RGC Ref.: M-HKU703/12
(please insert ref. above)

The Research Grants Council of Hong Kong
SRFDP & RGC ERG Joint Research Scheme
Completion Report

(Please attach a copy of the completion report submitted to the Ministry of Education by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Achieving high-efficiency polymer solar cells through newly solution-processed polymers, carrier transport layer materials and novel device structures

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Wallace C.H. Choy	Prof. Fei Huang
Post	Professor	Professor
Unit / Department / Institution	Department of Electrical & Electronic Engineering, the University of Hong Kong	State Key Laboratory of Luminescent Materials and Devices, South China University of Technology.
Contact Information		
Co-investigator(s) *(with title and Institution)*		
PhD student(s) (with period of involvement)	Name: Xinchen Li (01/09/2014 -31/08/2015), Shunmian Lu (1/09/2014 -29/02/2016), Hong Zhang (1/09/2014 -29/02/2016) Lu Zhu(1/09/2014 -29/02/2016) Institution: the University of Hong Kong	Ming Wang (2013/03/01-2015/02/28), Yang Dong (2013/05/01-2015/4/30), Shengjia Liu (2013/06/01-2015/05/30), Kai Zhang (2013/03/01-2015/02/28) Wei Li (2014/12/01-2016/2/29) South China University of Technology

Note: The Hong Kong project team must involve at least one research postgraduate student pursuing a Doctor of Philosophy degree at the UGC-funded university (PhD student) at any time throughout the project period.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01/03/2013		01/03/2013
Project Completion date	29/02/2016		29/02/2016
Duration *(in month)*	36		36
Deadline for Submission of Completion Report	30/11/2016		30/11/2016

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Synthesis new series of efficient polymer donor materials for high performance polymer solar cells (PSCs). Explore the new photoactive materials with the improved near-infrared absorption for tandem solar cells.

2. Develop the new solution-processed metal oxide as the carrier transport materials for improving the carrier extraction. Explore the underlying physics of the dipole layer as interconnecting layer of metal oxide/ dipole layer/ metal oxide in tandem solar cells.

3. Improve the carrier extraction and collection by the incorporation of the conjugated polymers and metal particles in metal oxide.

4. Enhance the light harvesting of polymer solar cells (PSCs) by plasmon-optical effects of the incorporated metal nanoparticles and Explore the manipulation of the transport path length of charge carriers (electron and hole) to corresponding electrodes by plasmon-electrical effects.

5. Train the PhD student and research colleagues for the growing field of organic optoelectronics. In addition, we will publish results in peer-reviewed journals

5.2 Revised Objectives

Date of approval from the RGC: _____

Reasons for the change: _____
_____

1.
2.
3. ....

6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

For photoactive materials, we have synthesized various polymer donor materials for PSCs with high VOC, good absorption and stability. [Adv. Mater. 25, 3683, 2013, Macromolecules 46, 3950, 2013; Chem. Asian J. 9, 2104, 2014] We found out the chain length of well-defined conjugated oligomers can be used to tune the thermal, optical, electrochemical and structural properties, which has promising applications as the complementary absorbers for tandem solar cells. [Adv. Funct. Mater. 24, 7538, 2014] Meanwhile, we have synthesized the polymer materials that emit light in different colors and the results have been published in Organic Electronics 15, 850, 2014 and ACS Appl. Mater. Interfaces. 6, 5113, 2014.

For carrier transport materials, we have developed the low temperature, ambient atmosphere, water free and solution processed approaches to make metal oxides based carrier transport layer with a highly modulated workfunction. [Adv. Funct. Mater. 24, 7348, 2014.] New organic-based electron transport layers are also developed. [Adv. Funct. Mater. 24, 6540, 2014.] With post-treatment of methanol and PFN, the performance of organic solar cells can be further improved as reported in Nanotechnology, 24, 484003, 2013.

For plasmon-optical effects, we have developed the multi-physics model for studying and exploring the device architectures and light managements for high performance PSCs. We introduced several optical designs using metal based nanostructures to increase the light trapping of PSCs and offered the design rules to improving the optical absorption of active layer with different optical modes and structural configurations. The works are published in Appl. Phys. Lett., 102, 251112, 2013, Chem. Comm., invited, 50, 11984-11993, 2014,Progress In Electromagnetics Research (PIER), invited, 146, 25-46, 2014 and Small, 12,. 1547–1571, 2016.

