Project 06

Scientific Progress - Fall 2009 to 2014

Polymer/Nanostructured Silicon Heterojunction Solar Cells

Background

Silicon is non-toxic, the second most abundant element in the earth's crust, and the bandgap of 1.12 eV is a reasonably good match to the solar spectrum [1]. The main PV technologies competing with silicon (CdTe and CIGS) for unconcentrated sunlight applications use scarce and toxic elements. It is therefore hardly surprising that silicon has always been the most widely used material for photovoltaics, and today accounts for over 75% of the terrestrial PV market. However, in the vast majority of silicon solar cells produced today most of the silicon serves only as a structural support. This is true in both conventional monocrystalline cells and cast large-grain multicrystalline material. Using ultra-pure silicon as a structural support is extremely wasteful not only in terms of dollar cost, but also in terms of the energy required to produce the material. In consequence the energy payback time of conventional silicon cells at mid-latitudes is estimated at between two and five years [2,3]. When coal-fired electricity is used to provide the energy for silicon production there is significant pollution and greenhouse gas generation associated with the use of PV [3]. Over an estimated 30-year lifetime for a conventional silicon PV installation there is still a net environmental benefit to the use of PV, but this benefit is not as great as might be expected or hoped for. This argues strongly for the development of a thin-film silicon PV technology in which a relatively thin electronically active silicon film is deployed on a low-cost (both in terms of dollars and energy payback) structural support.

Electronically silicon is an indirect gap material, so compared to competing direct-gap semiconductors such as CdTe relatively thick films are required to effectively absorb incident sunlight. This has lead to interest in modifying the silicon electron energy band structure to provide a direct gap. Simultaneously raising the bandgap closer to the Schockley-Queisser optimum of 1.4 eV [1] is highly desirable. The introduction of hydrogenated amorphous silicon (aSi:H) as a photovoltaic material in the 1970's could be viewed as an early and simple approach to band structure modification. aSi:H has proven to be quite successful both technologically and commercially. For example prior to its bankruptcy in 2012 United Solar was reporting AM1.5 efficiencies up to 13% in commercial triple-junction aSi:H based thin-film cells. However, despite decades of research, aSi:H is still limited by Stabler-Wronski degradation [4]. This leads one to speculate whether the advantages of aSi:H could be obtained through nanostructuring of a crystalline Si film, modifying the band structure through simple electron quantum confinement. Attempting to answer this question was the motivation for this network project.

To obtain bandgap modification through quantum confinement, it is necessary to nanostructure Si films on a distance scale comparable to the electron mean-free path, or roughly 10 nm. Producing thin-film Si with nanostructuring on this scale is a difficult undertaking. At the time this project was proposed one of the most promising techniques for forming nanostructured thin films was the Glancing Angle Deposition (GLAD) approach pioneered by the Brett group at the University of Alberta [5]. In early discussions leading to the formulation of this project M. Brett noted that GLAD could not directly

produce Si films with nanostructuring on the 10 nm scale. He instead proposed use of a technique that his group was at that time developing in which GLAD was used to produce SiO_2 columns that in turn could be coated with LPCVD silicon [6].

It should be noted that even without band structure modification the thickness of silicon required to make a useful solar cell is still quite small. At the wavelength at which the power density in the AM1.5 spectrum peaks (≈500 nm) the 1/e absorption depth in crystalline silicon is just 1 μm. Compared to an infinitely thick slab, a 10 μm thick layer of crystalline silicon absorbs approximately 80% of AM1.5 sunlight with photon energies greater than the bandgap. This reveals that even in the absence of band structure modification development of enhanced light-trapping and surface junction formation techniques in nanostructured material could produce viable thin-film Si solar cells. Light trapping also reduces the requirements on minority carrier lifetime in the film, since optical absorption will take place in or near the depletion region. For this reason a strong emphasis was placed on investigating the light-trapping properties of materials developed in this project.

