Research Assessment Exercise 2020
Impact Case Study

University: The University of Hong Kong
Unit of Assessment (UoA): 9 – Chemistry

Title of case study:
Luminescent d^8 Metal Complexes for Phosphorescent Organic Light-Emitting Devices (OLEDs)

(1) Summary of the impact

HKU's proprietary OLED materials have provided great opportunities for regional and global businesses to create a new mainstay industry in Mainland China. HKU has exclusively licensed patents on Pt(II) emitters to major global OLED display manufacturers, including Samsung, Merck, and Aglaia. We have attracted industrial capital to realize the commercial use of our inventions in display technology. HKU's pioneering work on Au(III) emitters has led to a joint laboratory with TCL Corporation, one of China's largest enterprises, to develop printable OLED materials. Our work has been used by the Hong Kong government as an exemplar in Innovation Science and Technology.

(2) Underpinning research

HKU Chemistry has a strong tradition of research in transition-metal complex chemistry and inorganic excited states, and their photophysics and photochemistry. Profs. C. M. Che and V. W. W Yam began their careers at HKU in 1983 and 1990, respectively, with both now serving as Chair Professors in Chemistry. They have made seminal and sustained contributions to the development of robust and highly emissive OLED materials. The ground-breaking uses of phosphorescent organometallic compounds in OLED were first described by Profs. Che and Y. G. Ma in 1998 [*Synthetic Metals*, **1998**, 94, 245-248] prior to Thompson and Forrest's work in *Nature* in the same year. These two successful demonstrations kick-started research luminescent metal complexes in OLED applications. Nowadays, the majority of work on phosphorescent materials is focused on iridium-based complexes, mainly dominated by the cyclometalated Ir(III)-phenylpyridine (Ir-ppy) system. In the early 2000s the HKU team took a different approach and successfully identified the unique role of C-donor ligands (e.g., arylacetylide) in boosting the photoluminescence quantum yields (PLQYs) of d^8 metal complexes via suppression of excited state metal-ligand structural distortion. Profs. Che and Yam demonstrated luminescent tetradentate[2] and pincer-type[3] d^8 metal complexes, particularly Pt(II) and Au(III) containing C-donor ligands. The planar geometry of Pt(II) complexes offers opportunities to manipulate inter-/intra-molecular interaction, allowing the manipulation of emissive sites that can improve the radiative decay. In principle, this design strategy can overcome the problem of Ir(III) emitters having structural isomerization upon thermal evaporation. The planar molecular arrangement can also yield a highly ordered structure with a preferred orientation of transition dipole moments with respect to the substrate, greatly improving the out-coupling efficiency and thus the external quantum efficiency (EQE) of the OLEDs from the theoretical limit of 20–22% up to 45.3% without the use of any light extraction technique [*Nature Communications*, **2014**, 5, 4769]. Pioneering work on robust and highly emissive tetradentate Pt(II) emitters has been followed by numerous scientists working in this area both in academia and in industry, as reflected by the 2,000-plus publications related to the development of Pt(II) and Au(III) emitters since 2000. Prof. Che's "one-chelating-ligand+one-metal" design strategy has successfully generated various classes of high-performance tetradentate Pt(II) and Pd(II) complexes with PLQYs up to 90% and corresponding OLEDs with EQEs up to 26.8% and 20.3% at 1000 and 10,000 nits, respectively.[3,4] The "one-chelating-ligand" approach has distinct advantages both in improved stability and lesser excited-state metal-ligand structural distortion. Various luminescent Au(III) emitters with extremely high PLQYs have also been generated, together with the demonstration of

highly efficient solution-processed OLEDs with small efficiency roll-offs.[5] Since 2013, Profs. Che and Yam have generated more than 20 patents related to the Pt(II) and Au(III) emitters that have been successfully granted or filed in the US, Germany, Japan, China, and Korea.[6] These distinct intellectual property (IP) rights provide a great opportunity to overturn business monopolies currently dominated by Universal Display Corporation (UDC) who receive the largest source of commercial revenue of USD56.1 million based on Q2 materials sales in 2018.

