOPCon solar cell efficiency. The ultrathin SiO_x (~1.5nm) passivation layers were grown in 68% HNO₃ acid at 60-110°C or in a mixed/concentrated acid of 68% HNO₃+H₂SO₄ at 60°C for 15 minutes on solar grade N-type c-Si wafers, following a 40-nm thick phosphorus doped hydrogenated amorphous silicon (n-a-Si:H) deposition on both sides. The double-side passivated samples were subjected to a high temperature annealing at 820°C for crystallizing the n-a-Si:H layer to form n⁺-poly-Si layer as the electron selective contact layer. Furthermore, various post-crystallization treatments were carried out to study the hydrogen passivation effect on the TOPCon structures by measurement the minority carrier lifetime and the implied open-circuit voltage (V_{oc}), including forming gas annealing, hydrogenated silicon nitride (a-SiN_x:H) coating and annealing, and atomic layer deposited Al₂O₃ coating and annealing. We found that the mixed/concentrated acid at 60°C has much stronger oxidization capability and produces more fully oxidized chemical structures with better passivation quality than the 68% HNO₃ process at 90-110°C. The relatively lower temperature oxidization process in the mixed/concentrated acid is suitable for mass production. For the hydrogenation of the TOPCon structure, the most effective method is the Al₂O₃ coating with an annealing at 450°C for 30 minutes, which results in a minority carrier lifetime of 1.5 ms at 5'10¹⁵ cm⁻³ carrier injection, saturated reverse recombination current density J₀=1.3 pA/cm², and iV_{oc}=743 mV. Using the improved hydrogenation procedure, we attained an energy conversion efficiency of 21.2% with the 4 cm² small area and 21.0% with 243 cm² large area n-TOPCon solar cells.

A. Richter, J. Benick, F. Feldmann, et al., *Solar Energy Materials & Solar Cells*, 173 (2017), 173: p. 96-105.

A. Richter, J. Benick, R. Müller, et al., *Progress in Photovoltaics Research & Applications*, 23 (2017), p.1-8.

9:45 AM ET02.01.04

Poly-Si Alloys Carrier-Selective Passivating Contacts for High-Efficiency c-Si Solar Cells Guangtao Yang¹, Gianluca Limodio¹, Paul Procel¹, Luana Mazzarella¹, Arthur Weeber^{1,2}, Olindo Isabella¹ and Miro Zeman¹; ¹Delft University of Technology, Delft, Netherlands; ²ECN part of TNO, Solar Energy, Petten, Netherlands.

Recently, carrier selective passivating contacts (CSPCs) based on poly-Si^{1,2} and poly-SiC_x^{3,4} have been developed and demonstrated record-high efficiency in both front back contacted (FBC, > 25%)³ and interdigitated back contacted (IBC, > 26%)¹ cell. However, the high free carrier absorption (FCA) of the CSPCs still limit the cell efficiencies⁵. Therefore, more transparent poly-SiO_x materials as CSPCs are developed^{6,7}. In this work, the poly-Si CSPCs are applied as both polarities in IBC cells. The well-passivated gap prepared between the back-surface field (BSF) and emitter poly-Si fingers can prevent their collected carriers to recombine with each other. The highest efficiency achieved here is 23.0%, with the potential of 24.0% to be reached in a short term. Our novel black solar cell front surface morphology, obtained by modulating nano-textured SiO₂ layer on top of standard micro-textured c-Si pyramids, enables a J_{sc} of 42.2 mA/cm². This approach decouples the light harvesting in Si from its surface passivation, which potentially results in the highest possible optical and electrical performances of the cells. Based on accurate TCAD simulation⁸, parasitic absorption, mainly in the form of FCA, in poly-Si BSF and emitter fingers was quantified as the main optical loss. Aiming at minimizing such loss, we developed oxygen-alloyed poly-SiO_x as CSPCs. Currently, our poly-SiO_x layers show excellent passivation and carrier selectivity, for both n-type (iV_{OC,flat} = 740 mV; contact resistance R_C = 0.7 mΩ•cm²; iV_{OC,texture} = 718 mV) and p-type (iV_{OC,flat} = 709 mV; R_C = 0.5 mΩ•cm²). Due to the O alloying inducing band gap widening, the absorption coefficient at long wavelengths in the poly-SiO_x layers becomes negligible. Both n-type and p-type poly-SiO_x layers are concurrently deployed in FBC cells with a front Indium-Tin-Oxide layer to facilitate carrier's lateral transport and as anti-reflection coating. A very high cell FF of 83.5% obtained in double-side flat FBC cells indicates the highly-efficient carrier collection. An active area cell efficiency of 21.5% is obtained on a front-side textured FBC cell, with a higher external quantum efficiency response below 600 nm comparing to the poly-Si reference cell. By using such CSPCs in an IBC cell, an efficiency of 19.7% is preliminarily achieved and mostly limited by processing issues. Compared to our reference IBC cells with poly-Si CSPCs, the one based on poly-SiO_x CSPCs shows higher internal quantum efficiencies at wavelengths above 1100 nm. This indicates that - for both FBC and IBC cells - poly-SiO_x CSPCs hold the potential to enhance the cells' J_{sc} by maximizing both short and long wavelength response.

1. F. Haase, et al. *SiliconPV*, 2018.

2. G. Yang, et al. *APL*, 2016.

3. S. W. Glunz, et al. *EUPVSEC*, 2015.

4. G. Nogay, et al. *SOLMAT*, 2017.

5. R. Santebergen, et al. *OSAPV*, 2017.

6. G. Yang, et al. *APL*, 2018

7. I. Mack, et al. *SOLMAT*, 2017.

8. P. Procel, et al. *SiliconPV*, 2016.

10:00 AM BREAK

SESSION ET02.02: Heterojunction Devices I

Session Chair: Delfina Muñoz

Monday Morning, November 26, 2018

Hynes, Level 3, Room 311

10:30 AM *ET02.02.01

EGP 3SUN 2.0—Towards the Demonstration of the Competitiveness of Silicon Heterojunction in the Global Market Giuseppe Condorelli¹, Andrea Canino¹, Pietro Rotoli¹, Marcello Sciuto¹, Antonio Ragonesi¹, Claudio Colletti¹, Wilfried Favre², Adrien Danel², Renaud Varache², Jordi Veirman², Delfina Muñoz², Charles Roux², Jean Francois Lerat², Frank Medlege², Vincent Barth², Lionel Sicot², Pierre Jean Ribeyron² and **Cosimo Gerardi**¹; ¹Enel Green Power, Catania, Italy; ²Department of Solar Technologies, Univ. Grenoble Alpes, INES, CEA, LITEN, Le Bourget du Lac, France.

Enel Green Power (EGP) which has so far produced more than 6 million of thin film silicon PV modules in its subsidiary company 3SUN has started a new program for the development and the implementation of bifacial Si-HJT (SHJ) technology to compete on the tough PV market scenario. SHJ technology has been selected for several reasons. One of them is certainly the potential of very high efficiency achievable with easy manufacturability. The low temperature processes facilitate the use of thinner silicon wafers, thus enabling further costs reductions. SHJ cells are also intrinsically bifacial and hence enable to produce more energy. These characteristics have a remarkable effect on the reduction of the LCOE, which is the relevant characteristic of a

PV installation.

EGP since more than two years has established a fruitful collaboration with CEA-INES to accelerate the development of SHJ technology, anticipate potential problems can occur during the industrial production and select materials for cell assembly.

EGP line will implement several features to reach both high cell efficiency and high level of quality standard. High-quality surface passivation is of extreme importance. Also surface manipulation is critical hence all the wafer automation has been designed with low contact and gentle handling approach. Surface condition and passivation level will be monitored through on-line photoluminescence (PL) equipment after deposition processes to intercept possible defectiveness and surface preparation issues.

To anticipate the production lines start and identify some of the main critical points, detailed studies have been performed using CEA-INES pilot line. The impact of wafers properties on cells parameters has been evaluated at the full ingot scale for several suppliers to mimic as much as possible the type of material that will be used in real production environment. Furthermore, it was demonstrated experimentally on the CEA-INES line that screen-printing layout changes could enable efficiency improvements up to 1% abs., going from four to six busbars. Finally, we will show recent progress on the fabrication and characterization of full bifacial SHJ modules.

11:00 AM *ET02.02.02

Reducing the Resistance of Heterojunction Contact Stacks in Silicon Solar Cells [Zachary Holman](#); Arizona State University, Tempe, Arizona, United States.

Amorphous silicon / crystalline silicon heterojunction (SHJ) solar cells have historically suffered from high series resistance that stems from transport across the heterojunction. We present a systematic analysis of the contributions from each layer of an a-Si:H(i)/a-Si:H(p/n)/ITO/Ag contact stacks and show that we can reproduce the measured series resistance of SHJ cells by summing the independently measured contributions. We find that contact resistance accounts for 50-80% of the series resistance and is most sensitive to the a-Si:H(i) layer thickness and ITO doping density. For example, a 2 nm increase in the a-Si:H(i) layer thickness above its baseline value will cause a 1.5% drop in fill factor, and this in turn narrows the processing windows of silicon heterojunction cell manufacturing. As one method to reduce contact resistance, we introduce a-Si:H(i)/a-Si:H(p/n)/Al contacts in which the Al begins to alloy with the doped a-Si:H but does not spike through the passivation layer. These contacts have resistances that are two orders of magnitude lower than conventional SHJ contacts, enabling partial-area contacts without appreciable fill factor loss.

11:30 AM ET02.02.03

Engineering of Thin-Film Silicon Materials for High Efficiency Crystalline Silicon Solar Cells [Mathieu Despeisse](#), Bertrand Paviet-Salomon, Antoine Descoedres, Laurie-Lou Senaud, Jonas Geissbühler, Gabriel Christmann, Sylvain Nicolay, Jan-Willem Schuttauf, Julien Bailat and Christophe Ballif; CSEM SA, Neuchatel, Swaziland.

Thin-film silicon layers can be produced with varying microstructure, composition and properties, depending on deposition process conditions and on the underlying substrate properties. This allows for designing selective contacts well suited to limit recombination losses in wafer-based crystalline silicon solar cells. The objectives of this work are to relate the properties of the deposited thin film silicon materials onto performance of silicon heterojunction and back-contacted silicon heterojunction solar cells.

Amorphous silicon intrinsic layers with high microstructure factor will be shown to yield cell precursors with higher passivation levels, but also resulting in increased series resistance losses. In particular, high passivation levels up to 32 ms achieved on 270 μm thick Fz wafer with resistivity of 3 ohmcm will be shown. In addition, we will show that contact resistance between n-type thin film layers and transparent conductive oxides can be controlled by the engineering of the n-type material properties (such as activation energy and defect density), providing contacting layers with increased resilience to the TCO work function. Implementing these advanced layers, silicon heterojunction cells on n-type wafers with efficiency up to 24.1 % will be presented, and cells on p-type wafers with noticeably up to 23.7 % certified efficiency will be shown. While different thin film silicon material properties can be obtained with proper deposition processes, the deposited material microstructure and composition also depend on the material on which it is deposited. These specificities of thin film silicon layers can be used in localized and selective contacts applied in back contacted devices architecture. In the developed innovative approach, so-called "tunnel-IBC" [1], both the hole collector patterning and its alignment to the electron collector are eliminated, drastically simplifying the process flow. Two prerequisites have to be fulfilled for such devices to work efficiently, (i) lossless carrier transport through the tunnel junction and (ii) low lateral conductance within the hole collector in order to avoid shunts with the neighboring electron-collecting regions. We meet these two contrasting requirements by exploiting the anisotropic and substrate-dependent growth mechanisms of n- and p-type hydrogenated nano-crystalline silicon layers. We report on the influence of processing conditions on the structural and selectivity properties of these layers. Tunnel-IBC devices integrating the developed layers are then shown to yield up to 24.42 % certified efficiency for a 25 cm^2 device.

This work will demonstrate thin film silicon properties enabling to achieve > 24 % efficiency for both standard heterojunction cells as well as for advanced tunnel-IBC heterojunction devices.

11:45 AM ET02.02.04

Contact Stack Evaluation for SHJ Solar Cells and Process Development for IBC-SHJ Solar Cells [Yifeng Zhao](#)¹, Engin Özkol¹, Paul Procel¹, Guangtao Yang¹, Luana Mazzarella¹, Olindo Isabella¹, Arthur Weeber² and Miro Zeman¹; ¹Delft University of Technology, Delft, Netherlands; ²Solar Energy, ECN part of TNO, Petten, Netherlands.

Silicon heterojunction (SHJ) solar cell is one of the most promising photovoltaic technologies owing to the outstanding passivation quality ensured by the a-Si:H layers. Together with the interdigitated-back-contacted (IBC) architecture, it enables the highest efficiency (η) so far of 26.7%. However, the mass production is limited, due to the complexity of the patterning processes.

In this work, our focus is on the evaluation of SHJ passivating contact stacks for high-efficiency simple processed IBC solar cells.

We first optimized intrinsic a-Si:H and doped nanocrystalline (nc-)SiO_x:H thin-film layers. The optimized 6-nm thick intrinsic (i-)a-Si:H layer provides > 3 ms lifetime and > 720 mV implied-V_{OC} (iV_{OC}) on double side textured n-type FZ wafer. On i-a-Si:H, an enhanced passivation quality is obtained (iV_{OC}> 730 mV) after (n)nc-SiO_x:H deposition. With a similar structure, no degradation in passivation quality (iV_{OC}= 720 mV) was observed after (p)nc-SiO_x:H deposition. This optimized 29-nm thick p-layer shows a dark conductivity (σ_d) of 0.174 S/cm and excellent activation energy of 51.4 meV, which is close to the optimal value that ensures a high efficient hole selectivity².

Our research on front-back-contacted (FBC) cells reveals that the effective minority carrier collection is essential to minimize the drop from SunsVoc to V_{OC}. Thick doped nc-SiO_x:H layers can effectively shield the device precursor from the influence of ITO's field effect and keep its overall passivation quality after ITO sputtering. Accordingly, the best FBC device performs promising SunsVoc with 727 mV and 734 mV, pseudo-Fill Factor (pFF) of 0.862 and 0.841, measured before and after metallization, respectively. Besides, we found that adding few nanometers of doped non-oxidic nc-Si:H between the nc-SiO_x:H and ITO leads to critical improvement in FF from 0.56 to 0.73. Currently, our best FBC cell exhibits η of 20.4% with J_{SC} measured from EQE, with the potential of large step improvement in short term by enhancing the FF via minimizing the cell series resistance.

Finally, we developed a novel one-step patterning process for fabricating tunneling IBC-SHJ solar cells. Since the non-HF resistant behavior of the doped nc-SiO_x:H layers and the excellent HF etching selectivity to intrinsic a-Si:H material, the process enables superior chemical passivation and no patterning

step for emitter due to the tunneling IBC concept³. With the optimized SHJ passivating contacts, the preliminary tunneling IBC device, exhibits an η of 18.2% with a V_{OC} of 659 mV, J_{SC} of 41.3 mA/cm², FF of 0.67. Further optimization of the layer thicknesses and patterning process in the second run enables much higher V_{OC} of 719 mV, with an average V_{OC} of 715 mV over 7 cells. By addressing the low σ_d of the non-optimized (n)mc-SiO_xH, which limits the cell FF (< 60%), a cell η over 22% is expected in short term.

¹K. Yoshikawa et al. Nat. Energy 2017

²P. Procel et al. SOLMAT 2018

³A. Tomasi et al. Nat. Energy 2017

SESSION ET02.03: Si-Based Absorbers I

Session Chair: Jan Benick

Monday Afternoon, November 26, 2018

Hynes, Level 3, Room 311

1:30 PM *ET02.03.01

High Performance Multi-Crystalline Silicon and Beyond [Chung-Wen Lan](#); National Taiwan Univ, Taipei, Taiwan.

The emergence of the high-performance multi-crystalline silicon (HP mc-Si) in 2011 has made a significant impact to photovoltaic industry. In addition to the much better ingot uniformity and production yield, HP mc-Si also has better material quality for solar cells. As a result, the average efficiency of solar cells made from HP mc-Si in production increased from 16.6% in 2011 to 19% or beyond in 2017. More importantly, the efficiency distribution became much narrower. Nowadays, with an advanced cell structure, such as the passivated emitter and rear cell (PERC), the efficiency in mass production is higher than 20.5%. The crystal growth technology for HP-mc Si is rather robust, so that the material quality from various wafer producers based on the same concept is about the same. Unlike the conventional way of having large grains and electrically-inactive twin boundaries, the crystal growth of HP mc-Si by directional solidification is initiated from uniform small grains having a high fraction of random grain boundaries. The grains developed from such grain structures significantly relax thermal stress and suppress the massive generation and propagation of dislocation clusters. The gettering efficacy of HP mc-Si is also superior to the conventional one. Currently, most of commercial mc-Si is grown by this approach, which could be implemented by either seeded with silicon particles or controlled nucleation, e.g., using nucleation agent coating. Besides the success, HP mc-Si is facing significant challenges recently, mainly from the mono-crystalline silicon (mono-Si). The diamond-wire (DW) slicing and the thinner cell processing are much more robust and economical for mono-Si wafers. The traditional acid texturing of DW sliced mc-Si wafers is incapable. As a result, mc-Si is rapidly losing its market share. Therefore, to keep mc-Si competitive in the future, besides the improvement of materials quality, the mechanical strength, especially for thin wafers, and texturing quality are crucial.

References

- [1] Y. M. Yang, A. Yu, B. Hsu, W. C. Hsu, A. Yang and C. W. Lan, Development of high-performance multi-crystalline silicon for photovoltaic industry, Prog. Photovolt: Res. Appl. 23 (2015) 340–351.
- [2] C.W. Lan, A. Lan, C.F. Yang, H.P. Hsu, M. Yang, A. Yu, B. Hsu, W.C. Hsu, A. Yang, The emergence of high-performance multi-crystalline silicon in photovoltaics, J. Crystal Growth, 485 (2016) 17-23 (for the 2016 International Organization for Crystal Growth (IOCG) Laudize Prize lecture).

2:00 PM ET02.03.02

On the Nature and Recombination Properties of the Defect Responsible for the Carrier-Induced Lifetime Degradation in Uncompensated N-Type Cz Silicon Elénore Letty¹, Mohamed-Amine Guerboukha¹, Jordi Veirman¹, [Wilfried Favre](#)¹ and Mustapha Lemiti²; ¹CEA INES, Le Bourget du Lac, France; ²INL, Villeurbanne, France.

High efficiency silicon (Si) cell architectures (Interdigitated Back Contacts, a-Si/c-Si heterojunction (SHJ)) require high quality substrates. The bulk carrier lifetime (τ) is the key material parameter that governs the cell performance. For the latter architectures, multi- μ s τ are needed, which also have to be stable under outdoor operating conditions.

Lately, we evidenced the fast formation under illumination of a recombination-active defect in uncompensated n-type Czochralski Si wafers, sampled from the seed-end of a “home-made” ingot. This effect was unexpected as uncompensated n-type Si was believed to be immune to Light-Induced Degradation (LID). It renders these wafers unsuitable for high efficiency solar cells (-13 mV open-circuit reduction) [Letty et al., Sol En Mat & Sol Cells 166 (2017) 147–156].

Yet, the nature of the formed defect remained unclear. The studied wafers contained high oxygen-related thermal donor concentrations ([TD]), in the upper range of what can be met in commercial wafers. Thus TD could be seen as a likely candidate. In the present study, and in order to assess this hypothesis, a TD-lean wafer from the ingot middle underwent a saw damage removal prior to a treatment at 450°C in a clean furnace, to generate TD in similar concentrations as in the LID-affected seed-end wafer ([TD] \approx 1.5x10¹⁵ cm⁻³). Wafers from both positions were passivated using PECVD amorphous silicon stacks, and were then light-soaked using intense flashes. We observe that contrary to the seed-end wafer, the TD-adjusted sample does not feature any τ degradation, despite the similar [TD] in both samples. This either demonstrates that TD are not related to the LID center, or that the LID effect requires the presence of an extra component to proceed (in addition to TD). This result represents a significant knowledge gain as high [TD] were believed to be a necessary and sufficient condition to trigger the LID effect [Letty et al., Energy Procedia 124 (2017) 657–664].

As the investigated crystal was pulled at low speed, the main point defect is likely to be self-interstitials (Si_i), which is supported by the patterns seen on E-PCD ingot lifetime mappings. Further work will aim to clarify their potential role in the observed LID effect, as Si_i could be involved in LID mechanisms [C. Möller and K. Lauer, Energy Procedia 55 (2014) 559 – 563].

In a second part of this work, the recombination parameters (capture cross sections and position in the gap) of the LID defect are studied using transient-PCD. The defect SRH signature is shown to be the same over the 36% of the ingot affected by the defect. We found that the experimental data cannot be reproduced by SRH parameters from either BO-, Copper- or FZ-related LID. We conjecture that either several SRH centers are simultaneously at play, or that the defect here is singular and specific. Eventually, we report its “effective” SRH parameters to lie within: 0.2 eV < E_c-E_i < 0.84 eV and 10⁻² < k < 4x10⁻¹.

2:15 PM ET02.03.03

Stability of Na Atoms at Stacking Faults in Si Depending on the Fermi Level [Yutaka Ohno](#)¹, Haruhiko Morito¹, Kentaro Kutsukake¹, Ichiro Yonenaga¹, Tatsuya Yokoi², Atsutomo Nakamura² and Katsuyuki Matsunaga²; ¹Tohoku University, Sendai, Japan; ²Nagoya University, Nagoya, Japan.

In megawatt-scale solar power plants, high-voltage stresses are inevitably applied between each cell and its module frame, and the stresses sometimes cause a power drop in the module (a so called potential induced degradation (PID)). The key factor of the PID in *p*-type Si solar cells is sodium (Na) impurities in solar module encapsulation. During operation, they agglomerate at stacking faults (SFs) in Si cells [1]. Na atoms would spontaneously diffuse into SFs and create an electrically conductive layers [2], resulting in a reduction of the shunt resistance [1]. Those SFs would nucleate from microscopic defects on Si cells such as dislocations, during the PID stress under the influence of Na penetration [3]. Also, the Na penetration process would be modified depending on the doping level [4]. These results suggest that the formation energy of SFs varies depending on the Fermi level, as well as on the existence of Na atoms. In this work, we examine the stability of Na atoms at SFs in Si crystals with different Fermi levels, which determines the PID phenomena in *p*-type solar cells.

