Research Assessment Exercise 2020
Impact Case Study

University: The University of Hong Kong
Unit of Assessment (UoA): 14 mechanical engineering, production engineering (incl. manufacturing & industrial engineering), textile technology and aerospace engineering

Title of case study: *Design, fabrication and applications of micro- and nanostructured components in consumer electronic devices*

(1) Summary of the impact

The teams led by Drs. Wen-Di Li, Shien-Ping Feng and Paddy Kwok Leung Chan are major innovators in the design and production of micro- and nanostructured components. Their research impact has been to:

a) design and produce (in collaboration with **Huawei Technology**) [redacted] for photoplethysmogram sensors in smartwatches for health monitoring. Over [redacted] Huawei smartwatches carrying these components have been released globally;

b) spin off two companies, one of which has received accumulative investment of over HKD 80,000,000 and produces high-performance transparent conductive films with an annual capacity of [redacted] m^2 for flexible electronic products such as displays.

(2) Underpinning research

Introducing functional micro- and nanostructures into key components in consumer electronic devices is reshaping this multi-hundred-billion-US-dollar industry with, for example, improved microsensors, higher-quality displays, upgraded touch panels, and enhanced energy storage and conversion. Fully realizing the potential uses of micro- and nanostructured components in future devices relies on in-depth scientific knowledge of device design and scalable capabilities for device manufacturing. Over the past eight years, the laboratories led by Drs. Wen-Di Li, Shien-Ping Feng, and Paddy Chan, all from the Department of Mechanical Engineering at HKU, have produced key advances in this area.

Dr. Li and his team have a long track record of developing optical devices by exploiting the unconventional properties of materials when their dimensions are reduced to micro- and nanoscale. Dr. Li has developed nanophotonic devices for various functions such as spectral filtering and surface-enhanced chemical sensing. Designing micro- and nanostructures for manipulating light emission and propagation forms Li group's core expertise, and has attracted companies that are building optical sensors for consumer electronic devices, such as Huawei **[5.1, 5.2]**.

The strength of Li group's research on devices also lies in the scalable nanomanufacturing methods for industrial production of micro- and nanostructured devices that they have developed over the years. Since 2005, Dr. Li and his team have made significant contributions in the nanofabrication area. Some recent achievements include the development of helium ion beam lithography with ultra-high resolution of sub-5 nm (2012), double transfer UV-curable nanoimprint lithography (2013) **[3.1]**, induction-heated direct-nanoimprint on glass (2016) **[3.2]**, and fast-reconfigurable fiber-optic interference lithography over large area (2018). All of this work aims to address the most important challenges in nanofabrication – high patterning resolution, cost-effectiveness, high-throughput, and scalable patterning area. Overcoming these challenges is essential for the industrial manufacturing of micro- and nanostructured devices in consumer electronics applications.

In 2014, Dr. Li teamed up with Dr. Feng and Dr. Chan to extend their expertise on consumer

electronics devices and scalable micro-/nanomanufacturing to the emerging field of flexible electronics, focusing specifically on transparent electrodes, which form a key component in solar cells, displays, and sensors. Existing transparent conductors used in current products have unsatisfactory conductivity and transmittance, and are often expensive to manufacture. Dr. Li's team addressed these issues through the invention of a flexible self-anchored metal-mesh transparent electrode. The new electrodes achieved an electrical to optical conductivity ratio of 1.5 x 10^4, among the highest performance in published results **[3.3]**. Such performance enables 1-2 orders of magnitude lower resistance for the transparent electrodes without sacrificing transmittance. Furthermore, the team developed an innovative manufacturing process that enables large-volume production of these high-performance transparent electrodes at half of the cost of conventional methods. Dr Li's team collaborated with Dr. Feng's team to apply this transparent electrode in dye-sensitized solar cells, achieving superior overall power conversion efficiency and flexibility **[3.4]**. Through further collaboration with Dr. Chan, their innovative fabrication processes have also been applied onto advanced flexible monolayer organic field effect transistors **[3.5]**, and sensors for hazard gases, protein, and saliva glucose **[3.6]**.

(3) References to the research

*Journal publications (*corresponding author)*

3.1 Yiming Shen, Lei Yao, Zhiwei Li, Junlong Kou, Yushuang Cui, Jie Bian, Changsheng Yuan, Haixiong Ge*, **Wen-Di Li***, Wei Wu, and Yanfeng Chen, "Double transfer UV-curing nanoimprint lithography", Nanotechnology, 24 (46), 465304, 2013

3.2 Jingxuan Cai, Shijie Li, Xu Guo, Haixiong Ge, and **Wen-Di Li***, "Induction-heated nanoimprint on soda-lime glass using sapphire molds", Journal of Vacuum Science & Technology B, 34(6), 06K408, 2016

3.3 Arshad Khan, Sangeon Lee, Taehee Jang, Ze Xiong, Cuiping Zhang, Jinyao Tang, L. Jay Guo, and **Wen-Di Li***, "High-Performance Flexible Transparent Electrode with an Embedded Metal Mesh Fabricated by Cost-Effective Solution Process", Small, 12(22), 3021-3030, 2016

3.4 Arshad Khan, Yu-Ting Huang, Tsutomu Miyasaka, Masashi Ikegami, **Shien-Ping Feng***, and **Wen-Di Li***, "Solution-processed Transparent Nickel-mesh Counter Electrode with In-situ Electrodeposited Platinum Nanoparticles for Full-Plastic Bifacial Dye-sensitized Solar Cells", ACS Applied Materials & Interfaces, 9(9), 8083-8091, 2017

