Natural Resources Canada Ressources naturelles Canada

CanmetENERGY

Leadership in ecoInnovation

OVERVIEW OF PHOTOVOLTAIC SOLAR CELL R&D CAPABILITY IN CANADA Ed. 3 (2007-2009)

Canada

OVERVIEW OF PHOTOVOLTAIC SOLAR CELL R&D CAPABILITY IN CANADA Ed. 3 (2007-2009)

Prepared by:

Dr. Y. Poissant & Dr. A.C. Vikis

April 2010

CITATION

Poissant, Y., Vikis, A. C., Overview of Photovoltaic Solar Cell R&D Capability in Canada, report # 2010-056 (RP-TEC), CanmetENERGY, Natural Resources Canada, April 2010, 10 pp.

DISCLAIMER

ACKNOWLEDGEMENTS

The preparation of this report was funded by Natural Resources Canada through the Program on Energy Research and Development.

TABLE OF CONTENT

Executive Summary

The Integration of Renewable and Distributed Energy Resources Program is managed by the Department of Natural Resources Canada's (NRCan), CanmetENERGY located at Varennes, Quebec. Since 2004, CanmetENERGY monitors the activities of Canadian universities in the field of photovoltaic solar cell R&D. This report is the third of a series of reviews [1,2] of the R&D capability in Canadian universities in the field of photovoltaic solar cells. The objective of these reviews is to highlight the activities done in this area in Canada, monitor the R,D&D investments and facilitate the creation of partnerships amongst the researchers, government, and industry.

Spurred by increasing emphasis on renewable energy development programs, both overall funding and staffing continued to increase relative to previous years. During the period under review (FY07/08 and FY08/09) Canadian capability was for the most part funded by NSERC at a level of about $5 million per annum and was involved in a broad range of basic research (organic solar cells, dye sensitized solar cells, thin silicon devices, etc.). An analysis of leading universities in Canada shows about 200-250 full-time equivalent staff in various science (chemistry, physics, materials science) and engineering (physics, chemical, electrical, computer, information technology, etc.) disciplines were involved in photovoltaic solar cell research and development. Relative to prior reviews, a larger fraction of the groups surveyed reported working in collaboration with a national or international manufacturing partner. Based on the current review, Canadian university capability to support research, development and implementation of photovoltaic solar cells in Canada is ample and diverse; also, as evidenced by the kind of research and the volume and quality of publications, the research is forefront and world-class.

The recent establishment by NSERC of the Photovoltaics Innovation Network championed by McMaster University in collaboration with 13 universities is a major boost to university R&D on photovoltaic devices, and eventually photovoltaic technology development in Canada. The new Network will undoubtedly improve the level of collaboration with industry partners with the objective of reducing the production cost of PV technologies.

Background

Photovoltaic (PV) technology for generating electricity presently amounts to a total global installed capacity of 13.4 GW in 2008 and is expected to surpass 1000 gigawatts of installed power by 2030, making it a significant component of the future distributed generation network [5]. In Canada, the domestic market growth has been averaging about 26% since 1993 and about 36% since 2000 ,amounting to a total installed capacity of 32.7 MW in 2008 [3]. In 2008, the Province of Ontario's Renewable Energy Standard Offer Program (RESOP), offering 42.0 cents/kWh for PV generated electricity, exceeded all expectations – achieving in excess of 525 MW of contracted PV projects and surpassing the ten year target for renewable energy in the first year.

Today, the main drawback of PV is its relatively high cost compared to electricity generated from conventional fossil fuels or hydro-power generation (PV electricity prices can range from 30 to 60 cents/kWh), mainly because of solar cell production costs. However, PV module prices are coming down at a rate of about 10% per annum [4] due to investments in technology improvements and plant automation, and there is an expectation that the trend will continue further with continued research, development and demonstration (R,D&D). This high potential in market growth is spurring worldwide investments in PV R,D&D, making it one of the highest recipients of renewable energy technology investments. Public funding of PV R&D,D in IEA PVPS countries amounted to 425 million $US in 2008, a 30% increase relative to 2007 [5]. In Canada, public funding of PV R,D&D in 2008 amounted to 7.5 million $Cdn [3]. If Canada is to benefit from this market growth, as well as remain competitive, significant investments in technology development and manufacturing will be required in order to bring down further the costs of PV.

In Canada, the Natural Science and Engineering Research Council of Canada (NSERC) and various provincial R&D funding programs targeting sustainable energy development are the main funding sources for material and solar cell research in the 21 universities included in this report. In addition, R&D supporting photovoltaics technology development is also being done at the National Research Council of Canada (NRC) Institute for Microstructural Sciences (IMS), and as noted below Sustainable Development Technology Canada (SDTC) in collaboration with NRC and several Canadian PV companies are investing in both the development and promotion of solar PV power systems in Canada.

Canadian University Capability in Photovoltaic Solar Cell R&D

This document is an update of a previous review carried out in 2007 [1,2] with a special emphasis on R&D capability of Canadian universities in the field of photovoltaic solar cells for the period covering April 2007 to March 2009. This update is based on information provided by researchers and the main R&D funding agencies, as well as information available from public sources through the internet. Basic research, carried out at Canadian universities, is summarized in Table 1 and discussed in more detail in Appendix 1.

As outlined in Table 1, Canadian university research underlying photovoltaics is carried out in about 50 university laboratories located mostly in Ontario and Quebec, and to a lesser extent in Alberta and British Columbia. The research is multidisciplinary, ranging from the most basic disciplines of Chemistry and Physics to Electrical & Computer Engineering, and covers a rather broad spectrum of forefront R&D. According to information provided by lead university scientists, about 200-250 full-time equivalent researchers (professors, postdoctoral fellows, research associates, graduate students, and technologists) are presently involved in PV solar cell R&D in Canadian universities.

Table 1. Researcher / Institution / Department / PV Area

Researcher	Institution	Department	PV Area
Adronov, Alex	McMaster University, ON	Chemistry	Carbon nanotubes in high efficiency flexible organic solar cells
Aimez, Vincent	Université de Sherbrooke, QC	Electrical Engineering and Information Technology	Characterization of nanostructures embedded in solar cell heterostructures; InP nanowires (NWRs) for photovoltaic applications
Ban, Dayan	University of Waterloo, ON	Electrical and Computer Engineering	Organic/inorganic hybrid structure) for PV devices and characterizing device performance
Barati, Mansoor	University of Toronto, ON	Chemistry	Production of solar grade silicon
Baumgartner, Thomas	University of Calgary, AB	Chemistry	Next-generation organic photovoltaics including bulk-heterojunction, as well as dye-sensitized devices
Bélanger, Daniel	Université du Québec à Montréal, QC	Chemistry	Photochemical solar cell
Bender, Timothy P.	University of Toronto, ON	Chemical Engineering and Applied Chemistry	High efficiency plastic/organic solar cells
Berlinguette, Curtis P	University of Calgary, AB	Chemistry	Dye-sensitized solar cells
Brett, Michael J.	University of Alberta, AB	Electrical and Computer Engineering	Nano-engineered thin film materials for dye sensitized cells
Brolo, Alexandre G	University of Victoria, B.C.	Chemistry	Nanostructured gold to enhance photo-conversion processes
Buriak, Jillian	University of Alberta, AB	Chemistry	Synthesis of Metal Nanoparticle Arrays of Semiconductor Surfaces and Complex Nanostructured Metals
Côté, Michel	Université de Montréal, QC	Physics	Computation of the electronic structure using ab initio methods
Demopoulos, George	McGill University, QC	Mining and Materials Engineering	Nanocrystalline Titania-based Dye Sensitized Solar Cells

Table 1. Researcher / Institution / Department / PV Area (continued)

Researcher	Institution	Department	PV Area
Ding, Zhifeng	University of Western Ontario, ON	Chemistry	Electrochemical deposition techniques to fabricate various layers of solar cells
Eichhorn, Holger S	University of Windsor, ON	Chemistry	Development of design criteria for discotic materials that function as active materials in PV devices
El Khakani, My Ali	Institut National de la Recherche Scientifique, QC	Physics	Carbon nanotubes for photovoltaic devices and their photoconversion performance
Gao, Jun	Queens University, ON	Physics	Polymer applications in light emitting devices and solar cells
Hill, Ian G.	Dalhousie University, NS	Physics	Organic photovoltaic devices and dye-sensitized solar cells
Hinzer, Karin	University of Ottawa, ON	Information Technology and Engineering	GaAs solar cells on Ge substrates, anti-reflection coatings for high efficiency solar cells
Holdcroft, Steven	Simon Fraser University, BC	Chemistry	Nanoarchitectures that improve solar cell efficiency
Hotchandani, Surat	Université du Québec à Trois-Rivières, QC	Chemistry	Performance of dye-sensitized solar cells
Izquierdo, Ricardo	Université du Québec à Montréal, QC	Information Technology	Fabrication of organic solar cells using new technologies; carbon nanotubes for the fabrication of flexible transparent electrodes
Kherani, Nazir P.	University of Toronto, ON	Electrical and Computer Engineering and Materials Science	Silicon photovoltaics, thin film nanocrystalline-amorphous silicon-carbon materials and devices
Kitai, Adrian	McMaster University, ON	Materials Science and Engineering Physics	Electro-optical properties of matter (Organic and Crystalline Silicon)
Kleiman, Rafael N.	McMaster University, ON	Engineering Physics	Crystalline Silicon-based PV
LaPierre, Ray	McMaster University, ON	Engineering Physics	Development of semiconductor nanowires for solar cells
Leclerc, Mario	Université Laval, QC	Chemistry	New organic materials (polycarbazoles, polyindolo-carbazoles) in PV cells
Lu, Z.H	University of Toronto, ON	Material Science and Engineering	High efficiency heterojunction solar cells
Marsan, Benoît	Université du Québec à Montréal, QC	Chemistry	Electrochemical PV cells
Mascher, Peter	McMaster University, ON	Engineering Physics	Defect spectroscopy in electronic materials; Plasma deposition of thin films; optical & structural characterization of luminescent Si-nanocluster systems
Mi, Zetian	McGill University, QC	Physics	Novel InGaN nanoscale materials and development of low cost solar cells on a Si platform
Morin, Jean-Francois	Laval University, QC	Chemistry	Synthesis & electrochemical characterization of new C60 derivatives for organic electronic application
Nunzi, Jean-Michel	Queens University, ON	Chemistry	Nanostructured organic and polymer solar cells: incorporation of carbon nanotubes, metal nanoparticles and charge transport in nanostructured polymers.
O'Leary, Stephen	University of British Columbia, B.C.	Engineering	Amorphous silicon
Ozin, Geoff	University of Toronto, ON	Chemistry	Photonic crystal solar cells (enhanced efficiency silicon, up-conversion silicon and dye sensitized

Table 1. Researcher / Institution / Department / PV Area (continued)

Researcher	Institution	Department	PV Area
Pearce, Joshua M.	Queens University, ON	Mechanical Engineering	Research to optimize amorphous a-Si:H and InGaN solar cells
Perepichka, Dimitri	McGill University, QC	Chemistry	Synthesis of organic semiconductors and dyes and studies of up-converting nanoparticles for NIR energy harvesting
Pulfrey, David	University of British Columbia, BC	Electrical and Computer Engineering	CdTe tandem cells, graphene/silicon solar cells
Rochefort, Alain	École Polytechnique de Montréal, QC	Engineering Physics	Theoretical calculations on organic PV materials
Ross, Guy	Institut national de la recherche scientifique, QC	Energy and Materials	Synthesis of Si and Ge nanocrystals
Ruda, Harry E.	University of Toronto, ON	Materials Science and Engineering	Crystalline silicon and tandem multijunction solar cells
Santato, Clara	École Polytechnique de Montréal, QC	Engineering Physics	Efficiency of organic PV cell with rare earth-doped nanoparticles Organic/Polymers)
Sargent, Edward H	University of Toronto, ON	Electrical and Computer Engineering	PV cells based on colloidal quantum dots processed from the solution phase
Sazonov, Andrei	University of Waterloo, ON	Electrical and Computer Engineering	Amorphous and nanocrystalline) thin film devices
Scholes, Gregory D.	University of Toronto, ON	Chemistry	Flexible three-dimensional solar cell technologies using quantum dots
Shih, Ishiang	McGill University, QC	Electrical and Computer Engineering	Growth of monocrystalline CuInSe2 to test effects of varying stoichiometry on characteristics and transport properties
Silva, Carlos	Université de Montréal, QC	Physics	Fundamental electronic processes in advanced electroactive materials, principally organic semiconductors
Sivoththaman, Siva	University of Waterloo, ON	Electrical and Computer Engineering	Epitaxial and Thin film solar cells, Nanowires and quantum dots for spectrally engineered photovoltaics, Si crystal growth, High efficiency Si-based solar cells
Tarr, Garry	Carleton University, ON	Electronics	Structured inorganic layer(s), initially single crystal Silicon (c-Si); Interfacial passivation of inorganic material(s), grown thermally of by ALD; Conformal organic layer(s) of conducting polymer
Utigard, Torstein	University of Toronto, ON	Materials Science and Engineering	Refining Si for solar cell applications
Zhifeng, Ding	University of Western Ontario, ON	Chemistry	Electrochemical deposition techniques to fabricate various layers of solar cells
Watkins, S.P.	Simon Frazer University, B.C.	Physics	Growth of III-V semiconductors and nanostructures; their transport, optical and structural properties relevant to PV devices.

Canadian university R&D funded by NSERC [6] for the period FY05/06 to FY08/09 is shown in Figure 1. NSERC funding for the last period under review was at about $5 million per annum for 21 universities, about twice the funding for the FY05/06-FY06/07 period - largely as a result of increased emphasis on renewable energy development. NSERC funds for the period FY07/08 to FY08/09 were distributed to universities in Ontario (45%), Québec (33%), Alberta (14%), British Columbia (8%) and Nova Scotia (<1%).

