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(please insert ref. above)

The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

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

Part A: The Project and Investigator(s)

1. Project Title

Synthesis of Anisotropic Perovskite Nanocrystals with Polarized Emission for Light Emitting Diodes

各向異性鈣鈦礦納米晶的可控製備與偏振發光應用研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Andrey ROGACH	Prof. Haizheng ZHONG
Post	Chair Professor	Professor
Unit / Department / Institution	Department of Materials Science and Engineering, City University of Hong Kong (CityU)	Beijing Institute of Technology (BIT)
Contact Information	andrey.rogach@cityu.edu.hk	hzzhong@bit.edu.cn
Co-investigator(s) *(with title and institution)*	Dr. KERSHAW Stephen Vincent He HUANG Dr. Yuan XIONG Julian SCHNEIDER (all CityU)	Dr. Bingkun CHEN Dr. Lei WANG Lige LIU Sheng HUANG Feng ZHANG Wengao LU (all BIT)

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01-Jan-2018		
Project Completion date	31-Dec-2021		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31-Dec-2022		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Develop room temperature synthetic strategies to form anisotropic perovskite nanocrystals, especially the strategies of “facet oriented growth” and “self-organization”
2. Study both experimentally and theoretically the growth mechanism of anisotropic perovskite nanocrystals and use the resulting models to optimize the resulting materials
3. Establish the strategies for the assembly of anisotropic perovskite nanocrystal into oriented thin films and optimize their polarized emission
4. Explore the fabrication of polarized light emitting diodes based on photoluminescence down-conversion and electroluminescence mechanisms.

5.2 Revised Objectives

N.A.

6. Research Outcome

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

We refer to the section 5.3 for the summary of major findings and the research outcome of this project. It was difficult for us to separate those from the "realisation of objectives"; from that reason, we decided to summarize them together under 5.3, while using app. two pages in total as a combined length of sections 5.3 and 6.

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

This research will further proceed along the following lines. We will continue to translate the technique of photoalignment of II-VI semiconductor nanorods to the best and most stable perovskite nanorods samples, while focusing on achievement of the highest possible anisotropy values (>0.4). We will further improve photoluminescence quantum yields of 2D Ruddlesden-Popper perovskite films, which are potentially suitable for down-conversion LED devices. For the charge-injection electroluminescent LEDs, we will focus on development of bright and stable perovskite cuboids self-assembled from single nanoplatelets. We will need to demonstrate our ability to reliably produce them in all three basic emitting colors (green and red, apart from the already demonstrated blue ones), while achieving high photoluminescence quantum yield and high stability. Then we will apply those samples in the different color LEDs. We are now preparing an application on this topic for a next joint NSFC-RGC grant, in collaboration with the group of Prof. Jianjun Tian (BUST). We are confident that based on an extended knowledge which has been accumulated and disseminated within the present project, we will be able to further improve both the performance characteristics and, even more important, the long-term stability under operational conditions for the electroluminescent perovskite LEDs.

7. The Layman's Summary

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

Lead halide perovskites as a class of materials have attracted a great deal of interest for light emitting devices (LEDs). These materials can be grown in solution as anisotropic elongated nanocrystals (so-called nanorods), and in this form they offer considerable advantages for applications such as color display devices. We have shown perovskites to possess very attractive optical performance: photoluminescence quantum yields reaching 100% whilst the emission spectra are narrow, which is useful for tri-color (red-green-blue) liquid crystal displays (LCDs). In these devices, perovskites could be emit light either as down converters, illuminated themselves by a blue LED from behind and generating green or red light; or as directly driven multi-color LEDs in their own right. Since the LCD part of the displays requires polarized light, an inherently polarized light emitted by the panel is highly desirable, which can be realized using anisotropic perovskite nanocrystals produced in this project. At the end, we brought all the potential advantages of anisotropic perovskite nanocrystals together in order to demonstrate two kinds of polarized emitters – one based on down-conversion of light, and the other based on direct electrical excitation, whilst simultaneously maintaining the high emission quantum yield and color purity of these light-emitting materials.

