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

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

Part A: The Project and Investigator(s)

1. Project Title

Photonic Integration in GaN Membranes on Silicon

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof Choi Hoi Wai	Prof Wang Yongjin
Post	Professor	Professor
Unit / Department / Institution	Electrical and Electronic Engineering, The University of Hong Kong	College of Telcommunications and Information Engineering, Nanjing University of Post and Telecommunications
Contact Information	852-39172693 hwchoi@hku.hk	wangyj@njupt.edu.cn
Co-investigator(s) *(with title and institution)*		

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01/01/2016		
Project Completion date	31/12/2019		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	31/12/2020		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To develop high-efficiency photonic crystal edge-emitting light-emitting diodes on GaN thin-film membranes from GaN-on-Si materials
2. To develop photonic components such as waveguides on GaN thin-film membranes
3. To integrate active (such as LEDs) and passive (such as waveguides) components on the same GaN membranous platform.
4. To demonstrate applications of the integrated GaN membranous platform such as optical communications.

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____
____

6. Research Outcome

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

The project aimed at exploring the possibilities of enabling additional devices on a chip-scale GaN platform for enabling enhanced functionalities through the monolithic integration approach, and it has successfully achieved its goals. It has been demonstrated that multiple types of devices, including light-emitting diodes, photodetectors, waveguides and microdisk resonators can co-exist on a single GaN-based wafer to perform functions beyond what the wafer was intended to do. Three major integrated platforms have been demonstrated, described as follows:

(1) **LED, PD and Waveguide photonic systems for on-chip-visible light communications**: The characteristics of monolithically integrated light-emitting diodes (LEDs), photodetectors (PDs), and waveguides on a GaN-on-Si wafer are investigated. The InGaN/GaN multi-quantum wells which are responsible for blue light emission in the LED are also used for photodetection in the PD. The PDs can be detached from the substrate and re-mounted on an elevated platform, owing to the flexibility of the thin-film waveguide. The LEDs and PDs exhibit rapid response on the nanosecond time-scale attributed to fast radiative recombination as well as minimized RC delays, enabling transmission of pseudo-random binary sequence (PRBS) data signals at rates of 250 Mbit/s with an opening in the eye diagram. Together with cross-talk free multi-channel transmission, the capability of the planar and 3D monolithic photonic systems for visible-light communication (VLC) applications is demonstrated.

(2) **LED and PD integrated systems for light-intensity stabilization**: To overcome light output degradations and fluctuations of intensities from light-emitting diodes (LEDs) over time, the monolithic integration of InGaN LEDs and photodetectors (PDs) is demonstrated. The InGaN/GaN multi-quantum wells (MQWs) play the role of light emission and detection from the LED and PD respectively. The tiny-sized PD detects light from the adjacent LED coupled through the sapphire substrate to generate a photocurrent that is proportional to its light output, but remains unresponsive to ambient lighting. The photocurrent can be used as a feedback signal for regulation of light output. A micro-controller based feedback circuit has been implemented to drive the LED; the photocurrent level is maintained to a preset value by adjustment of the driving current. Using this scheme, light output from the LED has been stabilized to within ~0.2% over 1 hour periods.

(3) **Microdisk-waveguide integration for lasing applications**: In this work, a waveguide with a width of 0.16 μm coupled to a microdisk with a diameter of 10 μm is fabricated on a 0.77 μm thick GaN thin film containing InGaN/GaN multi-quantum wells. The waveguide is connected directly to the microdisk at the circumference forming a coupling junction, eliminating the need for precision patterning as with evanescent coupling schemes whereby gaps of the order of tens of nanometers between the waveguide and resonator must be maintained. The fabrication was carried out using nanosphere and nanowire lithography. Non-evanescent coupling of whispering-gallery modes (WGMs) to the waveguide from the microdisk is successfully demonstrated.

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

The findings have verified the feasibilities of developing monolithically-integrated GaN photonic systems for achieving a variety of functions. Based on the observations arising from the work, the following scopes for further development are proposed:

(1) Monolithic integration of electronics and optoelectronics on a common GaN platform: Despite the success of GaN optoelectronics and electronics, the two technologies have been developed independent of each other. Nevertheless, optoelectronics and electronics are often dependent on each other in many real-life applications. In the simplest case, the LEDs have to be driven by LED drivers, which are essentially transistor-based circuits. However, LEDs are typically driven by a separate driver circuit which is typically fabricated on the Si platform (as with most electronics circuitry). If optoelectronics and electronics can be integrated onto the same platform (wafer), that would result in significant reduction in material costs (same wafer), processing costs (same wafer processing) and packaging costs (single chip).
(2) Hybrid monolithic and heterogeneous integration: Each form of integration has its merits, thus we should not restrict ourselves to one form of integration. As such, we propose a hybrid scheme of integration, where components are monolithically-integrated onto a single GaN wafer where possible (such as LEDs, PDs, waveguides, microdisks), and the other components through heterogenous integration (such as resistors, op-amps, ICs etc). Tight integration can be achieved through flip-chip bonding scheme.

