Project number: T23-612/12R

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: *1st November 2012*
Project completion date: *31st October, 2017*

1. Project Title:

Cost-effective and Eco-friendly LED System-on-a-Chip (SoC)

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Kei May LAU / Chair Professor	Engr/ECE/HKUST	20
Co-Principal Investigator(s)	Hoi Wai, CHOI / Associate Professor	EEE/HKU	4
	Thomas F. KUECH / UW-Foundation Chair Beckwith-Bascom Professor	Chemical and Biological Engr./ U. Wisconsin - Madison	2
	Shi-Wei Ricky LEE / Professor	Engr/MAE/HKUST	4
	Philip K. T. MOK / Professor	Engr/ECE/HKUST	4
	Johnny K. O. SIN / Professor	Engr/ECE/HKUST	4
	C. Patrick YUE / Professor	Engr/ECE/HKUST	4
Co-Investigator(s)	Wing-Hung KI / Professor	Engr/ECE/HKUST	2
Collaborators	Steven P. DenBaars / Professor	Materials & ECE/UCSB	N.A.
	Shuji Nakamura / Professor	Materials/UCSB	N.A.

\# *Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives*	**Percentage achieved**	**Remarks****
1. To create fundamental technology (device, display, optics and packaging) modules for LED-based microsystems, demonstrated by custom-designed and application-driven LED system on a chip (SoC) and system in package (SiP) via integration of LED with silicon IC manufacturing technologies;	100%	1. Integrated devices (HEMT-LED), high-voltage LEDs, and multi-cell LEDs have been developed and custom-made in-house for SoC and SiP systems has been integrated with driver ICs designed and fabricated at foundries. Special packaging technologies are also well developed by the packaging team at the EPack Lab
2. To explore a novel LED-enabled application—intelligent traffic light (iTL);	100%	2. The iTL prototype was demonstrated during the first review visit and a US patent has been filed.
3. To train the next generation of research scientists in all aspects of LED technology development;	100%	3. PhD and MPhil students trained in this project are listed in section 6.6, along with their graduation status.
4. Knowledge transfer – to develop technologies to be adopted by the LED industry and IC foundries.	100%	4. LEDoS display technologies have been licenced to JBD, a start-up company in Hong Kong under the Beida Jade Bird Group.

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

****** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

Five most exciting research accomplishments of the project were listed in the following sub-sections.

6.1.1 Demonstration of integration technologies

We demonstrated the integration of major components of a LED lighting system (named generation A of the LED lighting SoC system in previous reports) by flip-chip bonding and silicon backside embedded inductor techniques.

The system employed a single-stage DCM LED driver topology as shown in Fig. 6.1.1.1. To enable integration, our approach was to put major components including an LED driver, LEDs, and a power inductor on a silicon carrier which consisted of metal routing to connect the components. This can reduce solution size and parasitic effects to enhance performance. Next, the LEDs used in the circuit were tailor-made high voltage (HV) LED chips so that flip-chip technology could be applied. A copper-tin flip-chip bonding technique was developed to connect the HV LED chips to the silicon carrier. As shown in Fig. 6.1.1.2, copper (Cu) tin (Sn) pumps were first placed on both the silicon carrier and the HV LED chips. Then the HV LED chips were flip-chip placed on the silicon carrier. By applying a high temperature, tin melted to form the joint. These joints were placed on the P and N bonding pads of the HV LED chips for electrical connection. In addition, some joints were placed on the body of the HV LED chips in order to dissipate heat generated by the LEDs. These joints also provided mechanical support.

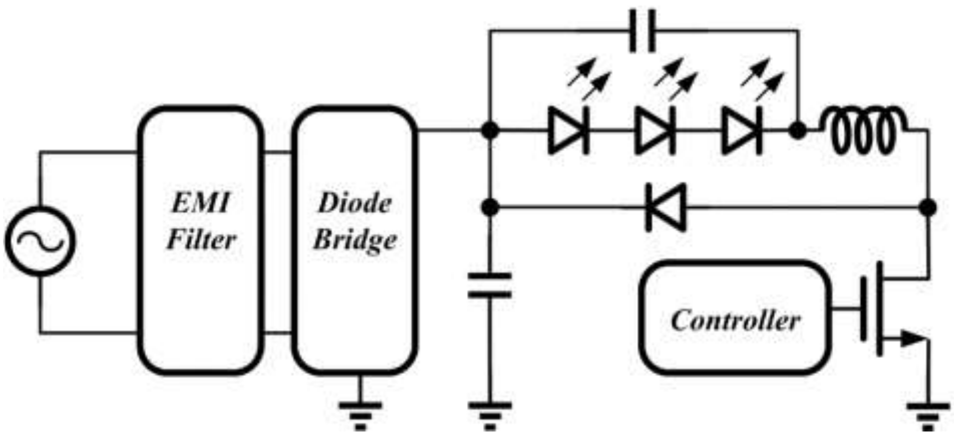


Fig. 6.1.1.1. Simplified schematic of generation A LED lighting SoC system.

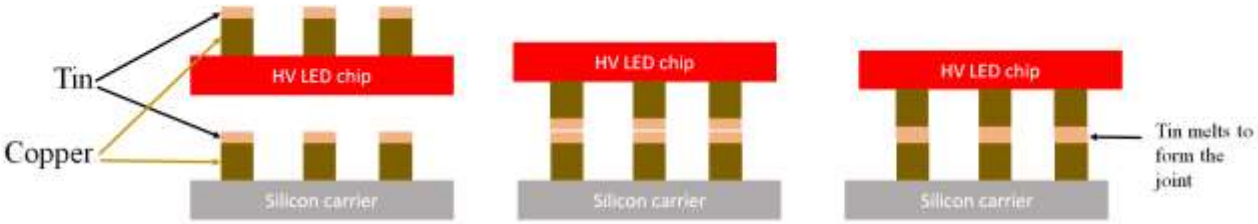


Fig. 6.1.1.2. Cu-Sn flip-chip bonding of HV LED chips on a silicon carrier.

Integration using flip-chip bonding of the HV LED chips provided a better heat dissipation path than wire bonding. Fig. 6.1.1.3 compares the heat dissipation paths using the two methods. For the flip-chip bonding used in this project, heat generated from the LED epi could be dissipated to the heat sink through the Cu-Sn joints (pillars) of about 20 μm in height. As Cu and Sn are good conductors, and the pillars were short, the Cu-Sn joints passed the heat to the silicon carrier effectively. Silicon is also a good conductor, and a silicon wafer of around 350 μm in thickness also passed the heat to the heat sink effectively. For the wire bonding case, heat generated from the LED epi was required to pass through the sapphire substrate and die attach adhesive, both of which are poor conductors. Then heat was passed to the heat sink through MCPCB. In summary, when wire bonding is applied, the heat dissipation path consists of poor conductors. But when flip-chip bonding is applied as in this project, heat generated from the LED passed to the heat sink through good conductors. Integration using flip-chip bonding of the HV LED chips could provide a good heat dissipation path.

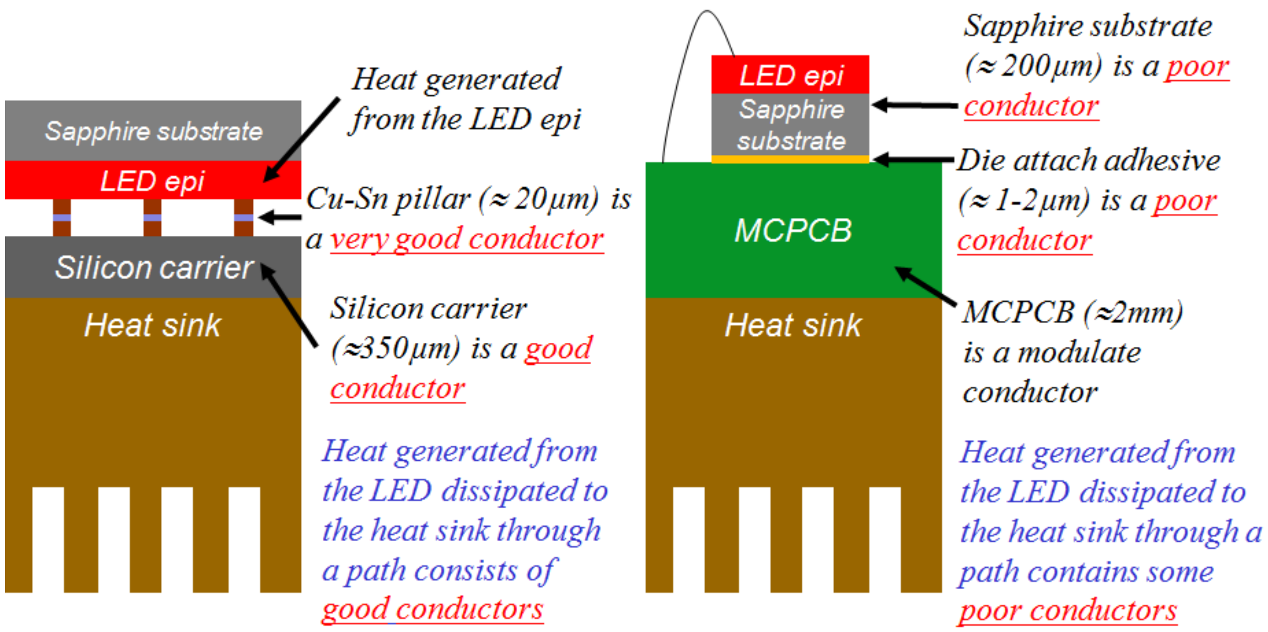


Fig. 6.1.1.3. Heat dissipation path of flip-chip bonding and wire bonding of HV LED chips.

We also demonstrated the integration of a power inductor embedded in the backside of the silicon carrier (Fig. 6.1.1.4). To facilitate the integration of a power inductor, the switching frequency of the circuit was increased to one in the MHz range in order to reduce the value and size of the power inductor. In the first step of fabrication, trenches and vias were first formed by deep silicon reactive-ion etching (DRIE) on the backside of the silicon carrier. The trenches formed the coil, and the vias were through silicon vias (TSVs) to connect the coil and the metal routing on the front side of the silicon carrier which connected the HV LED chips, the LED driver chip and other circuitry. The second step was to fill the trenches and vias with copper by means of electroplating. Finally, chemical mechanical polishing (CMP) was carried out to remove the excess copper.

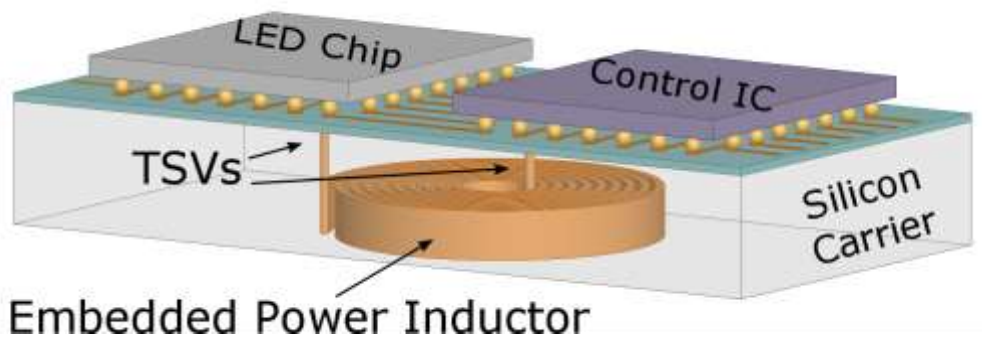


Fig. 6.1.1.4. Integration by embedding a power inductor in the backside of a silicon carrier.

6.1.2 High performance LED lighting system by wafer level integration

We developed a high performance LED lighting system by means of a novel circuit topology and wafer level integration technologies.

