RGC Ref.: N_CityU132/14 NSFC Ref. :
(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

Programmable and Integrated Fabrication of Nano-material Devices by Optically-Induced Force Field
基於光誘導的可編程一體化微納製造方法研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. LI Wen Jung	Prof. WANG Yuechao
Post	Chair Professor	
Unit / Department / Institution	Department of Mechanical Engineering	Shenyang Institute of Automation, CAS
Contact Information	wenjli@cityu.edu.hk	
Co-investigator(s) *(with title and institution)*		Prof. LIU Lianqing (Shenyang Institute of Automation, CAS)

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1 Jan 2015	N/A	N/A
Project Completion date	31 Dec 2018	N/A	N/A
Duration *(in month)*	48	N/A	N/A
Deadline for Submission of Completion Report	31 Dec 2019	N/A	N/A

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Demonstrate an automated OEK platform that is capable of automatically generating opto-electrokinetics phenomena such as the DEP force, AC electro-osmosis, and electro-thermal motion in a specialized OEK microfluidic device.
2. Perform parametric experimental studies to find optimal OEK conditions that allow rapid assembly or deposition of nano-materials such as carbon nanotubes, graphene, zinc oxide nanowires, conductive polymers, and metallic structures
3. Demonstrate automatic assembly of nanowire sensing elements, and automatic formation of micron-scale metal electrodes.
4. Explore theoretical models to elucidate the underlining relationship between the optically-induced electrokinetics force fields and the phenomena of field-induced ionic reaction, field-induced molecular reaction, and nano-material manipulation.
5. Demonstrate integrated nano-sensors and FET circuit elements in a single OEK chip.

5.2 Revised Objectives

Date of approval from the RGC: **N/A**

Reasons for the change: ______

6. Research Outcome

Major findings and research outcome

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

Our joint team has carried out the project and accomplished all the proposed objectives as described in Section 5 above. Presented below are the key research outcome of our team, which have been disseminated through well-known international journals since 2015. These research results include 1) the elucidation of temperature distribution inside an OEK chip during the electrokinetic manipulation process, 2) realization of integrated metal electrodes and semi-conductive thin film structures to serve as FETs, 3) demonstration of molybdenum disulphide based TFTs with performance better than conventional silicon-based TFTs, and 4) fabrication of OEK-based hydrogel mesh for biological applications.

Elucidation of temperature profile inside an OEK microfluidic chip
(Wang, F., et al., *Microsys. & Nanoeng*., doi:10.1038/s41378-018-0029-y)

We systematically measured the temperature distribution and changes in an OEK chip arising from the projected images and applied alternating current (AC) voltage using an infrared camera. We have found that the average temperature of a projected area is influenced by the light color, total illumination area, ratio of lighted regions to the total controlled areas, and amplitude of the AC voltage. As an example, optically induced thermocapillary flow is triggered by the light image-induced temperature gradient on a photosensitive substrate to realize fluidic hydrogel patterning. Our studies show that the projected light pattern needs to be properly designed to satisfy specific application requirements, especially for applications related to biological manipulation and assembly.

Rapid integration of FETs and metal electrodes using OEK Platform
(Liu, N., et al., *Scientific Reports*, doi:10.1038/srep32106)

The OEK platforms were used to create different types of electronic components (e.g., metallic and semiconductor structures) within a single OEK chip. Moreover, the fabrication time for these arrays of structures typically only takes about 10–30 seconds, which is far more rapid and cost-effective than any other micro/nano fabrication method. Semi-conductive devices fabricated include ZnO-based (n-type) FETs and SWNTs-based (p-type) FETs. Metallic conductive electrodes fabricated include Au, Ag, and Cu.

Fabrication of multilayer MoS_2 back-gate thin-film transistors (TFTs)
(Li, M., et al., *ACS Appl. Mater. Interfaces*, doi:10.1021/acsami.6b15419)

As discussed earlier, our team fabricated multilayer MoS_2 back-gate thin-film transistors (TFTs) that can achieve a relatively low subthreshold swing of 0.75 V/decade and a high mobility of 41 $cm^2V^{-1}s^{-1}$, which exceeds the typical mobility value of state-of-the-art amorphous silicon-based TFTs by a factor of 80. We have also found that smoother metal contacts exhibit better electronic characteristics and that MoS_2 film thickness should be controlled within a reasonable range of 30−40 nm to obtain the best mobility values, thereby providing valuable insights regarding performance enhancement for MoS_2 TFTs.