7. The Layman's Summary

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

Many of the commonly-used electronics appliances used today rely on GaN technology in one way or another, including InGaN lighting-emitting diodes (LEDs) for lighting and displays, GaN photodetectors for optical sensing, InGaN laser diodes (LDs) in blu-ray players and recorders, as well as AlGaN/GaN transistors in compact chargers. Although GaN devices span the electronics and optoelectronics sectors, the different types of devices have been developed mostly separately from each other, despite the close relation between them. This project has successfully opened the avenue towards tightly integrating two or more of such GaN devices on a single wafer towards achieving enhanced functionalities compared to the individual devices. For instances, LEDs, PDs and waveguides have been integrated to form photonic systems capable for high-speed visible-light on-chip optical communications. Additionally, PDs have been monolithically-integrated adjacent to LEDs for monitoring the light output on a real-time basis. Together with a control and driver circuit, the intensity and colour chromaticity can be stabilized both on a short and long durations.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) (**bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)	Title and Journal/ Book (with the volume, pages and other necessary publishing details specified)	Submitted to RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of this Joint Research Scheme (Yes or No)	Accessible from the institutional repository (Yes or No)
Year of publication	Year of Acceptance (For paper accepted but not yet published)	Under Review	Under Preparation (optional)						
2018				Y. Park, K.H. Li, W.Y. Fu, Y.F. Cheung and **H.W. Choi***	"Packaging of InGaN stripe-shaped light-emitting Diodes", Applied Optics 57, 2452	No	Yes	Yes	Yes
2018				K. H. Li, W. Y. Fu, Y. F. Cheung, K. K. Y. Wong, **Y. Wang**, K. M. Lau, and **H. W. Choi***	Monolithically integrated InGaN/GaN light-emitting diodes, photodetectors, and waveguides on Si substrate, Optica 5, 564	No	Yes	Yes	Yes
2019				K.H. Li, H. Lu, W.Y. Fu, Y.F. Cheung and **H.W. Choi***	Intensity-Stabilized LEDs With Monolithically Integrated Photodetectors, IEEE Transactions on Industrial Electronics, 66, 7426	No	Yes	Yes	Yes

2018				K.H. Li, Y.F. Cheung, W.Y. Fu, K.K.Y. Wong, and **H.W. Choi***	Monolithic Integration of GaN-on-Sapphire Light-Emitting Diodes, Photodetectors, and Waveguides, IEEE Journal of Selected Topics in Quantum Electronics 24, 3801706	No	Yes	Yes	Yes
2020				K.H. Li, Y.F. Cheung, W. Jin, W.Y. Fu, A.T.L. Lee, S.C. Tan, S.Y. Hui and **H.W. Choi***	InGaN RGB Light-Emitting Diodes With Monolithically Integrated Photodetectors for Stabilizing Color Chromaticity, IEEE Transactions on Industrial Electronics, 67, 5154	No	Yes	Yes	Yes
2020				C.H. To, W.Y. Fu, K.H. Li, Y.F. Cheung and **H.W. Choi***	GaN microdisk with direct coupled waveguide for unidirectional whispering-gallery mode emission, Optics Letters 45, 791	No	Yes	Yes	Yes
2020				K.H. Li, W.Y. Fu and **H.W. Choi***	Chip-scale GaN Integration, Progress in Quantum Electronics 70, 100247	No	Yes	Yes	Yes

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
May/2016/ Yokohama, Japan	GaN light-emitting diode with monolithically-integrated photodetector	4th International Conference on Light-Emitting Devices and Their Industrial Applications (LEDIA '16)	Yes	No	Yes, during oral presentation	Yes
Jul/2017/ Strasbourg, France	3D GaN Photonic Integrated Circuits	12th International Conference on Nitride Semiconductors	Yes	No	Yes, during oral presentation	Yes
Oct/2016/ Orlando, USA	Monolithically-integrated GaN Photonic Systems	International Workshop on Nitride Semiconductors 2016	No	Yes	Yes, during oral presentation	Yes
Jun/2018/ Sheffield, UK	Monolithic Integration of GaN Light-emitting Diodes and Photodetectors and their Applications	16th International Symposium on the Science and Technology of Lighting	No	Yes	Yes, during oral presentation	Yes
Jul/2019/ Bellevue, USA	GaN Bipolar Junction Transistor for Monolithic Integration	13th International Conference on Nitride Semiconductors	No	Yes	Yes, during oral presentation	Yes

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Zhang Yiyun	PhD	1 Nov 2012	Oct 2016
Feng Cong	PhD	1 Sep 2012	Sep 2016
Park Yonghua	MPhil	1 Sep 2015	Aug 2017
To Chap Hang	PhD	1 Dec 2015	May 2020

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

US Patent Application "Light-emitting Diodes (LEDs) with Monolithically-integrated Photodetectors for in situ real-time intensity monitoring:, US 2019/0157508 A1

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

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project [or conference]	7	5			