

Tuesday Afternoon, November 1, 2011

Energy Frontiers Focus Topic

Room: 108 - Session EN+TF-TuA

Thin Films for Solar Cells

Moderator: C.A. Wolden, Colorado School of Mines

2:00pm EN+TF-TuA1 **Thin Film Silicon Approaches to Future Generations of PV Materials**, P.C. Taylor, Colorado School of Mines

INVITED

Silicon is a material of choice for photovoltaic (PV) applications for several reasons. First, there is perhaps more known about the properties and processing of Si than any other semiconductor due to its prominence in electronic devices. In addition, Si is a non-toxic, abundant element that is potentially inexpensive to produce in large quantities. The major problems with Si for use in future PV applications are the inefficient absorption of light due to its electronic band structure and a fundamental limit on the efficiency of any single junction bulk device due to transmission of photons below the optical band gap energy and loss of energy to heat for photons above the optical gap energy (so-called Shockly Queiser limit). Nanostructured films of Si have the potential to overcome these problems by decoupling the absorption length for photons from the collection length for carriers and by introducing additional optically excited carriers due to the quantum confinement in nanostructured films. The most promising possibilities for more efficiently exciting and collecting carriers include the production of more than one electron-hole pair per absorbed photon for photon energies greater than twice the optical gap energy, the absorption of photons of below gap energies by the introduction of an intermediate band of states within the optical energy gap due to the inclusion of quantum confined structures with the appropriate properties, and the collection of excited carriers before they lose their energy to phonons. Progress in utilizing these mechanisms for dramatically increasing the efficiencies of future PV devices based on Si will be discussed.

2:40pm EN+TF-TuA3 **On the Influence of the Amorphous Silicon Microstructure on the Crystallization Kinetics Towards Polycrystalline Silicon for Solar Cells**, M. Creatore, K. Sharma, M.C.M. van de Sanden, Eindhoven University of Technology, the Netherlands

Polycrystalline silicon (poly-Si) is considered to be a promising candidate for thin film PV, coupling the high quality crystalline Si technology with large area and low-cost manufacturing. Our initial studies [1] on poly-Si layers have shown grains extending through the whole thickness (1 μm) upon solid phase crystallization (SPC) of high growth rate plasma deposited amorphous silicon (a-Si:H) films. Furthermore, larger grains are promoted by an increase in the a-Si:H microstructure parameter R^* [2], which represents the order (low R^*)/disorder (high R^*) in the matrix according to the Si-H bond distribution in mono-/di-vacancies (–low stretching mode-LSM) and nano-sized voids (–high stretching mode-HSM), and it is quantified by the integrated IR absorption band ratio $I_{\text{HSM}}/(I_{\text{LSM}}+I_{\text{HSM}})$.

The SPC of a-Si:H follows the steps of incubation, nucleation and grain growth. With the purpose of providing insight on the crystallization process, this contribution addresses a detailed crystallization kinetic study of plasma deposited a-Si:H films by means of in-situ X-ray diffraction (XRD). a-Si:H films having R^* in the range of 0.05-0.6, with a hydrogen content of 5-14 at. %, were annealed at 600 °C.

The medium range order (MRO) of the a-Si:H layers, quantified by the XRD line-width, and representing the most ordered regions in the matrix (up to 15-25 Å from the mono-vacancies), is found to affect the incubation time (t_0), in agreement with [3]: low R^* and high MRO promote a faster nucleation (t_0 in the range of 50-100 min), since the most ordered regions act as nucleation centers; as the structural disorder increases, the MRO decreases and the incubation step is delayed up to 450 min. However, for $R^* > 0.3$ and an hydrogen content above 9%, the incubation time unexpectedly decreases. Therefore, the R^* and the MRO evolutions during the annealing step are studied. High R^* layers, characterized by hydrogen mainly bonded to nano-sized voids, are more prone to hydrogen out-diffusion upon annealing, as inferred by the quantitative decrease of the HSM mode with respect to the LSM mode. The hydrogen evolution is then followed by the rearrangement of the a-Si:H into more ordered regions, as witnessed by the increase of the MRO upon annealing, promoting a decrease in incubation time. In conclusion, next to the established role of the MRO, the nano-sized voids play also a role in the crystallization kinetics, as they affect the overall microstructure and medium range order upon annealing.