OEK-based hydrogel formation and patterning
(Li, P., et al., *Biomaterials Science*, doi:10.1039/c7bm01153a)

We have discovered that OEK microfluidic chip and also be used to rapidly (typically several to tens of seconds) fabricate various two-dimensional (2D) hydrogel patterns and 3D hydrogel constructs. A theoretical layer-by-layer model that involves continuous polymerizing–delaminating–polymerizing cycles was formulated to explain the polymerization and structural formation mechanism of hydrogels. A large area of hydrogel structures was efficiently fabricated without the usage of costly laser systems or photoinitiators, i.e., a stereoscopic mesh-like hydrogel network with intersecting hydrogel micro-belts was fabricated via a series of dynamic-changing digital light projections. The pores and gaps of the hydrogel network mesh are tunable, which facilitates the supply of nutrients and discharge of waste in the construction of 3D thick bio-models. Cell co-culture experiments showed the effective regulation of cell spreading by hydrogel scaffolds fabricated by the new methods.

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

Using the OEK platform developed from this project, we will continue to explore the integration of more complex and functional electronic devices into functional electronic circuits. Our ultimate goal is to demonstrate a new nano-fabrication technology that can produce integrated functional circuits based on novel nano-materials without the need for conventional and expensive micro/nano fabrication equipment. We will continue to apply for funding from the Research Grants Council, the National Science Foundation of China, and the Innovation and Technology Commission to support our research ideas.

On the other hand, as discussed above, we have found the OEK platform can also be used to rapidly fabricate thin hydrogel 2D and 3D structures. This visible light enabled hydrogel microfabrication method may provide new prospects for designing cell-based units for advanced biomedical studies, e.g., for 3D bio-models or bio-actuators in the future. The development of micro-engineered hydrogels co-cultured with cells in vitro could advance in vivo bio-systems in both structural complexity and functional hierarchy, which holds great promise for applications in regenerative tissues or organs, drug discovery and screening, and bio-sensors or bio-actuators. Therefore, we propose to expand the applicability of the OEK platform into biomedical research fields by investigating how visible light induced electric field in microfluidic environment can be used to pattern different types of biopolymers, including cationic, anionic, or neutral hydrogels. Again, we will jointly apply for funding from the Research Grants Council, the National Science Foundation of China, and the Innovation and Technology Commission to support our research ideas.

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)

Since the 1990's, the isolation, alignment and connection processes for nanomaterials such as carbon nanoparticles (CNPs), carbon nanotubes (CNTs) and nanoparticles have been shown to be extremely challenging and have frustrated nanotechnology researchers world-wide. In this project, we developed an *Electokinetics (OEK) Platform* to integrate low-dimension nanomaterials such as graphene, nanowires, CNPs, and CNTs with conductive electrodes, and demonstrated an automated and systematic fabrication process to rapidly (i.e., with time span in terms of seconds) produce nano-sensors and nano-electronic elements in a single chip. We have shown that using dynamically reconfigurable light images to generate *electrokinetics forces* in order to manipulate and assemble nanomaterials into arrays of nanoscale and microscale structures is possible. And, combined with light-induced electrophoretic deposition and electric field-induced ionic/molecular reaction processes, we have created sensing elements, thin film transistors, and conducting electrodes using nanomaterials such as CNTs, graphene, molybdenum disulphide, silver nanowires, etc. Our research results pave the way for creating a new manufacturing technology for large-scale fabrication and integration of nano-devices that use nanomaterials as sensing and electronic elements.

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)*						
2019				**Liang, W.**, **Liu, L.***, Zhang, H., **Wang, Y.**, & **Li, W. J.*** "Optoelectrokinetics-based microfluidic platform for bioapplications: A review of recent advances"	*Biomicro-fluidics* doi:10.1063/1.5116737		*Yes*	*Yes*	*No*
2019				**Wen, Y.**, **Yu, H.**, **Zhao, W.**, **Wang, F.**, Wang, X., **Liu, L.***, & **Li, W. J.*** "Photonic nanojet sub-diffraction nano-fabrication with in situ super-resolution imaging. IEEE Transactions on Nanotechnology"	*IEEE Trans. on Nanotech.* doi:10.1109/TNANO.2019.2896220		*Yes*	*Yes*	*No*