Producing a complete photovoltaic device on a nanostructured silicon film requires a means of forming a rectifying junction that can be applied over very rough topographies and at temperatures low enough to avoid damage to the film. We proposed to investigate the use of conductive polymers, particularly poly(3,4-ethelenedioxythiophene) (PEDOT), for this application. These materials can offer high optical transparency and high conductivity and can be deposited at low pressure from the vapour phase, allowing penetration of nanostructured porous substrates. At the time of the proposal very little was know regarding the properties of electronic heterojunctions formed between PEDOT and silicon, so a full fundamental study of these junctions was required. Similarly it was necessary to develop suitable techniques for low pressure vapour phase polymerization (LVPP) deposition of PEDOT.

Development of Nanostructured Substrates

In the first year of the project the Alberta group demonstrated impressive results on the formation of silicon nanotubes with ultra-thin walls using LPCVD silicon coating of SiO_2 nanopost templates formed by GLAD [6]. Fig. 1 shows a TEM image of such a structure. Although the Si flm was deposited in the amorphous phase, it was shown that the structure could survive a crystallization anneal at 600 C. This crystallization is essential to avoid the well-known electronic problems associated with amorphous films.

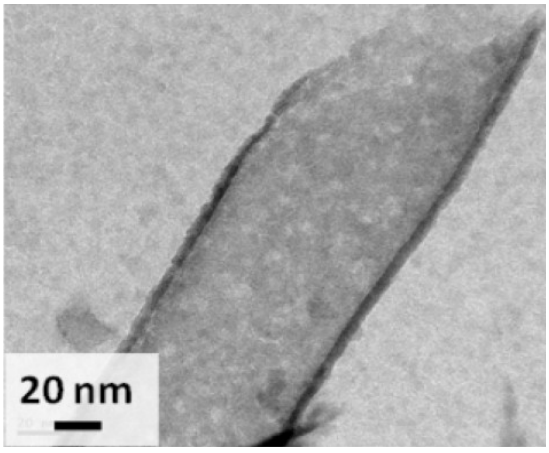

Fig. 1 TEM image of silicon nanotube with ≈6 nm wall thickness.

Use of an insulator such as SiO_2 as a templated substrate for nanostructured Si growth raises

obvious questions as to how current is to be extracted in a solar cell. For this reason the Alberta group focussed on developing GLAD techniques to form conductive nanostructured materials and templates. Although considerable effort was put into the growth of nanostructured Si over the course of this project, conditions to produce films with the feature sizes required for band structure modification were not identified. Attention then turned to the formation of nanostructured templates in the transparent conductor ITO. A new deposition technique, vapour-liquid-solid (VLS) GLAD was developed by PhD student A. Beaudry to produce crystalline ITO "nanotrees" [J12]. Results are illustrated in Fig. 2.

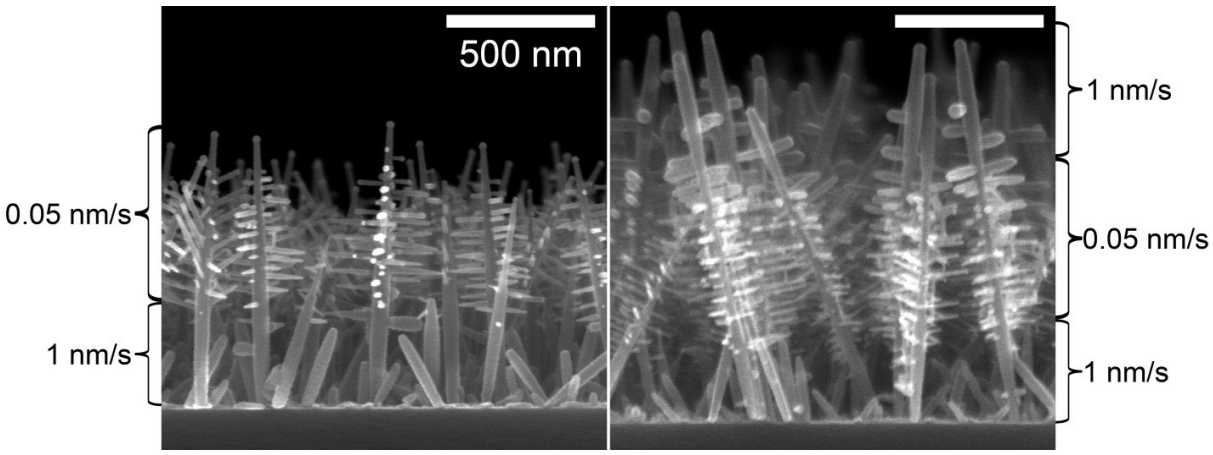

Fig. 2 Indium tin oxide trunks and branches grown by GLAD-moderated VLS. Branching is controlled by the deposition rate (relative to spin speed) indicated on the figure.

