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

Project # DE-FE0031908

Sreeprasad T. Sreenivasan (PI)
Department of Chemistry & Biochemistry
The University of Texas at El Paso
### Project Team, Management & Structure

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

**Project Objectives**

- **Dr. Ramana (co-PI)**: Characterization, spin manipulation, mentoring
- **Dr. Sreenivasan (PI)**: GQD synthesis, characterization, and electrical analysis
- **Dr. Chava (co-PI)**: Device fabrication, characterization, and electrical analysis

**Overall operations, management and sustainment of the project**

**Managing the funding and documenting all the budgetary expenditure**

**PI: Dr. Sreenivasan**

**UTEP-ORSP Post award office**

Graduate student (jointly supervised); conduct experiments, analyze results, article preparation, and presentation.
Technical Background & Motivation
Quantum Information Processing (QIP) and Quantum bits (qubits)

Physical Implementation of Qubits
- Atoms, ions, molecules
- Electronic and nuclear magnetic moments
- Charges in semiconductor quantum dots
- Charges and fluxes in superconducting circuits
- Spin

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

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

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

Advantages of Graphene:
1. Very low nuclear spin
2. Weak spin-orbit coupling

Quantum Dots in Graphene

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

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

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

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

**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:

- **YR 1:** Define GQDs in GNRs with smooth edges
  - Nanotomography & SPM-AOL
  - GQD quality evaluation (SPM, Raman, TEM, etc.)

- **YR 2:** Performance evaluation of single GQD devices
  - GQD single electron transport
  - Quantum point contact detector
  - Charge relaxation studies

- **YR 3:** Fabrication & Characterization of double GQD devices
  - Spin transport in double dot
  - Interdot coupling studies (tunable tunnel barriers)
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: Nanotomography and SPM Lithography


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)*

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

1. Electrical transport studies on GNR devices

2. Characterization of SET

3. Characterization of SET using QPC

![SET using QPC diagram](image)

4. Characterization of Double Quantum Dots

![Double Quantum Dots diagram](image)

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

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

Etched graphene quantum dots on hexagonal boron nitride

- Stable single-quantum dot behavior under magnetic field

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

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

- Initiated synthesis and optimization of process parameters
PROGRESS: GNR Synthesis and SPM-AOL

2D Height map

2D KPFM map

2D Height map

2D KPFM map

Upsilon
Project Milestones, Budget, and Schedule
<table>
<thead>
<tr>
<th>S. No.</th>
<th>Task Title</th>
<th>Yr1</th>
<th>Yr2</th>
<th>Yr3</th>
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<tbody>
<tr>
<td>1</td>
<td>Project Management and Planning</td>
<td>∅</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>Preparation of GNRs with prescribed width and smooth edges</td>
<td></td>
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<tr>
<td>3</td>
<td>Device fabrication and characterization of a single-electron transistor</td>
<td></td>
<td></td>
<td>∅</td>
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<td>4</td>
<td>Characterization of GQD charge stability and charge relaxation</td>
<td></td>
<td>∅</td>
<td>∅</td>
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<tr>
<td>5</td>
<td>Fabrication and Characterization of double GQD spin qubit system</td>
<td></td>
<td></td>
<td>∅</td>
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<tr>
<td>6</td>
<td>Final Verification</td>
<td></td>
<td></td>
<td>∅Δ</td>
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<td><strong>φ-Milestones</strong></td>
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<tr>
<td></td>
<td><strong>Δ-Go/No-Go Decision points</strong></td>
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### Milestone Summary Table

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

<table>
<thead>
<tr>
<th>Task</th>
<th>Deliverable title</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project Management Plan</td>
<td>Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the NETL Project Manager.</td>
</tr>
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</table>

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
  - Budget: 142,022
- **Yr2**: 9/1/21-8/31/22
  - Budget: 189,339
- **Yr3**: 9/1/22-8/31/23
  - Budget: 168,185

**Total Budget (3 years):** 499,546
<table>
<thead>
<tr>
<th>S. No.</th>
<th>Risk (s)</th>
<th>Probability</th>
<th>Impact</th>
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</thead>
<tbody>
<tr>
<td>i</td>
<td>Robustness of experimental design</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>ii</td>
<td>Fidelity of the experimental setup</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>iii</td>
<td>Measurement uncertainties: Bias and precision</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>errors</td>
<td></td>
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<tr>
<td>iv</td>
<td>Personnel health and safety</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
Acknowledgments

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