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.
Optimization of the Ultrathin SiOx Passivation Layer and n+-poly-Si Electron Selective Layers in TOPCon c-Si Solar Cells

Zhi Zhang, Yuqing Huang, Mingdun Liao, Pingqi Gao, Chunhui Shou, Jie Yang, Xinyu Zhang, Baojie Yan, and Jichun Ye
Ningbo Materials Institute, National Renewable Energy Laboratory

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, Nils Folchert, Felix Haase, Christina Klament, Yevgeniya Larionova, Jan Krügener, Agnes Merkle, Byungsul Min, Michael Rienäcker, Udo Römer, Sören Schönfeld, Dominic Tetzlaff, Tobias Wietler, and Rolf Brendel
Institute for Solar Energy Research Hamelin (ISFH), Emmerthal, Germany; Institute for Electronic Materials and Devices, Leibniz Universität Hannover, Hannover, Germany; Institute 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 S₀, 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 an 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 / SiOx / c-Si stack is determined, which is sufficiently low for a full area contact between bottom and top cell.

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

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Institute for Solar Energy Research Hamelin (ISFH), Emmerthal, Germany; Institute for Electronic Materials and Devices, Leibniz Universität Hannover, Hannover, Germany; Institute for Solid State Physics, Leibniz Universität Hannover, Hannover, Germany.

In this work, an overview of the amorphous/crystalline silicon 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 experimentally obtained 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 thank to efficient collaboration with the main R&D actors in the SHJ community, through collaborative projects.

Optimization of the Ultrathin SiOx Passivation Layer and n+-poly-Si Electron Selective Layers in TOPCon c-Si Solar Cells

Zhi Zhang, Yuqing Huang, Mingdun Liao, Pingqi Gao, Chunhui Shou, Jie Yang, Xinyu Zhang, Baojie Yan, and Jichun Ye
Ningbo Materials Institute, National Renewable Energy Laboratory

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 on recent progresses in the research and development of high efficiency TOPCon solar cells, including the fabrication and optimization of SiOx passivation layer, P-doped poly-Si contact layer, Al2O3/SiNx: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 SiOx (~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-i-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 (Voc), including forming gas annealing, hydrogenated silicon nitride (a-Si: N, 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 an minority carrier lifetime of 1.5 ms at 5'1013 cm-2carrier injection, saturated reverse recombination current density J0=1.3 pA/cm2, and IVoc=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.

9:45 AM ET02.01.04 Poly-Si Alloys Carrier-Selective Passivating Contacts for High-Efficiency c-Si Solar Cells Guantao Yang1, Gianluca Limodio1, Paul Procel1, Luana Mazzarella1, Arthur Weeber1, 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-SiCx 3,4 have been developed and demonstrated record-high efficiency in both front back contacted (FBC, >25%) 1 and interdigitated back contacted (IBC, >26%) 2 cell. However, the high free carrier absorption (FCA) of the CSPCs still limit the cell efficiencies 1,2. Therefore, more transparent poly-SiOx materials as CSPCs have been developed 3,4. 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 Jsc 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 simulation 3, 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-SiOx as CSPCs. Currently, our poly-SiOx layers show excellent passivation and carrier selectivity, for both n-type (IVoc,flat = 740 mV; contact resistance Rs = 0.7 mΩ●cm2; IVoc,texture = 718 mV) and p-type (IVoc,flat = 709 mV; Rs = 0.5 mΩ●cm2). Due to the 0 inducing band gap widening, the absorption coefficient at long wavelengths in the poly-SiOx layers becomes negligible. Both n-type and p-type poly-SiOx 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. The Jsc of 39.2 mA/cm2 and Voc of 659 mV reach 26.0% 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 Jsc 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 simulation 3, 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-SiOx as CSPCs. Currently, our poly-SiOx layers show excellent passivation and carrier selectivity, for both n-type (IVoc,flat = 740 mV; contact resistance Rs = 0.7 mΩ●cm2; IVoc,texture = 718 mV) and p-type (IVoc,flat = 709 mV; Rs = 0.5 mΩ●cm2). Due to the 0 inducing band gap widening, the absorption coefficient at long wavelengths in the poly-SiOx layers becomes negligible. Both n-type and p-type poly-SiOx 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-SiOx CSPCs shows higher internal quantum efficiencies at wavelengths above 1100 nm. This indicates that - for both FBC and IBC cells - poly-SiOx CSPCs hold the potential to enhance the cells’ Jsc by maximizing both short and long wavelength response.