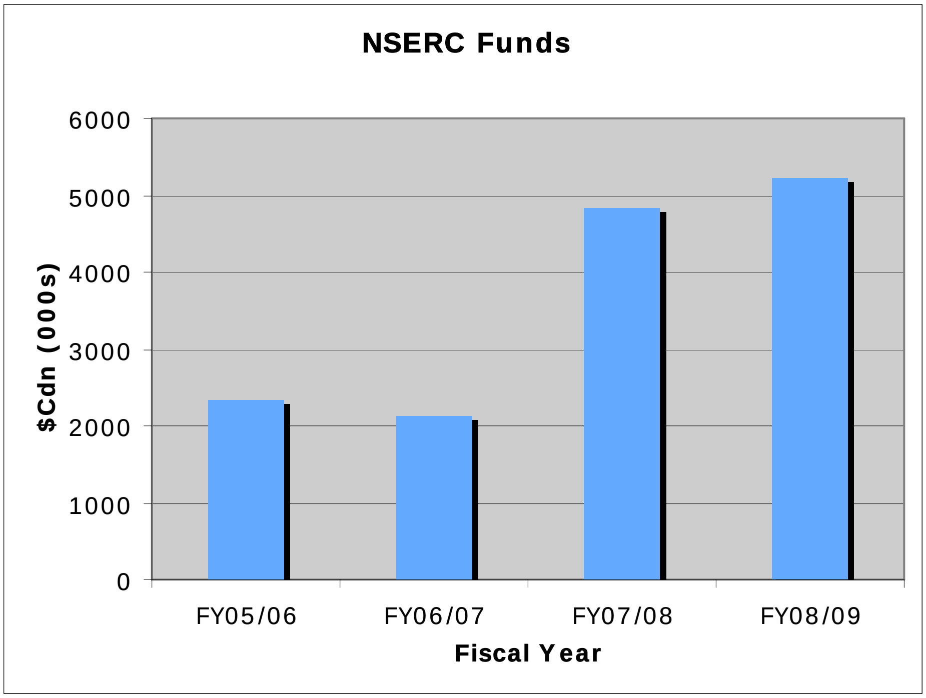

Fig.1 NSERC-funded University R&D for the Period FY05/06 to FY08/09

According to our survey, additional funding or co-funding of PV R,D&D and infrastructure support has become available, particularly for the last two years, to leading university researchers from several other federal sources (Canadian Foundation for Innovation (~$4,833k 2004-present), Canadian Institute for Photonic Innovations ($165k, for FY07/08 to FY09/10), Sustainable Development Technology Canada ($18.52M, 2005-present, see Table 2)), and provincial (Ontario Centres of Excellence (~$700k/year for 2008 & 2009), Ontario Research Fund ($1,400k/year for 2008 & 2009), Government of Quebec (~$180k, for FY07/08 to FY09/10), as well as industrial organizations.

Establishment of a Canadian Photovoltaics Innovation Network

The need for a network was recognized in a review [2] of photovoltaic R&D capability in Canada by CanmetENERGY, Natural Resources Canada. It was emphasized that, if Canada were to benefit from applications of PV technology, significant investments in R,D&D and manufacturing will be required; and, in particular, the federal government needed to encourage the development of a R&D network to strengthen the government / industry / university partnership in the PV field. As a result, CanmetENERGY facilitated several meetings and events to encourage networking between universities and industry. In addition, the meeting on Photovoltaic Solar Cell R&D in Canadian universities, held in March 2006, and the “Advances in Photovoltaic Science & Technology” workshop organized by the Ontario Centres of Excellence in November 2007, brought together about 65 stakeholders from academia, government and industry, further strengthening the case that a network approach was needed in

Canada. In February 2009, an initiative by key academic researchers, who organized a follow-up meeting at McMaster University, with over 150 people in attendance from across Canada, set the foundation for the formation of the current Photovoltaics Innovation Network with a mandate to serve as “a partnership between the research community, industry, government, funding agencies and advocacy groups to foster and accelerate the widespread adoption of photovoltaics as a renewable energy resource in Canada”.

Following NSERC approval of a preliminary application by a core group of academic researchers, a full proposal for the establishment of the NSERC Photovoltaics Innovation Network was developed under the leadership of Prof. Kleiman at the University of McMaster. The proposal was also supported by industry, OCE and CanmetENERGY. The Network, for which funding of $5 million for 2010-2015 has recently been approved by NSERC, is comprised of 29 scientists and engineers working in the field of advanced solar cell research at 13 universities across Canada. The Photovoltaic Innovation Network will support research under four main categories: Inorganic photovoltaic devices; organic photovoltaic devices; hybrid organic-inorganic photovoltaic devices; and nano-structured photovoltaic devices. Training, technology transfer and commercialization of R&D results are also part of the network’s mandate. This new Canadian PV Innovation network is a major step in strengthening university R&D and support for PV technology development in Canada.

Other Photovoltaic Research and Development Support in Canada

Solar cell and materials development is also being pursued at the National Research Council of Canada (NRC) Institute for Microstructural Sciences (IMS). The NRC-IMS role involves in-house R&D and extensive collaborations with universities, industry and other government organizations (Natural Sciences and Engineering Research Council of Canada (NSERC), Sustainable Development Technology Canada (SDTC), Business Development Bank of Canada(BDC)). NRC-IMS has a critical mass of experts and state-of-the-art facilities to develop relevant materials for electronic and photonic device applications, including compound semiconductors (e.g GaAs-, InP-, GaSb- GaN-based), silicon, organic semiconductors (e.g. small molecules or conducting polymers) as well as dielectric multilayers. Moreover, the NRC Canadian Photonics Fabrication Centre (CPFC) at NRC-IMS is a unique, industrial grade facility in North America providing PV component and device fabrication and pilot run production and prototyping services to industry and universities.

Table 2. Other Photovoltaic R&D Projects Announced

Year	Organization	Project	Funds and source ($millions)	Application
2005	ARISE Technology Corp.	Process to refine metallurgical (Si) into high purity solar (7N) grade Si plus recovery & reuse of waste Si	6.5 SDTC	Production of Si feedstock that can be fed into the ingot-making process that produces crystalline Si ingots for solar cell (PV).
2006	6N Silicon Inc.	Process for purifying metallurgical grade Si into solar grade Si (6N) using low cost metallurgical processing	4.0 SDTC	Development of low-cost silicon purification process to produce solar grade silicon for the PV industry.
2007	St-Jean Photochemicals	C60-C70 Bucky balls with poly-carbazole	2.0 SDTC	Next generation thin film printable hetero-junction organic PV cells
2007	MSR Innovations Inc.	Unique SolTrack™, solar roofing system which dramatically improves installation of solar PV.	0.34 SDTC	Improving systems installation of Building Integrated Photovoltaic (BIPV). Residential clamp on 2.5 kW nylon roofing tiles.
2007	Sixtron Advanced Materials Inc.	Si-C front and backside passivation and anti-reflective (AR) coatings for PV solar cells. Replaces silane source with a polymer powder alternative	3.33 SDTC	PV manufacturing process technologies using conventional PECVD to increase the relative efficiency of crystalline Si solar cells and enabling the use of thinner Si wafers. Need to eliminate silane to reduce manufacturing cost through better plant safety / increased manufacturing scale.
2009	Morgan Solar	Injection molded compact non-imaging optic with a curved light path,	2.35 SDTC	Manufacturing line for high concentration PV (HCPV) with flat plastic Light guide Solar Optics sub-assembly for solar farms (up to 10MW).
2009	Cyrium Technologies	SUNRISE: Semiconductors Using Nanostructures for Record Increases in Solar-Cell Efficiency	1.42 BDC	Development of GaAs multijunction solar cells for integration within solar PV concentrators.
2009	St-Jean Photochemicals	Polymeric / Inorganic Semiconductor Nano-Composite Materials for Low Cost Photovoltaic Applications	1.50 BDC	Next generation thin film printable hetero-junction organic PV cells

Conclusions

A survey of leading universities in Canada shows about 50 research laboratories employing an estimated 200-250 full-time equivalent researchers working in various science (chemistry, physics, materials science) and engineering (physics, chemical, electrical, computer, information technology, etc.) disciplines in photovoltaic solar cell research and development. Spurred by increasing emphasis on renewable energy development programs, both funding and staffing have doubled relative to the previous review period (FY05/06 and FY06/07). Canadian university capability to support research and development of photovoltaic solar cell in Canada is significant and forefront, as evidenced by the kind of research, and the volume and quality of publications produced. Although Canadian capability is for the most part involved in basic research, collaboration with Canadian based photovoltaic industry is increasing through a number of researcher-, industry- and government-driven initiatives.

Finally, the recent establishment of the Photovoltaics Innovation Network is a major boost to university R&D on solar cells and eventually photovoltaic energy development in Canada. The Network will undoubtedly raise the training capability of highly qualified researchers in this field while improving the level of collaboration with industry partners with the objective of reducing the production cost of PV technologies.

References

1. A.C. Vikis, Overview of Photovoltaic Solar Cell R&D Capability in Canada, CETC-Varennes 2005-077 (TR)

2. Y. Poissant and A.C. Vikis Overview of Photovoltaic Solar Cell R&D Capability in Canada Ed. 2 (2004-2007) CETC-Varennes 2008-075 (TR)

3. J. Ayoub and L. Dignard-Bailey, 2008 National Survey Report of PV Power Applications in Canada, CanmetENERGY Report 2009-128

4. J. Ayoub and L. Dignard-Bailey, Photovoltaic Technology Status and Prospects – Canadian Annual Report 2009, CanmetENERGY Report 2010-023

5. International Energy Agency Photovoltaic Power Systems Programme, Trends in Photovoltaic Applications, Report IEA-PVPS T1-18:2009, International Energy Agency 2009

6. NSERC Awards Search Engine (1991-2006) http://www.outil.ost.uqam.ca/crsng/Outil.aspx?Langue=Anglais, accessed in March 2010.

APPENDIX

Table of content

Leading Canadian University Research in Photovoltaic Solar Cells

The following highlights researchers receiving solar cell research funding from NSERC, CFI or other sources based on their responses to a questionnaire or information available on the researcher's website. (Note: "*Approximate group size*" and "*%devoted to PV research*" denotes the total size of the group and % effort devoted to PV research according, according to the lead researcher's response to a questionnaire. Also, "*publications*" denotes sample of PV relevant publications). Any, missing information indicates that it was unavailable to us.

Adronov, Alex, McMaster University

This work aims to develop a new class of photovoltaic devices (solar cells) that utilize advanced nano-scale materials for efficient charge generation and conduction. The main focus of the project is the preparation of carbon nanotube complexes with conjugated polymers that can be electrophoretically deposited on transparent electrodes in a manner similar to electroplating of metals. It has already been found that light-induced electron injection from conjugated molecules adsorbed to the nanotube surface is an efficient process, laying the foundation for the development of photovoltaic devices. By varying the structure of the conjugated polymer, we are able to tune its absorption properties to perfectly match the solar irradiation spectrum at the Earth's surface, while maintaining a high photoinduced electron transfer efficiency. The use of electrophoretic deposition to fabricate the devices provides a powerful method that allows precise control over film thickness, homogeneity, and composition. We are attempting to introduce multiple polymers, absorbing at different regions of the electromagnetic spectrum, to not only harvest a maximum amount of light, but also to introduce energy transfer processes that will allow a reduction in the required nanotube quantity, while enhancing the efficiency of photon-to-electron conversion. This strategy closely mimics the natural photosynthetic processes that occur in plants and photosynthetic bacteria, capitalizing on the concepts that Nature has evolved over millions of years.

Approximate Groupe Size:12

% devoted to PV research: 40%

Collaboration with Industry: No

Facilities:

Synthetic laboratory equipped with optical spectroscopy equipment (UV/Vis, NIR, fluorescence, Raman). Access available to evaporators and I-V measurement equipment.

Publications:

- Cheng, F.; Imin, P.; Lazar, S.; Botton, G.; de Silveira, G.; Marinov, O.; Deen, J.; Adronov, A. "Supramolecular Functionalization of Single-Walled Carbon Nanotubes (SWNTs) with Conjugated Polyelectrolytes and their Patterning on Surfaces" *Macromolecules* **2008**,*41*, 9869-9874.
- Mohseni, P.K.; Lawson, G.; Couteau, C.; Weihs, G.; Adronov, A.; LaPierre, R.R. "Growth and Characterization of GaAs Nanowires on Carbon Nanotube Composite Films: Towards Flexible Nano-Devices" Nano Lett. 2008, 8, 4075-4080.

- Casagrande, T.; Lawson, G.;Li, H.; Wei, J.; Adronov, A.; Zhitomirsky, I., "Electrodeposition Of Composite Materials Containing Functionalized Carbon Nanotubes", Mater. Chem. Phys., 2008, 111, 42-49.
- Cheng, F.; Imin, P.; Maunders, C.; Botton, G. A.; Adronov, A., "Soluble, Discrete Supramolecular Complexes of Single-Walled Carbon Nanotubes with Fluorene-Based Conjugated Polymers", Macromolecules, 2008, 41, 2304-2308.

Website: http://www.chemistry.mcmaster.ca/faculty/adronov/Adronov_-_New/Home.html

Aimez, Vincent (in collaboration with Denis Morris), Université de Sherbrooke

Research on advanced photonic characterization of nanostructures embedded in solar cell heterostructures mainly support our crystal growth activities. Room-temperature photoluminescence (PL) mapping and low-temperature measurements are used to quantify energy-level properties of the quantum dots and to give valuable insights on the crystalline quality of the overall quantum dot structure.

Minority carrier lifetimes are key parameters that enter into the simulation of solar cell I-V characteristics. A combination of time-resolved optical measurements (PL, reflectivity and absorption) could be used for the investigation of the photocarrier dynamics in the different layers of the solar cell structure. Minority carrier lifetimes have been determined recently, using time-resolved PL measurements, in doped GaInP ternary layer grown lattice-matched to germanium.

We have also launched a new research project on InP nanowires (NWRs) for photovoltaic applications, in collaboration with l'Institut de Nanotechnologies de Lyon, in France. Fundamental studies of the NWRs optical properties will be performed at Sherbrooke. Time-resolved photoconductivity measurements using visible pump and terahertz probe experiments will allow us to investigate the effect of the doping and the surface passivation process on the electronic properties of the NWRs.

Approximate Groupe Size: 11

% devoted to PV research: 10%

Collaboration with Industry: Yes

Facilities:

All of the projects are realized within the NanoQuebec Major facility "Centre de recherche en Nanofabrication et en Nanocaractérisation" www.crn2.ca

The group has developed advanced expertise covering

- All the fabrication steps required for the realization of triple junction cells based on Ge/III-V heterostructures.
- CBE Based epitaxial growth of III-V heterostructures on Ge substrates, tunnel junctions, high doping concentration.
- Advanced photonic characterization of nanostructures embedded within solar cells heterostructures.
- Development of novel metallic based cell carriers for high concentration applications of solar cells.

Website: http://www.gel.usherbrooke.ca/labn2/

Ban, Dayan, University of Waterloo

Current research related to photovoltaics is mainly on designing and simulating new structure (for example, organic/inorganic hybrid structure) for photovoltaic devices and characterizing the device performance (for example, using scanning probe microscope to explore the voltage distribution profile in a solar cells as it is in operation) and proposing solutions to technological challenges that hinder the applications and commercialization of the photovoltaic devices.

Approximate Groupe Size: 8

% devoted to PV research: 10%

Collaboration with Industry: No

Facilities:

Semiconductor fabrication facilities (Clean-room, shared).

Optoelectronic device characterization facilities

- FTIR – Fourier transform Infrared spectroscopy,
- Mode-lock Ti:Sapphire laser,
- Liquid helium closed-cycle cryostat,
- Lock-in amplifier,
- pulse generator,
- Cryo-temperature atomic force microscope,
- Digital-instrument atomic force microscopy,
- UV solid-state laser
- Si Charge-coupled device camera

Website: http://ece.uwaterloo.ca/~dban/

Barati, Mansoor, University of Toronto

Production of solar grade silicon (SoG-Si) has been one of the primary subjects of his research, working on production of SOG-Si by two different methods. One method deals with metallurgical refining including purification of metallurgical grade silicon. In the other method, reduction of high purity silica, that is present as rice husk ash or silica fume is investigated. Both methods have shown promising results, based on which, two US provisional patents have been filed. These projects in this area are supported by ARISE Technologies and Process Research Ortech Inc.