SF ribbons bound by pairs of partial dislocations were intentionally introduced into B-doped *p*-type Si ($c = 8 \times 10^{18} \text{ cm}^{-3}$), P-doped *n*-type Si ($3 \times 10^{19} \text{ cm}^{-3}$), and nominally undoped *n*-type Si ($3 \times 10^{13} \text{ cm}^{-3}$), by applying a compressive stress at an elevated temperature. Each crystal and a Na sample were sealed within a stainless steel tube with Ar gas, and the crystal was doped with Na atoms by heating the tube in a furnace at 973 K for 5 h. The width of each SF ribbon w_{SF} was estimated by TEM, as a function of the line orientation α defined by the angle of \mathbf{b} to \mathbf{u} in which \mathbf{b} is the sum of the Burgers vectors of the dislocations and \mathbf{u} is a vector along the dislocations, and the formation energy of SFs E_{SF} was calculated with $w_{\text{SF}}(\alpha)$. In all the examined crystals, $w_{\text{SF}}(\alpha)$ increased by Na doping, and the ratio between the $w_{\text{SF}}(\alpha)$ after Na doping and that before doping was almost independent of α . Therefore, Na atoms would agglomerate at the SFs due to an attractive electronic interaction, and the interaction results in the reduction of E_{SF} . The degree of the energy reduction would decrease with rising the Fermi level: E_{SF} was reduced by more than 10 mJ/m² in *p*-Si while it was barely reduced in *n*-Si [5]. These results indicate that Na agglomerates at SFs in *p*-Si are stable in comparison with in *n*-type one, and this is consistent with the PID phenomena in *p*-type solar cells. The SF formation energy depending on the Fermi level can be explained by using *ab-initio* calculations [5]. For comparison, the stability of Na atoms at $\Sigma 3 \{111\}$ GBs will be discussed.

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2:30 PM DISCUSSION TIME

2:45 PM ET02.03.05

Annealing Effects on the Layer Structure in BaSi₂ Thin Films Studied by DB-PAS Ana B. Montes^{1,2}, Yilei Tian¹, Daan Schopmeijer¹, Stephan Eijl¹, Hendrik Schut¹, Takashi Suemasu⁴, Noritaka Usami³, Joao Serra², Olindo Isabella¹ and Miro Zeman¹; ¹TU Delft, Delft, Netherlands; ²Universidade de Lisboa, Lisboa, Portugal; ³Nagoya University, Nagoya, Japan; ⁴University of Tsukuba, Tsukuba, Japan.

BaSi₂ is a promising material for solar cell applications due to its elemental abundance, non-toxicity and electrical and optical properties [1,2]. Presently, heterojunction BaSi₂/c-Si solar cells with efficiency reaching 9.9% have been reported [3]. As an industrially applicable technique, radio frequency (RF) sputtering was employed in this research. Doppler-Broadening Positron Annihilation Spectroscopy (DB-PAS) is applied to study the layer structure, material composition and the open volume deficiencies therein.

BaSi₂ films were deposited by sputtering and subsequently crystallized by annealing treatment. Samples were analysed by DB-PAS depth profiling and Raman spectroscopy. Thus, *S* and *W* parameter curves vs positron implantation energy (roughly reflecting thickness of layers) were acquired. *S* and *W* physically represent annihilation events with low- and high-momentum electrons, respectively. *S* and *W* are fitted by VEPFIT software [4] with a five-layer model (oxide/oxide-BaSi₂ interface/BaSi₂/BaSi₂-substrate interface/substrate) based on our previous research [5].

In the *S* profiles, three regions are recognized as function of positron energy: surface, bulk and substrate. Once *S* and *W* are sensitive to the composition of the layer, such variations can be caused by changes either in composition or formation/presence of vacancies. According to our previous research, surface and bulk material hold different compositions. In the surface region, an increase of *S* is observed by increasing annealing temperature (T_a) from 650 to 700°C. This can be caused by the oxidation enhancement with T_a . For $T_a = 700^\circ\text{C}$, increasing the annealing time (t_a) from 1 to 5 min induces a shift to higher positron implantation energies of the oxide/BaSi₂ interface, suggesting that the surface oxidation mainly occurs within the first 5 min, and subsequently saturates.

In the bulk, either a higher T_a or a longer t_a decreases the *S*. Higher T_a enhances crystallization, which can decrease the defect concentrations. This may cause a lower *S*. A decrease in *S* is observed within the first 5 min. This can be caused by the crystallization of BaSi₂, as supported by Raman analysis. Longer t_a cause a decrease in *S* which is attributed to Ba diffusion. Further characterizations, e.g., positron lifetime studies, are needed to determine the presence/formation of vacancies. Films produced by molecular beam epitaxy and thermal evaporation as potential references are being studied, in order to benchmark the quality of sputtered BaSi₂ films by normalizing of *S* and *W* to those of reference films. This contribution serves as a platform for material development and solar cell devices based on BaSi₂.

References

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3:00 PM BREAK

SESSION ET02.04: Dopant-Free Contacts

Session Chair: Zachary Holman

Monday Afternoon, November 26, 2018

Hynes, Level 3, Room 311

3:30 PM *ET02.04.01

Metal Oxide and Fluoride Heterocontacts for High Efficiency Silicon Solar Cells James Bullock; University of California, Berkeley, Berkeley, California, United States.

The fast-growing terrestrial solar cell industry is currently dominated by crystalline silicon cell architectures which employ doping and direct metallization

for electron/hole separation. Despite being commonplace, the use of doping and direct metallization is known to incur a range of fundamental and practical performance limitations. A new strategy to address these shortcomings is to replace such regions with surface passivating heterocontacts. One burgeoning stream of research utilizes low-temperature materials like metal oxides, fluorides, sulphides and organic molecules to form such heterocontacts. I will discuss recent breakthroughs in this research area, which demonstrate the potential of this concept to simultaneously reduce fabrication costs and remove efficiency limitations.

4:00 PM ET02.04.02

Post-annealing Temperature Effect on Electrical Properties of Al₂O₃ Films on Silicon by Atomic Layer Deposition for Solar Cell Applications Ergi Dönerçark, Bilge Imer and Rasit Turan; The Center for Solar Energy Research and Applications (GUNAM), Middle East Technical University, Ankara, Turkey.

Silicon wafers, being the most dominant and almost inevitable material for solar cell production, require surface passivation to increase the solar cell efficiency by decreasing recombination losses. For this reason, several research groups are currently focused on the usage of thin alumina (Al₂O₃) as a passivation layer. The success of Tunnel Oxide Passivating CONTACT (TOPCon) solar cell, Passivated Emitter Rear Totally diffused (PERT) solar cell and Passivated Emitter Rear solar cell (PERC) structures demonstrate enhanced passivation quality of crystalline silicon (c-Si) solar cells with Al₂O₃ films [1]. The determining parameters for the passivation quality of Al₂O₃ can be summarized as interface trap states (D_{it}), fixed charge density (Q_f) and flat band voltage (V_{FB}). Due to enhanced field effect passivation quality of thin Al₂O₃ layer, high ratio Q_f can be accomplished. Q_f has been reported as high as 1 - 4x10¹² cm⁻² in literature by several research groups and this charge density is sensitive to both deposition conditions and post-thermal treatments [2]. In addition to field effect passivation, Al₂O₃ layer also provides chemical passivation with relatively low density of D_{it} [5]. In this context, the effect of different deposition conditions and post-annealing temperatures on Al₂O₃ films formed by atomic layer deposition (ALD) were investigated using conductance method to identify and clarify relation between interface properties and fixed charge densities under initial deposition conditions varying in between 160 - 200°C in combined with various post-annealing conditions (400°C to 600°C for 30 minutes). C-V and G-V measurements were done for each sample with various frequencies from 1kHz to 5MHz. From C-V measurements, the oxide capacitance and V_{FB} values were calculated and conductance method was applied to determine D_{it} values. It was shown that Q_f decreased when the post-thermal annealing was applied. The highest Q_f was -5.13x10¹³ cm⁻² and the lowest one was -2.43x10¹¹ cm⁻². D_{it} decreased at 400°C post-annealing temperature for different deposition temperatures. The highest D_{it} value was 2.79x10¹³ cm⁻²eV⁻¹ and the lowest one was 2.39x10¹¹ cm⁻²eV⁻¹. The lowest D_{it} was found at 400°C post-thermal annealing temperature under N₂ ambient with 165°C prior deposition temperature. It was concluded that when Q_f values increase, D_{it} values also increase. High variation on V_{FB} was found where it changed in between 1.09V to 4.19V.

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4:15 PM ET02.04.03

Band Alignment at the Heterojunction Between Plasma Enhanced Atomic Layer Deposited SnO₂ and N-Doped Hydrogenated Amorphous Silicon Ganna Chistiakova, Mathias Mews and Lars Korte; Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany.

Tin oxide, SnO₂, is a "classical" transparent conductive oxide (TCO) material used for a variety of optoelectronic devices, including thin film silicon solar cells. Its alloy with indium, ITO, is widely used for silicon heterojunction solar cells. Furthermore, the pure tin oxide material has recently been demonstrated to perform well as electron transport layer in perovskite solar cells. Thus, it can be surmised that SnO₂ on silicon might also be used as part of the recombination contact in silicon-perovskite tandem solar cells.

Motivated by these applications, we study atomic layer deposition (ALD) of SnO₂ on hydrogenated amorphous silicon. We use TDMASn as precursor, which is a prominent choice for SnO₂ ALD due to its low temperature requirements and high uniformity¹. For this work plasma enhanced atomic layer deposition (PEALD) of TDMASn with an oxygen plasma as oxidizer was used. With the ALD process it is possible to monitor changes at the interface with thickness changes on the monolayer scale. In our study we investigate the interface between n-doped a-Si:H and SnO₂ with increasing SnO₂ thickness. Using in-system UPS and XPS measurements, we monitor the change of the chemical state of the system and the shifts in valence band position and work function. These measurements enable to characterize the SnO₂/n-a-Si:H heterojunction as a function of SnO₂ thickness. We determine the conduction and valence band offsets at the SnO₂/a-Si:H interface and evaluate the interface for application as electron contact in silicon heterojunction solar cells, or as part of the tunnel junction for silicon/perovskite tandem devices.

During the ALD process no growth delay was observed, and the Sn 3d core level signal was already detectable after the first growth cycle. We find that during the first cycles an oxide interlayer is formed, which influences the valence band position, work function and the total band bending. The main cause is assumed to be the formation of a dipole at the interface, due to the oxygen rich conditions during the initial growth stages². Upon continued deposition, the dipole vanishes, and we observe a reversal of the band bending and the formation of a chemically clean SnO₂ layer. The conduction band offset from (n)a-Si:H to SnO₂ was determined to be -270 meV. Therefore, SnO₂ could be applied as an electron contact to (n)a-Si:H, if the formation of the strong interface dipole can be suppressed.

¹ J.W. Elam, D. a. Baker, A.J. Hryn, A.B.F. Martinson, M.J. Pellin, and J.T. Hupp, *J. Vac. Sci. Technol. A Vacuum, Surfaces, Film*, **26**, 244 (2008).

² K.T. Butler, J. Buckeridge, C. Richard, A. Catlow, and A. Walsh, *Phys. Rev. B* **89**, (2014).

4:30 PM ET02.04.04

Room-Temperature Sputtered Nanocrystalline Nickel Oxide Hole Transport Layers for Fully Textured Perovskite/Silicon Tandem Solar Cells Erkan Aydın, Joel Troughton, Michele de Bastiani, Esmat Ugur, Muhammad Sajjad, Areej Alzahrani, Marios Neophytou, Udo Schwingenschlogl, Frédéric Laquai, Derya Baran and Stefaan De Wolf; King Abdullah University of Science and Technology, Jeddah, Saudi Arabia.

In the past eight years, perovskite solar cells (PSCs) have quickly evolved into a high-efficiency technology due to the excellent electronic and optical properties of the perovskite absorbers. Among the two (*n-i-p* and *p-i-n*) device configurations, the *n-i-p* case has now reached record power conversion efficiencies (PCE) close to 23%, followed at some distance by its *p-i-n* counterpart. The choice of solvent-compatible HTLs and the lack of efficient *p-type* metal oxides represent the main causes hampering the rise of *p-i-n* PSCs, whose options were limited to hole transport polymers for several years. In this regard, nickel oxide (NiO_x) offers promising characteristics to replace the polymers, such as chemical stability, high broadband optical transparency, intrinsic *p-type* semiconducting nature, higher open circuit voltage (V_{OC}) and its deeper work function. Thanks to these unique properties, NiO_x has been studied widely and several successful reports have been published for solution processing such as sol-gel and combustion methods. However, these techniques require high-temperature annealing which increases the processing time and hinders its use on low-temperature stable substrates; low-temperature processing is crucial for monolithic perovskite/silicon tandem solar applications which promises very high efficiency beyond the single junction limit. The most promising silicon bottom cells for perovskite tandems is silicon heterojunction technology (SHJ) which has the highest V_{OC} and PCE for perovskite/silicon tandem applications. However, SHJ solar cells are only compatible with top cell processes up to ≈200 °C. Above this

temperature, V_{OC} of the devices sharply drop because of hydrogen effusion from the amorphous silicon layers, hampering the passivation effect. Based on this limitation, we took advantage of RF sputtering deposition to fabricate amorphous NiO_x layers. RF sputtering offers room temperature processing, flexibility to control composition by simply changing the deposition parameters, and fast deposition. Moreover, RF sputtering enables conformal deposition on complex surfaces such as random-pyramid textured silicon solar cells. Besides, owing to its high transparency NiO_x is well fit as a scalable HTL for tandem applications. In this work, we explore by various characterization methods and DFT analysis how the electrical and optical properties of optimized films correlate strongly with the specific defect chemistry of NiO_x . For planar, *p-i-n* configured $MAPI_3$ based PSCs, RF-sputtered NiO_x at room-temperature enables PCE values of 17.6%, which is highest achieved among the PSCs adopting sputtered NiO_x as HTL without heteroatom doping. These results pave the road for the development of the perovskite/silicon tandem solar cells on pyramidal textured surfaces.

4:45 PM ET02.04.05

Effectively Transparent Contacts (ETCs) for Al-BSF and PERC Silicon Cells Sisir Yalamanchili¹, Kelly McKenzie¹, Thomas Russell¹, Michael Kelzenberg¹, Rebecca Saive¹, Utkarshaa Varshney², Tian Zhang², Bram Hoex² and Harry A. Atwater¹; ¹California Institute of Technology, Pasadena, California, United States; ²UNSW, Sydney, New South Wales, Australia.

Triangular cross-section effectively transparent contacts (ETC) have been shown to reduce the front contact shading losses by as much as 6% for silicon heterojunction solar cells, with improvements in short circuit current density of 2.2 mA/cm², and absolute efficiency by 1%. We report here ETC printing on textured Al-BSF and PERC cells. We first show the preparation of high aspect ratio wider ETCs prepared via inductively coupled plasma reactive ion etching (ICPRIE) along with the preparation of PDMS stamps for ETC printing and ETC superstrates with a glass handle from them. We show the impact of firing on the shape of these high aspect ratio ETCs. We also demonstrate that aligning the ETC superstrates over conventional screen printed contacts can be an alternative to ink spillage and firing problems associated with the standard ETC printing on textured Al-BSF and PERC cells. The printing process for these triangular contacts involves making a master typically by etching triangular grooves in silicon and making polydimethylsiloxane (PDMS) stamps from them. Such stamps are placed over HIT solar cells and silver ink is flown into the triangular grooves to make the ETCs. However, printing these ETCs over textured substrates is a significant challenge as the gaps between the PDMS stamp and the textured surface provides pathways for silver ink to spill over into the gaps between fingers. Apart from spillage, printing these ETCs over conventional homojunction solar cells like Al-BSF or PERC that are very relevant to the industry, has an additional challenge of making a low resistance contact and retaining the shape of the ETCs when printed over the silicon nitride (SiN_x) antireflective layer after firing. Additionally, the typical screen printed contacts over Al-BSF and PERC cells are 40µm or wider. Employing ETCs on these cells have an additional requirement of being complementary to the widely used screen printing process for this technology to be more acceptable in the photovoltaic industry.

SESSION ET02.05/ET04.04: Joint Session: Perovskite and Silicon Solar Cells
Session Chairs: Antonio Abate and Stefaan De Wolf
Tuesday Morning, November 27, 2018
Hynes, Level 3, Room Ballroom C

8:00 AM ET02.05.01/ET04.04.01

Light Management in Perovskite/Silicon-Heterojunction Tandem Solar Cells—Influence of Texture Position on Efficiency and Energy Yield Marko Jost¹, Eike Köhnen¹, Benjamin Lipovsek², Amran Al-Ashouri¹, Klaus Jäger¹, Anna B. Morales-Vilches¹, Janez Krc², Lars Korte¹, Marko Topic², Bernd Rech¹, Bernd Stannowski¹ and Steve Albrecht¹; ¹Helmholtz-Zentrum Berlin, Berlin, Germany; ²LPVO, University of Ljubljana, Ljubljana, Slovenia.

Monolithic perovskite/silicon-heterojunction (SHJ) tandem solar cells have already shown that efficiency-wise they can compete with high efficiency silicon single junction cells; just recently a result with efficiency above 25% has been certified and published [1]. To further increase the tandem device performance to a level well above the best silicon single junctions at 26.7%, optical optimizations as well as a detailed device understanding of this advanced tandem architecture need to be developed. The highest potential for the tandem design is to utilize a textured silicon bottom cell, however, wet chemical processing of the perovskite topcell on top of the textured surface is challenging [1]. A solution could be in applying a textured foil onto a flat top-cell (or frontside) to improve light management as we have recently shown for perovskite single junctions [2].

Here we present how light trapping from textured surfaces changes the optics and with that the efficiency and also energy yield of monolithic tandem solar cells. By implementing a textured foil on a planar tandem solar cell front, we enabled a power conversion efficiency above 25.0%. This experimental achievement was realized by photocurrent enhancements due to light-trapping and -incoupling. The experimental results were verified with optical simulations to valid the correctness of the simulations. Based on the simulations we show the influence of the texture position and their respective efficiency differences also under non-ideal illumination conditions, such as high angle of incident light. Interestingly, we find that a planar front side with textured foil shows < 1% absolute less efficiency under STC conditions. To enable a high energy yield at all angles of illumination, we find that it is important to utilize textured front surfaces either by textured wafers or textured foils and we give guidelines to optical optimization of perovskite/silicon tandem devices.

References:

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8:15 AM ET02.05.02/ET04.04.02

Towards CIGS Perovskite Tandem Cells Jesper Jacobsson¹, Adam Hultqvist², Håkan Rensmo² and Gerrit Boschloo¹; ¹Chemistry, Uppsala University, Uppsala, Sweden; ²Uppsala University, Uppsala, Sweden.

Perovskite solar cells will have a hard time to reach competitiveness with respect to conventional PV-technologies; unless they are integrated in tandem-architectures that possibly could outperform single junction silicon cells. One interesting potential perovskite tandem companion is CIGS, $CuIn_{1-x}Ga_xSe_2$, which is a commercial thin film technology with record efficiencies above 22 % and a variable band gap. In this project, we strive for constructing efficient 2-terminal CIGS-perovskite tandem cells. We will here discuss progress and challenges connected to recombination layers, perovskite engineering, and transparent top contacts in CIGS-perovskite tandem architectures.

8:30 AM ET02.05.03/ET04.04.03

Thermal, Oxidative, and Operational Stability in Low Band Gap Tin-Lead Perovskite Solar Cells for Robust All-Perovskite Tandems Rohit Prasanna¹, Tomas Leijtens¹, Aryeh Gold-Parker¹, Eli Wolf¹, James A. Raiford¹, Stacey F. Bent¹, Michael F. Toney¹ and Michael McGehee^{1,2}; ¹Stanford University, Stanford, California, United States; ²Chemical Engineering, University of Colorado Boulder, Boulder, Colorado, United States.

Low gap ABX₃ perovskites tin and lead at the B-site are a breakthrough that have enabled fabrication of efficient all-perovskite tandem solar cells. However, tin is susceptible to oxidation to the 4+ state, a degradation pathway unique to tin-containing perovskites. Suppressing this oxidation reaction is essential to ensure that highly efficient all-perovskite tandem solar cells are also stable against long term environmental stressors. We identify the specific chemical mechanism by which pure tin-based perovskites undergo oxidation using a combination of chemical methods including thermogravimetric analysis and solvent extraction of degradation products. We find that the oxidation reaction depends on a cooperative mechanism that involves simultaneous oxidation of multiple adjacent tin iodide octahedra. Critically, the most favorable oxidation pathway is blocked by substitution of 50% or more of the B-site with lead because this significantly lowers the chances of there being multiple adjacent tin octahedra that can facilitate the cooperative mechanism. As a result, the stability of tin perovskites toward oxidation is improved by orders of magnitude upon alloying with lead. The resulting guideline is that low band gap perovskites can be designed to have significantly enhanced oxidative stability by keeping the tin fraction at 50% or below.

We proceed to design solar cells to withstand aging under elevated temperatures in air. We probe the thermal stability of high-performing low band gap solar cells by aging at 85 C in air. Encouragingly, there is no measurable change in the bulk absorption of the perovskite absorber under thermal aging in air, indicating that the strategy of suppressing oxidation by using a mixed tin-lead perovskite successively avoids oxidative breakdown. However, the fill factor drops due to the formation of an S-kink after 100 hours of aging. We develop a treatment of the tin-lead perovskite film by exposure to methylammonium chloride vapour that results in significant grain growth and healing of cracks between grains. This post-treatment drastically improves the thermal stability of the full solar cells. Using an MACI-vapour-treated low gap perovskite with 50% tin, capped with a sputtered Indium Tin Oxide (ITO) top electrode, we successfully demonstrate a solar cell that maintains its full power conversion efficiency for 150 hours in air at 85 C, and remains above 85% of initial PCE for over 300 hours. In addition, we demonstrate stable operation of a tin-lead solar cell at maximum power point under 1-sun illumination for over 100 hours with no drop in performance. These measurements are a huge improvement upon any thermal stability results reported for tin-containing perovskites. The fact that good thermal stability in air is achieved with no encapsulation represents a major step toward proving the long-term stability of tin-lead low band gap perovskite solar cells, and of efficient all-perovskite tandem solar cells.

