Thrust Area 1: *Novel 2D Materials for More Efficient High Frequency Communication Devices/System*

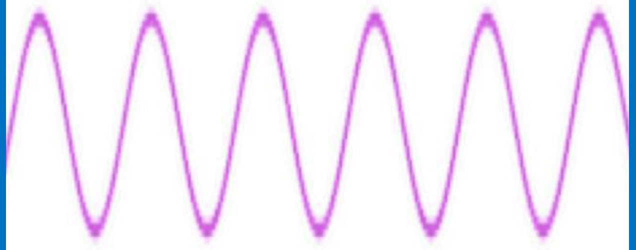
Vision for materials

Data Transmission

Quantum 2D Source Materials for long mean free path, high mobility, efficient high frequency Transmitters/Receivers

Wide Bandgap Materials for Power Amplifier

Materials Converting RF to Optical



Materials Converting Optical back to RF

Potential for all on one Platform: SiC, Si, or Sapphire

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Thrust Area 1:Focused but Diverse Team

***Uche Wejinya**, PhD, University of Arkansas – Fayetteville*

***Hugh Churchill**, PhD, University of Arkansas – Fayetteville*

***Nicole McFarlane**, PhD, University of Tennessee – Knoxville*

***Gong Gu**, PhD, University of Tennessee – Knoxville*

***Gregory Salamo**, PhD, University of Arkansas – Fayetteville*

***Fisher Yu**, PhD, University of Arkansas – Fayetteville*

***Samir M. El-Ghazaly**, University of Arkansas – Fayetteville*

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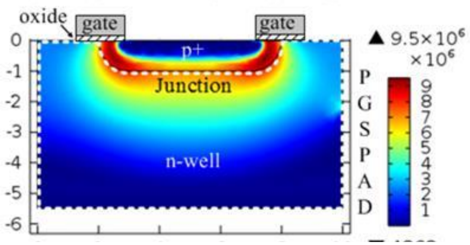
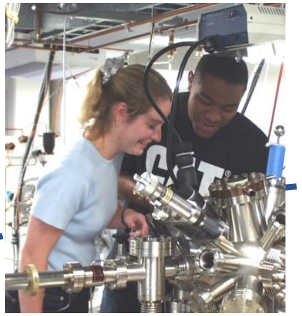


Modeling device and electronics integration

Nicole McFarlane Samir M. El-Ghazaly

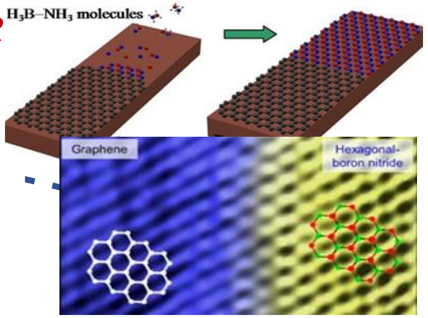


Devices/Students skilled in RF

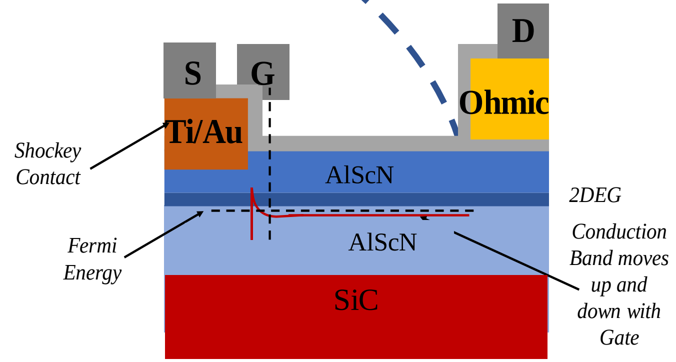
Growth/Characterize

New 2D materials with higher power capability

Gong Gu



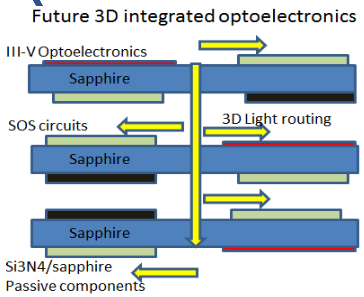
Focus: Innovating 2D Materials to Achieve Efficient High Frequency (GHz to THz) Devices