Approximate Groupe Size: 6

% devoted to PV research: 70%

Collaboration with Industry: Yes

Facilities:

- Several high temperature furnaces: for melting, alloying and refining of Si
- Leaching facility: for digestion and chemical analysis of Si
- Characterization facilities (of UofT), SEM, EDS, XRD, ICP-OES

Publications:

- K. K. Larbi, M. Barati, A. McLean, R. Roy, "Synthesis of Solar-grade Silicon from Amorphous Silica (Rice Husk Ash)" in *Materials Challenges in Alternative & Renewable Energy 2010*, 21-24 Feb. 2010, FL, USA. [OCE–PRO]
- M. Johnston, M. Barati, "Metallurgical Refining of Silicon for Solar Applications by Slagging of Impurity Elements", in *Materials Challenges in Alternative & Renewable Energy 2010*, 21-24 Feb. 2010, FL, USA. [N–ARISE]
- S. Esfahani, M. Barati, "A Novel Purification Method for Production of Solar Grade Silicon", in *Materials Challenges in Alternative & Renewable Energy 2010*, 21-24 Feb. 2010, FL, USA.

Website: http://www.mse.utoronto.ca/contacts/Professors/barati.htm

Baumgartner, Thomas, University of Calgary

The research in the Baumgartner group related to photovoltaics is devoted to the development of novel, highly tunable organophosphorus materials with light-harvesting, as well as n-type semiconducting/electron acceptor properties. The unique approach towards PV research lies in the design of a variety of building blocks on the molecular, supramolecular, as well as polymeric level that all involve organophosphorus components as central units within these materials. The group is among the first researchers internationally that have comprehensively established organophosphorus pi-conjugated materials as promising building blocks for organic electronics; the materials show exceptional electronic tunability and luminescence efficiencies, next to the n-type semiconduting properties that arise from the presence of the phosphorus center(s). PV research thus involves the development of material components for a variety of next-generation organic photovoltaics including bulk-heterojunction, as well as dye-sensitized devices. To this end, the group has been engaged in the synthesis of improved low-bandgap, light-harvesting polymers for bulk-heterojunction cells, novel molecular organophosphorus dyes for dye-sensitized cells, and they are currently looking into developing liquid crystalline light-harvesting components for improved charge separation.

Approximate Groupe Size: 11

% devoted to PV research: 50%

Collaboration with Industry: Yes

Facilities:

Research facilities allow for synthesis and advanced characterization (including optical, electrochemical, and thermal) of organophosphorus-based molecular, supramolecular, and polymeric materials. Access to basic dye-sensitized solar cell fabrication is available.

Publications:

- "Toward Low-Band Gap Dithienophosphole Copolymers for Application in Organic Solar Cells", S. Durben, D. Nickel, R. A. Krüger, T. C. Sutherland, T. Baumgartner, *J. Polym. Sci. Part A: Polym. Chem.* **2008**, *46*, 8179-8190. "Recent Developments in Phosphole-Containing Oligo- and Polythiophene Materials", M.G. Hobbs, T. Baumgartner, *Eur. J. Inorg. Chem.* **2007**, 3611-3628

Website: http://www.chem.ucalgary.ca/research/groups/ttbaumga/index.html

Bélanger, Daniel, UQAM

Investigates three different materials (silicon, InP and GaP) as semiconductor electrodes for the reduction of carbon dioxide. In addition, since the reduction reaction is relatively slow at these semiconductor surfaces, metallic and molecular electrocatalysts are deposited at their surfaces. The resulting electrodes are characterized by several methods that include scanning electron microscopy, FTIR and X-ray photoelectron spectroscopy. The nature of the reaction products is determined by coupling a mass spectrometer to the electrochemical solar cell. In addition, the efficiency of these electrodes for the electrochemical and photoelectrochemical reduction of CO_2 is measured.

Approximate Groupe Size: 4

% devoted to PV research: 25%

Collaboration with Industry: Yes

Facilities:

Complete set-up for the characterization of electrochemical solar cells; 150 W Xe arc source for illumination, photoelectrochemical cells and potentiostats.

Publications:

- "Modification of p-type Silicon for the Photoelectrochemical Reduction of CO_2 " T. Cottineau, M. Morin, D. Bélanger, Electrochemical Society Transactions, 19(35), (2009), 1.

Website: http://www.nanoqam.uqam.ca/?page_id=49&language=en

Bender, Timothy P., University of Toronto

Prof. Bender carries out research focused toward the design, engineering and application of newmaterials to enable a plastic/organic solar cell to harness >90% of the incident radiation receivedfrom the sun and to convert that radiation into electrical energy. This he expects to accomplishby the use of a novel array of phthalocyanines pigments/crystals (organic materials known toabsorb light and produce electrical charge) which when used together will produce a flexible, organic solar cell capable of absorbing all of the incident radiation from the sun. Along with this set of phthalocyanine pigments/crystals, polymeric hole- and electron-transporting materials willneed to be designed and synthesized. Their responsibility in the integrated photovoltaic device isto move the generated electrical charges to their respective electrodes thereby completing anelectrical circuit and generating electrical current. Prof. Bender uses a unique approach to research: the full integration of (1) computer aidedmolecular modeling and materials design, (2) chemical synthesis and engineering and (3) chemical characterization, into materials design, synthesis and discovery. While the researchfocus of the lab is unique and innovative, the techniques and skills utilized in the pursuit of thisresearch are directly translatable to other chemical sectors operating in Canada including organicelectronic chemicals, other high value added materials (e.g. catalysts) and fine chemicals (e.g. pharmaceuticals).

Approximate group size: 8

Facilities:

- Workstation grade computers for molecular modeling and design (Dell Precision Workstation); molecular modeling software (HyperChem); and file server (Dell Power Edge); Waters Alliance High Performance Liquid Chromatography (HPLC) & Gel Permeation; Chromatography (GPC) System; train sublimation apparatus (for purification of organic materials); Bioanalytical Epsilon Electrochemical Workstation; UV-Vis-NIR-IR, fluorescence, FT-IR spectrometers; Motionless Xerographic Scanner (MXS); Newport Corporation Oriel Class A Solar Simulator

Publications:

- "Silicon-containing layers for electrophotographic photoreceptors and methods for making thesame" Bender , T.P.; Hu, N.X.; Graham, J.F.; Gagnon, Y.; Coggan, J.A.; US **7,238,456** . July 3, **2007** .
- "A Pronounced Anionic Effect in the Pd-catalyzed Buchwald-Hartwig Amination Revealed inPhosphonium Salt Ionic Liquids". McNulty, J.; Cheekoori, S.; Bender , T. P. ; Coggan, J.A.; *Chem. Eur. J.* , **2007** , 1423–1428.
- "The Synthesis of Poly(arylene ether)s in Solution at Pilot-Plant Scale with Control over Molecular Weight and End-Group Composition". Bender , T. P. ; Burt, R.A.; Hamer, G.K.; DeVisser, C.; Smith, P. F.; Saban, M.; *Org. Process Res. Dev.* , **2002** , *6* (5), 714-720.

Website: http://web.chem-eng.utoronto.ca/index.php?option=content&task=view&id=991&Itemid=62

Berlinguette, Curtis P., University of Calgary

The main goal of this program is to develop methods to improve the conversion efficiency of sunlight to electrical and chemical energy. A major component involves the design and synthesis of metal complexes for applications in the dye-sensitized solar cell (DSSC). Our program is playing a leading role in the development of cyclometalated Ru chromophores for DSSC applications, and other complexes with enhanced light-harvesting capabilities. We are also devising ways to replace the mesoporous film common to champion DSSCs with linear TiO2 nanowires using sol-gel growth techniques. The goal is to improve the charge-transport properties within these linear nanostructures to drive up the power that can be extracted from the cell. Finally, we are also seeking new electrolyte materials, the third major component in the DSSC, to increase the voltage and stability of the cell.

Approximate group size: 11

% devoted to PV research: 50%

Collaboration with Industry: Yes

Facilities:

Facilities to fabricate and characterize high performance dye-sensitized solar cells, including a specialized screen printer, backhole sealer, and a press for making highly reproducible cells; also, a fluorescence spectrometer capable of measuring lifetimes over the 5 ps – 10 ms time regime (a pulsed white-light excitation source is also capable of exciting over the 300-1000 nm range), and a solar simulator.

Publications:

- Koivisto, B. D.; Robson, K. C. D.; Gordon, T. J.; Berlinguette, C. P.* "Hybridisation of Organic and Inorganic Dye Elements: Triphenylamine-Modified Ruthenium Terpyridyine Complexes with High Molar Extinction Coefficients." *Inorg. Chem*. **2009** (In Press)
- Wasylenko, D. W.; Koivisto, B. D.; Ganesamoorthy, C.; Henderson, M. Berlinguette, C. P.* "Insights into the Mechanism of Water Oxidation" *Inorg. Chem*. **2009** (In Press)
- Koivisto, B. D.; Robson, K. C. D.; Berlinguette, C. P.* "Systematic Manipulation of the Light-Harvesting Properties for Tridentate Cyclometalated Ruthenium(II) Complexes" *Inorg. Chem.* **2009**, *48*, 9644-9652.
- Bomben, P. G.; Robson, K. C. D.; Sedach, P.; Berlinguette, C. P.* "On the Viability of Cyclometalated Ru(II) Complexes for Light-Harvesting Applications" *Inorg. Chem*. **2009** *48*, 9631-9643.

Website: http://homepages.ucalgary.ca/~cberling/Home.html

Brett, Michael J., University of Alberta

Research is focused on the Glancing Angle Deposition (GLAD) process developed by the group to produce new nano-engineered thin film materials. They are using this technique to develop a new generation of photonic devices that could allow more powerful integrated optical circuits for telecommunications and other photonics applications. Recently, they fabricated a 3-dimensional photonic crystal with a new geometric design consisting of a periodic array of micrometer-sized square spirals. The fabrication process used is a technique patented by the University of Alberta and an industry sponsor, which also has application to devices in other areas, such as sensors, displays, and materials for energy storage.

Approximate group size: 5

Facilities:

The GLAD lab is equipped with six vacuum chambers for physical vapour deposition of thin films. Each one has the GLAD substrate motion control system incorporated into it, as well as a computer software module used to control the deposition. Two styles of vacuum chambers, are used. The systems like Dagda use electron-beam evaporation to deposit the films and a cryopump (maintained at -262°C) to maintain the high vacuum. Systems like Pluto use thermal evaporation for the deposition and a diffusion pump. In addition, some of the systems have an ion mill, allowing the user to bombard thin films with ions and change their shape and properties. The GLAD lab is located immediately beside the University of Alberta Nanofabrication Facility. This facility boasts an impressive array of nanotechnology processing equipment. Extensive deposition, lithography, and wet/plasma etching capabilities using cutting-edge technology are all readily available to us for use in conducting research.

Publications:

- G.K. Kiema, M.J. Colgan and M.J. Brett "Dye sensitized solar cells incorporating obliquely deposited titanium oxide layers" *Solar Energy Materials and Solar Cells* **85**, 321-331 (2005)

Website: http://www.ece.ualberta.ca/~glad/

Brolo, Alexandre G., University of Victoria

The objective of this research is to use nanostructured gold to enhance photo-conversion processes. We were able to setup our measurement infrastructure, prepare the photocells, perform preliminary tests and develop an initial prototype.

Approximate group size: 4

% devoted to PV research: 20%

Collaboration with Industry: Yes

Facilities:

Thermal deposition system, instrument for electrochemical and optical measurements, specroscopic characterization facilities, access to nanofabrication laboratory at SFU

Publications:

- "Enhanced Fluorescence from Arrays of Nanoholes in a Gold Film", A.G. Brolo, S.C. Kwok, M.G. Moffitt, R. Gordon, J. Riordon, and K.L. Kavanagh,; J. Am. Chem. Soc. 2005 (in press).
- "Basis and Lattice Polarization Mechanisms for Light Transmission through Nanohole Arrays in a Metal Film", R. Gordon, B. Leathem, M. Hughes, K.L. Kavanagh, A.G. Brolo; Nano. Lett. 5 (2005) 1243-1246
- "Nanohole-Enhanced Raman Scattering", A. G. Brolo, E. Arctander, R. Gordon, B. Leathem and K. L. Kavanagh, Nano Lett. 4 (2004) 2015-2018 .
- "Surface Plasmon Sensor Based on the Enhanced Light Transmission through Arrays of Nanoholes in Gold Films", A. G. Brolo, R. Gordon, B. Leathem and K. L. Kavanagh, Langmuir, 20 (2004) 4813.

Buriak, Jillian, University of Alberta

Synthesis of Metal Nanoparticle Arrays of Semiconductor Surfaces and Complex Nanostructured Metals; Patterning of Organic Monolayers on Surfaces of Semiconductors; Homogeneous Catalyst Design and Synthesis; Hybrid Nanoscale Inorganic-Organic Structures; Fundamental semiconductor surface chemistry; and Development of Light Emitting Materials for Sensor Design.

Approximate group size: 10

% devoted to PV research: 50%

Collaboration with Industry: No

Facilities:

Large array of equipment and instrumentation at NINT and at the University of Alberta; also solar characterization facilities necessary to rapidly screen PV devices.

Publications:

- Thienylsilane-Modified Indium Tin Oxide as an Anodic Interface in Polymer/Fullerene Solar Cells, David A. Rider, Ken D. Harris, Dong Wang, Jennifer Bruce, Michael D. Fleischauer, Ryan T. Tucker,§ Michael J. Brett, and Jillian M. Buriak
- Electrostatic Layer-by-Layer Assembly of CdSe Nanorod/Polymer Nanocomposite Thin Films Sean A. McClure, Brian J. Worfolk, David A. Rider, Ryan T. Tucker, Jordan A. M. Fordyce, Michael D. Fleischauer, Ken D. Harris, Michael J. Brett, and Jillian M. Buriak

Website: http://www.chem.ualberta.ca/~buriak/

Côté, Michel, Université de Montréal

The focus of this research is in the computation of the electronic structure using ab initio methods. Although this group uses many methods, they specialize in the application of density-functional theory (DFT) to study the different systems under consideration. The approach is not only limited to the study of compounds that have already been synthesized, but they also explore new ideas through highly accurate simulations with the aim of proposing interesting avenues to be pursued. Presently, the main efforts are the investigation of inorganic semiconductors, novel polymers to be used in photovoltaic applications, superconductors such as fullerenes, transition nitride metals and high-Tc materials.

Approximate group size: 5

% devoted to PV research: 50%

Collaboration with Industry: No

Facilities:

The calculations and simulations are carried out on the supercomputers of the RQCHP, the High Performance Computer Consortiums financed by the Canada Foundation for Innovation and the Quebec Government.