Conventionally, switching converters were widely used in LED drivers because of their high efficiency. Unfortunately, the losses introduced by switching dramatically increased with input voltage because a large parasitic capacitor for the high voltage switch (e.g. a power MOSFET) had to be charged and discharged in each switching cycle with a large voltage swing. High voltage power diodes used in switching converters were not fast devices so their reverse recovery loss was another source of switching loss. Switching-free LED drivers were an alternative solution that can eliminate the switching loss problem. But low-frequency (usually 100Hz/120Hz) flicker was the biggest drawback for the conventional switching-free LED drivers.

We developed a new switching-free LED driver using a quasi-constant power (QCP) control scheme to reduce the flicker issue. The system diagram and key waveforms of this solution are shown in Fig. 6.1.2.1(a) and (b), respectively. The LEDs were grouped into N parts. A valley-fill circuit was added to provide a good power factor for the system. Then, the LED current can be adjusted by the QCP controller to reduce flicker.

As the LEDs were grouped into N parts, the number of LEDs used was larger than the number of switching LED drivers, and therefore the area occupied by the LEDs was large. When QCP was applied, the average light output power of each part was different (refer to Table 6.1.2.1 for a typical example). It is difficult to obtain a uniform light-emitting area if the LEDs occupy a large area. But considering the large number of LEDs used and the size of a packaged LED, reducing the LED area was not easy.

Table 6.1.2.1. Typical output power of each part using QCP for a 5W input prototype.

Part	Number of LEDs	Output power per LED (mW)
1	15	143.9
2	3	143.9
3	3	143.5
4	3	91.8
5	3	72.4
6	3	65.4
7	3	58.9
8	3	52.5
9	3	46.1
10	6	33.3

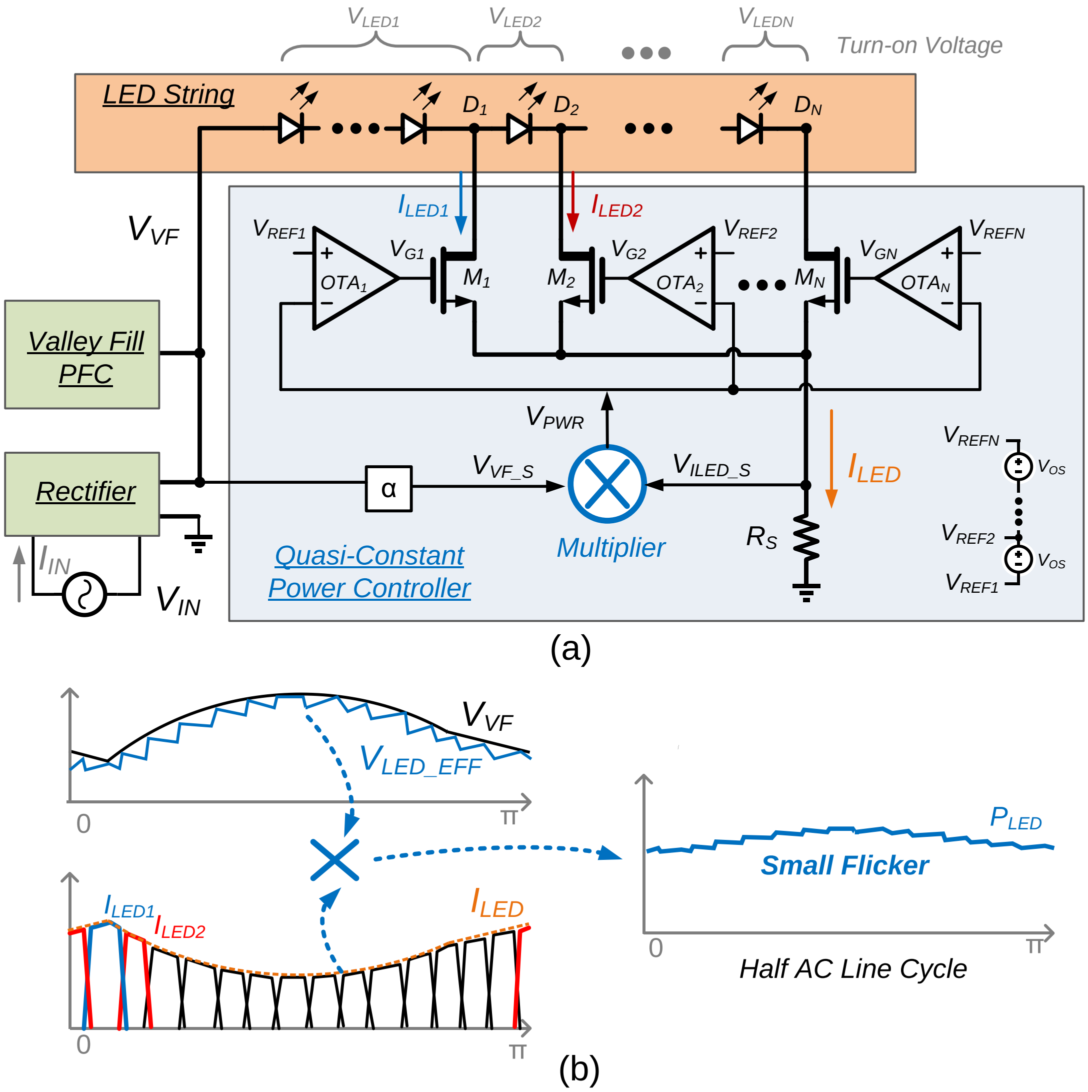
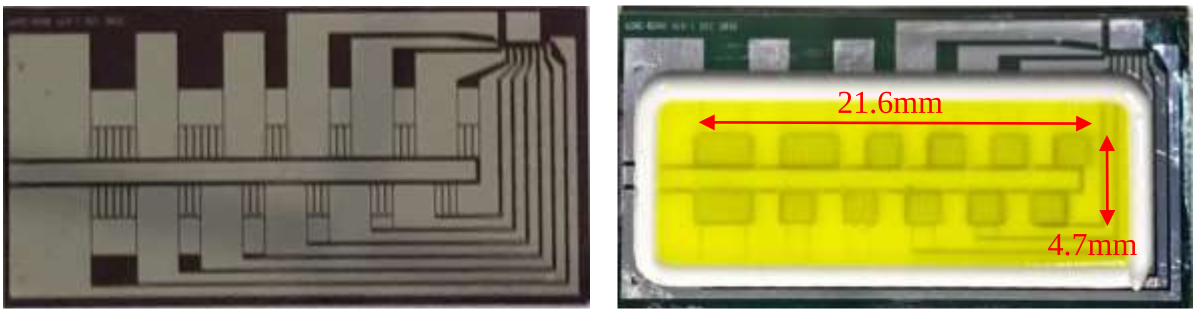


Fig. 6.1.2.1. (a) System diagram and (b) key waveforms of proposed LED driver with QCP control scheme.

To reduce the LED area, we proposed to use a silicon carrier and HV LED chips instead of single LEDs. As the HV LED chips were fabricated in-house, they could be flip-chip bonded on the silicon carrier so that packaging of the chips was not required to further reduce area. Moreover, small feature size could be fabricated on the silicon carrier, which allows placing multiple chips in a fine pitch. The application of Cu-Sn flip-chip bonding of HV LED chips on the silicon carrier dissipated heat effectively. The LED driver chip was also flip-chip bonded on the silicon carrier by Au stud bonding because small chips instead of a full wafer were obtained from the foundry which fabricated the chip. Cu-Sn bumps could not be deposited on such a small chip. The process of Au stud bonding was to first bump the Au stud on the silicon carrier pads. Then coining was applied to make each gold stud the same height. Finally the LED driver chip was flip-chip bonded on the silicon carrier applying normal force and ultrasonic amplitude to ensure good ball-bond quality. The process is illustrated in Fig. 6.1.2.2.

Fig. 6.1.2.2. Au stud flip-chip bonding process: Au stud bumping (left); coining (middle); bonding (right).

The silicon carrier for the prototype is shown in Fig. 6.1.2.3(a). After flip-chip bonding of the HV LED chips, they were coated with phosphor by dam and fill, as shown in Fig. 6.1.2.3(b). The area occupied by all HV LED chips is only 21.6mm × 4.7mm which was small enough to obtain a uniform light-emitting area. The silicon carrier was small enough to fit to a light bulb to form a prototype as shown in Fig. 6.1.2.4.



(a) (b)

Fig. 6.1.2.3. Silicon carrier of the prototype.

Fig. 6.1.2.4. Prototype of the high performance LED lighting system by wafer level integration.

6.1.3 LEDoS µ-display system

We demonstrated an LEDoS µ-display system using an in-house LED µ-array and an active matrix (AM) LED driver designed by our team. The system is aimed at display applications which require high performance, small size and low power consumption.

A prototype of the system is shown in Fig. 6.1.3.1. The lighting part of the picture located in the middle of the PCB consisting of an in-house designed and fabricated LED µ-array consisting of 400 × 240 pixels with 30 µm pitch, flip-chip bonded on an AM LED driver using indium bonding. The LED µ-array was fabricated on a 2" sapphire wafer (Fig. 6.1.3.2). The AM LED driver was fabricated on an 8" silicon wafer using a 0.5 µm CMOS process by CSMC. The system could display text as well as video at a WQVGA resolution with a frame rate exceeding 100 frames per second. The display supported 16-level gray scale. Examples of images shown on the prototype are shown in Fig. 6.1.3.3.

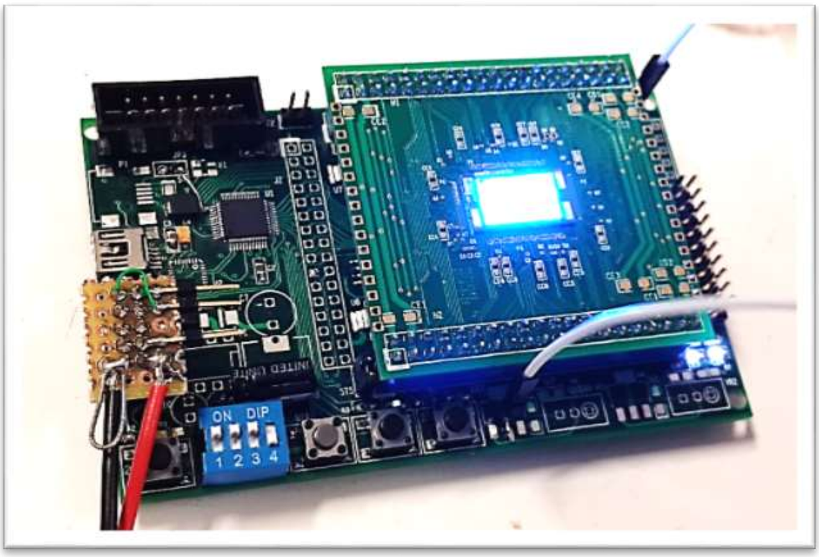


Fig. 6.1.3.1. Prototype of generation 1 of the LEDoS µ-display system.

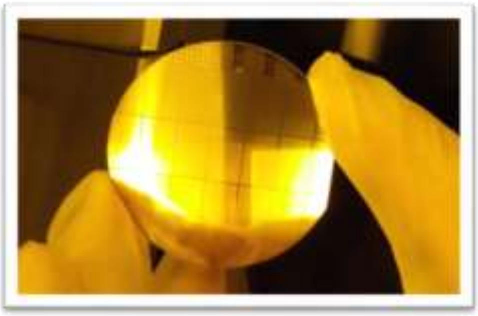


Fig. 6.1.3.2. LED μ-array chip fabricated on a 2” wafer.