(3) References to the research

[1] Lin, Y. Y.; Chan, S. C.; Chan, M. C. W.; Hou, Y. J.; Zhu, N.; **Che, C. M.***; Liu. Y.; Wang, Y. ''Structural, Photophysical, and Electrophosphorescent Properties of Platinum(II) Complexes Supported by Tetradentate N_2O_2 Chelates'', *Chemistry –A European Journal*, **2003**, *9*, 1264–1272. (DOI: 10.1002/chem.200390143).

[2] Lu, W.; Mi, B. X.; Chan, M. C. W.; Hui, Z.; **Che, C. M.***; Zhu, N.; Lee, S. T. ''Light-Emitting Tridentate Cyclometalated Platinum(II) Complexes Containing σ-Alkynyl Auxiliaries: Tuning of Photo- and Electrophosphorescence'', *Journal of the American Chemical Society*, **2004**, *126*, 4958–4971. (DOI: 10.1021/ja0317776).

[3] Cheng, G.; Kui, S. C. F.; Ang, W. H.; Ko, M. Y.; Chow, P. K.; Kwong, C. L.; Kwok, C. C.; Ma, C.; Guan, X.; Low, K. H.; Su, S. J.; **Che, C. M.*** "Structurally Robust Phosphorescent [Pt(O^N^C^N)] Emitters for High Performance Organic Light-Emitting Devices with Power Efficiency Up to 126 lm W^{-1} and External Quantum Efficiency Over 20%", *Chemical Science* **2014**, *5*, 4819–4830 (DOI: 10.1039/c4sc01105h).

[4] Mao, M; Peng, J; Lam, T. L.; Ang, W. H.; Li, H; Cheng, G; **Che, C. M.*** ''High-performance organic light-emitting diodes with low-efficiency roll-off using bulky tetradentate [Pt(O^N^C^N)] emitters'', *Journal of Material Chemistry C*, **2019**, *7*, 7230–7236. (DOI: 10.1039/C9TC00682F).

[5] Wong, B. Y. W.; Wong, H. L.; Wong, Y. C.; Chan, M. Y.*; **Yam, V. W. W.*** "Versatile Synthesis of Luminescent Tetradentate Cyclometalated Alkynylgold(III) Complexes and Their Application in Solution-Processable Organic Light-Emitting Devices", *Angewandte Chemie International Edition* **2017**, *56*, 302–305 (DOI: 10.1002/anie.201607816).

[6] Lists of 16 granted and 5 filed patents related to Pt(II) and Au(III) emitters developed by Che and Yam.

(4) Details of the impact

I) Patent Licensing and Collaborative Agreements. The intellectual property (IP) rights to the technologies based on phosphorescent materials centred on iridium-based complexes are owned by UDC and Merck. These IP monopolies with high licensing fees present challenges to commercialization activities, especially for Mainland China industries. Emerging from the HKU team's different approach, started in 2000, license agreements on two Che's Pt(II) OLED emitter inventions were executed in July 2009 with Merck. Merck sold HKU Pt(II) material to the net value of EUR3,414 in 2014, and conducted sublicensing negotiations with Samsung Electronics Co. Ltd (Samsung) in 2017, although a sublicensing agreement has not yet been signed [Sect. 5 item 1]. But in June 2015, Samsung executively licensed Che's new OLED material inventions [Sect. 5 item 2] for the advantages over iridium phosphors of high internal quantum efficiency and out-coupling efficiency [Sect. 5 item 3a]. The licensed fee paid by Samsung was over USD2.3 million seeing HKU's proprietary OLED materials utilized in commercial products. Following the execution of licenses, Che and Samsung have set up two collaborative projects to develop fit-for-purpose green- and red-emitting Pt(II) complexes, leading to filing joint Korean (KR10-2017-0114705) and US patents (US16/030,074) co-owned by HKU and Samsung. Che has awarded HKD19 million donation and a licensing fee of RMB2 million for the OLED material patents licensed to Aglaia, a major OLED material provider in China. Although the current legal limitations with respect to the commercialization of OLEDs comprising organometallic complexes owned by UDC prevent HKU's

proprietary phosphorescent emitters from being in commercial use before March 2020, all of the industrial partners, Samsung, Merck, and Aglaia, value HKU's IP, as evidenced by their huge investment in its work, and their supporting letters [Sect. 5 item 3]. Notably, Merck renegotiated the exclusivity of Che's patents with HKU in 2018 and highlighted that "the exclusive license from HKU is of high importance for Merck".

