ULTRA-LOW DISORDER GRAPHENE QUANTUM DOT-BASED SPIN QUBITS FOR CYBER SECURE FOSSIL ENERGY INFRASTRUCTURE

Project # DE-FE0031908

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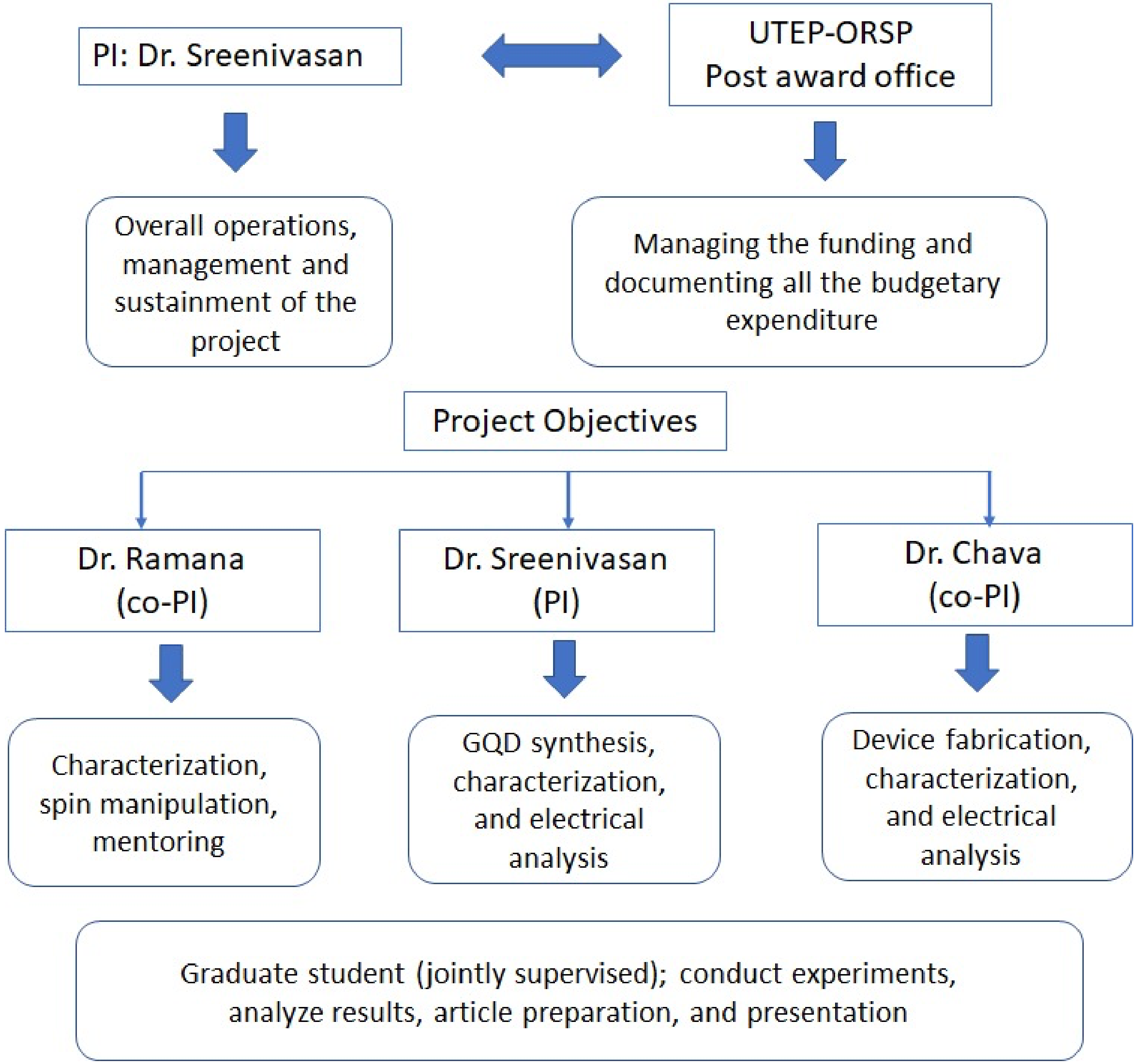
Department of Chemistry & Biochemistry
The University of Texas at El Paso

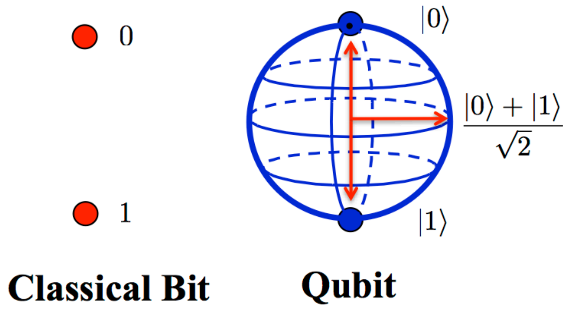
Project Team, Management & Structure

S. No.	Name	Role	UTEP Affiliation
1	Dr. Sreeprasad T. Sreenivasan	PI	Asst. Professor, Chemistry
2	Dr. Ramana Chintalapalle	Co-PI	Professor, Mechanical Engineering
3	Dr. Venkata Surya N. Chava	Co-PI/Postdoc	Postdoc, Chemistry
4	Aruna N. Nair	Research Assistant	Graduate student, Chemistry



Technical Background & Motivation

Quantum Information Processing (QIP) and Quantum bits (qubits)



https://www.bbvaopenmind.com/en/technology/digital-world/towards-the-quantum-computer-qubits-and-qudits/

https://physicsworld.com/a/quantum-communications-boosted-by-solid-memory-devices/

Physical Implementation of Qubits

- Atoms, ions, molecules
- Electronic and nuclear magnetic moments
- Charges in semiconductor quantum dots
- Charges and fluxes in superconducting circuits
- **Spin**

Nature Physics, *3*(3), 192-196 (2007)

DiVincenzo criteria

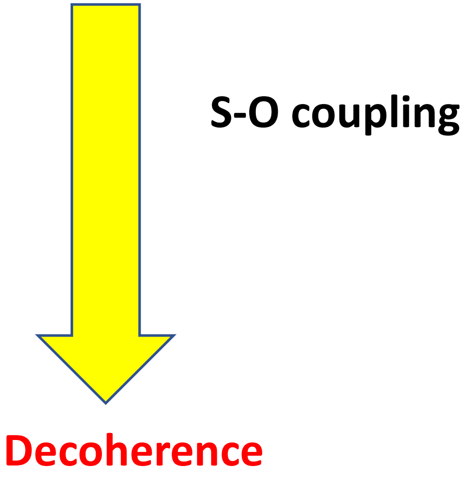
1. Long coherence time
2. Efficient initialization
3. Scalable
4. Readout
5. Universal quantum gates

Progress of Physics, 48(9-11), 771-783. (2000)

GQDs for Spin Qubits

Coherence time depends on spin-orbit and hyperfine interactions in the material

III	IV	V	VI
5 B 10 (3) 20% 11 (3/2) 80%	6 C **12 (0) 99%** 13 (1/2) 1%	7 N 14 (1) 99.6% 15 (1/2) 0.4%	8 O **16 (0) 99.76%** 17 (5/2) 0.04% **18 (0) 0.20%**
13 Al 27 (5/2) 100%	14 Si **28 (0) 92%** 29 (1/2) 5% **30 (0) 3%**	15 P 31 (1/2) 100%	16 S **32 (0) 95%** 33 (3/2) 1% **34 (0) 4%**
31 Ga 69 (3/2) 60% 71 (3/2) 40%	32 Ge **72 (0) 27%** 73 (9/2) 8% **74 (0) 36%**	33 As 75 (3/2) 100%	34 Se 77 (1/2) 8% **78 (0) 24%** **80 (0) 50%** **82 (0) 9%**
49 In 113 (9/2) 5% 115 (9/2) 95%	50 Sn **118 (0) 24%** 119 (1/2) 9% **120 (0) 33%**	51 Sb 121 (5/2) 57% 123 (7/2) 43%	52 Te 125 (1/2) 7% **126 (0) 19%** **128 (0) 32%** **130 (0) 34%**