8:45 AM ET02.05.04/ET04.04.04

What Makes an Economically Successful Tandem? Ian Marius Peters, Sarah Sofia and Tonio Buonassisi; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Two conflicting characteristics compete where the commercial viability of one-sun tandem solar cell is concerned: On the one hand, tandem solar cells have fundamentally higher efficiencies than single junction solar cells. On the other hand, tandem solar cells are intrinsically more complex than single junction solar cells and require more fabrication steps, which makes them more expensive. Only if the benefit from the additionally generated energy outweighs the higher fabrication cost can tandem solar cells be successful.

The question under which conditions the last sentence is true is a multilayered one. The value of efficiency is highest when considering the integrated PV system, which makes it necessary to explore system level aspects. These aspects include, among others, economic considerations as well as topics from material science; for example degradation.

In this work we attempt to provide an overview of what is needed to make tandem solar cells economically successful. Central to our findings is the concept of a “marriage of equals”, which states that the sub cells in a tandem should be similar, as well as enable high efficiencies. We will take a look at different material pairings, including perovskite on silicon, III-V on silicon and thin-film on thin-film tandems and investigate how these tandems compare to single junction solar cells in various types of systems and various locations.

We find that under the right circumstances one-sun tandem solar cells can outperform single junction solar cells economically. Yet more than techno-economic considerations are needed to make these types of solar cell a wide-spread reality. As an outlook we hope to offer a perspective of future opportunities for this technology.

9:00 AM *ET02.05.05/ET04.04.05

Designing Metal Halide Perovskites Solar Cells to be Stable for High Efficiency Tandems Michael D. McGehee; Department of Chemical Engineering, University of Colorado Boulder, Boulder, Colorado, United States.

The talk will begin by showing what we have done to make perovskite on silicon tandem solar cells with 25 % efficiency and how 30 % efficiency can probably be obtained in the coming years. Then the challenge of making solar panels with metal halide perovskite semiconductors that will last for more than 25 years will be addressed. We will show that packaged solar cells can survive industry standard reliability tests such as 1000 hrs at 85°C and 85% humidity, 200 temperature cycles between -40°C and 85°C, and ultraviolet exposure. The strategies for making stable perovskite cells include choosing perovskite compositions that have higher thermal and oxidative stability, managing stress during the formation of the film to prevent buckling that makes subsequent processing difficult, minimizing tensile stress in the final film since it appears to make bonds weaker, using solution processing of the top contact layer to fill in gaps at grain boundaries so that a sputtered transparent conducting oxide layer can form a superb barrier layer, using polyolefin as the encapsulant since it does not chemically react with the perovskite and has an ideal elastic modulus, using butyl rubber edge seals and using glass on glass packaging.

9:30 AM BREAK

10:00 AM *ET02.05.06/ET04.04.06

High Efficiency Perovskite/Silicon Tandem Solar Cells Kylie Catchpole; Australian National University, Acton, Australian Capital Territory, Australia.

Combining perovskites with well-established photovoltaic materials such as silicon or CIGS is an attractive option for producing cheap, high efficiency and high voltage solar cells. Perovskite-based tandem solar cells can potentially achieve over 30% tandem efficiency. We demonstrate a 4-terminal tandem perovskite-silicon configuration in which the efficiency is as high as 26%. We also demonstrate a two-terminal monolithic tandem device with a perovskite top subcell and a high-temperature tolerant homojunction c-Si bottom subcell, with an efficiency of over 22%, and a perovskite/CIGS tandem with an efficiency of over 23%, which is the highest efficiency that has been reported for this configuration. We describe the optical and electronic factors that have been instrumental in reaching these efficiencies. We also show that interface passivation can lead to open circuit voltages over 1.2V for a 1.6eV bandgap perovskite, and that semi-transparent cells can achieve high stability under combined heat and light. These results show the clear potential of perovskites in practical high efficiency tandem devices.

10:30 AM *ET02.05.07/ET04.04.07

Optimizing Interfacial Layers on Silicon Heterojunction Bottom Cells for Perovskite/Silicon Tandem Solar Cells with 25% Power Conversion Efficiency and Beyond Lars Korte, Anna B. Morales-Vilches, Luana Mazzarella, Eike Köhnen, Philipp Tockhorn, Lukas Kegelmann, Ganna Chistiakova, Mathias Mews, Bernd Stannowski and Steve Albrecht; Helmholtz-Zentrum Berlin, Berlin, Germany.

With open circuit voltages (V_{oc} s) above 730 mV, silicon heterojunction (SHJ) solar cells are promising candidates for the bottom cells in organic-inorganic lead halide perovskite/silicon tandem solar cells. Using simulation studies, we have shown that under realistic assumptions, power conversion efficiencies up to 30% should be achievable with such devices [1]. To attain this goal, starting from first devices with moderate stabilized efficiencies of 18.1% [2] we carefully optimized the optical and electrical properties of the device in order to achieve low parasitic absorption and reflection, photocurrent matching between the two sub-cells and lowly resistive current transport across the internal tunnel-recombination junction.

In this presentation, I will discuss how we were recently able to demonstrate certified 25% efficient perovskite/SHJ tandem cells [3] by addressing these issues. I will focus on the silicon bottom cell and contact stack optimization: Starting from a rear junction SHJ cell design on double side textured wafers with 22.6% power conversion efficiency ($j_{sc} = 38.3$ mA/cm², $V_{oc} = 731$ mV, FF = 80.6 %) [4], we developed a rear side only-textured SHJ cell, which allows to process the perovskite top cell using conventional spin-coating methods. Optimizing film thicknesses at the perovskite/SHJ interface and tuning the refractive index of the nc-SiO_x:H film used as front surface field in the SHJ to an intermediate value of ~2.6 (at 800 nm) were instrumental in achieving 25% efficient cells with photocurrents above 17.8 mA/cm². On this basis, I will briefly discuss the potential to further enhance device performance using alternative deposition methods, such as plasma-enhanced ALD for tin oxide interlayers, and alternative materials such as tungsten oxide alloys for carrier selective contacts.

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11:00 AM *ET02.05.08/ET04.04.08

Progress on Si Tandems Anita Ho-Baillie¹, Hamid Mehrvarz¹, Jianghui Zheng¹, Fajun Ma¹, Chuq Yi¹, Stephen Bremner¹, Shujuan Huang¹, Hidenori Mizuno² and Tyler J. Grassman³; ¹Australian Centre for Advanced Photovoltaics, The University of New South Wales, Sydney, New South Wales, Australia; ²Fukushima Renewable Energy Institute, National Institute of Advanced Industrial Science and Technology, Fukushima, Japan; ³The Ohio State University, Columbus, Ohio, United States.

Tandem solar cell is a promising approach for achieving high efficiencies for photovoltaics [1]. The challenge is to find an efficient, economical and stable technology for each cell stack to realize true savings in the system's levelised cost of energy. Nevertheless, substantial progress has been made in the demonstrations of two-terminal Si tandem cells. The advantage of 2-terminal over 4-terminal configuration is the reduced complexity in wiring and packaging [2]. The challenge lies in the integration of the cell stacks without electrical and optical losses.

Recently, a simple perovskite/Si tandem cell structure has been reported [3]. It does not require additional interface layer for the integration of perovskite and Si cells. Instead, the electron transport layer in the perovskite top cell serves as the recombination layer between the top and bottom sub cells. The lack of lateral conductivity in this recombination layer means undesirable shunts are effectively localized. Another advantage of this structure is its compatibility with homo-junction Si cells – the most common choice for incumbent commercial Si photovoltaic technology. Recent optimizations have improved cells' performance from 20.5% to 22.7% on 4cm².

Great progress has been made on 2-terminal III-V//Si and III-V/Si tandems via wafer bonding and direct growth. Many of these tandem cell structures require smooth interface negating the use of textured Si bottom cell. This means external measures are required for anti-reflection and light trapping. Strategies for improving the optical performances of InGaP/GaAs//Si tandem by SmartStack [4] and monolithic epitaxial GaAsP/Si tandem [5] will be presented in this talk.

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D. S. Lee, J. Bing, Y. Cho, C. Chen, M. A. Green, S. Huang and Anita W. Y. Ho-Baillie, *Energy & Env. Sci.*, DOI: 10.1039/C8EE00689J

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11:30 AM *ET02.05.09/ET04.04.09

Textured Monolithic Perovskite/Crystalline Silicon Tandem Solar Cells with >25% Power Conversion Efficiency Jeremie Werner¹, Florent Sahli¹, Brett Kamino², Matthias Bräuninger¹, Raphaël Monnard¹, Gizem Nogay¹, Philippe Wyss¹, Andrea Ingenito¹, Bertrand Paviet-Salomon², Loris Barraud², Laura Ding², Juan Diaz Leon², Gianluca Cattaneo², Arnaud Walter², Soo-Jin Moon², Terry Chien-Jen Yang¹, Peter Fiala¹, Fan Fu¹, Mathieu Boccard¹, Matthieu Despeisse², Bjoern Niesen², Sylvain Nicolay², Quentin Jeangros¹ and Christophe Ballif^{1,2}; ¹Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland; ²PV-Centre, CSEM, Neuchâtel, Switzerland.

As crystalline silicon (c-Si) solar cells are approaching their efficiency limit of 29%, novel solutions must be found to increase the competitiveness of Si photovoltaics compared to conventional energy sources. One of the most promising approaches lies in combining c-Si solar cells with a low-cost wide-bandgap top cell to form a tandem device. Organic-inorganic halide perovskite solar cells are particularly attractive candidates for top cells, showing high efficiencies with simple and potentially cost-effective device fabrication. Calculations have shown that the practical efficiency potential of perovskite/c-Si tandem solar cells is beyond 30%.

Here, we present perovskite/silicon tandem devices featuring fully textured bottom cells, through a careful control of the top cell deposition conditions and hence of the optoelectronic properties and interfaces of the different materials. These cells were employed as a platform to address the most crucial questions for tandem development:

- **Reaching maximal performance:** fully conformal perovskite top cells were developed and optimized, enabling the use of industrially viable textured bottom cells for maximal optical performance given the reduced reflection losses and enhanced light trapping. This enabled current-matching conditions with >20 mA/cm² in both the perovskite and silicon subcells (excluding metallization-induced shadow losses). Parasitic absorption was minimized thanks to the development of highly transparent charge transport layers and electrodes. This optical optimization of the tandems led to a certified steady-state efficiency of 25.2% for an aperture area of >1 cm².

- **Up-scaling:** a nanocrystalline silicon intermediate recombination layer was developed to increase the shunt resistance and enable large-area tandem

devices, achieving 13-cm² cells with a steady-state efficiency above 20%.

- **Silicon bottom cell technology:** we tested our process with different bottom-cell technologies (silicon heterojunction or tunnel oxide passivated contact) and reached >25% efficiencies on both cell types for an aperture area of >1 cm².

- **Industrially viable metallization:** a screen-printed silver (Ag) metallization method was developed for the front grid. It employs a low-temperature Ag paste that can be cured without affecting the perovskite properties.

- **Encapsulation and cell reliability:** an encapsulation process involving a glass/glass configuration with a butyl rubber edge sealant was developed.

Encapsulated tandems were subjected to standard reliability testing conditions, including damp heat at 85 °C/85%RH and light soaking for 1000 hours.

Overall, these results suggest a path in the development of monolithic perovskite/silicon tandem solar cells with realistic efficiency potential >30% on large area with enhanced stability.

SESSION ET02.06: Si-Based Absorbers II
Session Chairs: Paul Stradins and Noritaka Usami
Tuesday Afternoon, November 27, 2018
Hynes, Level 3, Room 311

1:30 PM *ET02.06.01

Multicrystalline Informatics for Silicon Ingot with Ideal Microstructures [Noritaka Usami](#), Kazuya Tajima, Soichiro Kamibeppu, Yusuke Hayama, Kentaro Kutsukake, Tetsuya Matsumoto and Hiroaki Kudo; Nagoya University, Nagoya, Japan.

We will review our recent attempt to integrate data science with experimental science, theory, and computation in order to enable a paradigm shift in development of complicated multicrystalline materials. This multidisciplinary scientific approach, “multicrystalline informatics”, is shown to be useful to realize ideal multicrystalline silicon (mc-Si) ingot for solar cells by various aspects.

Photoluminescence (PL) images of mc-Si wafers with intentional partial introduction of the reflected incident laser contains information of crystal defects and microstructures. We captured PL images from mc-Si wafers produced from the same ingot, and attempted to clarify the distribution of crystal defects inside the ingot. Although the surface of mc-wafers sliced by diamond wires is mirror-like with one directional saw marks, image processing could successfully visualize crystal defects as dark regions and microstructures with different average luminance. By sequentially stacking PL images of mc-Si wafers from the bottom to top of the ingot, the structural variation in the ingot could be visualized. Furthermore, by extracting crystal defects with thresholding, three-dimensional distribution of crystal defects could be visualized. These revealed that crystal defects, which are most likely assigned as dislocation clusters, are generated at grain boundaries followed by propagation and annihilation. This permits to extract a hundreds of generation points of crystal defects for further analysis of underlying physics. To obtain information on orientation distribution in mc-Si, optical images of mc-Si wafers with white light illumination would be useful. We captured a series of optical images with different illumination angles, and investigated the relationship between angular variation of average luminance and crystal orientation. Machine learning would be utilized for fast prediction of orientation distribution in mc-Si.

By combining these information, physics of crystal defects in complicated mc-Si will be manifested to show the guide to realize high-quality mc-Si ingot for solar cells.

This work was supported by Japan Science and Technology Agency (JST), CREST, JPMJCR17J1.

2:00 PM ET02.06.02

Effects of Amorphous Si Capping Layer on Sputtered BaSi₂ Film Properties [Yilei Tian](#)¹, Ana B. Montes^{1,2}, Olindo Isabella¹ and Miro Zeman¹; ¹Delft University of Technology, Delft, Netherlands; ²Universidade de Lisboa, Lisbon, Portugal.

BaSi₂ has gained interest as a promising light-absorbing material for thin-film solar cells. BaSi₂ is stable in ambient condition and possesses a suitable band gap ~1.3 eV for solar energy conversion [1]. Its potential also stems from attractive optical and electrical properties, i.e., a high absorption coefficient reaching 10⁵ cm⁻¹ for $h\nu > 1.5$ eV [1], a long minority carrier lifetime ~27 μ s [2], and essentially elemental abundance and non-toxicity. Theoretically, the attainable conversion efficiency of the BaSi₂ solar cell is up to 25% [3]. However, BaSi₂ is confronted with the issue of surface oxidation due to its reactivity with oxygen. The oxidation-induced structure transformation, altering the stoichiometry and degrading the film quality, has been uncovered by our previous research [4]. Hence, it is essential to develop anti-oxidation capping layer to improve BaSi₂ film quality.

In this contribution, hydrogenated amorphous silicon (a-Si:H) is studied as capping layer. Effects of a-Si:H on film properties are investigated by Raman, atomic force microscopy, and spectrophotometry. BaSi₂ films were deposited by RF magnetron sputtering and then capped by PECVD a-Si:H. Samples were subsequently annealed at temperatures ranging from 650 to 750 °C.

Raman spectra confirm the formation of crystalline BaSi₂ in annealed a-Si (10 nm)/BaSi₂ films. Aside from the BaSi₂ peaks, the crystalline Si peak is noticeable for films annealed at 650 °C, resulting from Si crystallization in both a-Si:H and BaSi₂ layers. Only a Si peak is displayed instead in spectra of a-Si (10 nm)/BaSi₂ film annealed at 700 or 750 °C. Besides, a-Si:H (10 nm)/BaSi₂ annealed at 650 °C exhibits similar optical properties to those of an uncapped BaSi₂ film annealed at 700 °C. The existence of a-Si:H capping can, therefore, decrease the thermal budget for crystallizing BaSi₂ but we found that such effect is influenced by the a-Si:H thickness. In fact, increasing the thickness of a-Si:H layer to 50 nm, sample annealed at 650 °C presents similar optical properties to the bare BaSi₂ film annealed at 650 °C rather than 700 °C. Thinner a-Si:H layers may suppress the formation of defective structures and/or metallic phases, thus altering positively the optical properties of the fabricated a-Si:H (10 nm)/BaSi₂. Furthermore, a 10-nm thick capping a-Si:H layer increases sample surface roughness from 20 nm (bare BaSi₂) to 47 nm.

The mechanism of tailoring BaSi₂ properties via a-Si:H capping layer is being investigated by further composition and electrical characterizations.

Additionally, the in-situ fabrication of a-Si/BaSi₂ films by a multi-targets sputtering method is being investigated. These results lay the groundwork for the development of BaSi₂-based thin-film solar cells.

References

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2:15 PM ET02.06.04

Status of and Pathways to Achieve Wafer Equivalent Crystalline Silicon Solar Cells on Glass by Liquid Phase Crystallization [Daniel Amkreutz](#)¹, Cham T. Trinh¹, Martina Trahms¹, Klaus Jäger², Christiane Becker² and Rutger Schlatmann³; ¹Silicon Photovoltaics, Helmholtz Zentrum Berlin, Berlin,

Germany; ²Young Investigator Group Nano-SIPPE, Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany; ³PVcomB, Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany.

Laser- or electron-beam induced zone-melting crystallization of silicon films is a fast and scalable technology to fabricate polysilicon layers on glass with customizable thicknesses and grain sizes up to several centimeters. Liquid-phase crystallized (LPC) silicon is thus a very interesting material for large area applications. Especially for PV, but also for microelectronics, MEMS or microfluidic applications. In the past, most effort was put on the development of a suitable layer stack between glass substrate and silicon absorber. This interlayer is mandatory for surface passivation, provides an antireflective coating and prevents impurity diffusion into the silicon absorber during the LPC process. Based on the progress in interlayer development, we demonstrated open circuit voltages up to 660 mV using n-type silicon. Nevertheless, fabricating a suitable contact system is challenging, because the carrier lifetime amounts to a few microseconds resulting in bulk diffusion lengths in the range of 30 to 60 micrometers. An interdigitated-back-contact system (IBC) was developed which is compatible with the crystallization process on glass and which is well suited for these diffusion lengths. With this contact system we were able to show conversion efficiencies up to 14.2% with current densities up to 31 mA/cm² for an IBC cell, which exhibits a planar silicon-glass interface and a pyramidically textured silicon rear side. In this contribution we summarize the current status of liquid-phase crystallized silicon on glass with emphasis on interlayer and contact system development. Future steps towards wafer-equivalent conversion efficiencies for silicon (thin-) film solar cells on glass are discussed. It is shown that the device performance is no longer governed by surface recombination at the interlayer so that the focus for further development shifts to the reduction of losses related to imperfect contact system and light trapping scheme. Aside from losses due to grain boundary recombination, the short circuit current mainly suffers from electrical shading because of insufficiently passivated contacts. Together with optical losses, these effects result in a reduction of the theoretical short circuit current density by approximately 30%. While alternative ways to passivate the absorber contact are currently under investigation, optical losses have to be reduced using improved light trapping schemes. The main challenge is to texture the interlayer-silicon and silicon-air interfaces without sacrificing the electronic quality by disturbing the crystal growth process. It is shown that the SMART (smooth anti-reflective texture) scheme is well suited to enhance the optical absorption while enabling theoretical short circuit current densities exceeding 37 mA/cm². Based on this estimation, first IBC cells with front- and rear-side texture are evaluated.

2:30 PM ET02.06.05

Fabrication of SiGe Layer on Si Substrate by Screen-Printing Masahiro Nakahara^{1,2}, Moeko Matsubara¹, Shota Suzuki¹, Shogo Fukami², Marwan Dhamrin¹ and Noritaka Usami²; ¹Toyo Aluminium K.K., Shiga, Japan; ²Engineering, Nagoya University, Nagoya, Japan.

During the past few years, the photovoltaics market has grown rapidly and the total cumulative installations amounted to 400GW at the end of 2017, capable of producing roughly 2% of the world wide electricity demand. And crystalline silicon has continued to dominate the solar industry with over 90% of the market share. However the energy conversion efficiency of crystalline solar cell is approaching its theoretical limit, Shockley-Queisser limit, of around 29%, giving the industry no choice but to search for new alternatives of solar cell structures that exceed this limit [1]. Meanwhile multi-junction solar cells, which combine multiple pn-junctions of different band gap energies to absorb the spectrum of the sun, are the state-of-the-art approach for achieving high efficiencies. However, compared with single junction silicon solar cells, the cost is still very high because it utilize Ge wafer as a bottom cell, which substrate for its best lattice match to grow Three Five films on it. Therefore substitution of Ge with low cost material, such as silicon, has a great interest to expand the Three Five solar cell market for terrestrial applications. The lattice mismatch between the epitaxially grown Three Five materials like a GaAsP and Si will result in a low open circuit voltage because of a high threading dislocation density when growing it directly on Si. There are few solutions to address this issue including wafer bonding, lift-off, sample recycling and growing sacrificial thick buffer layers of SiGe/Ge which increase the time and fabrication cost [2].

In this work, single-crystalline SixGe1-x thick layers grown by screen-printing technique on Si substrate is investigated. Pastes with different Ge, Al, and Si contents were screen-printed on Si (100) substrate and annealed at different temperature in air and Inert gas to investigate the impact of different Ge paste deposition on the Si substrate. After annealing, the residue pastes on the surface were selectively removed by wet etching with a phosphoric acid solution (H3PO4: CH3COOH: HNO3: H2O=16: 1: 1: 2) at 60 degree. Then, the morphology, atomic composition, crystal orientation and crystal quality were characterized by scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD). The SEM-EDX analysis indicated that SixGe1-x layers with good uniformity and thickness up to 30µm were obtained. Also Ge content of more than 20% is achieved. From the XRD patterns, the crystalline SixGe1-x peak has been detected in the vicinity of 2θ=66.2~68.8 deg. The strong SiGe (400) detected peak confirms the epitaxial growth with respect to Si (100) substrate. The formed SixGe1-x / Si wafer can be used with Ge buffer layer to fabricate high efficiency Three Five solar cells on cheap silicon substrates

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2:45 PM BREAK

3:15 PM *ET02.06.06

Minority Carrier Lifetime Characterization from Silicon Bricks to Modules—Current Status and Future Opportunities Harrison Wilterdink, Adrienne Blum, Cassidy Sainsbury, Wes Dobson, Justin Dinger and Ronald Sinton; Sinton Instruments, Boulder, Colorado, United States.