Growth/Characterize

higher frequency MQW Nitride power amplifiers

Greg Salamo



RF to **Optical** to RF

Fisher Yu

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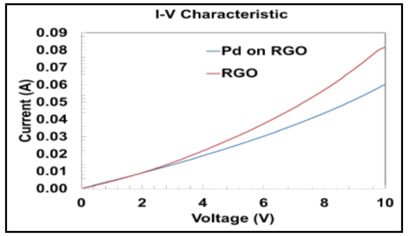
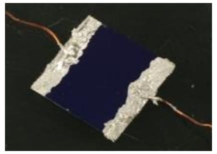
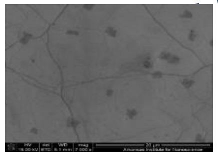
Prototype Device &Measuring 2D Transport, Power, Frequency Response

Uche Wejinya

Hugh Churchill







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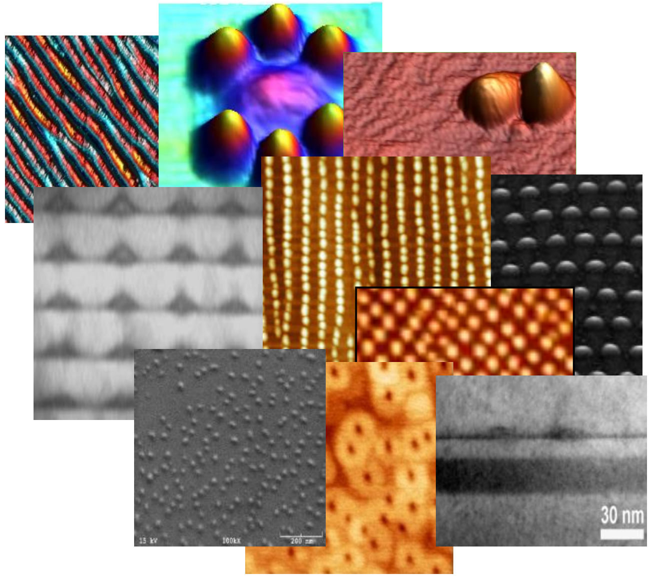
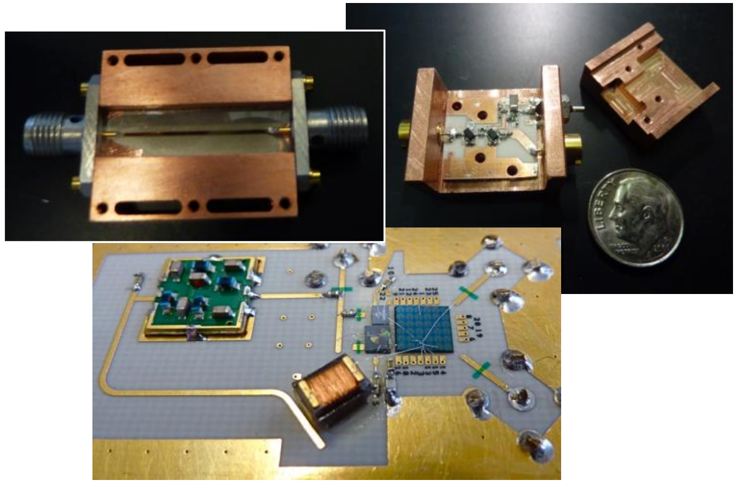
Team Current Research Areas