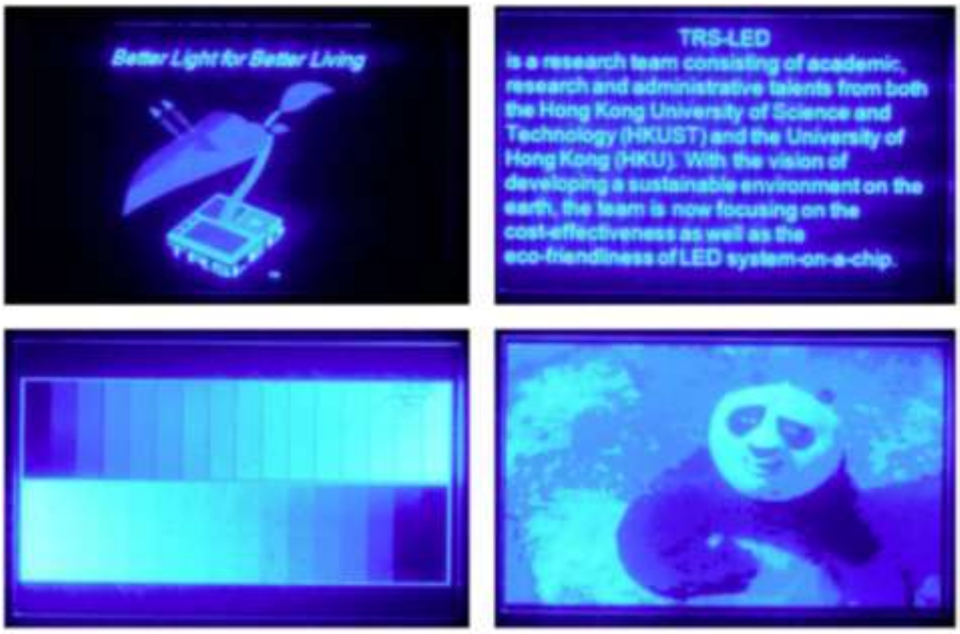


Fig. 6.1.3.3. Images shown on the prototype.

The prototype also supported visible light communication (VLC). Fig. 6.1.3.4 shows an experimental setup with the prototype of the LEDoS μ-display system on the left, and a receiver module on the right. Data were modulated and transmitted using visible light displayed on the LED μ-array during the display of a video. Fig. 6.1.3.5 shows the receiver module with a LCD dot-matrix display to show the received text data transmitted by VLC.

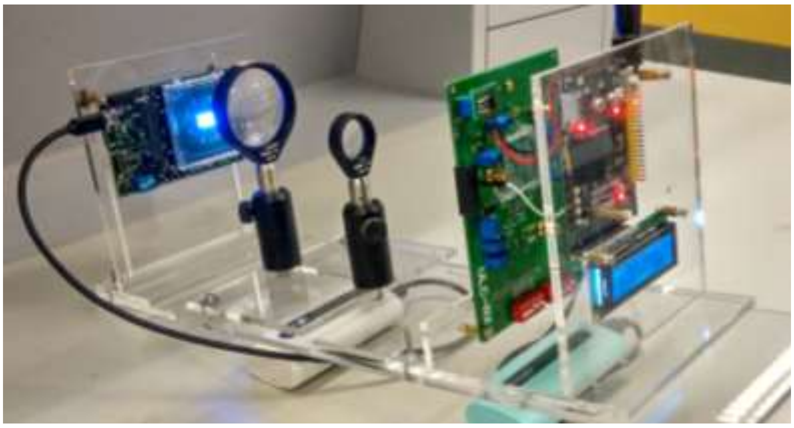


Fig. 6.1.3.4. The prototype implements the visible light communication feature.

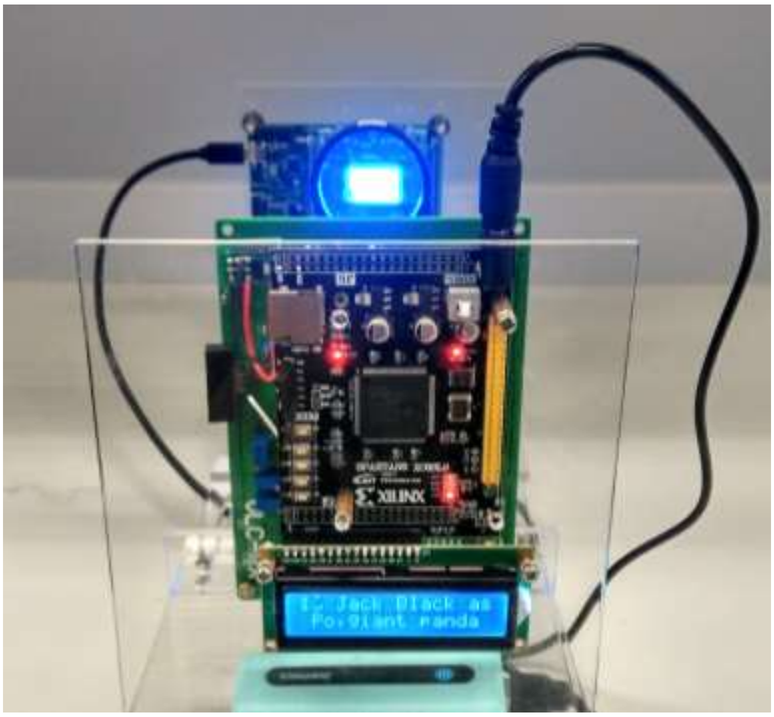


Fig. 6.1.3.5. Data received were shown on a LCD dot-matrix display.

The LED μ-array was designed and fabricated in-house so that we can provide an LED μ-array of any size and dimension. To demonstrate, a generation 2 LEDoS μ-display system was developed with a downsized LED μ-array of 64 × 36 pixels (16:9), and the AM LED driver was also downsized accordingly. In addition, a dc-dc power converter was integrated on the same chip to power the system by a lithium-ion battery with an input ranging from 2.7V to 4.2V. Since the loading of the system was relatively light, a switched capacitor dc-dc power converter was implemented. The converter consisted of 101 blocks, and they can be placed around the AM LED driver, 25 blocks (phases) on each side. A layout of the chip integrating the AM LED driver and the switched capacitor dc-dc power converter is shown in Fig. 6.1.3.6. The LED μ-array was fabricated on a 2” sapphire wafer and was flip-chip bonded on the integrated chip as shown in Fig. 6.1.3.7. The system could also display text, images and animation. Some examples are shown in Fig. 6.1.3.8.

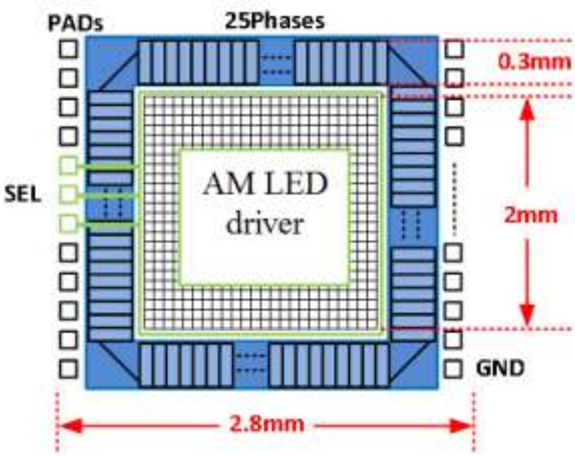


Fig. 6.1.3.6. Layout of the integrated chip.

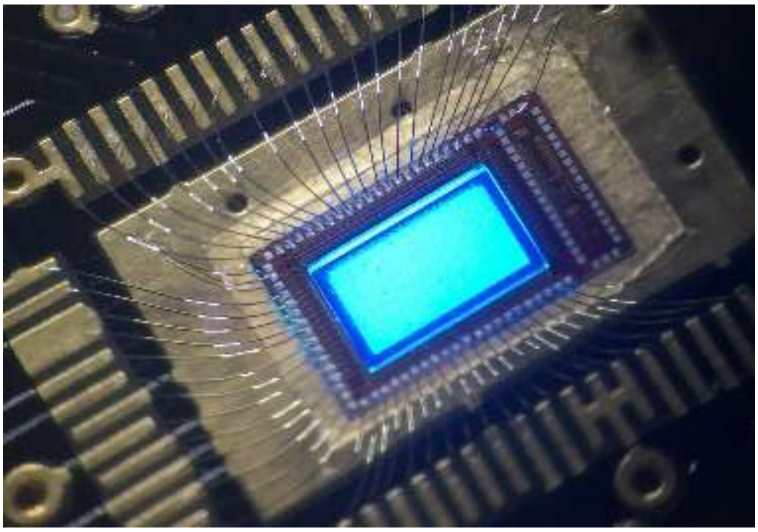


Fig. 6.1.3.7. Generation 2 LED μ-array flip-chip bonded on the integrated chip.

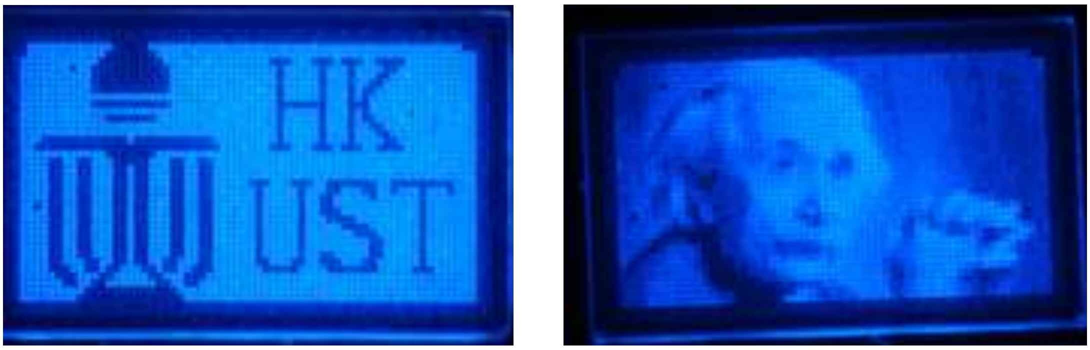


Fig. 6.1.3.8. Images shown on the generation 2 LEDoS μ-display system.

6.1.4 Knowledge transfer

LEDoS display technologies were licenced to Jade-Bird Display (JBD), a start-up company in Hong Kong under the Beida Jade Bird Group. Licence and collaboration agreements are attached in **Annex 1: JBD Licence and Agreements**.

6.1.5 Journal and conference papers

A large number of papers were generated in this project and published in international journals and conferences. Please refer to **Annex 2: List of TRS-LED Publications**.

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

This research project cannot be achieved fruitful results if no TRS funding scheme supporting because the project involved and integrated ten professors in different professional skills with the breadth of knowledge required, the need to recruit new research assistant, training postgraduate students to be scientists from different fields, and the need to share expertise. Moreover, the TRS provided five-year funding period, comparable a longer time and more budget to develop many new invention patentable and transfer special techniques to industry. We would well arrange the critical schedule in every stage, as the first one and half years required significant developments in the way of infrastructure, training of students, methodology and prototype structure advancements. The interaction and regular meetings could bring researchers working closely and adopt a more complete perspective of our own focus. This would not possible happen in standard project grant funding.