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 Scialo1, Antonio Ragonese1, Claudio Colletti1, Wilfried Favre2, Adrien Dane1, Renaud Varache2, Jordi Veirman2, Delfina Muñoz2, Charles Roux3, Jean Francois Lerat3, Frank Medlege4, Vincent Barth4, Lionel Sicot4, Pierre Jean Ribeyron3 and Cosimo Gerardi1; 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 wafer 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/Ta contacts 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 Matthieu Despeisse, Bertrand Paviet-Salomon, Antoine Descoeudres, Laurie-Lou Senuad, Jonas Geissbühler, Gabriel Christmann, Sylvain Nicolay, Jan-Willem Schuttauf, Julien Bailat and Christophe Ballif; CSEM SA, Neuchatel, Switzerland.

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 cm2 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 Zhao1, Engin Özkol1, Paul Procel1, Guangtai Yang1, Luana Mazzarella1, Olimo Isabella1, Arthur Weeber1 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 assured 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%1. 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)-SiOx:H thin-film layers. The optimized 6-nm thick intrinsic (i)-a-Si:H layer provides > 3 ms lifetime and > 720 mV implied Voc (iVoc) on double side textured n-type Fz wafer. On i-a-Si:H, an enhanced passivation quality is obtained (iVoc> 730 mV) after (n)nc-SiOx:H deposition. With a similar structure, no degradation in passivation quality (iVoc= 720 mV) was observed after (p)nc-SiOx:H deposition. This optimized 29-nm thick p-layer shows a dark conductivity (σd) 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 collection is essential to minimize the drop from SunsVoc to Voc. This doped nc-SiOx: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-SiOx: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 JRc 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-SiOx: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 concept. With the optimized SHJ passivating contacts, the preliminary tunneling IBC device, exhibits an η of 18.2% with a VOC of 659 mV, JSC 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 VOC of 719 mV, with an average V oc of 715 mV over 7 cells. By addressing the low η of the non-optimized (n)mc-Si:H, 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
Chang-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

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 Favre1 and Mustapha Lemiti2; 1CEA INES, Le Bourget du Lac, France; 2INL, Villeurbanne, France.

High efficiency silicon (Si) cell architectures (Interdigitated Back Contacts, a-Si/a-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-ms 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, we performed a series of lifetime mappings and lifetime maps under outdoor test conditions (sunsim, outdoor). 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), 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, could be involved in LID mechanisms [C. Möller and K. Lauer, Energy Procedia 55 (2014) 559 – 563].

In a second part of this study, 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 < 8x10⁻¹⁰.

2:15 PM ET02.03.03
Stability of Na Atoms at Stacking Faults in Si Depending on the Fermi Level
Yutaka Ohno1, 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 = 8×10¹⁸ cm⁻³), P-doped n-type Si (3×10¹⁷ cm⁻³), and nominally undoped n-type Si (3×10¹⁷ cm⁻³) by applying a compressive stress at an elevated temperature. Each crystal and 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 w₆₉ was estimated by TEM, as a function of the line orientation α defined by the angle of b to u in which b is the sum of the Burgers vectors of the dislocations and u is a vector along the dislocations, and the formation energy of SFs E₆₉ was calculated with w₆₉(α). In all the examined crystals, w₆₉(α) increased by Na doping, and the ratio between the w₆₉(α) 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 E₆₉. The degree of the energy reduction would decrease with rising the Fermi level: E₆₉ was reduced by more than 10 mJ/m² in p-Si while it was barely reduced in n-Si [3]. 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 Σ₃{111} GBs will be discussed.