2019				**Jia, B.**, **Wang, F**., **Chan, H**., Zhang, G., & **Li, W. J.*** "In situ printing of liquid superlenses for subdiffraction-limited color imaging of nanobiostructures in nature"	*Microsys. & Nanoeng.* doi:10.1038/s41378-018-0040-3		*Yes*	*Yes*	*No*
2018				**Li, P., Yu, H.**, **Liu, N.**, **Wang, F**., Lee, G., **Wang, Y.**, **Liu, L.***, & **Li, W. J.*** "Visible light induced electropolymerization of suspended hydrogel bioscaffolds in a microfluidic chip"	*Biomaterials Science* doi:10.1039/c7bm01153a		*Yes*	*Yes*	*No*
2018				**Wang, F**., **Liu, L**., Li, G., Li, P., **Wen, Y**., Zhang, G., **Wang, Y**., Lee, G., & **Li, W. J**. "Thermometry of photosensitive and optically induced electrokinetics chips"	*Microsys.& Nanoeng.* doi:10.1038/s41378-018-0029-y		*Yes*	*Yes*	*No*
2017				**Liang, W**., Zhao, Y., **Liu, L.***, **Wang, Y.**, **Li, W. J.***, & Lee, G. "Determination of cell membrane capacitance and conductance via optically induced electrokinetics"	*Biophysical Journal* doi:10.1016/j.bpj.2017.08.006		*Yes*	*Yes*	*No*

2017				Li, M., **Liu, N., Li, P.**, Shi, J., Li, G., Xi, N., **Wang, Y.**, & **Liu, L.*** "Performance investigation of multilayer MoS2 thin-film transistors fabricated via mask-free optically induced electrodeposition"	*ACS Appl. Mater. Interfaces* doi:10.1021/acsami.6b15419		*Yes*	*Yes*	*No*
2017				Wu, C., Lin, G., **Zhan, Z.,** Li, Y., Tung, C. H., Tang, C., & **Li, W. J.*** "Fabrication of all-transparent polymer-based and encapsulated nanofluidic devices using nano-indentation lithography"	*Microsys. & Nanoeng.* doi:10.1038/micronano.2016.84		*Yes*	*Yes*	*No*
2017				**Wen, Y., Wang, F., Yu, H., Li, P., Liu, L., & Li, W. J.*** "Laser-nanomachining by microsphere induced photonic nanojet"	*Sensors and Actuators A: Physical* doi:10.1016/j.sna.2017.03.009		*Yes*	*Yes*	*No*
2016				**Liu, N., Wang, F., Liu, L.*, Yu, H.,** Xie, S., Wang, J., **Wang, Y.,** Lee, G., & **Li, W. J.*** "Rapidly patterning micro/nano devices by directly assembling ions and nanomaterials"	*Scientific Reports* doi:10.1038/srep32106		*Yes*	*Yes*	*No*

2016				**Li, P., Liu, Na., Yu, H**., **Wang, F., Liu, L.*,** Lee, G., **Wang, Y., & Li, W. J.*** "Silver nanostructures synthesis via optically induced electrochemical deposition"	*Scientific Reports* doi: 10.1038/srep28035		*Yes*	*Yes*	*No*
2016				**Wang, F**., **Liu, L.*,** Yu, P., Liu, Z., **Yu, H.**, **Wang, Y.**, & **Li, W. J.*** "Three-dimensional super-resolution morphology by near-field assisted white-light interferometry"	*Scientific Reports* doi:10.1038/srep24703		*Yes*	*Yes*	*No*
2016				**Wang, F., Liu, L.***, **Yu, H.**, **Wen, Y.**, Yu, P., Liu, Z., **Wang, Y.**, & **Li, W. J.*** "Scanning superlens microscopy for non-invasive large field-of-view visible light nanoscale imaging"	*Nature Comm.* doi:10.1038/ncomms13748		*Yes*	*Yes*	*No*
2015				**Wang, F.,** Lai, H., **Liu, L.***, **Li, P., Yu, H.,** Liu, Z., **Wang, Y.**, & **Li, W. J.*** "Super-resolution endoscopy for real-time wide-field imaging"	*Optics Express* doi:10.1364/OE.23.016803		*Yes*	*Yes*	*No*