- ***Growth and Characterization** of Quantum 2D Materials such as GeSe, black phosphorus, WSe2, graphene, hBN and wide bandgap materials such as GaN, AlN, Ga_2O_3.*
- *Fabrication of nano/microfabricated optical and electronic **devices, lasers, detectors,** and **sensors** with integrated electronics (CMOS).*
- *Physics based **modeling** and SPICE modeling of devices and noise theory for electronic systems*
- *Analog based encryption for secure **data transmission as well as optical modulators** to encode information.*





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Team Current Supported Projects/Sponsors

- *Breaking Symmetry and Optical Limiting- DARPA*
- *Hall Effect to Simultaneously Sense Current and Temperature – NSF-ERC*
- *Ferroelectric Single Monolayer Films - NSF-EPSCoR*
- *Nonlinear Cavity Optical Limiter - AFRL*
- *Spin Polarized Electrons – ARL*
- *Wireless Hardware Analog Encryption for Secure, Ultra Low Power Transmission of Data – NSF*
- *Low Cost Silicon Photomultipliers for Neutron Detection – DOE*
- *A CMOS ASIC for Gas Sensors – N5 Sensors*
- *Qubit Development in 2D Semiconductors – AFOSR*
- *Symmetry Engineering of Topological Semimetals – DOE*
- *Exciton Control in Ultrathin Black Phosphorus – NSF*

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Team Lab Facilities & Capability

1. *MBE growth/characterization of semiconductor and ferroelectrics*
2. *Growth of 2D materials*
3. *Optical properties of semiconductors.*
4. *Atomic Resolution STM and Cross Section STEM*
5. *XRD, XPS, SEM and AFM*
6. *Full Electrical Characterization of 2D Materials*
7. *Semiconductor parameter analyzers, network-spectrum analyzers, source measure units.*
8. *THz Time-domain Spectroscopy*

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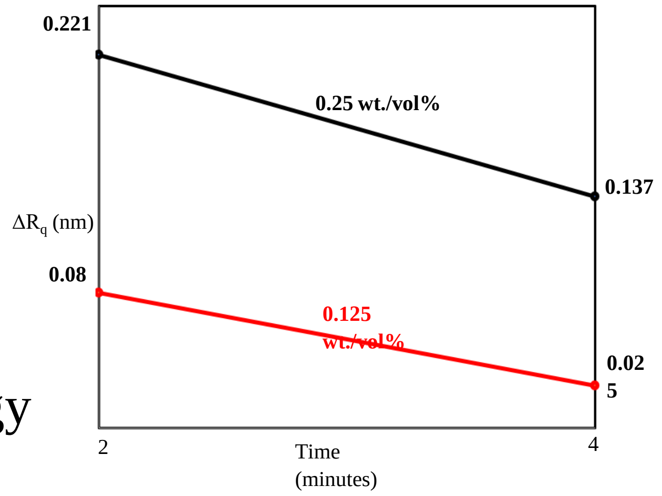
Completed Project: Electrical Property Measurement of Graphene Decorated Nanoparticles

Problem: Non-covalent functionalization graphene without delamination of graphene sample from substrate has been challenging. Delamination of the graphene from substrate prevents decoration of sample with nanoparticle for applications such as sensing and wireless communication.

New idea: Developed method to successfully functionalized graphene with surfactants by incorporating solvents in treatment of graphene.

Deliverable:

- ❖ Surfactant treated graphene samples
- ❖ Effect of surfactant treatment on the graphene morphology



Change in RMS Roughness (ΔR_q) for the two concentrations and time show a reduction in ΔR_q for longer treatment time and lower treatment concertation.

