IITB-Monash
Research Academy

Indian Institute of Technology Bombay

MONASH University

An Indian-Australian research partnership

Project Title:	**Quantum Dot Spin Qubits in Graphene**	
Project Number	**IMURA0622**	
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Research Academy 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. Infrastructure Engineering
3. Clean Energy
4. Water

5. Nanotechnology
6. Biotechnology and Stem Cell Research
7. Humanities and Social Sciences

The research problem

Electron spins confined in quantum dots (QDs) are promising candidates as quantum bits (qubits) in solid state quantum information processing [1, 2]. Carbon-based materials in particular [3] have been highlighted as qubit host material, promising long spin life and coherence times [3]. This is owing to the inherently weak spin-orbit coupling and an abundance of isotopes with a net zero nuclear spin [3], respectively providing robustness against electric field fluctuations and limited decoherence due to the nuclear hyperfine interaction [3]. One of the most intriguing carbon allotrope is graphene [4], an atomically thin sheet of carbon atoms in a hexagonal lattice, providing charge confinement vertically to within atomic length scales.

Although graphene's potential as a qubit host material has been theoretically explored [5, 6], experimental demonstrations of quantum dot qubits in graphene have been largely elusive. Reasons for this are graphene's semi-metallic properties with large carrier densities and the lack of a semiconducting band gap – as well as quasi-relativistic Klein tunnelling [7] – making confinement of electron spins challenging [2]. Few demonstrations of graphene quantum dot devices exist [8, 9], typically fabricated by conventional lithography and etching techniques. Such devices, however, often suffer from limited electrostatic control over charge confinement and a poor quality of Coulomb blockade signatures [8]. Both factors combined have mostly limited the ability to reach to few-electron regime where spin properties can be probed [10, 14, 16, 18].

Recently, two groups have independently demonstrated the templated growth of lateral heterostructures of graphene and semiconducting group-VI transition metal dichalcogenides – one at MIT [11] and one at Monash University [12]. These co-planar metal-semiconductor heterostructures show sharp and well-defined boundaries with transition regions of only a few nanometres. Patterning of such lateral heterostructure with conventional lithography techniques (optical or electron beam lithography) [11, 12] promises avenues for large-scale (and potentially wafer-scale) integration of nanoelectronic devices [11], providing a pathway towards scalable quantum computing architectures.

Project aims

We propose confining single electron spins in graphene by embedding small graphene quantum dots laterally within semiconducting tungsten disulphide (WS_2). Due to the good electrostatic tuneability of large-bandgap TMDCs over graphene, this approach can be expected to provide superior electrostatic gate control of both charge confinement and coupling strength of the QD to proximal electron reservoirs. The smooth and well-defined boundaries of the heterostructure promises improved charge stability over previous device fabrication approaches.

This project aims at exploring a range of different device structures including single graphene QDs of varying sizes, double and triple quantum dots (DQDs/TQDs), as well as QDs with proximal single electron transistor (SET) charge and spin sensors [13, 14]. The latter will allow the investigation of pathways for initialization, readout, and life-time measurements of prospect graphene spin qubits [15, 16].

Below we propose a rough time line for the project:

PHASE I (IITB) – 3-6 months:

Commencement of Training of HDR student on electron beam lithography (EBL) and electrical transport: In the first phase of the project the student will be trained to perform high-resolution EBL, required to fabricate electronic devices at the nanoscale. In parallel, the student will gain hands-on experience in using a cryogenic refrigerator for electrical transport measurement at low temperatures (T = 300 mK).

PHASE II (Monash University) – approx. 12 months:

Synthesis of lateral Graphene-WS_2 Heterostructures by Chemical Vapour Deposition (CVD): In the second phase of the project, the lateral heterostructures will be synthesized in Prof Michael S. Fuhrer's laboratories, using CVD. The work will be performed with Dr Changxi Zheng, ARC DECRA Fellow at the School of Civil Engineering.

Fabrication of Graphene Quantum Dots: High-resolution electron beam lithography (EBL) of the heterostructures, will allow confining small (<100nm) graphene quantum dots and systems thereof within the semiconducting WS_2. The work will be carried out at the state-of-the-art facilities (VISTEC 100keV system) of the Melbourne Centre for Nanofabrication (MCN), in close proximity to Monash's Clayton Campus.