With partners NRC-NINT,and Micralyne, a U.S. patent application was filed for the nanotree process, and is now under evaluation [P1].

PhD students Tucker and LaForge developed the ability to precisely control trunk and branch geometries of "nanotree" ITO structures [J6, J8]. This work was featured on the cover of the *Applied Physics Letters* 50th anniversary edition (Fig. 3).

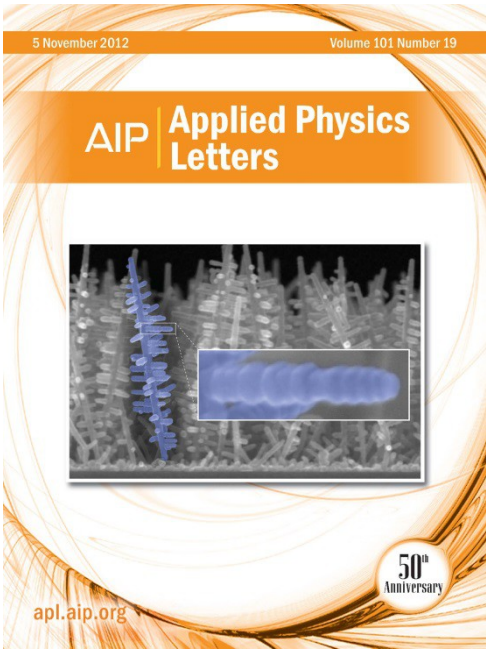

Fig. 3 *Applied Physics Letters* 50th anniversary cover

ITO nanotree substrates are broadly applicable to both inorganic and organic PV applications. For this reason the Alberta group devoted some effort to the side issue of incorporating the nanotrees in orgnaic solar cells. C60/polythiophene organic solar cells based on the ITO nanotrees showed performance improvement relative to planar C60 devices [J14].

Attention was also given to characterization of the electrical properties of the nanotrees. In paticular A. Lalany has developed techniques for characterizing the axial conductivity of nanoposts, using the cross-bridge Kelvin resistor layout shown in Fig. 4 [J5].

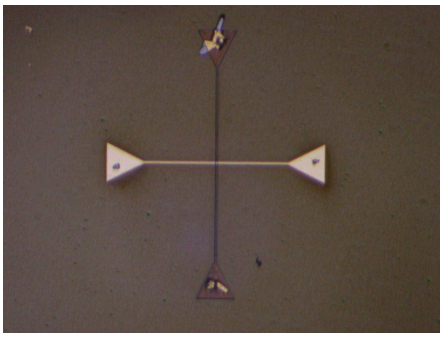

Fig. 4 SEM of Cross-Bridge Kelvin Resistor geometry used to measure through-post conductivity.

Fundamental Studies of the PEDOT/Si Heterojunction

At Carleton PhD student S. Demtchenko has undertaken a comprehensive study of the heterojunction formed between PEDOT and crystalline nSi [C32]. The study has included the introduction of ultrathin thermally-grown SiO_2 "tunnel oxides" between the conductive polymer and the silicon to control carrier flow. Typically the oxide has been grown at 500°C. The C-V characteristics of these junctions reveal barrier heights high enough to produce surface inversion of n-type material. Junction reverse leakage current density is comparable to that of *pn* junction diodes (<1 $nAcm^{-2}$). The devices show comparable performance to *pn*-junction photodiodes but with extremely low thermal budget for formation. They may therefore be of interest for post-processing integration of photodiodes with other silicon devices. We have also constructed lateral bipolar transistors using PEDOT emitters surrounded by PEDOT collectors, and have used these devices to demonstrate minority carrier injection from the PEDOT. We believe this to be the first direct evidence for minority carrier dominated current flows in PEDOT junction devices. A deep-level transient spectroscopy (DLTS) system was set up band used to to investigate carrier trapping at the interface. It was found that the electronic "band structure" of the PEDOT:PSS in this system is much more complicated than that of a simple metal, and must be taken into account to optimize the junction for photovoltaic applications. This has led to creation of a numerical model for carrier transport in the PEDOT:PSS/SiO_2/Si junction to guide future device design [C4].