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)*	
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						Accessib the insti repositor *(Yes or*
2018				**J. Schneider, T. Dudka, Y. Xiong, Z. Wang**, N. Gaponik, **A. L. Rogach***	Aqueous-Based Cadmium Telluride Quantum Dot/Polyurethane/ Polyhedral Oligomeric Silsesquioxane Composites for Color Enhancement in Display Backlights. J. Phys. Chem. C 2018, 122, 13391-13398	2019	Yes	Yes	Yes
2018				W. Zhang, **J. Schneider**, V. G. Chigrinov, H. S. Kwok, **A. L. Rogach***, A. K. Srivastava*	Optically Addressable Photoaligned Semiconductor Nanorods in Thin Liquid Crystal Films for Display Applications. Adv. Opt. Mater. 2018, 1800250	2019	Yes	Yes	Yes
2018				W. Zhang, M. F. Prodanov, **J. Schneider**, S. K. Gupta, **T. Dudka**, V. V. Vashchenko, **A. L. Rogach***, A. K. Srivastava*	Ligand Shell Engineering to Achieve Optimal Photoalignment of Semiconductor Quantum Rods for Liquid Crystal Displays. Adv. Funct. Mater. 2018, 1805094	2019	Yes	Yes	Yes
2018				X. Zhang, X. Bai*, H. Wu, X. Zhang, C. Sun, Y. Zhang, W. Zhang, W. Zheng*, W. W. Yu, **A. L. Rogach***	Water-Assisted Size and Shape Control of $CsPbBr_3$ Perovskite Nanocrystals. Angew. Chem. Int. Ed. 2018, 57, 3337-3342	2019	Yes	Yes	Yes

2018				C. Geng, S. Xu, H. Zhong, **A. L. Rogach**, W. Bi*	Aqueous Synthesis of Methylammonium Lead Halide Perovskite Nanocrystals. Angew. Chem. Int. Ed. 2018, 57, 9650-9654	2019	Yes	Yes	Yes
2018				**Y. Li, H. Huang, Y. Xiong, S. V. Kershaw, A. L. Rogach***	Revealing the Formation Mechanism of $CsPbBr_3$ Perovskite Nanocrystals Produced via a Slowed-Down Microwave Assisted Synthesis. Angew. Chem. Int. Ed. 2018, 57, 5833-5837	2019	Yes	Yes	Yes
2019				**T. Dudka**, W. Zhang, **J. Schneider**, S. K. Gupta, M. P. Prodanov, V. V. Vashchenko, A. K. Srivastava*, **A. L. Rogach***	Formulation of a Composite System of Liquid Crystals and Light-Emitting Semiconductor Quantum Rods: from Assemblies in Solution to Photoaligned Films. Adv. Mater. Technol., 2019, 1900695	2019	Yes	Yes	Yes
2019				S. K. Gupta, M. F. Prodanov, W. Zhang, V. V. Vashchenko, **T. Dudka, A. L. Rogach***, A. K. Srivastava*	Inkjet-printed Aligned Quantum Rod Enhancement Films for their Application in Liquid Crystal Displays. Nanoscale 2019, 11, 20837-20846.	2019	Yes	Yes	Yes
2019				A. K. Srivastava*, W. Zhang, **J. Schneider**, J. E. Halpert, **A. L. Rogach***	Luminescent Down-Conversion Semiconductor Quantum Dots and Aligned Quantum Rods for Liquid Crystal Displays. Adv. Sci. 2019, 1901345	2019	Yes	Yes	Yes

