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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

Photovoltaic, Spin Field Effect Transistor and Sensing Devices Based on Polar Oxide Heterostructural Two-dimensional Electron Gas

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Professor Jiyan DAI	Professor Changgan ZENG
Post	Professor	Professor
Unit / Department / Institution	Department of Applied Physics / The Hong Kong Polytechnic University	Department of Physics / University of Science and Technology of China
Contact Information	Jiyan.dai@polyu.edu.hk	cgzeng@ustc.edu.cn
Co-investigator(s) *(with title and institution)*	Professor YAN Feng / The Hong Kong Polytechnic University	Prof. Zhang Zhenyu University of Science and Technology of China

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	1-Jan-2015	N/A	N/A
Project Completion date	31-Dec-2018	N/A	N/A
Duration *(in month)*	48	N/A	N/A
Deadline for Submission of Completion Report	31-Dec-2019	N/A	N/A

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1) To investigate the transport properties in various orientated interfaces of polar/non-polar oxides, so as to achieve deeper understanding on the formation of 2DEG at heterostructure interface;

2) To achieve giant photovoltaic effect in polar/non-polar oxides heterostructural 2DEG in order to realize energy harvesting;

3) To investigate spin injection and transportation in polar/non-polar oxides heterostructural 2DEG, so as to fabricate spin polarized field effect device and understand related spintronic physics;

4) To explore new sensing phenomena based on the field effect device with such heterostructure 2DEG, so as to achieve deeper understanding of the sensing mechanism.

5.2 Revised Objectives
N.A.

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)

A study about modulating the electrical transport in the 2DEG at LAO/STO heterostructures by interfacial flexoelectricity was conducted. Thin film flexoelectricity is attracting more attention because of its enhanced effect and potential application in electronic devices. Here we find that a mechanical bending induced flexoelectricity significantly modulates the electrical transport properties of the interfacial two-dimensional electron gas at the LAO/STO heterostructure. Under variant bending states, both the carrier density and mobility of the 2DEG are changed according to the flexoelectric polarization direction, showing an electric field effect modulation. By measuring the flexoelectric response of LAO, it is found that the effective flexoelectricity in the LAO thin film is enhanced by 3 orders compared to its bulk. These results were published in Physical Review Letter (see Part C and attached paper).

The dynamic modulation of the transport properties of the LAO/STO interface using uniaxial strain was investigated. Among the interfacial transport modulations to the $LaAlO_3/SrTiO_3$ (LAO/STO) heterostructure, mechanical strain has been proven to be an effective approach by growing the LAO/STO films on different substrates with varying lattice mismatches to STO. However, this lattice-mismatch-induced strain effect is static and biaxial, hindering the study of the strain effect in a dynamic way. In this work we realize dynamic and uniaxial strain to the LAO/STO oxide heterostructure at low temperature, through mechanical coupling from a magnetostrictive template. This anisotropic strain results in symmetry breaking at the interface and induces further splitting of the electronic band structure and therefore produces different conductivities along the x and y in-plane directions. This approach of strain engineering provides another degree of freedom for control of transport properties of oxide heterostructures and opens an additional way to investigate strain effects in materials science. There results were published in Physical Review B (see Part C and attached paper).

We also carried out research on the LAO/STO heterostructure for light and gas sensing applications. The main difficulty to apply this 2DEG system in electronic devices is its relatively low response to external stimulus such as light and gas (since gas cannot react and be absorbed onto the heterostructure). We successfully invented a method to modify the surface of the LAO/STO heterostructure and significantly enhance the response to ultraviolet light and gases, therefore, made this fascinating 2DEG system close to real application in sensing devices. Palladium (Pd) nanoparticles (NP) have been successfully grown on the LAO/STO structure. The Pd NP-decorated LAO/STO heterostructure exhibits a giant photo-response in the ultraviolet (UV) range. The conductance of the interface increases under the irradiation of UV light and a giant optical switching effect with a photoconductivity on/off ratio as high as 750% has been achieved at room temperature. Besides the UV light sensing, the Pd NP-decorated LAO/STO heterostructure has also been found to be very sensitive to hydrogen gas down to ~2ppm in concentration, demonstrating the highly-sensitive and room-temperature workable gas sensing properties. Cross sensitivity tests indicate that the sensor shows response to ethanol, acetone and water gas vapor. These works are still going on and will be published later.