For plasmon-electrical effects, besides the enhanced exciton generation by plasmon-optical effects, we conceived the concept of plasmon-electrical effects for improve the electrical properties of PSCs such as carrier accumulation, extraction and transportation etc. (a) The plasmonic excited hot carriers favor the trap filling in carrier transport layer and thus eliminate charge accumulations for better carrier extractions. [Adv. Funct. Mater. 23, 4255, 2013, ACS Appl. Mater. Interfaces, 6, 5367, 2014] (b) Through modifying the locations of exciton generation regions by plasmonic metal nanostructures, we offered an approach to break the space charge limit which is fundamentally important for achieving high performance and good stability PSCs. Meanwhile, we can achieve a better balance of carrier transportations in active layer through manipulate the carrier transport path length by plasmon-electrical effects in terms of optimizing the spatially distributed metal nanostructures. The results are published in Scientific Reports, 4, 6236, 2014 and Scientific Reports, 5, 8525, 2015.

For tandem solar cells, we theoretically have explored thermionic emission that has a significant impact on the recombination layer between top and bottom junction in tandem solar cells. We proposed a new interconnecting layer with structure of metal oxide/dipole layer/metal oxide for tandem solar cells. The underlying physics of the proposed interconnecting layer for reducing the V_{OC} loss and removing the *S*-shaped *J*-*V* curves are elucidated. The results are published in Adv. Energy Mat., 5, 1500631, 2015 and Nano Energy, 21, 123–132, 2016.

Potential for further development of the research and the proposed course of action *(maximum half a page)*

The synthesized low bandgap polymer materials can be used to fabricate high efficiency tandem solar cells. The further studies of the donor materials with the well matched bandgap as active materials for the top and bottom cells are essential for high performance tandem PSCs.

The incorporation of conjugated polymers and metal NMs can be used to improve the optical and electrical properties for other types solution-processed metal oxides. The modified transport layer can be used to other types solar cells for favoring the carrier extraction. Meanwhile, the physical understanding of the plasmon-optical and plasmon-electrical effects can be applied to the emerging perovskite-based solar cells and light emitting.

We provide the in-depth understanding of the thermionic emission in interconnecting layer and propose the new structure of metal oxide/dipole layer/metal oxide as the interconnecting layer for tandem solar cells. The proposed interconnecting layer will be examined in the emerging perovskite based tandem solar cells.

7. The Layman's Summary

(describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

In this project, through synthesizing the new series of donor polymers materials with tunable bandgap, high optical absorption and efficient carrier transport capabilities, we have achieved a high performance PSCs with good stability, absorption and high V_{OC}. For tandem PSCs, we propose a new metal oxide/dipole layer/metal oxide as the interconnecting layer between two cell junctions and achieve an ignorable V_{OC} loss and thereby high performance tandem PSCs.

The carrier extraction and collection of metal-oxide based carrier transport layers is improved through incorporating the conjugated polymers and metal nanomaterials. In addition, the plasmon-electrical effects of metal nanomaterials are introduced for enhancing the carrier extraction and eliminating the carriers accumulation through manipulating the carrier transport path length of carriers (electron and hole) to their corresponding electrodes. We offer the designs of the device architectures and optical engineering to improve the optical and electrical characteristics of the PSCs.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.))

The Latest Status of Publications	Author(s)	Title and	Submitted to	Attached	Acknowledge	Accessible

Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*	***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	RGC *(indicate the year ending of the relevant progress report)*	to this report *(Yes or No)*	[redacted]	[redacted]
2015				**S. Lu, X. Guan, X. Li,** W.E.I Sha, F.X. Xie, H. Liu, J. Wang, **F. Huang*, W.C.H. Choy***	Adv. Energy Mat., "A New Interconnecting Layer of Metal Oxide/ Dipole Layer/ Metal Oxide for Efficient Tandem Organic Solar Cells", 2015, 5, 1500631.		Yes	Yes,	Yes
2016				**S. Lu, X. Guan, X. Li, J. Liu, F. Huang, W.C.H. Choy***	Nano Energy, "The incorporation of Thermionic Emission and Workfunction Tuning layer into Intermediate Connecting Layer for High Performance Tandem Organic Solar Cells", 2016, 21, 123–132..		Yes	Yes.	Yes