Publications:

- First principles elaboration of low band gap ladder-type polymers J. Chem. Phys. **130**, 114906 (2009); doi:10.1063/1.3081184 Simon Pesant, Guillaume Dumont, Sébastien Langevin and Michel Côté
- Excitons in perylene tetracarboxdiimide crystals for optoelectronics Phys. Stat. Sol (c) 6, No 1, 93-96 (2009), doi: 10.1002/pssc.200879887 Françoise Provencher, Jean-Frédéric Laprade, Michel Côté, Carlos Silva

Website: http:// www.phy.umontreal.ca/~michel_cote

Demopoulos, George P, McGill University

Nanocrystalline Titania-based Dye Sensitized Solar Cells: The overall objective of this project is the development of new generation solar cell technology with the potential of rendering solar energy an economically attractive sustainable energy source. Dye-sensitized nano-crystalline titania-based solar cells hold the promise of achieving this breakthough; however, to become a successful commercial reality major advances in the area of photoelectrode material preparation and electrolyte development are required. It is the scope of the present research to address these two critical R&D issues by aiming at: (1) the elaboration of a low temperature (hence low cost) aqueous-based synthesis method for tailor-made nano-crystalline titania material; (2) the application/development of new coating, annealing and senstization processes for the deposition/sintering of titania films on plastic materials hence facilitating cell manufacturing;(3) and the development of aleakage-free gel electrolyte that overcomes the short lifespan of the present liquid electrolyte-based solar cell design.

Approximate group size: 7

% devoted to PV research: 50%

Collaboration with Industry: Yes

Facilities:

Equipment for low temperature solution and solvothermal synthesis of nanomaterials; film deposition by screen printing and electrophoretic methods; access to wide range of spectroscopic and electron microscopic characterization instrumentation; grant application pending on acquisition of photovoltaic cell testing instrumentation (solar simulator and I-V station, QE/IPCE and EIS).

Website: http://people.mcgill.ca/george.demopoulos/

Ding, Zhifeng, University of Western Ontario

The primary focus is on electrochemical deposition techniques to fabricate various layers of solar cells. The group studied different types of solar cells including hybrid and thin film on either flexible substrate or molybdenum substrate as back contact. Among many solar absorbing semiconductor materials, the absorption spectrum of copper indium gallium diselenide (CIGS) thin films matches the best the solar spectrum when the stoichiometry of $Cu(In_xGa_{1-x})Se_2$, with x ranging about 0.6 to 0.8, is reached. They have great potentials to reach very high PV conversion in solar cells because of this behaviour. The bottleneck impeding the adoption of solar energy is the low efficiency of the photovoltaic (PV) conversion and high manufacturing costs of solar cells. Electrodeposition is an attractive technology because of its low cost and extensive applications in large-scale mass production by both the metal surface finishing industry and electronics packaging industry.

Approximate group size: 7

% devoted to PV research: 60%

Collaboration with Industry: Yes

Facilities:

The lab is equipped with several electrochemical stations, sun simulator lamps for power efficiency measurements, set-up fo incident photon to charge carrier efficiency, Raman microspectroscopy and AFM from WITech (Germany), scanning electrochemical microscopy (SECM), and electro-chemiluminescence instruments. We use facilities in Nanofabrication lab at western including, sputtering, e-beam, and CVD. Besides, we use facilities at Surface Science Western including, SEM, EDX, XPS and SIMS. In addition, we have access to TEM and XRD through Biotron and the Department of Earth Science at Western University.

Publications:

- Electrochemical method for stoichiometric CIGS solar cells (Provisional US patent, No. 61/240 551)
- M. Harati, David Love, Leo W. M. Lau, and Z. Ding, One Stage Electrochemical Preparation of Stoichiometric CIGS Thin Film, (To be submitted)
- M. Harati, David Love, Leo W. M. Lau, and Z. Ding, Preparation and Characterization of Thin Film Zinc Oxide, (To be submitted)

Website: http://publish.uwo.ca/~zfding/pub.htm

Eichhorn, Holger S., University of Windsor

The objective of this research is to develop design criteria for discotic materials that function as active materials in photovoltaic devices. This is a complex task because any structural change at the molecular level affects many properties important to their use in OPVs such as their mesomorphism, surface alignment, red/ox potentials, light absorption, self-organization into electron donor/acceptor type domains, charge carrier formation and mobility, and stability. Individual studies comprise of comprehensive sets of properties but by far not all relevant properties. We rather follow a hierarchy of properties and, for example, only test the most promising materials in devices. Most known discotics are electron donors and some of our early efforts focused on the design of discotics with electron acceptor properties because both types of materials are required as active materials in bulk heterojunction OPV.

Approximate group size: 6

% devoted to PV research: 65%

Collaboration with Industry: Yes

Facilities:

The group is equipped with modern facilities for the synthesis and characterization of small molecules and polymers (modern fume hoods, GPC, HPLC, GC-MS, glove boxes, etc.). Also, equipped for the temperature dependent characterization of anisotropic materials such as aligned polymer fibres and liquid crystals (e.g. (polarized) spectroscopy (UV-Vis, IR, Raman, and CD), thermal analysis (DSC and TGA/DTA-MS) and 2D X-ray diffraction. In addition, the group has basic facilities for the preparation of simple devices and thin films on substrates (e.g. e-beam and thermal evaporators, spin-coater, LB trough, liquid crystal cells, alignment layers, etc.).

Publications:

- Quasi Temperature Independent Electron Mobility in Hexagonal Columnar Mesophases of an H-Bonded Benzotristhiophene Derivative. Demenev et al., Chem. Mater. 2010 (22,4) 1420.
- Halide effect in electron rich and deficient discotic Phthalocyanines. Ahmida et al., J. Mater. Chem. 2010 (20,7) 1292.
- Synthesis, mesomorphism and electronic properties of nonaflate and cyano-substituted pentyloxy and 3-methylbutyloxy triphenylenes. Mahoney et al., J. Mater. Chem. 2009 (19,48) 9221.
- Measurements and Prediction of Electronic Properties of Discotic Triphenylenes and Phthalocyanines. Ahmida et al., ECS Transactions 2010 (25,26) 1.

Website: http://cronus.uwindsor.ca/users/e/eichhorn/main.nsf

El Khakani, My Ali, Institut national de la recherche scientifique

The objective is to use forefront nanotechnologies to develop novel solar cells. Specifically, these cells are to be formed by an optimized combination of multiple-exciton-generation Quantum Dots (QDs) and high-mobility Single-Wall-Carbon-NanoTubes (SWCNTs). The QDs serve as highly productive charge-creation pools, while the SWCNTs are the charge transport highways. The aim is to: (i) Better control of the synthesis of carbon nanotubes and to perform appropriate characterization and photoconduction measurements, as a function of key parameters during synthesis; (ii) to perform systematic studies to clarify the physicochemical reasons of the generation of photocurrent in carbon nanotubes; and (iii) to insert carbon nanotubes into photovoltaic devices and assess their photoconversion performance.

Approximate group size: 15

% devoted to PV research: 33%

Collaboration with Industry: Yes

Facilities :

Key facilities include :

- Two laser based reactors for the synthesis of SWCNTs; a high vacuum system for the deposition of various nanomaterials by means of Pulsed Laser Deposition (PLD); and An advanced tri-sources magnetron sputtering system for thin films deposition.
- Various characterization tools, including XPS, XRD, TGA, FTIR, STM/AFM, HR-SEM/TEM, Raman, UV-photoluminescence, a wavelength-resolved quantum efficiency measurements setup and I-V electrical measurements.
- Access to a state-of-the-art fully-equiped micro- and nano-fabrication laboratory (6”-wafers-CMOS compatible).

Publications:

- P. Castrucci, M. Scarselli, M. De Crescenzi, M. A. El Khakani, F. Rosei, “Probing the electronic structure of carbon nanotubes by nanoscale spectroscopy”, Invited Feature Article, Nanoscale (2010).
- D. Wang, H. Zhao, N. Wu, M. A. El Khakani, D. Ma, “Tuning the Charge-Transfer Property of PbS-Quantum Dot/TiO2-Nanobelt Nanohybrids via Quantum Confinement”, J. Phys. Chem. Lett., 1 (2010) pp. 1030–1035.
- M. A. El Khakani, V. Le Borgne, B. Aïssa, F. Rosei, C. Scilletta, E. Speiser, M. Scarselli, P. Castrucci, M. De Crescenzi, “Photocurrent generation in random networks of Multiwall-carbon nanotubes grown by an “all-laser” process”, Appl. Phys. Lett., 95 (2009) 083114.

Website: http://www.plasmaquebec.ca/Universites_Membres/reguliers/Elkhakani_en.htm

Gao, Jun, Queens University

The research focuses on certain polymers which are not only conductive, but also luminescent with device applications in light-emitting devices and solar cells. Polymer photonic devices offer a number of advantages over traditional photonic devices which are based on expensive inorganic semiconductors. Specifically, the research focuses on light-emitting electrochemical cells (LECs), which are solidstate polymer devices operating on the principle of in situ electrochemical doping. LECs are attractive candidates for potential display and energy conversion applications. Because of doping, LECs have dramatically reduced bulk and contact resistance, and can operate in a large planar device configuration. Recently this group demonstrated world's largest planar LECs with an interelectrode spacing up to 11 mm. The extremely large planar devices offer unparalleled spatial and temporal resolution for direct imaging of many intriguing LEC processes.

Facilities:

Low temperature vacuum deposition; spectroscopy; optical and electron microscopy; fluorescence imaging; transport, impedance and photometric measurements; polymer processing

Publications:

- Photovoltaic response of a polymer p-I-n junction, by Y. Zhang, Y. Hu and J. Gao in Applied Physics Letters, 91, 233509 (2007)
- Polymer bulk homojunction light-emitting electrochemical cells, by C. Tracy and J. Gao in Journal of Applied Physics 100, 104503 (2006)
- Cationic effects in polymer light-emitting electrochemical cells, by Y. Hu and J. Gao in Applied Physics Letters, 89, 253514 (2006)

Website: http://www.physics.queensu.ca/~jungao/

Hill, Ian G., Dalhousie University

The research focuses on: Chemical doping (n- and p-type) of organic photovoltaic devices to optimize open circuit voltage, carrier separation, fill-factor by minimizing (internal) series resistance Development of platinum-free counter electrodes for dye-sensitized solar cells Nano-structuring of MOCVD deposited TiO_2 for working electrodes in dye-sensitized solar cells Interface modification in organic/inorganic hybrid solar cells to optimize exciton dissociation, and therefore photon-to-current efficiency Impedance spectroscopic studies of organic PV and hybrid PV devices to determine depletion widths, carrier concentrations and distributions Ultraviolet and x-ray photoelectron spectroscopies to determine interfacial electronic and chemical structures in organic and hybrid PV devices.

Approximate group size: 5

% devoted to PV research: 50%

Collaboration with Industry: No

Facilities:

Key facilities include: Class 1000 clean room; photolithography; dry and wet etching; organic, metal, and inorganic semiconductor vacuum deposition; organic deposition equipped with automated shutters for combinatorial fabrication; 150W small spot solar simulator; 500W large area solar simulator; IPCE and electrical (I-V, C-V) characterization; and photovoltaic efficiency measurements

Publications:

- A.G. Ismail and I.G. Hill, "Nchannel organic thin-film transistors with alkyl phosphonic acid monolayer modified dielectrics", submitted to Organic Electronics (2009).
- C. K. Chan, W. Zhao, A. Kahn and I. G. Hill, "Influence of chemical doping on the performance of organic photovoltaic cells", Applied Physics Letters 94, 203306 (2009).
- T. R. Colbourne, I. G. Hill and L. Kreplak, "Electric field induced assembly of vimentin
- microscaffolds around metallic electrodes", Biomacromolecules 10, 1986 (2009).

Website: http://fizz.phys.dal.ca/~ihill/OEMD_Home.html

Hinzer, Karin, University of Ottawa

SUNRISE (Semiconductors Using Nanostructures for Record Increases in Solar-Cell Efficiency): R&D to improve the efficiency of III-V multi-junction solar cells under 500• solar concentration; develop standardized fabrication process for high-efficiency cells and solar receivers; characterize solar receivers under high concentration of ≥500 suns; develop computer modeling of multi-junction solar device incorporating layers with quantum materials.

Novel III-V and I-III-VI Based Multi-Junction Solar Cells: study passivation of CIGS interfaces to improve efficiency; develop III-V metamorphic layers on Si and CIGS substrates; develop device designs, computer modeling, and monolithic integration strategies towards highly efficient quadruple-junction solar cells incorporating CIGS and III-V layers; in collaboration with McGill University.

Third Generation Spectral Engineering for Increased Solar Cell Efficiencies: study of rare earth-doped silicon nanocrystal material properties for up-conversion to capture low-energy photons and down-conversion to more efficiently capture high-energy photons; form optically series-connected multi-layered solar cell in collaboration with McMaster University.

Lunar Rover Photovoltaic Power Subsystem: design and concept study for several types of power subsystems to power lunar rovers, including photovoltaic assemblies and battery energy storage; assemble demonstrator high-efficiency photovoltaic solar panel and control electronics; in collaboration with Neptec Design Group Ltd.

Approximate group size: 10

% devoted to PV research: 75%

Collaboration with Industry: Yes

Facilities:

Key facilities include:

Low concentration continuous-wave solar simulator and device characterization station: measure current-voltage behavior over intensities of 1-150 suns using a 1.6 kW Oriel 92191 solar simulator with a 2”•2” output beam; determine parameters such as fill factor and efficiency; illuminate with various standard spectra including AM0, AM1, AM1.5G, AM1.5D, AM2.

High concentration continuous-wave solar simulator and device characterization station: measure current-voltage behavior using intensities up to >1000 suns using a 3 kW Spectrolab XT-30 solar simulator with a 1 cm2 output beam; determine parameters such as fill factor and efficiency; illuminate with standard AM1.5D spectrum which can be modified with 6 continuously variable band filters.

Photoluminescence station: liquid nitrogen-cooled platform for sample excitation under intensity-controlled laser light; spatially-dependent measurements are made at the micrometer-scale; spectral measurements cover the 300-3000 nm range.

Computer modeling software suites: active device performance using Synopsis Sentaurus and COMSOL Multiphysics; thin film design via Essential Macleod; ray-tracing in Zemax; mask design in DW-2000.