6.3 If the project has not met its original objectives, why?

N/A

6.4 (a) Peer-reviewed journal publication(s) arising directly from this project:

(Please attach a copy of the 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. Please mark the symbol "#" next to the publications involving inter-institutional collaborations)

The Latest Status of Publications				Author(s) *(denote the corresponding author with an asterisk*)*	Title and journal/book *(with the volume, pages and other necessary publishing details specified)*	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknow-ledged the support of RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of acceptance *(for paper accepted but not yet published)*	review Under	Under preparation *(optional)*						
2013				Z. J. Liu, W. C. Chong, K. M. Wong, C. W. Keung, and K. M. Lau*	"Investigation of Forward Voltage Uniformity in Monolithic Light-Emitting Diode Arrays", *IEEE Photonics Technology Letters*, Vol. 25, Issue 13, pp. 1290-1293, Jul 2013.	2013	No (S1J1)	Yes	Yes
2013				Z. J. Liu, W. C. Chong, K. M. Wong, and K. M. Lau*	"360 PPI Flip-Chip Mounted Active Matrix Addressable Light Emitting Diode on Silicon (LEDoS) Micro-displays", *IEEE/OSA Journal of Display Technology*, Vol. 9, Issue 8, pp. 678-682, Aug 2013.	2013	No (S1J2)	Yes	Yes
2013				X. B. Zou, K. M. Wong, X. L. Zhu, W. C. Chong, J. Ma, and K. M. Lau*	"High-Performance Green and Yellow LEDs Grown on SiO_2 Nanorod Patterned GaN/Si Templates," *IEEE Electron Device Letters*, Vol. 34, Issue 7, pp. 903-905, Jul 2013.	2013	No (S1J3)	Yes	Yes
2013				X. Fang*, R. Wu, L. Peng, and J.K.O. Sin	"A Novel Silicon-Embedded Toroidal Power Inductor With Magnetic Core," *IEEE Electron Device Letters*, Vol. 34, Issue 2, pp. 292–294, Feb 2013.	2013	No (S1J4)	Yes	Yes
2013				T. D. Huang, Z. J. Liu, X. L. Zhu, J. Ma, X. Lu and K. M. Lau*	"DC and RF Performance of Gate-last AlN/GaN MOSHEMTs on Si with Regrown Source/Drain", *IEEE Transactions on Electron Devices*, vol. 60, issue 10, pp. 3019-3024, Oct. 2013.	2013	No (S2J1)	Yes	Yes
2013				Z. J. Liu, W. C. Chong, K. M. Wong, K.H. Tam and K. M. Lau*	"A Novel BLU-Free Full-Color LED Projector using LED on Silicon Micro-Displays", *IEEE Photonics Technology Letters*, vol. 25, issue 23, pp. 2267-2270, Dec. 2013.	2013	No (S2J2)	Yes	Yes

2013				Cheng Huang, Philip K. T. Mok*	"A 100 MHz 82.4% Efficiency Package Bondwire Based Fully-Integrated Buck Converter with Flying Capacitor for Area Reduction", *IEEE Journal of Solid-State Circuits*, vol. 48, issue 12, pp. 2977-2988, Dec. 2013.	2013	Yes (S2J3)	Yes	Yes
2014				K.H. Li*, C. Feng, H.W. Choi	"Analysis of Micro-lens Integrated Flip-chip InGaN Light-emitting Diodes by Confocal Microscopy", *Applied Physics Letters* 104, 051107 (2014), 3rd Feb. 2014.	2014	No (S2J4)	Yes	Yes
2014				Z. J. Liu, T. D. Huang, J. Ma, C. Liu and K. M. Lau*	"Monolithic Integration of AlGaN/GaN HEMT on LED by MOCVD", *IEEE Electron Device Letters*, vol. 35, issue 3, pp. 330-332, Mar. 2014.	2013	No (S2J5)	Yes	Yes
2014				X. Lu, J. Ma, Z. J. Liu, H. Jiang, T. D. Huang and K. M. Lau*	"In-Situ SiNx Gate Dielectric by MOCVD for Low-Leakage-Current Ultra-Thin-Barrier AlN/GaN MISHEMTs on Si", *Physica Status Solidi (a)*, vol. 211, issue 4, pp. 775-778, Apr. 2014.	2013	No (S2J6)	Yes	Yes
2014				X. B. Zou, K. M. Wong, W. C. Chong, J. Ma and K. M. Lau*	"High Efficiency Blue and Green LEDs Grown on Si with 5 µm Thick GaN Buffer," *Physica status solidi. C, Current topics in solid state physics*, vol. 11, no. 3-4, pp. 730-733, Apr. 2014.	2013	No (S2J7)	Yes	Yes
2014				T. D. Huang, J. Ma, X. Lu, Z. J. Liu, X. Zhu, and K. M. Lau*	"Self-Aligned Gate-Last Enhancement- and Depletion-Mode AlN/GaN MOSHEMTs on Si", *Physica status solidi. C, Current topics in solid state physics*, vol. 11, no. 3-4, pp. 890-893, Apr. 2014.	2014	No (S2J8)	Yes	Yes
2014				Xinbo Zou, Xing Lu, Ryan Lucas, **Thomas F. Kuech**, Jonathan W Choi, Padma Gopalan, and **Kei May Lau***	# "Growth and characterization of horizontal GaN wires on silicon", *Applied Physics Letters,* vol. 104, iss. 26, 262101, Jun. 2014.	2015	No (S3J1)	Yes	Yes
2014				Quan Pan*, Zhengxiong Hou, Yu Li, Andrew W. Poon, and C. Patrick Yue	"A 0.5-V P-Well/Deep N-Well Photodetector in 65-nm CMOS for Monolithic 850-nm Optical Receivers," *IEEE Photonic Technology Letters*, vol. 26, no. 12, pp. 1184-1187, 15th Jun. 2014.	2015	No (S3J2)	Yes	Yes
2014				Jun Ma, Xing Lu, Huaxing Jiang, Chao Liu, and Kei May Lau*	"In situ growth of SiNx as gate dielectric and surface passivation for AlN/GaN heterostructures by metalorganic chemical vapor deposition" *Applied Physics Express*, vol.7(9), 091002 (2014) 28th Aug. 2014.	2015	No (S3J3)	Yes	Yes
2014				Xing Lu, Jun Ma, Huaxing Jiang, Chao Liu, and Kei May Lau*	"Low trap states in in situ SiNx/AlN/GaN metal-insulator-semiconductor structures grown by metal-organic chemical vapor deposition", *Applied Physics Letters*, vol. 105, 102911 (2014) 12th Sep. 2014.	2015	No (S3J4)	Yes	Yes

2014				Wing Cheung Chong, Kei May Lau*	"Performance Enhancements of Flip-Chip Light-Emitting Diodes with High-Density n-Type Point-Contacts", *IEEE Electron Device Letters*, vol. 35, no. 10, pp. 1049-1051, Oct. 2014.	2015	No (S3J5)	Yes	Yes
2014				X. Fang*, R. Wu, L. Peng, and J.K.O. Sin	"A Novel Integrated Power Inductor with Vertical Laminated Core for Improved L/R Ratios", *IEEE Electron Devices Letters*, vol. 35, iss. 12, pp. 1287-1289, Dec. 2014.	2015	No (S3J6)	Yes	Yes
2015				Cheng Huang and Philip K. T. Mok*	"Undershoot suppression technique for fully integrated pulse-width modulated switching converters," *Electronics Letters*, vol. 51, no. 1, pp. 96-97, 8th Jan. 2015.	2016	No (S3J7)	Yes	Yes
2015				Quan Pan*, Yipeng Wang, Zhengxiong Hou, Li Sun, Yan Lu, **Wing-Hung Ki**, Patrick Chiang, and **C. Patrick Yue**	"A 30-Gb/s 1.37-pJ/bit CMOS Receiver for Optical Interconnects," *IEEE/OSA Journal of Lightwave Technology*, vol. 33, no. 4, pp. 778-786, 15th Feb. 2015.	2016	No (S3J8)	Yes	Yes
2015				Jun Ma, Xing Lu, Xueliang Zhu, Tongde Huang, Huaxing Jiang, Peiqiang Xu, Kei May Lau*	"MOVPE growth of in situ SiNx/AlN/GaN MISHEMTs with low leakage current and high on/off current ratio", *Journal of Crystal Growth*, vol. 414, pp. 237-242, 15th Mar. 2015.	2015	No (S3J9)	Yes	Yes
2015				Chao Liu, Zhaojun Liu, Tongde Huang, Jun Ma, and Kei May Lau*	"Improved breakdown characteristics of monolithically integrated III-nitride HEMT–LED devices using carbon doping", *Journal of Crystal Growth*, vol. 414, pp.243-247, 15th Mar. 2015.	2015	No (S3J10)	Yes	Yes
2015				L. Cheng, J. Ni, Y. Qian, M. Zhou, W. H. Ki, B. Liu, G. Li, Z. Hong*	"On-chip compensated wide output range boost converter with fixed-frequency adaptive off-time control for LED driver applications," *IEEE Trans. Power Elec.*, vol. 30, iss. 4, pp 2096-2107, Apr. 2015.	2015	No (S3J11)	Yes	Yes
2015				Chao Liu, Yuefei Cai, Zhaojun Liu, Jun Ma, and Kei May Lau*	"Metal-interconnection-free integration of InGaN/GaN light emitting diodes with AlGaN/GaN high electron mobility transistors," *Applied Physics Letters*, vol. 106, iss. 18, 181110 (2015), 8th May 2015.	2015	No (S4J1)	Yes	Yes
2015				Xing Lu, Jun Ma, Huaxing Jiang, Chao Liu, Peiqiang Xu, and Kei May Lau*	"Fabrication and Characterization of Gate-Last Self-Aligned AlN/GaN MISHEMTs With In Situ SiNx Gate Dielectric ", *IEEE Trans. Electron Devices*, vol. 62, no. 6, pp. 1862-1869, Jun. 2015.	2016	No (S4J2)	Yes	Yes
2015				Fuliang Le, Shi-Wei Ricky Lee*, Jeffery C.C. Lo, and Chaoran Yang	"Failure analysis and experimental verification for through-silicon-via underfill dispensing on 3-D chip stack package," *IEEE Trans. Components, Packaging and Manufacturing Technology*, vol. 5, no. 10, pp. 1525-1532, Oct. 2015.	2016	No (S4J3)	Yes	Yes

2015				K.H. Li, Y.F. Cheung, W.S. Cheung and H.W. Choi*	"Confocal microscopic analysis of optical crosstalk in GaN micro-pixel light-emitting diodes", *Applied Physics Letters*, vol. 107, iss. 17, 171103 (2015), 26th Oct. 2015.	2016	No (S4J4)	Yes	Yes
2015				L. Li, Y. Gao, P.K.T. Mok*, I.M. Sun, and N. Park	"A 16-28W 92.8% Efficiency Monolithic Quasi-Resonant LED Driver with Constant-Duty-Ratio Frequency Regulator", *IEEE Trans. Circuits and Systems - II*, vol. 62, no. 12, pp. 1199 - 1203, Dec. 2015.	2015	No (S4J5)	Yes	Yes
2015				Babar Hussain*, Xianbo Li, Fengyu Che, C. Patrick Yue, and Liang Wu	"Visible Light Communication System Design and Link Budget Analysis," *IEEE/OSA Journal of Lightwave Technology*, vol. 33, no. 24, pp. 5201–5209, Dec 2015.	2016	No (S4J6)	Yes	Yes
2016				X. Fang*, R. Wu, and J.K.O. Sin	"Analytical Modelling of AC Resistance in Thick Coil Integrated Spiral Inductors", *IEEE Transactions on Electron Devices*, vol. 63, no. 2, pp. 760-766, Feb. 2016.	2015	No (S4J7)	Yes	Yes
2016				Xing Lu, Chao Liu, Huaxing Jiang, Xinbo Zou, Anping Zhang, and Kei May Lau*	"Ultralow reverse leakage current in AlGaN/GaN lateral Schottky barrier diodes grown on bulk GaN substrate", *Applied Physics Express*, vol. 9, issue. 3, pp. 031001-1 to 031001-4, Mar. 2016.	2016	No (S4J8)	Yes	Yes
2016				Xing Lu, Huaxing Jiang, Chao Liu, Xinbo Zou, and Kei May Lau*	"Off-state leakage current reduction in AlGaN/GaN high electron mobility transistors by combining surface treatment and post-gate annealing," *Semiconductor Science and Technology*, vol. 31, 055019 (7pp), 5th Apr. 2016.	2016	No (S4J9)	Yes	Yes
2016				Chao Liu, Yuefei Cai, Huaxing Jiang, and Kei May Lau*	"Optimization of a Common Buffer Platform for Monolithic Integration of InGaN/GaN Light-Emitting Diodes and AlGaN/GaN High-Electron-Mobility Transistors", *Journal of Electronic Materials*, vol. 45, no. 4, pp. 2092-2101, Apr. 2016.	2016	No (S4J10)	Yes	Yes
2016				Xinbo Zou, Yuefei Cai, Wing Cheung Chong, Kei May Lau*	"Fabrication and Characterization of High-Voltage LEDs using Photoresist-filled-trench Technique," *Journal of Display Technology*, vol. 12, no. 4, pp. 397–401, Apr. 2016.	2016	No (S4J11)	Yes	Yes
2016				Huaxing Jiang, Xing Lu, Chao Liu, Qiang Li, and Kei May Lau*	"Off-state drain leakage reduction by post metallization annealing for Al2O3/GaN/AlGaN/GaN MOSHEMTs on Si", *Physica Status Solidi A*, vol. 213, no. 4, pp. 868-872, Apr 2016.	2016	No (S4J12)	Yes	Yes
2016				Xinbo Zou, Xu Zhang, Wing Cheung Chong, Chak Wah Tang, and Kei May Lau*	"Vertical LEDs on Rigid and Flexible Substrates Using GaN-on-Si Epilayers and Au-Free Bonding," *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1587–1593, Apr. 2016.	2016	No (S4J13)	Yes	Yes
2016				Xinbo Zou, Xu Zhang, Xing Lu, Chak Wah Tang, and Kei May Lau*	"Fully-vertical GaN p-i-n diodes using GaN-on-Si epilayers," *IEEE Electron Device Letters*, vol. 37, no. 5, pp. 636-639, May 2016.	2017	No (S5J1)	Yes	Yes
2016				Chao Liu, Yuefei Cai, Xinbo Zou, and Kei May Lau*	"Low-leakage high-breakdown laterally integrated HEMT-LED via n-GaN electrode", *IEEE Photonics Technology Letters*, vol. 28, iss. 10, pp. 1130-1133, 15th May 2016.	2017	No (S5J2)	Yes	Yes