Objective: Demonstrate:

1. Treatment of CVD graphene with surfactant without delamination of graphene from substrate.
2. Decorate treated graphene with palladium and platinum nanoparticles.
3. Electrical measurement of nanoparticle decorated graphene devices

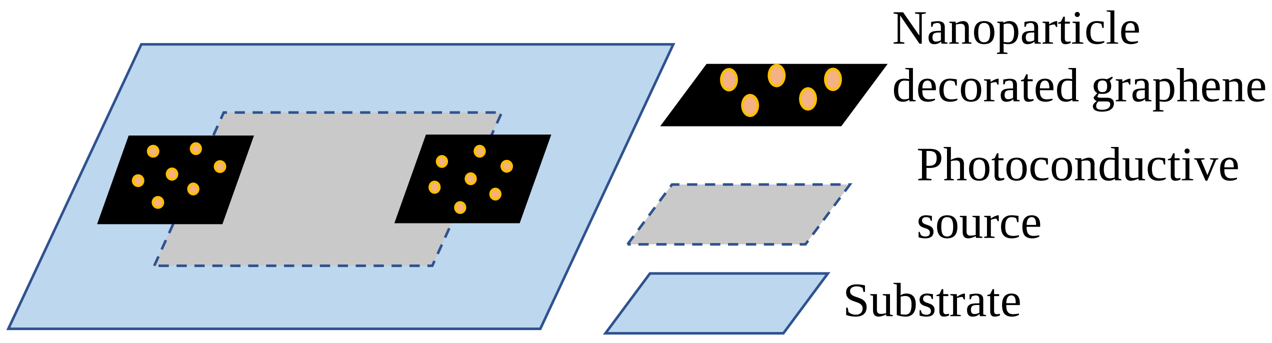
What is new here?

- ❖ Successful treatment of graphene with surfactant without graphene delamination from substrate
- ❖ Quantify the effect of surfactant on CVD graphene

Example of what we want to do: Fabricate graphene nanoparticles decorated tunable films to Advance Communication

Problem: Frequency tunability/reconfigurability of high frequency communication devices.

New idea: Incorporate nanoparticle decorated graphene



Deliverable:

- ❖ Fabricated nanoparticle-decorated graphene antenna
- ❖ Antenna properties for nanoparticle-decorated graphene antenna.
- ❖ Communication parameter performance Correlation

Objective: Demonstrate:

1. Use nanoparticle-decorated graphene for wireless communication device.
2. Measure the nanoparticles on the properties of wireless communication device

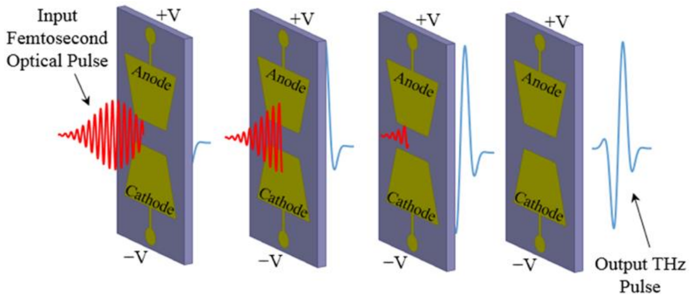
What is new here?

- ❖ Nanoparticles incorporated in graphene-based wireless device.
- ❖ Test High frequency.

Completed Project: Black Phosphorus THz Photoconductive Antenna

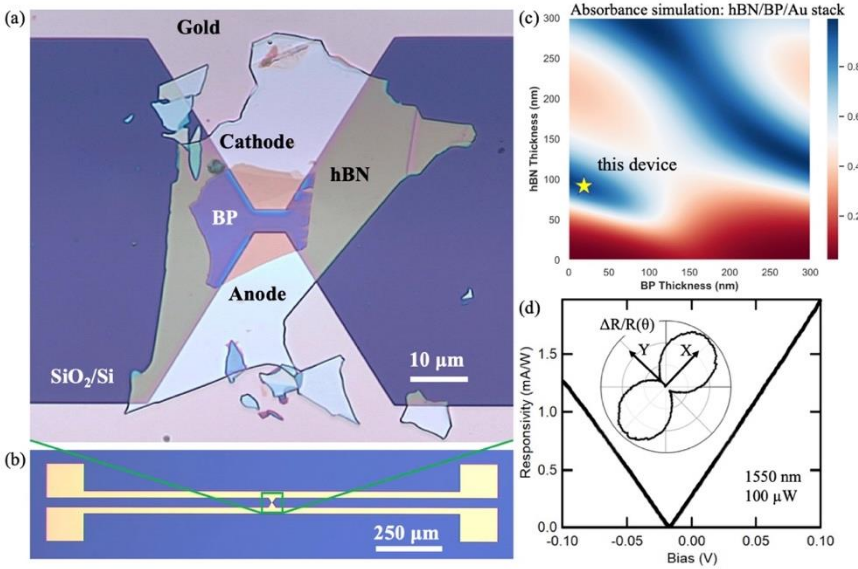
Problem: Efficiency of state-of-the-art commercial THz Photoconductive Antennas (PCAs) is very low, ~0.01%.