Publications:

- J. F. Wheeldon, C. E. Valdivia, A. Walker, G. Kolhatkar, A. Jaouad, A. Turala, B. Riel, D. Masson, S. Fafard, R. Arès, V. Aimez, K. Hinzer, "Performance Comparison of AlGaAs, GaAs and InGaP Tunnel Junctions for Concentrated Multi-Junction Solar Cells," *submitted to* Progress in Photovoltaics.
- J. F. Wheeldon, C. E. Valdivia, D. Masson, F. Proulx, B. Riel, N. Puetz, E. Desfonds, S. Fafard, B. Rioux, A. J. SpringThorpe, R. Arès, V. Aimez, M Armstrong, M. Swinton, J. Cook, F. Shepherd, T. J. Hall, K. Hinzer, "High Efficiency Commercial Grade 1 cm2 AlGaInP/GaAs/Ge Solar Cells with Embedded InAs Quantum Dots for Concentrator Demonstration System," *invited to* Photonics North 2010, Niagara Falls, Canada.
- J. F. Wheeldon, C. E. Valdivia, A. Walker, G. Kolhatkar, D. Masson, B. Riel, S. Fafard, A. Jaouad, A. Turala, R. Arès, V. Aimez, T. J. Hall, K. Hinzer, "GaAs, AlGaAs and InGaP Tunnel Junctions for Multi-Junction Solar Cells Under Concentration: Resistance Study", AIP, 6th International Conference on Concentrating Photovoltaic Systems, Freiburg, Germany (Apr 2010).
- J. F. Wheeldon, C. E. Valdivia, A. Walker, G. Kolhatkar,T. J. Hall, K. Hinzer, D. Masson, S. Fafard, A. Jaouad, A. Turala, R. Arès, V. Aimez, "AlGaAs tunnel junction for high efficiency multi-junction solar cells: Simulation and measurement of temperature-dependent operation," Photovoltaic Specialists Conference, 135, Philadelphia, PA, USA (Jun 2009).
- C. E. Valdivia, Research roundtable panel, Canadian Solar Industries Association (CanSIA) Solar Conference 2008, Toronto, Canada (Dec 2008). Invited.

Website: http://SUNLAB.site.uottawa.ca/

Holdcroft, Steven, Simon Fraser University

The research involves the study of bicontinuous nanoarchitectures that improve the efficiency of solar into electrical energy conversion within a donor-acceptor (DA) heterojunction of a typical bilayer polymerfullerene photovoltaic cell. For the purpose of studying bicontinuous, donoracceptor π-conjugated nanostructures, poly(3-hexylthiophene) is post-functionalize with TEMPO and used to initiate the pseudo-living polymerization of chloromethylstyrene (CMS) from the thienyl backbone. Attachment of C60 by atom transfer radical addition provides the first example of a polythiophene-based main chain polymer bearing side chains of multiply grafted fullerene moieties. In another approach a graft copolymer is obtained by NMRP of an electron transport monomer (vinyl triazole) onto post-functionalized poly(3-hexyl)thiophene to produced phasesegregated morphologies.

Approximate group size: 9

% devoted to PV research: 30%

Collaboration with Industry: Yes

Facilities:

Donor-Acceptor, phase phase-segregated morphologies are characterized by a wide range of techniques including spectroscopy, electrochemistry, microscopies, and surface analytic techniques, and in working PV devices.

Publications:

- G. L. Schulz, X. Chen and S. Holdcroft**,** High Band Gap Poly(9,9-Dihexylfluorene-alt-Bithiophene) Blended with [6,6]-Phenyl C_{61} Butyric Acid Methyl Ester for Use in Efficient Photovoltaic Devices, *App. Phys. Lett*., **94**, 023302, 2009.
- Xiwen Chen, Xu Han, George Vamvounis, Steven Holdcroft. Polythiophene-*graft*-styrene and Polythiophene-*graft*-(styrene-*graft*-C_{60}) Copolymers, *Macromolecular Rapid Communications,* 28 (2007) 1792.
- X. Han, X. Chen, S. Holdcroft, " Nanostructured Photovoltaic Devices from Thermally-Reactive Pi-Conjugated Polymer Blends", *Chem. Mater*., 21 (2009) 4631–4637.
- .F. C. Krebs,,* S. A. Gevorgyan, B. Gholamkhass, Steven Holdcroft, + 39 others, "A round robin study of flexible large area roll-to-roll processed polymer solar cell modules." Sol.Energy Mater. Sol.Cells *93* (2009) 1968-1977
- Z. Zhou, X. Chen, S. Holdcroft, "Stabilizing Bicontinuous Nano-Phase Segregation in πCP-C60 Donor-Acceptor Blends", *J. Amer. Chem. Soc.,* 30 (2008)11711–11718.

Website: http://www.holdcroftgroup.ca/?Welcome

Hotchandani, Surat, Université du Québec à Trois-Rivières

The research deals with dye-sensitized solar cells (DSC). In a DSC, a dye is deposited on a semiconductor. Upon visible photoexcitation, the excited dye injects electrons in the semiconductor which flow in the external circuit to produce photocurrent. The holes left on the dye are taken up by the electron donor in redox electrolyte. This process regenerates the original dye and maintains the continuous functioning of the cell. The objective is to improve the performance of DSCs by suppressing the charge recombination with the use of coupled semiconductors and suitable electron acceptors, and using different dyes to increase the absorption of light. In addition, we are also interested in charge transport parameters.

Approximate group size: 2

% devoted to PV research: 100%

Collaboration with Industry: No

Facilities:

UV-visible Illumination system, Dye Laser

Publications:

- Barazzouk, S, P. V. Kamat, and S. Hotchandani, "Photoinduced electron transfer in chlorophyll *a* and gold nanoparticles", **J. Phys. Chem. B** 109, 716-723 (2005).
- Barazzouk, S, and S. Hotchandani, "Enhancement of charge separation in chlorophyll *a* cell by gold nanoparticles", **J. Appl. Phys.** 96, 7744-7746 (2004).

Izquierdo, Ricardo, Université du Québec à Montréal

Research on the fabrication of organic solar cells using new technologies such as aerosol direct write and dip pen lithography in combination with other technologies such as ink jet printing, evaporation and spin coating, in order to better understand the behaviour of organic solar cells. The use of carbon nanotubes for the fabrication of flexible transparent electrodes is also explored, as well as the use of plasmonic structures in order to improve the efficiency of solar cells.

Approximate group size: 12

% devoted to PV research: 25%

Collaboration with Industry: No

Facilities:

Facilities for fabrication of organic solar cells for polymer and small molecules, including: Evaporator, spin coater in glove box, clean room, materials ink jet printer, solar simulator. Also, funded by CFI, to be installed in 2010-2011: Evaporator in glove box, electrical characterization apparatus in glove box, aerosol jet direct writing system.

Website: http://www.nanoqam.uqam.ca/?page_id=55&language=en

Kherani, Nazir P., University of Toronto

The advanced photovoltaics and devices research group at the University of Toronto carries out innovative research into photovoltaic and allied materials and devices. The research areas include high efficiency photovoltaics, photonic crystal photovoltaics, optical coatings, micropower sources, sensors, and photonic materials and devices. A range of thin film material systems are investigated using advanced plasma enhanced chemical vapour deposition techniques as well as other thin film deposition methods.

Approximate group size: 26

% devoted to PV research: 90%

Collaboration with Industry: Yes

Facilities:

The facilities consist of state of the art thin film photovoltaic and allied materials and devices fabrication facilities, including affiliated clean rooms, and characterization facilities. These include advanced plasma enhanced chemical vapour deposition capabilities for a variety of materials including silicon and carbon, multi-target sputtering and contacts deposition systems, and a range of optoelectronic characterization tools.

Publications:

- P.G. O'Brien, A. Chutinan, K. Leong, N. P. Kherani, G. A. Ozin, S. Zukotynski "Photonic crystal intermediate reflectors for micromorph solar cells: a comparative study", *Optics Express*, **18**(5) (2010) 4478-4490.
- Barzin Bahardoust, Alongkarn Chutinan, Keith Leong, Adel B. Gougam, Davit Yeghikyan, Tome Kosteski, Nazir P. Kherani and Stefan Zukotynski, "Passivation Study of the Amorphous-Silicon Interface Formed Using DC Saddle-Field Glow Discharge", *Physica Status Solidi A* **207**, No. 3, (2010) 539–543.
- Paul G. O'Brien, Daniel P. Puzzo, Alongkarn Chutinan, Leonardo D. Bonifacio, Geoffrey A. Ozin, Nazir P. Kherani, Selectively-Transparent and Conducting Photonic Crystals, *Adv. Mater.* **22** (5) (2009) 611-616.
- *Alongkarn Chutinan, Nazir P. Kherani, Stefan Zukotynski "High-Efficiency Photonic Crystal Solar Cell Architecture",* Optics Express ***17****(11) (2009). 8871–8878.*

Website: http://www.ecf.utoronto.ca/~kherani

Kitai, Adrian, McMaster University

Research interests include:

- Fundamental luminescent materials: Visible emission from oxide phosphor materials Zn2Si04:Mn, Ga203:Eu and relatedcompounds is being studied under electroluminescence, photoluminescence and cathodoluminescence. Thin films of these oxide phosphors are being grown by RF sputtering, on glass and ceramic substrates. Defects in II-VI phosphors are being studied to determine the relationship between point defects and luminescence in these materials. Commercial brightness and efficiency values achieved on glass substrates with the new green phosphor achieved stable operation of Zn2Si0.5Ge0.5O4:Mn thin films paving the way for industrial use of these materials
- New luminescent devices: A new and unique type of luminescent "Sphere Supported Thin Film Electroluminescent" (SSTFEL) device has been developed. This involves spherical ceramic particles coated with a thin film semiconductor phosphor material, and then embedded in a polymer sheet. Flexible light emitting sheets are enabled, which are capable of long life, high brightness performance.
- New avalanche injection devices: Two new research projects involve avalanche-injection electroluminescence. Here, electrons are injected into a semiconductor using high electric fields. High efficiency and low voltage EL devices suitable for flexible display devices may be realized by this research.
- Optical Fiber Liquid Crystal Display Technology: A new type of display using the combination of a uniquely woven optical fiber array, light emitting diodes, and liquid crystal-based light modulation achieves an intense full colour display suitable for public information in the form of an electronic poster. New optical components are being developed to optimize the performance of this system.

Approximate group size: 6

Facilities: Key facilities include sputter deposition and e-beam deposition equipment.

Publications:

- A.H. Kitai, Y. Xiang, G. Quan, F. Zhang, Q. Liu, "Sphere-Supported Thin Film Electroluminescent Technology", Proc. EL2004, 347-350, 2004.
- Y. Xiang, A. H. Kitai "Sphere-Supported Thin Film Electroluminescence, Properties and Modelling", Proc. EL2004, pp314-316, and p366.
- A.H. Kitai, "Oxide Phosphor and Dielectric Thin Films For Electroluminescent Devices", Thin Solid Films 445, 367-376, 2003.

Website: http://mse.mcmaster.ca/faculty/kitai/index.htm

Kleiman, Rafael N., McMaster University

The approach taken by this group is to combine different materials to capture a greater share of the solar spectrum, into multi-junction photovoltaic solar cells. The strategy commonly used today uses high-cost substrates such as germanium, and has mostly been deployed for spacebased applications. However, solar-grade silicon crystal technology being developed by ARISE Technologies has the potential to make the discovery cost-competitive for large-scale down-toearth applications. Rafael Kleiman and John Preston, professors of engineering physics at McMaster, discovered a patent-pending method of applying single crystal layers of compound semiconductors, such as gallium-arsenide, on single crystal silicon crystal which they expect will convert sunlight to electricity twice as efficiently as other materials systems commonly in use. The ability to deposit high quality single crystal layers of selected chemical elements is key to absorbing and converting more sunlight to electricity, but achieving the necessary alignment on silicon was thought to be highly improbable at a large scale. The silicon-based multi-junction solar cells being developed leverage existing solar cell manufacturing technologies, which should speed time to commercialization and keep costs competitive.

Approximate group size: 13

% devoted to PV research: 80%

Collaboration with Industry: Yes

Facilities:

Facilities include:

- Centre for Emerging Device Technologies (CEDT): III-V MBE, PECVD, ion implantation, full fabrication capabilities, thin film x-ray characterization, and optical characterization. The new Laboratory for Advanced Photovoltaic Research will add MOCVD and extensive electro-optical material and device characterization specific to solar cells.
- Canadian Centre for Electron Microscopy (CCEM):SEM, FIB, high resolution TEM
- Brockhouse Institute for Materials Research (BIMR): Extensive x-ray characterization suite

Publications:

- “Fabrication of nanoscale single crystal InP membranes”, O. V. Hulko, B. J. Robinson and R. N. Kleiman, Appl. Phys. Lett., 91, 053119 (2007).
- "Drift-Free, 1000G Mechanical Shock Tolerant Single-Crystal Silicon Two-Axis MEMS Tilting Mirrors in a 1000x1000-Port Optical Crossconnect", A. Gasparyan, H. Shea, S. Arney, V. Aksyuk, M.E. Simon, F. Pardo, H.B. Chan, J. Kim, J. Gates, J. S. Kraus, S. Goyal, D. Carr and R. N. Kleiman, post deadline paper PD36-1, OFC (2003).
- "Alternative Training Methodologies for Large Scale Optical Crossconnects", R. N. Kleiman, LU Proprietary Technical Memorandum, April 10, 2002.

*Website:*http://engphys.mcmaster.ca/faculty_staff/faculty/kleiman/index.htm

LaPierre, Ray, McMaster University

The focus is developing semiconductor nanowires for solar cells. Nanowires are one-dimensional rods with lengths of several microns and diameters typically around 10 to 100 nm. Nanowires are grown by a metal-assisted deposition process in which metal nanoparticles collect vapor-deposited adatoms. In this lab nanowires are grown using physical vapor deposition which allows precise control of nanowire geometry. The diameter of nanowires is determined by the size distribution of the metal seed particles, while their length is controlled by the growth duration. The implementation of p-n junctions and III-V compound semiconductor heterostructures in the nanowires, essential for high efficiency photovoltaics, are accomplished by gas phase switching during growth. Single crystal nanowires can be grown with excellent electronic and optical properties comparable to Generation I material. The photon absorption, electron-hole separation, and charge transport mechanisms can all be improved in solar cells by implementing nanowire technology. Semiconductor nanowires therefore have great potential for improving the efficiency and reducing the manufacturing cost of solar cells.

Approximate group size: 9

% devoted to PV research: 90%

Collaboration with Industry: Yes

Facilities:

Epitaxial growth facilities (molecular beam epitaxy) for III-V materials are available at McMaster's Centre for Emerging Device Technologies. High resolution transmission electron microscopy facilities are available at the Brockhouse Institute for Materials Research. Solar cell testing facilities are available in the lab.

Publications:

- J. Caram, C. Sandoval, M. Tirado, D. Comedi, J. Czaban, and R. R. LaPierre, *Electrical characteristics of core-shell p-n GaAs nanowire structures with Te as the n-dopant*, Nanotechnology (accepted for publication, April, 2010).
- E. De Jong, R R LaPierre, and J. Z. Wen, *Detailed modeling of the epitaxial growth of GaAs nanowires*, Nanotechnology 21 (2010) 045602.
- P.K. Mohseni, A.D.Rodrigues, J.C.Galzerani, Y.A. Pusep, and R.R. LaPierre, *Structural and optical analysis of GaAsP/GaP core-shell nanowires*, J. Appl. Phys. 106 (2009) 124306.
- H. Bi and R.R. LaPierre, *GaAs nanowire/P3HT hybrid photovoltaic device*, Nanotechnology 20 (2009) 465205.
- M.C. Plante and R.R. LaPierre, Analytical description of the metal-assisted growth of III–V nanowires: axial and radial growths, J. Appl. Phys. 105 (2009) 114304.