II) Setting Up a New Factory for Production of Pt(II) Emitters. Aglaia, collaboration with the Foshan Shun Platinum Foundation Management Co LP, has invested one billion RMB in building a factory, Sichun AG-Ray New Materials Co. Ltd. in Sichuan, dedicated to producing Pt(II)-based OLED materials. They plan to produce no less than 30 tonnes of these emitters per year from 2020 and to become the top national OLED material producer [Sect. 5 item 3c]. With the support of the Meishan government, a research institute led by Prof. Che – which focuses on developing molecular medicines and OLED emitters – is being set up in Sichuan [Sect. 5 item 4]. Che's original patents on Pt(II) emitters are also vital for Aglaia to grow from a small chemical company to one with projected capital of over RMB2 billion. Since 2015, Aglaia has deployed a team of 11 research personnel, including two experienced engineers from the display panel industry, to accelerate the development of Pt(II) emitters for commercial use. A recent breakthrough came as the team realized green OLED devices based on a new Pt(II) emitter from the licensed patent with CIE coordinates of (0.32-0.35,0.62-0.65), a full-width-at-half-maximum (FWHM) of *ca.* 50 nm, a prolonged operational lifetime at 10,000 nits (LT_{95}) of up to 269 hours, and high EQEs, power and current efficiencies of 17.3%, 44.0 lm/W and 59.3 cd/A, respectively [Sect. 5 item 3c]. Their collaborative team was selected for the "Southern China Outstanding Contribution Award" in 2016, for Che's distinguished research to helping the OLED industry in Southern China [Sect. 5 item 5].

III) Establishment of a Joint Laboratory for Au(III) Emitters. Prof. Yam signed a five-year collaborative agreement with TCL in 2014 for the development of Au(III) emitters. TCL has invested HKD10 million, together with sponsorship of HKD7.682 million, for setting up a "HKU-TCL Joint Laboratory for New Printable OLED Materials and Technology" to develop Au(III) emitters [Sect. 5 item 6; TCL's supporting letter in Sect. 5 item 7].

IV) Industrial Impact. Che's works on tetradentate Pt(II) emitters have been followed by major industrial companies, as evidenced by Merck filing >30 patents and Aglaia filing four patents on tetradentate Pt(II) emitters. Samsung has also followed Che's work on [Pt(O^N^C^N)] bearing 6^6^5 metallacycles and filed more than ten patents solely. All of these patents share a very similar/same Pt[(O^N^C^N)] core with different metallacycles. UDC has also filed 20 patents related to tetradenate Pt(II) and Pd(II) systems.

V) Social Impact. Profs. Che and Yam's innovative works have generated huge publicity, as reflected in the awards and podcasts highlighting their achievements on luminescent metal complexes [Sect 5, items 8–10].

(5) Sources to corroborate the impact

[1] Merck's commercialization reports on HKU's platinum(II) materials from 2009 to 2014 and 2017.

[2] Licensing of OLED-related patents to Samsung (from HKU President and Vice-Chancellor's speech

[3] Supporting letters from our collaborative partners, a) Samsung; b) Merck; c) Aglaia.

[4] Setting up of a research institute with Meishan City of Sichuan Province and Sichun Knowledge Express Institute for Innovative Technologies

[5] Collaborative team with Aglaia was selected as "Southern China Outstanding Contribution Award" in 2016

[6] Establishment of "HKU-TCL Joint Laboratory for New Printable OLED Materials and Technology" with TCL

[7] Supporting letter from our collaborative partner, TCL

[8] Social impact made by Prof. Che and Prof. Yam's achievements, and their selected awards and honours

[9] a) Highlights of the development of OLED materials in the Final Report of Comprehensive Review on the ITF in LegCo paper in 2014 (LC Paper No. CB(1)211/14-15(03); p.18); b) Highlights of the licensing affair in LegCo paper in 2016 (LC Paper No. CB(1)436/15-16(06); p.7-8)

[10] Interview with Prof. Che as one of the six featured scientists in a series of 45-minute TV documentaries – "Our Scientists" in 2017 (https://podcast.rthk.hk/podcast/item.php?pid=1291; flyer attached), and interview with Prof. Yam in a series of TV documentaries – "Working Women 2015" (http://podcast.rthk.hk/podcast/item_epi.php?pid=938&lang=zh-CN&id=62046), both produced by RTHK Television Division