[1] Illiberi et al., *Material Letters* **2009**, 63, 1817.

[2] Sharma et al., *Advanced Energy Materials* **2011**, DOI: 10.1002/aenm.201000074

[3] Mahan et al., *Adv. Funct. Mater.* **2009**, 19, 2338.

3:00pm EN+TF-TuA4 **Deposition of Microcrystalline Silicon Thin Films by Radio Frequency PECVD using Voltage Waveform Tailoring**, S. Pouliquen, P.-A. Delattre, E.V. Johnson, J.-P. Booth, Ecole Polytechnique (Palaiseau), France

This paper shows the feasibility of depositing thin films of hydrogenated microcrystalline silicon ($\mu\text{-Si:H}$) for photovoltaic applications by radiofrequency discharge using voltage waveform tailoring. Contrary to typically used sinusoidal waveforms, the films were deposited using asymmetric voltage waveforms, resembling “peaks” and “valleys”, composed of a fundamental frequency of 15 MHz and three harmonics. Such waveforms lead to an electrical asymmetry effect in the plasma, and a different ion bombardment energy on each electrode. For these experiments, we used a gas mixture of silane diluted in hydrogen (from 1-4%), a total flow rate less than 100 sccm, and a range of pressure from 100 up to 1000 mTorr. We show that the chemical, optical and structural properties - as measured by FTIR, spectroscopic ellipsometry, Raman scattering and profilometry - are strongly determined by the shape of the voltage waveform, and therefore the ion bombardment energy. We observe this effect on the Si-Si bond configuration (microcrystalline vs amorphous peaks in Raman scattering between 480 and 520 cm^{-1}) as well as on the Si-H bond configuration (FTIR peaks at 2000-2100 cm^{-1}). We examine the strength of the effect for varying process parameters, including pressure, total gas flow, voltage amplitude, and SiH_4/H_2 dilution ratio. For the range of parameters used, a growth rate for highly microcrystalline silicon of up to 3 Å/s was achieved without exceeding a pressure of 100 mTorr.

4:00pm EN+TF-TuA7 **Amorphous and Nanocrystalline Silicon Thin Film Photovoltaic Technology on Flexible Substrates**, B. Yan, A. Banerjee, J. Yang, S. Guha, United Solar Ovonic LLC

INVITED

Because of the rapid increase of energy demand and growing concern of environmental impact, renewable energy from photovoltaic (PV) has gained a great deal of attention in the last decade. Various PV technologies have been developed. However, solar panels using conventional crystalline silicon have dominated the market. Thin film silicon is one of the so-called second generation PV technologies. Nowadays, majority of thin film silicon PV products are made with hydrogenated amorphous silicon (a-Si:H) and amorphous silicon germanium (a-SiGe:H) alloy. The advantages of a-Si:H based technology are low cost, capability of large scale manufacturing, abundance of raw materials, and no environmental concerns. One disadvantage of a-Si:H PV technology is its lower efficiency than solar panels made of crystal silicon and compound crystal thin film semiconductors. To resolve the low efficiency issue, significant effort has been made by the researchers. In order to use the solar spectrum effectively, multi-junction structures are normally used by incorporating a-SiGe:H in the bottom cell. In recent years, hydrogenated nano-crystalline silicon (nc-Si:H) has been used as a potential replacement of a-SiGe:H bottom cell in multi-junction structures. The pros of nc-Si:H are its stability under sun light, high photocurrent capability, and no Ge-containing gases required in the process; the cons are thick intrinsic layer that needs high rate deposition and technical challenges for large-area deposition. United Solar has been heavily involved in research and development of a-Si:H and nc-Si:H based PV technology. We have made significant progress in efficiency improvements of a-Si:H and nc-Si:H multi-junction solar cells and modules. We have achieved (i) a 15.4% initial active-area ($\sim 0.25 \text{ cm}^2$) solar cell efficiency, (ii) an NREL measured stable total area ($\sim 0.25 \text{ cm}^2$) efficiency of 12.5%, and (iii) NREL measured initial and stable module ($\sim 400 \text{ cm}^2$) efficiencies of 12.0% and 11.4%, which all set new record efficiencies achieved by a-Si:H, a-SiGe:H, and nc-Si:H multi-junction cell structures. Based on these achievements, we have started working on the development of roll-to-roll manufacturing technology for a-Si:H and nc-Si:H multi-junction structures on flexible substrates. We expect to launch 12% stable aperture area a-Si:H and nc-Si:H product in 2012. In this presentation, we will review the progress made by the community and challenges a-Si:H and nc-Si:H PV technology face.