Website: http://engphys.mcmaster.ca/faculty_staff/faculty/lapierre/

Leclerc, Mario, Université Laval

The research focuses on the synthesis and characterization of new organic materials (polycarbazoles, polyindolocarbazoles) in different applications such as photovoltaic cells, organic field-effect transistors and thermoelectric materials; also, the characterization of these new molecules with respect to their thermal, physical, and electrical properties. Once we have established a certain potential for the materials it will be possible to test them in real devices. For many applications, it is well known that there is great interest in materials which are able to organize efficiently in three dimensions. This properties enhances the charge transport in the materials which is a requirement to provide a good organic field-effect transistors and photovoltaic cells. Recent work includes studies of new low-bandgap poly(2,7-carbazole) derivative for use in high-performance solar cells; studies towards a rational design of poly(2,7-carbazole) derivatives for solar cells; and charge transport, photovoltaic, and thermoelectric properties of poly(2,7-carbazole) and poly(indolo[3,2-b]carbazole) derivatives.

Approximate group size: 12

% devoted to PV research: 50%

Collaboration with Industry: Yes

Facilities:

Key facilities include equipment for the synthesis and characterization of novel polymeric materials, and basic characterization of solar cells.

publications:

- S. Beaupré, P.-L. T. Boudreault, and M. Leclerc, (Invited Review), "Solar Energy Production and Energy Efficient Lighting: Photovoltaic Devices and White-Light-Emitting Diodes Using Poly(2,7-fluorene), Poly(2,7-carbazole) and Poly(2,7-dibenzosilole) derivatives", *Adv. Mater*., adma.200903484, in press.
- B. Liu, A. Najari, C. Pan, M. Leclerc, D. Xiao, and Y. Zou, 'New Low Bandgap Dithienylbenzothiadiazole Vinylene Based Copolymers : Synthesis and Photovoltaic Properties', *Macromol. Rapid Commun*., DOI:10.1002/marc.200900654, on the web.
- P.-L. T. Boudreault, S. Beaupré, and M. Leclerc (Invited Review for the First Issue), "Polycarbazoles for Plastic Electronics", *Polym. Chem*., DOI:10.1039/b9py00236g, on the web.
- T.-Y. Chu, S. Alem, P.G. Verly, S. Wakim, J. Lu, Y. Tao, S. Beaupré, M. Leclerc, F. Bélanger, D. Désilets, S. Rodman, D. Waller, R. Gaudiana, "Highly efficient polycarbazole-based organic photovoltaic devices" *Appl. Phys. Lett*., 95, 063304 (2009).
- Y.P. Zou, D. Gendron, R. Neagu-Plesu, and M. Leclerc, "Synthesis and Characterization of New Low-Bandgap Diketopyrrolopyrrole-Based Copolymers", *Macromolecules,* 42, 6361-6365 (2009).

Website: http://www.chm.ulaval.ca/poly_conducteurs/site_e.htm

Lu, Z.H., University of Toronto

High efficiency heterojunction solar cells; thin-film organic semiconductors; organic electronic and optoelectronic materials and devices; nano-structured materials; Atomic structure of surfaces and interfaces.

Approximate group size: 6

% devoted to PV research: 30%

Collaboration with Industry: No

Facilities:

Spin coating of polymer solar cells; vacuum deposition of small organic cells; solar cell testing facilities; organic optoelectronic device fabrication cluster tools; XPS/UPS characterization

Publications:

- G.B. Murdoch, S. Hinds, E.H. Sargent, S.W. Tsang, L. Mordoukhovski, and Z.H. Lu, "Aluminum doped zinc oxide for organic photovoltaics", Appl. Phys. Lett. **94**, 213301 (2009).
- Z.B. Wang, M.G. Helander, M.T. Greiner, J. Qiu, and Z.H. Lu, "Analysis of charge-injection characteristics at electrode-organic interfaces: Case study of transition-metal oxides", Phys. Rev. B **80**, 235325 (2009).
- M.G. Helander, Z.B. Wang, M.T. Greiner, J. Qiu, and Z.H. Lu, "Substrate dependent charge injection at the V_2O_5/organic interface", Appl. Phys. Lett. **95**, 083301 (2009).
- Z.B. Wang, M.G. Helander, M.T. Greiner, J. Qiu, and Z.H. Lu, "Carrier mobility measurement of organic semiconductors based on current-voltage characteristics", J. Appl. Phys. **107**, 034506 (2010).

Website: http://www.ecf.utoronto.ca/~luzheng/

Marsan, Benoît, Université du Québec à Montréal

The long term objective of the research is to develop a compact, flexible, highly efficient, stable and low-cost Electrochemical Photovoltaic Cell (EPC) based on a novel solvent-free gel electrolyte in junction with highly porous n-type CuInS2 or Cu(In,Al)S2. To reach this objective, the three main components of the cell (thin-film nanocrystalline semiconductor anode, redox gel electrolyte and CoS-based cathode) are being studied. Modifications of a published colloidal method to prepare n-type CuInS2 particles led to a significant improvement of the material chemical and crystalline properties. An original aspect of this work is that the nature of the sulphur precursor (inorganic vs organic) strongly influences the particles properties. However, material surface contamination (or oxidation) and the large excess of indium motivated us to develop a novel and simple colloidal method using a coordinating solvent. The new method provides pure and more crystalline CuInS2 particles with a better control of the stoichiometry, yielding to an n-type (Cu/In<1.0) or a p-type (Cu/In>1.0) semiconductivity. Gel electrolytes with a liquid component containing new redox couples dissolved in an ambienttemperature ionic liquid are also studied. These liquid systems are transparent and characterized by a high electrochemical reversibility, a very good ionic conductivity, a high thermal stability, an electropositive potential that can be modulated by the choice of the molecules and a low toxicity.

Approximate group size: 18

Facilities:

Solar simulator, glove box, multipotentiostat / frequency analyzer (electrochemical measurements, impedance spectroscopy), BET analyzer (specific surface area), SEM/EDX, XRD, ICP-AES, FTIR, Van der Pauw method (material electrical resistivity), XPS, UV-Visible spectroscopy, NMR (300 and 600 MHz), ionic conductivity cells, programmable oven (annealing under vacuum possible), DSC/TGA, spin coater.

Publications:

- Courtel, R.W. Paynter, R. Imbeault, B. Marsan and M. Morin (2007), "Synthesis of Colloidal CuInS2 for Electrochemical Photovoltaic Cells", Solar Energy Mat. Solar Cells, accepted on December 20, 2007.
- Renard, H. Li and B. Marsan (2003), "Ionic properties of non-aqueous liquid and PVdF-based gel electrolytes containing a cesium thiolate/disulfide redox couple", Electrochim. Acta, 48/7, 831-844.
- Hammami, A. Ndedi Ntepe, F. Courtel, R. Imbeault, M. Hébert, A. Anghel and B. Marsan (2006), "Optimization, prototyping and scale-up of a photovoltaic electrochemical cell", final report, 12 pages. (NSERC: Idea to Innovation, I2I – Phase 2a)

Website: http://www.cqmfscience.com/fr/membres/benoitmarsan.html

Mascher, Peter, McMaster University

Defect Spectroscopy in Electronic Materials: The focus is on III - V semiconductors, Cd and Zn based

II-VI compounds, and oxide dielectics and as titanates and tantalates.

Plasma Deposition of Oxide and Nitride Thin Films : Of primary interest are silicon oxynitride films

which act as anti- or high reflection coatings and are also the basic materials for optical waveguides

Optical and Structural Characterization of Luminescent Si-nanocluster Systems: We are working on the characterization Si-nc/Si oxide/nitride materials obtained from thin films deposited by plasma-enhanced chemical vapor deposition and subsequent thermal annealing, towards an understanding of the formation process of and light emission from Si-nc embedded in amorphous Si oxide/nitride systems. We are also exploring rare-earth (Tb, Ce, Eu, Er) doped silicon oxides (oxygen-rich or silicon-rich), deposited by ECR-PECVD, as light emitting materials.

Facilities:

Publications:

- J. N. Milgram, *J. Wojcik*, P. Mascher, and A. P. Knights, "Optically pumped Si nanocrystal emitter integrated with low loss silicon nitride waveguides," Opt. Express **15**, 14679-14688 (2007)
- J. N. Milgram, *J. Wojcik*, P. Mascher, and A. P. Knights, "Opticallypumped Si nanocrystal emitter integrated with low loss silicon nitride waveguides," Opt. Express **15**, 14679-14688 (2007)
- *S. Neretina*, R.A. Hughes, J.F. Britten, N.V. Sochinskii, J.S. Preston, and P. Mascher, “Vertically aligned wurtzite CdTe nanowires derived from a catalytically driven growth mode”, Nanotechnology **18**, 275301 (2007) [paper chosen as a featured article and for the cover page]
- *S. Neretina*, R.A. Hughes, J.F. Britten, N.V. Sochinskii, J.S. Preston, and P. Mascher, “Vertically aligned wurtzite CdTe nanowires derived from a catalytically driven growth mode”, Nanotechnology **18**, 275301 (2007) [paper chosen as a featured article and for the cover page]

Website: http://engphys.mcmaster.ca/faculty_staff/faculty/mascher/

Mi, Zetian, McGill University

The group is currently exploring the full potential of novel InGaN nanoscale materials and developing low cost solar cells on a Si platform, with efficiency comparable to, or better than the best reported III-V solar cells. Recently, it has been discovered that the energy band-gap or absorption spectrum of $In_xGa_{1-x}N$ alloy can be continuously varied from 0.7 to 3.4 eV, representing the only semiconductor that can match almost perfectly to the solar spectrum. Therefore, drastically improved efficiency is expected from InGaN solar cells, compared to any other devices. More importantly, high quality InGaN can be grown directly on Si substrates, which eliminates the use of expensive III-V substrates. The nitrides also exhibit many favorable photovoltaic properties, including high carrier mobility, low effective carrier mass, high peak and saturation velocities, and high absorption coefficients. Additionally, the use of a single ternary alloy material for the design of tandem solar cells offer a number of distinct advantages, including greatly reduced manufacturing costs and improved device reliability, due to the minimal thermal and lattice mismatches. InGaN is also non toxic and environmentally friendly.

Approximate group size: 6

% devoted to PV research: 50%

Collaboration with Industry: No

Research facilities:

Molecular beam epitaxial growth system of III-nitride based compound semiconductors; Photoluminescence, Hall, solar simulator

Publications:

- Y.-L. Chang, J. L. Wang, F. Li and Z. Mi, "High efficiency green, yellow, and amber emission from InGaN/GaN dot-in-a-wire heterostructures on Si(111)," Appl. Phys. Lett., vol. 96, 013106, 2010. Also appeared in *Virtual Journal of Nanoscale Science & Technology*, vol. 21, iss. 3, 2010.
- Y.-L. Chang, F. Li, A. Fatehi, and **Z. Mi**, "Molecular beam epitaxial growth and characterization of non-tapered InN nanowires on Si(111)," *Nanotechnol.*, vol. 20, 345203, 2009.
- S. Vicknesh, F. Li, and **Z. Mi**, "Optical microcavities on Si formed by self-assembled InGaAs/GaAs quantum dot microtubes," *Appl. Phys. Lett.,* vol. 94, 081101, 2009.
- M. Zhang, P. Bhattacharya, **Z. Mi**, and J. Moore, "Polarization effects in self-organized InGaN/GaN quantum dots grown by RF-plasma assisted molecular beam epitaxy," *J. Crystal Growth*, vol. 311, pp. 2069-2072, 2009.

Website: http://www.ece.mcgill.ca/~zmi/

Morin, Jean-Francois, Université Laval

Research activities aim to use chemical reactions to introduce electron-withdrawing and electron-deficient moieties onto the fullerene cage in order to modulate the LUMO level to obtain perfect match with LUMO level of different conjugated polymers. The modulation can be accomplished either by through-bond or through-space interactions. C_{60} derivatives with specific LUMO energy level can be prepared for each conjugated polymers such as P3HT, poly(2,7-carbazole) derivatives or other high performance polymers. In addition, to synthesize those derivatives, we perform all the basic characterization such as cyclic voltammetry, optical and fluorescence spectroscopy, electronic microscopy of polymer/C_{60} derivatives blend and stability test. The objective is to replace the « universal » PCBM by more efficient tailor-made n-type materials.

Another project involves the preparation of a block copolymer with high mass percentage of C_{60} into the structure. In this case, the goal is to obtain better morphological control in active thin film of a BHJ solar cells.

Approximate group size: 17

% devoted to PV research: 25%

Collaboration with Industry: Yes

Facilities:

Facilities consist mostly of brand new labs for organic synthesis with all the characterization tools needed to achieve small molecules and polymeric materials analysis, and include a state-of-the-art scanning probe microscopes.

Publications:

- Fiset, E.; Morin, J.-F. Synthesis, Characterization and Modification of Dendronized Diblock Copolymers Having Azide-Containing Surface, *Polymer* 2009, *50*, 1369.
- Rondeau-Gagné, S.; Grenier, F.; Curutchet, C.; Scholes, G. D.; Morin, J.-F. Synthesis and Electrochemical Characterization of New C_{60} Derivatives for Organic Electronic Applications, *Tetrahedron*, accepted.

Website: http://www.chm.ulaval.ca/jfmorin/2009/Accueil.html

Nunzi, Jean-Michel, Queens University

The research covers nanostructured organic and polymer solar cells: incorporation of carbon nanotubes, metal nanoparticles and the multiscale aspects of charge transport in nanostructured polymer materials.

Approximate group size: 7

% devoted to PV research: 70%

Collaboration with Industry: Yes

Facilities:

Chemistry lab, spin coatingfacilities, spectrometers, LBIC, XPS, vacuum deposition system, semiconductor probe analyzer

Publications:

- F. Liu, G. Aldea, J.M. Nunzi, J. 'Metal Plasmon Enhanced Europium Complex Luminescence', *Lumin*. 130, 56-59 (2010)
- C. Peptu, V. Harabagiu, B.C. Simionescu, G. Adamus, M. Kowalczuk, J.M. Nunzi, J. 'Disperse Red 1 End Capped Oligoesters. Synthesis by Non-catalyzed Ring Opening Oligomerization and Structural Characterization', *Polym. Sci. A: Polym. Chem.* 47, 534-547 (2009)
- A.K. Pandey, P.E. Shaw, I.D.W. Samuel, J.M. Nunzi, 'Effect of metal cathode reflectance on the exciton- dissociation efficiency in heterojunction organic solar cells', *Appl. Phys. Lett*. 94, 103303 (2009)
- A.M.C. Ng, A.B. Djurisic, W.K. Chan, J.M. Nunzi, 'Near infrared emission in rubrene:fullerene heterojunction devices', *Chem. Phys. Lett*. 474, 141-145 (2009)

Website: http://www.chem.queensu.ca/Publications/nunzi.asp

O'Leary, Stephen, University of British Columbia

Current research on optical response of disordered semiconductors; dislocations and occupancy in III-V semiconductors; occupancy in disordered semiconductors; the mobility edge and the properties of disordered semiconductors. The research program aims (1) to study some of the fundamental materials issues related to novel electronic materials, and (2) to explore the resultant device implications. The overall goal of these research endeavors is to advance our understanding of novel electronic materials, to provide researchers in the field with tools for the analysis of these materials, and to equip the emerging novel electronic materials industry with engineering methodologies for device design and optimization.