2018				M. Lu, X. Zhang, X. Bai*, H. Wu, X. Shen, Y. Zhang*, W. Zhang, W. Zheng, H. Song, W. W. Yu, **A. L. Rogach***	Spontaneous Silver Doping and Surface Passivation of $CsPbI_3$ Perovskite Active Layer Enable Light-Emitting Devices with an External Quantum Efficiency of 11.2%. ACS Energy Lett. 2018, 3, 1571-1577	2019	Yes	Yes	Yes
2019				H. Wang, X. Zhang, Q. Wu, F. Cao, D. Yang, Y. Shang, Z. Ning, L. Zhang, W. Zhang, W. Zheng, Y. Yan, **S. V. Kershaw, A. L. Rogach***, X. Yang*	Trifluoroacetate Induced Small-Grained $CsPbBr_3$ Perovskite Films Result in Efficient and Stable Light-Emitting Devices. Nature Comm. 2019, 10, 665	2019	Yes	Yes	Yes
2019				C. Bi, S. Wang, **S. V. Kershaw**, J. Tian*, **A. L. Rogach***	Thermally Stable Copper(II)-Doped Cesium Lead Halide Perovskite Quantum Dots with Strong Blue Emission. J. Phys. Chem. Lett. 2019, 10, 943-952	2019	Yes	Yes	Yes
2019				C. Bi, **S. Wang, S. V. Kershaw**, K. Zheng, T. Pullerits, S. Gaponenko, J. Tian*, **A. L. Rogach***	Spontaneous Self-Assembly of Cesium Lead Halide Perovskite Nanoplatelets into Cuboid Crystals with High Intensity Blue Emission. Adv. Sci. 2019, 1900462	2019	Yes	Yes	Yes

2019				**Y. Li, H. Huang, Y. Xiong**, A. F. Richter, **S. V. Kershaw**, J. Feldmann, **A. L. Rogach***	Using Polar Alcohols for the Direct Synthesis of Cesium Lead Halide Perovskite Nanorods with Anisotropic Emission. ACS Nano 2019, 13, 8237-8245	2019	Yes	Yes	Yes
2019				S. Wang, J. Yu, M. Zhang, D. Chen, C. Li, R. Chen, G. Jia, **A. L. Rogach***, X. Yang*	Stable, Strongly Emitting Cesium Lead Bromide Perovskite Nanorods with High Optical Gain Enabled by an Intermediate Monomer Reservoir Synthetic Strategy. NanoLett. 2019, 19, 6315-6322	2019	Yes	Yes	Yes
2019				L. Meng, C. Yang, J. Meng, Y. Wang, Y. Ge, Z. Shao*, G. Zhang, **A. L. Rogach**, H.-Z. Zhong*	*In-situ* Fabricated Anisotropic Halide Perovskite Nanocrystals in Polyvinylalcohol Nanofibers: Shape Tuning and Polarized Emission. Nano Research 2019, 12, 1411-1416	2019	Yes	Yes	Yes
2020				**Y. Li**, X. Zhang, **H. Huang*, S. V. Kershaw, A. L. Rogach***	Advances in Metal Halide Perovskite Nanocrystals: Synthetic Strategies, Growth Mechanisms, and Optoelectronic Applications. Mater. Today 2020, 32, 204-221	2022	Yes	Yes	Yes

