S&R 8 (10/15)

RGC Ref.: M_CityU102/12
(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

Surface Plasmon Enhancement of Quantum Dot Based Intermediate Band Solar Cells

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. ROGACH, Andrey	Prof. WANG, Zhiming
Post	Chair Professor	Professor of National 1000-Talents Program
Unit / Department / Institution	Department of Physics and Materials Science, City University of Hong Kong	School of Microelectronics and Solid State Electronics, University of Electronic Science and Technology of China (UESTC), Chengdu, China
Co-investigator(s) *(with title and institutions)*	N/A	Assoc. Prof. LI Handong Prof. JIA Chunyang School of Microelectronics and Solid State Electronics, University of Electronic Science and Technology of China (UESTC), Chengdu, China
PhD student(s) (with period of involvement)	Name: Frederik HETSCH Institution: CityU Period from 01.03.2013 to 30.09.2013 Name: Shuchi GUPTA Institution: CityU Period from 01.03.2013 to 31.03.2014	

	Name: Claas RECKMEIER Institution: CityU Period from 01.06.2014 to 31.10.2015	

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	18.12.2012
Project Completion date	28.02.2016	28.02.2016	
Duration *(in month)*	36	36	
Deadline for submission of Completion Report		30.11.2016	

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Development of high quality quantum dots as active materials for Quantum Dot Based Intermediate Band Solar Cells by advanced epitaxial growth techniques

2. Design and simulation of Quantum Dot Based Intermediate Band Solar Cells and plasmonic nanostructures

3. Fabrication of plasmonic nanostructures by chemical synthesis in solution

4. Development of quantum dot film and plasmonic metal nanoparticle coupling techniques, and optimisations of the resulting solar cell configurations

5.2 Revised Objectives

Same as original ones

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

We have shown [*Fu et al, Nanoscale 2014*] that the surface plasmon resonances in the single Ag nanowire antenna can be tuned from the dipole plasmon mode to a higher order plasmon mode, which would result in the emission with different intensities and polarization states, for the semiconductor quantum dots coupled to the nanowire antenna. In addition, we demonstrated that the single Ag nanowire antenna can work as an energy concentrator for enhancing the two-photon excited fluorescence of semiconductor quantum dots.

By employing various visible luminescent down-shifting layers based on CdTe quantum dots or CdSe/CdS core–shell quantum dots and tetrapods, we have shown [*Kalytchuk et al., J. Phys. Chem. C 2014*] enhancement in the quantum efficiencies of thin-film CdTe/CdS solar cells predominantly in the ultraviolet regime, the extent of which depends on the photoluminescence quantum yield of the quantum dots. Similarly, a broad enhancement in the quantum efficiencies of crystalline Si solar cells, from ultraviolet to visible regime, has been demonstrated for an infrared luminescent down-shifting layer based on PbS quantum dots. A photoluminescence quantum yield of 80% or higher is generally required to achieve a maximum possible short-circuit current increase of 16 and 50% for the CdTe/CdS and crystalline Si solar cells, respectively.

The multispiked nanostars provided broadband scattering and absorption cross-sections, which can be engineered to dramatically boost the performance of the quantum dot based solar cells [*Wu et al., NanoEnergy 2015*]. The localized near field modes of nanostars resulted in an external quantum efficiency enhancement over 400% for short-wavelength light absorbed in the emitter, while plasmon light trapping caused distinct improvement in quantum efficiency (10-50%) in the long-wavelength region up to 1100 nm.

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

The broadband light concentration by plasmonic nanostars can significantly reduce the amount of quantum dot materials required for a solar cell and provide efficient utilization of the full solar spectrum. In particular for the field of recently risen perovskite based solar cells this may become a very useful approach, when combined with a suitable fabrication method. To address this demand, we developed [*Tavakoli et al., Sci. Rep. 2015*] a facile one-step method to fabricate planar heterojunction perovskite solar cells by chemical vapor deposition (CVD), with a solar power conversion efficiency of up to 11.1%. We have performed a systematic optimization of CVD parameters such as temperature and growth time to obtain high quality films of $CH_3NH_3PbI_3$ and $CH_3NH_3PbI_{3-x}Cl_x$ perovskites. Scanning electron microscopy and time resolved photoluminescence data showed that the perovskite films have large grain size of more than 1 micrometer, which should allow for their easy combination with plasmonic nanostars in the follow up work (currently under exploitation).