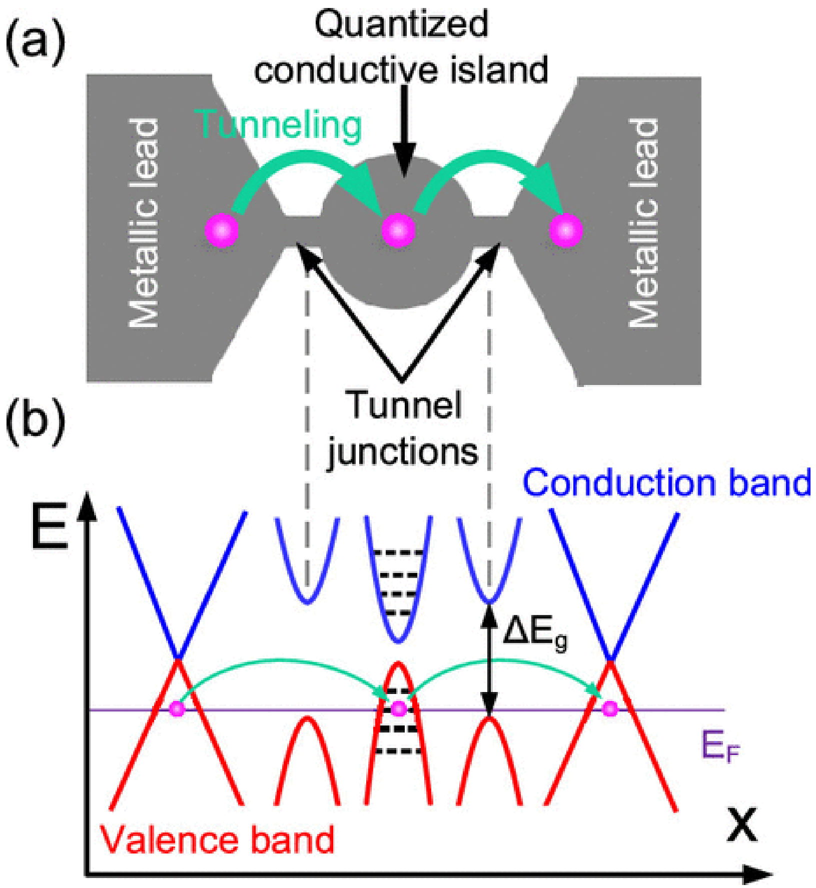


Advantages of Graphene:

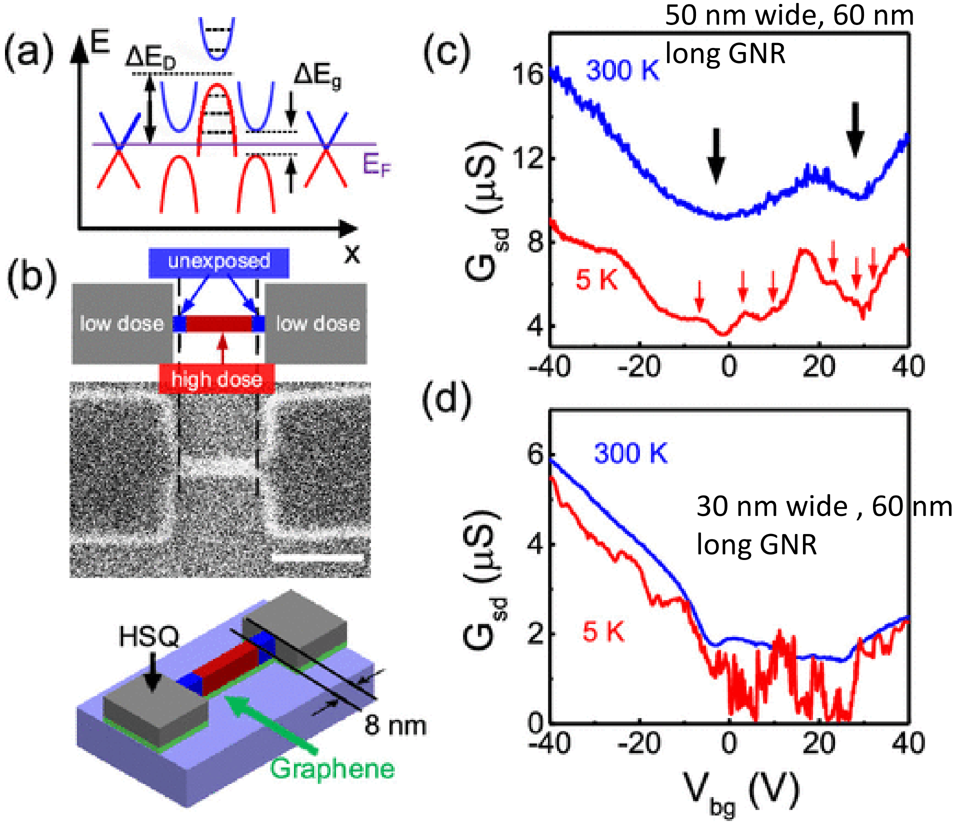
1. Very low nuclear spin
2. Weak spin-orbit coupling

Nature Physics 3.3 (2007): 192-196.

Quantum Dots in Graphene



- **Fabrication residues**
- **Substrate defects**
- **Edge effects (disorder)**



ACS nano 13.7 (2019): 7502-7507.