2016				Fengyu Che, Liang Wu*, Babar Hussain, Xianbo Li and C. Patrick Yue	"A fully integrated IEEE 802.15.7 visible light communication transmitter with on-chip 8-W 85% efficiency boost LED driver," *IEEE Journal of Lightwave Technology*, vol. 34, no. 10, pp. 2419–2430, 15th May 2016.	2017	No (S5J3)	Yes	Yes
2016				K.H. Li, Y.F. Cheung, C.W. Tang, C. Zhao, **K.M. Lau** and **H.W. Choi***	# "Optical crosstalk analysis of micro-pixelated GaN-based light-emitting diodes on sapphire and Si substrates", *Physica Status Solidi A*, vol. 213, no. 5, pp. 1193-1198, 17th May 2016.	2017	No (S5J4)	Yes	Yes
2016				Yuefei Cai, Xinbo Zou, Wing Cheung Chong, Kei May Lau*	"Optimization of electrode structure for flip-chip HVLED via two-level metallization," *Physica Status Solidi A*, vol. 213, no. 5, pp. 1199-1203, 17th May 2016.	2017	No (S5J5)	Yes	Yes
2016				Xianbo Li*, Liang Wu, Zhaojun Liu, Babar Hussain, Wing Cheung Chong, **Kei May Lau** and **C. Patrick Yue**	"Design and characterization of active matrix LED microdisplays with embedded visible light communication transmitter," *IEEE Journal of Lightwave Technology*, vol. 34, no. 14, pp. 3349–3457, 15th July 2016.	2017	No (S5J6)	Yes	Yes
2016				Xing Lu, Chao Liu, Huaxing Jiang, Xinbo Zou, Anping Zhang, and Kei May Lau*	"Monolithic integration of enhancement-mode vertical driving transistors on a standard InGaN/GaN light emitting diode structure", *Applied Physics Letters*, vol. 109, 053504, Aug 2016.	2017	No (S5J7)	Yes	Yes
2016				X. Zou, X. Zhang, X. Lu, C. W. Tang, and K.M. Lau*	"Breakdown ruggedness of quasi-vertical GaN-based p-i-n diodes on Si substrates," *IEEE Electron Device Letters*, vol. 37, no. 9, pp. 1158-1161, September 2016.	2017	No (S5J8)	Yes	Yes
2016				Quan Pan*, Yipeng Wang, Yan Lu and C. Patrick Yue	"An 18-Gb/s fully integrated optical receiver with adaptive cascaded equalizer," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 22, no. 6, November/December 2016.	2017	No (S5J9)	Yes	Yes
2017				Y. Lu*, J. Jiang, and W.H. Ki	"A multiphase switched-capacitor DC–DC converter ring with fast transient response and small ripple," *IEEE J. Solid-State Circuits*, vol. 52, no. 2, pp. 579–591, February 2017.	2017	No (S5J10)	Yes	Yes
2017				X. Zhang, X. Zou, X. Lu, C. W. Tang, and K. M. Lau*	"Fully- and quasi-vertical GaN-on-Si p-i-n diodes: high performance and comprehensive comparison," *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 809-815, March 2017.	2017	No (S5J11)	Yes	Yes
2017				Xing Lu, Kun Yu, Huaxing Jiang, Anping Zhang, and Kei May Lau*	"Study of interface traps in AlGaN/GaN MISHEMTs using LPCVD SiNx as gate dielectric", *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 824-831, March 2017.	2017	No (S5J12)	Yes	Yes
2017				Huaxing Jiang, Chao Liu, Yuying Chen, Xing Lu, Chak Wah Tang, and Kei May Lau*	"Investigation of in situ SiN as gate dielectric and surface passivation for GaN MISHEMTs", *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 832-839, March 2017.	2017	No (S5J13)	Yes	Yes
2017				Lisong Li, Yuan Gao, Philip K.T. Mok*	"An AC input switching-converter-free LED driver with low-frequency-flicker reduction", *IEEE J. Solid-State Circuits*, vol. 52, no. 5, pp. 1424-1434, May 2017.	2017	Yes (S6J1)	Yes	Yes

2017				Xing Lu*, Chao Liu, Huaxing Jiang, Xinbo Zou, and Kei May Lau	"High performance monolithically integrated GaN driving VMOSFET on LED", *IEEE Electron Device Letters*, vol. 38, no. 6, pp. 752-755, June 2017.	2017	Yes (S6J2)	Yes	Yes
2017				J. Jiang*, W.H. Ki, and Y. Lu	"Digital 2-/3-phase switched capacitor converter with ripple reduction and efficiency improvement", *IEEE J. Solid-State Circuits*, vol. 52, iss. 7, pp. 1836-1848, July 2017.	2017	Yes (S6J3)	Yes	Yes
2017				Yuefei Cai, Xinbo Zou, Yuan Gao, Lisong Li, **Philip K.T. Mok**, and **Kei May Lau***	"Low-flicker lighting from high-voltage LEDs driven by a single converter-free driver", *IEEE Photonics Technology Letters*, vol. 29, pp. 1675-1678, 1st October 2017.	2017	Yes (S6J4)	Yes	Yes
2018				Yuefei Cai, Xinbo Zou, Chao Liu, and **Kei May Lau**	" Voltage-Controlled GaN HEMT-LED Devices as Fast-Switching and Dimmable Light Emitters ", *IEEE ELECTRON DEVICE LETTERS, Vol. 39, No. 2, 2018 (Featured in IEEE Spectrum)*	2018	Yes (S6J5)	Yes	No
2018				Huaxing Jiang, Chak Wah Tang, and **Kei May Lau**	" Enhancement-Mode GaN MOS-HEMTs With Recess-Free Barrier Engineering and High-k ZrO2 Gate Dielectric ", *IEEE ELECTRON DEVICE LETTERS, Vol. 39, No. 3, 2018*	2018	Yes (S6J6)	Yes	No
2018				Lisong Li, Yuan Gao, Huaxing Jiang, **Philip K.T. Mok***, and **Kei May Lau**	"An auto-zero-voltage-switching quasi-resonant LED driver with GaN FETs and fully integrated LED shunt protectors", *IEEE Journal of Solid-State Circuits, Vol.53, No.3, 2018*	2018	Yes (S6J7)	Yes	No
2018				Jie Ren, Chak Wah Tang, Hao Feng, Huaxing Jiang, Wentao Yang, Xianda Zhou, **Kei May Lau**, and **Johnny K. O. Sin**	" A Novel 700 V Monolithically Integrated Si-GaN Cascoded Field Effect Transistor ", *IEEE ELECTRON DEVICE LETTERS, Vol. 39, No. 3, 2018*	2018	Yes (S6J8)	Yes	Yes
2018				Chao Liu, Yuefei Cai, Huaxing Jiang, and **Kei May Lau**	" Monolithic integration of III-nitride voltage-controlled light emitters with dual-wavelength photodiodes by selective-area epitaxy", Optics Letters , Vol. 43, No. 14, 2018	2018	Yes (S6J9)	Yes	Yes

(b) Recognised international conference(s) in which paper(s) related to this project was/were delivered:
(Please attach a copy of each conference abstract)

Month/Year/ Place	Title	Conference name	Submitted to the RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknow -ledged the support of the RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
San Francisco, CA, USA, Feb. 2013	An 82.4% Efficiency Package-Bondwire-Based Four-Phase Fully Integrated Buck Converter with Flying Capacitor for Area Reduction	IEEE International Solid-State Circuits Conference	2013	No (S1C1)	Yes	Yes
Beijing, China, Nov. 2013	Cost-effective and Eco-friendly LED System-on-a-Chip	ChinaSSL 2013	2014	No (S2C1)	Yes	No
19th-20th May 2014, Denver, USA	High Performance Self-aligned AlN/GaN MISHEMT with In-situ SiNx Gate Dielectric and Regrown Source/Drain	2014 International Conference on Compound Semiconductor Manufacturing Technology	2015	No (S3C1)	Yes	Yes
27th -30th May 2014, Orlando, FL, USA	# Through silicon underfill dispensing for 3D die/interposer stacking (jointly authored by **K.M. Lau**, **S.W.R. Lee**, **C.P. Yue**, **J.K.O. Sin**, **P.K.T. Mok**, **W.H. Ki**, **H.W Choi**, *et. al.*)	IEEE 64th Electronic Components and Technology Conference (ECTC)	2015	No (S3C2)	Yes	Yes

