RGC Ref.: M-HKU/709-12
(please insert ref. above)

The Research Grants Council of Hong Kong
SRFDP & RGC ERG Joint Research Scheme
Completion Report

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

Part A: The Project and Investigator(s)

1. Project Title

Strained topological insulator thin films

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	M.H. Xie (Prof.)	J.F. Jia (Prof.)
Post	Professor & Head	Professor
Unit / Department / Institution	Physics/HKU	Physics/SJTU
Contact Information	mhxie@hku.hk	jfjia@sjtu.edu.cn
Co-investigator(s) *(with title and Institution)*		
PhD student(s) (with period of involvement)	X. Guo and Bin LI (HKU) 01/03/2013-30/11/2013(GX) 01/03/2013-29/02/2016 (BL)	Meixiao Wang, Jinpeng Xu, and Lin Miao (SJTU)

Note: The Hong Kong project team must involve at least one research postgraduate student pursuing a Doctor of Philosophy degree at the UGC-funded university (PhD student) at any time throughout the project period.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01/03/2013		
Project Completion date	29/02/2016		
Duration *(in month)*	36		

Deadline for Submission of Completion Report	28/02/2017		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. MBE growth of topological insulator thin films (such as Bi_2Se_3) on different substrates and for different thicknesses for varying strains;
2. MBE growth of Sb_2Se_3, an ordinary insulator, on substrates for varying strains;

3. Low-temperature ARPES and STM/STS studies of strained films for their structural and electronic properties.

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)

(1) Strain relaxation dynamics of epitaxial Bi_2Se_3 (111) was followed at the initial stage deposition on GaN and graphene/SiC substrate, where a tensile strain was measured on GaN but it was strain-free when grown on graphene. Strain relaxation in Bi_2Se_3 grown on GaN was found gradual. (Refer to Publication 1 listed in Part C)

(2) The high-index Bi_2Se_3 (221) film was achieved on In_2Se_3-buffered GaAs(001), in which a much retarded strain relaxation dynamics was recorded. We further revealed strong chemical bonding at the hetero-interface and the results suggested the feasibility of growing strained topological insulators for manipulation of properties of topological systems. (Refer to Publication 2 listed in Part C)

(3) Strain-free Bi_2Se_3 (221) film was realized on a suspended Ga_2Se_3 (001) on GaSb (001) despite the large lattice misfit. This might be attributed to strain accommodation in the suspended Ga_2Se_3 formed by selenation of GaSb (001). (Refer to Publication 3 listed in Part C)

(4) The metastable rhombohedral phase Sb_2Se_3 was successfully realized, on which topological insulator Bi_2Se_3 was deposited. ARPES measurements revealed the Dirac cone state induced on such a Sb_2Se_3 surface when grown on the TI Bi_2Se_3 for thicknesses up to 15 nm, contrasting that when deposited on the ordinary insulator In_2Se_3. This evidences an induced topological state on surfaces of an ordinary insulator by heterostructuring, a result with great fundamental and practical relevance. (Refer to Publication 4 listed in Part C).

(5) An unexpected (2×2) reconstruction was observed on epitaxial Bi_2Se_3 (111) (Paper is under preparation). Also, a position dependent density-of-state profile on Bi_2Se_3 (221) was noted. The latter is still under further investigation.

(6) In addition to the findings of TI systems, this project has led to some joint efforts on researches of transition-metal dichalcogenides, a two-dimensional semiconductor

receiving extensive research attention worldwide, and a few joint publications, e.g., Publications 5 and 6 listed in Part C below.

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

This collaborative project has led to some new discoveries yet to be fully understood. Examples include the above-mentioned position dependent density-of-state profile on Bi_2Se_3 (221) and the physics behind Dirac cone states observed on Sb_2Se_3 surface when heterostructured with Bi_2Se_3. They require not only additional experiments but also strong theoretical support. On the front of strain effect, theory has predicted topological phase transition by a strain field of ≥ 10%, which remains to be realized experimentally. A strain as high as this may not sustainable in an epifilm, however, one might consider applying uniaxial strain.

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)

Topological insulator (TI) is a new class of materials possessing some interesting properties and potentials in energy-saving electronic applications. It has been under intensive research attention in recent years. Bi_2Se_3 compound is a known TI material whose crystal structure consists of weakly stacked atomic layers and therefore does not support large strain. Strain, on the other hand, could be a useful parameter for one to tune the properties of a material. The main objective of the project is to monitor and control strain in Bi_2Se_3 films and develop methods to realize highly strained layers. We firstly followed strain relaxation process during initial stage Bi_2Se_3 growth and found clear substrate-dependence behaviors. We then succeeded in growing much greatly strained Bi_2Se_3 by controlling its growth along a special, the so called high-Miller index direction. This is made possible because of much stronger interface interaction in this direction. Finally, we obtained the metastable Sb_2Se_3 film, an ordinary insulator, yet it would support topological surface states – the property inherent to TIs. The latter has been experimentally verified on our samples, and the result thus indicated not only new physics but also potentials of extending the TIs to non-TI materials.

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)*						

2015				**B. Li, X. Guo**, W.K. Ho, **M.H. Xie***	"Strain in Epitaxial Bi_2Se_3 grown on GaN and Graphene substrates: a reflection high-energy electron diffraction study", *Appl. Phys. Lett*. 107, 081604		Yes	Yes	
2017				**B. Li**, W.G. Chen, **X. Guo**, W.K. Ho, X.Q. Dai, **J.F. Jia**, **M.H. Xie***	"Strain in epitaxial high-index Bi_2Se_3 (221) films grown by molecular-beam epitaxy", *Appl. Surf. Sci*. 396, 1825		Yes	Yes	
2017				**B. Li**, Y.P. Xia, W.K. Ho, **M.H. Xie***	"Suspended Ga_2Se_3 film and epitaxial Bi_2Se_3 (221) on GaSb (001) by molecular-beam epitaxy", *J. Cryst. Growth* 459, 76		Yes	Yes	

		√		**B. Li,** Q.S. Lu, S.G. Xu, Y.P. Xia, W.K. Ho, N. Wang, C. Liu,* **M.H. Xie***	"Induced robust topological order on an ordinary insulator hetero-structured with a strong topological insulator", aXiv1611.04688		Yes	Yes	
2014				H.J. Liu, L. Jiao, F. Yang, Y. Cai, X.X. Wu, W.K. Ho, C.L. Gao, **J.F. Jia**, N. Wang, H. Fan, W. Yao, **M.H. Xie***	"Dense network of one dimensional midgap metallic modes in monolayer MoSe2 and their spatial undulations", *Phys. Rev. Lett.* 113, 066105	Yes, in report year ending 31/08/2014		Yes	
2015				H.J. Liu, H. Zheng, F. Yang, L. Jiao, J.L. Chen, W.K. Ho, C.L. Gao, **J.F. Jia, M.H. Xie***	"Line and Point Defects in MoSe2 Bilayer Studied by Scanning Tunneling Microscopy and Spectroscopy", ACS Nano. 9, 6619		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)*
07/2016/beijing	"Epitaxy of strained topological insulator Bi2Se3 thin films"	International Conference on the Physics of Semiconductors (ICPS)		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
Xin GUO	PhD	01/09/2009	31/11/2013
Bin LI	PhD	01/09/2012	31/08/2016

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

This joint project has led to collaboration between the two PIs on another research topic of transition-metal dichalcogenides, which has led to some interesting results and a couple publications (e.g., publication 5 and 6 in Part C).