Overarching Goals

1. Minimizing the defects in GQDs to realize high fidelity and reliable qubits

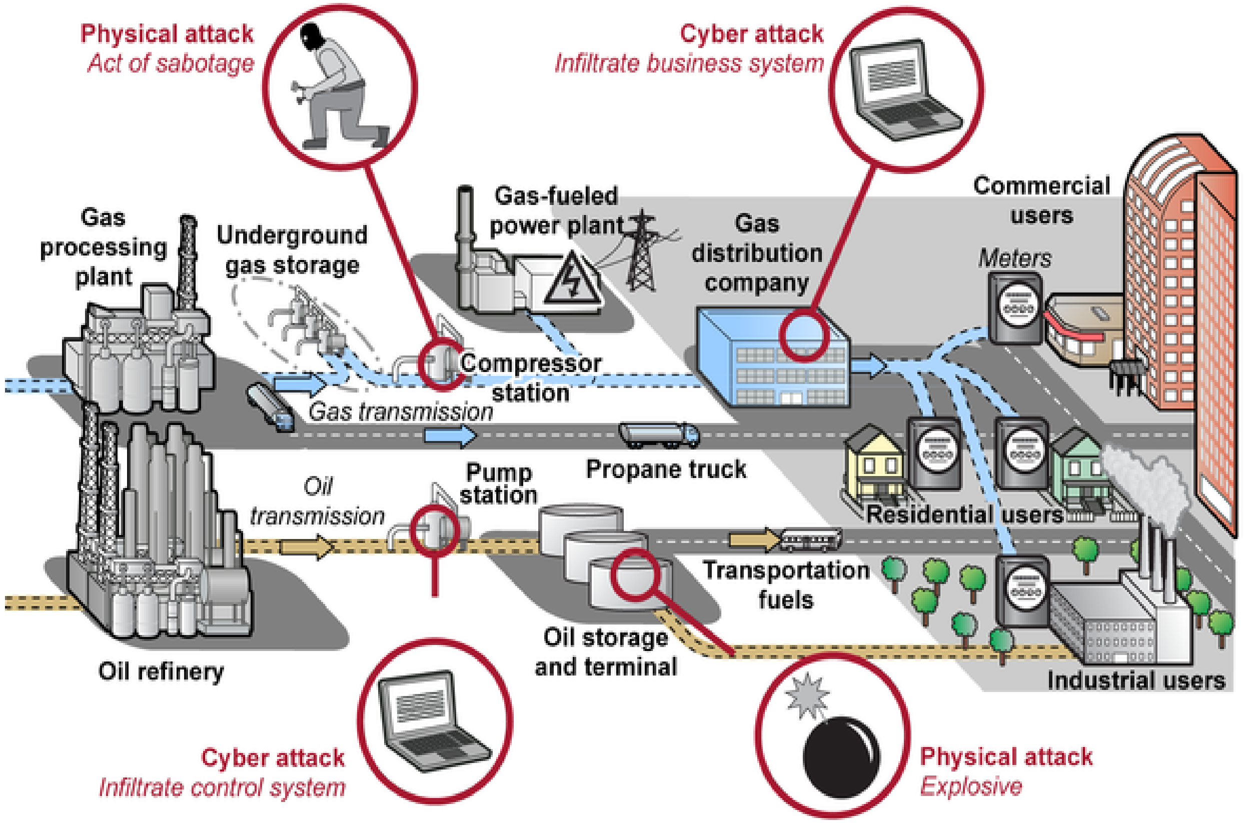
2. Deciphering the effects of disorder, defects, and noise

Significance of the Proposed Work

The project aims to employ ultra-low disorder graphene nanoribbons for GQD-based spin qubit applications

- ❖ Better understanding of the qubit structure-function relationship
- ❖ Lead to high-quality qubits with superior coherence times for QIP
- ❖ A potentially scalable QIP device platform
- ❖ Understanding processing/technological limitations that can be adapted for other qubits.

Relevance to Fossil Energy



Source: GAO analysis of Transportation Security Administration information. | GAO-19-48

https://www.gao.gov/products/GAO-19-48#summary

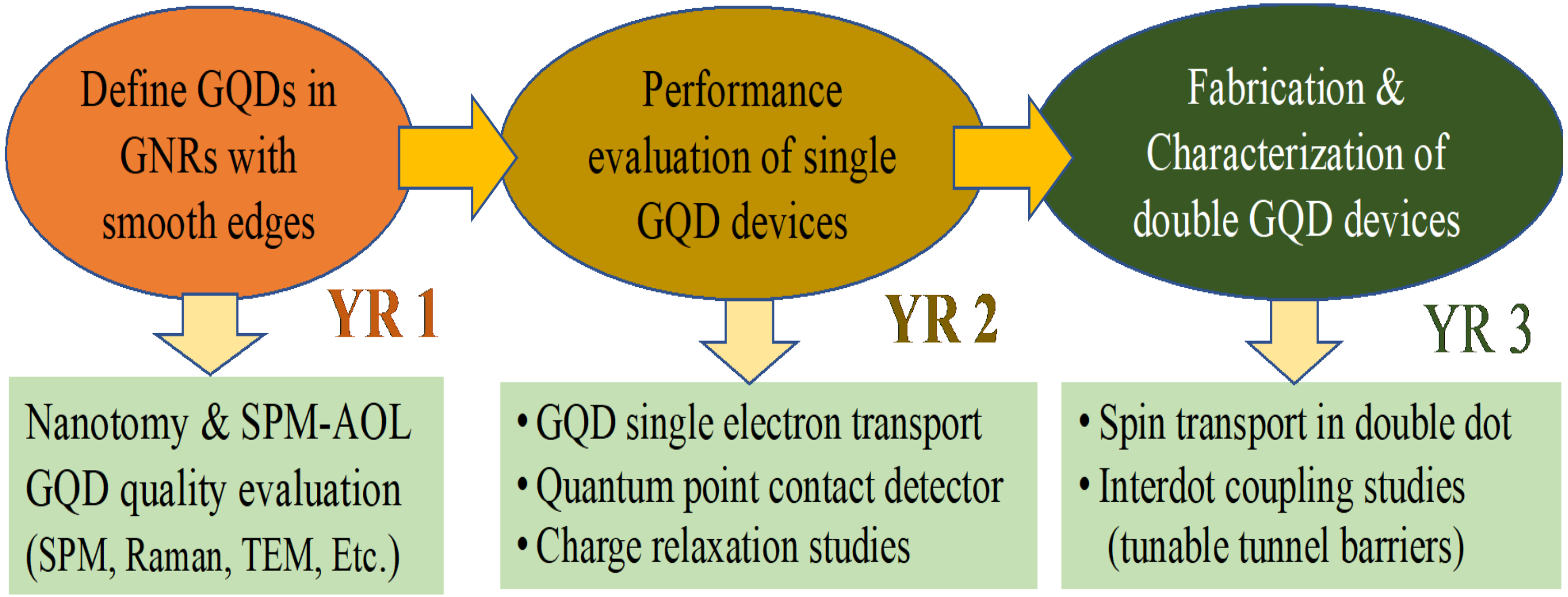
- **Quantum computing:** Energy system optimization
- **Quantum communication:** Long-distance secured communication

Project Objectives

Objective 1: Define GQDs on GNR with ultralow local defects

Objective 2: Low-temperature characterization of quantum transport and spin relaxation times in GQDs

Objective 3: Develop double GQD-based qubit platform and characterize coupling effects



Outline of the overall effort of the proposed project

Proposed Technical Tasks

Technical task 1. Preparation of GNRs with prescribed width and smooth edges

Subtask 1.1 *Preparing baseline GNRs using EBL*

Subtask 1.2 *Nanotomy-based preparation of GNRs with comparatively smooth edges*

Subtask 1.3 *Evaluation of GNR quality, edge roughness, and local disorder*

Technical task 2. Device fabrication and characterization of a single-electron transistor

Subtask 2.1 *Device fabrication*

Subtask 2.2 *Device Characterization*

Subtask 2.3 *Define tunnel barriers in GNR through SPM-AOL and investigate transport*

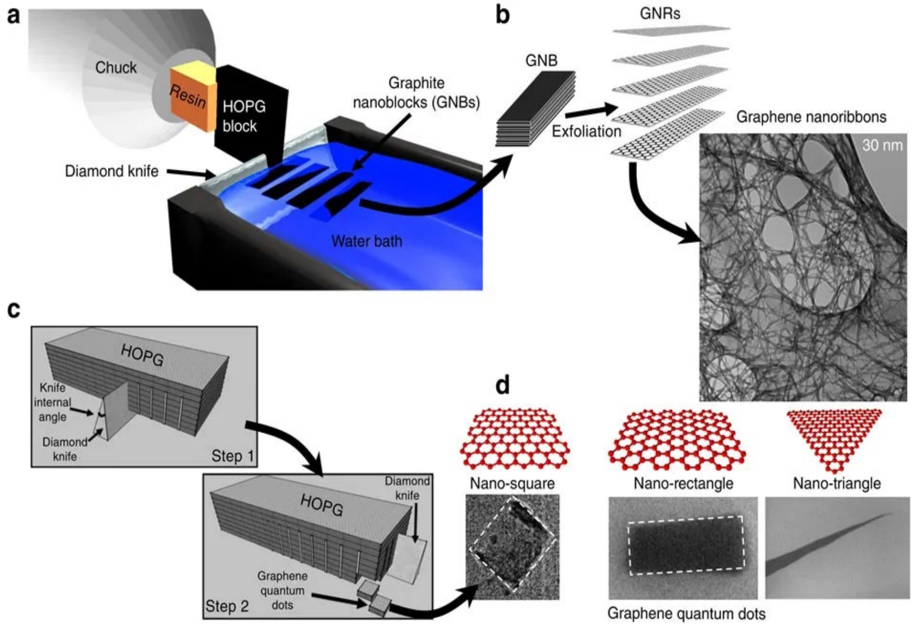
Technical task 3. Characterization of GQD charge stability and spin relaxation