Approximate group size: 6

% devoted to PV research: 40%

Collaboration with Industry: No

Publications:

- F. Orapunt and S.K. O'Leary, Optical transitions and the mobility edge in amorphous semiconductors: A joint density of states analysis, Journal of Applied Physics, Volume 104, pages 073513-1-14, 2008.
- S.K. O'Leary, B.E. Foutz, M.S. Shur, and L.F. Eastman, Steady-state and transient electron transport within the III-V nitride semiconductors, GaN, AlN, and InN: A review, Journal of Materials Science: Materials in Electronics, Volume 17, pages 87-126, 2006.

Website: http://web.ubc.ca/okanagan/engineering/faculty/o_leary.html

Ozin, Geoff, University of Toronto

The unique ability of photonic crystals to localize and slow light is applied to the development of drastically more efficient solar cells - specifically, a chemistry approach is utilized for the creation of enhanced efficiency silicon photonic crystal solar cell, up-conversion silicon photonic crystal solar cell and dye sensitized photonic crystal solar cell.

An innovative strategy that simultaneously amplifies the harvesting of both photons and improves charge collection in a new kind of DSSC whereby a composite cathode in which current collector, photoactive element, sensitizer and electrolyte are integrated into a single unit without sacrificing light harvesting capabilities is investigated. Dramatic efficiency gains are anticipated using the proposed new design of DSSC that are expected to go well beyond the incremental improvements in performance currently being realized by continued refinement of molecules and materials exploited by DSSC practitioners around the world.

Approximate group size: 8

% devoted to PV research: 30%

Collaboration with Industry: Yes

Facilities:

- Centre for Nanostructure Imaging (SEM, TEM, Confocal, …)
- Emerging Communications Technology Institute (Clean Rooms, E-Beam Nanolithography, Etching, …)
- Institute for Optical Sciences (Lasers, Spectrophotometry, …)
- Surface Interface Ontario (XPS, SIMS, …)

Publications:

- Wang, W., Grozea, D., Kim, A., Perovic, D.D., Ozin, G.A., 2010, Vacuum-Assisted Aerosol Deposition (VAAD) of Low k Periodic Mesoporous Organosilica (PMO) Film, *Adv. Mater*. 22, 99-102.
- O'Brien, P.G., Puzzo, D.P., Chutinan, A., Bonifacio, L.D., Kherani, N.P., Ozin, G.A., 2010, Selectively Transparent and Conducting One-dimensional Photonic Crystals, *Adv. Mater*. 22, 611-616.
- Mirkovic, T., Zacharia, N., Scholes, G.D., Ozin, G.A., 2010, Nanolocomotion:
- Catalytic Nanomotors and Nanorotors, *Small* 6, 159-167 .
- Bonifacio, L.D., Puzzo, D.P., Willey, B.M., Kamp, U., McGeer, A., Ozin, G.A., 2009, The Photonic Nose: Combinatoric Molecule to Bacteria Sniffing, *Adv. Mater*. 21, early view.

Website: http://www.chem.utoronto.ca/staff/GAO/index_old.htm

Pearce, Joshua M., Queens University

Research to control or eliminate the Staebler-Wronski Effect (SWE), which limits the ecological and economic promise of a-Si:H solar cells because of the light induced degradation of its electronic properties. Also, research to create a well-designed InGaN solar cell that can absorb and convert a much higher fraction of the sun's light energy into electricity. In addition, research to optimize amorphous PV cells at high temperatures for integration into a PV/T systems using a-Si and InGaN materials; developing incentives to encourage green design and recycling into PV manufacturing; snow cover and hydrophobic thin film coatings for Canadian applications; methodology for designing photovoltaic systems in the unique environmental, financial and political environment of Ontario.

Approximate group size: 17

% devoted to PV research: 80%

Collaboration with Industry: Yes

Facilities:

Solar photovoltaic characterization laboratory: class AAA solar simulator; temperature controlled light and dark current voltage (LIV, DIV) and photoconductivity; an integrating sphere with a spectrophotometer to do emissivity measurements; Woollam Vase spectroscopic ellipsometer with extended range 190-1700nm and ability for T&R and scatterometry; temperature controlled PV measurements spectral response; custom designed dual beam photoconductivity for looking at sub-bandgap absorption; fully automated outdoor test facilities and meteorological station.

Publications:

- H.T. Nguyen and J.M. Pearce, "Estimating Potential Photovoltaic Yield with r.sun and the Open Source Geographical Resources Analysis Support System" *Solar Energy (in press).*
- L.K. Wiginton, H. T. Nguyen, J.M. Pearce, "Quantifying Solar Photovoltaic Potential on a Large Scale for Renewable Energy Regional Policy", *Computers, Environment and Urban Systems*, (in press)
- R. Kenny, C. Law, J.M. Pearce**,** "Towards Real Energy Economics: Energy Policy Driven by Life-Cycle Carbon Emission", *Energy Policy* 38, pp. 1969–1978, 2010.
- J. M. Pearce, "Expanding Photovoltaic Penetration with Residential Distributed Generation from Hybrid Solar Photovoltaic + Combined Heat and Power Systems", *Energy* **34**, pp. 1947-1954 (2009).

Website: http://me.queensu.ca/people/pearce/

Perepichka, Dimitri, McGill University

Synthesis of organic semiconductors for photovoltaic energy harvesting. Synthesis and studies of up-converting nanoparticles for NIR energy harvesting. Synthesis of organic dyes for fluorescent solar concentrations

Approximate group size: 11

% devoted to PV research: 30%

Collaboration with Industry: No

Facilities:

Organic/nanomateirals synthesis lab; UV-Vis-IR spectroscopy, electrochemistry, electrical measurements probe station.

Publications:

- M. MacLeod, O. Ivasenko, C. Fu, T. Taerum, F. Rosei, D.F.Perepichka, Supramolecular ordering in oligothiophene-fullerene monolayers studied by STM, *J. Am. Chem. Soc.* **2009**, 131, 16844
- A. Demenev, S. H. Eichhorn, T. Taerum, D. F. Perepichka, S. Patwardhan, F. C. Grozema, L. D. A. Siebbeles, Quasi Temperature Independent Charge Carrier Mobility in Hexagonal Columnar Mesophases of H-Bonded Benzotristhiophene Derivative, *Chem. Mater*. **2010**, *22*, 1420.
- S. Jeeva, O. Lukoyanova, A. Karapanayiotis, A. Dadvand, D.F. Perepichka, New Highly Emissive Thienylene-Vinylene Oligomers and Co-Polymers for Organic Electronics, *Adv. Funct. Mater*. in press.

Website: http://perepichka-group.mcgill.ca/

Pulfrey, David, University of British Columbia,

Improvement of the efficiency of CdTe-based cells by the use of a tandem cell, CdTe/Ge structure. Fabrication of graphene/silicon solar cells. The novelty is that the graphene performs the multiple functions of transparent top metal contact and inducer of a depletion region (Schottky barrier).

Approximate group size: 2

% devoted to PV research: 80%

Collaboration with Industry: No

Facilities:

Full facilities of AMPEL laboratory are available.

Publications:

- D.L. Pulfrey, J. Dell and L. Faraone, "Performance predictions for CdTe/Ge thin-film tandem solar cells", Photonics North 2010.

Website**:** http://www.ece.ubc.ca/~pulfrey/#Research Interests

Rochefort, Alain, École Polytechnique de Montréal

Perform quantum mechanical calculations such as DFT on organic photovoltaic materials, more especially on blend of polymer and molecular species. Mainly interested on the effect of structural organization on the electronic properties of organic bulk heterojunctions.

Approximate group size: 2

% devoted to PV research: 25%

Collaboration with Industry: No

Facilities:

The group has 2 computer clusters (16 and 64 processors), and access to the RQCHP for high performance computing

Publications:

- Arnaud Maillard, Alain Rochefort, Structural and Electronic Properties of poly(3-hexylthiophene) π-Stacked Crystal, *Physical Review B, 79* (2009), 115207.
- Arnaud Maillard, Alain Rochefort, Electronic Properties of Well-Ordered rrP3HT/C60 Bulk Heterojunction,
- submitted to J. Phys. Chem. C., march 2010.

Website : http://www.polymtl.ca/recherche/rc/en/professeurs/details.php?NoProf=269

Ross, Guy, Institut national de la recherché scientifique, Varennes

The objective is to establish the parameters of synthesizing nanocrystals of Si and Ge to acquire high efficiency (~45%) photovoltaic cells, based on expertise acquired in the study of nanocrystals for the development of a laser (see A. Lacombe, et al., Appl. Phys. Lett., 94 (2009) 012112).

Approximate group size: 4

% devoted to PV research: 10%

Collaboration with Industry: Yes

Facilities:

- Ion implanter in clean room for the production of silicon nanocrystals
- Furnace for annealing up to 1500 ^{o}C for Si-SiO_2 phase separation
- Two spectrometers for photoluminescence and electroluminescence characterization; Ellipsometer;I-V characterization

Website: http://www.emt.inrs.ca/Anglais/indexProfesseur.jsp?page=RossGuyG_ProjetEquipe&param=RossGuyG

Ruda, Harry E., University of Toronto

Working in PV for past 15 years. Crystalline silicon and tandem multijunction solar cells

Approximate group size: 25

% devoted to PV research: 30%

Collaboration with Industry: Yes

Facilities:

Semiconductor Growth (MBE, MOCVD and CVD), Processing (eBL, Photolithography, Dry and Wet Processing) in Clean Rooms, Optical Characterisation (Solar Simulators, Absorption, SPV, PL, PLE, PR, time resolved ultrafast measurements, NSOM, etc), Electrical Characterisation (Hall, DLTS, IV/CV, all variable temperature, Ultra-low temperature measurements in dilution refrigerator), EBIC, CL.

Website: http://www.mse.utoronto.ca/contacts/Professors/Ruda__Harry_E_.htm

Santato, Clara, École Polytechnique de Montréal

Research in the following three areas:

Harvesting Lost Photons: Minimizing Sub-Bandgap Losses in Organic Photovoltaic Devices by Up-conversion: The objective is to increase the efficiency of organic photovoltaic (OPV) cells in the near-infrared region of the solar spectrum by blending the organic semiconductors with rare-earth doped nanoparticles with up-converting photophysical properties.

*New self-assembled polymerazomethines for photoactive layers in photovoltaic devices:*The project objectives are to synthesize new polyazomethines to be used as photo-active materials (PAM) and to fabricate *bottom-up* organic photovoltaic devices from these polymers.

Bio-organic molecules for electronic applications and electrochemistry; melanin compounds: This project deals with the exploration of thin films of melanin pigments for the realization of organic transistors, phototransistors, and photovoltaic devices.

Approximate group size: 8

% devoted to PV research: 40%

Collaboration with Industry: Yes

Research facilities:

- Solution processing equipment for organic semiconductors.
- Glove box for working in inert (nitrogen) atmosphere of organic semiconductors and PV cell assembly.
- Optoelectronic probe station to characterize the electrical properties of the organic films that are the active components of the PV devices.
- Shared facility in Pav. Bombardier, UdeM campus: solar simulator and electronic equipment for PV device characaterization. Possibility to measure the PV performance as a function of the temperature. Thermal evaporating system to deposit by vacuum sublimation PV films.

Publications:

- J. Miwa, F.Cicoira, J.Lipton-Duffin, C.Santato, D.F.Perepichka, F.Rosei, *Scanning Tunneling Microscopy of rubrene thin films on Cu(111)*, Nanotechnology (2008) *19*, 424021-26 (featured on nanotechweb.org, Sept. 2008).
- C.Santato, C.M.Lopez, K.-S.Choi, *Synthesis and characterization of polycrystalline Sn and SnO2 films with wire morphologies,* Electrochemistry Communications (2007) *9*, 1519-1524.
- R. Solarska, C.Santato, C.Jorand-Sartoretti, M.Ulmann, J.Augustynski, *Nanostructured WO3 photoanodes for sea-water splitting*. SPIE Proc., 2006, 6340, 63400J/1-63400J/9.

*Website:*http://www.polymtl.ca/recherche/rc/en/professeurs/details.php?NoProf=388

Sargent, Edward H., University of Toronto

The objective is to make solar cells that are high in efficiency and low in cost. Over the past several years this group has made tremendous progress in this direction. The work involves colloidal quantum dots, semiconductor particles a few nanometres in diameter, processed from the solution phase. Quantum dots' energy gap, which determines the portion of the solar light spectrum the material can absorb, is programmed both by the choice of semiconductor material used, and also by the size of the particles. The approach relies on our proven ability to tune the size, and thus the bandgap, of our quantum dots, such that they absorb across the sun's full spectrum or - better still - to build devices whose constituent layers each efficiently harvest specific bands within the sun's broad spectrum. Any solar architecture that seeks to achieve ultra-high power conversion efficiencies must efficiently harvest the considerable energy of high-energy (blue) photons from the sun, and yet absorb low-energy (infrared) photons as well.

Approximate group size: 19

% devoted to PV research: 80%

Collaboration with Industry: Yes

Facilities:

Research and development takes place in three chemistry and film deposition laboratories, and four materials and device characterization laboratories. The facilities are a result of a multimillion dollar investment done over the last nine years, with two million dollars invested over the last year into the main solar facilities.

Publications:

- E. H. Sargent, "Infrared photovoltaics made by solution processing," Nature Photonics, vol. 3, pp. 325-331, 2009.
- V. Sukhovatkin, S. Hinds, L. Brzozowski, E. H. Sargent, "Colloidal quantum dot photodetectors exploiting multiexciton generation," Science, vol. 324, no. 5934, pp. 1542-1544, 2009.
- J. Tang, G. Konstantatos, S. Hinds, S. Myrskog, A. G. Pattantyus-Abraham, J. Clifford, E. H. Sargent, "Heavy-metal-free solution-processed nanoparticle-based photodetectors: Doping of intrinsic vacancies enables engineering of sensitivity and speed," ACS Nano, vol. 3, pp. 331-338, 2009.
- E. H. Sargent, "Solar cells, photodetectors, and optical sources from infrared colloidal quantum dots," Advanced Materials, vol. 20, no. 20, pp. 3958-3964, 2008.
- D. A. R. Barkhouse, A. G. Pattantyus-Abraham, L. Levina, E. H. Sargent, "Thiols passivated recombination centers in colloidal quantum dots leading to enhanced photovoltaic device efficiency," ACS Nano, vol. 2, pp. 2356 – 2362, 2008.

