RGC Ref.: M-HKU/709-12

(please insert ref. above)

The Research Grants Council of Hong Kong SRFDP & RGC ERG Joint Research Scheme <u>Completion Report</u>

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

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 (<i>must be quoted</i>)
			(musi be quoted)
Project Start date	01/03/2013		
Project Completion date	29/02/2016		
Duration (in month)	36		

Deadline for Submission of	28/02/2017	
Completion Report		

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 Sb₂Se₃, an ordinary insulator, on substrates for varying strains;

S&R 8 (10/15)

- *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 Bi₂Se₃ (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 Bi₂Se₃ grown on GaN was found gradual. (Refer to Publication 1 listed in Part C)
 - (2) The high-index Bi₂Se₃ (221) film was achieved on In₂Se₃-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 Bi₂Se₃ (111) (Paper is under preparation). Also, a position dependent density-of-state profile on Bi₂Se₃ (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 $\geq 10\%$, 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 <u>in layman's language</u> 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. Bi₂Se₃ 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 Bi₂Se₃ films and develop methods to realize highly strained layers. We firstly followed strain relaxation process during initial stage Bi₂Se₃ growth and found clear substrate-dependence behaviors. We then succeeded in growing much greatly strained Bi₂Se₃ by controlling its growth along a special, the so called high-Miller index direction. Finally, we obtained the metastable Sb₂Se₃ 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 <u>directly</u> 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	e Latest Status	of Publicat	tions	Author(s)	Title and	Submitted to	Attached	Acknowledge	Accessible
Year of	Year of	Under	Under	(bold the	Journal/	RGC	to this	d the support	from the
publication	Acceptance	Review	Preparation	authors	Book	(indicate the	report (Yes	of this Joint	institutional
-	(For paper			belonging to	(with the	year ending	or No)	Research	repository
	accepted but		(optional)	the project	volume,	of the		Scheme	(Yes or No)
	not yet			teams and	pages and	relevant		(Yes or No)	
	published)			denote the	other	progress			
				corresponding	necessary	report)			
				author with an	publishing				
				asterisk*)	details				
					specified)				

0.017	I	1		1	**	**	1
2015			B. Li, X.	"Strain in	Yes	Yes	
			Guo, W.K.	Epitaxial			
			Но, М.Н.	Bi ₂ Se ₃			
			Xie*	grown on			
			-	GaN and			
				Graphene			
				substrates:			
				a			
				reflection			
				high-ener			
				gy			
				gy electron			
				diffraction			
				study",			
				Appl.			
				Phys.			
				<i>Lett.</i> 107,			
				081604			
				001004			
2017			B. Li,	"Strain in	Yes	Yes	
2017				epitaxial	105	105	
			W.G.				
			Chen, X.	high-inde			
			Guo, W.K.	$x Bi_2Se_3$			
			Ho, X.Q.	(221)			
			Dai, J.F.	films			
				grown by			
			Jia, M.H.	molecular			
			Xie*	-beam			
				epitaxy",			
				Appl.			
				Surf. Sci.			
				396, 1825			
2017			B. Li, Y.P.		Yes	Yes	
			Xia, W.K.	ed Ga_2Se_3			
				film and			
			Ho, M.H.	epitaxial			
			Xie*	Bi_2Se_3			
				(221) on			
				GaSb			
				(001) by			
				molecular			
				-beam			
				epitaxy",			
				J. Cryst.			
				Growth			
				459, 76			
				157,70			