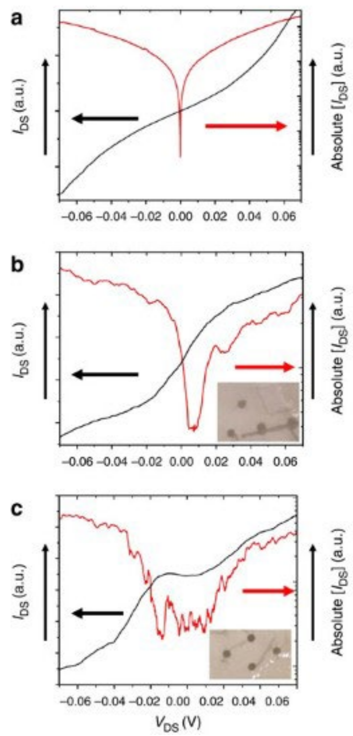
Subtask 3.1*:* Investigate the effect of disorder on GQD charge stability

Subtask 3.2 *Charge-relaxation studies*

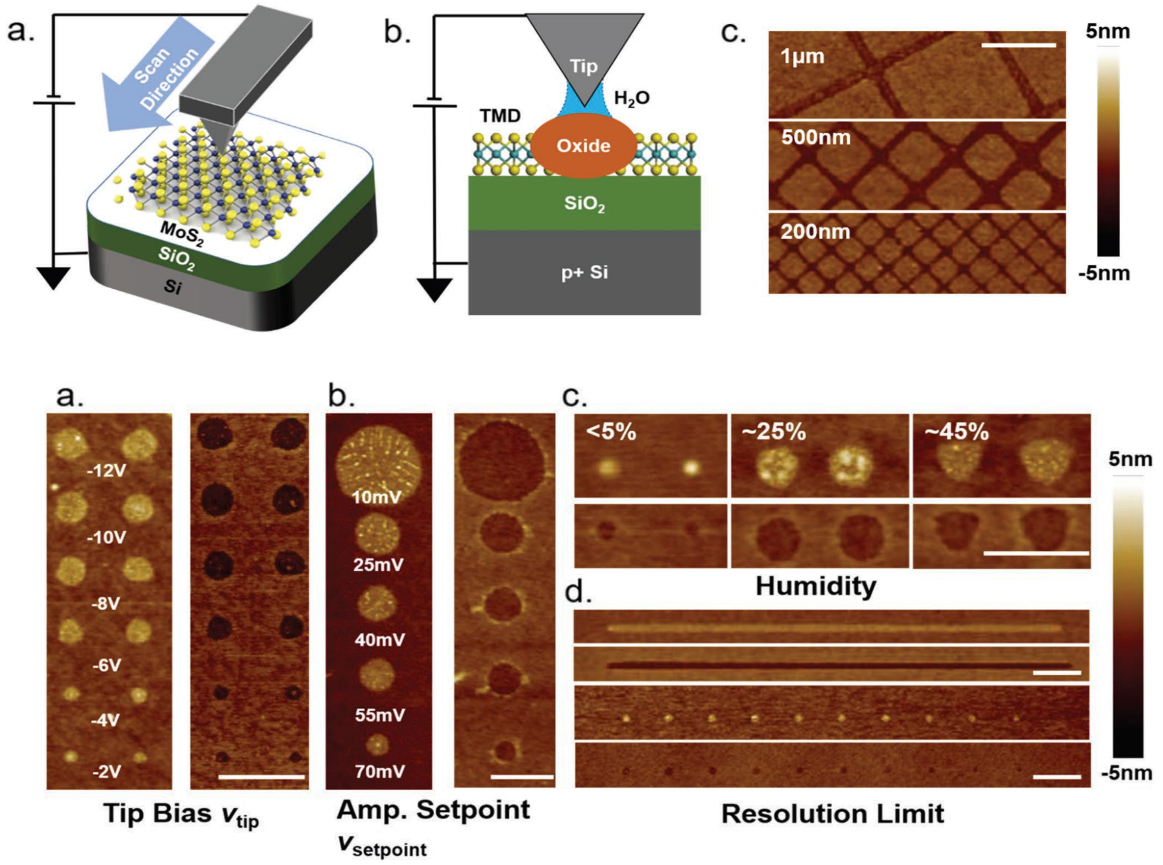
Technical task 4. Fabrication and testing of double GQD spin qubit system

Technical task 1: GNR Fabrication : Nanotomy and SPM Lithography





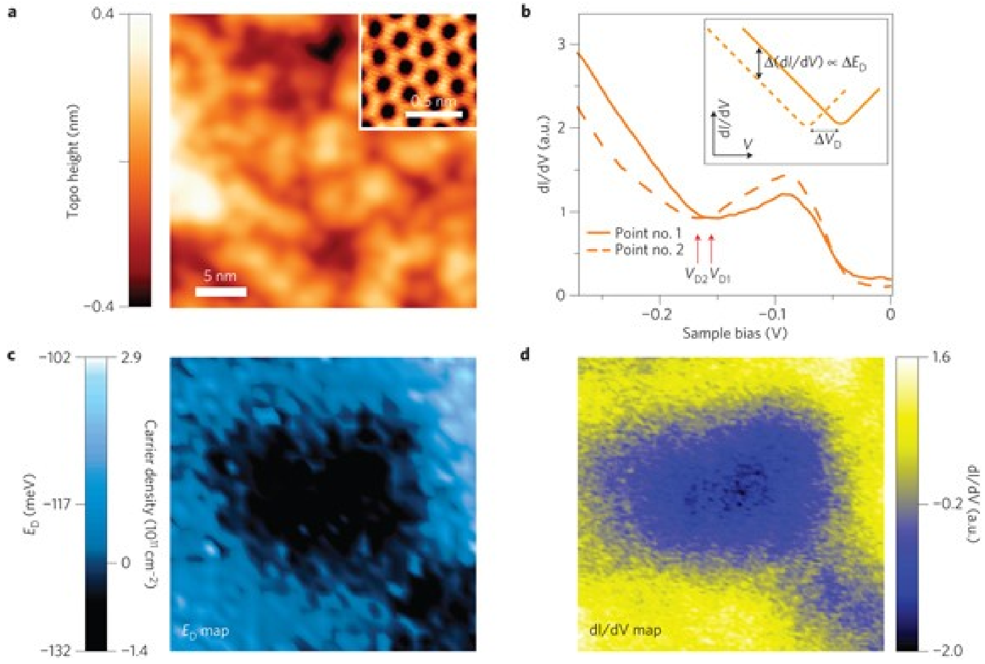
Nature communications, **volume 3**, 844 (2012)