1st-3rd Jun. 2014, Tampa, FL, USA	A 3-mW 25-Gb/s CMOS Transimpedance Amplifier with Fully Integrated Low-Dropout Regulator for 100GbE Systems (jointly authored by **C.P. Yue**, **W.H. Ki**, *et. al.*)	2014 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium	2015	No (S3C3)	Yes	Yes
1st-3rd Jun. 2014, Tampa, FL, USA	A 23-mW 30-Gb/s Digitally Programmable Limiting Amplifier for 100GbE Optical Receivers	2014 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium	2015	No (S3C4)	Yes	Yes
18th-20th Jun. 2014, Chengdu, China	Monolithically Integrated Drivers for Eco-friendly LED System-on-a-Chip Applications (jointly authored by <u>**K.M. Lau**</u>, **C.P. Yue**, **J.K.O. Sin**, **P.K.T. Mok**, *et. al.*)	2014 IEEE International Conference on Electron Devices and Solid-State Circuits	2015	No (S3C5)	Yes	Yes
25th-27th Jun. 2014, University of California, Santa Barbara	# Growth and Characterization of GaN Wires Grown on Nano-scale Porous SiO2 Patterned GaN/Si Templates (jointly authored by **K.M. Lau**, **Thomas F. Kuech**, *et. al.*)	56th Electronic Materials Conference	2015	No (S3C6)	Yes	Yes
13th-18th Jul. 2014, Lausanne, Switzerland	Improved breakdown characteristics of monolithically integrated III-nitride HEMT-LED devices using carbon doping	17th International Conference on Metalorganic Vapor Phase Epitaxy (ICMOVPE)	2015	No (S3C7)	Yes	Yes
13th-18th Jul. 2014, Lausanne, Switzerland	MOVPE growth of in situ Sinx/AlN/GaN MISHEMTs with low leakage current and high on/off current ratio	17th International Conference on Metalorganic Vapor Phase Epitaxy (ICMOVPE)	2015	No (S3C8)	Yes	Yes
13th-18th Jul. 2014, Lausanne, Switzerland	Improved buffer resistivity for GaN-based HEMTs using a medium-temperature and low-pressure GaN insertion layer	17th International Conference on Metalorganic Vapor Phase Epitaxy (ICMOVPE)	2015	No (S3C9)	Yes	Yes
24th-29th Aug. 2014, Wrocław, Poland	Cross-talk free optically-isolated micro-light-emitting diode arrays	International Workshop on Nitride Semiconductors	2015	No (S3C10)	Yes	Yes
14th-18th Sep. 2014, Chicago, Illinois	Towards Indoor Localization using Visible Light Communication for Consumer Electronic Devices	2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)	2015	No (S3C11)	Yes	Yes
6th-8th Oct. 2014, Boston, USA	Integrated Magnetics for Eco-Friendly LED System-on-a-Chip Applications (jointly authored by <u>**C.P. Yue**</u>, **J.K.O. Sin**, **P.K.T. Mok**, *et. al.*)	4th International Power Supply on Chip Workshop	2015	No (S3C12)	Yes	Yes
19th-22nd Oct. 2014, Lo Jolla, CA, USA	1700 pixels per inch (PPI) Passive-Matrix Micro-LED Display Powered by ASIC	2014 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICs)	2015	No (S3C13)	Yes	Yes
28th-31st Oct 2014, Guilin, China	Design and Implementation of IEEE 802.15.7 VLC PHY-I Transceiver	IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT)	2015	No (S3C14)	Yes	Yes
2nd-5th Dec. 2014, Canberra, Australia	Integration Scheme toward LED System-on-a-Chip (SoC) (jointly authored by **K.M. Lau**, **J.K.O. Sin**, **P.K.T. Mok**, *et. al.*)	Solid-State and Organic Lighting	2015	No (S3C15)	Yes	Yes
15th-17th Dec. 2014, San Francisco, CA, USA	Efficient Wireless Power Transmission Technology Based on Above-CMOS Integrated (ACI) High Quality Inductors (**C.P. Yue**, **W.H. Ki**, *et. al.*)	IEEE International Electron Devices Meeting (IEDM) Technical Digest	2015	No (S3C16)	Yes	Yes
30th Mar. – 1st Apr. 2015, Shenzhen, China	Link budget analysis for visible light communication systems	2015 IEEE International Wireless Symposium (IWS)	2016	No (S3C17)	Yes	Yes
10th-14th May 2015, Hong Kong	A Low Substrate Loss, Monolithically Integrated Power Inductor for Compact LED Drivers (jointly authored by <u>**K.M. Lau**</u>, <u>**J.K.O. Sin**</u>, <u>**P.K.T. Mok**</u>, *et. al.*)	27th International Symposium on Power Semiconductor Devices and ICs	2016	No (S4C1)	Yes	Yes
15th-19th Jun. 2015, Kyoto, Japan	A 5.5W AC Input Converter-Free LED Driver with 82% Low-Frequency-Flicker Reduction, 88.2% Efficiency and 0.92 Power Factor	IEEE Symposium on VLSI Circuits	2016	No (S4C2)	Yes	Yes
24th-26th Jun. 2015, Columbus, Ohio, USA	Buffer structure optimization of monolithically integrated HEMT-LED using a metal-interconnection-free integration scheme	57th Electronic Materials Conference (EMC)	2016	No (S4C3)	Yes	Yes
28th Jun. - 2nd Jul. 2015, Santa Barbara, CA, USA	Off-state Drain Leakage Reduction by Post Metallization Annealing for Al2O3/GaN/AlGaN/GaN MOSHEMTs on Silicon	Compound Semiconductor Week 2015	2016	No (S4C4)	Yes	Yes
6th-9th Jul. 2015, San Francisco, CA, USA	Modeling and parametric study of light scattering, absorption and emission of phosphor in a white light-emitting diode	InterPACKICNMM2015	2016	No (S4C5)	Yes	Yes
11th-14th Aug. 2015, Changsha, China	Investigation on the influence of Ag reflective layer on the correlated color temperature and the angular color uniformity of LED with conformal phosphor coating	ICEPT 2015	2016	No (S4C6)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	# Optical characteristics of GaN/Si micro-pixel light-emitting diode arrays (jointly authored by <u>**K.M. Lau**</u>, <u>**H.W Choi**</u>, *et. al.*)	11th International Conference on Nitride Semiconductors	2016	No (S4C7)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	Confocal microscopic analysis of optical crosstalk from micro-pixel light-emitting diodes	11th International Conference on Nitride Semiconductors	2016	No (S4C8)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	Control of Threshold Voltage in Ultrathin-barrier AlGaN/GaN based MISHEMTs with Low-frequency SiNx Gate Dielectric and Al2O3 Interfacial Layer	11th International Conference on Nitride Semiconductors	2016	No (S4C9)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	Improved Performance of AlGaN/GaN HEMTs by O2-plasma and HCl Surface Treatment	11th International Conference on Nitride Semiconductors	2016	No (S4C10)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	Enhanced optical performance of monolithically integrated HEMT-LED by buffer optimization	11th International Conference on Nitride Semiconductors	2016	No (S4C11)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	Fabrication and characterization of Large Area High Voltage LEDs with 2 Micron Gap	11th International Conference on Nitride Semiconductors	2016	No (S4C12)	Yes	Yes
30th Aug. - 4th Sep. 2015, Beijing, China	High-efficiency vertical-injection LEDs on rigid and flexible substrates using GaN-on-Si epilayers	11th International Conference on Nitride Semiconductors	2016	No (S4C13)	Yes	Yes

14th-18th Sep. 2015, Graz, Austria	A 60GHz 4Gb/s Fully Integrated NRZ-to-QPSK Modulator SoC for Backhaul Links in Fiber-Wireless Networks	IEEE European Solid-State Circuits Conference (ESSCIRC)	2016	No (S4C14)	Yes	Yes
21st-23rd Oct. 2015, Taipei, Taiwan	Wafer Level Bumping Technology for High Voltage LED Packaging	10th International Microsystems, Packaging, Assemble and Circuits Technology Conference (iMPACT)	2016	No (S4C15)	Yes	Yes
25th-28th Jan. 2016, Macao	An AC Powered Converter-Free LED Driver with Low Flicker	21st Asia and South Pacific Design Automation Conference	2016	No (S4C16)	Yes	Yes
13th-14th Mar. 2016, Shanghai, China	Experimental Parametric Study on the Bumping and Coining of Gold Studs for Flip Chip Bonding	China Semiconductor Technology International Conference (CSTIC) 2016	2016	No (S4C17)	Yes	Yes
13th-14th Mar. 2016, Shanghai, China	Void-Free Underfill Encapsulation for Flip Chip High Voltage LED Packaging	China Semiconductor Technology International Conference (CSTIC) 2016	2016	No (S4C18)	Yes	Yes
17th-20th Apr. 2016, Montpellier, France	Investigation of Reliability of EMC and SMC on Reflectance for UV LED Applications	EuroSimE 2016: IEEE International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems	2016	No (S4C19)	Yes	Yes
27th-29th Apr. 2016, Sapporo, Japan	Numerical Prediction and Experimental Validation of Multiple Phosphor White LED Spectrum	International Conference on Electronics Packaging (ICEP2016)	2016	No (S4C20)	Yes	Yes
16th-19th May, 2016, Miami, USA	Suppression of current collapse in AlGaN/GaN MISHEMTs using in-situ SiN gate dielectric and PECVD SiN passivation	2016 International Conference on Compound Semiconductor Manufacturing Technology (CS Mantech)	2017	No (S5C1)	Yes	Yes
22nd-25th May 2016, Montreal, QC, Canada	A more accurate steady state analysis of zero-voltage switching quasi-resonant converters	IEEE International Symposium on Circuits and Systems	2017	No (S5C2)	Yes	Yes
14th-16th June 2016, Honolulu, HI, USA	A multiple-string hybrid LED driver with 97% power efficiency and 0.996 power factor	2016 IEEE Symposium on VLSI Technology	2017	No (S5C3)	Yes	Yes
26th-30th June, 2016, Toyama, Japan	High voltage low current collapse AlGaN/GaN MISHEMTs with in-situ SiN gate dielectric	2016 Compound Semiconductor Week (CSW)	2017	No (S5C4)	Yes	Yes
26th-30th June, 2016, Toyama, Japan	Efficient use of uniform GaN HVLEDs for small-flicker general illumination applications with converter-free LED drivers (jointly authored by **P.K.T. Mok**, **K.M. Lau**, *et. al.*)	2016 Compound Semiconductor Week (CSW)	2017	No (S5C5)	Yes	Yes
2nd-7th October 2016, Orlando, FL, USA	Voltage-controlled light modulation enabled by monolithically integrated HEMT-LED device	2016 International Workshop on Nitride Semiconductors (IWN 2016)	2017	No (S5C6)	Yes	Yes
2nd-7th October 2016, Orlando, FL, USA	Switching performance of quasi-vertical GaN-based p-i-n diodes on Si	2016 International Workshop on Nitride Semiconductors (IWN 2016)	2017	No (S5C7)	Yes	Yes
2nd-7th October 2016, Orlando, FL, USA	# Monolithically-integrated GaN Photonic Systems (jointly authored by **K.M. Lau**, **H.W. Choi**, *et. al.*)	2016 International Workshop on Nitride Semiconductors (IWN 2016)	2017	No (S5C8)	Yes	Yes
5th-9th February 2017, San Francisco, CA, USA	A dual-symmetrical-output switched-capacitor converter with dynamic power cells and minimized cross regulation for application processors in 28nm CMOS	2017 IEEE Solid-State Circuits Conference (ISSCC)	2017	No (S5C9)	Yes	Yes
5th-9th February 2017, San Francisco, CA, USA	An AC input inductorless LED driver for visible-light-communication applications with 8Mb/s data-rate and 6.4% low-frequency flicker	2017 IEEE Solid-State Circuits Conference (ISSCC)	2017	No (S5C10)	Yes	Yes
22nd - 25th May, 2017, Indian Wells, CA, USA	Low Leakage High Breakdown GaN MOSHEMTs on Si with a ZrO2 Gate Dielectric	2017 Compound Semiconductor manufacturing Technology (CS MANTECH)	2018	Yes (S6C1)	Yes	Yes
28th May–1st June, 2017, Royton Sapporo, Sapporo, Japan	Switching Characteristics of Monolithically Integrated Si-GaN Cascoded Rectifiers	The 29th International Symposium on Power Semiconductor Devices and ICs (ISPSD)	2018	Yes (S6C2)	Yes	Yes
9th - 13th July, 2017, Daejeon, Korea	Top-down III-N single nanowire p-i-n photodetector	International Conference on Neutron Scattering 2017	2018	Yes (S6C3)	Yes	Yes
18th –21st Sep., 2017 Fukuoka Japan	A Micro-LED Driver with Bandwidth Expansion for Visible Light Communications	JSAP-OSA Joint Symposia 2017	2018	Yes (S6C4)	Yes	Yes
25th -28th Sep., 2017 Matsue, Japan,	Effects of Interconnect Layout and Underfill Thermal Conductivity on the Thermal Resistance of Flip-Chip LEDs	19th International Conference on Electronics Materials and Packaging, EMAP 2017	2018	Yes (S6C5)	Yes	Yes
1st -5th Oct. 2017 Orlando, FL, USA	A 2.2-mW 24-Mb/s CMOS LiFi receiver system-on-a-chip with ambient light rejection and post-equalization	2017 IEEE Photonics Conference (IPC)	2018	Yes (S6C6)	Yes	Yes
1st -5th Oct. 2017 Orlando, FL, USA	An adaptive threshold decoding algorithm for visible light communication data recovery from LED-based display systems	2017 IEEE Photonics Conference (IPC)	2018	Yes (S6C7)	Yes	Yes
6th – 8th Nov., 2017 Seoul, Korea	Fully-Integrated AMLED Micro Display System With a Hybrid Voltage Regulator	2017 IEEE Asian Solid-State Circuits Conference	2018	Yes (S6C8)	Yes	Yes

c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

N/A

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

6.5.1 Collaboration between Professor Lau (HKUST) and Professor Choi (HKU)

Prof. Choi's group focused on the development of monolithically-integrated photonic systems using GaN-on-Si epi-materials grown by Prof. Lau's group. The GaN materials could be used to realize emitters, photodetectors and waveguides; by integrating them all on the same chip, the efficiencies could be greatly enhanced. As Si was used as the substrate, the Si materials beneath the waveguides could be readily removed by selective wet etching to form highly-confining optical transmission channels. Our preliminary results showed that appreciable photocurrents could be measured from photodetectors separated from the emitters by as much as 2.7 mm via suspended waveguides, which could be attributed to optimal coupling between the various photonic components.