New idea: Use an ultrathin, strongly absorbing, and high saturation velocity 2D semi-conductor, black phosphorus (BP)



Deliverable

BP THz PCA with record-high bandwidth and output power



Objectives: Fabricate and characterize THz PCAs using BP as the photoconductive element.

1. Extend the bandwidth of THz PCAs beyond 5 THz
2. Extend the power output of THz PCAs beyond a few µW
3. Model and optimize device structure
4. Demonstrate polarization sensitive THz detection by BP for spectroscopy and imaging applications

What is new here? Demonstrated integration of 2D BP with THz bowtie antennas.

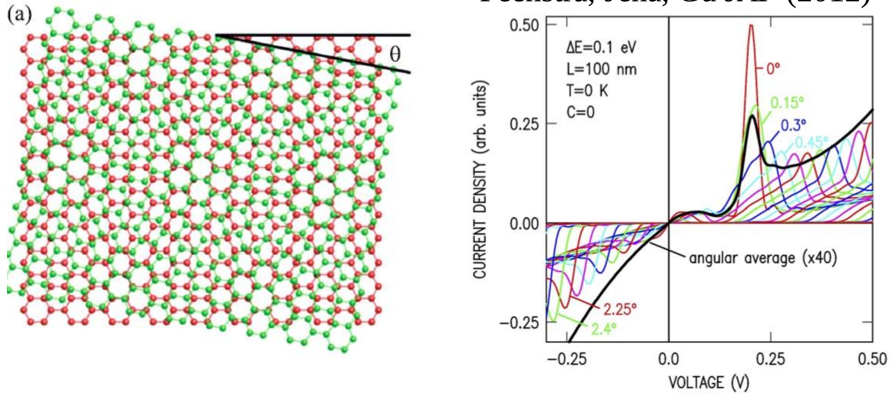
- 780 nm pump absorption 10x > GaAs
- Permits low-cost pump at 1550 nm
- Saturation velocity 2x > GaAs
- Anisotropic absorption of BP (ratio 5x) for polarization selectivity
- Ultrathin structure (~20 nm) for very short transit times → high bandwidth

Example of what we want to do: to fabricate and characterize perfectly aligned graphene/hBN/graphene resonant-tunneling diodes (RTDs)

Problem: Resonant-tunneling using traditional materials are limited to ~ 1 THz. Graphene can do better, but crystal misalignment and thick hBN limit frequency performance because of momentum non-conservation.

New ideas: Use a new tear-and-stack method to create perfectly aligned graphene layers and integrate them with THz antennas. Use CVD-grown few-layer hBN tunnel barriers.

Feenstra, Jena, Gu *JAP* (2012)



Deliverable: Graphene RTDs with f_{max} > 2 THz and high output power

Objectives:

(1) Fabricate graphene/hBN/graphene tunnel junction with 0° misalignment.

(2) Design/integrate antennas and ancillary circuitry for ultrafast RLC resonators.

(3) Demonstrate record-high f_{max} for a resonant-tunneling diode, measured with our THz time-domain spectroscopy system.