V B. Li, Q.S. "Induced robust" Yes Yes Xu, Y.P. topologica Xia, W.K. l order on Ho, N. an Wang, C. ordinary insulator Wang, C. ordinary Liu,* M.H. insulator Xie* hetero- structured with a strong topologica Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in report year Qait H.J. Liu, L. "Dense Gait, X.X. Wu, W.K. al midgap 31/08/201 Yes Wang, H. rModes in Jiao, J.F. monolaye Wang, H. rModes in Jia, N. monolaye Wang, H. rModes in Jia, N. an dheir ranget Yae H.J. Liu, H. "Yes Yes Yes H.J. Liu, H. "Denser Pinys, Rev. Lett. Jiao, F. point Yang, Y. of one year Gaitor, J.F. monolaye Wang, H. rModes in nonolaye Wang, H. rModes in ns "
2014 H.J. Liu, H. Jiao, F. Vang, Y. 2014 H.J. Liu, L. H.J. Liu, L. H.J. Liu, K. H.J. Liu, L. H.J. Liu, H. H.J. Liu, H. H. H.J. Liu, H. H. H.J. Liu, H. H. H.J. Liu, H. H. H.J. Liu, H. H
2014 H.J. Liu, * H.H. Liu, * Yes, in subtract 2014 H.J. Liu, L. * Yes, in subtract 2015 H.J. Liu, H. * Yes 2014 H.J. Liu, H. Yes Yes 2015 H.J. Liu, H. Yes Yes
2014 H.J. Liu, * M.H. Nie* I order on Ho, N. an Wang, C. Liu,* M.H. insulator with a strong topologica l insulator", aXiv1611. 04688 Yes, in report year ending Wu, W.K. al midgap 31/08/201 Ho, C.L. metallic Gao, JF. Modes in Jia, N. Wang, H. CL. metallic Gao, JF. Modes in Jia, N. Wang, H. CL. metallic Gao, JF. Nonolaye Wang, H. CL. metallic Gao, JF. Modes in Jia, N. Monolaye Wang, H. Spatial Modes in Jia, N. Monolaye Wang, H. Spatial Modes in Jia, N. Modes in Modes in Modes in Jia, N. Modes in Modes in Modes in Jia, N. Modes in Modes in Mo
2014 Ho, N. Wang, C. Liu,* M.H. Xie* ordinary insulator hetero- structured with a strong topologica 1 insulator", aXiv1611. 04688 Yes 2014 H.J. Liu, L. Vang, Y. Cai, X.X. Wu, W.K. Jiao, F. Yang, Y. Cai, X.X. Wu, W.K. Jian, N. Wu, W.K. Jian, N. Wu, W.K. Jian, N. Wu, W.K. Jian, N. Wodes in Jia, N. Wao, M.H. Yao, M.H. Xie* Yes, in report year ending 4 Yes 2015 H.J. Liu, H. Vinstantia "Dense network Yang, Y. Modes in Jian, N. Modes in Nia, Nia, Nia, Nia, Nia, Nia, Nia, Nia,
2014 Wang, C. Liu,* M.H. Xie* ordinary insulator betero- structured with a strong topologica l insulator", aXiv1611. Yes 2014 H.J. Liu, L. Jiao, F. Yang, Y. Gai, X.X. "Dense report year Cai, X.X. Yes, in report year Cai, X.X. Yes W.W.K. Ho, C.L. Mang, H. Yao, M.H. Xie* al midgap undlatio ns ". Phys. Rev. Lett. 113, 066105 31/08/201 4 2015 H.J. Liu, H. Yes
2014 H.J. Liu, * M.H. Xie* insulator hetero- structured with a strong topologica l insulator", aXiv1611. Yes, in report year Yes 2014 H.J. Liu, L. Jiao, F. Yang, Y. Cai, X.X. "Dense network year Yes, in report year Yes 2014 H.J. Liu, L. Jiao, F. Yang, Y. Cai, X.X. "Dense network dimension ending Yes Yes 2015 H.J. Liu, H. Kie* "Phys. Rev. Lett. Yes Yes 2015 H.J. Liu, H. Zheng, F. Yes Yes
2014 H.J. Liu, L. "Dense and their spatial undulation", axiv1611. Yes, in report year 2014 H.J. Liu, L. "Dense and their spatial undulation", axiv1611. Yes, in year 2014 H.J. Liu, L. "Dense and their spatial undulation", axiv1611. Yes 2014 H.J. Liu, L. "Dense and their spatial undulation", axiv1611. Yes 2014 H.J. Liu, L. "Dense and their spatial undulation", axiv1611. Yes 2015 H.J. Liu, H. "Line and and their spatial undulation spatial undulation", Phys. Rev. Lett. Yes 2015 H.J. Liu, H. "Line and yes Yes