The work of spin FET and photovoltaic were extensively studied by our Mainland collaborator. Please see attach report of our collaborator.

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

Inspired by the rich physical properties of the LAO/STO heterostructure such as 2D superconductivity, flexoelectricity and strain modulated resistance, in this project, we also extent our research work on other oxide thin film heterostructures. Efforts we and our collaborators made includes studies on plasma-enhanced pulsed-laser deposition of ferroelectric-induced resistive switching in ultrathin (Ba,Sr)TiO_3 tunnel junctions due to strain modulation and self-electroforming and high-performance complementary memristor based on ferroelectric tunnel junctions. Results have been published in two journal papers in Applied Physics Letters (see Part C and attached paper).

The two-dimensional electron gas system of this oxide heterostructure is a model system. More applications and physics beyond deserve to be further studied.

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)

Under the financial support from this joint fund program, extensive and comprehensive research works were conducted to study the complex oxide heterostructural two dimensional electron gas (2DEG) system, ranging from investigations on fundamental physical origin of the conductive nature at the $LaAlO_3/SrTiO_3$ (LAO/STO) heterostructure interface to demonstrations of effective modulation methods on its interfacial electrical transport properties and application designing as oxide electronic devices like strain sensors, light sensors and gas sensors. Based on the results of this project, four journal papers were published, including one published on *Physical Review Letters* and selected as *Editors' Suggestion* and featured in the *Physics* magazine.

These results broaden the horizon of study on the flexoelectricity effect in the hetero-oxide interface and more research on the oxide interfacial flexoelectricity may be stimulated. The concept of coupling between flexoelectricity and novel electrical properties of ultra-thin oxide films, such concept might be useful in future energy-harvesting devices or mechanical sensors.

The two-dimensional electron gas system of this $LaAlO_3/SrTiO_3$ oxide heterostructure is a model system. More applications and physics beyond deserve to be further studied.

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)*						
2016				**Fang Zhang,** Yue-Wen Fang, Ngai Yui Chan, Wing Chong Lo, Dan Feng Li, Chun-Gang Duan, Feng Ding, **Ji Yan Dai***	Dynamic modulation of the transport properties of the LaAlO3/SrTiO3 interface using uniaxial strain PHYSICAL REVIEW B 93, 214427 (2016)		yes	yes	yes

2016				Z. B. Yan, **H. M. Yau**, Z. W. Li, X. S. Gao, **J. Y. Dai***, and J.-M. Liu*	Self-electroforming and high-performance complementary memristor based on ferroelectric tunnel junctions Appl. Phys. Lett. 109, 053506		yes	yes	yes
2018				Hei-Man Yau, Zhongnan Xi, Xinxin Chen,Cheuk Ho Chan, Zheng Wen, and **Ji-Yan Dai***	Ferroelectric-induced resistive switching in ultrathin (Ba,Sr)TiO3 tunnel junctions due to strain modulation, APPLIED PHYSICS LETTERS 113, 042905		yes	yes	yes
2019				**Fan Zhang**, Peng Lv, Yiteng Zhang, Shujin Huang, Chi-Man Wong, Hei-Man Yau,1 Xinxin Chen, Zheng Wen, Xiaoning Jiang, Changgan Zeng, Jiawang Hong⋆, and **Ji-yan Dai⋆**	Modulating the Electrical Transport in the Two-Dimensional Electron Gas at LaAlO3/SrTiO3 Heterostructures by Interfacial Flexoelectricity. PHYSICAL REVIEW LETTERS 122, 257601 (2019)		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)*
2017/07	Strain-Induced Giant Electroresistance Nonvolatile Memory Based on Multiferroic Tunnel Junctions Memory	2017 Conference for Atomic force microscopy and advanced functional materials	No	Yes	Yes	No
2016/12	Low-field Switching Four-state Nonvolatile Memory Based on Multiferroic Tunnel Junctions	International Conference on ICTAM	No	Yes	Yes	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
Yua Hei MN	PhD	01/09/2014	31/08/2018

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

NIL