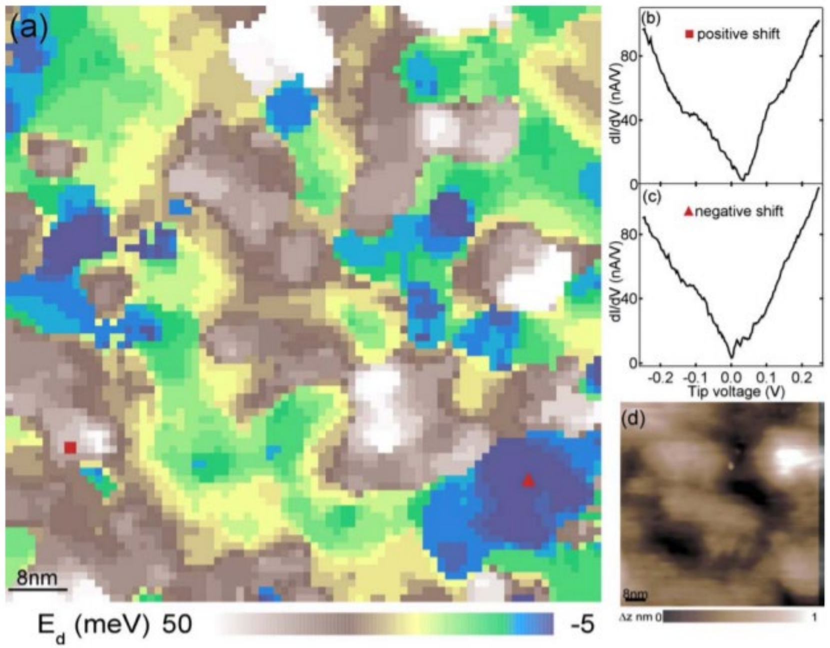
Adv. Mater. **2019**, *31*, 1900136

Scanning Tunneling Microscopy (STM)

➢ Identifying E_D at each point. Charge puddles can be mapped by measuring the tunnel spectrum (dI/dV vs bias)



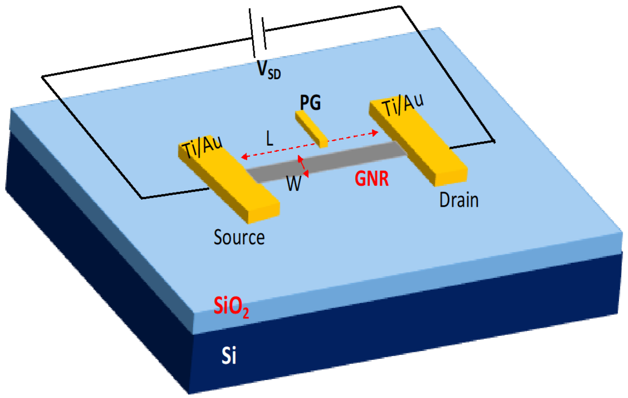
Nature Phys. **5**, 722 (2009)

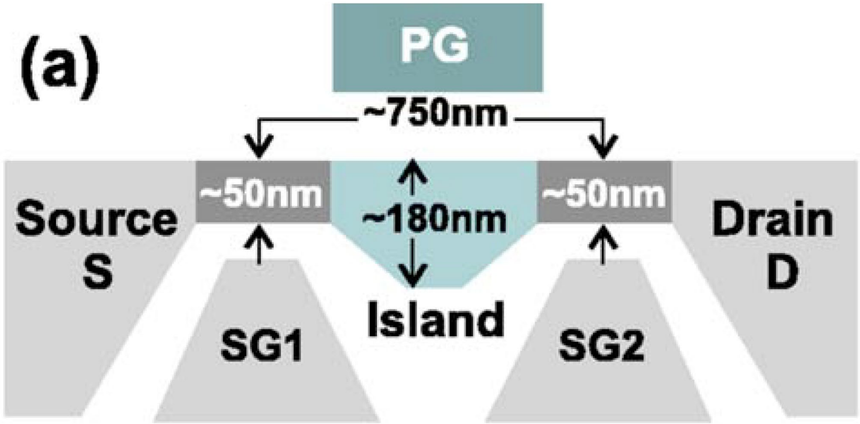


Applied Physics Letters 95.24 (2009): 243502.

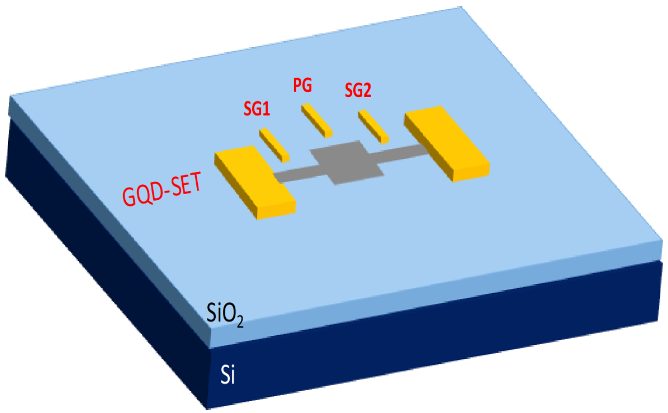
Technical tasks 2-4: Proposed GQD-based SET and QPC Device Structure

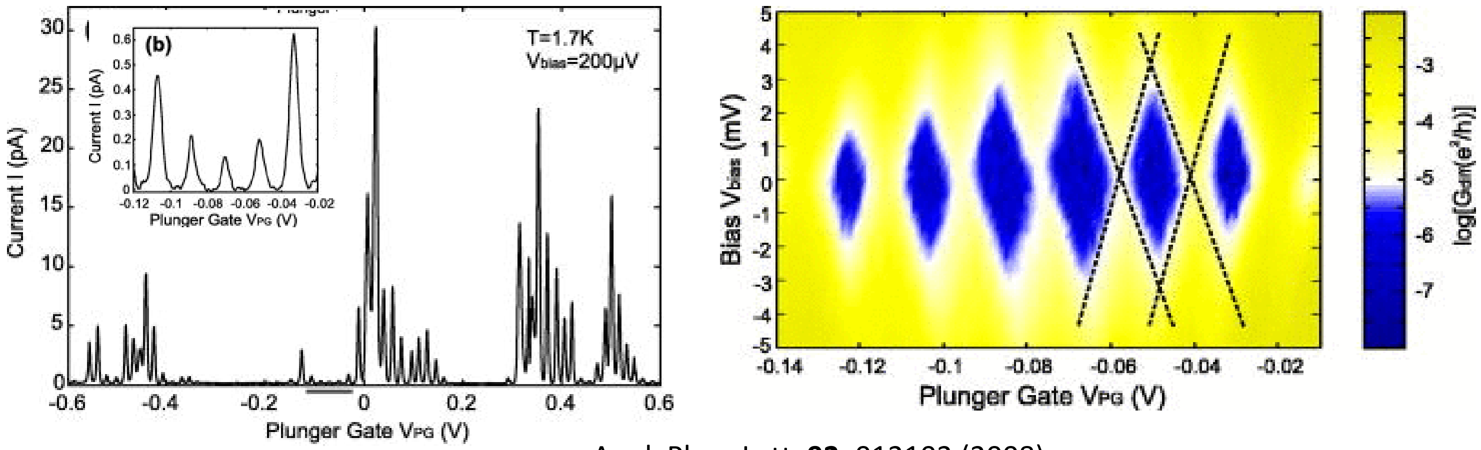
1. Electrical transport studies on GNR devices