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)

This project developed the surface plasmon enhanced quantum dot based intermediate band solar cells. Nanometer-sized semiconductor crystals, or quantum dots have been used as the sunlight absorber materials. The discrete energy levels in quantum dots form an energy band which has been used as a middle band assisting absorption of photons at different wavelength. Due to low absorption volume and cross-section of quantum dots, it is challenging to obtain practical quantum dot based intermediate band solar cells.
We introduced a solution to enhance the sunlight absorption in quantum dots using a strong electromagnetic near-field generated by metallic nanoparticles, which amplifies the sunlight absorption in quantum dots by a few orders in magnitude. Besides engineering and design of optimized semiconductor and metallic nanomaterials and solar cell devices, we found out how to integrate epitaxial semiconductor quantum dots and colloidal metallic nanoparticles. The success in realisation of surface plasmon enhanced quantum dot solar cells opens opportunities for full utilization of solar energy spectrum.

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) *(bold the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	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)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						

2014				M. Fu*, L. Qian, H. Long, K. Wang, P. Lu*, Y. P. Rakovich, **F. Hetsch, A. S. Susha, A. L. Rogach**	Tunable Plasmon Modes in Single Silver Nanowire Optical Antennas Characterized by Far-Field Microscope Polarisation Spectroscopy. Nanoscale, 2014, 6, 9192-9197.	2014	Yes (but the CityU internal project reference no. was used by mistake)	Yes	Yes
2014				**S. Kalytchuk, S. Gupta, O. Zhovtiuk, A. Vaneski, S. V. Kershaw**, H. Fu, Z. Fan, E. C. H. Kwok, C.-F. Wang, W. Y. Teoh, **A. L. Rogach***	Semiconductor Nanocrystals as Luminescent Down-Shifting Layers to Enhance the Efficiency of Thin-Film CdTe/CdS and Crystalline Si Solar Cells. J. Phys. Chem. C. 2014, 118, 16393-16400.	2014	Yes	Yes	Yes
2015				**J. Wu, P. Yu, A. S. Susha**, K. A. Sablon, **H. Y. Chen, Z. H. Zhou, H. D. Li, H. N. Ji, X. B. Niu**, A. O. Govorov, **A. L. Rogach, Z. M. Wang**	Broadband Efficiency Enhancement in Quantum Dot Solar Cells Coupled with Multispiked Plasmonic Nanostars. Nano Energy 2015, 13, 827-835.		Yes	Yes	Yes
2015				M. M. Tavakoli, L. L. Gu, Y. Gao, **C. Reckmeier**, J. He, **A. L. Rogach**, Y. Yao, Z. Fan.	Fabrication of Efficient Planar Perovskite Solar Cells using a One-Step Chemical Vapour Deposition Method. Sci. Rep. 2015, 5, 14083.		Yes	Yes	Yes

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)*
June 30 – July 5, 2013, Singapore	Nanomaterial Architectures for Charge Separation and Transfer	ICMAT 2013	2014	No	No	No
November 4-7, 2013, Jeju, Korea	Functional Hybrid Structures of Semiconductor and Metal Nanocrystals	4th Asian Conference on Coordination Chemistry (ACCC4)	2014	No	No	No
August 25-28, 2014, Guangzhou, China	Light Harvesting and Charge Separation with Semiconductor Quantum Dots	Progress in Electromagnetics Research Symposium (PIERS 2014)	2014	No	No	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
Frederik HETSCH	PhD	01.10.2010	30.09.2014
Shuchi GUPTA	PhD	09.05.2011	31.03.2014
Claas Reckmeier	PhD	01.09.2013	23.08.2016

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

Collaboration with:

Wuhan National Laboratory for Optoelectronics and School of Physics, Huazhong University of Science and Technology, Wuhan, China

Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong S.A.R.

Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

Du Pont Apollo Limited, Hong Kong Science Park, Hong Kong S.A.R.