Minority carrier lifetime characterization is integral to the design and production of silicon PV devices in both laboratory and industry settings. Since development of the quasi-steady-state photoconductance (QSSPC) technique for silicon wafers in 1994, comparable lifetime characterization methods have been extended to span the entire silicon PV production chain—it is now possible to track relevant lifetime parameters from bulk material (ingots/bricks) all the way to finished solar cells and modules. Already this has enabled implementation of sophisticated quality control systems in production settings, for example: screening incoming material lifetime prior to processing, and monitoring/optimizing changes in lifetime for critical production processes—e.g., diffusion, passivation, laser ablation, nitride deposition, metallization, etc.

Applications of lifetime characterization at the finished cell and module stages have so far been largely untapped, but may prove especially insightful for high-efficiency cell designs featuring passivated emitters (PERC, PERT), rear contacts (IBC), or heterojunction interfaces (HJT). For cell production lines, lifetime characterization allows power losses to be quantified and sorted by specific loss mechanisms—bulk recombination, emitter recombination (J_{0e}), shunt resistance, and series resistance. This advanced characterization is possible at line-speed, which then enables continuous data feedback to inform material screening criteria and process optimizations for the entire production line. For finished modules, lifetime characterization can enhance understanding of power degradation observed in the field. For degradation modes with distinct lifetime signatures, such characterization enables development of device-physics-based degradation models, which can inform accelerated degradation protocols and highlight potential cell-level solutions to degradation issues.

This presentation will present an overview of the applications of lifetime characterization across the whole silicon production chain mentioned above, with an emphasis on potential future applications.

3:45 PM ET02.06.07

Improvement of Electrical Properties of Laser-Induced Liquid-Phase-Crystallized Silicon Thin Films for Photovoltaic Application Hiroshi Umishio, Takuya Matsui, Hitoshi Sai and Koji Matsubara; National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.

In crystalline silicon (c-Si) solar cells, decreasing wafer thickness is expected to be a way for reducing material cost. However, using thinner wafers has two major technical problems. First, wafer slicing creates extensive kerf loss that cannot be reduced easily when thinning the wafer. Second, manufacturing solar cells with thin wafers (<100 μm) is still technically challenging because of the high probability of wafer breakage. If the high quality c-Si thin films can be formed on cheap and strong glass substrates, one could avoid the kerf loss and the breakage risk of thin wafers. In addition, the long process chain for making wafers can be shortcut and that makes the wafer fabrication cost cheaper. Liquid-phase-crystallization (LPC) has emerged as a new technique to make high-quality poly-Si thin films with high crystallinity and large grains (several mm to a few cm in size) on glass. In LPC process, an amorphous silicon (a-Si) precursor film deposited on glass is melted and crystallized rapidly with a line-shaped laser or an electron beam. To achieve sufficient conversion efficiency using LPC-Si absorbers, the deeper understanding of the electrical properties of LPC-Si and their impact on photovoltaic performance are of importance. A factor that has a large impact on the electrical properties of LPC-Si is the grain quality such as grain size and defects present in the intra-grain and/or grain boundaries. In the fabrication process of multicrystalline silicon wafer, cooling rate of molten silicon is an important factor that determines grain size and dislocation densities. In case of LPC-Si, laser scan speed might play an important role in controlling the cooling rate of Si during crystal growth. Another important factor is the doping concentration that affects the carrier mobility and the carrier lifetime. In this study, to gain insight into the electrical properties of LPC-Si, we studied the majority carrier mobility and the minority carrier lifetime of the LPC-Si films prepared in a wide range of doping concentration and laser scan speed. In addition, test solar cells were made and their open-circuit voltage (V_{OC}) and internal quantum efficiency (IQE) were evaluated.

4:00 PM ET02.06.08

Impact of Undoped Substrates on High Performance Silicon Solar Cells André Augusto, Apoorva Srinivasa, Richard King and Stuart G. Bowden; Arizona State University, Tempe, Arizona, United States.

We investigate the potential advantages of using undoped silicon wafers, including high resistivity n- and p-type, to manufacture high performance solar cells. As the quality of Czochralski material improves and carrier selective contact architectures deliver superior surface passivation ($J_0 < 5 \text{ fAcm}^{-2}$), the cell injection regime increases by a factor of 10 and Auger recombination becomes more predominant. This is particularly true for substrates with Shockley-Read-Hall minority carrier lifetime over 1ms. For silicon heterojunction solar cells, high-resistivity base shows potential to increase both the V_{OC} and FF. We experimentally investigate silicon heterojunction solar cells on substrates in a wide range of dopant concentrations (8-20000 ohm.cm), observing closely the transition from low-level to high-level injection. The idea is to understand the device physics in this regime where neither limiting case of injection level is an accurate approximation. In field conditions modules experience different illumination conditions and as a result we also included in this study simulation and experimental measurements of the performance of these cells under light intensities from 0.2-1 suns. Preliminary results on solar cells using 8-20000 Ohm.cm n-type wafers shows excellent surface passivation ($J_0 < 2 \text{ fAcm}^{-2}$) regardless the base doping, impacting positively the pFF, FF and V_{OC} . These cells show similar performance behavior for different light intensities regardless their base resistivity. These studies have important implications for the manufacturing yield of Czochralski-grown wafers for which dopant concentration varies along the length of the ingot, and for the effect of Fermi level position on light and polarization-induced degradation mechanisms. Moreover, we are interested to understand if by changing the base doping we are able to mitigate same impurities by tuning the Fermi level. The insight provide by this study can impact positively the LCOE of PV systems through its effect on cell and ingot manufacturing yield, silicon cell power output, and module reliability.

4:15 PM ET02.06.09

Liquid Phase Crystallized Silicon for Application in an All-Thin-Film Perovskite/Silicon Tandem Cell Martina Trahms¹, Cham T. Trinh¹, Maurice Nuys², Uwe Breuer³, Uwe Zastrow², Natalie Preissler⁴, Marko Jost⁵, Steve Albrecht⁵, Rutger Schlatmann⁴ and Daniel Amkreutz¹; ¹Institute for Silicon Photovoltaics, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany; ²Institute of Energy and Climate Research 5 - Photovoltaics- (IEK), Forschungszentrum Jülich GmbH, Jülich, Germany; ³Central Institute for Engineering, Electronics and Analytics (ZEA), Forschungszentrum Jülich GmbH, Jülich, Germany; ⁴PVcomB, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany; ⁵Young Investigator Group Perovskite Tandem Solar Cells, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany.

Liquid phase crystallization (LPC) of silicon is an emerging photovoltaic technology that is based on laser-induced melting and subsequent crystallization of an amorphous or nano-crystalline Si-absorber. This technique avoids kerfloss which is typically associated with wafer processing. The absorber is deposited on glass with a thickness between 5 μm and 40 μm . During the crystallization process, a poly-crystalline Si-absorber with grain sizes in the order of cm in length and mm in width is formed. With an interdigitated back contact (IBC) system, conversion efficiencies of up to 14.2 % were achieved and V_{OC} values of up to 660 mV were demonstrated. Due to its high electronic quality, LPC-Si is a promising candidate for the application as bottom cell in a tandem device. Paired with a perovskite top cell, an all-thin-film tandem device can be fabricated. Various device concepts to combine the high-temperature processes for LPC and low-temperature requirements for the perovskite part are feasible. In particular, a four-terminal tandem device can be implemented by stacking the sub-cells via their glass substrates. First measurements with a perovskite filter show efficiencies of up to 3.5 % in the LPC-Si bottom cell. For this result no infra-red optimization of the LPC-Si cell was implemented yet. Increasing the thickness of the absorber and antireflective coating as well as 3D texturing will improve the efficiency further. However, even without these optimizations an overall efficiency of over 18 % can be expected for a state of the art Perovskite/LPC-Si tandem cell. An upper limit for the device performance of this four-terminal tandem design can be estimated using optical simulations and the main loss mechanisms can be evaluated. Aside from technological issues, such as parasitic absorption and reflection losses, recombination processes within the LPC-Si absorber prevent the bottom cell from achieving its full potential. These recombination mechanisms not only generally reduce the generated current, but also have a detrimental influence on the open circuit voltages in the filtered cells. It is estimated that up to 20 mV can be gained when assuming an electronically ideal cell with a filter. The recombination mechanisms are investigated in more detail by means of secondary ion mass spectroscopy (SIMS) to identify impurities in the absorber material. High amounts of carbon and oxygen are found within the absorber and are likely to segregate at grain boundaries. Impurities at the LPC-Si/a-Si heterojunction interface can also be responsible for a strong reduction of V_{OC} . The SIMS results suggest that defects at the heterojunction, decorated grain boundaries as well as intra-grain defects might be responsible for the observed losses. To develop a suitable strategy for further device improvement, it is crucial to investigate which of these loss mechanisms are limiting the cell performance.

4:30 PM ET02.06.03

Watching Nanodefets Grow in Si Crystals Andreas Magerl; University of Erlangen-Nurnberg, Erlangen, Germany.

Nucleation and growth of oxygen precipitates in moderately p- ($[B] \approx 10^{15} \text{ 1/cm}^3$) and highly p+ ($[B] \approx 10^{18} \text{ 1/cm}^3$) boron doped Czochralski Si crystals has been investigated in-situ up to 1000°C to monitor continuously the evolution of the defect properties from their very early stages to the long time behavior. Thickness-dependent Pendellösung oscillations as described by the dynamical theory of X-ray diffraction are extremely sensitive to strain fields from

defects in a host crystal. Based on this, we initiated a novel approach to study the precipitation kinetics of oxygen in Si. The data is interpreted within a diffusion-limited model of growing spherical precipitates, where two growth regimes are identified. An initial diffusion driven growth is followed by a long time precipitation behavior, which is interpreted as Ostwald ripening. In addition, synchrotron-based rocking curves (ID15, ESRF, Grenoble) provide information about the size distribution and morphology of the precipitates. A quantitative analysis of the in-situ experiments during annealing at 1000 °C shows two growing particle populations differing in polydispersity and particle density.

4:45 PM ET02.06.10

Improving Sub-Bandgap Photoresponsivity in Silicon Photodiodes via Pulsed Laser Melting-Tailored Hyperdoping Philippe K. Chow¹, Qi Lim², Jim S. Williams² and Jeffrey M. Warrender¹; ¹Benet Laboratories - ARDEC, Watervliet, New York, United States; ²The Australian National University, Canberra, Australian Capital Territory, Australia.

Extending the absorption edge of silicon to harvest below-bandgap-energy photons is one route towards improving/extending the short-wave infrared (SWIR) performance capability of optoelectronic silicon devices including intermediate-band photovoltaics and photodetectors. Non-equilibrium pulsed-laser melting (PLM) and resolidification of silicon containing highly-substitutional chalcogen (e.g. sulfur) and transition metal (e.g. gold) impurities at above-solubility limit concentrations is known to enhance the room-temperature sub-bandgap absorption coefficient dramatically, to the order of $\sim 10^4$ cm⁻¹ in the 1-2 micron range. However, the best demonstrated external quantum efficiencies (EQE) of photodiodes formed by a junction between the laser-doped layer and the Si substrate have been rather low, on the order of 10^{-3} - 10^{-2} %. It remains to be investigated how PLM condition-dependent material characteristics including impurity lattice location, concentration profile, microstructural homogeneity and chemistry influence photodiode EQE. In a general effort to boost EQE, we investigate the PLM-dependent structure-property relationships as is relevant to optoelectronic material development. We report our findings from complementary material and photodiode characterization using the most well-studied hyperdoping impurities, gold and sulfur. To explain the observed photoresponsivity results, we employ Rutherford backscattering spectrometry, secondary ion-mass spectrometry, optical absorption spectroscopy and scanning electron microscopy. Among the results, we report order-of-magnitude sub-bandgap EQE enhancement in gold-doped photodiodes, which were fabricated using a recently developed physical vapor deposition-based doping technique. This work aims to unify the state-of-the-art understanding of PLM-induced material properties and of the resulting optoelectronic device performance. Our results showcase the flexibility of PLM-based methods towards their tailoring the structural and electronic properties of silicon for real device applications.

SESSION ET02.07: Poly-Silicon Contacts II

Session Chair: Robby Peibst

Wednesday Morning, November 28, 2018

Hynes, Level 3, Room 311

8:30 AM *ET02.07.01

Material Limitations for High-Efficiency Silicon Solar Cells Jan Benick; Fraunhofer ISE, Freiburg, Germany.

Passivating and carrier-selective contacts such as amorphous Si heterojunctions or TOPCon have led the way to further push the efficiency of silicon solar cells to the theoretical material limit. The replacement of partial rear contacts (PRC) by passivating contacts as a full-area rear contact for both sides contacted solar cells so far resulted in efficiencies records up to 25.8% for mono- and 22.3% for multi-crystalline silicon (20x20 mm²). Achieving highest efficiencies requires both, a technology and cell architecture as well as a silicon base material which allows such high conversion efficiencies. In this paper we discuss the technology of our mono- and multi-crystalline n-type solar cells featuring a front side boron emitter and a rear side passivating electron contact. We further address material aspects and limitations in the cell efficiency associated with the silicon base material (e.g. resistivity and impurity contamination). Whereas the efficiency limitation caused by base material is more obvious in the case of multi-crystalline silicon, we show that even for mono-crystalline n-type silicon, which is less sensitive to common impurities than p-type silicon, even quite low impurity concentrations can be sufficient to limit the cell efficiency potential below 25%.

9:00 AM *ET02.07.02

Upscaling Passivating and Carrier Selective Contacts for Industrial Applications Ingrid Romijn, Maciej Stodolny, Paula Bronsveld, Agnes Mewe, Piero Spinelli and Kees Tool; ECN part of TNO, Petten, Netherlands.

The performance of current industrial solar cells is for a large part limited by recombination at metallic contacts. A solution to overcome this is to screen minority carriers from the metal by using so-called passivating carrier selective contacts. Using carrier selective contacts based on doped polysilicon layers combined with tunnel oxides, efficiencies well above 25% have already been reached on front and back contacted cells on laboratory scale.

In this contribution, we will first focus on upscaling of these polysilicon passivating contacts to 6" bifacial cells using industrial screen printed and fired metallization. The main challenge for such solar cells lies in keeping the contact recombination low, while applying a cost effective, industrial metallization approach. The contact mechanism of commercial silver and silver/aluminum pastes on both n+ and p+ doped polysilicon layers has been extensively studied using scanning and tunneling electron microscopy (SEM, TEM), $J_{0,contact}$ and contact resistance (TLM) characterization and a comprehensive model has been built. Contact recombination on n+ poly-Si surfaces has been reduced down to 80 fA/cm² while keeping the contact resistance low enough to enable FFs above 79.5%. $V_{oc,s}$ up to 685 mV have been obtained enabling initial cell efficiencies of 21.5%. Further optimization of the passivating polysilicon layers itself has yielded record low values for J_0 on textured surfaces: we present J_0 and implied V_{oc} measurements with best values of <1 fA/cm² and 741 mV for n-type, and <10 fA/cm² and 721 mV for p-type polysilicon on textured n-Cz wafer, which are maintained after firing.

Furthermore, results of an even more innovative type of carrier selective contacts based on transparent metal-oxides will be presented. Electron beam (E-beam) deposited molybdenum oxide (MoO_x) has been investigated for its potential as a hole selective contact. The high work function of MoO_x induces strong band bending in the silicon absorber, which diminishes the electron density at the c-Si surface, while allowing band-to-band transport for holes. Additionally, its high transparency, due to the wide bandgap and dopant-free hole selectivity, makes it a good candidate to replace other high-quality carrier-selective contacts based on doped layers (e.g. a-Si and polysilicon) at the sunny side of the cell or in bifacial solar cells.

By making large-area "moly-poly" cells, with a front side MoO_x/aSi:H(i) passivating contact and a rear-side poly-Si/SiO_x stack, we have demonstrated that MoO_x based c-Si solar cell technology can be scaled to industrial 6" wafer size. Excellent surface passivation was achieved using MoO_x and poly-Si, leading to implied V_{oc} values > 725 mV, and a final cell V_{oc} of 687 mV. Using thin PECVD poly-Si layers to avoid too high FCA losses, a 18.1% efficient

9.2×9.2 cm² moly-poly cell was made, which is to our knowledge the highest reported efficiency so far for moly-poly cells.

9:30 AM ET02.07.03

Carrier-Selective Passivating Contacts Based on polySiC for High Efficiency Si Solar Cells Luana Mazzarella¹, Guangtao Yang¹, Gianluca Limodio¹, Paul Procel¹, Arthur Weeber^{1,2}, Olindo Isabella¹ and Miro Zeman¹; ¹PVMD group, Delft University of Technology, Delft, Netherlands; ²Solar Energy, ECN part of TNO, Petten, Netherlands.

Carrier-selective passivating contacts (CSPCs) based on an ultra-thin SiO₂ capped with doped thin Si based layers exhibit excellent surface passivation of the Si wafers by the SiO₂ and selective carrier extraction thanks to the polysilicon layers. Poly-Si material exhibits generally poor transparency, owing to high parasitic and free carrier absorption, enabling the use of those materials in interdigitated back contacted (IBC) cell configuration¹ with efficiency up to 26.1%². On the other hand, using such material at the front side of the device induces current losses. Therefore some efforts have been carried out to reduce the layer's thickness³ and to incorporate carbon⁴ or oxygen^{5,6} to improve their transparency.

Recently, CSPC based on poly-Si alloyed with C_x⁴ or O_x^{1,6} demonstrated their potential on device level resulting in conversion efficiency up to 25.7% in front back contacted (FBC) cell configuration⁷.

In this study, we develop polysilicon carbide (poly-SiC) CSPCs with both doping polarities grown by plasma enhanced chemical vapor deposition in an initial amorphous arrangement (a-SiC:H) on top of a chemically-grown SiO₂ (<1.5 nm⁶). We thus monitor the passivation quality during the fabrication process to obtain poly-SiC material. Firstly, we investigate the effect of C alloying, doping and layer thickness on the final material properties and passivation performances.

Furthermore, we optimize the annealing treatment varying both the temperature and time in a wide range (800-950 °C, 5-60 min) to identify the optimum conditions to crystallize the layer stack and drive-in the dopants beneath the passivating SiO₂ thin film into the c-Si absorber. Contextually, we enhance the passivation quality of the CSPS stacks by using sacrificial layer(s) schemes that act as source of hydrogen. In this respect, we test SiN_x, Al₂O₃ and Al₂O₃/SiN_x in forming gas annealing atmosphere at 400 °C.

Preliminary results obtained on symmetric test samples capped with 75-nm thick SiN_x layer feature promising passivation quality for potential application in both FBC and IBC solar cells. We found that n-type poly-SiC ensures much higher temperature stability than the p-type counterpart with implied open circuit voltage (i-V_{OC}) above 700 mV for the range of annealing temperature / time investigated. For the p-type, the value is limited to 653 mV, with much more margin of improvement. For a stack initially consisting of (i)a-Si/(n)a-SiC:H (5 nm/30 nm), we measure i-Voc above 710 mV, carrier lifetime of 7.5 ns and recombination current densities of 12 fA/cm².

¹ G. Yang et al. SOLMAT (accepted)

² F. Haase et al. SiliconPV (2018).

³ F. Feldmann et al. SOLMAT, 159 (2017)

⁴ G. Nogay et al. SOLMAT, 173 (2017)

⁵ I. Mack et al. SOLMAT, 181 (2018)

⁶ G. Yang et al. APL, 112 (2018)

⁷ A. Richter et al. SOLMAT, 173 (2017)

9:45 AM ET02.07.04

Inkjet Printing as a New Method for the Preparation of POLO Contacts Fabian Kiefer¹, Nadine Wehmeier¹, Till Brendemühl¹, Larysa Mettner¹, Felix Haase¹, Michael Holthausen², Christian Daeschlein², Christoph Mader², Odo Wunnicke² and Sarah Kajari-Schroder¹; ¹Institut für Solarenergieforschung GmbH, Emmerthal, Germany; ²Evonik Creavis GmbH, Marl, Germany.

The increase of Si solar cell efficiencies in the last years have been mainly driven by passivating contacts, either with amorphous Si (heterostructure with intrinsic thin layer, HIT) or silicon oxide (poly-Si on oxide, POLO; tunnel oxide passivating contact, TopCon) as an interface layer¹⁻³. Interdigitated back-contact (IBC) solar cells have demonstrated the highest efficiencies of more than 26 %^{4,5}, as they combine a high voltage resulting from the passivating contacts and a higher current compared to front-contacted solar cells due to the absence of metal shading. A drawback shared by all presented techniques for the deposition of POLO contacts so far is that they cover the full area of one or both sides of the wafer⁶. During the process of an IBC Si solar cell, a structuring of the deposited poly-Si layer is necessary.

To overcome these hurdles, Evonik developed an inkjet printable, doped precursor (Evonik's liquid silicon) which can be used for the direct generation of structured amorphous and polycrystalline Si layers^{7,8}. As direct printing on silicon oxide layers used for POLO junctions is possible, this is a novel, unique possibility to prepare in-situ doped and in-situ structured poly-Si layers with only three process steps: Printing of the liquid Si ink onto the wafer under inert atmosphere with an inkjet printer – conversion of the liquid Si into amorphous Si on a hotplate – annealing of the layer stack in a tube furnace with break-up of the silicon oxide and conversion of the amorphous Si into poly-Si. The shape of the printed Si layer can be designed freely, the minimum structure size of the printed POLO contact is limited only by the drop size of the inkjet process.

In this work, we present the preparation and properties of phosphorous-doped inkjet-printed POLO layers. The electrical characterization of the layers includes measurements of the recombination current densities J₀ via photoconductance decay and the contact resistances between aluminum and the printed Si layer and between poly-Si and substrate via transfer length method. We print the ink on one side of the wafer in quadratic fields with an area of 4 x 4 cm², which is a suitable size for the measurements. The rear side of the wafer is passivated with a silicon nitride passivation layer. We investigate the influence of two process parameters on the electrical properties of the POLO contacts: the thickness of the printed liquid Si layer and the thermal budget of the annealing process. For several poly-Si layer thicknesses and annealing temperatures between 900°C and 1000°C, we achieve J₀ of the first P-doped inkjet-printed POLO contacts of < 20 fA/cm² with a minimum value of 14 fA/cm².

Ref.:

¹doi:10.1016/j.solmat.2014.06.003

²doi:10.1016/j.solmat.2013.09.017

³doi:10.1016/j.solmat.2017.05.042

⁴doi:10.1038/nenergy.2017.32

⁵F. Haase, et. al., SOLMAT, acc. for publ., 2018.

⁶R. Peibst, et.al., 32nd EUPVSEC, p. 323, 2016.

