Monash_IITB_masterhead

Project Title:	2-D topological quantum field effect transistors for emerging low-power electronics	
Project Number	**IMURA1018**	
Monash Main Supervisor (Name, Email Id, Phone)	Prof. Michael S Fuhrer Michael.fuhrer@monash.edu	*Full name, Email*
Monash Co-supervisor(s) (Name, Email Id, Phone)	Prof. Nikhil Medhekar Nikhil.medhekar@monash.edu	
Monash Head of Dept/Centre (Name,Email)	Prof. Michael Morgan Michael.morgan@monash.edu	*Full name, email*
Monash Department:	Physics and Astronomy/ Materials Science and Engineering	
Monash ADGR (Name,Email)	Timothy Scott	*Full name, email*
IITB Main Supervisor (Name, Email Id, Phone)	Prof. Bhaskaran Muralidharan bm@ee.iitb.ac.in	*Full name, Email*
IITB Co-supervisor(s) (Name, Email Id, Phone)		*Full name, Email*
IITB Head of Dept (Name, Email, Phone)	Prof. Kishore Chatterjee	*Full name, email*
IITB Department:	Electrical Engineering	

Research Clusters:

Highlight which of the Academy's CLUSTERS this project will address? *(Please nominate JUST* ***one.*** *For more information, see www.iitbmonash.org)*	
1	*Semi-Conductors, Optics, Photonics, Networks, Telecomm, Power Eng*
2	*Math, CFD, Modelling, Manufacturing*
3	*Material Science/Engineering (including Nano)*

Research Themes:

Highlight which of the Academy's Theme(s) this project will address? ***(****Feel free to nominate more than one. For more information, see www.iitbmonash.org)*	
1	*Advanced computational engineering, simulation and manufacture*
2	*Artificial Intelligence and Advanced Computational Modelling*
3	*Nanotechnology*
4	*Smart Materials*

The research problem

The transistor forms the fundamental building block of today's electronics hardware with billions of them packed inside a chip, performing reliable computational operations. As more and more transistors get packed in, a fundamental issue is the power dissipation which stems from the increasing power density. Reducing the overall power density entails new developments at various levels, one of them being at the very fundamental level- the individual transistor.

The power dissipated by an individual transistor happens at the instance of switching between "on" and "off" states, where a fundamental limit called the Boltzmann's limit exists. Overcoming this so called "Boltzmann's tyranny" will involve novel ideas that stem from fundamental physics. One of the ways to overcome this Boltzmann's tyranny is by tapping on novel properties of quantum phase transitions. Quantum materials – a class of materials that exhibit quantum phase transitions will be an embedding platform for the upcoming Quantum Technology era. Their marvellous properties can also be extended to applications in futuristic low-power electronics in the "Beyond Moore" era. Recent theoretical and experimental have hinted at the ability of switching a 2D device using a novel method of Rashba field effect – a quantum phase transition that can potentially overcome this Boltzmann tyranny. This effect can be used to conceptualize and build a quantum field effect transistor, which will be the motif of the proposed project.

This project's goal is to make comprehensive explorations on exploiting 2D quantum materials, devices and device structures to ultimately facilitate the quantum field effect transistor. The project will have both experimental and theoretical components complementing each other to achieve the goals. The theoretical part will comprise of materials modelling and quantum transport simulations of viable materials and device structures for the applications. We will cover various device structures including the topological field effect transistor and the negative capacitance based topological field effect transistor. Based on important insights gained from the theoretical side, experimental aspects of fabrication of field effect devices will also be carried out.

Project aims

This project's goal is to take comprehensive steps on exploiting the quantum field effect transistor for low-power transistor applications. The project will have both experimental and theoretical components complementing each other. The theoretical part will comprise of materials modelling of topological materials and quantum transport simulations of viable device structures whose inputs will be carried forward toward experimental realizations. We will cover various device structures including the topological field effect transistor and the negative capacitance based topological field effect transistor, thus providing a holistic outlook on the development of topological quantum field effect devices.

A part of the theoretical and the experimental aspect will be carried out at Monash University.