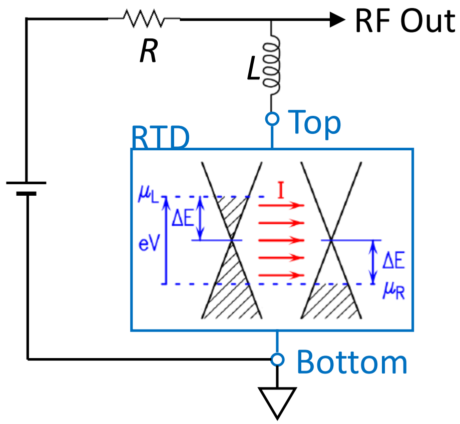
What is new here?

- Methods to obtain perfectly aligned graphene stacks invented very recently
- Tunnel current and f_{max} increase dramatically for thin hBN; we have 1-, 2-, 3-layer hBN available
- Graphene RTDs exist, but have not yet been integrated with THz antennas

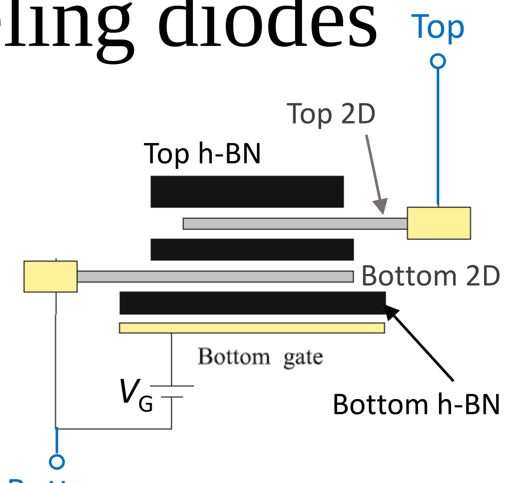
Example of what we what we want to do: resonant-tunneling diodes (RTDs) based on rotation-insensitive 2D materials

Problem: Traditional resonant-tunneling devices (e.g. Esaki diodes) require epitaxial structures, hindering heterogeneous integration.

New ideas: 2D materials friendly to heterogeneous integration, 2D-2D like-band tunneling promises higher peak-valley ratio (PVR) but requires rotational alignment between 2D sheets. We will eliminate/relax the alignment requirement and integrate 2D RTD into a functional circuit.



Part of figure from Feenstra, Jena, Gu, *JAP* **111**, 043711 (2012)



Bottom gate (controlling carrier densities) ac grounded: no loading

Deliverable: Integrated RTDs with f_{max} > 2 THz and high output power

Objectives:

(1) Fabricate 2D RTDs with high PVR.

(2) Design/integrate antennas and ancillary circuitry for ultrafast RLC resonators.

(3) Demonstrate record-high f_{max} for a resonant-tunneling diode, measured with our THz time-domain spectroscopy system.

What is new here?

❖ Materials that relax alignment requirement and methods to perfectly align 2D sheets

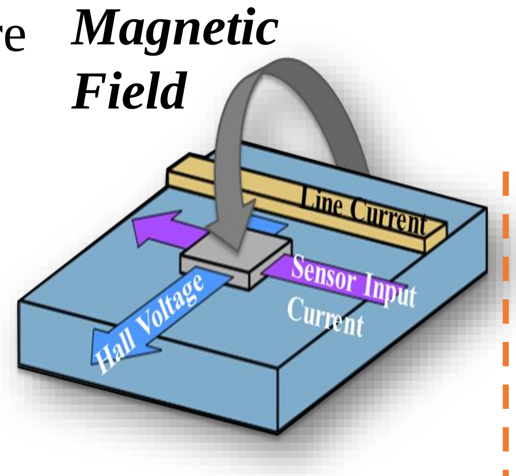
❖ Ultrathin h-BN with uniform layer count to achieve high current and reproducibility

❖ 2D RTDs with significantly improved PVR over existing demonstrations, integratible with other functional components