2014 H.J. Liu, L. Wesking Yesking 2014 H.J. Liu, L. Wesking Yesking 2014 H.J. Liu, L. Wesking Yesking Yang, Y. of one year Yesking Yang, Y. of one year Yesking Wu, W.K. al midgap 31/08/201 Holder Wu, W.K. al midgap 31/08/201 4 Gao, J.F. modes in Jiaa, N. monolaye Wang, H. r MoSe2 and their spatial Yao, M.H. spatial undulatio ns Nie* Nie* Nie Nie Nie 2015 H.J. Liu, H. "Line and Yes Yes
2014 H.J. Liu, L. "Dense year Yes, in Yes 2014 H.J. Liu, L. "Dense year Yes, in Yes 2014 H.J. Liu, L. "Dense year Yes, in Yes Yang, Y. of one year Yes Yes Yes Yang, Y. of one year Yes Yes Yes Wu, W.K. al midgap 31/08/201 Ho, C.L. metallic 4 4 Gao, J.F. modes in Jia, N. monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. Spatial undulatio ns ", Phys. Rev. Lett. 113, 066105 Yes 2015 H.J. Liu, H. "Line and Yes Yes Yes
2014 H.J. Liu, L. Jiao, F. Cai, X.X. Wang, Y. Of one Cai, X.X. H.J. Liu, L. Jiao, F. Strong topologica insulator", aXiv1611. 04688 Yes, in report year ending Wear ending Wu, W.K. Jian, N. Wonolaye Wang, H. Jia, N. Wonolaye Wang, H. Jia, N. MoSe2 Fan, W. Yao, M.H. Xie* Yes Yes 2015 H.J. Liu, H. J.Liu, H. Zheng, F. "Dense Yes, in report year ending Jian, N. MoSe2 Fan, W. Solution NS ", Phys. Rev. Lett. Jian, N. Mine and Zheng, F. Yes Yes
2014 H.J. Liu, L. "Dense Jiao, F. Yes, in network Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in report year Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in report year Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in report year Yes 2015 H.J. Liu, H. "Tense Jiao, F. Yes Yes 2015 H.J. Liu, H. "Lin and Zheng, F. Yes Yes
2014 H.J. Liu, L. "Dense Jiao, F. network Yang, Y. of one Cai, X.X. dimension Wu, W.K. al midgap Ho, C.L. metallic Gao, J.F. modes in Jia, N. monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial Xie* Yes 2015 H.J. Liu, H. "Line and Zheng, F. Point Yes
2014 H.J. Liu, L. "Dense Jiao, F. Yes, in network Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in network Yes Yang, Y. of one Cai, X.X. dimension dimension Yes Wu, W.K. al midgap 31/08/201 Ho, C.L. modes in Jia, N. monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial Xie* undulatio ns ", Phys. Rev. Lett. 113 H.J. Liu, H. "Line and Zheng, F. Yes 2015 H.J. Liu, H. "Line and Zheng, F. Yes
2014 H.J. Liu, L. "Dense Jiao, F. Yes, in network Yes 2014 H.J. Liu, L. "Dense Jiao, F. Yes, in network Yes Yang, Y. of one Cai, X.X. dimension dimension Yes Wu, W.K. al midgap 31/08/201 Ho, C.L. modes in Jia, N. monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial Xie* undulatio ns ", Phys. Rev. Lett. 113 H.J. Liu, H. "Line and Zheng, F. Yes 2015 H.J. Liu, H. "Line and Zheng, F. Yes
2014H.J. Liu, L. "Dense Jiao, F. Cai, X.X."Dense report year ending 31/08/201 Ho, C.L. metallic Gao, J.F. modes in Jia, N. Wang, H. report Wang, H. report Wang, H. report Yao, M.H. spatial Xie" modes in Mathematical No New Lett. 113, 066105Yes, in Yes2015H.J. Liu, H. Zheng, F.Yes Point