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
Erk Dinèrçark, Bülge İmer 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 (Dit), fixed charge density (Qf) and flat band voltage (VFB). Due to enhanced field effect passivation quality of thin Al2O3 layer, high ratio Qf can be accomplished. Qf has been reported as high as 1 x 10^{13} 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 Ds [3]. 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 VFB values were calculated and conductance method was applied to determine Dit values. It was shown that Qf decreased when the post-thermal annealing was applied. The highest Qf was ~5.13x10^{13} cm^{-2} and the lowest one was ~2.43x10^{11} cm^{-2}. Dit decreased at 400°C post-annealing temperature for different deposition temperatures. The highest Dit was 2.79x10^{13} cm^{-2}eV^{-1} and the lowest one was 2.39x10^{11} cm^{-2}eV^{-1}. The lowest Dit was found at 400°C post-thermal annealing temperature under N_{2} ambient with 165°C prior deposition temperature. It was concluded that when Qf values increase, Dit values also increase. High variation on VFB was found where it changed in between 1.09V to 4.19V.

REFERENCES


4:15 PM ET02.04.03
Band Alignment at the Heterojunction Between Plasma Enhanced Atomic Layer Deposited SnO2 and N-Doped Hydrogenated Amorphous Silicon
Gina Mihalikova, Mathias Mews and Lars Korte; Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany.

Tin oxide, SnO_{2}, 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 inter 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 SnO_{2} 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 SnO_{2} on hydrogenated amorphous silicon. We use TDMASn as precursor, which is a prominent choice for SnO_{2} ALD due to its low temperature requirements and high uniformity [1]. 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 SnO_{2}, with increasing SnO_{2} 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 SnO_{2}/n:Si:H heterojunction as a function of SnO_{2} thickness. We determine the conduction and valence band offsets at the SnO_{2}/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 delay was observed, and the Sn 3d core level signal was already detectable after the first growth cycle. We find that the conduction band offset from (n)a-Si:H to SnO_{2} was determined to be ~270 meV. Therefore, SnO_{2} could be applied as an electron contact to (n)a-Si:H, if the formation of the strong interface dipole can be suppressed.


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, Esma 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 tandem 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 MAP$_x$I$_3$ 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
Stefan Yalamanchili1, Kelly McKenzie2, Thomas Russell1, Michael Kelzenberg1, Rebecca Saive1, Utkarshaa Varshney1, Tian Zhang1, Brant Hoex1 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/cm$^2$, 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 (ICP-RIE) 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 Krč2, Lars Korte1, Marko Topić2, 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 validate 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:

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$_x$Se$_2$, 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
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 propose 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-link after 100 hours of aging. We develop a treatment of the tin-lead perovskite film by exposure to methylammonium chloride vapor 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? Jan 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 economy. Tandem solar cells are multi-terminal devices which 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 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 encapsulant since it does not chemically react with the perovskite and has an ideal elastic modulus.

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
Optimizing Interfacial Layers on Silicon Heterojunction Bottom Cells for Perovskite/Silicon Tandem Solar Cells with 25% Power Conversion Efficiency and Beyond


With open circuit voltages ($V_{oc}$) 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 low 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/Si 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 ($PCE_{sc} = 380 mA/cm^2$, $V_{oc} = 731$ 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/Si 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/cm$^2$. 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.

3. E. Köhnen, S. Albrecht et al., to be submitted.
devices, achieving 13-cm² cells with a steady-state efficiency above 20%.

- Silicon bottom cell technology: we test 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, Yusuake 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 develop 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 lumiance. 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 lumiance 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.

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2:00 PM ET02.06.02
Effects of Amorphous Si Capping Layer on Sputtered BaSi2 Film Properties
YiLei Tian¹, Ana B. Montes², Olindo Isabella¹ and Miro Zeman³; 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 10⁴ cm⁻¹ for hv > 1.5 eV [1]; a long minority carrier lifetime ~27 µs [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

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 Amkreutz¹, Chanh T. Trinh¹, Martina Trahms¹, Klaus Jäger¹, Christiane Becker² and Rutger Schlatmann³; ¹Silicon Photovoltaics, Helmholtz Zentrum Berlin, Berlin,
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 pyramidal texturally 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 recombinations 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 recombinations, 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 Nakahara1,2, Moeko Matsumura1, Shota Suzuki2, Shogo Fukami2, Marwan Dhamrin3 and Noritaka Usami1; 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 silicon 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. However the energy conversion efficiency of crystalline silicon 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. 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. 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.