2016				G. Luo, **X. Ren**, S. Zhang, H. Wu*, **W.C.H. Choy*,** Z. He*, Y. Cao	Small, "Recent advances in organic photovoltaic: device structure and optical engineering optimization in nanoscale", 2016, 12, 1547–1571.		Yes	Yes.	Yes.
2015				**W.E.I. Sha, H.L. Zhu, L. Chen,** W.C. Chew, and **W.C.H. Choy***	Scientific Reports, "A General Design Rule to Manipulate Photocarrier Transport Path in Solar Cells and Its Realization by the Plasmonic-Electrical Effect", 2015, 5, 8525.		Yes	Yes.	Yes.
2014				C. Zhou, Y. M. Liang, F. Liu, C. Sun, X. L. Huang, Z. Q. Xie, **F. Huang*****,** J. Roncali*****, T. P. Russell*****, Y. Cao	Adv. Funct. Mater., "Chain Length Dependence of the Photovoltaic Properties of Monodisperse Donor-Acceptor Oligomers as Model Compounds of Polydisperse Low Band Gap Polymers", 2014, 24, 7538-7547.		No	Yes.	Yes

2015				W. Li, Q. D. Li, S. J. Liu, C. H. Duan, L. Ying*, **F. Huang***, Y. Cao,	Science China-Chemistry, "Synthesis of two-dimensional pi-conjugated polymers pendent with benzothiadiazole and naphtho[1,2-c:5,6-c]bis[1,2,5]thiadiazole moieties for polymer solar cells", 2015, 58, 257-266.		No	Yes.	Yes
2013				K. Zhang, Z.C. Hu, C.H. Duan, L. Ying*, **F. Huang***, Y. Cao	Nanotechnology, "The effect of methanol treatment on the performance of polymer solar cells", 2013, 24, 484003.		No.	Yes	Yes
2014				Ye, Xinliang; Zhang, Jie; Chen, Hui, Wang, Xiaohui; **Huang, Fei***	ACS APPLIED Materials & Interfaces, "Fluorescent Nanomicelles for Selective Detection of Sudan Dye in Pluronic F127 Aqueous Media",2014, 6, 5113		No	Yes	Yes

2014				Liu, Shengjian; Zhong, Chengmei; Dong, Sheng; Zhang, Jie; Huang, Xuelong; Zhou, Cheng; Lu, Junming; Ying, Lei*; Wang, Lei*; **Huang, Fei***, Yong Cao	Organic Electronics, "Novel aminoalkyl-functionalized blue-, green- and red-emitting polyfluorenes", 2014, 15, 850		No	Yes	Yes
2013				Zhang, Kai; Hu, Zhicheng; Duan, Chunhui; **Ying, Lei*; Huang, Fei***; Cao, Yong	Nanotechnology, "The effect of methanol treatment on the performance of polymer solar cells", 2013,24,484003		No	Yes	Yes
2013				Dong, Yang; Cai, Wanzhu; Wang, Ming; Li, Qingduan; Ying, Lei*; **Huang, Fei***; Cao, Yong	Organic Electronics, "[1,2,5]Thiadiazolo[3,4-f]benzotriazole based narrow band gap conjugated polymers with photocurrent response up to 1.1 um", 2013,14,2459		No	Yes	Yes

2013				Zhang, Di; **Choy, Wallace C. H.***; Xie, Fengxian; Sha, Wei E. I.; Li, Xinchen; Ding, Baofu; Zhang, Kai; **Huang, Fei**; Cao, Yong	Advanced Functional Materials, "Plasmonic Electrically Functionalized TiO2 for High-Performance Organic Solar Cells",2013,23,4255		No	Yes	Yes
2013				Liu ShengJian; Zhang ZhiPeng; Chen DongCheng; Duan ChunHui; Lu JunMing; Zhang Jie; **Huang Fei*;** Su ShiJian*; Chen JunWu; Cao Yong	Science China-Chemistry, Synthesis and optoelectronic properties of amino-functionalized carbazole-based conjugated polymers, 2013,56,1119		No	Yes	Yes
2013				Dong, Yang; Hu, Xiaowen; Duan, Chunhui; Liu, Peng; Liu, Shengjian; Lan, Liuyuan; Chen, Dongcheng; Ying, Lei; Su, Shijian; Gong, Xiong, **Fei Huang, *** and Yong Cao	ADVANCED MATERIALS, A Series of New Medium-Bandgap Conjugated Polymers Based on Naphtho[1,2-c:5,6-c]bis(2-octyl-[1,2,3]triazole) for High-Performance Polymer Solar Cells, 2013 ,25,3683		No	Yes	Yes