2014H.J. Liu, L. Jiao, F. of one Cai, X.X. dimension ending Wu, W.K. al midgap al midgap 31/08/201 Ho, C.L. metallic Gao, J.F. modes in Jia, N. monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial undulatio ns ", Phys. Rev. Lett. 113, 066105YesYes2015H.J. Liu, H. Zheng, F.YesYesYes
Jiao, F.networkreportYang, Y.of oneyearCai, X.X.dimensionendingWu, W.K.al midgap31/08/201Ho, C.L.metallic4Gao, J.F.modes inJia, N.monolayeWang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113, 0661052015H.J. Liu, H."Line and Zheng, F.YesYesYes
2015Yang, Y. Cai, X.X.of one dimensionyear ending al midgapWu, W.K. Gao, J.F. modes in Jia, N. Wang, H. Yao, M.H. Yao, M.H. Spatial Muluatio ns ", Phys. Rev. Lett. 113, 066105year ending al/08/2012015H.J. Liu, H. Zheng, F.YesYes
Cai, X.X.dimensionending undigapWu, W.K.al midgap31/08/201Ho, C.L.metallic4Gao, J.F.modes inJia, N.monolayeWang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113,113,0661052015H.J. Liu, H."Line andYesYesYes
Wu, W.K.al midgap31/08/201Ho, C.L.metallic4Gao, J.F.modes inJia, N.monolayeWang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113,113,0661052015H.J. Liu, H."Liu, H."Line andZheng, F.PointYesYes
Ho, C.L.metallic4Gao, J.F.modes inJia, N.monolayeWang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113,113,0661052015H.J. Liu, H."Line andYesYesYeng, F.Point
Gao, J.F. Jia, N.modes in monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial UndulatioiXie* * * 066105ii2015H.J. Liu, H. Zheng, F.Yes Point
Gao, J.F. Jia, N.modes in monolaye Wang, H. r MoSe2 Fan, W. and their Yao, M.H. spatial UndulatioiXie* * * 066105ii2015H.J. Liu, H. Zheng, F.Yes Point
Jia, N.monolayeWang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113,0661052015H.J. Liu, H."Liue andYesYes
Wang, H.r MoSe2Fan, W.and theirYao, M.H.spatialXie*undulations", Phys.Rev. Lett.113,0661052015H.J. Liu, H."Line andYesZheng, F.Point
Fan, W. Yao, M.H. Spatial undulatioand their spatial undulatioXie*ns ", Phys. Rev. Lett. 113, 0661052015H.J. Liu, H. Zheng, F.Yes Point
Yao, M.H. Xie*spatial undulatio ns ", Phys. Rev. Lett. 113, 066105
Xie*undulatio ns ", Phys. Rev. Lett. 113, 066105New Yes2015H.J. Liu, H. Zheng, F.YesYesYes
2015H.J. Liu, H."Line and China PointYesYesZheng, F.PointYesYes
2015H.J. Liu, H. Zheng, F.YesYes
Rev. Lett. 113, 066105Rev. Lett. 113, 0661052015H.J. Liu, H. "Line and Zheng, F. PointYes
2015H.J. Liu, H."Line and Zheng, F.YesYes
20150661052015H.J. Liu, H. "Line and Zheng, F. PointYes
2015H.J. Liu, H."Line and PointYesYes
Zheng, F. Point
Nona Datasta m
Yang, L. Defects in
Jiao, J.L. MoSe2
Chen, W.K. Bilayer
Ho, C.L. Studied
Gao, J.F. by
Jia, M.H. Scanning
Xie* Tunneling
Microsco
py and
Spectrosc
opy",
ACS
Nano. 9,
6619

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/	Title	Conference Name	Submitted	Attached	Acknowledged	Accessible
Place			to RGC	to this	the support of	from the
			(indicate the			institutional
			year ending	(Yes or No)	Research	repository
			of the		Scheme	(Yes or No)
			relevant		(Yes or No)	
			progress			
			report)			
07/2016/beij	"Epitaxy of	International		Yes	Yes	
ing	strained	Conference on the				
	topological	Physics of				
	insulator	Semiconductors				
	Bi2Se3 thin	(ICPS)				
	films"					

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).