2:45 PM BREAK

3:05 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 (J0e), 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 Liquid-Induced Liquid-Phase-Crystallized Silicon Thin Films for Photovoltaic Application [Hiroshi Umishio, Takuya Matsui, Hitoshi Sai and Koji Matusbara; 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 excessive 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 polishing 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 shorter 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 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 ($\mu_{0} < 5 \text{ cm}^2/\text{V s}$), the cell injection regime increases by a factor of 10 and Auger recombination becomes more predominant. This is particular true for substrates with Shockley-Read-Hall minority carrier lifetime over 1 ms. For silicon hetero-junction 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 ($\mu_{0} < 2 \text{ cm}^2/\text{V s}$) regardless the base doping, impacting positively the FF, 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 Trabahn1, Cham T. Trinh1, Maurice Nuyts2, Uwe Breuer2, Uwe Zastrow2, Natalie Preissler1, Marko Josif, Steve Albrecht1, Rutger Schlatmann4 and Daniel Amkreutz5; 1 Institute for Silicon Photovoltaics, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany; 2 Institute for Silicon Photovoltaics, Forschungszentrum Jülich GmbH, Jülich, Germany; 3 Central Institute for Engineering, Electronics and Analytics (ZEA), Forschungszentrum Jülich GmbH, Jülich, Germany; 4PVcomB, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany; 5 Young 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 kerf loss which is typically associated with wafer processing. The absorber is deposited on glass with a thickness between 5 and 40 µm. During the crystallization process, a poly-crystalline Si-absorber with grain sizes in the order of an amorphous or nano-crystalline Si-absorber. This technique avoids kerf loss which is typically associated with wafer processing. 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.

4:30 PM ET02.06.03
Watching Nanodefects Grow in Si Crystals [Andreas Magerl; University of Erlangen-Nurnberg, Erlangen, Germany.

Nucleation and growth of oxygen precipitates in moderately p-type (\(P_{o}>10^{18} \text{ cm}^{-3}\)) and highly p-type (\(P_{o}>10^{19} \text{ cm}^{-3}\)) 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 Penfield Young 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-Tailed Hyperdoping Philippe K. Chou1, Qi Lim2, Jim S. Williams3 and Jeffrey M. Warrender4; 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 ~10^-1 - 10^-2 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^-4 - 10^-5 %. 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.

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), I(V) 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%. Voc 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 Jsc on textured surfaces: we present Jsc and implied Voc 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 (MoOx) has been investigated for its potential as a hole selective contact. The high work function of MoOx 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) on the sunny side of the cell or bifacial solar cells.

By making large-area “moly-poly” cells, with a front side MoOx/aSi:Hi(i) passivating contact and a rear-side poly-Si/SiOx stack, we have demonstrated that MoOx based c-Si solar cell technology can be scaled to industrial 6” wafer size. Excellent surface passivation was achieved using MoOx and poly-Si, leading to implied Voc values > 725 mV, and a final cell Voc of 687 mV. Using thin PECVD poly-Si layers to avoid too high FCA losses, a 18.1% efficient
Carrier-selective passivating contacts (CSPCs) based on a 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 oxygen5,6 to improve their transparency.

Recently, CSPC based on poly-Si alloyed with C4 or O2,7,8 demonstrated their potential on device level resulting in conversion efficiency up to 25.7% in front back contacted (FBC) cell configuration1.

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 nm). 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 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 SiNₓ, Al₂O₃ and Al₂O₃/SiNₓ in forming gas annealing atmosphere at 400 °C.

Preliminary results obtained on symmetric test samples capped with 75-nm thick SiNₓ 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 (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 V-OC above 710 mV, carrier lifetime of 7.5 ms and recombination current densities of 12 fA/cm².

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 layer1,2. Interdigitated back-contact (IBC) solar cells have demonstrated the highest efficiencies of more than 26.6%3,4, 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 layers5,7. 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 photovoltaic decay and the contact resistances between aluminium 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.
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 ($\tau_{e0}$) 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$_3$OH) was mixed with the solutions to control the surface tension. It was found that 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; 1-KIER-UNIST Advanced Center for Energy, Korea Institute of Energy Research, Ulsan, Korea (the Republic of); 2-Department of Integrated Energy and Photon Technology, Cheonju University, Cheonju, Korea (the Republic of).