Light Trapping in Nanostructured Substrates

At the start of her PhD studies S. Demtchenko completed comprehensive modelling of the optical properties of GLAD Si films in collaboration with M. Taschuk at Alberta. The reflectance of these films has been modelled as a function of wavelength for different film structures, and the results compared to experiment. *More detail needed here*

Later in the project Carleton MASc student K. Wang deposited ultra-thin (nominally 4 and 8 nm) Si films by LPCVD on ITO "nanotree" templated substrates provided by the Alberta group. Although duplicate LPCVD deposition conditions (same tube pressure, temperature and flow rate) were established at Carleton as had been used at Alberta, film morphology was radically different, with much thicker Si deposits at the top of the trees than the base. The dependence of the absorption coefficient α on wavelength was very similar to that in bulk cSi, with α showing a long "tail" extending out to about 1100 nm, corresponding to a bandgap near 1.1 eV. There is therefore no evidence for bandgap widening in the nanostructured material. This result was unexpected in view of the thickness of the Si coating. The nanostructured samples did show significant light trapping, with absorption of about 50% of incident light at 500 nm. This is considerably higher absorption than would be expected for a planar film 400nm thick (the approximate height of the nanotree "forest"), and all the more impressive considering that most of the "forest" is empty space. The Si-coated ITO nanoforest approach has therefore demonstrated strong light trapping, providing very efficient use of a small amount of silicon in creating an absorbing layer.

Vacuum Deposition of Conductive Polymers

The studies of PEDOT/Si heterojunctions described above were done primarily on devices produced using simple spin casting of commercial PEDOT:PSS, with a few side experiments using liquid phase *in-situ* polymerization of PEDOT. Formation of heterojunctions on nanostructured silicon requires vapour phase deposition of the polymer to create a conformal coating. To this end MASc student Scott Ferguson has designed, constructed and is now testing a vapor-phase deposition system for conductive polymers (Fig. 5). The system includes novel thermoelectrically controlled vapour sources for the monomers and catalysts along with thermal control hardware and software.