2014				Wang, Ming; Hu, Xiaowen; Liu, Liqian; Duan, Chunhui; Liu, Peng; Ying, Lei; **Huang, Fei***; Cao, Yong	MACROMOLECULES, "Design and Synthesis of Copolymers of Indacenodithiophene and Naphtho[1,2-c:5,6-c]bis(1,2,5-thiadiazole) for Polymer Solar Cells",2013,46,3950		No	Yes	Yes
2014				Cheng Zhou, Yamin Liang, Feng Liu, Chen Sun, Xuelong Huang, Zengqi Xie, **Fei Huang***, Jean Roncali*, Thomas P. Russell*, and Yong Cao	ADVANCED. FUNCTION. MATERIALS, "Chain Length Dependence of the Photovoltaic Properties of Monodisperse Donor–Acceptor Oligomers as Model Compounds of Polydisperse Low Band Gap Polymers",		No	Yes	Yes

2014				Li-Qian Liu, Gui-Chuan Zhang, Peng Liu, Jie Zhang, Sheng Dong, Ming Wang, Yu-Guang Ma, Hin-Lap Yip,* **Fei Huang***	CHEMISTRY AN ASIAN JOURNAL, "Donor–Acceptor-Type Copolymers Based on a Naphtho[1,2-c:5,6-c]bis(1,2,5-thiadiazole) Scaffold for High-Efficiency Polymer Solar Cells", 2014, 9,2104		No	Yes	Yes
2014				W.Y. Tan, R. Wang, M. Li, G. Liu, P. Chen, X.C. Li, S. Lu, Q.M. Peng, X.H. Zhu,*,W. Chen*, **W.C.H. Choy*,** F. Li*, J. Peng, Y. Cao	Adv. Funct. Mat., "Lending Triarylphosphine Oxide to Phenanthroline: a Facile Approach to High-Performance Organic Small-Molecule Cathode Interfacial Material for Organic Photovoltaics Utilizing Air-Stable Cathodes", DOI: 10.1002/adfm.201401685.		No	Yes	Yes

2014				X.C. Li, F.X. Xie, S.Q. Zhang, J.H. Hou and **W.C.H. Choy***	Adv. Function. Mat., "Over 1.1 eV Workfunction Tuning of Cesium Intercalated Metal Oxides for Functioning as Both Electron and Hole Transport Layers in Organic Optoelectronic Devices, DOI: 10.1002/adfm.201401969.		No	Yes	Yes
2014				**W.C.H. Choy*,**	Chem. Comm., "The Emerging Multiple Metal Nanostructures for Enhancing the Light Trapping of Thin Film Organic Photovoltaics", invited, 2014, DOI: 10.1039/C4CC03767G.		No	Yes	Yes

2014				F.X. Xie, S.J. Cherng, S. Lu, Y.H. Chang, W.E.I. Sha, S.P. Feng, C.M. Chen*, **W.C.H. Choy***,	ACS Applied Materials & Interfaces, "The Functions of Self-assembled Ultrafine TiO2 Nanocrystals for High Efficient Dye-Sensitized Solar Cells", vol. 6, pp. 5367-5373, 2014.		No	Yes	Yes
2014				**W.C.H. Choy*,** W.E.I. Sha, X. Li, D. Zhang,	Progress In Electromagnetics Research, "Multi-physical Properties of Plasmonic Organic Solar Cells", invited, vol. 146, pp. 25-46, 2014.		No	Yes	Yes
2014				W.E.I. Sha, X. Li, **W.C.H. Choy***	Scientific Reports, "Breaking the Space Charge Limit in Organic Solar Cells by a Novel Plasmonic-Electrical Concept", DOI: 10.1038/srep06236.		No	Yes	Yes

2013				L.Chen, **W.C.H. Choy*,** W.E.I. Sha,	Appl. Phys. Lett., "Broadband absorption enhancement of organic solar cells with interstitial lattice patterned metal nanoparticles", vol. 102, 251112 (4pp), 2013.		No	Yes	Yes

*** Note: the publications above are partially supported by the grant: M-HKU703/12.***

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
13-18 September, 2015, Aachen, Germany, invited	Novel Approaches to Improve Optical Absorption and Carrier Extraction of Organic Photovoltaic Cells	the 26th International Conference on Amorphous and Nanocrystalline Semiconductors (ICANS2015)	N. A.	Yes	Yes	No
9-13 Aug, 2015, San Diego, USA, invited	New concept to break the intrinsic properties of organic semiconductors for optical sensing applications	SPIE Optics and Photonics 2015	N. A.	Yes	Yes	No