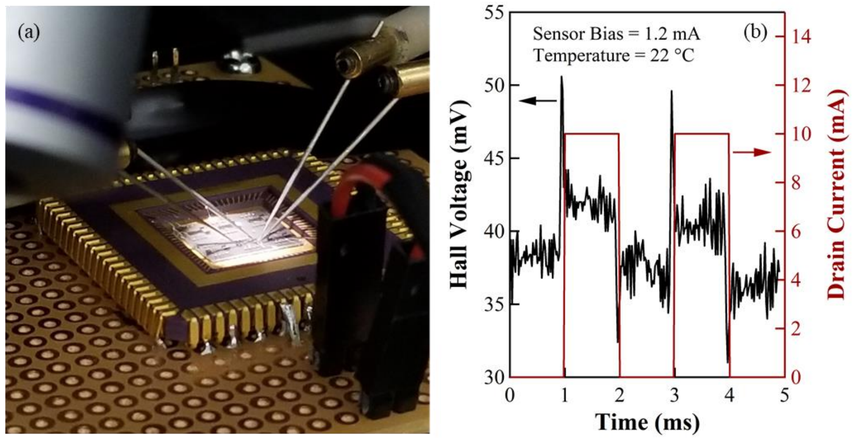
Completed Project: AlGaN/GaN/(SiC & templates) Transistor & Sensor

Problem: High current and temperature can lead to catastrophic failure of high frequency electronic systems.

New idea: Develop integrated on-chip Hall device that map high current and temperature as feedback system.



Deliverable
Single GaN chip with high power transistor and sensor



Objectives: Use Hall effect sensors to provide real-time current and temperature profiles on high frequency transistor

Wide bandgap material is developed to:

1. Extend the operating temperature range beyond 600^{o}C of the current state-of-the-art Hall sensors
2. Decrease the temperature dependence of the Hall signal
3. Decrease active cooling needs
4. Integrate the high voltage switching components with sensors on a GaN single chip

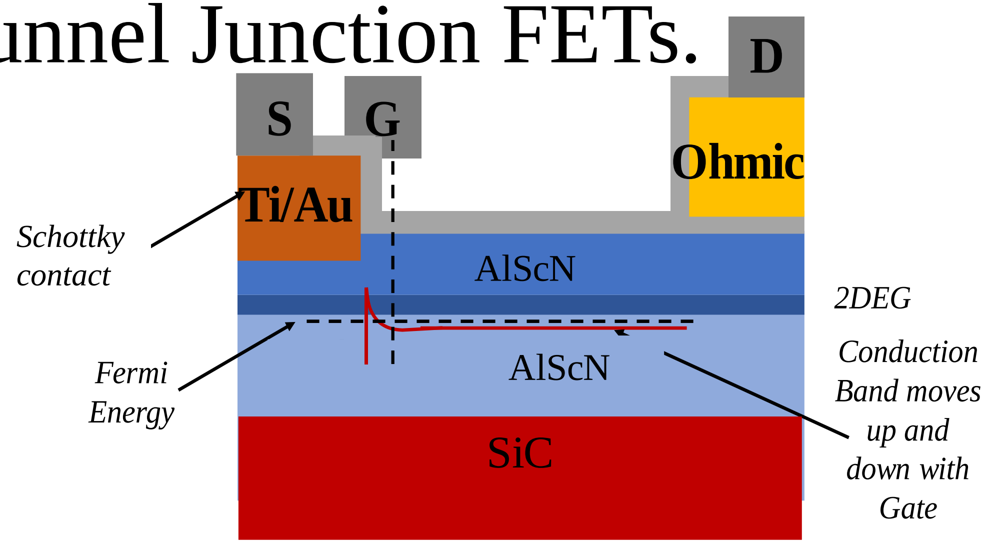
What is new here? Achieved new sensor that measures both current and temperature

- ❖ Operates up to 600°C,
- ❖ Maps current with sensitivity ~ 100 mv/T & temperature with sensitivity ~ 6 mV/ ^{o}C
- ❖ Bandwidth of at least 12 MHz.
- ❖ Invented new Schottky-Hall sensor with higher sensitivity

Example of what we want to do: to grow and fabricate normally-off high frequency AlScN/GaN metal-2DEG Tunnel Junction FETs.