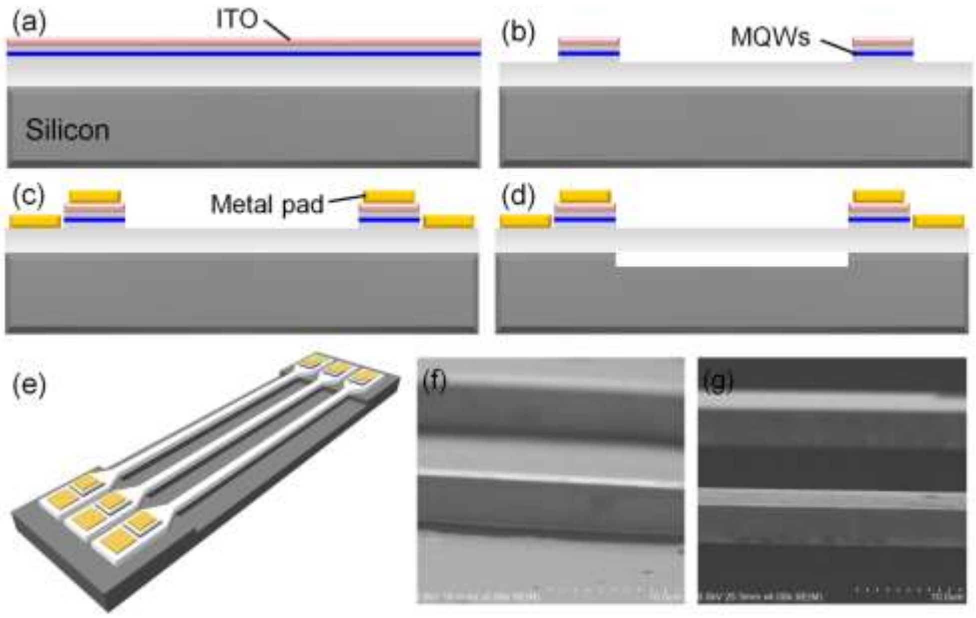


Fig. 6.5.1. Schematic diagrams depicting (a)-(d) fabrication flow and (e) resultant device of the proposed photonic system. FE-SEM images showing the waveguides (g) before and (f) after wet-etching.

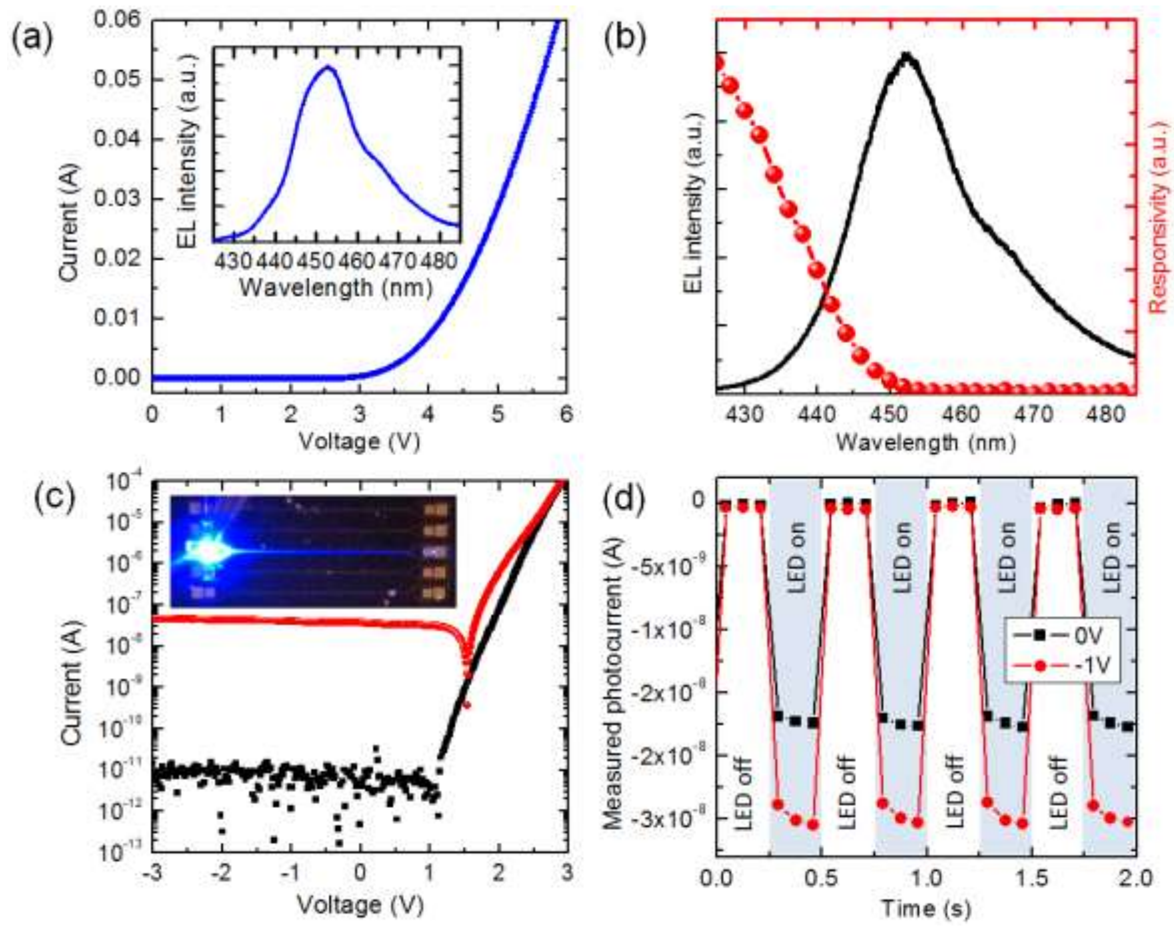


Fig. 6.5.2. (a) Current-voltage (I-V) characteristics and emission spectrum of the LED. (b) Emission and absorption spectra of the detector. (c) I-V characteristics of the detector measured in the dark from the LED operating at 5 mA; the inset shows a plan-view microphotograph of the photonic system (d) Measured photocurrent response of the photodetector as the LED was being switched on and off at a frequency of 2 Hz

6.5.2 Collaboration between professors Lau (HKUST) and Kuech (University of Wisconsin–Madison)

Collaborative work continued between the HKUST and the University of Wisconsin/Madison on GaN-based nanotechnology for devices after having demonstrated the technology on the growth of in-plane GaN microwires on silicon by MOCVD. In June 2014, the joint work was presented at the 56th Electronic Materials Conference (EMC). Also in June 2014, a post-doctoral fellow from the HKUST visited the University of Wisconsin/Madison and learned the diblock copolymer lithography process there. Based on the nanopatterned template prepared at Madison, we successfully shrank the size of a GaN wire from micrometers to nanometers by tuning MOCVD growth parameters and using another MO bubbler source. These nanowires could be as thin as 180 nm but could still maintain a length of several millimeters. Preliminary tests showed that the GaN nanowires exhibited high electrical conductivity and the resistivity was 20 to 30 mΩ cm. Ongoing work includes doping the nanowires with Si (n-type) and Mg (p-type) as well as growing MQWs on the sidewalls of GaN nanowires for photonic applications.

6.6 Research students trained (registration/awards):

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Xing LU	Ph.D.	Sep 2010	Graduated in Jan 2015
Huaxing JIANG	Ph.D.	Sep 2012	Graduate in Aug 2017
Tsz Him MAK	M.Phil.	Sep 2012	Graduated in Jan 2015
Wing Cheung CHONG	Ph.D.	Sep 2010	Graduated in Aug 2015
Yuefei CAI	Ph.D.	Sep 2013	Graduate in Aug 2018
Chao LIU	Ph.D.	Sep 2012	Graduated in Aug 2016
Xu ZHANG	Ph.D.	Sep 2014	Expected to graduate in Aug 2019
Fuliang LE	Ph.D.	Sep 2010	Graduated in Aug 2014
Mian TAO	Ph.D.	Sep 2011	Graduated in Aug 2016
Jiaqi WANG	Ph.D.	Sep 2013	Graduate in Aug 2017
Zhenhuan TIAN	Ph.D.	Sep 2013	Graduate in Aug 2017
Xing QIU	Ph.D.	Sep 2014	Graduate in Aug 2018
Andrew W. SHANG	M.Phil.	Feb 2016	Graduate in Feb 2018
Cheng HUANG	Ph.D.	Sep 2008	Graduated in Aug 2014
Yuan GAO	Ph.D.	Sep 2012	Graduated in Aug 2017
Lisong LI	Ph.D.	Sep 2012	Graduated in Aug 2017
Xiangming FANG	Ph.D.	Sep 2009	Graduated in Dec 2014
Jie REN	Ph.D.	Sep 2012	Graduate in Mar 2018
Yixiao DING	Ph.D.	Sep 2015	Expected to graduate in Aug 2019
Xianbo LI	Ph.D.	Sep 2013	Graduated in Jul 2017
Fengyu CHE	M.Phil.	Sep 2012	Graduated in Jan 2015
Babar HUSSAIN	M.Phil.	Sep 2013	Graduated in Aug 2015
Liusheng SUN	M.Phil.	Sep 2015	Graduated in Oct 2017
Lin CHENG	Ph.D.	Fall 2011	Graduated in Aug 2016
Junmin JIANG	Ph.D.	Fall 2013	Graduated in Aug 2017
Shing Hin YUEN	M.Phil.	Sep 2016	Graduate in Aug 2018
Yiyun ZHANG	Ph.D.	Nov 2012	Graduated in Oct 2016

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

N/A

6.8 Other education activities and/or training programmes developed:

N/A

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

N/A

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

In addition to monthly executive meetings attended by most Co-PIs, Prof. Lau has also initiated weekly meetings with the PGs and researchers working on the integrated systems to ensure regular communication among group members and improve coordination. Group members were also encouraged by the collaborative effort.

Instead of an equal allocation of funds to all Co-PIs, the PC established the practice of allocating funds based on contribution/effort made towards the project. Postdoctoral fellows and PGs who contributed to the TRS project received support. The PC also particularly encouraged collaborative effort to achieve the final goals and the importance of joint publications.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

Yes. ITC funding was awarded for a platform Tier 2 project, ITS/382/17FP. Professor Lau was the PIs too. The ITC project was associated with the TRS funded project as we further explored the development of monolithic LED micro-display by scaling down the single color pixel size to 30 x 30 µm2 in the ITC project. In TRS, we had achieved large-scale and high resolution LED micro-displays, such as the first 1700 PPI passive-matrix LEDs on silicon (LEDoS) micro-displays powered by ASIC display driver with 6-bit grayscale, and 400 × 240 active-matrix LEDoS micro-displays. We will combine top-emitting passive-matrix micro-LED array with the dual wavelength blue / green colors. Only the red color will be obtained by QD color conversion technology on a blue pixel underneath. We will demonstrate a 40 × 40 full color LED micro-display. The proof of concept illustrates the potential of monolithic LED micro-arrays for next generation display applications. The TRS project was completed, while there is still much room for novel technologies development, especially for refinement of full-color. In the near future, we will submit Tier 3 proposals based on the results of this TRS project.