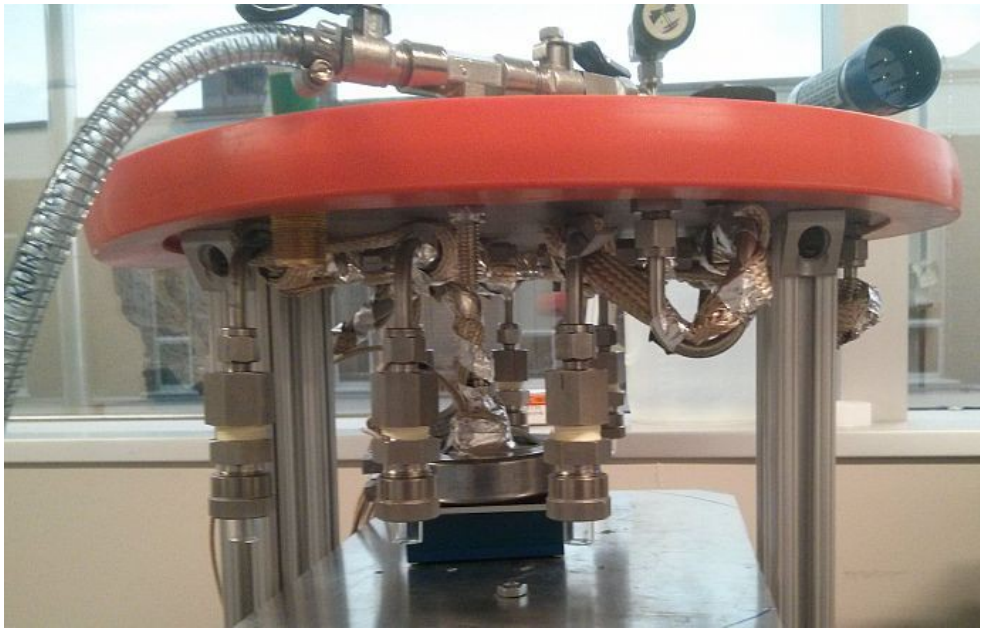

Fig. 5 System for vapour-phase deposition of conductive polymers

Future Work

While this project was underway, S. McGarry and collaborators at Carleton successfully applied for CFI funding to construct a new facility for advanced research on sensors and interfaces. This facility includes a new PicoSun atomic layer deposition (ALD) system. ALD is used extensively in the CMOS industry to produce ultra-thin gate dielectrics, and offers great potential to form tunnel barriers of precisely controlled thickness and electronic properties in polymer/silicon heterojunctions. Carleton MSc student Goran Bacic (jointly supervised with Carleton's Chemistry Department) has begun research on the use of ALD alumina and other potential metal oxide barriers in this application. In the longer term (beyond the scope of this project) ALD of transparent conductive oxides could provide an attractive alternative to conductive polymers in heterojunction formation for photovoltaics on nanostructured substrates.

References

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Publications Arising From Project

Journal Papers:

J1 A.L. Beaudry, J.M. LaForge, R.T Tucker, J.B. Sorge, N.L. Adamski, P. Li, M.T. Taschuk and M.J. Brett, "Directed Branch Growth in Aligned Nanowire Arrays", *Nano Letters* **14**, p 1797-1803, April 9, 2014.

J2 M.T. Taschuk, R.T. Tucker, J.M. LaForge, A.L. Beaudry, M.R. Kupsta and M.J. Brett, "Towards engineered branch placement: Unreal™ match between vapour-liquid-solid glancing angle deposition nanowire growth and simulation", *J. Appl. Phys*. **114**, 244304/1-10 (2013).

J3 J.M. LaForge, T.L. Cocker, A.L. Beaudry, K. Cui, R.T. Tucker, M.T. Taschuk, F.A. Hegmann and M.J. Brett, "Conductivity control of as-grown branched indium tin oxide nanowire networks", *Nanotechnology* **23**, 035701/1- 9 (2013).

J4 J.M. LaForge, B. Gyenes, S. Xu, L.K. Haynes, L.V. Titova, F.A. Hegmann and M.J. Brett, "Tuning iron pyrite thin film microstructure by sulfurization of columnar iron precursors", *Solar Energy Materials and Solar Cells*, **117**, 306-314 (2013).

J5 A. Lalany, R. Tucker, M. Taschuk, M. Fleischauer, and M. Brett, "Axial resistivity measurement of a nanopillar ensemble using a cross-bridge Kelvin architecture", *J. Vac. Sci. and Tech.* **A 31**(3), 031502/1-6 (Mar 2013)

J6 A.L. Beaudry, J.M. LaForge, R.T. Tucker, P. Li, M.T. Taschuk and M.J. Brett, "Flux engineering for indium tin oxide nanotree crystal alignment and height-dependent branch orientation", *Crystal Growth and Design* **13**(1), 212-219 (2013).

J7 R.T. Tucker, N.A. Beckers, M.D. Fleischauer and M.J. Brett, "Electron beam deposited Nb-doped TiO_2 toward nanostructured transparent conductive thin films", *Thin Solid Films* **525**, 28-34 (2012).

J8 R.T. Tucker, A.L. Beaudry, J.M. LaForge, M.T. Taschuk and M.J. Brett, "A little ribbing: flux starvation engineering for rippled ITO nanotree branches", *Appl. Phys. Lett.* **101**(19), 193101/1-4 (2012).

J9 M. Thomas, W. Li, Z.S. Bo and M.J. Brett, "Inverted photovoltaic cells of nanocolumnar C60 filled with solution processed small molecule 3-Q", *Organic Electronics* **13**(11), 2647–2652 (2012).

J10 J.G. Van Dijken and M.J. Brett, "Dry etching of copper phthalocyanine thin films: effects on morphology and surface stoichiometry", *Molecules* **17**(9), 10119-10130 (2012).

J11 J.G. Van Dijken and M.J. Brett, "Nanopillar ITO electrodes via argon plasma etching", *J. Vac. Sci. Tech. A* **30** (4), 040606/1-5 (2012).