1-3 Jul., 2015, Kyoto, Japan, invited	Plasmonic and metal oxide systems for high performance OLEDs and OPVs	22nd International Workshop on Active-Matrix Flat Panel Displays and Devices -TFT Technologies and FPD Materials- (AM-FPD '15)	N. A.	Yes	Yes	No
13-18 September, 2015, Aachen, Germany, invited	Novel Approaches to Improve Optical Absorption and Carrier Extraction of Organic Photovoltaic Cells	the 26th International Conference on Amorphous and Nanocrystalline Semiconductors (ICANS2015)	N. A.	Yes	Yes	No
23-24 May, 2015, Beijing, China, invited	New schemes of room-temperature solution-processed carrier transport layers for high performance Organic/Inorganic Solar Cells	The 2nd conference on New Generation Solar Cells	N. A.	Yes	Yes	No
25-28 Jun, 2015. Hangzhou, China, Invited	New approaches and concept of hybrid material system for high efficiency OSCs and OLEDs	the 13th International Conference of Polymers for Advanced Technologies (PAT2015)	N. A.	Yes	Yes	No
14-19 June, 2015, Hong Kong, Invited	Comprehensive studies of new schemes for enhancing the carrier extraction and light absorption of Organic/Inorganic Solar Cells	the 11th International Conference on Optical Probes of Conjugated Polymers and Organic Nanostructures (OP 2015)	N. A.	Yes	Yes	No

5-8 January 2015, Hong Kong, invited	New Schemes for Enhancing the Optical Management and Carrier Transport Properties of Organic Optoelectronic Devices	International Conference on Molecular Electronic Materials and Devices (MEMD2015)	N. A.	Yes	Yes	No
12-14 Nov., 2014 Washington, DC, invited,	Breaking the Space Charge Limit in Organic Solar Cells by a Novel Plasmonic-Electrical Concept	OSA Incubator on the Fundamental Limits of Optical Energy Conversion	N. A.	Yes	Yes	No
17 Sept, 2014. Taipei, Taiwan. invited	Multiple Metal (Plasmonic) Nanostructures, Novel Carrier Transport Layers & Transparent Flexible Electrodes for High-Performance Organic Photovoltaics A new approach of efficient carrier transport layer for organic optoelectronics	Sustainability-Science Summer Workshop for Organic Solar Cells.	N. A.	Yes	Yes	No
8-10 December 2014, Sydney, Australia, invited	A new approach of efficient carrier transport layer for organic optoelectronics	9th Asian Conference on Dye-sensitized and Organic Solar Cells (DSC-OPV9)	N. A.	Yes	Yes	No
25-28 Aug., 2014 Guangzhou, China, invited tutorial	The Recent Progress of Organic Solar Cells	the 34 th Progress in Electromagnetic Research Symposium (PIERS).	N. A.	Yes	Yes	No

25-28 Aug., 2014 Guangzhou, China, invited	Plasmonic-electrical effects of metal nanoparticles for Highly Efficient Organic Solar Cells	the 34th Progress in Electromagnetic Research Symposium (PIERS)	N. A.	Yes	Yes	No

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Xinchen Li	PhD	1 Sept 2011	30, Aug. 2015
Shunmian Lu	PhD	1 Sept 2012	30, Aug. 2016

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

- Top 1% of most-cited scientists in Thomson Reuter's Essential Science Indicators (ESI). 2015

- Top 1% of most-cited scientists in Thomson Reuter's Essential Science Indicators (ESI). 2014

- Recognized as Prolific researcher on organic solar cells in the index (WFC in physical sciences) in *Nature Index* 2014 Hong Kong published **by *Nature*.**
2014

Patents:
W.C.H. Choy, F. Xie, C.D. Wang, "Solution-Processed Transition Metal Oxides", Patent Application Pending. PCT/CN2013/082830, 05 Sept, 2012.

W.C.H. Choy, H.F. Lu, "A simple approach for integration of silver nanowires and silver nanoparticles as conductive metal network", Patent Application Pending. 14/455,584. 2014.

W.C.H. Choy, F. Jiang, "A Simple Approach for Preparing Post-Treatment-Free Solution Processed Non-Stoichiometric NiOx Nanoparticles as Conductive Hole Transport Materials", Patent Application Pending. 14/883,131, 2015.

Book Chapter:
W.C.H. Choy, Chapter 7, "Solution-processed Metal Oxides and Hybrid Metal Oxides as Efficient Carrier Transport Layers of Organic Optoelectronic Devices" in Polymer Photovoltaics: Materials, Physics, and Device Engineering, (Royal Society of Chemistry, 2015), ISBN: 978-1-84973-987-0.