Wafer 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 splitting 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, enable 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 wafer to fabricate silicon heterojunction solar cells. The fabricated cell exhibited an efficiency of 11.42 % (Jsc : 32.8 mA/cm2, Voc : 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 can be used for both photovoltaic conversion and energy storage4.


2:00 PM ET02.09.02
Effect of Permanent Dipole Layers in the Electrical Characteristics of Electronic Devices and Solar Cells Eloi Bos1, Zaira Barquera1,2, Isidro Martin1, Pablo Ortega1, Cristobal Voz2,3, Joaquim Puigdollers1 and Ramon Alcubilla1; 1-University of Politecnica-Catalunya, Barcelona, Spain; 2-UCM, 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, span style="font-size:10.8333px;" type="cs") for 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 build-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. Amine 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 atorganic
materials such as Silicon, can ultimately increase biocompatibility of the original material and open the field to new applications on biointerfaces. To first approximation, we have studied the electric contact using Transfer Length Method (TLM) of n-type crystalline silicon with an Atomic Layer Deposition Al2O3/TiO2 stack, reaching a maximum contact resistance of 0.75 Ohms cm². 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/V2O5/n-cSi/a-Si:H/Glycine/Al and ITO/V2O5/n-cSi/Al2O3/TiO2/Glycine/Al.

1:15 PM ET02.09.03
Effect of Slow-Speed Evaporation of BaSi2 on the Performance of P-Type BaSi2/n-Type Crystalline Si Solar Cells
Michinobu Fujisawa, Kazuma Takahashi, Yoshihiko Nakagawa, Kazuhiro Gotoh, Yasuyoshi Kurekawa 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 BaSi2 (p-BaSi2) as a promising candidate for a hole selective material, since device simulation (Affors-Het ver. 2.5) showed that p-type BaSi2 improves open-circuit voltage ($V_{oc}$) of SHJ solar cells [1]. To deposit p-BaSi2 on a large-area substrate, we developed a simple method to perform thermal evaporation of BaSi2 on B-doped hydrogenated a-Si (a-Si:H) deposited by plasma enhanced chemical vapor deposition (PECVD). To realize high-quality p-BaSi2/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 BaSi2 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 SiH₄, H₂ and 1% B₂H₆ were 40, 40 and 40 sccm, respectively. Substrates were heated at 60°C for 3 h in the evaporation chamber. BaSi2 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 increased to 140 A. Rapid thermal annealing (RTA) was performed for some samples to diffuse B into the evaporated BaSi2 thin films. After that, the solar cell structure (Ag/TiO2 thickness (t): 80 nm/p-BaSi2, t: 30 nm/n-c-Si, t: 280 mm/Au-Sb) was fabricated, and their $J-V$ characteristics were measured under AM1.5G illumination. BaSi2 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 that the holding time of 180 s a-axis-oriented BaSi2 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.


2:30 PM BREAK

3:00 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 material in TMO-based CSC solar cells, respectively [2-3]. Meanwhile, TMO-based CSCs have demonstrated significant progress in Si solar cell properties and solar cell characteristics.

In this study, we have investigated:

- The performance of TiO2 and MoO3-based CSCs on shallowly doped n⁺ and p⁺ Si surfaces.
- The effects of various ultra-thin tunnel layers on the performance of TiO2 and MoO3-based CSCs.
- The stability of the fabricated TiO2 and MoO3-based CSCs on shallowly doped n⁺ and p⁺ Si surfaces under light illumination for developing cost-effective, high-performance and stable Si solar cell and elucidating the effects of the surface doping of Si absorbers and the ultra-thin tunnel layers on the performance of TiO2 and MoO3-based CSCs. During our presentation, we will discuss the experimental results and suggest ways to enhance the performance and stability of CSCs.