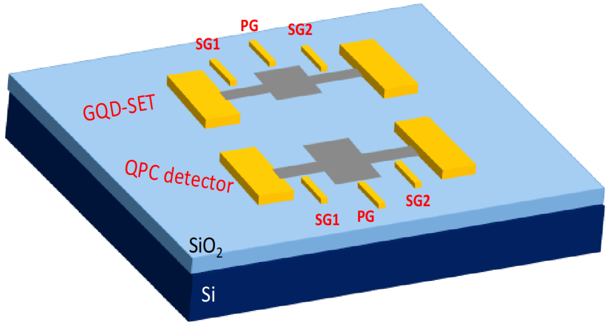
2. Characterization of SET

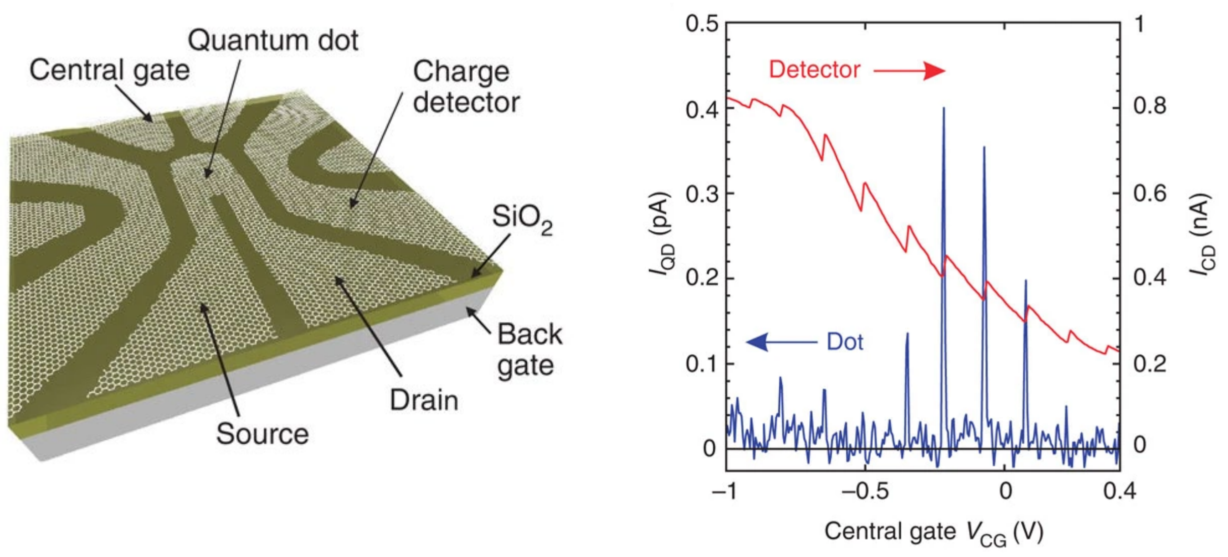




Appl. Phys. Lett. **92**, 012102 (2008)

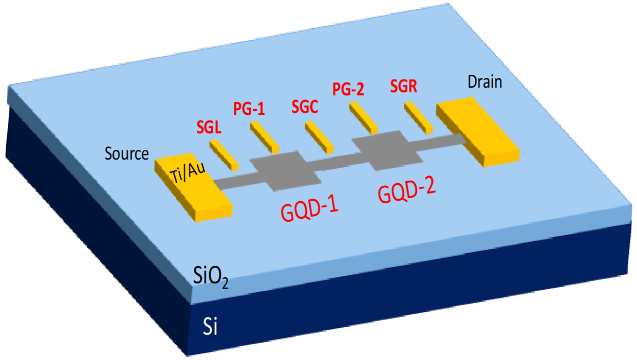
3. Characterization of SET using QPC

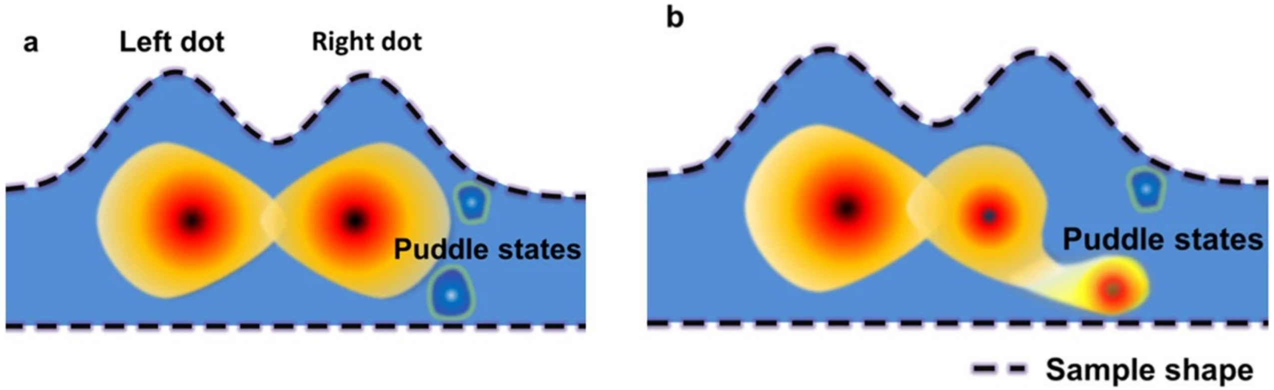




Nature communications **volume 4**, 1753 (2013)