*Integration of high-*k *Dielectrics for Superior Electrostatic Control:* High-*k* dielectric materials (HfO_2, Al_2O_3, …), will be deposited on top of the heterostructure crystals by atomic-layer deposition (ALD) at the MCN. Local gate electrodes will be aligned to the heterostucture QDs to allow independent tuning of charge occupation and tunnel barriers.

Initial Electrical Characterizations at 4 Kelvin: Initial test will be performed on the graphene quantum dots devices throughout the second phase of the project, using electron transport measurements at 4.2 Kelvin. These initial measurements will be utilized to aid in the fabrication process and to select high-quality samples for the in-depth electrical characterizations at IITB.

PHASE III (IITB) – 18–21 months:

Electronic Transport Measurements at Cryogenic Temperatures: In-depth electrical characterizations will be performed in the Physics Department of IITB using a ^{3}He refrigerator equipment at T = 300 millikelvin and magnetic field up to B = 10 T. The samples will be tested for their quality in terms of the stability of Coulomb blockade signatures. Magnetotransport measurements will be used to resolve their Fock-Darwin spectrum (orbital-) and spin states in perpendicular and parallel fields, respectively. Time-resolved measurements will be used in order investigate charge pumping, charge sensing, and spin read-out for spin life-time measurements to investigate the potential of graphene QDs as spin qubits. The measurements will be supervised locally at IITB by A/Prof Suddhasatta Mahapatra and Dr Bent Weber, who will be joining the measurements in the first month.

Data Analysis and Thesis Writing: Electrical Data will be analysed by the HDR student at IITB, in discussion with A/Prof Mahapatra and Dr Weber. Data obtained will subsequently be prepared for the PhD thesis during the final 6 months of the project.

Expected outcomes

We anticipate a range of quantum dot devices to be fabricated using this novel fabrication scheme. These will include single and multiple quantum dot and quantum dot systems, as well as device architectures for the single shot spin read-out of prospective graphene spin qubits. These devices will be characterized at cryogenic temperatures at IITB to infer the quality of quantum dots devices in terms of charge stability of their Coulomb blockade signatures and their electrostatic tuneability. We will resolve spin signatures in the few-electron (or hole) [10] regime using both time averaged and time-resolved electrical measurements and work towards spin read-out of single electron spins to infer spin lifetimes. The latter will be an important step towards the implication of graphene-based electron spin qubits for their use in quantum information processing architectures.

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

This project promises advances in *nanotechnology*. Confining electron spins in graphene to within ~100nm length scales and with good electrostatic tuneability will be a critical step towards spin-based quantum computation, whereby graphene spin quantum bits promise long spin life- and coherence times. The novel device fabrication process has – in principle – the potential for large-scale (or even wafer-scale) integration of arrays of spin qubits – a promising pathways for scalable quantum information processing architectures in an industrially compatible graphene-based materials platform.

Capabilities and Degrees Required

The successful candidate will require a B.Sc., honours or M.Sc. degree or equivalent, as well as (ideally) experience in *one or more* the following areas:

(1) Synthesis of atomically thin crystals (graphene and/or transition metal dichalcogenides) using chemical vapour deposition (CVD)
(2) nanofabrication of electronic devices (ideally based on 2D material and using electron beam lithography or related techniques
(3) Characterization of electronic devices in electron transport (ideally at cryogenic temperatures).

Potential Collaborators

This project will strongly benefit from the mentorship by Prof Michael S Fuhrer, director of the Monash Centre for Atomically Thin Materials (MCATM) and a world-leading expert in the field of 2D materials. With over 250 publications and over 13,000 citations, Fuhrer has an H-index of 44. Fuhrer will provide laboratories, equipment and expertise at Monash University.

Crystal growth will be performed in collaboration with Dr Changxi Zheng, ARC DECRA Fellow at the School of Civil Engineering at Monash University. Dr Zheng is an expert in the synthesis of 2D materials using chemical vapour deposition (CVD) [17], including the lateral graphene/WS_2 heterostructures subject to this proposal.

The lithography aspects of the proposal will be carried out at the Melbourne Centre for Nanofabrication (MCN) with its state-of-the-art capabilities for electron beam lithography (VISTEC 100keV system) and metal evaporation tools. The MCN is in close proximity to the Monash University's Clayton campus.

Please provide a few key words relating to this project to make it easier for the students to apply.

Graphene quantum dots, transition metal dichalcogenides (TMDC), lateral heterostructures, spin quantum bits (qubits), quantum computation.