References

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 Ω/□). 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 µs to 272.24 µs). 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**

*Khaleed H. Khafagy*, Tarek M. Hatem and Salah M. Bedair; 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 Oh*, Ji-Eun Hong, Hee-Eun Song, Ka-Hyun Kim and Dong Suk Kim; 1KIER-UNIST Advanced Center for Energy, Korea Institute of Energy Research, Ulsan, Korea (the Republic of); 2Photovoltaics 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 ~200 °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 ~200 µs/659 mV to ~2 ms/730 mV) when average pyramidal size increases from 1 µm to 15 µm. 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 transparence 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 67 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**

Senal Dissanayake1, Matthew Wilkins2, Philippe K. Chow3, Wenjie Yang4, Quentin Hudspeth4, Shao Qi Lim5, Jim S. Williams6, Jeffrey M. Warrender7, 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.


**ET02.10.06**

**Tunnel Oxide Passivated Contact for Crystalline Silicon Solar Cells Using Hot-Wire Chemical Vapor Deposition**

Kaining Ding1, Manuel Ponsa1,
In this work, hot-wire chemical vapor deposition (HWCDV) was utilized to fabricate amorphous silicon(a-Si) thin films for tunnel oxide passivated contacts of crystalline silicon n solar cells. So far low pressure chemical vapor deposition or plasma enhanced chemical vapor deposition are usually used to deposit Si:H or Si 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 mm/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 Σ3{111} Grain Boundaries in High-Performance Si Ingots Yutaka Ohno1, Kentaro Kutsukake1, Takehiro Tamaoka2, Seiji Takeda2, Yasuo Shimizu3, Naoki Ehsawa4, Koji Inoue3, Yusayoshi Naga5 and Noritaka Usami6, 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 found 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 Σ3{111} GBs with the <110> 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 Σ3{111} GBs was negligible. High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) revealed that, most parasts of the asymmetric GBs were composed of arrays of GB dislocations lying on symmetric Σ3{111} GB segments. Those dislocations were edge-type with the Burgers vector of 1/3<111>. 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 near the dislocation cores. Small amount of metal precipitates such as iron silicides were occasionally observed along 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.

Acknowledgments: This work is partly supported by “Multicrystalline informatics toward establishment of general grain boundary physics & realization of high-quality silicon ingot with ideal microstructures” project in JST/CREST, Grant No. JPMJCR17J1 (2017-2023).

ET02.10.08
P-Type Molecular Monolayer Deposition of Silicon for Photovoltaic and Semiconductor Devices Megan E. Dewilker, Scott Humski, Jenna Doran, Scott Williams and Santosh Kuriniec; 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 create 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. The reason for this is even though low defect density of 1011 eV−1 cm−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 characteristic of the stack layers has shown that in-as-deposited states on Al2O3, H2O-TiO2 has lower saturation current density (Jsat) than H2O2-TiO2, in which both H2O and O3 are used as oxidants. Annealing is beneficial for H2O2-TiO2 to decrease Jsat, which is analogous to H2O-Al2O3 vs. O3-Al2O3.
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 how 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 Patwardhan1,2; Sandeep Maurya3 and Halasubramaniam Kavaipatti3; 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 phosphor-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 (JL) was higher by nearly 40% than the control cells. The average fill factor different (AFF) observed between them was 0.14. By using the equation AFF = (1 - n)VMP/VOC, it yields ratio of light-generated to short circuit currents, that is n = JL/JSC to be 0.78 at maximum power point (MPP). Here, VMP and VOC 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 JL 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 JL for the control cell to be Jsc (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 VOC. 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**

Yasu 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 systems 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 mechnochemical 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, 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 prepared by Ga-FIB. The intermediate layers 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.

This work was supported in part by JSPS KAKENHI Grant No. 15H05413 and JST/CREST Grant No. JPMJCR17J1.

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 can 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.

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 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/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.

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 micro-spheres 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 range, 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 junctions 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.
Absorption Enhancement of a Thin Silicon Film Using a 3D Photonic Band Gap Crystal with Finite Support

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.

Field Effect Passivation of High Aspect Ratio Silicon Surfaces

Denz Türkay1,2, Çağil Koroglu3 and Selekç Yerci3, 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 has 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-ininitely thick structures2. 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 to the field effect.

References

Modeling of Effective Secondary Electron Emission Yield from Black Silicon

Jonathan Mitchell; National Institute of Advanced Industrial Science and Technology, 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 is 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 flat surface. Our analytical 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 to electronic circuits or used as elements of all-silicon photonic devices.