J12 A. Beaudry, R T Tucker, J M LaForge, M T Taschuk and M J Brett, "Indium tin oxide nanowhisker morphology control by vapour–liquid–solid glancing angle deposition", *Nanotechnology* **23**, 105608 (2012).

J13 J.G. Van Dijken, M.D. Fleischauer and M.J. Brett, "Solvent effects on ZnPc thin films and their role in fabrication of nanostructured organic solar cells", *Organic Electronics*, **12**(12), 2111-2119 (2011).

J14 M. Thomas, B.J. Worfolk, D.A. Rider, M.T. Taschuk, J.M. Buriak, M.J. Brett, "C60 fullerene nanocolumns - polythiophene heterojunctions for inverted organic photovoltaic cells", *ACS Applied Materials and Interfaces*, **3**(6), 1887-1894 (2011)

J15 D.A. Rider, B.J. Worfolk, K.D. Harris, A. Lalany, K. Shahbazi, M.D. Fleischauer, M.J. Brett and J.M. Buriak, "Stable inverted polymer/fullerene solar cells using a cationic polythiophene-modified PEDOT:PSS cathodic interface", *Advanced Functional Materials*, **20**(15), 2404–2415 (2010).

J16 N.J. Gerein, M.D. Fleischauer and M.J. Brett, "Effect of TiO_2 film porosity and thermal processing on TiO_2-P3HT hybrid materials and photovoltaic device performance", *Solar Energy Materials and Solar Cells*, **94**(12), 2343-2350 (Dec 2010).

J17 J.G. Van Dijken, M.D. Fleischauer and M.J. Brett, “Controlled nanostructuring of CuPc thin films via glancing angle deposition for idealized organic photovoltaic architectures”, *Journal of Materials Chemistry* **21**, 1013-1019 (Jan 2011).

J18 M. Thomas, B. Worfolk, D.A. Rider, M.T. Taschuk, J.M. Buriak, M.J. Brett, “C60 Fullerene Nanocolumns - Polythiophene Heterojunctions for Inverted Organic Photovoltaic Cells”, *ACS Applied Materials and Interfaces* **3**, n 6, p 1887-1894, June 22, 2011.

Patents:

P1 R.T. Tucker, A.L. Beaudry, J.M. LaForge, M.T. Taschuk, and M.J. Brett. “Branched Nanowires”, United States Patent Application, USSN 14-092720, Nov 27, 2013. Patent Pending.

P2 M. Brett, J. Buriak, M. Fleischauer, N. Gerein, K. Harris, S. McClure, D. Rider, “Photovoltaic Device Based on Conformal Coating of Columnar Structures”: U.S. Patent Application Serial No. 12/370,429, International Patent Application Serial No. PCT/CA2009/000132, Canadian Patent Application Serial No. 2,713,910, European Patent Application Serial No. 09709521.0

Conference Presentations:

C1. A.L. Beaudry, J.M. LaForge, T.L. Cocker, R.T. Tucker, M.T. Taschuk, F.A. Hegmann, and M.J. Brett, (2013) "Flux engineering for 3D ITO nanowire network transparent electrodes" (oral). Society of Vacuum Coaters TechCon 2014, Chicago, IL, May 3 – 8, 2014.

C2. R.T. Tucker, S. Elmallah, M.T. Taschuk, A.L. Beaudry, J.M. LaForge, S. Garner, P. Cimo, and M.J. Brett, (2013) " Robust indium tin oxide nanowire networks on flexible Corning® WillowTM Glass" (oral). FlexTech 2014, Phoenix, AZ, Feb 3 – 6, 2014.

C3. R.T. Tucker, A.L. Beaudry, J.M. LaForge, M.T. Taschuk, and M.J. Brett, (2013) " Nanowires via flux engineering: encoding rippled branches" (poster). Nanowires 2013, Rehovot, Israel, Nov 12 – 15, 2013.

C4. S. Demtchenko, S. McGarry and N.G. Tarr, “Effects of non-idealities of the organic conductor on the electrical characteristics of PEDOT: PSS/SiO2/Si Schottky junctions”, presented at MRS Fall meeting, Boston, October 2013

C5. A.L. Beaudry, J.M. LaForge, R.T. Tucker, P. Li, M.T. Taschuk, and M.J. Brett, (2013) "Branch placement and competitive crystal alignment in nanotree arrays" (oral). 5th International Conference on One Dimensional Nanomaterials, Annecy, France, Sept 23 – 26, 2013.