2020				S. Li, D. Lei*, W. Ren, X. Guo, S. Wu, Y. Zhu, **A. L. Rogach**, M. Chhowalla, A. K.-Y. Jen	Water-Resistant Perovskite Nanodots Enable Robust Two-Photon Lasing in Aqueous Environment. Nature Comm. 2020, 11, 1192	2022	Yes	Yes	Yes
2020				S. Chang*, **E. V. Ushakova**, A. P. Litvin, S. A. Cherevkov, A. V. Sokolova, D. Gets, A. Berestennikov, S. Makarov*, T. Chen, **A. L. Rogach**, H.-Z. Zhong	Tunable Mie Resonances of Tin-based Iodide Perovskite Islandlike Films with Enhanced Infrared Photoluminescence. J. Phys. Chem. Lett. 2020, 11, 3332-3338	2022	Yes	Yes	Yes
2020				Y. Dou, F. Cao, **T. Dudka**, Y. Li, S. Wang, C. Zhang, Y. Gao, X. Yang*, **A. L. Rogach***	Lattice Distortion in Mixed-Anion Lead Halide Perovskite Nanorods Leads to their High Fluorescence Anisotropy. ACS Mater. Lett. 2020, 2, 814-820	2022	Yes	Yes	Yes
2020				J. Guo, Y. Fu, M. Lu, X. Zhang, **S. Kershaw**, J. Zhang, S. Luo, **Y. Li**, W. W. Yu, H. Song, **A. L. Rogach***, L. Zhang*, X. Bai*	Cd-Rich Alloyed $CsPb_{1-x}Cd_xBr_3$ Perovskite Nanorods with Tunable Blue Emission and Fermi Levels Fabricated through Crystal Phase Engineering. Adv. Sci. 2020, 2000930	2022	Yes	Yes	Yes
2020				C. Zhang, J. Chen, S. Wang, L. Kong, S. Lewis, X. Yang*, **A. L. Rogach***, G. Jia*	Metal Halide Perovskite Nanorods: Shape Matters. Adv. Mater. 2020, 2002736	2022	Yes	Yes	Yes

2021				W. Yin, M. Li, W. Dong, Z. Luo, **Y. Li**, J. Qian, J. Zhang, W. Zhang, Y. Zhang, **S. V. Kershaw**, X. Zhang*, W. Zheng*, **A. L. Rogach***	Multidentate Ligand Polyethyleneimine Enables Bright Color-Saturated Blue Light-Emitting Diodes Based on $CsPbBr_3$ Nanoplatelets. ACS Energy Lett. 2021, 6, 477-484	2022	Yes	Yes	Yes
2021				**S. Wang**, J. Popovic, S. Burazer, **A. Portniagin**, F. Liu, K.-H. Low, **Z. Duan, Y. Li, Y. Xiong**, Y. Zhu, **S. V. Kershaw**, A. B. Djurisic, **A. L. Rogach***	Strongly Luminescent Dion–Jacobson Tin Bromide Perovskite Microcrystals Induced by Molecular Proton Donors Chloroform and Dichloromethane. Adv. Funct. Mater. 2021, 2102182	2022	Yes	Yes	Yes
2021				**Z. Duan**, G. Na, **S. Wang, J. Ning**, B. Xing, **F. Huang, A. Portniagin, S. V. Kershaw**, L. Zhang*, **A. L. Rogach***	Proton Transfer Driven Modification of Three-Dimensional Hybrid Perovskites to Form Oriented Two-Dimensional Ruddlesden-Popper Phases. Small Science, 2021, 2100114	2022	Yes	Yes	Yes
2021				**Z. Duan, S. Wang, J. Qi, A. Portniagin, A. Döring, S. V. Kershaw, A. L. Rogach***	Highly Luminescent and Stable 2D/3D Octadecylammonium/Formamidinium Lead Bromide Perovskite Films. J. Phys. Chem. C. 2021, 125, 17501-17508	2022	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)*	Accessib the instit repositor *(Yes or N*