3.5 Zhiwen Zhou, Qisheng Wu, Sijia Wang, Yu-Ting Huang, Hua Guo, **Shien-Ping Feng***, **Paddy Kwok Leung Chan***, "Field-Effect Transistors Based on 2D Organic Semiconductors Developed by a Hybrid Deposition Method", Advanced Science, 1900775, 2019

3.6 Xudong Ji, Ho Yuen Lau, Xiaochen Ren, Boyu Peng, Peng Zhai, **Shien-Ping Feng** and **Paddy Kwok Leung Chan***, "Highly sensitive metabolite biosensor based on organic electrochemical transistor integrated with microfluidic channel and poly(N-vinyl-2-pyrrolidone)-capped platinum nanoparticles", Advanced Materials Technologies, 1, 1600042, 2016

(4) Details of the impact

4.1 Micro- and nano-optic structures for sensors in smartwatches

Smartwatches are poised to become the next popular personal mobile device **[5.1]**. In addition to time and communication functions, these devices can potentially monitor personal health and perform other sensing functions through the integration of different microsensors. Due to space limitations in smartwatches, integrated micro- and nanoscale structures are needed for the production of increasingly smaller sensors, particularly optical sensors. However, conventional industry has lacked the capability to design micro- and nano-optic components – a competence that

has been confined to research labs up until recently. Moreover, cost-effective and high-throughput manufacturing of micro- and nanoscale functional structures has not yet been available in traditional industry. Attracted by the team's previous work on controlling light propagation using nanostructures, Huawei Technology Limited - the world's largest telecommunication company and now a major player in the consumer electronics market – sought a collaboration to investigate the feasibility of applying [redacted] components and [redacted] manufacturing in their upcoming products. In this collaborative project, Dr. Li and his team's overall expertise in the design and manufacturing of micro- and nano-optic devices was utilized to address Huawei's needs in product development.

Among various devices developed in this project, the photoplethysmography (PPG) sensor is now being used in Huawei's smartwatches. PPG sensors, which are used for heart-rate monitoring, emit light to illuminate the skin and detect scattered light to monitor changes in light absorption due to blood flow. The significant space limitations in smartwatches mean that light-focusing and collection must be done by [redacted]. Through numerical modeling based on ray tracing methods, Dr. Li's team designed [redacted] for the PPG sensors. [redacted] Furthermore, Dr. Li's team developed [redacted] and helped set up a large volume production line for Huawei. The [redacted] smartwatches carrying [redacted] designed by Dr. Li's team were released on [redacted] and have been available on the worldwide market with a production volume [redacted], corresponding to a market value of [redacted] USD ([redacted] market price: approximately [redacted] USD). The PPG sensor which was enabled by [redacted] designed and produced through the collaboration with Dr. Li's team has been described as "a big new addition… that delivers 24/7 continuous heart rate monitoring" by major online technology review sources **[5.1]**. This is the first Huawei smartwatch with a PPG sensor that enables health monitoring and sports applications, and it has received a very positive market response **[5.1, 5.2]**.

4.2 Flexible electronics devices with record-high performance enabled by innovative scalable micromanufacturing

The research team's other key innovations are in emerging flexible electronics area, particularly based on Dr. Li's group's invention of the new type of flexible metal-mesh transparent electrode with record-high performance, and its innovative manufacturing method suitable for lower-cost industrial production than other manufacturing approaches. Since 2015, Dr. Li, Dr. Feng and Dr. Chan have teamed up to work together on developing and commercializing end applications by combining the flexible transparent conductive film technology developed by Dr. Li's group and the strong device-research capability in Dr. Feng's and Dr. Chan's groups.

Dr. Li and Dr. Feng co-founded a start-up company – **Flectrode Technology Limited** (www.flectrode.com) – together with a private investor, New Asia Group Holdings Limited. Flectrode has exclusively licensed **[5.3]** the team's flexible metal-mesh transparent electrode technology **[5.4]** from HKU and the investor has so far injected HK$ 80 million **[5.5]** to establish the mass production capability of this product. Flectrode's first production line is established in September 2019 with an annual production capacity of [redacted]. The company's initial product samples are being tested by multiple industry partners in Greater China, Japan, and Europe. Flectrode has recently been awarded the Gold Award with the Congratulation of the Jury at the 47th International Exhibition of Inventions of Geneva **[5.6]** and also been highlighted by a leading market study company, IDTechEx, as a rising new player developing novel transparent conductive film solutions. Dr. Li and Dr. Feng's team has further extended its technology to biosensor applications by collaborating with Dr. Chan's team and his spin-off company, **Eonzen Limited**, a bio-sensor company currently focused on saliva glucose sensing.

(5) Sources to corroborate the impact

5.1 “Honor S1 smartwatch goes big on heart rate monitoring”, Smartwatch News on Wareable, last accessed on 21 September 2019 at https://www.wareable.com/smartwatches/honor-s1-smartwatch-release-date-specs-price-3382

5.2 Corroborating statement from Functional Materials Group, 2012 Noah’s Ark Lab, Huawei Technology Co. Ltd.

5.3 Licensing agreement between HKU Technology Transfer Office and Flectrode Technology Limited on Dr. Li’s invention

5.4 Wen-Di Li, Arshad Khan, “Transparent conductive films with embedded metal grids”, PCT Patent Application No. PCT/CN20 16/081100, May 5, 2016

5.5 Corroborating statement from the Chief Executive Officer of Flectrode Technology Limited, Mr. Kent Chung on the progress of Flectrode; Mr. Chung is also the Chairman of Flectrode’s investor, New Asia Group Holdings Limited.

5.6 Certificate of the Gold Award with the Congratulations of Jury at the 47th International Exhibition of Inventions of Geneva (awarded to Flectrode Technology Limited)