⁷doi:10.1002/aenm.201301871

⁸doi:10.1016/j.solmat.2017.11.003

10:00 AM BREAK

10:30 AM *ET02.08.01

SunPower's Next Generation Technology—Taking IBC Mainstream [Gabriela Bunea](#), Jeff Cotter, David Smith and David Kavulak; SunPower Corporation, San Jose, California, United States.

The crystalline silicon photovoltaic industry, research institutes and universities have continued to push the practical limits for solar cell and module efficiencies. Reports of c-Si solar cells with a total area efficiency above 25% have been made in recent years. SunPower is currently producing >400MW of the Gen III Maxeon solar cell with an average production efficiency of >25%, made possible by improvement in edge recombination, series resistance and front surface passivation on our 5" platform. This has made Sunpower the leader in cell and module efficiency in production for many years, with an average module efficiency >22.5%.

We have seen the c-Si solar cell technology moving towards high efficiency by significant investment in mono PERC that reached >50 GW installed global capacity, as well as new method to make modules using shingled cells that made possible modules >19% efficiency. We are seeing more companies investing in both IBC and HIT cell technologies, and working to figure out cost effective ways to scale.

In this paper we are presenting the progress that Sunpower Corporation has made towards making interdigitated back contact (IBC) main stream by step change in cost enabled by moving towards a standard 6" wafer size, simplify the production and reduce cost while continuing to push the limits of efficiency in production. Cell to module conversion efficiency have reached the point where the trade-offs between efficiency versus module area power optimization needs to happen.

11:00 AM ET02.08.02

The Influence of Surface Passivation on High Performance Silicon Solar Cells of Different Thicknesses André Augusto, Pradeep Balaji, [Stuart G. Bowden](#) and Joseph Karas; Arizona State University, Tempe, Arizona, United States.

Recently Kaneka set higher passivation requirements ($J_{0S} < 3 \text{ fA/cm}^2$) to surpass 26% efficiency. Intrinsic efficiency limit indicates that thinner cells are required to further increase the efficiency, as a result of voltage increase. In this paper, we study how passivation impacts the performance of silicon solar cells at different injection levels for different wafer thicknesses. In particular we quantify the recombination mechanisms at maximum power and open-circuit voltage, and we show how different cell architectures are limited by their passivation capabilities. To produce an experimental evidence of high voltage silicon device operating close to the recombination intrinsic limit, we manufactured thin silicon heterojunction test structures designed to minimize surface recombination ($J_{0S} < 1 \text{ fA/cm}^2$), and to measure voltages and effective lifetimes near the Auger and radiative limit. Open-circuit voltages over 760 mV and pseudo-fill factors of 86% were measured on 50- μm -thick structures, leading to bandgap-voltage offsets down to 0.35V. The bandgap-voltage offset is in line with the best reported for direct bandgap materials such as GaInP and GaAs. Additionally, we will present our latest results on sub-50 μm -thick solar cells that are presently being manufactured. Preliminary results on 40 μm -thick and 6-inch pi/Cz/in samples show implied- $V_{OC} > 760 \text{ mV}$ across the wafer for intrinsic layer thicknesses below 6 nm.

11:15 AM ET02.08.03

Nanocrystalline and Amorphous Doped Layers in Contact with Room Temperature Sputtered Al-Doped Zinc Oxide for Silicon Heterojunction Solar Cells [Oleksandr Astakhov](#), Huimin Li, Jürgen Hüpkens, Kaining Ding and Uwe Rau; IEK-5 Photovoltaik, Forschungszentrum Jülich GmbH, Jülich, Germany.

Recent progress in development of silicon heterojunction (SHJ) solar cells promotes this technology for mass production of future PV modules. In view of technology upscaling use of abundant materials for cell production is highly desirable. Particularly the tin-doped Indium oxide (ITO) - the transparent conductive oxide contact applied in high efficiency SHJ cells may be challenging in mass production due to indium-related supply/economic and environmental issues. One viable alternative for ITO in SHJ solar cells is more environmentally friendly, abundant and low-cost Al-doped Zinc Oxide (AZO). In our work we develop rear emitter SHJ solar cells with AZO contacts prepared at room temperature to explore the potential for reduction of thermal budget of SHJ cell preparation.

From the long lasting experience in the field of thin film silicon solar cells it is widely accepted that AZO as a window TCO forms better contact with microcrystalline or nanocrystalline Si (nc-Si:H) p-layer compared to the amorphous Si (a-Si:H) p-layer. Formation of the barrier for hole transport has been reported by several groups for thin film Si solar cells with a-Si:H layers deposited on the AZO front contact. In view of this experience we performed a comparative study where SHJ solar cells have been prepared with nc-Si:H doped layers and a-Si:H doped layers and room temperature magnetron sputtered AZO contacts. For the case of p-type layers, contrary to the expectations the cells with nc-Si:H p-layer showed distinct transport barrier in IV characteristics, while a-Si:H p-layer provided proper operation of cells with room temperature AZO. IV measurements taken at different temperature show evident thermal activation of fill factor confirming presence of the carrier transport barrier in the cells with a combination of nc-Si:H p-layer and AZO contact.

As for the n-type layers, both amorphous and nanocrystalline Si n-layers form proper contacts with room temperature AZO. In the rear emitter cells with n-type base the n-layer is at the front and nc Si:H is more beneficial than a-Si:H concerning transmission in short wavelength region of the solar spectrum. With combination of the a-Si:H p-layer, nc-Si:H n-layer, and room temperature AZO cell efficiency of 20.2% has been achieved.

11:30 AM ET02.08.04

Importance of Solution Surface Tension in Cleaning to Obtain High Passivation Quality with Extremely Low Surface Recombination Velocity of 0.6 cm/s for Small Size Textured Surface [Cong Thanh Nguyen](#), Keisuke Ohdaira and Hideki Matsumura; Japan Advanced Institute of Science and Technology (JAIST), Nomi, Japan.

Reducing thickness of crystalline silicon (c-Si) <100 μm is one of the keys to low-cost solar cells. On such thin c-Si, small textures are necessary to reduce c-Si losses by texturing process and to keep the robust property in fabrication processes. To obtain small textures with a size <2 μm , we already established "Microparticle-Assisted Texturing" (MPAT) process and reported elsewhere. However, cleaning of such small texture surface is always challenging. Therefore, in this work, we aimed to develop a suitable cleaning procedure for the small texture surface. After attempted many cleaning procedures, finally we found a novel cleaning method to obtain large effective minority carrier lifetime (τ_{eff}) of 7.8 ms corresponding to an extremely low surface recombination velocity (SRV) of 0.6 cm/s. In this cleaning method, we noticed an importance role of solution surface tension, hence methanol (CH_3OH) was mixed with the solutions to control the surface tension. It should be noted that without using methanol in the cleaning, only SRV=3.5 cm/s was obtained. We named this finding "Methanol-Assisted Cleaning (MAC)" process. We also verified that mixing methanol reduces contact angles or surface tensions of the solutions on the flat c-Si (100), flat c-Si (111), and textured c-Si (100). Owing to the low surface tension, the solution can reach even the

bottom of the complicated small texture surface, leading to uniform chemical cleaning and better passivation quality. Features of the MAC process is also presented in this work, which are expected to be useful for cleaning of any kinds of Si wafers other than solar cell ones.

11:45 AM ET02.08.05

Fabrication of Silicon Heterojunction Solar Cells Using PECVD-Grown 40 μm -Thick Epitaxial Silicon Wafers Ji-Eun Hong¹, Ka-Hyun Kim², Dong Suk Kim¹ and Joon-Ho Oh¹; ¹KIER-UNIST Advanced Center for Energy, Korea Institute of Energy Research, Ulsan, Korea (the Republic of); ²Department of Integrated Energy and Photon Technology, Cheongju University, Cheongju, Korea (the Republic of).

Wafer cost occupies about 40 % of module cost in the crystalline silicon solar cells. Current wafering technology relies on wire sawing that produces wasteful kerf-loss and high mechanical stress, resulting in additional production cost and limited production yield. Various kerf-less wafering technologies, such as exfoliation or spalling of silicon wafer from an ingot, growth of wafers directly from a silicon melt, and chemical vapor deposition of silicon on release layer or sacrificial substrate, enables to reduce kerf-loss as reported by D. M. Powell *et al.* Among these, epitaxy silicon growth on mono- or multi-crystalline silicon seems to be the most promising candidate for the next generation wafering technology due to the fact that epitaxy growth also enables to fabricate built-in junction structure simultaneously during growth. In other word, epitaxy growth process can significantly reduce solar cell fabrication steps (i.e. gas-to-wafer) compared to the conventional solar cells using wire sawn wafers, as also reported by R. Hao *et al.* Recently, many research results were reported mentioning that epitaxial growth of Si films on c-Si substrates was achieved by Atmospheric Pressure Chemical Vapor Deposition (APCVD). However, this technology usually disassociates the gas precursors at substrate temperatures higher than 1000 °C. As Kambara *et al.* reported in a recent paper that high temperature process is one of the most cost generating factors in mass production, necessity of such high temperature for APCVD makes the commercialization of the silicon epitaxy technology using APCVD less attractive. Compared to APCVD, Plasma Enhanced CVD (PECVD)-based epitaxy can be performed at a low substrate temperature of ~200 °C, leading it to the far more cost-effective alternative. Thus, in this presentation, we studied on epitaxy silicon growth at 200 °C using PECVD, and also demonstrated kerfless wafering using direct exfoliation. We succeeded in depositing 40 μm -thick silicon epitaxy layer at 200°C. Measurements showed that there were porous and H-rich interface layers, which can be utilized as a separation layer. Growth mechanism of epitaxy layer was further confirmed by ellipsometry using Bruggeman effective medium approximation (BEMA). And, cross-sectional transmission electron microscopy (TEM) images showed that there were hydrogen rich interface layers, and atomic arrangement at the interface was not disturbed. In addition, we investigated the exfoliation of epitaxy layer using metallic stress layer. Finally, we used the exfoliated 40 μm -thick free-standing epitaxial wafers to fabricate silicon heterojunction solar cells. The fabricated cell exhibited an efficiency of 11.42 % (J_{sc} : 32.28 mA/cm², V_{oc} : 610 mV, FF : 58 %).

SESSION ET02.09: Alternative Approaches to Contacting
Session Chair: David L. Young
Wednesday Afternoon, November 28, 2018
Hynes, Level 3, Room 311

1:30 PM *ET02.09.01

Organic-Silicon Heterojunction Solar Cell Baoquan Sun; Institute of Functional Nano and Soft Materials Laboratory (FUNSOM), Soochow University, Suzhou, China.

Numerous new materials and device structures have been widely explored in order to cut the cost of photovoltaic (PV) manufacture. Organic-inorganic hybrid solar cells based on nanostructured semiconductor have built up in few years ago, which may promise the low cost and high performance. However, the device performances are relatively lower than its pristine all-inorganic PV devices, resulting from the numerous surface defect and improper organic-inorganic phase segregation. Here, we demonstrate that hybrid PVs based on organic conjugated molecular and nanostructured silicon nanowire arrays can achieve a high PCE by controlling the phase separation as well as surface passivation.

An advantage of hybrid devices presents the excellent light harvest capability of nanostructured as well as simple fabrication process. Especially, hybrid composites of conjugated organic materials and nanostructured inorganic materials are potential candidates for cost-effective and efficient solar-energy-harvesting devices¹. This device can be worked by a light-modulated field effect solar cell, which can be potentially integrated with halide perovskite². In addition, this type device can be easily integrated with other type energy device, for example, an energy harvesting structure that integrates an organic-Si heterojunction solar cell and a triboelectric nanogenerator (TENG) device is built to realize power generation from both sunlight and raindrop³. In addition, a self-charging power unit based on an organic-Si heterojunction solar cell and a polypyrrole supercapacitor, which simultaneously achieved both photoelectric conversion and energy storage⁴.

1. Sun, B.; Shao, M.; Lee, S.-T. *Advanced Materials* **2016**, 28, (47), 10539-10547.

2. Wang, Y.; Xia, Z.; Liu, L.; Xu, W.; Yuan, Z.; Zhang, Y.; Sirringhaus, H.; Lifshitz, Y.; Lee, S. T.; Bao, Q.; Sun, B. *Advanced Materials* **2017**, 29, (18), 1606370.

3. Liu, Y.; Sun, N.; Liu, J.; Wen, Z.; Sun, X.; Lee, S.-T.; Sun, B. *ACS Nano* **2018**, 10.1021/acsnano.8b00416.

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2:00 PM ET02.09.02

Effect of Permanent Dipole Layers in the Electrical Characteristics of Electronic Devices and Solar Cells Eloi Ros¹, Zaira Barquera^{1,2}, Isidro Martín¹, Pablo Ortega¹, Cristóbal Voz^{1,2}, Joaquim Puigdollers¹ and Ramon Alcubilla¹; ¹University of Politecnica-Catalunya, Barcelona, Spain; ²Investav, Querétaro, Mexico.

In the last years, there has been a generalized tendency towards the use of novel materials for the formation of electron-selective contacts on n-type crystalline silicon (c-Si) heterojunction solar cells. Until recently transition metal oxides (TiO₂) or alkali and alkaline earth metal salt interlayers (LiF, MgF₂) have been mainly used. However new organic molecules with a permanent dipole moment are on the rise as promising candidates to improve the electric contact with the metallic electrode.

Conceptually speaking, the dipole of the molecule induces a built-in tension on the layer that can move the effective work function of the metallic electrode at the interface with the semiconductor.

This effect is strongly dependent on the dipole package and orientation, but also the on the individual molecular dipole moment.

Amino acids, are known for strong spatial charge splitting as amino group protonation yields a net positive charge and Carboxylate ionization yields a net negative charge. This accounts for many amino acids strong dipole moment. In this group we can find Glycine, as a stable and easy processable material with a very strong permanent dipole moment over 10Debyes, much greater than the already established n-type contact LiF, with a dipole moment of 6.2Debyes [1]. Furthermore, amino-acids can change the physical and chemical properties of surfaces. This functionalization performed on inorganic

materials such as Silicon, can ultimately increase biocompatibility of the original material and open the field to new applications on biointerfaces. In a first approximation, we have studied the electric contact using Transfer Length Method (TLM) of n-type crystalline silicon with an Atomic Layer Deposited $\text{Al}_2\text{O}_3/\text{TiO}_2$ stack, reaching a maximum contact resistance of 0.75 Ohms cm^2 . Furthermore, the effect of the dipole layer has been confirmed on Thin-Film Transistors (TFTs) by depositing a glycine thin-film layer (20 and 5 nm thick) between the silicon dioxide and the semiconductor. The incorporation of the glycine interlayer results in a significant increase of the threshold voltage. Variation of the threshold voltage allows to estimate the dipole moment of the interlayer.

Finally, the influence of the incorporation of the glycine dipole was studied on final solar cells devices. In particular, low temperature dopant-free c-Si solar cells were fabricated using Glycine as a new ETL with the following structures ITO/ V_2O_5 /n-cSi/a-Si:H/Glycine/Al and ITO/ V_2O_5 /n-cSi/ $\text{Al}_2\text{O}_3/\text{TiO}_2$ /Glycine/Al.

2:15 PM ET02.09.03

Effect of Slow-Speed Evaporation of BaSi_2 on the Performance of P-Type BaSi_2 /n-Type Crystalline Si Solar Cells Michinobu Fujiwara, Kazuma Takahashi, Yoshihiko Nakagawa, Kazuhiro Gotoh, Yasuyoshi Kurokawa and Noritaka Usami; Nagoya University, Nagoya-shi, Japan.

Alternatives to p-type amorphous Si (a-Si) for hole selective contacts in Si heterojunction (SHJ) solar cells have attracted significant attention. We have recently proposed p-type BaSi_2 (p- BaSi_2) as a promising candidate for a hole selective material, since device simulation (Afers-Het ver. 2.5) showed that p-type BaSi_2 improves open-circuit voltage (V_{oc}) of SHJ solar cells [1]. To deposit p- BaSi_2 on a large-area substrate, we developed a simple method to perform thermal evaporation of BaSi_2 on B-doped hydrogenated a-Si (a-Si:H) deposited by plasma enhanced chemical vapor deposition (PECVD). To realize high-quality p- BaSi_2 /n-type crystalline Si (c-Si) heterostructures, control of the deposition rate during the evaporation is of crucial importance. In fact, we have shown that employment of a slow deposition rate at the initial stage of the evaporation improves V_{oc} presumably due to the enhanced diffusion of Ba into the Si substrate [2]. In this study, we changed the time to hold slow-speed deposition of BaSi_2 and investigated the effect on film properties and solar cell characteristics.

B-doped a-Si:H thin film with a thickness of about 10 nm was deposited on a c-Si(111) substrate (resistivity: 3-6 Ωcm) by PECVD. The flow rates of SiH_4 , H_2 and 1% B_2H_6 were 40, 40 and 40 sccm, respectively. Substrates were heated at 600°C for 3 h in the evaporation chamber. BaSi_2 granules with the weight of 0.008 and 0.1 g were evaporated by resistive heating. The heating current was initially held at 90 A for 0, 30, 180 and 600 s and then raised to 140 A. Rapid thermal annealing (RTA) was performed for some samples to diffuse B into the evaporated BaSi_2 thin films. After that, the solar cell structure (Ag/ITO thickness (t): 80 nm/p- BaSi_2 t: 30 nm/n-c-Si t: 280 nm/Au-Sb) was fabricated, and their J - V characteristics were measured under AM1.5G illumination. BaSi_2 single films were characterized by Raman spectroscopy and X-ray diffraction (XRD).

As a result of J - V characteristics, we achieved conversion efficiency of 8.37% by holding slow-speed deposition for 180 s. Changing the holding time of slow deposition from 0 to 180 s improved V_{oc} and fill factor ($F.F.$) from 402 to 464 mV and from 24.1 to 60.1%, respectively. At the holding time of 600 s, the highest V_{oc} of 554 mV was obtained although $F.F.$ was degraded to 28.0%. Raman spectroscopy showed that the a-Si layer, which was found at the surface after evaporation, disappeared after RTA. XRD patterns showed at the holding time of 180 s a -axis-oriented BaSi_2 was the most predominant after evaporation. After RTA for the sample at the holding time of 180 and 600 s, a -axis orientation was enhanced and FWHM was reduced. These results show that the slow-speed evaporation improved the homogeneity and film quality, and led to the improvement of solar cell performance.

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2:30 PM BREAK

3:30 PM ET02.09.04

Effects of Surface Doping of Si Absorbers on the Performance of Carrier-Selective Contacts Hyunju Lee¹, Takefumi Kamioka¹, Noritaka Usami² and Yoshio Ohshita¹; ¹Toyota Technological Institute, Nagoya, Japan; ²Graduate School of Engineering, Nagoya University, Nagoya, Japan.

Recently, a new alternative to the conventional silicon heterojunction (SHJ) solar cell concept has been suggested and intensively studied. In this new concept, a set of dopant-free carrier-selective contacts (CSCs) is employed to separate and collect photo-generated free carriers in a single cell structure [1]. One of the most promising materials for dopant-free CSCs is transition metal oxides (TMOs). TMOs were first used in organic solar cells. So far, as dopant-free n- and p-type CSC materials, amorphous titanium dioxide (TiO_2) and sub-stoichiometric molybdenum oxide (MoO_x) is the most promising material in TMO-based CSC Si solar cells, respectively [2-3]. Meanwhile, TMO-based CSCs have demonstrated significant progress in Si solar cell performance. However, the performance of TMO-based CSC Si solar cells is still inferior to that of thin tunnel SiO_x /phosphorus-doped hydrogenated poly silicon (n^+ poly-Si:H) stack-based CSC Si solar cells (also referred as TOPCon structured solar cells) owing to the higher level of surface recombination and contact resistance of TMO-based CSCs [2]. In particular, the higher performance of the TOPCon seems to be partially due to shielding of the tunnel oxide/Si interface recombination without appreciably introducing Auger recombination by shallow phosphorus diffusion from an n^+ poly-Si:H layer into an n-type Si absorber through an ultra-thin tunnel oxide layer during polysilicon annealing [4].

In this study, we have investigated:

The performance of TiO_2 and MoO_x -based CSCs on shallowly doped n^+ and p^+ Si surfaces.

The effects of various ultra-thin tunnel layers on the performance of TiO_2 and MoO_x -based CSCs.

The stability of the fabricated TiO_2 and MoO_x -based CSCs on shallowly doped n^+ and p^+ Si surfaces under light illumination. for developing cost-effective, high-performance and stable CSC Si solar cells and elucidating the effects of the surface doping of Si absorbers and the ultra-thin tunnel layers on the performance of TiO_2 and MoO_x -based CSCs. During our presentation, we will discuss the experimental results and suggest ways to enhance the performance and stability of CSCs.

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3:45 PM ET02.09.05

Radial Junction Crystalline Silicon Solar Cells with an Efficiency of Over 20% Using Vertically Aligned Microwires Inchan Hwang, Han-Don Um, Kangmin Lee, Namwoo Kim and Kwanyong Seo; Ulsan National Institute of Science and Technology, Ulsan, Korea (the Republic of).

Vertically aligned silicon microwires (MWs) have been extensively investigated as a means for developing highly efficient c-Si solar cells because of the outstanding broadband antireflection and radial junction effect which enables efficient charge collection. The incident light is absorbed along the long MW axis, while photo-induced carriers can be collected along the short radial direction. To realize the highly efficient radial junction c-Si solar cells, we have

developed novel technologies such as fabrication process of MWs, high conductive and transmittance top electrode, shape-controlled MWs, and high purity doping process.

The high-aspect-ratio MWs ($> 10:1$) were successfully fabricated through both optimized metal-assisted chemical etching (MACE) and deep reactive ion etching (DRIE) processes. To achieve the high efficiency of MW radial junction solar cells, we developed the high conductive and transparent top electrode to replace the conventional bus-finger electrode which has a significant shading loss. We devised a novel micro-grid top electrode which shows superior transmittance (over 97%) and low sheet resistance (less than $30 \Omega/\square$). By applying the micro-grid electrode on the top surface, the MWs solar cells showed outstanding fill factor (81.2%) and improved efficiency (16.5%).

