RGC Ref.: N_HKUST624/15 NSFC Ref. : 61531166006
(please insert ref. above)

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

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

Part A: The Project and Investigator(s)

1. Project Title

Single-crystalline silicon cantilever-resonator gas sensor array fabricated using silicon-migration technology for air quality monitoring

面向空氣質量監測的基於硅遷移技術單晶硅諧振懸臂梁氣體傳感器陣列

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	WONG Man (王文)	王曉紅 (WANG Xiaohong)
Post	Professor (教授)	教授 (Professor)
Unit / Department / Institution	ECE/HKUST	IME/Tsinghua University
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Co-investigator(s) *(with title and institution)*		

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	Jan/1/2016		
Project Completion date	Dec/31/2019		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	Dec/31/2020		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Apply the silicon-migration technology to realize a micro-balance based on MEMS cantilever resonator.
2. Apply gas-sensitive materials to the cantilever resonator and obtain specific gas sensitivities for major air pollutants.
3. Realize an air quality monitoring system based on the micro-balance and assess its potential for commercialization.

5.2 Revised Objectives

Date of approval from the RGC: _____

Reasons for the change: _____
_____

1.
2.
3. ....

6. Research Outcome

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

Unlike capacitive and piezoelectric transduction mechanisms, the thermally actuated and piezoresistively sensed resonator could extract energy from a direct-current (DC) power supply. Physics-based mathematical models of (1) the temperature distribution along an actuation beam subjected to both DC and time-varying electrical bias and (2) the piezoresistance-induced feedback mechanisms have been developed. Extracting energy from the DC component of the power supply is akin to an effective reduction in damping, hence an increase in the effective quality factor. When the effective damping becomes zero, the resonator oscillates without requiring a time-varying excitation signal. In conventional resonators, such sustained resonance requires an external feedback circuit. Applying the model, an in-plane flexural mode resonator was designed and subsequently fabricated using the silicon-migration technology. By increasing the DC bias applied to the actuation beam from 5 to 13 V, the loss due to heat dissipation and mechanical damping were partially compensated due to the aforementioned piezoresistive feedback mechanism, thus resulting in an increase in the quality factor. Such tuning of the quality factor has been demonstrated and presented in the paper by Sen Xu at the Transducers 2019 conference.

A novel high-performance graphene-based gas sensor based on the design of mosaic-like assembled monolayer of reduced graphene oxide/silver sensing membrane was demonstrated. Combining spin-coating and the self-assembly methods, the film deposition scheme was simple and highly reproducible. The good quality of the resulting film morphology contributed to the sensing performance of the sensor. Even when operated at room temperature, the sensor could fully recover to the initial state without requiring any power-consuming treatment like UV/IR irradiation or resistive heating. The response of the sensor showed good agreement with the Langmuir isotherm. This work was presented in the paper by Xinyan Jia at the Transducers 2019 conference, which was extended and subsequently published in the Journal of Microelectromechanical Systems, also in 2019.

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

Sensors for both particulate and gas detection could be further improved. In addition to increasing the sensitivities, gas sensing specificity needs to be investigated and characterized. Specificity refers to the ability of a sensor to distinguish different gas contaminants, such as carbon monoxide, nitrous oxide, and sulfur dioxide, etc. One possible approach is the construction of functionalized interdigitated electrodes on micro hot-plates operating at different temperatures. Metal-oxide semiconductors, such as tin (IV) oxide are commonly deployed as functional receptor materials. The deployment of different functional materials to improve specificity can also be investigated. A second development effort is the monolithic integration of particulate- and gas-sensors. Such integration generally offers better system performance and lower system cost. Silicon-migration technology is a feasible approach in resolving process incompatibility issues during monolithic integration of disparate devices.

7. The Layman's Summary

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

Sensing of contaminants is an important endeavor for air-quality assessment in open environments, factories and homes. Contaminants are generally classified as particulates and gases, both are harmful when present in excess. Micro-sensors for both have been developed in this project, with a thermomechanical resonator for particulate sensing and interdigitated electrodes functionalized with reduced graphene oxide for gas sensing. Encouraging preliminary performance have been obtained. Improvement and deployment of the sensors developed in the present work will be beneficial to air-quality assessment.

Part C: Research Output

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

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

The Latest Status of Publications				Author(s) ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2019 J1				**Xinyan Jia, Xiaohong Wang***	Mosaic-Like Micropatterned Monolayer RGO/AgNPs Film Gas Sensor With Enhanced Room-Temperature NO2 Response/Recovery Properties JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, 28(5)：833~840	2020	Yes	Yes (Please note the equivalent project code for the Tsinghua partner is 615311660006)	No

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered

(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Jun/2019/ Germany C1	Thermal Piezoresistive Q-Tuning of P-Type Silicon Resonator with Feedthrough Reduction	2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII	2020	Yes	Yes (Please note the equivalent project code for the Tsinghua partner is 61531166006)	Yes

Jun/2019/ Germany C2	Mosaic-Like Monolayer RGO/Ag Film via Ultrafast Two-dimensional Assembly for High Performance Room-Temperature Gas Sensor	2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII	2020	Yes	Yes (Please note the equivalent project code for the Tsinghua partner is 61531166006)	No
Jan/2018/ United Kingdom C3	A Novel Potential Modulated Amino Acid Sensing Chip Modified by MXENE for Total Internal Reflection Imaging Ellipsometry Biosensor	2018 IEEE Micro Electro Mechanical Systems (MEMS)	2020	Yes	Yes (Please note the equivalent project code for the Tsinghua partner is 61531166006)	No

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
S1	Sen XU	PhD (Switched to MPhil)	2016	Jun/2020
S2	Yushen Hu	PhD	2018	Jun/2022

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

Patent application:

單片集成的有源矩陣微熱板及其製造方法.

一種低阻抗電極的製備方法及低阻抗電極.

複合電極材料及其用途.

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]	1	3	0	0	0