Theoretical Work (IITB and Monash University):

a) Develop a basic understanding of 2D materials with Rashba spin orbit interaction and the topological phases.
b) Develop materials modelling of 2D materials for transistor applications- includes electronic structure calculations from Ab-initio models and developing empirical tight binding methods
c) Develop quantum device modelling of topological field effect devices from ab-initio inputs
d) Understanding and developing quantum device modelling involving novel switching mechanisms in the field effect devices
e) Developing realistic device modelling by including scattering and dephasing. This will also involve an atomistic understanding of power dissipation in these devices.

Experimental Work (Monash University): The focus here will be on fabrication of field effect devices based on materials and structural inputs from the theoretical work. This would involve the following aspects:

a) Fabrication of novel FET structures using 2D materials
b) Fabrication and measurements of novel gating mechanisms as a proof of concept of quantum FET operations.

How skills/experience of the IITB and the Monash supervisor(s) support the proposed project

The IIT Bombay PI, Prof. Bhaskaran Muralidharan has a strong expertise in quantum transport modelling at the nanoscale and has the right experience and expertise to support this project.

The Monash PI, Prof. Michael Fuhrer is a world-renowned expert in the field of fabrication and characterization of 2D materials and their electrical and optical properties. His activities also include recent interests in the quantum field effect transition that include a Nature paper in 2018, followed by various publications on exploiting such a phase transition for low-power electronics.

The Monash Co-PI, Prof. Nikhil Medhekar is an expert in materials modelling for various nanoscience applications spanning 2D nanoelectronics, optoelectronics, electrochemistry and clean energy. His expertise on materials modelling will form a backbone for the understanding of the novel structures to be proposed and fabricated.

Expected outcomes

Apart from the technical outcomes briefly detailed here, this project will develop talent and workforce needs for the future quantum technologies. The project involves a comprehensive exploration on quantum-field effect transistors with the following outcomes that will lead to an impactful PhD research outcome, along with high quality publications and possible patents.

1) Theoretical understanding of novel quantum materials which will aid the design of the quantum field effect transistor. Materials modelling of 2D materials for transistor applications- includes Ab-initio models and developing empirical tight binding methods
2) Modeling and design of novel device structures for demonstration of quantum field effect transition. This will also involve effective gate design strategies that exploit particular aspects of the topological phase space. The work could also progress along the nascent direction of coupling the concept of negative capacitance with the quantum field effect, potentially leading to further disruptive device design possibilities, with respect to ultra-low power transistor operation.
3) Experimental investigations based on theoretical inputs for a viable demonstration of such a quantum field effect transition using novel quantum materials.
4) Develop fabrication of novel FET structures using 2D materials and develop characterization and measurement techniques of novel gating mechanisms as a proof of concept of quantum FET operations.

How will the project address the Goals of the above Themes?

The project strongly aligns with the themes related to smart materials, nanotechnology and computational modelling. This work features the simulation, modelling and fabrication of a novel device proposal- the topological quantum field effect transistor. Furthermore, this project will develop talent and workforce needs for the future quantum technologies.

Potential RPCs from IITB and Monash

IIT Bombay:

1) Prof, Ashwin Tulapurkar (EE Department)
2) Prof. Kantimay Das Gupta (Physics Department)

Monash University:
1) Dr. Mark Edmonds (Physics)
2) Dr. Julie Karel (Materials Science and Engineering)

Capabilities and Degrees Required

The student is expected to have a degree in Physics, Materials Science or Electrical Engineering with experience in materials modelling, device physics and quantum physics. Training in programming (MATLAB or Python) will be an added advantage.

Necessary Courses

The following courses from IIT Bombay could be taken (depending on the background of the student) for carrying out the research activities:

1) EE-755- Quantum Transport
2) EE-787- Topological Electronics
3) EE-735 – Microelectronics Simulation Lab
4) PH-436 – Introduction to Condensed Matter Physics
5) PH-534- Quantum information and computing
6) PH-576 – Nanoscale quantum transport
7) MM-719 – Introduction to ab-initio methods in materials modelling

Potential Collaborators

The team of three researchers from IITB and Monash are well connected and multiple collaborators at various levels who can be involved if necessary.

Select up to **(4)** keywords from the Academy's approved keyword list **(available at http://www.iitbmonash.org/becoming-a-research-supervisor/)** relating to this project to make it easier for the students to apply.

1) Novel functional materials
2) Nanotechnology/Nanoscience
3) Semiconductors
4) Modelling and simulation