As an efficient way to decrease the flat-top-surface reflection of the MWs and increase the light absorption property of the radial junction solar cells, a tapered-MW structure was employed using a simple wet-etching process. When a c-Si wafer with MWs is dipped in a silicon etchant (RSE-100, transene), the top part of the MWs that has a shorter diffusion path compared to the bottom part is etched more quickly. Since the diameter of the tapered MWs gradually increased from the top to the bottom, the tapered MWs can act as a buffer layer to compensate for the mismatch between the refractive indexes of air (1) and the silicon substrate (4). Thus, the surface reflection of the tapered MWs was observed to be less than 2% at a wavelength of 550 nm. The tapered MW based radial junction solar cells exhibit improved efficiency up to 18.9% thanks to the enhanced light absorption property.

As the last step for optimizing the device structure of the MWs solar cells, we used high purity doping process using acid dopant sources that showed improved minority carrier lifetime (from $79.29 \mu\text{s}$ to $272.24 \mu\text{s}$). Accordingly, we achieved high efficiency (20.2%) MWs radial junction solar cell by applying all of the developed our technologies such as the micro-grid electrode, tapered MWs, and high purity doping process. At present, we are aiming at developing an ideal passivation layer to achieve the more than 25% efficiency of the radial junction solar cells. Therefore, we believe the MW structures with the suggested technologies become a foundational technology for the highly efficient radial junction solar cells.

SESSION ET02.10: Poster Session

Session Chairs: Stefaan De Wolf, Olindo Isabella, Takuya Matsui and David L. Young

Wednesday Afternoon, November 28, 2018

8:00 PM - 10:00 PM

Hynes, Level 1, Hall B

ET02.10.01

Study of Defects Evolution in Ingan/Si Thin Films with Embedded Voids Khaled H. Khafagy², Tarek M. Hatem² and Salah M. Bedair¹; ¹Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina, United States; ²Centre for Simulation Innovation and Advanced Manufacturing, The British University in Egypt, Cairo, Egypt.

The present study focuses on suppressing/sinking dislocations generated at the interface during the fabrication of single-junctions with high lattice and thermal mismatches of multi-junction photovoltaic, e.g. Indium Gallium Nitride (*InGaN*) thin-film on Silicon (*Si*) substrate. Such defects act as scattering centers that impact the minority carrier lifetime, reduce thermal conductivity, and form easy pathways for impurity diffusion. Thus, limit the performance, reliability, and lifetime of PV devices. Embedded Void Approach (EVA) to reduce defects at heterogeneous interfaces of thin-films by overcoming the thermal expansion coefficient mismatch and lattice mismatch between different layers is studied.

In the current study, a novel three-dimensional multiple-slip crystal plasticity based model and specialized finite-element formulations are used to address *InGaN* growth on Si substrates. The new formulations account for threading dislocations generation, mobility and interaction to account for lattice and thermal expansion coefficients mismatch during the growth of *InGaN* thin-film on *Si* substrate, both with/without embedded micro-voids. Further, a parametric study of voids aspect and volume ratios impact on dislocation evolution is studied.

ET02.10.02

Effects of Different Pyramidal Texture Size and Interfacial Abruptness on the Performance of Silicon Heterojunction Solar Cells Joon-Ho Oh¹, Ji-Eun Hong¹, Hee-Eun Song², Ka-Hyun Kim³ and Dong Suk Kim¹; ¹KIER-UNIST Advanced Center for Energy, Korea Institute of Energy Research, Ulsan, Korea (the Republic of); ²Photovoltaic Laboratory, Korea Institute of Energy Research, Daejeon, Korea (the Republic of); ³Department of Integrated Energy and Photon Technology, Cheongju University, Cheongju, Korea (the Republic of).

Silicon hetero-junction (SHJ) with intrinsic thin-layer solar cells are of considerable technological importance due to its high efficiency (26.7 %, Kaneka Co., *Nature Energy* (2017)), low-temperature fabrication processes (down to $\sim 200^\circ\text{C}$), superior passivation properties introduced by i-a-Si:H layers, and so forth. To realize its full potential, optimization of n-type c-Si/i-a-Si:H interfaces are of utmost significance. Generally, diamond wire-sawn Cz-Si wafers are textured in chemical solutions to make pyramidal textures at the both surfaces. Then, i-a-Si:H thin films (~ 10 nm thick) are deposited on top of pyramidal textures. Thus, if surface texturing including saw damage removal is not optimized, it would lead to enhanced surface recombination properties, leading to deteriorated performances of the SHJ solar cells. Furthermore, making abrupt pyramidal textured c-Si/i-a-Si:H interface is of significant importance. For example, Stefaan De Wolf *et al.* (*J. Appl. Phys.* (2007)) reported that for a-Si:H films with no crystalline component the passivation properties enhances by annealing most likely by film relaxation, which is not the case when an epitaxial layer was grown at the interface. However, there are few reports regarding combined effects of surface texturing and abruptness of c-Si/i-a-Si:H interfaces on the passivation properties and subsequent performance of SHJ solar cells.

Thus, in this presentation, we report on the combined effects of saw damage removal and different pyramidal texture size on passivation characteristics of i-a-Si:H/n-c-Si/i-a-Si:H structures. Transmission electron microscopy (TEM) observations showed that the peaks of the pyramids are not sharp but somewhat flat, and flat and side-wall area of pyramids exhibited different crystalline orientations ((100) and (111), respectively). Cross-sectional TEM measurements also showed that the c-Si/i-a-Si:H interface was abrupt when i-a-Si:H was deposited on the side walls (i.e. (111) side) of the pyramids whilst at the c-Si/(100)/i-a-Si:H interface, there was some epitaxial crystallites at the interface, leading to non-abrupt interface. QSSPC (quasi-steady-state photo-conductance decay) measurements for i-a-Si:H/n-c-Si/i-a-Si:H structures showed that minority carrier lifetime (MCLT) and implied open-circuit voltage ($V_{oc,imp}$) was increased (from $\sim 200 \mu\text{s}$ / 659 mV to $\sim 2 \text{ ms}$ / 730 mV) when average pyramidal size increases from $1 \mu\text{m}$ to $15 \mu\text{m}$. Light J-V measurements were done for four types of SHJ solar cells with different pyramidal size and the results are explained combined with microstructural and MCLT characteristics.

ET02.10.03

Enhancement of Light Trapping for Thin-Film Silicon Solar Cells Ya Sha Yi, Mao Ye and Dachuan Wu; University of Michigan, Dearborn, Michigan, United States.

Next generation thin film solar cells (inorganic or organic) are generating wide interests recently as it promises to reduce the materials usage and

significantly lower the cost of electricity generated by solar cells. One of the main types of thin film solar cells, with Si as the absorbing layer, presents two main challenges for further development; (1) how to achieve broadband antireflection at the front surface; (2) how to achieve broadband light trapping at the bottom surface (especially at longer wavelength) within the AM1.5 solar spectrum. With the rapid progress of nanotechnology, many nano scale photonic devices as small as 30 nm have been realized, which is very promising for achieving manipulation of photons at chip scale and having broad applications in renewable energy (photovoltaic cells, solid state lighting), telecommunications and the bio medical field. Accordingly, there are many routes to enhance the light absorption for thin film. Various methods of enhancing optical absorption have been proposed, including the use of dielectric photonic structures or plasmonic metallic nanoparticles; most of which are mainly focused on either front side antireflection film, or light trapping structures on the back side. Few works have been proposed that take into account the two challenges stated above; broadband antireflection photonic structures on the front side and light trapping photonic structures at the bottom side, as well as their correlation for enhancing the light absorption for thin film solar cells.

In this work, we have studied light trapping effects utilizing both top and bottom nanophotonic structures. We propose broadband nano scale pyramid light trapping top photonic structures to increase the absorption of thin film solar cells, especially at short wavelength; and broadband light trapping bottom omni directional photonic crystal structures to increase the optical path length for longer wavelength, especially to increase the near bandgap wavelength absorption of thin film solar cells. The correlation between the front side and bottom side nano photonic structures suggests the importance of light trapping from both aspects.

ET02.10.04

Investigation of Metal Oxide/Amorphous Silicon Interfacial Conductivity Towards Solar Cells Based on Ultra-Sparse Metal Mesh Qingyu Cui and L. Jay Guo; Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, United States.

In large-area optoelectronic and display industries, Indium Tin Oxide (ITO) is the most widely used transparent electrodes, because of its excellent transparency and conductivity. However, the storage of indium is becoming more and more limited, which will give rise to the increasing cost and concerns. In recent decades, researchers showed wide interests to the alternative candidates of ITO, including other cost-efficient conductive oxides, ultra-thin metal films, carbon-based electrodes, metal mesh and so on. Among them, the metal mesh is drawing extensive attentions, due to its easy fabrication, including nano-imprinting, electroplating, photo-lithography, even solution-coating of nanowires. However, it is not that desirable for solar cell or light emitting devices because of the large non-conductive holes in the metal mesh. As a result, people usually use conductive polymer to enhance the local conductivity.

Here we report on the device structure of amorphous silicon (a-Si) solar cells without such a conductive layer for metal mesh, which incorporates the dramatically increased interfacial conductivity for tungsten oxide (WOx) and a-Si.

Based on the inter-digitated Tungsten (W) electrodes, we found the film lateral conductance of 60nm a-Si deposited on 30nm WOx is at least 4 orders higher than individual a-Si or WOx films, where the obtained resistances are 677 ohm, 6.67E+6 ohm and over 1E+10 ohm for WOx / a-Si, WOx and a-Si, respectively. Probably this is due to the quantum confinement and reduced recombination site density for carriers along the WOx / a-Si interface, then resulting in the enhanced lateral carrier transportations.

Utilizing the WOx / a-Si interface, we fabricated solar cells (ITO / WOx / a-Si / Cathode) based on ITO-mesh with different size. The ITO mesh period is 420 um x 420 um, and the edge length of non-ITO window increases from 0 um to 410 um (the window ratio from 0% to 95.3%). We found that the WOx / a-Si interface is still sufficiently conductive to collect the photo-generated holes even under ultra-sparse mesh (window ratio 95.3%), without sacrificing the Photo-Conversion Efficiency (PCE), which remains around 3.5% for 60nm a-Si. Moreover, Jsc increased from 11.2 mA/cm² to 13.2 mA/cm², which is partly because of the increased overall transparency of ITO. Then Voc decreases from 0.60 V to 0.51 V, probably due to the reduced overall work-function of anode. The serial resistance decreased from 43 to 26 ohm*cm² and the ambipolar diffusion length increased from 55.3 nm to 98.8 nm, possibly resulting from the increased lateral electric field, faster carrier transportation and reduced recombination site density along the WOx / a-Si interface.

The results reported here verified the lateral carrier transportation along the interfaces between different active interlayers can be well utilized to achieve simpler device designs, especially based on the metal mesh with a much higher overall transparency than ITO.

ET02.10.05

Figure-of-Merit Evaluation of Gold-Hyperdoped Silicon for Photovoltaic Applications Senali Dissanayake¹, Matthew Wilkins², Philippe K. Chow³, Wenjie Yang⁴, Quentin Hudspeth³, Shao Qi Lim⁴, Jim S. Williams⁴, Jeffrey M. Warrender³, Jacob J. Krich² and Meng-Ju Sher¹; ¹Physics Department, Wesleyan University, Middletown, Connecticut, United States; ²Department of Physics, University of Ottawa, Ottawa, Ontario, Canada; ³U.S. Army ARDEC - Benet Labs, Watervliet, New York, United States; ⁴Research School of Physics and Engineering, The Australian National University, Canberra, Australian Capital Territory, Australia.

Laser hyperdoping offers a viable method to introduce large concentrations of impurities into silicon, introducing states deep in the silicon band gap that could enable an intermediate band solar cell architecture. A previously reported quantitative figure of merit has been advanced as a heuristic for assessing the promise of a candidate silicon-hyperdopant system. The figure of merit is proportional to the product of the electron mobility, the recombination lifetime, and the square of the average sub-gap absorption coefficient.[1] For the first extensively-studied dopant, sulfur, the figure of merit was found to be fairly low at all S concentrations due to extremely short (<130 ps) carrier lifetimes.[2] Recent work has shown evidence of sub-band gap photocurrent response resulting from the introduction of transition metals in hyperdoping concentrations.[3] Ion implantation followed by melting is a well-established hyperdoping method for heavy chalcogen dopants (S, Se and Te), but incorporating transition metals at supersaturated concentrations with high crystalline quality has been challenging. One complication of working with transition metals as impurities is the incidence of cellular breakdown – a microstructure that results from instability during solidification – under some solidification conditions. In this work we optimize maximum concentrations that can be practically synthesized for the prospect for PV device. We use time-resolved THz spectroscopy measurements to study carrier lifetime, and we compare these to the previously reported results for S. This work reports on a systematic study to experimentally determine the mobility, lifetime, and absorption coefficient for gold-hyperdoped silicon at several concentrations, and use these to compute a figure of merit for each dopant and dose.

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ET02.10.06

Tunnel Oxide Passivated Contact for Crystalline Silicon Solar Cells Using Hot-Wire Chemical Vapor Deposition Kaining Ding¹, Manuel Pomaska¹,

Shenghao Li¹, Jan Lossen², Jan Hoss², Maurice Nuys¹, Friedhelm Finger¹ and Uwe Rau¹; ¹Research Center Juelich, Juelich, Germany; ²ISC Konstanz, Konstanz, Germany.

In this work, hot-wire chemical vapor deposition (HWCVD) was utilized to fabricate amorphous silicon(a-Si) thin films for tunnel oxide passivated contacts of crystalline silicon solar cells. So far low pressure chemical vapor deposition or plasma enhanced chemical vapor deposition are usually used to deposit a-Si:H thin films on crystalline silicon covered by a thin tunnel oxide (SiO₂/c-Si) to form the passivated contact, giving rise to excellent solar cell performances of up to 26.1 % energy conversion efficiency. As the fabrication process of the solar cell includes several high temperature process steps of up to 900 °C, the a-Si precursor layer needs to have the property of remaining blister-free after all process steps. At the same time, the c-Si surface should be very well passivated by the a-Si/SiO₂ layers at the end of all process steps. Last, the deposition rate should be high, in order to be attractive for photovoltaic mass production. We developed ex-situ as well as in-situ n-doped a-Si films for the electron selective passivated contacts. The films remain blister-free after all process steps, give rise to promising passivation qualities with implied open circuit voltages of more than 720 mV, and were deposited with rates of more than 1 nm/s. To correlate the passivation quality to the material properties of the n-doped layer, X-ray diffraction was measured before and after every high temperature process step. Additionally, the investigation was completed by measuring the hydrogen and phosphorus concentration profiles using secondary ion mass spectrometry and by measuring the doping profiles using the electrochemical capacitance-voltage profiling technique.

ET02.10.07

Recombination Activity of Inclined $\Sigma\{111\}$ Grain Boundaries in High-Performance Si Ingots Yutaka Ohno¹, Kentaro Kutsukake¹, Takehiro Tamaoka², Seiji Takeda², Yasuo Shimizu³, Naoki Ebisawa³, Koji Inoue³, Yasuyoshi Nagai³ and Noritaka Usami⁴; ¹IMR, Tohoku University, Sendai, Japan; ²ISIR, Osaka University, Osaka, Japan; ³The Oarai Center, IMR, Tohoku University, Oarai, Japan; ⁴GSE, Nagoya University, Nagoya, Japan.

Grain boundaries (GBs) are inevitably introduced in polycrystalline silicon (Si) ingots for solar cells, and they have substantial influences on electronic properties such as minority carrier lifetime, via the segregation of impurity atoms. Especially, asymmetric GBs with higher- Σ value of the associated coincident site lattice (CSL) are frequently introduced in Si ingots, and they severely affect the overall material properties even when their density is very low. Therefore, a comprehensive knowledge of the recombination activity of the GBs, as well as their structural properties, is indispensable to produce cost-effective high-efficiency solar cells by controlling the formation of those detrimental GBs.

In the present study, we discuss the recombination activity of asymmetric $\Sigma\{111\}$ GBs with the $\langle 110 \rangle$ tilt axis, whose GB planes are slightly inclined from $\{111\}$, introduced frequently in high-performance Si ingots. The activity of those asymmetric GBs was high even when their inclination angle was small, while the activity of the symmetric $\Sigma\{111\}$ GBs was negligible. High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) revealed that, most parts of the asymmetric GBs were composed of arrays of GB dislocations lying on symmetric $\Sigma\{111\}$ GB segments. Those dislocations were edge-type with the Burgers vector of $1/3\langle 111 \rangle$. Atom probe tomography (APT) revealed that oxygen atoms segregated at the atomic sites under tensile stress above about 2 GPa, which were presumably introduced along the GB plane due to the GB dislocations [1, 2]. Carbon atoms also segregated, while they would locate only nearby the dislocation cores. Small amount of metal precipitates such as iron silicides were occasionally observed on the asymmetric GBs, presumably along the GB dislocations [3, 4]. The correlation between the segregation ability of impurity atoms and the recombination activity will be discussed.

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ET02.10.08

P-Type Molecular Monolayer Doping of Silicon for Photovoltaic and Semiconductor Devices Megan E. Detwiler, Scott Humski, Jenna Doran, Scott Williams and Santosh Kurinec; Rochester Institute of Technology, Rochester, New York, United States.

P-type doping of silicon wafers using molecular monolayer deposition (MLD) will be presented. Our method minimizes additional lattice defects, allows the formation of ultra-shallow junctions, and enables doping of non-planar surfaces. This is an attractive alternative to the industry standards as the process does not induce crystalline damage, unlike ion implantation, and utilizes materials less hazardous than those involved in spin-on diffusion. Monolayers are formed with allylboronic acid pinacol ester (ABAPE) as well as other selected boron-containing molecules. The wafer was then photonically or thermally treated to create the ultra-shallow junction with optimized sheet resistivities. The doping concentrations and profiles are evaluated using sheet resistance measurements, SIMS, DLTS, and TXRF. MLD temperature and time optimization will be discussed.

ET02.10.09

Effects of Oxidants of Atomic-Layer-Deposited Al₂O₃/TiO₂ Films on Silicon Surface Passivation Dongchul Suh; Division of Chemical Engineering, Hoseo University, Asan, Korea (the Republic of).

Al₂O₃ thin films have attracted substantial interest for their use as alternative passivation films of crystalline silicon (c-Si) solar cells because of their improved field-effect and chemical passivation. Among several methods that have been employed for the growth of Al₂O₃ films, atomic layer deposition (ALD) is very suitable in the sense that it is a self-limiting film growth process based on sequential surface reactions that offers excellent thickness uniformity. The most common ALD process is the deposition of Al₂O₃ by alternating exposures of trimethyl aluminium (TMA) and H₂O, due to the broad ALD process window, but less extensively for passivation. In typical ALD of Al₂O₃ thin film for surface passivation, O₂ plasma has been widely used as an oxygen source due to higher negative charge density, in particular for low deposition temperature. Thermal ALD using reactive O₃ has also been introduced because it is easy to purge as well as reactive, enabling batch ALD process for high throughput.

In the formation of Al₂O₃ film, chemical exchange reaction is dominant between TMA and H₂O. However, growth mechanism of ALD Al₂O₃ using O₂ plasma and O₃ is not clearly studied but believed that film growth is accomplished by combustion of methyl group. Different growth mechanism and high reactivity of the O₂ plasma and O₃ would cause different physical structures, electrical properties, and surface passivation qualities of Al₂O₃. The minimal Al₂O₃ thickness without compromising the passivation properties is 5 nm for plasma ALD Al₂O₃, whereas for thermal ALD, films >10 nm are required. In addition, even though low interface defect density of 10¹¹ eV⁻¹cm⁻² is obtained after annealing of Al₂O₃ made from all oxidants, field-effect passivation is dominant for O₂ plasma and O₃-based Al₂O₃ after annealing, but less prominent for H₂O-based Al₂O₃ before and after annealing.

The oxidant has a significant influence on the surface passivation mechanism during atomic layer deposition. In this work, we studied the influence of different oxidants and thermal post-deposition treatments for the passivating ALD Al₂O₃ single layers and Al₂O₃/TiO₂ stacks. Al₂O₃ thin films have been deposited on crystalline silicon by atomic layer deposition using various oxygen precursors, such as H₂O and O₃. The electrical characterization of the stack layers has shown that in as-deposited states on Al₂O₃, H₂O-TiO₂ has lower saturation current density (J_{0c}) than H₂O/O₃-TiO₂ in which both H₂O and O₃ are used as oxidants. Annealing is beneficial for H₂O/O₃-TiO₂ to decrease J_{0c}, which is analogous to H₂O- Al₂O₃ vs. O₃-Al₂O₃.

ET02.10.10

The Effect of H in the Atomic and Electronic Structure of Amorphous Si and Hydrogenated Amorphous Si Reza Vatan Meidanshahi, Stuart G. Bowden and Stephen M. Goodnick; School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, Arizona, United States.

Hydrogen incorporation in the fabrication of amorphous Si (a-Si) plays an important role in improving its electronic and optical properties. An important question is how H interacts with the a-Si atomic network, and consequently affects the electronic properties of a-Si. The common assumption is that the role of H is to passivate the dangling bonds (DBs) of the a-Si structure, which subsequently leads to a reduction in the density of midgap states and localized states within the mobility gap. In the present work, we first employ a combined molecular dynamic (MD) and density functional theory (DFT) method to create stable configurations of a-Si:H, and then analyze the atomic and electronic structure to investigate which structural defects interact with H, and how the electronic structure changes with H addition. We show that in contrast with the simple dangling bond picture, atoms bonded by highly strained bonds (SBs) are most significantly affected by the addition of H, in terms of the lowest energy configuration, with similar if not greater importance to that of dangling bonds in passivating a-Si. We find that H atoms decrease the density of mid-gap states of a-Si by bonding to the Si atoms with SBs. Our results also indicate that Si atoms with SBs creates highly localized orbitals in the mobility gap of a-Si and a-Si:H, and the bonding of H atoms to them can significantly decrease the degree of orbital localization. The results demonstrate the beneficial effects of hydrogenation of a-Si in terms of reducing the overall strain energy of the a-Si network, with commensurate reduction of mid-gap states and orbital localization.

ET02.10.11

Estimation of Voltage-Dependent Photocurrent Factor in Metal-Oxide Based Carrier-Selective Contact Silicon Solar Cell Suren Patwardhan^{1,2}, Sandeep Maurya¹ and Balasubramaniam Kavaipatti¹; ¹Indian Institute of Technology Bombay, Mumbai, India; ²K J Somaiya College of Engineering, Mumbai, India.

