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(please insert ref. above)

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

Part A: The Project and Investigator(s)

1. Project Title

Key technologies for the next-generation real-time high-resolution minimally-invasive implantable Electrocorticography (ECoG) system
下一代實時高解析度微創植入式腦皮層電圖系統關鍵技術的研究

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Jie Yuan, Associate Professor 袁杰教授	Zhihua Wang, Professor 王志华教授
Post	Associate Professor，副教授	Professor，教授
Unit / Department / Institution	Electronic & Computer Engineering Department/HKUST 香港科技大學電子與計算機工程學系	Microelectronics Institute /Tsinghua University 清華大學微電子學院
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Co-investigator(s) *(with title and institution)*	Prof. Jun Ohta Nara Institute of Science & Technology	Associate Prof. Hanjun Jiang Tsinghua University 姜汉钧副教授，清华大学

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	2015.01.01		
Project Completion date	2018.12.31		
Duration *(in month)*	48		
Deadline for Submission of Completion Report	2019.12.31		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To develop switch-matrix-based high-density micro-electrode array (MEA) technology and polymer-coating technology to enable enzyme-catalyzed neurotransmitter sensing;
2. To develop single-chip highly sensitive ultra-low-power voltage and current acquisition circuits;
3. To develop ultra-low-power wireless bio-telemetry technology;
4. To develop wireless energy harvesting technology;
5. To develop silicone-substrate-based low-temperature chip bonding and packaging technology;

6. To develop a prototype ECoG implant, and to test it on free-moving rats.

2. Background

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)

In this project, we have made major breakthrough in following areas.

1) Bio-sensing electrodes

We have developed a reliable CNT coating process on the Au electrode for dopamine sensing. We have also developed a process to fabricate miniaturized Ag/AgCl reference electrode for micro-electrode array, which has been a challenge for microelectrodes. We have studied the mechanism of Ag/AgCl electrodes. The findings were published in the following two journal papers.

2) Energy-efficient acquisition circuits

We have designed efficient acquisition circuits for voltage, current and impedance. In particular, the impedance acquisition circuit design is one of the first array designs for impedance acquisition. The designs were published in two conference papers.

3) Energy-efficient quantization circuits

As the acquisition circuits need high resolution (>12bits), we have studied the energy efficient design of incremental ADCs (IADC). We have designed an IADC with the one of the highest energy efficiency reported so far. The IADC design is published in JSSC, which is the best journal for chip design.

4) Telemetry

A 10 Mbps 400MHz transceiver has been designed in 65nm CMOS with the energy efficiency among the state-of-the-arts. A 20 Mbps ΔΣ-based 2.4GHz transmitter has been designed in 180nm CMOS with the energy efficiency of 20pJ/bit, which outperforms all the other similar designs. The results are published in TCAS-I and TCAS-II.

5) Energy harvesting

The in-body energy harvesting circuit has been implemented in the 0.8μm BCD process. The measured rectifier efficiency is 92%, and the charging efficiency is 80%. The receiving coil shows an energy efficiency of 60% with 10mm distance. The results are published in IEEE TPE.

6) Passives on flexible substrate

We have developed a low-temperature process to integrate passives with silicon chips on the PDMS substrate. This is a major breakthrough for integrated bio-sensing as PDMS has good bio-compatibility. We are preparing a journal to publish our work with such processes.

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

The technologies developed from this project can be applied to many future research:

1. Bio-sensing applications: One future direction is to apply these technologies to sense bio-markers. We have experimented to modify the electrodes to sense proteins. With such research, we have attracted pharmaceutical companies to collaborate with us to develop project on detecting specific bio-markers. Teamed up with groups from MIT and CUHK, we have developed a HKD$12M ITF Tier2 project with the support of Merck on cytokine detection based on the technologies developed from this project.

2. Energy-efficient ADC design: Along the direction of ADC design, our research has also attracted many interests from industry. In particular, ZTE has proposed to collaborate with us on ADC design. They have granted a HKD$500K contract research for us to investigate further on energy efficient high-resolution ADC. After completing this contract research, we have also developed a HKD$1.4M ITF Tier3 project on the design of highly efficient ADCs.

3. PDMS-based integrated bio-electronics: We are also pushing the PDMS-based integration process further for wearable electronics. Together with the energy harvesting technologies developed in the GRF project 16234316, we are in the process of developing an integrated wearable sensing node with flexible substrate.

4. Further development on telemetry

The telemetry circuit techniques have been used in other implantable medical devices developed by our group, such as the wireless intracranial pressure sensing device which received fund from Shenzhen government under grant number JCYJ20170307145728497, and the implantable long-term ECG monitoring device which has been funded by NSFC starting from 2007 under grant number 61661166010.

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)

In this project, the team has developed a wide range of technologies for an implantable ECoG system including sensing electrodes, reference electrodes, acquisition circuits, quantization circuits, telemetry circuits, energy harvesting circuits for implants, and flexible substrate based bio-electronics integration technologies. Under the framework of one project, the investigation with such breadth is only possible through the joint collaboration scheme.

The project team researched deeply into these areas, and has resulted in verifiable technologies, chips and electronic prototypes. In particularly, the project team has developed new miniaturized electrodes to sense neurotransmitters, developed energy-efficient acquisition circuits to sense all signals in bio-sensing applications, developed energy-efficient ADCs to quantize the acquired bio-signals with very low power, developed telemetry circuits for implants, developed harvesting circuits to power up the implants, and developed a process to integrate electronic circuits on flexible substrate.

Most of the research outcome have achieved the state-of-the-art in the relevant area.

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*	Title and Journal/ Book *(with the volume, pages and other necessary*	Submitted	Attached	Acknowledged	Accessible

Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*	*belonging to the project teams and denote the corresponding author with an asterisk*)*	*publishing details specified)*	to RGC *(indicate the year ending of the relevant progress report)*	to this report *(Yes or No)*	the support of this Joint Research Scheme *(Yes or No)*	from the institutional repository *(Yes or No)*
2019				*Kai Chun Eddie Tjon*, Jie Yuan*	Impedance characterization of silver/silver chloride micro-electrodes for bio-sensing applications, Electrochimica Acta, Vol. 320	2019	Yes	Yes	Yes
	2019			*Saqib Mohamad*, Jie Yuan*	A 102.2dB, 181.1dB FoM extended counting analog-to-digital converter with capacitor scaling, IEEE Journal of Solid-State Circuits	2019	Yes	Yes	No
		Yes		*Kai Chun Eddie Tjon*, Jie Yuan*	Fabrication of Thin Film Silver/Silver Chloride Electrodes with Finely Controlled Single Layer AgCl, Journal of Visualized experiments	2019	Yes	Yes	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)*
09/2018/Tokyo	The design of voltage and current acquisition front-ends for brain-machine interface	*2018 International Conference on Solid State Devices and Materials*	2019	Yes	Yes	No
06/2017/Baltimore	A power-area-efficient impedance sensor design for 10*10 microelectrode array sensing	*IEEE International Symposium on Circuits and Systems*	2016	No	Yes	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
Saqib Mohamad	PHD	September, 2014	January 2019

Kai Chun Eddie	PHD	September, 2017	Aug. 2021

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

The research from this project has raised interests from industrial partners. Merck is collaborating with us to carry out an industrial project towards commercializing the techniques from this project. ZTE is collaborating with us to carry out another industrial project towards commercializing the techniques from this project.

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]	3	2			Industrial collaboration with Merck and ZTE towards commercializatio n