10:00 AM BREAK

10:00 AM ET02.11.06
Effects of Tunnel Layers and Light Illumination on the Performance of Electron-Selective TiO2 Contacts
Hyanju Lee1, Changhyun Lee2, Yoonmook Kim1; 1Department of Power and Energy Systems Engineering, POSTECH, Pohang, Gyeongbuk, South Korea; 2Department of Electrical Engineering, POSTECH, Pohang, South Korea.

Recent studies have shown that TiO2/Al tunnel diodes can provide high performance as electron-selective contacts for dye-sensitized solar cells (DSSCs). The contact performance of TiO2/Al diodes is highly dependent on the experimental parameters, such as the substrate treatment prior to the TiO2 deposition, TiO2 deposition temperature, post-deposition annealing temperature, and film thickness. Another important factor is the contact resistance which is determined by the interface between TiO2 and Al layers. It has been reported that the contact resistance can be reduced by introducing tunnel layers between TiO2 and Al layers.

In this study, we investigate the contact resistance of TiO2/Al tunnel diodes and its dependence on the experimental parameters. We found that the contact resistance can be reduced by introducing tunnel layers between TiO2 and Al layers. This suggests that the introduction of tunnel layers can improve the contact performance of TiO2/Al diodes.

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 enabling technology in the field of nanotechnology and advanced energy technologies. ALD allows for the precise control of the composition of thin films, which is crucial for the development of new materials for applications such as solar cells and water splitting catalysts.

In this presentation, we will discuss the use of ALD to couple efficient water splitting catalysts and high-performance photovoltaics. We will focus on the development of TiO2-based materials for these applications, using ALD to tailor the properties of these materials to optimize their performance.

11:00 AM ET02.12.02
On the Passivating Contact Performance of Atomic-Layer-Deposited TiO2, for Silicon Solar Cells
Jimmy Melskens1, Willem-Jan Berghuis1, Bas van de Loo2, 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 (TiOx) 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 TiOx/Al stack [Yang et al., SOLMAT 2016; Adv. Mater. 2016; PVP 2017]. However, there are still many open questions with respect to the passivating contact performance of TiOx that need to be addressed. For example, when trying to exploit the TiOx 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 [Boecard et al., IEEE PVSC 2016], contradicting simulations which indicate that this should be achievable.

We have investigated the TiOx 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)tinum (TDMAT) as ALD Ti precursor, while good results have also been reported for titanium(IV)chloride (TiCl4) [Cui et al., SOLMAT 2016].

Other experimental parameters, such as the substrate treatment prior to the TiOx deposition, TiOx 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 (Sftact = 11.6 cm/s, Rs = 10^2 Ωcm²). 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 TiOx 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 TiOx film sufficiently thin. This underscores that carefully engineering a thin TiOx 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 TiO2 Contacts
Hyanju Lee1, Changhyun Lee2, Yoonmook Kim1; 1Department of Power and Energy Systems Engineering, POSTECH, Pohang, Gyeongbuk, South Korea; 2Department of Electrical Engineering, POSTECH, Pohang, South Korea.

Recent studies have shown that TiO2/Al tunnel diodes can provide high performance as electron-selective contacts for dye-sensitized solar cells (DSSCs). The contact performance of TiO2/Al diodes is highly dependent on the experimental parameters, such as the substrate treatment prior to the TiO2 deposition, TiO2 deposition temperature, post-deposition annealing temperature, and film thickness. Another important factor is the contact resistance which is determined by the interface between TiO2 and Al layers. It has been reported that the contact resistance can be reduced by introducing tunnel layers between TiO2 and Al layers.

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Other experimental parameters, such as the substrate treatment prior to the TiOx deposition, TiOx 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 (Sftact = 11.6 cm/s, Rs = 10^2 Ωcm²). This is similar to state-of-the-art results reported in the literature [Titova et al, Energy Proc. 2017].

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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 charges and the electronic structure of tunnel layers on the performance of TiOx electron-selective contacts. During our presentation, we will discuss the experimental results and suggest ways to enhance the performance and stability of electron-selective TiOx contacts.