Typical heterojunction carrier-selective contact silicon (CSC-Si) solar cell has hole and electron selective layers on same or opposite faces of crystalline Si (c-Si) wafer. This is done by depositing thin films of either doped amorphous silicon (a-Si) or transition metal oxides/alkali metal fluorides. In our work, we fabricated heterojunction CSC-Si cells using molybdenum trioxide (MoO₃) as hole selective layer and titanium dioxide (TiO₂) as electron selective layer – to be called as “Test Cell”. It was made on a 280 μm thick n-type Si wafer (n-Si) of 1-5 Ω cm resistivity. MoO₃ was thermally evaporated and TiO₂ was deposited by atomic layer deposition (ALD). The control cell structure consisted of phosphorous diffused back surface field on n-Si (n/n⁺ BSF) in place of TiO₂ film. Dark and light current-voltage (I-V) measurements were taken at 1 sun simulated radiation with class AAA solar simulator. We tried to estimate the voltage-dependent photocurrent factor (n) due to TiO₂/Si interface based on our experimental data and available literature on heterojunction solar cells. All of our control cells (25) followed current superposition. On the other hand, all the test cells did not follow current superposition as their dark and light current densities crossed-over each other. They also possessed lower fill factor. The CSC-Si cell has many non-idealities such as voltage dependent photocurrent due to which, the current superposition is generally not obeyed. In our test cells, the light-generated current density (J_L) was higher by nearly 40% than the control cells. The average fill factor different (ΔFF) observed between them was 0.14. By using the equation $\Delta FF = (1 - n) * V_{MP} / V_{OC}$, it yields ratio of light-generated to short circuit currents, that is $n = J_L / J_{SC}$ to be 0.78 at maximum power point (MPP). Here, V_{MP} and V_{OC} are voltages at maximum power and open circuit conditions respectively. (n is unity for conventional Si solar cell). n for our control cells is taken to be unity and voltage-independent as they showed current superposition. Average J_L for these cells at MPP was 15.95 mA/cm² while for the test cell, it reached 20.45 mA/cm². This ratio comes out to be 0.78, matching with that obtained from the equation above by assuming J_L for the control cell to be J_{SC} (as n = 1). The cell parameters obtained from I-V measurements showed consistency over different sets of samples prepared. This voltage dependence results in loss of fill factor as it is mainly effective for voltages below V_{OC}. Hence estimation of n is a key factor while designing heterojunction carrier selective contact types of cells.

ET02.10.12

Impurity Distribution at Si/GaAs Heterointerfaces Fabricated by Surface-Activated Bonding Analyzed by Atom Probe Tomography Yasuo Shimizu¹, Naoki Ebisawa¹, Yutaka Ohno², Jianbo Liang³, Naoteru Shigekawa³, Koji Inoue¹ and Yasuyoshi Nagai¹; ¹Tohoku University, Ibaraki, Japan; ²Tohoku University, Sendai, Japan; ³Osaka City University, Osaka, Japan.

Tandem solar cells composed of Si and III-V materials have attracted considerable attention for next generation photovoltaic system towards 30% efficiency. Surface-activated bonding (SAB) is reported as a method to fabricate tough Si/III-V heterointerfaces, by creating dangling bonds under ion irradiation prior to bonding at room temperature in a high vacuum environment [1]. More recently, intrinsic microstructure of Si/GaAs heterointerface fabricated by SAB was examined by plane-view TEM and cross-sectional STEM [2]. Although the thin foils for TEM specimens were carefully prepared by mechanochemical etching, the TEM inspections revealed that Si/GaAs heterointerface fabricated at room temperature suggests a defective crystalline GaAs layer with less than 1 nm-thick and amorphous Si layer with around 3 nm-thick. For a comprehensive understanding of the electrical property at the SAB interfaces towards complete fabrication processes, distribution analysis of impurities at the SAB interface is required. Here we employ laser-assisted atom probe tomography (APT) for three-dimensional mapping of the impurity distribution, which has been proven useful to examine a specific grain boundary [3]. Quantitative analysis of the impurity concentration at the SAB interfaces by TEM is insufficient due to its lower detection limit than that by APT. In this meeting, we report on the impurity concentration at the SAB interfaces. In this work, p-Si/n-GaAs heterointerfaces fabricated by SAB method at room temperature were utilized [1]. For comparison, p-Si/p-Si and n-GaAs/n-GaAs homointerfaces were fabricated under the same SAB condition. For APT specimen preparation, Ga-FIB apparatus equipped with SEM (Helios NanoLab600i, FEI) was used. A local electrode atom probe (LEAP4000X HR, CAMECA) equipped with a 355 nm wavelength pulsed laser was employed for APT analysis. Our APT reveals the existence of impurities such as Fe, Ni, and Cu at the Si/GaAs interface. These impurities, which may affect the electrical property, were introduced prior to bonding, even though the surface of both Si and GaAs substrates are activated by creating dangling bonds via the removal of native oxide under Ar bombardment in high vacuum. It should be noted that needle-shaped specimens for APT measurements were processed by Ga-FIB. The intermediate layer around SAB interfaces bonded at room temperatures seems to be unstable in an atomistic level under the Ga bombardment. One should take the FIB condition into account for precisely analyzing the impurity distributions. Their distributions found at the homointerfaces will be also shown in the meeting.

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ET02.10.13

Material Removal Simulation in Sawing Processes of Photovoltaic Silicon Florian Wallburg^{1,2,3} and Stephan Schoenfelder^{1,2}; ¹Faculty of Mechanical and Energy Engineering, Leipzig University of Applied Sciences, Leipzig, Germany; ²Fraunhofer Center for Silicon Photovoltaics CSP, Halle (Saale), Germany; ³Institute of Mechanics and Fluid Dynamics, TU Bergakademie Freiberg, Freiberg, Germany.

The mass production of wafers, the basic substrates of solar cells, is realised with the multi-wire sawing technology in which silicon wafers are sawn from high-purity silicon bricks. In crystalline photovoltaics the wafering processes and the material costs represent a considerable cost share of about 40% of the complete photovoltaic module. During wire sawing material removal mechanisms resulting from the interaction between hard cutting particles and the silicon surface play an important role regarding the reliability of the processes and products. However, it has not been possible so far to numerically model the mechanically complex process of material removal and subsurface damage as a function of the process parameters. Thus, it is absolutely essential to investigate the direct relationship between removal processes and sawing parameters concerning a reliable production of wafers that are continually getting thinner and thinner.

The investigations made here are focused on the diamond wire sawing process as it has become the major technique to slice bricks into wafers. Due to fixed abrasives the material removal mechanism is significantly defined by grinding processes. In order to analyse the cutting behaviour in fixed diamond wafering single grain scratch experiments were carried out since they can provide better insights into the complex material removal mechanism of grinding processes. By means of several scratch grooves at defined distances, interaction effects and their influence on the fracture process can furthermore be observed. Within this research work this relationship is investigated numerically as well as experimentally.

The basis of the numerical modelling is a pressure-sensitive Drucker-Prager material law with modified caps in the tensile and compressive zone. With the aid of that model phase transformation processes and thus, closely related volumetric changes of the silicon crystal can be predicted which is necessary for crack development. Considering the anisotropic mechanical properties in conjunction with a cleavage-plane illustrating cohesive network it can be shown that different crack systems can be described fundamentally and in interaction with each other – which ultimately leads to the material removal processes. Surface and subsurface damage processes, that are also experimentally investigated, can be examined consequentially in more detail. From this, it is feasible in future to derive possibilities for a microstructure-based control of the wire process design, for example, via the cutting geometry shape and arrangement as well as the feed speed. It is well understood that changes to these parameters have a strong impact on the substrate strength and, as a consequence, on the breakage rate. The necessary further developments in substrate production are therefore directly connected to an increase in product quality.

ET02.10.14

Improved Al/n-Si Electron Selective Contact by Intermediate PFN Dipole Layer Zaira Barquera^{1,2}, Eloi Ros¹, Cristobal Voz¹, Pablo Ortega¹, Isidro Martin¹, Ramon Alcubilla¹ and Joaquim Puigdollers¹; ¹University of Politecnica-Catalunya, Barcelona, Spain; ²CINVESTAV-I.P.N. Unidad Querétaro, Querétaro, Mexico.

Selective contacts used in crystalline silicon solar cells require both good surface passivation and very good carrier conductivity, i.e. low ohmic contact resistances, to reach high-efficiency solar cells. Traditionally selective contacts are made using high doped regions by thermal and/or laser process diffusion stages, which are expensive and high-cost energy. Alternatively a cost-effective approach to obtain good selective contacts relies on the use of electron or hole transport layers (ETL and HTL) processed at low temperatures. Carrier selectivity of these transport layers can be benefited from the incorporation of dipole interlayer between the metal electrode and the ETL (HTL) layers. By using dipole interlayers a better energy band alignment can be achieved by reducing the work function of the electrode. In this work, we report on the use of a polymer dipole (PFN) to improve ohmic contact with n-type crystalline silicon. In particular, the following solar cell configuration Al/ PFN /ETL/n-Si/V2O5/ITO/Ag were studied. Poly (9,9-bis(3'-(N,N-dimethylamino) propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)(PFN) was used as intermediate dipole. The influence of PFN interlayer dipole was studied on two different electron selective contacts: Al2O3/TiO2 deposited by ALD and a-Si:H(i)/a-Si:H(n) deposited by PECVD. Best results were obtained by using a-Si:H(i)/a-Si:H(n) configuration, with Voc=0.67 V, Jsc=33.3 mA/cm2, FF=76.6% and a efficiency of 17.2 %. However, using dopant-free electron transport layer (TiO2-based), fabricated solar cells provided a Voc= 0.61 V, Jsc= 30.5 mA/cm2, FF=76% and 14% conversion efficiency.

ET02.10.15

High Performance Transparent Electrodes in the Red/Infrared Range Made by Colloidal-Structured Metallic Micro-Grids Antonio Terrasi^{2,1}, Giacomo Torrisi^{2,1}, Olalla Sanchez-Sobrado³, Manuel Joao Mendes³, Hugo Aguas³, Elvira Fortunato³ and Rodrigo Martins³; ¹IMM-CNR, Catania, Italy; ²Department of Physics and Astronomy, University of Catania, Catania, Italy; ³Cenimat-i3n, Faculdade de Ciencia e tecnologia, Caparica, Portugal.

One of the most promising approaches to produce industrial compatible Transparent Conducting Materials (TCMs) with excellent characteristics is the fabrication of TCO/metal/TCO multilayers. In this work, we report on the electro-optical properties of a particular type of TCO/metal/TCO, in which the intra-layer is a metallic grid instead of a uniform thin film. The grid is obtained by evaporation of Ag through a mask of polystyrene colloidal microspheres deposited by the Langmuir-Blodgett method and partially dry-etched in plasma. IZO/Ag grid/IZO with different thicknesses and size of the mesh have been fabricated, exhibiting excellent electrical characteristics and a particularly high optical transmittance in the red and infrared (IR) spectral region, as compared to planar (unstructured) TCM multilayers. This optical behaviour is of primary importance for the new generation of four-terminal mechanically-stacked tandem solar cells, such as the Perovskite-on-Si double junctions or the bi-facial Si solar cells. In the former case the red-IR light must pass through the junction entering into the Si bottom cell, while in the latter case a consistent amount of red-IR light can be reflected by the ground and collected from the back side of the cell. Numerical simulations were also used to highlight and understand the role of the Ag mesh structure on the electrical properties of the material.

SESSION ET02.11: Optics
Session Chair: Olindo Isabella
Thursday Morning, November 29, 2018
Hynes, Level 3, Room 311

8:30 AM *ET02.11.01

Current Loss Mechanisms in Textured Crystalline Si-Based Solar Cells Hiroyuki Fujiwara; Gifu University, Gifu, Japan.

We have developed a quite general device analysis method that allows the direct evaluation of optical and recombination losses in crystalline silicon (c-Si)-

based solar cells. By applying this technique, the optical and physical limiting factors of the state-of-the-art solar cells with ~20% efficiencies have been revealed. In the established method, the current loss mechanisms are characterized from the external quantum efficiency (EQE) analysis with very low computational cost. We find that the developed method provides almost perfect fitting to EQE spectra reported for various textured c-Si solar cells, including c-Si heterojunction solar cells, a dopant-free c-Si solar cell with a MoO_x layer, and a PERL solar cell. Detailed analyses show that a-Si:H layers incorporated into a-Si:H/c-Si and MoO_x/a-Si:H/c-Si devices are dead layers that allow no carrier extraction and J_{sc} of the solar cells is limited by the presence of the a-Si:H as well as the front/rear TCO layers. We further established that the modeling of the recombination loss allows the extraction of the minority carrier diffusion length and surface recombination velocity from the EQE analysis. Based on the EQE analysis results, the current loss mechanisms in various types of c-Si solar cells will be discussed.

9:00 AM ET02.11.02

Absorption Enhancement of a Thin Silicon Film Using a 3D Photonic Band Gap Crystal with Finite Support D Devashish, [Rebecca Saive](#), Jaap van der Vegt and Willem Vos; University of Twente, Pasadena, California, United States.

Currently, the efficiency of thin silicon film solar cells is constrained by a limited intrinsic absorption of silicon. The efficiency could be significantly increased by using a highly efficient back reflector that sends unabsorbed light back into the solar cell. As an interesting candidate for a back reflector, we study here a thin 3D photonic band gap crystal that forbids light within the band gap for all directions and for all polarizations. We consider a dispersive complex refractive index obtained from experiments. We find by extensive finite-element computations of the 3D time-harmonic Maxwell equations that even a very thin silicon 3D photonic band gap crystal slab reflects broadband visible light omnidirectionally for all polarizations. Our results show a nearly 2.6 times enhanced angle- and polarization-averaged absorption between 680 nm and 890 nm compared to a 2400 nm thin silicon film. We observe that a 3D inverse woodpile photonic crystal enhances the absorption of a thin silicon film by (i) behaving as a perfect reflector exhibiting nearly 100% reflectivity in the stop bands, and by (ii) generating guided resonant modes at many discrete wavelengths. We find that the absorption is enhanced by positioning an inverse woodpile back reflector at the back side of a thin silicon film, which will keep the length of the solar cell unchanged and also reduce the mass of the thin film solar cell. For a very thin sub-wavelength absorbing layer with a photonic crystal back reflector, we identify two physical mechanisms that cause the large enhancement at discrete wavelengths: (i) a guided resonance due to the Bragg attenuation length of the photonic crystal and (ii) confinement due to the effective surface defect on the photonic crystal.

9:15 AM ET02.11.03

Field Effect Passivation of High Aspect Ratio Silicon Surfaces Deniz Türkay^{1,2}, Cagil Koroglu³ and [Selcuk Yerci](#)^{1,2,4}; ¹Center for Solar Energy Research and Applications (GUNAM), Ankara, Turkey; ²Department of Micro and Nanotechnology, Middle East Technical University, Ankara, Turkey; ³Department of Electrical Engineering, Stanford University, Serra Mall, California, United States; ⁴Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey.

A high efficiency silicon solar cell combines high electrical performance with high optical performance. A common method to improve the optical performance is to utilize subwavelength, high aspect ratio structures, resulting in a surface with a graded refractive index and low reflectance throughout the wavelength spectrum. Although such high aspect ratio structures are relatively harder to passivate than conventional structures, reasonably high surface passivation quality have also been achieved by several research groups. However, surface recombination losses remain to be one of the major loss mechanisms for high efficiency silicon solar cells. One of the widespread methods to achieve high passivation performance on undiffused silicon surfaces is to use passivating dielectric layers with high density of fixed dielectric charges. The combination high aspect ratio structures and dielectric charges is commonly expected to result in an enhanced field effect passivation, resulting in less recombination losses in the textured region than what would be expected from the high surface area enhancement. Yet, despite the comprehensive experimental studies, quantitative analyses of the field effect passivation are mostly based on one-dimensional theory utilizing semi-infinitely thick structures¹. A detailed numerical analysis of the field effect passivation in multi-dimensional structures is still missing. In this work, we provide numerical and analytical analyses of field effect passivation for two-dimensional and undiffused surface textures coated with dielectrics. We show that when the dielectric charge density is very large, an enhancement in field effect passivation is only very minor at surfaces upon texturing. Then, the local surface recombination rate is very similar for textured and planar surfaces with similar interfaces and surface recombination losses increase in proportion with surface area. For moderately-large dielectric charge densities, on the other hand, we show the effect the enhanced field effect is much more significant at the surfaces and surface recombination losses increase sub-linearly with surface area. Thus, through proper material and process choice enabling moderate dielectric charge densities and high interface quality, surface recombination losses are expected to decrease further by taking full advantage the field effect.

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9:30 AM ET02.11.04

Modeling of Effective Secondary Electron Emission Yield from Black Silicon [Jonathon Mitchell](#); Koriyama, Japan.

Black Silicon, a material with a small reflection over a broad wavelength range and large fraction of absorbed photons, introduces a complex surface architecture based on structured absorbers which can also significantly reduce the total effective emission of photogenerated charges. Although overall reflection of incident photons are reduced, the increased surface area from the sub-micron relief vertical formation introduces inherent losses in the collection of photogenerated charges and from the interference by low-energy, secondary charges emitted from the sides and lowermost region of the structures. An analytical model was developed to calculate both the cumulative secondary charge emission from the vertical surface of the black silicon and the resulting parasitic net loss in photogenerated charges based on parameters including height (above base), lateral size and packing density. In the numerical simulations performed, a set of conditions were identified, which must be adhered to in order to suppress the effect of secondary charge emissions; and that these conditions are highly dependent on incident angle of photons to the surface coupled with the aspect ratio. In one case, a nearly 90% reduction in the parasitic secondary charge emission was observed for shallow angles, while almost 40% was achieved for normal incidence, compared to the flat surface. Our analysis assumes that secondary charge emission occurs only at the material surface, with no bulk effects. Although the formation of black silicon is becoming increasingly standard, analysis of a limited experimental sample set has shown while some low secondary charge emission yields were achieved from the material surface, many samples demonstrated significantly higher secondary charge emission yields either across the full sample size, or in regions. In this work we present the optimal aspect ratio (including packing density, lateral and vertical size) of the black silicon architecture which demonstrated the greatest suppression of secondary charge emission. This work may offer design improvements to the large scale development of black silicon to photovoltaics with optimised opto-electronic properties based on relatively controllable structural morphology features.

9:45 AM ET02.11.05

Multiscale Design of Disordered Porous Silicon Heterostructures for Infrared Light Control Alessio Palavicini Cruz and Chumin Wang; Instituto de Investigaciones en Materiales, Mexico City, Mexico.

Disordered multilayer heterostructures based on porous silicon are designed using a hybrid quantum-classical approach consisting of a Density Functional Theory calculation of the dielectric function of semiconductor layers. Each layer is modelled with a supercell of silicon atoms forming a crystalline structure where missing atoms characterize the porosity and these periodic pores are saturated with hydrogen and oxygen atoms. The ab-initio calculations are followed by the application of the transfer matrix method to compute the electromagnetic wave propagation along the heterostructure. Optical transmittance of the multilayer designs is verified by synthesizing freestanding samples of porous silicon multilayered films, obtained by means of electrochemical anodization of crystalline silicon wafers which allows us to etch each layer with specific porosities by varying current density, thus producing films with arbitrary dielectric function profiles. These samples are characterized through scanning electron microscope images and its transmittance is measured with a Fourier transform infrared spectrophotometer to compare theoretical and experimental results. Layer sequences with distinct types of disorder are assessed and compared with periodic ones for their performance as photonic structures such as mirrors and filters which could potentially be integrated into electronic circuits or used as elements of all-silicon photonic devices.

10:00 AM BREAK

SESSION ET02.12: ALD Processing for Silicon
Session Chair: Takuya Matsui
Thursday Morning, November 29, 2018
Hynes, Level 3, Room 311

10:30 AM *ET02.12.01

Materials for Solar Fuels—Coupling Efficient Water Splitting Catalysts and High-Performance Photovoltaics by Atomic Layer Deposition Paul C. McIntyre; Department of Materials Science and Engineering, Stanford University, Stanford, California, United States.

Atomic layer deposition (ALD), a cyclic form of chemical vapor deposition that occurs via a series of self-limiting chemisorption reactions, is an increasingly important enabler of nanotechnology and advanced energy technologies. Exciting energy-related applications of ALD that have emerged in recent years include surface passivation of photovoltaics, electrode coating for advanced batteries, and catalyst synthesis. In this presentation, I will summarize recent research in which ALD has been used to promote stable photoelectrolysis of water for solar fuel synthesis. ALD-grown TiO_2 layers are found to be particularly effective in inhibiting oxidative corrosion of high-quality semiconductor absorbers and in electronically coupling these semiconductors to efficient catalysts for oxygen evolution, the kinetically-limiting step in water splitting. In addition, ALD is used to alloy TiO_2 with transition metal oxides that are themselves good catalysts for water oxidation and that exhibit a high work function. These layers produce high photovoltages in excess of 600 mV in n-Si Schottky MIS junction water splitting photoanodes. Such ALD-grown metal oxide alloys have the potential to become “all-in-one” catalyst/protection/hole-selective contact layers for photoelectrochemical devices. Finally, results obtained from a novel multijunction silicon photoelectrochemical cell incorporating ALD- TiO_2 protection and exhibiting > 10% solar-to-hydrogen efficiency will be described.

11:00 AM ET02.12.02

On the Passivating Contact Performance of Atomic-Layer-Deposited TiO_x for Silicon Solar Cells Jimmy Melskens¹, Willem-Jan Berghuis¹, Bas van de Loo^{2,1}, Bart Macco¹, Lachlan Black¹ and Wilhelmus (Erwin) Kessels¹; ¹Department of Applied Physics, Eindhoven University of Technology, Eindhoven, Netherlands; ²Tempress, Vaassen, Netherlands.

Transition metal oxides are attractive as full-area passivating contact materials for silicon solar cells due to their transparency which can be combined with good surface passivation and low contact resistivity [Melskens et al., IEEE JPV 2018]. A promising example is titanium oxide (TiO_x) fabricated by atomic layer deposition (ALD), which can form an electron-selective contact to silicon and has enabled solar cell efficiencies above 22% using a full-area rear contact involving a TiO_x/Al stack [Yang et al., SOLMAT 2016; Adv. Mater. 2016; PiP 2017]. However, there are still many open questions with respect to the passivating contact performance of TiO_x that need to be addressed. For example, when trying to exploit the TiO_x transparency by combining it with a transparent conductive oxide (TCO) in a front contact, a high open-circuit voltage has so far not been achieved [Boccard et al., IEEE PVSC 2016], contradicting simulations which indicate that this should be achievable.