4. Characterization of Double Quantum Dots

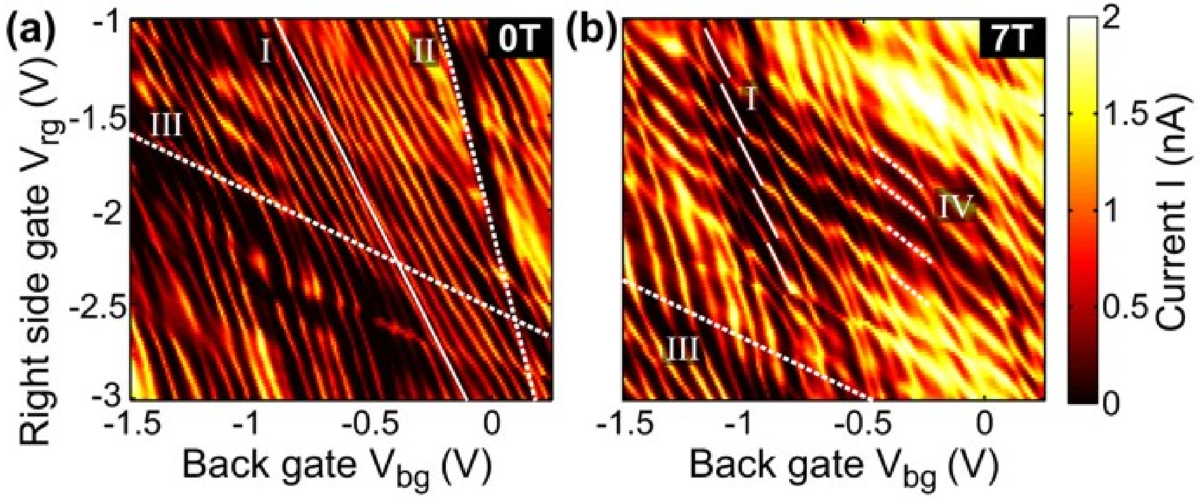




https://www.nature.com/articles/srep03175#Fig5

Stability of Quantum Dot Behavior

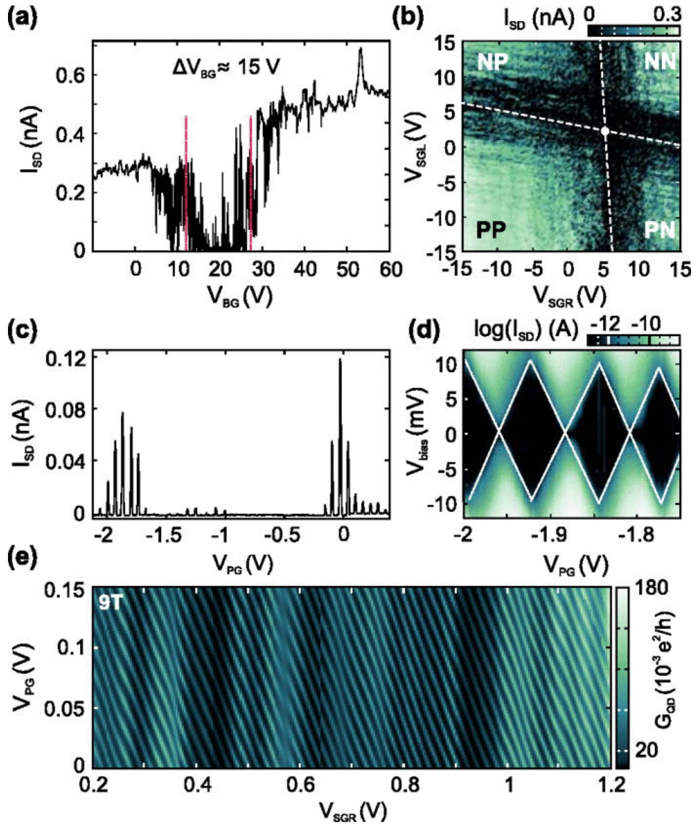
Transport through a strongly coupled graphene quantum dot in perpendicular magnetic field



- Under magnetic field, new features (hexagonal) appear that are related to disorder

Nanoscale research letters, *6*(1), 253 (2011).

Etched graphene quantum dots on hexagonal boron nitride



✓ Stable single-quantum dot behavior under magnetic field

Applied Physics Letters, *103*(7), 073113 (2013)

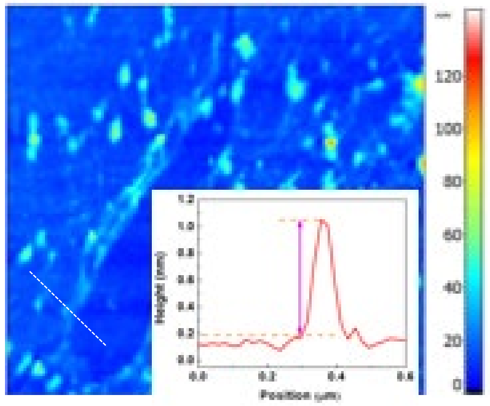
Characterization Technique	Property Measured
Scanning Probe Microscopy (SPM)	Graphene layer thickness and roughness, Edge roughness of the fabricated (EBL and our hybrid approach) tunnel barrier constrictions and GQD structures
Raman spectroscopy	Graphene layer quality (defect density)
Transmission Electron Microscopy	Edge roughness and structure
Scanning Tunneling Microscopy	Local Density of states (LDOS)
Room temperature current-voltage measurements	GNR electrical transport gap
Current-voltage measurements at liquid He temperatures (in dilution refrigerator)	GQD Coulomb blockade transport, tunnel barrier resistance
Current measurements in QPC	Charge detection sensitivity in response to electron transport through nearby GQD device
Pulsed gate spectroscopy	Spin relaxation time
Current voltage measurement of double GQD	Tunnel current transport between adjacent dots and tunable coupling

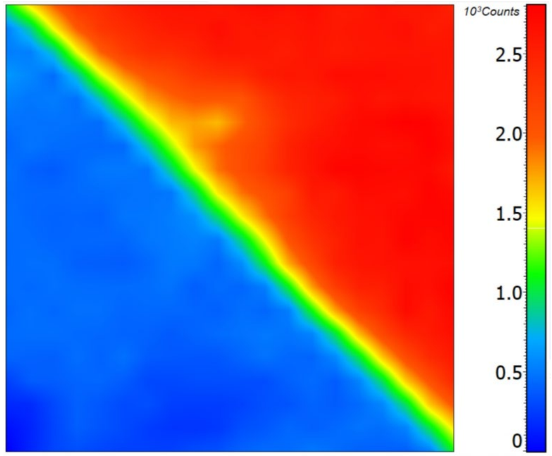
Project Status: Material Synthesis and Characterization