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

Prof. Johnny Sin, General Chair, the 27th International Symposium on Power Semiconductor Devices & ICs, 2015, Hong Kong, 10-14, May, 2015.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

Prof. Philip Mok
Associate Editor of IEEE Trans. on Circuits and System – II (2012 – 2015)
Associate Editor of IEEE Trans. on Circuits and System – I (2016 – present)

Prof. Johnny Sin
Advisory Committee Member, the International Symposium on Power Semiconductor Devices & ICs.

Prof. Wing-Hung Ki
Associate Editor of IEEE Trans. on Power Electronics

7.4 Any documentary proof of the application of technologies arising directly from this project?

N/A

7.5 Other awards and recognitions as a result of this project (please specify):

Prof. Shi-Wei Ricky Lee
2015 Best Paper Award (ASME 2015 InterPack & 13th ICNMM)
Best Conference Paper Award (ICEPT 2015)

Prof. Johnny Sin
Runner-up of Charitat Award of the 27th International Symposium on Power Semiconductor Devices & IC's, May, 2015.

8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organisations, etc.)?

We have accelerated the adoption of eco-friendly solid-state lighting (SSL) in HK and the world by unleashing the power of intrinsic LEDs with innovative device fabrication and packaging technologies. The LED system on a chip (SoC) has given way to new applications including active matrix micro-arrays displays, intelligent traffic and visible light communications.

The formation of a spin-off company (JBD, LEDoS) located on the Hong Kong Science & Technology campus will provide new jobs, including some for graduates trained by this TRS program. The research output will facilitate the development of commercial ventures and may include activities associated with new, high-resolution LED micro-displays. We can provide our expertise and access to facilities to JBD.

During the research, we generated many deliverables or new ideas and filed patents for them (see list below). These patents are jointly owned by HKUST and JBD.

Other researchers in Hong Kong and U.S.A. have expressed interest in collaborating with us thanks to the technologies we now possesses. Our technology provides both environmental and commercial incentives. Multidisciplinary researchers have been trained and new ventures have spawned, contributing to the transformation of Hong Kong into a knowledge-based economy.

The following patents were filed:

[1] J. Jiang, Y. Lu and W. H. Ki, "Two-Phase, Three-Phase Reconfigurable Switched-Capacitor Power Converter", TTC.PA.0927 / HKSTP229WO, PCT patent application, February 2017.

[2] Y. Gao, P.K.T. Mok, and L. Li, "Converter-free LED driver with low-frequency-flicker reduction", PCT International Patent Application No. PCT/CN2016/085417, filed on 12th June 2016.

[3] L. Li, P.K.T. Mok, and Y. Gao, "Hybrid-type LED Driver", US Provisional Patent Application No 62/392,254, 26th May 2016.

[4] Y. Gao, P.K.T. Mok, and L. Li, "Converter-free LED driver with low-frequency-flicker reduction", US Provisional Patent 62/174907, 12th Jun. 2015.

[5] Kei May Lau, Wing Cheung Chong, "Gallium nitride flip-chip light emitting diode", US Patent (No. 9,966,519), 8 May 2018; Chinese Patent (No, 201580025962.5), 29 April 2019; TTC.PA.0760

[6] Kei May Lau, Zhaojun Liu, Wing Cheung Chong, Wai Keung Cho, Chu Hong James Wang, "Passive-matrix light-emitting diodes on silicon micro-display", US Patent (No. 10,229,630) 17 Nov. 2018; TTC.PA.0759

[7] J.K.O. Sin, Rongxiang Wu and Xiangming Fang, "Large inductance integrated magnetic induction device and methods of fabricating the same", US Patent (No. 8,754,737), 17th Jun.2014; Chinese Patent (No. 201210086236.2), 28 March 2012; TTC.PA.0527

[8] Kei May Lau, Chik Patrick Yue, Liang Wu, Zhaojun Liu, Wing Cheung Chong, Xianbo Li, "LED micro-displays with visible light communication", US Provisional Patent 61/997928, 13th Jun. 2014.

[9] Kei May Lau, Zhaojun Liu, Wing Cheung Chong, Wai Keung Cho, Chu Hong James Wang, "Light emitting diode micro-display on application specific integration circuits", US Provisional Patent 61/996667, 15th May 2014.

[10] Kei May Lau, Wing Cheung Chong, "Light emitting diodes with high density of point-contacts", US Provisional Patent 61/996747, 15th May 2014.

[11] Kei May Lau, Zhaojun Liu, " Monolithic Integrated HEMT-LED Devices", US Provisional Patent, 7th Nov 2013.

[12] Kei May Lau, Chik Patrick Yue, Zhaojun Liu, " LEDoS Projection System", US Patent (No. 9,424,775), 23 August 2016; TTC.PA.0606

[13] J.K.O. Sin, X. Huang and X. Fang, "Monolithic Multilayer Embedded Capacitor and Method for Fabricating Same", US Provisional Patent 61/960527, 20th Sep. 2013.

8.2 Others (please specify):

N/A

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

We have made significant advances in LED micro-displays including passive and active matrix LEDoS (LED on silicon) micro-displays with high resolution and small pixel size, and full-color micro-displays using QD color conversion technology. These remarkable achievements laid the groundwork for further improvement of LEDs micro-displays, in particular, full-color displays.

1) A novel full-color display system has been developed based on our well-developed LEDoS technology combining dual wavelength LEDs and red light emission QDs. By growing blue and green InGaNGaN quantum wells sequentially in a single LED structure, blue and green color emission can be obtained at different driving current densities. With monolithically blue and green pixels on the wafer, only red color needs to be converted by a blue pixel underneath. This means that only one kind of QD needs to be coated on the red sub-pixels, significantly simplifying the process and reducing the cost of QDs to a large degree.

2) On-chip integration of III-nitride voltage-controlled light-emitting diodes (HEMT-LEDs) have been developed with visible and ultraviolet (UV) photodiodes (PDs). The integration scheme can be extended to develop a variety of applications such as smart lighting, on-chip optical interconnect, optical wireless communication, and opto-isolators.

3) The LED lighting SoC system demonstrated an AC-DC LED driver with high-voltage GaN devices. It was powered (by?) a string of LEDs at 110VAC without a high-frequency switching converter but maintained low flickering and high efficiency. By employing GaN MISHEMTs, the system was powered by higher AC or DC input voltages. The LED driver chip was fabricated through an 110V process because of the high breakdown voltage of the GaN MISHEMTs. Functional testing was carried out and the feasibility of the proposed circuit was confirmed. We can enhance the breakdown voltage of GaN MISHEMTs to >220V, i.e. extend the input voltage of the SoC lighting system from 110VAC to 220VAC to suit more countries.

4. A high-speed visible light communication (VLC) system consisting of monolithically-integrated emitters, photodetectors and waveguides capable of transmission at 250 Mbit/s was jointly fabricated using GaN-on-Si LED wafers. The transmission speed was doubled for communication application.

9.2 Whether there are new projects evolved directly from this project?

The new ITF project, ITS/382/17FP, is for the full-color display. We can use the idea from TRS project to simplify our work on dual wavelength LEDs. It inspired us to seize the opportunity to realize full-color displays by exploiting this dual wavelength LED with the micro-display techniques that we have developed in previous related ITF projects. Based on the dual wavelength LEDs, two-color emission LEDs (blue and green) can be integrated monolithically. In the meantime, red light emission can be converted from original blue LEDs coated with CdSe/ZnS QDs. Thus, for the full-color display, an LED array with three color pixels can be fabricated monolithically with only red light converted from blue/green pixels using QDs. Consequently, the consumption of expensive QD materials will be minimized and the manufacturing process will be significantly simplified, which will allow for an innovative and manufacturing-friendly full-color LED micro-display technology for many practical applications.

9.3 Whether there are new collaborations developed directly from this project?

N/A

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

ITS/382/17FP; ITF Funding: HK$2,947,450.; Industry sponsorship: HK$500,000.

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	57	56	0	6		

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

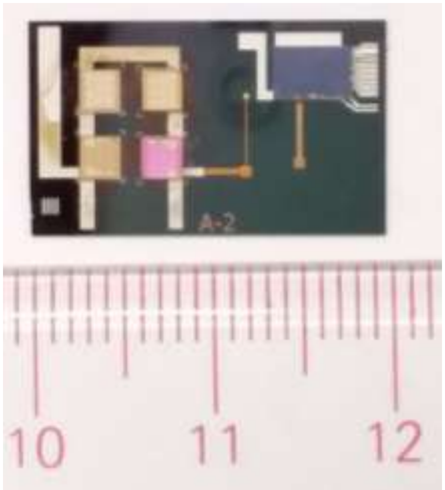
In the past five years, this team of professionals have obtained fruitful results on LED technologies including materials, devices, circuits and systems. New technologies for fabricating LED chips, GaN HEMTs, LED micro-arrays, nanowires, backside silicon embedded inductors, LED drivers for general lighting and display, and on-chip power management units, and packaging technologies have been developed. Through the effective collaboration among team members, modules that integrate research results of different team members on general lighting and LED micro-display applications have been built. A new generation of multidisciplinary researchers have been trained.

LED lights using switching mode LED drivers are common in the market. However, owing to bulky components like power inductors, existing solutions are large in size. To reduce their size, the switching frequency of the circuit must be increased, leading to a small inductor value. The inductor should be embedded on the backside of a silicon wafer to further reduce the size. In our module, an LED driver chip and four LED chips are flip-chip bonded on a silicon carrier which consists of metal routing to connect the chips. The embedded inductor is fabricated on the backside of the silicon carrier. It is connected to the metal routing by through silicon vias. The size of the silicon carrier is 20 mm × 12 mm.

Apart from using switching mode LED drivers, an alternative solution for general lighting applications is non-switching LED drivers. Existing non-switching solutions suffer from the flickering problem which may be hazardous to health. Our solution significantly reduces this problem. Our circuit divides a string of LEDs into groups and turns on these groups of LEDs according to the input voltage, which is an AC input with varying instantaneous voltage. As the LED chips are designed and fabricated in house, a high flexibility in grouping the LEDs in the circuit design is allowed. All LED chips and the LED driver are flip-chip bonded on a silicon carrier. Underfill is dispensed under the LED chips to enhance the mechanical support and thermal dissipation, and the LED chips are coated with phosphor to give a white light.

Other than general lighting applications, we also developed LED micro-display systems. A 400 × 240 pixel LED micro-array was designed and fabricated in house, and an LED driver was also designed to drive the LED micro-array which was flip-chip bonded on the driver. The micro-display system can display text, images and videos and also support visible light communication.

System integration was one of the most important aspects of this project. Using the fundamental technologies on fabrication and packaging developed in the project, we developed small form factor modules for general lighting applications and micro-display applications. For general lighting applications, high switching frequency LED drivers reduce component values to enable fabrication of on-chip power inductors. In-house designed and fabricated LED chips provide high flexibility in terms of the size and number of LEDs in system design, which can be achieved according to the specifications of applications. We can even provide different circuit topologies (e.g. inductorless topology), depending on customer requirements. For the micro-display applications, our in-house fabricated micro LED arrays are low pitch and have a large pixel size. This developed micro LED array technology was transferred to a local company in 2015, which is a good example of academic outputs supporting industry. Considering the small size of components, packaging technologies developed in this project also play an important role in our integrated systems. Highly integrated systems and a small form factor are future requirements, which can be met with the technologies developed and demonstrated in this project.



Left: An LED light bulb with reduced flickering and a lifetime of 5000 hours (increased from 2000 hours by eliminating the electrolytic capacitor).

Right: Major power components including LED chips, an LED driver and a backside silicon-embedded inductor are integrated on a silicon carrier to provide a general lighting solution with a small form factor.Right photo: Major power components including LED chips, LED driver and a backside

A 400×240 micro-display system that can display text, images and videos using an active matrix LED micro-array fabricated in house, a CMOS LED
driver designed in house but fabricated externally and a dc-dc converter.