We have investigated the TiO_x contact performance in terms of passivation quality and contact resistivity by conducting a systematic study and by making a careful comparison with the existing literature. We found that there are several ways to achieve state-of-the-art passivation performance with typical optimum lifetimes of 1-2 ms. First of all, good passivation results can be obtained using titanium(IV)isopropoxide (TTIP) or tetrakis-dimethylamido titanium (TDMAT) as ALD Ti precursor, while good results have also been reported for titanium(IV)chloride (TiCl_4) [Cui et al., SOLMAT 2016]. Other experimental parameters, such as the substrate treatment prior to the TiO_x deposition, TiO_x deposition temperature, post-deposition annealing temperature, and film thickness have a much stronger impact on the contact performance. We found that ideally, the film is prepared at low temperature (50-200 °C) on HF-dipped Si such that crystallization is also avoided. The film thickness is particularly critical and we found that approximately 3 nm yields an optimal contact performance ($S_{\text{eff,max}} = 11.6 \text{ cm}^2/\text{s}$; $\rho_c = 10^{-2} \Omega\text{cm}^2$). This is similar to state-of-the-art results reported in the literature [Titova et al, Energy Proc. 2017].

It appears that there is a large field-effect contribution to the passivation that is induced by a net negative fixed charge, which is surprising for a material that can function as an electron-selective contact. The associated upward band bending in the silicon yields a rectifying contact, in particular when increasing the growth temperature or film thickness too much, although contacting the TiO_x layer by either a TCO or Al might play an important role here. An Ohmic contact that provides excellent surface passivation is achievable after annealing when keeping the TiO_x film sufficiently thin. This underlines that carefully engineering a thin TiO_x layer is key both in improving the passivating contact performance and the understanding of the underlying working principles.

11:15 AM ET02.12.03

Effects of Tunnel Layers and Light Illumination on the Performance of Electron-Selective TiO_2 Contacts Hyunju Lee¹, Changhyun Lee², Yoonmoek Kang³, Hae-Seok Lee³, Donghwan Kim^{2,3}, Noritaka Usami⁴ and Yoshio Ohshita¹; ¹Toyota Technological Institute, Nagoya, Japan; ²Department of

Materials Science and Engineering, Korea University, Seoul, Korea (the Republic of); ³KU-KIST Green School, Graduate School of Energy and Environment, Korea University, Seoul, Korea (the Republic of); ⁴Graduate School of Engineering, Nagoya University, Nagoya, Japan.

Recently, a new alternative to the silicon heterojunction (SHJ) solar cell concept has been suggested and intensively studied. In the new concept, a set of dopant-free asymmetric heterocontacts (also referred as carrier-selective contacts, CSCs) is employed to separate and collect photo-generated free carriers in a single cell structure [1]. Up to now, dopant-free CSCs with *electron-selective transport material* such as titanium dioxide (TiO_x) and *hole-selective transport material* such as molybdenum oxide (MoO_x) have been implemented on *n*-type crystalline Si (c-Si) wafers, and significant progress has been made. In particular, TiO_x is one of the few industrially matured materials and many fabrication techniques have been developed to deposit TiO_x thin layers, such as sputtering, chemical vapor deposition (CVD), atomic layer deposition (ALD), physical vapor deposition (PVD), and sol-gel processes. In addition, it is widely known that the electrical and optical properties of TiO_x thin layers depend on fabrication techniques. It is also reported that similar to ALD AlO_x thin layers, the passivation performance of CVD, ALD, and sol-gel TiO_x thin layers can be largely enhanced under light illumination due to a light-enhanced negative fixed charge density in TiO_x thin layers though the stability of electron-selective TiO_x contacts has not been evaluated under light illumination [2]. Meanwhile, the performance of electron-selective TiO_x contacts strongly depends the thickness and electrical property of a SiO_x tunnel layer between a TiO_x thin layer and a Si substrate according to previous research [3].

In this study, we have investigated:

1. The performance of electron-selective TiO_x contacts fabricated by ALD and e-beam evaporation and oxidation of Ti thin layers.
2. The effects of various metal oxide or nitride tunnel layers on the performance of electron-selective TiO_x contacts.
3. The stability of the fabricated electron-selective TiO_x contacts under light illumination.

for developing cost-effective, high-performance and stable electron-selective TiO_x contacts and elucidating the effects of the level and polarity of fixed charges and the electronic structure of tunnel layers on the performance of TiO_x electron-selective contacts. During our presentation, we will discuss the experimental results and suggest ways to enhance the performance and stability of electron-selective TiO_x contacts.

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SESSION ET02.13: Characterization
Session Chair: Hiroyuki Fujiwara
Thursday Afternoon, November 29, 2018
Hynes, Level 3, Room 311

1:30 PM *ET02.13.01

The Challenges and Opportunities of Bifacial Passivating Contact and SHJ-Perovskite Solar Cells—A Device-to-System Perspective M. Ashraf Alam¹, Raghu A. Chavali¹ and Stefaan De Wolf²; ¹Purdue University, West Lafayette, Indiana, United States; ²King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

A deep physical analysis – coupled with multiprobe characterization – is finally offering insights into the key factors that limit the performance and reliability of passivating contact heterojunction solar cells. These insights have encouraged generalization of the classical technology to multiple new formats: (a) new passivation contacts, (b) exploration of interdigitated back contact (IBC) and tunnel-IBC topologies, (b) optimization for bifacial performance, and (d) determination of performance limits for SHJ-Perovskite bifacial tandem cells, especially in response to location-specific diffused and albedo illumination. In this talk, I will discuss the physics and technology of the classical heterojunction solar cells, as well as the vibrant new research/technology options for the highly promising technology.

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2:00 PM ET02.13.02

Local Evaluation of Non-Uniform Charge Distribution in Al₂O₃ Passivation Layers for Silicon Solar Cells Using Super-Higher-Order Scanning Nonlinear Dielectric Microscopy Kento Kakikawa¹, Yuji Yamagishi¹, Katsuto Tanahashi², Hidetaka Takato² and Yasuo Cho¹; ¹Tohoku University, Sendai, Japan; ²Fukushima Renewable Energy Institute, National Institute of Advanced Industrial Science and Technology, Koriyama, Japan.

One of the factors that lower the efficiency of monocrystalline silicon solar cells is the recombination of carriers at the surface of bulk Si layers [1]. Aluminum oxide (Al₂O₃) is a promising candidate for the passivation of the bulk Si layers of monocrystalline silicon solar cells. It has been reported that the deposition of atomic-layer-deposited (ALD) Al₂O₃ passivation layers on the bulk Si layers effectively reduce the recombination losses. In the case of the passivation of the rear side of p-type passivated-emitter-and-rear-cell (PERC) solar cells, Al₂O₃ is reported to be as effective as thermally-grown SiO₂, which is also regarded as one of the good candidates for the passivation layers.

It is widely accepted that the suppression of the carrier recombination by the Al₂O₃ passivation layers is attributed to the reduction of the density of interface states (D_{it}) and the increase of the density of negative interface fixed charges (Q_f). The reduction of D_{it} is effective because it reduces the number of recombination centers and consequently directly reduces the carrier recombination velocity. The increase of the negative fixed charges is also effective to reduce the carrier recombination velocity because the fixed charges produce a local electric field at the surface and suppresses the diffusion of minority

carriers to the recombination centers near the surface. While a number of studies investigate the passivation mechanism by Al_2O_3 from a macroscopic view, a microscopic knowledge on the passivation mechanism, which is also expected to be useful information on the properties of $\text{Al}_2\text{O}_3/\text{Si}$ interfaces, is still missing.

In this study, we investigated the $\text{Al}_2\text{O}_3/\text{Si}$ interfaces using scanning nonlinear dielectric microscopy (SNDM) [2] and super-higher-order SNDM (SHO-SNDM) [3]. SNDM is a kind of capacitance microscopy with a sensitivity of as high as $2 \times 10^{-22} \text{ F Hz}^{-1/2}$ and has been used in the evaluation of a number of dielectric and semiconductor materials. SHO-SNDM is an extended technique of SNDM and is capable of obtaining local $C-V$ curves over the sample surface. This ability enables to investigate distribution of local charges at oxide/semiconductor interfaces by analyzing the shift or the change of local $C-V$ curves. We demonstrate that these techniques are applicable in the evaluation of non-uniform distribution of charges at $\text{Al}_2\text{O}_3/\text{Si}$ interfaces. We also show that the size of the patterns observed in SNDM and SHO-SNDM images are changed by a post deposition annealing of the $\text{Al}_2\text{O}_3/\text{Si}$ samples. Moreover, the increase of the areal density of negative fixed charges by the post deposition annealing was estimated by analyzing the local $C-V$ curves obtained by SHO-SNDM.

[1] ITRPV, "International Technology Roadmap for Photovoltaic," no. October, p. 4, 2015.

[2] Y.Cho, A. Kirihaara, and T. Saeki, *Rev. Sci. Instrum.*, 67, 2297, 1996

[3] N. Chinone, T. Nakamura, and Y. Cho, *J. Appl. Phys.*, 116, 084509, 2014

2:15 PM ET02.13.03

Mitigating Heat Generation and Thermal Effects in Silicon Solar Cells Lujia Xu¹, Thomas Allen¹, Michele de Bastiani¹, Hang Xu¹, Jingxuan Kang¹, Wenzhu Liu¹, Xinbo Yang¹, Erkan Aydin¹, Konstantinos Kotsovos², Ahmed Saggaf², Aqil Jamal², Issam Gereige³ and Stefaan De Wolf¹; ¹KAUST Solar Center (KSC), King Abdullah University of Science & Technology (KAUST), Thuwal, Saudi Arabia; ²Saudi Aramco Research and Development Center, Dhahran, Saudi Arabia.

For the sustained growth of the silicon PV market, a continued increase in cell efficiency, traditionally characterized at 25 °C, is noted as a prerequisite. However, the energy yield under field conditions, in which the cell temperature can deviate considerably from standard test conditions, is of primary importance. In this work, we analyze the thermal effects that contribute to cell heating, and so energy yield loss, in a variety of silicon solar cell designs. This knowledge will be of consequence for cells and modules deployed in high insolation, high temperature environments which are suitable for PV generation.

To demonstrate the significance of heat generation in silicon solar cells, first we analyze the energy loss in the ideal Shockley-Queisser limit of a single junction solar cell with a bandgap of 1.12 eV operating under the AM1.5 spectrum. Here, only ~34% energy from the solar spectrum is converted to electricity. The remaining energy is lost, either via transmission (19%), re-emission (15%), or thermalization (32%). It is the latter process which is the main source of heating, accounting for an increase in cell temperature above the ambient. In real devices, additional energy losses that decrease the cell efficiency from the theoretical limit contribute further to cell heating, e.g. resistive losses, extrinsic recombination and parasitic absorption.

In the above calculation, sub-gap photons are transmitted through the device. However, recent emissivity measurements on an aluminum back surface field (Al-BSF) cell by Riverola *et al.* demonstrate that over 80% of this energy is actually absorbed, further contributing to the thermal load of the cell. In this study we assess the absorption of sub-gap photons in the most prominent cell architectures – Al-BSF, passivated emitter and rear cell (PERC), mono- and bi-facial silicon heterojunction (SHJ) – via spectrophotometry measurements over the entire AM1.5 spectral range. We complement these measurements with quantum efficiency, and temperature dependent current-voltage (TD-IV), to assess both the current losses and the cell's temperature coefficients.

While it is known that the SHJ cell's temperature coefficient out-performs the Al-BSF and PERC devices, little is known of the relative difference in heat generation between these architectures. Our investigation extends this work by analyzing the thermal contribution from each material in the SHJ device. Spectroscopic ellipsometry is used to characterize each layer over the whole AM1.5 spectrum and optical modeling is utilized to estimate the contribution of each layer to cell heating. To this end, various TCOs, dopant-free contact layers, as well as the conventional a-Si layers are analyzed. These results enable accurate thermal simulation and optimization for minimizing heat generation and maximizing energy yield. Both the mono-facial and bi-facial cases are considered in our analysis.

2:30 PM ET02.13.04

In Situ Stressing Capability of Electrical AFM for Study of Silicon Solar Cell Degradation Chuanxiao Xiao, Chunsheng Jiang, Steve Johnston and Mowafak Al-Jassim; National Renewable Energy Laboratory, Lakewood, Colorado, United States.

The nanometer-scale electrical study of various degradation mechanisms in solar cells is in its infancy; in particular, in-situ microscopy studies have not been widely reported. Here, we have developed an in-situ stressing capability on atomic force microscopy (AFM) platform and applied it to study solar cells degradation mechanisms. The stressing capability includes high temperature (HT) up to 200 °C, high voltage (HV) up to 1500 V, and high illumination up to 2 suns. Technical challenges such as thermal drift at HT, HV interference with measurements, and arc discharge caused by HV, have been overcome along with the development. No measurement artifacts were observed during the stress conditions. Based on the in-situ AFM, Kelvin probe force microscopy potential imaging monitors the evolution of electrical potential across the junction along with the stress, which can provide vital information in understanding various degradation mechanisms. We applied the new capability to investigate potential-induced degradation (PID) of aluminum back surface field (Al-BSF) silicon solar cells, light and elevated temperature-induced degradation (LeTID) of passivated emitter and rear contact (PERC) cells. We observed the nanoelectrical properties change with the degradations and recovery. In PID issue of Al-BSF cells, we found a large area of material and p-n junction damage by PID that occurred at the millimeter scale, rather than point shunts associated with stacking faults. And for LeTID of PERC cells, we confirmed the role of Boron-Oxygen defect and hydrogen passivation.

2:45 PM ET02.13.05

Electrical, Optical and Structural Properties of Indium Tungsten Oxide as Carrier Selective Contact for Silicon Solar Cells Dorothee Menzel, Mathias Mews and Lars Korte; Helmholtz-Zentrum Berlin, Berlin, Germany.

High work function materials such as molybdenum oxide (MoO_x) [1] and tungsten oxide (WO_x) [2] have recently been investigated as carrier-selective hole contacts for silicon heterojunction solar cells, where they could replace the p-type amorphous silicon layer: They provide a higher optical transparency, and due to their high work function it is expected that they can improve the cell's fill factor due to a more efficient carrier separation [3]. However, we have found in previous studies [3] that tungsten oxide suffers from a tradeoff of rather poor conductivity for high work function films close stoichiometry, or a strongly reduced work function for more conductive, substoichiometric films. Therefore, we investigate possibilities to improve the electrical properties by combining the high work function and wide band gap of WO_x with the good conductivity of indium oxide (InO_x) in InWO_x alloys. Recently, we have presented investigations of InWO_x deposited with different ratios of indium-to-tungsten oxide by thermal evaporation, spanning the full range from pure tungsten oxide to pure indium oxide. Using *in-situ* (X-ray and UV) photoelectron spectroscopy, optical spectroscopy and surface photo voltage measurements, we found a pronounced decrease of the work function from $\Phi = 6.3 \text{ eV}$ for pure WO_x down to $\Phi = 4.5 \text{ eV}$ for 40% of indium

content in the alloy. Within the same indium tungsten oxide range, this was accompanied by a decrease of the band bending in the crystalline silicon substrate by 200 meV [4].

In the present study, we provide further insight into InWO_x materials properties upon annealing of the layers up to 600 °C: We investigate the crystalline structure using X-Ray diffraction and find that InO_x is fully crystallized at 250 °C, whereas WO_x only starts to crystallize at 550 °C. For an indium content of more than 40 % the mixture remains in the indium oxide structure (also above 550 °C), while the tungsten rich layers show two different structures after crystallization, one at about 25 % InO_x content (In₂O₁₂W₃) and another one for even lower InO_x content, which resembles the one of pure tungsten oxide. Concomitantly, optical transmission and reflection measurements show an increase in transmission for indium rich layers with increasing annealing temperature up to 400 °C, while tungsten rich layers showed a lower or even no change in transmission. We explore, whether such high-temperature annealed films yield improved performance when incorporated into devices.

[1] C. Battaglia *et al.*, *Nano Lett.*, 14, 967–971, 2014.

[2] M. Bivour *et al.*, *Sol. Energ. Mat. Sol. Cells*, 142, 34–41, 2015.

[3] M. Mews *et al.*, *Sol. Energ. Mat. Sol. Cells*, 158, 77–83, 2016.

[4] D. Menzel *et al.*, *Appl. Phys. Lett.*, 112, 1–13, 2018.

3:00 PM BREAK

SESSION ET02.14: Silicon Devices
Session Chair: Stefaan De Wolf
Thursday Afternoon, November 29, 2018
Hynes, Level 3, Room 311

3:30 PM *ET02.14.01

Passivated Contact Silicon Cells with Bulk Defect Engineering [Paul Stradins](#); National Renewable Energy Lab, Golden, Colorado, United States.

Silicon, the dominant PV technology, is rapidly evolving. The current new industry standard p-PERC is likely to be replaced by even more efficient cells based on passivated contacts in the longer term. It is likely that passivated contact technology will gradually replace parts of the p-PERC process while preserving its advantages: high temperature metal paste firing for reliable contacting, process simplicity, and low cost. In my talk, I will outline the key research directions that enable high-temperature passivated contacts based on poly-Si and SiO₂ buffer layer to get widely adopted: and bulk defect engineering, passivation of contacts, and their metallization. We have extended our previous Tabula Rasa method to suppress O-precipitate related defects, to bulk intrinsic defect engineering in n-Cz wafers that are used to produce double-sized passivated contact cells. We explore how the dopant diffusion from the poly-Si layer into the wafer beneficially affects the passivated contact properties and distinguish between pinhole and tunneling transport in contacts with different buffer oxide thickness. Finally, we demonstrate high performance, lithography-free solar cell fully based on poly-Si passivated contacts in FSF/back p-n junction configuration.

4:00 PM *ET02.14.02

Large Area Industrial nPERT Cells—Status And Perspectives [Loic Tous](#), Patrick Choulat, Sukhvinder Singh, Jia Chen, Richard Russell, Filip Duerinckx and Jozef Szlufcik; imec, Leuven, Belgium.

Czochralski-grown n-type Passivated Emitter Rear Totally Diffused (nPERT) promise high and stabilized energy conversion efficiencies due to high bulk lifetimes and the absence of significant light-induced degradation (LID). Critical elements of large area (>239 cm²) industrial nPERT cell design and fabrication include: (i) junction formation, (ii) surface passivation, (iii) contact metallization, and (iv) cell interconnection. In this work, we give an overview of the various methods employed and results achieved globally for large area industrial nPERT cells. Then, we will present in greater details large area monofacial and bifacial nPERT cells results achieved at imec using either screen-printed or plated contacts and discuss limitations of both approaches. Based on experimental data and device simulations we discuss future improvements needed towards nPERT cell efficiencies above 24%. Finally, we present nPERT module efficiency and cost roadmaps.

4:30 PM *ET02.14.03

Integration Strategies for High Temperature Passivating Contacts [Andrea Ingenito](#)^{2,3,4}, Gizem Nogay¹, Christophe Allebé³, Josua Stuckelberger¹, Philippe Wyss¹, Jorg Horzel³, Florent Sahli¹, Jeremie Werner¹, Laura Ding³, Juan Diaz Leon³, Mario Lehmann¹, Arnaud Savoy¹, Santhana Eswara⁴, Tom Wirtz⁴, Sylvain Nicolay³, Quentin Jeangros¹, Matthieu Despeisse³, Franz-Josef Haug¹ and Christophe Ballif^{1,3}; ¹École Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland; ²Institute of Microengineering (IMT) Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Swaziland; ³CSEM, PV-Center, Neuchâtel, Swaziland; ⁴Luxembourg Institute of Science and Technology, Materials Research and Technology Department, Advanced Instrumentation for Ion Nano-Analytics (AINA), Belvaux, Luxembourg.

Passivating contacts provide a close to ideal scenario to obtain collecting junctions with an excellent selective carrier extraction, even when metallized. Industrialization of such technology represents a fundamental milestone for sustained growth of the PV market. Here, we present our strategies for industrialization of passivating contacts either as drop-in replacement of partial rear contacts or as full-area front and rear passivating contacts for high-efficiency and patterning-free solar cells. For this, we use the large versatility of the plasma process which enables the tuning of the electrical, micro-structural and compositional properties of the deposited layer, and the advantage of a single side processing. Finally, to extend the PV-learning curve beyond the single-junction efficiency-limit, two-terminal monolithic fully-textured tandem perovskite/c-Si with passivating contacts will be shown.

Passivating contacts as drop-in replacement of partial rear contacts: for a “lean” process integration, we developed passivating contacts that are manufactured with the thermal processes employed in the PV-industry such as P-diffusion or firing. Boron-doped micro-crystalline silicon oxide layers (μc-SiO_x(p)) enabled to withstand long annealing at high temperature (>800°C, >30min) typical of diffusion processes.

For a firing-compatible passivating contact, the incorporation of C in nano-crystalline-SiC_x(p) ensures a resilience to blistering, that may otherwise occur due to the fast firing (>800°C, <10s). The cell integration of the nc-SiC_x(p) in a co-fired process with a Ag-paste contacting a front P-diffused emitter resulted in a conversion efficiency of 22.5% on 2x2 cm².

Passivating contacts for front and rear contacted c-Si solar cells: P and B doped silicon carbide layers were developed as electron and hole selective contacts, respectively. Very high degree of surface passivation on p-type planar c-Si is evidenced by *iV*_{OC} values of 735mV and 746mV for the hole and electron contacts, respectively. The performance of the SiC_x layers is demonstrated at device level with a simple patterning-free and co-annealed process flow enabling high-level of current extraction and surface passivation with FF=84%, *V*_{OC}=727mV on planar cells, and efficiencies up to 22.6% with front-textured-cells. Highly-transparent P-doped microcrystalline silicon (μc-Si(n)) were developed as alternative to front SiC_x(n) layer. High surface passivation

with iV_{OC} of 729mV and 707mV were reached on planar and textured samples without post-hydrogenation, respectively. In a first attempt, solar cell characteristic include a promising J_{SC} of 39.92mA/cm².

Monolithic textured perovskite/c-Si tandem solar cells: the SiC_x-based cell architecture with passivating contacts deposited on both sides was used as bottom cell. This bottom cell had a textured front side, on which a fully conformal perovskite top cell was deposited to achieve a steady-state efficiency >24.5% (area >1 cm²).