- **Initiated synthesis and optimization of process parameters**

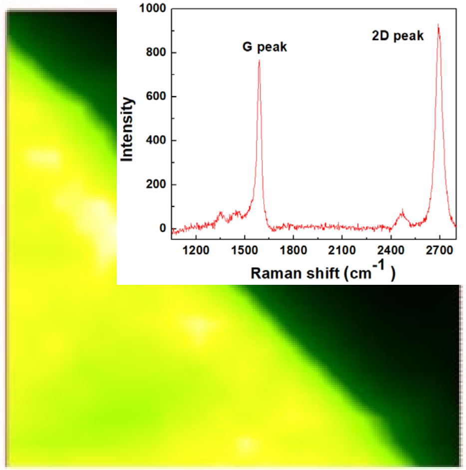
Two zone CVD furnace

Integrated setup for SPM and Raman characterization





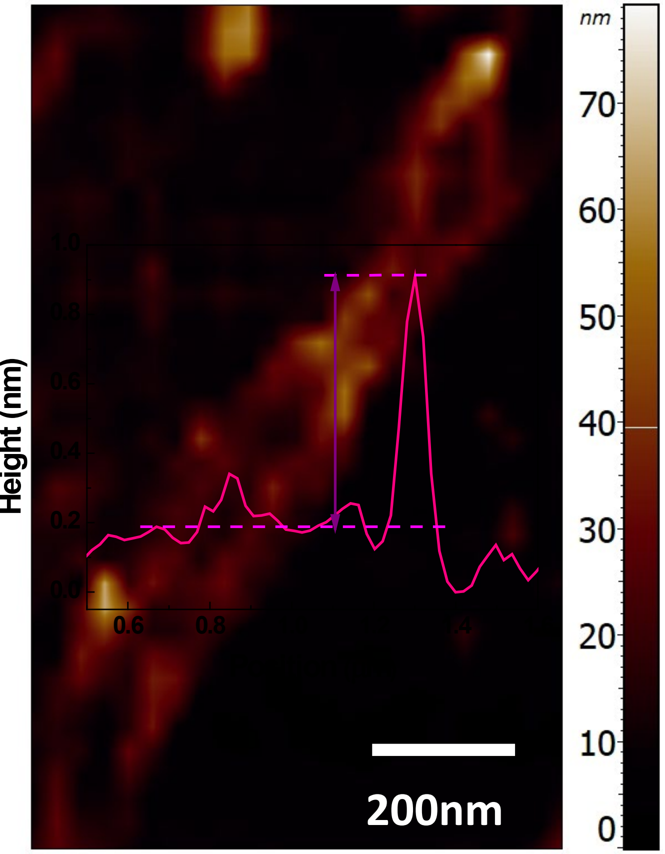
Raman spectrum 2D map



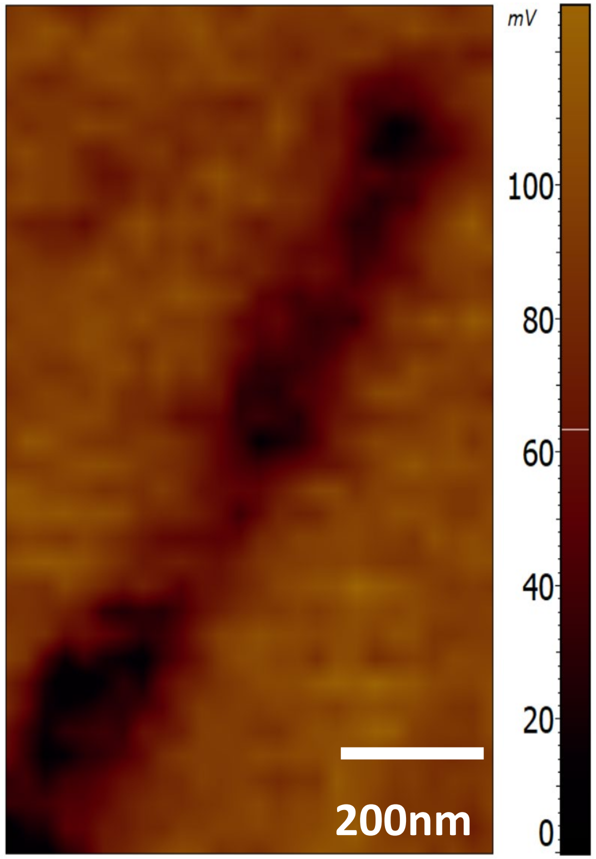
G peak

PROGRESS: GNR Synthesis and SPM-AOL

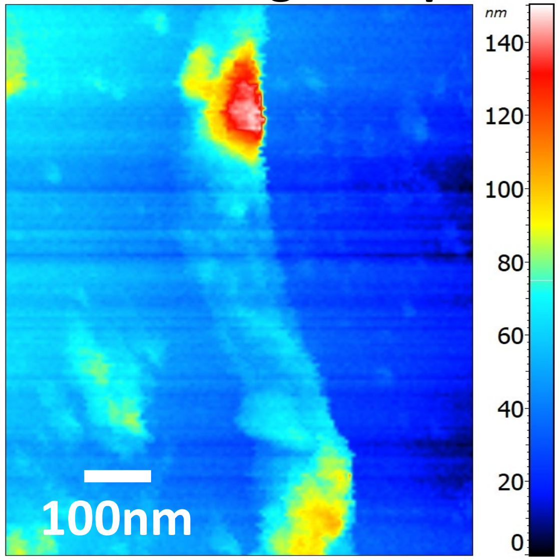
2D Height map



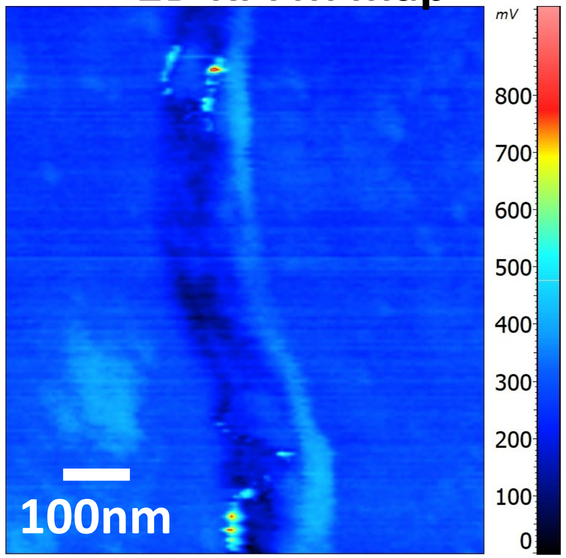
2D KPFM map



2D Height map



2D KPFM map



Project Milestones, Budget, and Schedule

PROJECT SCHEDULE													
		Yr1				Yr2				Yr3			
S. No.	Task Title	1	2	3	4	1	2	3	4	1	2	3	4
1	**Project Management and Planning**	ϕ											
2	**Preparation of GNRs with prescribed width and smooth edges**		ϕ		ϕ								
3	**Device fabrication and characterization of a single-electron transistor**					ϕ	ϕ		ϕ				
4	**Characterization of GQD charge stability and charge relaxation**							ϕ		ϕ	ϕ		
5	**Fabrication and Characterization of double GQD spin qubit system**												ϕ
6	**Final Verification**												ϕΔ
	ϕ-Milestones	**Δ-Go/No-Go Decision points**											

Milestone Summary Table

Task #	Milestone description	Anticipated Date
1	1.1 Project Management Plan	9/30/2020
2	2.1 Develop lithographic (i.e. EBL and etching) method to formulate GNRs of defined widths	2/28/2021
	2.2 Refined nanotomy process to develop GNRs with edge roughness <0.5 nm and comparable widths	6/30/2021
	2.3 Understanding of structural properties and local density of states of GNRs fabricated using nanotomy and traditional lithography	8/31/2021
3	3.1 Completely optimized architecture of GQD-based single electron transistor (SET) defined on GNRs	9/30/2021
	3.2 Correlation between GNR widths, quality (measured as local density of states) and conduction properties of the GQD-based SETs	12/31/2021
	3.3 Details regarding the effect of SPM-AOL on the structure and local disorder of GQDs	2/28/2022
	3.4 Identify the impact of SPM-AOL on the transport properties of idealized GQD device	8/31/2022
4	4.1 Optimize the capacitive coupling between the GQD and QPC to achieve better charge readout	04/30/2022
	4.2 Detailed understanding of the effect of disorder on GQD charge stability under a magnetic field	10/31/2022
	4.3 Fully characterized charge relaxation time in GQD and evaluating its superiority compared to baseline device	02/28/2023
5	5.1 Details of the inter-dot coupling strength as a function of the voltage applied to the gate that controls the coupling between adjacent dots	06/30/2023
6	6.1 Complete understanding about the superiority of nanotomy-SPM-AOL pathway to realize superior GQD spin qubit for quantum communication	08/31/2023

Project Deliverables

Task	Deliverable title	Due Date
1	Project Management Plan	Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the NETL Project Manager.

2. Periodic and final reports shall be submitted in accordance with the "Federal Assistance Reporting Checklist" and the instructions accompanying the checklist.

BRIEFINGS/TECHNICAL PRESENTATIONS

Detailed briefings for presentation to the NETL Project Manager at their facility located in Pittsburgh, PA, Morgantown, WV, or via WebEx.

Budget Profile and Duration

Project duration: 9/1/2020–8/31/2023 (36 Months)

- ❑ **Yr1**: 9/1/20-8/31/21
- ❑ **Yr2**: 9/1/21-8/31/22
- ❑ **Yr3**: 9/1/22-8/31/23

Budget Period	Budget ($)
Yr 1	142,022
Yr 2	189,339
Yr 3	168,185
Total Budget (3 years)	499,546

Project Risks and Risk Management Plan

S. No.	Risk (s)	Probability	Impact
i	Robustness of experimental design	Low	Moderate
ii	Fidelity of the experimental setup	Low	High
iii	Measurement uncertainties: Bias and precision errors	Low	Moderate
iv	Personnel health and safety	Low	High

Acknowledgments

- Dr. Adam Payne (Project Manager, DOE)
- Functional Quantum Materials Laboratory (FQML), UTEP
- Office of Research and Sponsored Projects (ORSP), UTEP

U.S. DEPARTMENT OF ENERGY
Office of Fossil Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank You!