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)*
N/A	N/A	N/A	N/A	N/A	N/A	N/A

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
CHEN Meng	PhD	01-Oct-2017	Projected on September 30, 2020

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

- Training of researchers through the funding of this project:
  - Postdoctoral Fellow: Dr. ZHAN Zhikun (currently an Associate Professor at Yanshan University, China)
  - Research Fellow: Dr. CHAN Hoyin (currently a Research Assistant Professor at CityU)
  - Research Assistants: JIA Boliang (currently a Postdoctoral Fellow at CityU)
    KONG Kawai (currently a PhD student at CityU)
    LAW Junhui (currently a PhD student at the University of Toronto)
    YU Huiyang (currently a Research Assistant at CityU)

- Collaboration with other research institutions:

We have collaborated with the following institutions from China and USA using the ***optically-induced electrokinetics*** technologies developed from this project. The names of team members from this joint project are in bold fonts.

- **University of California, Irvine**: Prof. William C. TANG and **University of Arkansas**: Prof. Steve TUNG

  Wu, C., Lin, G., **Zhan, Z.**, Li, Y., Tung, C. H., Tang, C.*, & **Li, W. J.***, "Fabrication of all-transparent polymer-based and encapsulated nanofluidic devices using nano-indentation lithography", *Microsystems and Nanoengineering*, doi:10.1038/micronano.2016.84 **(support from the RGC was acknowledged in this paper)**

- **Northeastern University** at Qinghuangdao: Dr. ZHAO Yuliang

  Yuliang Zhao*, Dayu Jia, Xiaopeng Sha, Guanglie Zhang, and **Wen Jung Li***, "Determination of the Three-Dimensional Rate of Cancer Cell Rotation in an

Optically-Induced Electrokinetics Chip Using an Optical Flow Algorithm", Micromachines 2018, 9(3), 118, doi:10.3390/mi9030118

- **Shanghai University**: Dr. LIU Na and **University of Toronto**: Prof. SUN Yu.

  1. N Liu*, M Li, **L Liu**, Y Yang, J Mai, H Pu, Y Sun and **W J Li*,** "Single-step fabrication of electrodes with controlled nanostructured surface roughness using optically-induced electrodeposition", *J. Micromech. Microeng.*, 28, 025011, 2018.

  2. Na Liu, Yanbin Lin, Yan Peng, Liming Xin, Tao Yue, Yuanyuan Liu, Changhai Ru, Shaorong Xie, Liang Dong*, Huayan Pu*, Haige Chen, **Wen J. Li**, and Yu Sun, "Automated Parallel Electrical Characterization of Cells Using Optically-Induced Dielectrophoresis", *IEEE Trans. on Automation Science and Engineering*, accepted, November 2019.

- **Shenyang Jianzhu University**: Dr. LIANG Wenfeng
  Wenfeng Liang, Yuliang Zhao, **Lianqing Liu*, YuechaoWang**, **Wen Jung Li***, Gwo-Bin Lee, "Determination of Cell Membrane Capacitance and Conductance via Optically Induced Electrokinetics", *Biophysical Journal*, Volume 113, Issue 7, 3 October 2017, Pages 1531-1539, Doi:1016/j.bpj.2017.08.006 **(featured as cover article)**

- The following published papers were especially featured by publishers:
  - *Microsystems and Nanoengineering* (2018 impact factor: 5.616, considered as the 'highest impact factor' journal for the field of MEMS) selected the following paper as the Feature Article on the journal's website (with featured image from the paper) for the week of January 14, 2019:
    Jia, B., Wang, F., **Chan, H.,** Zhang, G., & **Li, W. J**.*, "In situ printing of liquid superlenses for subdiffraction-limited color imaging of nanobiostructures in nature", *Microsystems & Nanoengineering, January 2019,* doi: 10.1038/s41378-018-0040-3 **(support from the RGC was acknowledged in this paper).**

  - *Biophysics Journal* featured the following paper as the Cover Article in 2017:
    Liang, W., Zhao, Y., **Liu, L.*, Wang, Y**., **Li, W. J.*,** & Lee, G., "Determination of cell membrane capacitance and conductance via optically induced electrokinetics", *Biophysical Journal*, doi:10.1016/j.bpj.2017.08.006 **(support from the RGC was acknowledged in this paper).**