References

In this study, we have investigated:
1. The performance of electron-selective TiOx 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 TiOx contacts.
3. The stability of the fabricated electron-selective TiOx contacts under light illumination.

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

References
1. “Device Physics Underlying Passivating Contact Silicon Solar Cells: A Review”, R. V. Chaval1, Steffan De Wolf2, ‘Purdue University, West Lafayette, Indiana, United States; 2King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

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-Peroxvskite Solar Cells—A Device-to-System Perspective M. Ashraf Alam1, Raghu A. Chaval1 and Stefana 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-Peroxvskite 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.

References
1. “Device Physics Underlying Passivating Contact Silicon Solar Cells: A Review”, R. V. Chaval1, Steffan De Wolf2, ‘Purdue University, West Lafayette, Indiana, United States; 2King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

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, Kazutoshi 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]. A 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 (Dit) and the increase of the density of negative interface fixed charges (Qf). The reduction of Dit 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

References
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 Al2O3 from a macroscopic view, a microscopic knowledge on the passivation mechanism, which is also expected to be useful information on the properties of Al2O3/Si interfaces, is still missing.

In this study, we investigated the Al2O3/Si interfaces using scanning nonlinear dielectric microscopy (SNMD) [2] and super-higher-order SNMD (SHO-SNMD) [3]. SNMD is a kind of capacitance microscopy with a sensitivity of as high as 2×10−12 F Hz−1 and has been used in the evaluation of a number of dielectric and semiconductor materials. SHO-SNMD is an extended technique of SNMD and is capable of obtaining local C−V curves over the whole AM1.5 spectrum. This ability enables to investigate the distribution of local charges at oxide-semiconductor interfaces by analyzing the shift or the change of the local C−V curves. We demonstrate that these techniques are applicable in the evaluation of non-uniform distribution of charges at Al2O3/Si interfaces. We also show that the size of the patterns observed in SNMD and SHO-SNMD images are changed by a post deposition annealing of the Al2O3/Si samples. Moreover, the increase of the area density of negative fixed charges by the post deposition annealing was estimated by analyzing the local C−V curves obtained by SHO-SNMD.


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 Sagger3, Aqil Jamal3, Issam Gereige3 and Steafa De Wolf3; 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-face 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-V) measurements, 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 contacted 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 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, 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.

2:45 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 (MoO3) [1] and tungsten oxide (WO3) [2] have recently been investigated as carrier-selective hole contact for silicon heterojunction (SHJ) solar cells, where they could replace the n-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 WO3 with the good conductivity of indium oxide (In2O3) in InWOx alloys. Recently, we have presented investigations of InWOx 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
Passivating contacts for front and rear contacted c-Si solar cells


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, microstructural 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.

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Passivating contacts as drop-in replacement of partial rear contacts:

In the present study, we provide further insight into InWOx materials properties upon annealing of the layers up to 600 °C. We investigate the crystalline structure using X-Ray diffraction and find that InOx is fully crystallized at 250 °C, whereas WOx 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% InOx content (InOx-WOx) and another one for even lower InOx 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.


SESSION ET02.14: Silicon Devices
Session Chair: Stefano 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 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 that will differ 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

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 beyond 24%. Finally, we present nPERT module efficiency and cost roadmaps.

4:30 PM *ET02.14.03
Integration Strategies for High Temperature Passivating Contacts
Andreas Ingenier2,3,4, Gizem Nogay1, Christophe Allebé1, Josua Stuckelberger1, Philippe Wyss1, Jörg Horzel3, Florent Sahli1, Jeremie Werner1, Laura Ding1, Juan Diaz Leon1, Mario Lehmann1, Arnaud Savoy1, Santhana Eswara1, Tom Wirtz2, Sylvain Nicolay2, Quentin Jeangros1, Matthieu Despeisse1, Franz-Josef Haug1 and Christophe Ballif2,3; 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, Switzerland; 3CSEM, PV-Center, Neuchâtel, Switzerland; 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, microstructural 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 “learn” 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-SiO2(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(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(p) in a co-firing 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 HVOC values of 735mV and 746mV for the hole and electron contacts, respectively. The performance of the SiCx 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%, VOC=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 $\mu_{OC}$ 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).