4:40pm EN+TF-TuA9 **High Efficiency, Large Area Silicon Thin Film Solar Modules**, L. Li, T. Guo, Y. Meng, Z. Xu, F. Dai, F. Zhang, W. Li, Z. Lei, C. Cai, H. Li, B. Tang, D. Zhou, ENN Solar Energy Co. Ltd.

INVITED

Hydrogenated amorphous and microcrystalline silicon based thin film solar cells have long shown great potential for various photovoltaic applications due to its better electricity generation under low light and high temperature, shorter energy payback time and greener manufacturing processes, as well as unique applications for BIPV. However, this technology hasn't fully

realized its market potential, as low module efficiencies at mass-production level being one of the major limiting factors. In this paper we report over 9% stabilized module efficiencies in volume production achieved on 5.7 m² substrates from a-Si:H/uc-Si:H tandem junction solar modules, which reflects significant efficiency improvement by process tuning of silicon thin films, back contact, and device structure, etc.. Several application case studies are also reported which demonstrate excellent field performance of ENN silicon thin film solar modules.

5:20pm **EN+TF-TuA11 Metal-Modulated Epitaxy Growth of InGaN/GaN p-i-n Solar Cells**, *B. Gunning, M.W. Moseley, J.E. Lowder, W.A. Doolittle*, Georgia Institute of Technology, *J. Wierer, S. Lee, D. Koleske, Q. Li*, Sandia National Laboratories

InGaN alloys have great potential in the field of photovoltaics due to their excellent light absorption and tunable bandgap (0.7-3.4eV) which spans the visible spectrum. However, the growth of this material remains a challenge due to thermal decomposition, indium surface segregation, and phase separation. To combat these issues, low substrate temperatures and high growth rates must be implemented in combination with in situ surface monitoring via RHEED. Metal modulated epitaxy (MME) has been shown to achieve single-phase InGaN alloys throughout the miscibility gap with sub-nm RMS roughness.

In this study, MME is applied to the growth of n-GaN/i-InGaN/p-GaN solar cells. Unintentionally doped InGaN layers 50/200nm thick with 16% In composition are grown on a 3 μ m n-type GaN template. The topmost layer consists of p-type GaN with varying hole concentrations. Transient RHEED signals are monitored closely during InGaN growth to prevent indium surface segregation and ensure a smooth film.

The absorption characteristics are determined as shown in Figure 1, and the material is characterized via AFM, XRD and PL prior to being fabricated into device structures. The InGaN layers are found to be approximately 80% strain relaxed as determined by XRD analysis of the (20-25) reflection (Figure 2). During device testing, the solar cells exhibit low turn-on voltages below the expected value, as well as low external quantum efficiency. These inconsistencies indicate carrier loss due to electrical shorts and defects. The scanning TEM images in Figure 3 show striations in the InGaN layer similar to those in a superlattice structure but with a period that does not correspond to the shutter cycles. Even though the x-ray diffraction indicates predominantly relaxed epitaxy, TEM images are unable to resolve individual threading dislocations. It is not clear at present if this is indicative of extremely large dislocation density or a new method of relaxation related to the above mentioned striations. Finally, post-growth annealing processes are explored as possible ways to improve device performance.

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