C6. A.L. Beaudry, J.M. LaForge, R.T. Tucker, P. Li, M.T. Taschuk, and M.J. Brett, (2013) "Engineered three-dimensional indium tin oxide nanotree transparent electrodes" (poster). 28th European PV Solar Energy Conference and Exhibition, Paris, France, Sept 30 – Oct 4, 2013.

C7. M. Kupsta, P. Li, A. Beaudry, J. LaForge, R.Tucker, M. Taschuk, and M. Brett, (2013) “Combining focused ion beam microscopy and transmission electron microscopy (TEM) for quantitative analysis of indium tin oxide nanotrees using tomography” (oral). 40th Microscopical Society of Canada Annual Meeting, Victoria, BC Canada, June 19 – 21, 2013.

C8. A.L. Beaudry, J.M. LaForge, R.T. Tucker, P. Li, M.T. Taschuk, and M.J. Brett, (2013) "Flux engineering for height dependent nanotree morphological control " (poster). Materials Research Society Spring Meeting, San Francisco, CA USA, Apr 1 - 5, 2013.

C9. R.T. Tucker, A.L. Beaudry, J.M. LaForge, B.J. Worfolk, M.T. Taschuk, J.M. Buriak, and M.J. Brett, "Engineered branched ITO nanowires for 3D OPV electrodes" (poster). Materials Research Society Spring Meeting, San Francisco, CA USA, Apr 1 - 5, 2013.

C10 B.J. Worfolk, J.M. LaForge, M.J. Brett and J.M. Buriak, "Nanostructure and surface energy control of iron pyrite thin films for photovoltaics", poster presentation at the 95th Canadian Chemistry Conference and Exhibition, Calgary, AB, Canada, May 26-30, 2012.

C11 R.T. Tucker*, D.A. Rider, J.G. Van Dijken, M. Thomas, B.J. Worfolk, A. Lalany, M.D. Fleischauer, M.T. Taschuk, K.D. Harris, J.M. Buriak and M.J. Brett, "Nanostructured organic photovoltaic architectures via glancing angle deposition", oral presentation at Next Generation Solar (Photovoltaics Canada), Montreal, QC, Canada, May 14-15, 2012.

C12 A.L. Beaudry, R.T. Tucker, J.M. LaForge, M.T. Taschuk and M.J. Brett, "Vapour liquid solid glancing angle deposition of indium tin oxide nanowhiskers", poster presentation at Next Generation Solar (Photovoltaics Canada), Montreal, QC, Canada, May 14-15, 2012. Award winning poster: Public Choice Award and Second Place Award.

C13 J.G. Van Dijken*, N.L.-Y. Wu, M.D. Fleischauer, J.M. Buriak and M.J. Brett, "Morphology control and nanoscale patterning of small molecule organic thin films", SPIE Photonics Europe 2012, Brussels, Belgium, April 16-19, 2012.

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C15 C. Soza-Cansines, N. Cranston, M. Rahman, M. Turnbull and N.G. Tarr, "Staebler-Wronski Degradation of RF Sputtered Hydrogenated Amorphous Silicon", Next Generation Solar (Photovoltaics Canada), Montreal, QC, Canada, May 14-15, 2012.

C16 J.G. Van Dijken, N.L.-Y. Wu, M.D. Fleischauer, J.M. Buriak and M.J. Brett, "Morphology control and nanoscale patterning of small molecule organic thin films", Proc. SPIE 8435, 84350R/1-8 (Jun 2012).

C17 J.G. Van Dijken, M.D. Fleischauer, M.J. Brett. "Advanced nanostructuring of metal phthalocyanines for organic photovoltaic devices," Proc. 37th IEEE Photov. Spec. Conf. (2011).

C18 R.T. Tucker, "Nanostructured electrodes: a platform technology for energy conversion", invited talk at the ACAMP Cleantech Seminar, Edmonton, AB, Canada. Mar 13, 2013.

C19 B. Gyenes, J.M. LaForge and M.J. Brett, "Nanostructured iron pyrite films for solar applications", oral presentation at the University of Alberta Undergraduate Research Symposium, Edmonton, AB. Nov 15, 2012.