May 2018, Hangzhou, China	Light-Emitting Colloidal Nanostructures	International Symposium on Advanced Nanomaterials	2019	No	Yes	No
June 2018, Hong Kong	Light Emission from Perovskite Nanocrystals and Their Application in Optoelectronic Devices	Gordon Research Conference on Hybrid Electronic and Photonic Materials and Phenomena	2019	No	Yes	No
June 2018, Hong Kong	Light Emission from Perovskite Nanocrystals and Their Application in Optoelectronic Devices	The 14th International Conference on Nanostructured Materials	2019	No	Yes	No
August 2018, Dresden, Germany	Synthesis of Light Emitting Perovskite Nanocrystals and Their Application in Optoelectronic Devices	International Workshop on Single Nanostructures, Nanomaterials, Aerogels and Their Interactions	2019	No	Yes	No
Sept. 2019, Warsaw, Poland	Synthesis of Light Emitting Perovskite Nanocrystals and Their Application in Optoelectronic Devices	E-MRS Fall Meeting	2019	No	Yes	No
May 2019, XiAn, China	Light-Emitting Perovskite Nanocrystals	2019 Xi'An Symposium on Materials Chemistry	2019	No	Yes	No
May 2019, Hong Kong	Shape and Morphology Control of Perovskite Nanocrystals	ACS Materials Letters Summit	2019	No	Yes	No
June 2019, Singapore	Light Harvesting and Emission with Perovskite Nanocrystals	10th International Conference on Materials for Advanced Technologies (ICMAT 2019)	2019	No	Yes	No
July 2019, Moscow, Russia	Perovskite Nanocrystals in Light-Emitting Devices	20th International Conference on Physics of Light-Matter Coupling in Nanostructures	2019	No	Yes	No
August 2019, Chengdu, China	Light-Emitting Perovskite Nanocrystals and their Application in Optoelectronic Devices	2019 International Symposium on Perovskites for Optoelectronic Applications and Beyond	2019	No	Yes	No
August 2019, Beijing, China	Light-Emitting Perovskite Nanocrystals and their Application in Optoelectronic Devices	ChinaNANO2019	2019	No	Yes	No
June 2020, Online	Perovskite Nanocrystals in Light-Emitting Devices	NanoGE Online Meetup Conference „Perovskite Quantum Dots: Syntheses, Physical Properties and Applications to Optoelectronic Devices“	2022	No	Yes	No
July 2020, Online	Light-Emitting Devices with Perovskite Nanocrystals	NanoGE Online Meetup Conference „Internet Conference for Quantum Dots (iCQD)“	2022	No	Yes	No
Novem. 2020, Singapore Online	Perovskite Nanocrystals in Light-Emitting Devices and Beyond	9th MRS-S National Conference on Advanced Materials	2022	No	Yes	No

December 2020, Online	Hybrid Perovskite Based Nanomaterials for Photovoltaics and Optoelectronics	NanoGE International Online Conference „Hybrid Materials and Optoelectronic Devices“ (HYBRIDOE)	2022	No	Yes	No
January 2021, Hong Kong Online	Synthesis and Polarized Emission of Perovskite Nanorods	Workshop on Advanced Display Materials	2022	No	Yes	No
June 2021, Online	Perovskite Nanocrystals in Light-Emitting Devices	SmartMat (Wiley) Webinar	2022	No	Yes	No
September 2021, Porto, Portugal, Online	Synthesis and Spectroscopy of Perovskite Nanocrystals	International Meet & Expo on Nanotechnology (NANOMEET2021)	2022	No	Yes	No
October 2021, Online	Perovskite Nanocrystals in Light-Emitting Devices	NanoGE Online Fall Meeting 2021	2022	No	Yes	No
Novem. 2021, Hanoi, Vietnam, Online	Perovskite Nanocrystals in Light-Emitting Devices	10th International Workshop on Advanced Materials Science and Nanotechnology (IWAMSN 2021)	2022	No	Yes	No
December 2021, Nur-Sultan, Kazachstan, Online	Perovskite Nanocrystals in Light-Emitting Devices	International Symposium on Emerging Materials and Devices	2022	No	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
Tetiana DUDKA	PhD	01/09/2016	31/08/2019
Yanxiu LI	PhD	01/09/2017	27/08/2020
Zonghui DUAN	PhD	01/09/2018	25/08/2021

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

Related to the research conducted for this project, the Hong Kong PI Prof. Rogach has been awarded the Croucher Foundation Senior Research Fellowship in 2018.

Collaborations have been established with the groups of:

- Prof. Jianjun Tian, University of Science and Technology Beijing, China
- Prof. Xuyong Yang, Shanghai University, China

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	26	21	0	0	0