Website: http://light.utoronto.ca/

Sazonov, Andrei, University of Waterloo

Research is focusing on low-temperature thin film silicon devices, especially research on amorphous and nano-crystalline semiconductors and dielectrics for electronics on flexible substrates. Recently, the group developed materials and fabrication process for flexible amorphous silicon solar cells. Non-optimized test cells made of amorphous silicon at maximum temperature of 75 ºC (compatible with low-cost Mylar plastic foils) demonstrated efficiency of 4%, which is state of the art for deposition on such substrates. The group also developed lowtemperature deposition processes for nano-crystalline silicon (nc-Si) and proto-crystalline silicon (pc-Si) thin films which show enhanced light absorption in visible and infra-red ranges, respectively. Two strategies of increasing thin film solar cell conversion efficiency are pursued: i) tandem solar cells based on pc-Si/nc-Si; ii) single layer nc-Si QD/QW solar cells. Most recently, nc-Si thin films were fabricated changing the deposition conditions to obtain films with highly crystalline microstructure and small grain size. Optical, electrical, and structural properties of films were characterized which revealed implications for solar cell applications. It was shown that optical and electrical properties of nc-Si can be controlled by the grain boundary states and can be tuned between those of amorphous and crystalline Si by adjusting the deposition conditions. Nanocrystalline Si films with high crystallinity show enhanced photoconductivity typical for crystalline Si but with a-Si:H features as well.

Approximate group size: 12

Facilities:

Major facilities include a giga-to nanoelectronics fabrication centre for thin film single and tandem solar cells, including roll-to-roll deposition cluster tool (plasma enhanced CVD, RF and DC sputtering, thin film encapsulation and antireflective coating deposition), wet and dry etching facilities, optical and electrical characterization.

Publications:

- A.G. Kazanskii, O.G. Koshelev, A. Sazonov, and A.A. Khomich, "Photoconductiviy of amorphous hydrogenated silicon thin films," Semicond. (2008) 42: 192-194.
- M. R. Esmaeili Rad, A. Sazonov, A.G. Kazanskii, A.A. Khomich, and A. Nathan, "Optical Properties of Nanocrystalline Silicon Deposited by PECVD," *Journal of Materials Science: Materials in Electronics,* (2007) *18 (suppl.1):* 405-409.
- A.Sazonov, M.Meitine, D.Striakhilev, and A.Nathan, (2006) "Low Temperature Amorphous and Nanocrystalline Silicon Based TFTs for Flexible Electronics," *Fizika i Technika Poluprovodnikov* 40: 986-994 (*Semicond.* 40: 986-994).

Website: http://www.ece.uwaterloo.ca/~asazonov/

Scholes, Gregory D., University of Toronto

The development, operation, and improvement of a number of optoelectronic technologies hinge on understanding the relationships between light absorption or emission, structure at the molecule level, and the motion of charge. Studies of nanoscale systems are revealing details of their properties, characterized by atoms or molecules working together to capture and redistribute the energy carried by light. Most relevant to photovoltaics include development of flexible threedimensional

solar cell technologies using quantum dots, and designing semiconductors for the manipulation of light. Specifically, recent studies have focused on controlling the optical properties of inorganic nanoparticles; nanoscale organization of quantum dots and conjugated polymers using polymeric micelle templates (bio-inspired light-harvesting complexes; demonstration of bulk semiconductor optical properties in processible nanocrystalline Ag2S and EuS systems; exciton trapping and recombination in type II CdSe/CdTe nanorod heterostructures; insights into excitons confined to nanoscale systems: electron–hole interaction; interaction between excitons determines the nonlinear response of nanocrystals; and loading quantum dots into thermo-responsive microgels by reversible transfer from organic solvents to water.

Approximate group size: 10

% devoted to PV research: 30%

Collaboration with Industry: No

Facilities:

Nanocrystal synthesis, ultrafast spectroscopy, photoluminescence measurements. Major facilities: state-of-the-art multidimensional femtosecond spectroscopy laboratories.

Publications:

- Elisabetta Collini & Gregory D. Scholes, "Quantum coherent energy migration in a conjugated polymer at room temperature" Science 323, 369-373 (2009).
- Gregory D. Scholes, "Controlling the optical properties of inorganic nanoparticles" Adv. Funct. Mater., Invited Feature Article 18, 1157–1172 (2008).
- Karolina P. Fritz, Serap Guenes, Joseph Luther, Sandeep Kumar, N. Serdar Sariciftci, & Gregory D. Scholes, "IV-VI Nanocrystal–Polymer Solar Cells" J. Photochem. Photobiol. A Chem. 195, 39–46 (2008).
- Gregory D. Scholes, "Insights into Excitons Confined to Nanoscale Systems: Electron–hole Interaction, Binding Energy and Photodissociation" ACS Nano 2, 523–537 (2008).
- Sandeep Kumar & Gregory D. Scholes, "Colloidal nanocrystal solar cells" Microchimica Acta,Electrochemistry of Semiconductor Nanocrystals Special Issue 160, 315–325 (2008).

Website: http://www.chem.utoronto.ca/staff/SCHOLES/scholes_home.html

Shih, Ishiang, McGill University

Research activities with this group involve the growth of monocrystalline $CuInSe_2$ (CIS) in order to test the effects of varying stoichiometry on the characteristics and transport properties of the material. This is done through a comparison of thermoelectric power, electrical resistivity and Hall coefficient, used in combination to determine changes in carrier concentration and mobility with elemental composition. Work investigating the beneficial role of sodium on thin-film photovoltaic cells by growing bulk crystals in the presence of this element is ongoing. This work has cast doubt on the common belief that sodium acts as an acceptor in CIS by showing, for the first time, that the monocrystalline material is converted from p- to n-type when sufficient sodium is present during crystal growth. More recent work has refined this by showing the sufficient quantity of sodium required to be between 0.2 % and 0.3 atomic %. As well, we have discovered that this effect is heavily affected, and even negated, by the amount of selenium, above stoichiometry, present.

Approximate group size: 4

% devoted to PV research: 50%

Collaboration with Industry: No

Facilities:

Wet lab at McGill University containing Bridgman growth furnace for growing monocrystals of $CuInSe_2$, as well as a polisher for polishing wafers in the fabrication of solar cells, equipment for vacuum deposition, measurement instruments (current-voltage and capacitance-voltage, Hall effect and thermoelectric power), solar simulator, SEM.

Publications:

- C.H. Champness Bridgman-grown $CuInSe_2$, Chapter in "Thin Film Solar Cells," Nova Science Pub. Inc., 2010.
- H.F.Myers, C.H.Champness & I.Shih. Hall effect measurements on Bridgman-grown $CuInSe_2$ with sodium, Nanotechnology, **20**, 2009.
- C.H.Champness, H.F.Myers and I.Shih. Bridgman-grown $CuInSe_{2+x}$ with Na or Na_2Se. Thin Solid Films, **517**, 7, 2178-2183, 2009.
- C.H.Champness, T.Cheung & I.Shih. Room temperature transport measurements on Bridgman-grown p-type $CuIn_{1-x}Ga_xSe_2$ substrates. Solar Energy Materials & Solar Cells, **91**, 791-800, 2007.

Website: http://people.mcgill.ca/ishiang.shih/

Silva, Carlos, Université de Montréal

The thrust of our research addresses fundamental electronic processes in advanced electroactive materials, principally organic semiconductors. We focus on understanding primary photoexcitation dynamics in such advanced electroactive materials. To do so, we exploit various ultrafast, steady-state, and quasi-steady-state spectroscopies. In order for solar energy to have a more substantial impact on our energy requirements, we need to find alternative technologies that reduce energy payback periods and device processing costs. Our research group focuses on conjugated polymers, which now provide a technologically viable class of solution-processable, film-forming semiconductors.

Plastic solar cells, where the active semiconductors are conjugated polymers, are an exciting prospect because they provide an opportunity to produce low-cost devices for solar energy conversion, both in terms of processing and energy payback costs. In our research programme we characterise new materials and photovoltaic diode architectures, and we probe the physics underpinning device function to achieve sufficiently high solar power conversion efficiencies for real applications. Specifically, we seek to understand, by means of time-resolved optical spectroscopy, the dynamics of interfacial charge separation and recombination in polymer-based photovoltaic diodes fabricated in order to identify efficiency loss mechanisms.

Approximate group size: 10

% devoted to PV research: 75%

Collaboration with Industry: Yes

Facilities:

Extensive facilities to study photoexcitation dynamics in advanced electroactive materials by means of time-resolved and quasi-steady-state optical spectroscopies, including : Variable temperature double-optical-modulation apparatus; CCD camera for time-resolved photoluminescence spectroscopy; time-resolved photoluminescence facility for materials research; solution processing of organic semiconductor materials

Publications:

- Glowe, J. F. , Perrin, .M , Beljonne, D. , Hayes, S. C. , Gardebien, F. and Silva, C. (2010) *Charge-transfer excitons in strongly coupled organic semiconductors.* PHYSICAL REVIEW B, 81(4):041201. (BibTeX) Clark, J. , Chang, J. F. , Spano, F. C. , Friend, R. H. and Silva, C. (2009) *Determining exciton bandwidth and film microstructure in polythiophene films using linear absorption spectroscopy.* APPLIED PHYSICS LETTERS, 94(16):163306. (BibTeX)
- Schmidtke, J. P. , Friend, R. H. and Silva, C. (2008) *Tuning interfacial charge-transfer excitons at polymer-polymer heterojunctions under hydrostatic pressure.* PHYSICAL REVIEW LETTERS, 100(15):157401. (BibTeX)

Website: http://www.phys.umontreal.ca/~silva/

Sivoththaman, Siva, University of Waterloo

Research activities are underway on several fronts of photovoltaics: Epitaxial thin film solar cells, c-Si wafer devices, buried emitter PV devices, quantum dots as spectral converters, nanowire growth and device deployment, Si crystal growth and characterization, wire-sawing technology with low kerf losses, recrystalliaztion of thin films, electrochemical nanoporous formation, new spherical Si solar technology.

The overall aim is to develop high efficiency, affordable technologies that are scalable. The two major pathways of the research are, (i) working to improve current-industrial and near-future technologies, and (ii) technology- and knowledge- build-up for future (medium to long-term) PV technologies including third-generation PV. To meet the challenge of reaching ultra-high efficiencies with simplified nano-technologies, a comprehensive processing and characterization facility has just been set up.

Approximate group size: 14

% devoted to PV research: 100%

Collaboration with Industry: Yes

Facilities:

Crystal Growth: Czochralski crystal puller, Si recrystallization furnaces, ingot grinder, internal diameter saw, wiresaw, polishing & grinding equipment.

Thin Films: PECVD, LPCVD, Sputtering (dc/RF) tools

Metallization: Evaporator (e-beam/thermal), metal screenprinter, infer-red firing furnacs

Pattern Transfer: resist-coater, mask aligner

High temperature processes: Oxidation/diffusion (4-stak) furnaces, rapid thermal processor

Nano-PV: glove-box for Q-dot processing, e-beam writer, plasma and LPCVD processes for nanowires.

Characterization: Quantum efficiency, Solar simulator, High and low frequency C-V, Parametric analyzer, Lifetime/LBIC/Resistivity mapping, Hall effect, DLTS, Spectroscopic ellipsometry, FTIR, UV-Vis spectrophotometer, Photoluminesence, SEM, EBIC , Cathodoluminescence, EBSD.

Solar cell fabrication: Class 10,000 and 1000 cleanroom for prototyping, solar cell pilot line.

Module making: 60 cm x 60 cm lamination capability.

Publications:

- M. Gharghi and S. Sivoththaman, "Spherical silicon photovoltaic devices with surface-passivated shallow emitters", Semiconductor Science and Technology, vol.23, pp.(105008)1-6, 2008.

- M. Gharghi and S. Sivoththaman, “Growth and Structural Characterization of Spherical Silicon Crystals Grown from Polysilicon”, IEEE/TMS Journal of Electronic Materials, vol. 37, pp.1657-1664, 2008.
- Farrokh-Baroughi and S. Sivoththaman, "A Novel Silicon Photovoltaic Cell using a Low-temperature Quasi-epitaxial Silicon Emitter", IEEE Electron Device Letters, vol.28, pp.575-577, 2007.
- M. Gharghi and S. Sivoththaman, "Photoconductivity Decay in Silicon Spheres in Response to Impulse Light Stimulation", Journal of Materials Science: Materials in Electronics, vol.18, pp.S111-115, 2007.

Website: http://ece.uwaterloo.ca/~sivothth/

Tarr, Garry, Carleton University

Research involves experimentally characterizing photovoltaic devices incorporating a heterojunction(s) between structured inorganic semiconductor layers and coated organic layers. The three main components under investigation are:

1) Structured inorganic layer(s), initially single crystal Silicon (c-Si)
2) Interfacial passivation of inorganic material(s), grown thermally of by ALD
3) Conformal organic layer(s) of conducting polymer

Approximate group size: 3

% devoted to PV research: 40%

Collaboration with Industry: No

Facilities:

Silicon Microfab facility capable of all standard silicon processing operations, including LPCVD of doped and undoped polysilicon and PVD of a wide range of thin films; in-house photomask generation; extensive semiconductor device characterization capability; polymeric ink printing.

Utigard, Torstein, University of Toronto

The research is based on silicon alloying with copper, followed by slow cooling and solidification. This leads to the formation of nearly pure silicon dendrites and with most impurities collecting in the copper rich eutectic phase. By crushing and grinding we liberate the silicon grains from the eutectic phase. By the use of a heavy media with produce a nearly pure silicon section and a dense copper section. The light silicon fraction is nearly pure silicon but needs some additional surface cleaning such as acid rinsing etc. Further size reduction may also be needed. Another approach is to again alloy the silicon with copper, but this time use a molten flux to remove the impurities into the flux phase.

Approximate group size: 4

% devoted to PV research: 40%

Collaboration with Industry: No

Facilities:

High temperature silicon refining facilities, vapor deposition facilities

Publications:

- A. Mitrasinovic and T. Utigard, “Refining Si for solar cell application by Cu alloying”, Silicon, Accepted Dec 2009
- S.Fan, G. Plascencia and T. Utigard, High temperature electric conductivity of pure silicon, Canadian Metallurgical Quarterly, 47, 2008, 509-512(NSERC)
- M. Barati and T. Utigard, Solar Silicon, Patent Application, June 2009

Website: http://www.mse.utoronto.ca/contacts/Professors/utigard.htm

Watkins, S.P., Simon Frazer University

Growth of III-V semiconductors and nanostructures; transport in semiconductors; optical and structural properties of semiconductors; in general, materials issues relevant to PV devices.

Approximate group size: 6

% devoted to PV research: 20%

Collaboration with Industry: No

Facilities:

Two MOCVD facilities for growth of III-V and II-VI semiconductors by MOCVD.

Publications:

- He Huang, Z.W. Deng, D.C. Li, E. Barbir, W.Y. Jiang, M.X. Chen, K.L. Kavanagh, P.M. Mooney, S.P Watkins, "Effect of Annealing on Structural and Optical Properties of Heavily Carbon-Doped ZnO", accepted in Semicond. Science and Tech., 15 Feb. 2010
- D. Lackner, M. Martine, Y. T. Cherng, M. Steger, W. Walukiewicz, M. L. W. Thewalt, P. M. Mooney, and S. P. Watkins, "Electrical and optical characterization of n-InAsSb/n-GaSb heterojunctions", J. Appl. Phys., **107**, 014512 (2010) .
- O.J. Pitts, D. Lackner, Y.T. Cherng, S.P. Watkins, "Growth of InAsSb/InPSb heterojunctions for mid-IR detector applications", J. Cryst. Growth, **310** 4858 (2008).