C20 A.L. Beaudry, R.T. Tucker, J.M. LaForge, M. T. Taschuk and M.J. Brett. “Engineered indium tin oxide nanowhiskers via Vapour-Liquid-Solid Glancing Angle Deposition”, oral presentation at AVS 59th International Symposium & Exhibition, Tampa, FL, USA. Oct 28- Nov 2, 2012.

C21 J.M. LaForge, G. L. Ingram, M. T. Taschuk and M.J. Brett. “Flux engineering to control in-plane crystal and morphological orientation” oral presentation at AVS 59th International Symposium & Exhibition, Tampa, FL, USA. Oct 28- Nov 2, 2012.

C22 A. Lalany, R.T. Tucker, M.T. Taschuk, M.D. Fleischauer and M.J. Brett, “Through-post electrical characterization of GLAD thin film”, oral presentation at AVS 59th International Symposium & Exhibition, Tampa, FL, USA. Oct 28- Nov 2, 2012.

C23 R.T. Tucker, A.L. Beaudry, J.M. LaForge, M.T. Taschuk and M.J. Brett. “Advanced indium tin oxide nanowhisker control by Vapour-Liquid-Solid Glancing Angle Deposition”, oral presentation at European Materials Research Society Fall Meeting 2012, Warsaw, Poland. Sept 17-21, 2012.

C24 P. Li, M. Kupsta, K, Cui, M. Malac, H. Hosseinkhannazer, Y. Ning, J. LaForge, A. Beaudry and M. Brett. “Electron tomography applied to an indium tin oxide nanowhisker”, Microscopy and Microanalysis, Phoenix, AR, USA. July 29- Aug 2, 2012.

C25 B.J. Worfolk, R.T. Tucker, M. Thomas, D.A. Rider, A. Lalany, M.T. Taschuk, K.D. Harris, M.J. Brett and J.M. Buriak, “Glancing angle deposition as a fabrication technique for organic photovoltaics”, poster presentation at the 95th Canadian Chemistry Conference and Exhibition, Calgary, AB, Canada, May 26-30, 2012.

C26 J.G. Van Dijken, M.D. Fleischauer, M.J. Brett. "Advanced Nanostructuring of MetalPhthalocyanines for Organic Photovoltaic Devices," Proc. 37th IEEE Photov. Spec. Conf. (2011)., Oral presentation at Seattle, June 20, 2011

C27 M. Thomas, B.J. Worfolk, D.A. Rider, M.T. Taschuk, J.M. Buriak, and M.J. Brett, "Inverted organic photovoltaic cellsbased on Glancing Angle Deposited C60 fullerene nanocolumns", poster presentation at the 37th IEEE Photovoltaics Specialists Conference, Seattle, WA, USA, June 19-24, 2011. http://www.ieee-pvsc.org/PVSC37. Best Poster Award

C28 J.G. Van Dijken, M.D. Fleischauer, M.J. Brett, "Nanostructured metal phthalocyanines for organic solar cells", oral presentation at Photonics North 2011, Ottawa, ON, Canada, May 16-18, 2011.

C29 A. Amos-Binks, B. Nemeth, S. Demtchenko, S.P. McGarry and N.G. Tarr, “RF Sputtered aSi:H Solar Cells with Conductive Polymer Emitters”, oral presentation at Photonics North 2011, Ottawa, ON, Canada, May 16-18, 2011

C30 M. Thomas, B.J. Worfolk, D.A. Rider, M.T. Taschuk, J.M. Buriak, M.J. Brett, "Engineered morphologies for inverted organic photovoltaic cells: Glancing Angle Deposited C60 fullerene nanocolumns", oral presentation at Photonics North 2011, Ottawa, ON, Canada, May 16-18, 2011

C31 B.J. Worfolk, D.A. Rider, R.T. Tucker, J.A.M. Fordyce, M.D. Fleischauer, K.D. Harris, M.J. Brett and J.M. Buriak, “Assembly of semiconductor nanorod/polymer nanocomposite multilayer films for photovoltaics”, 93rd Canadian Society for Chemistry Conference and Exhibition, Toronto, ON,

Canada, May 29 - June 2 , 2010.

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