Problem: Given the growing number of devices that make use of wireless communications there is a need for NEXT-G high power, high voltage, frequency, low leakage current transistors.

New idea: Develop 2 DEG high frequency AlScN/GaN/AlScN normally-off tunnel junction transistor with high I_{on}/I_{off} ratio by controlling the thickness of the ***quantum well***.



Deliverable: Initially-off AlN/GaN/AlN/SiC multiple quantum well

Objectives: (1) Develop high drive current, low OFF-state current, and high breakdown voltage transistor suitable for the high power-high temperature systems.

(2) Investigate operating frequency as a function of 2DEG at the AlN/GaN well of different thickness,

(3) Demonstrate that when a reversed biased Schottky source junction is in the off-state, the off-state leakage is very low and the on-state very sharp, giving a high I_{on}/I_{off} - switch.

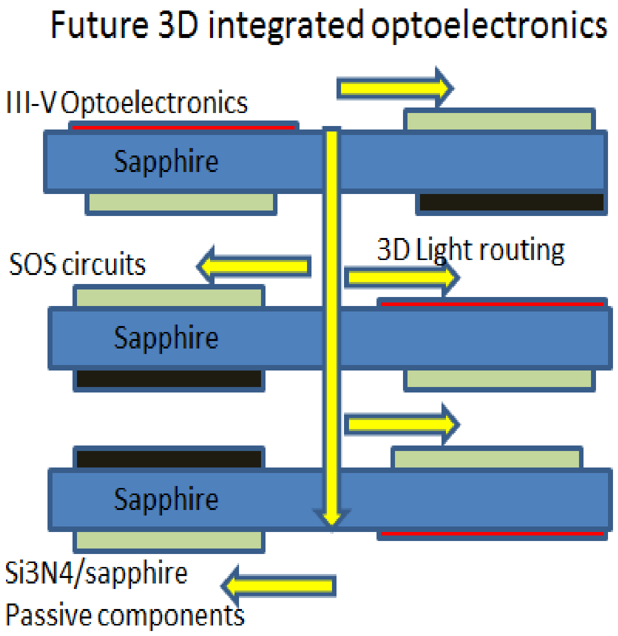
What is new here?

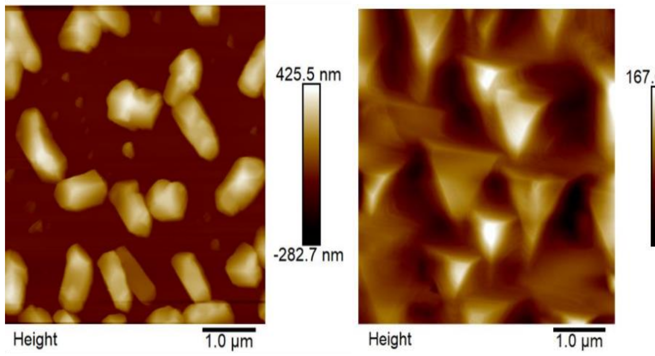
- Develop control over the 2DEG by varying the width and frequency response of the AlScN/GaN/AlScN quantum well.
- Phase 1 – 100MHz and high I_{on}/I_{off} *ratio.*
- Phase 2 – 500MHz and high I_{on}/I_{off} *ratio*

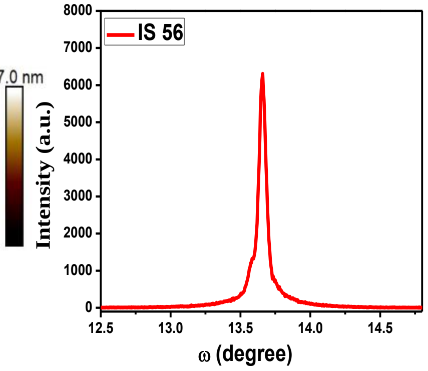
Completed Project: Semiconductor on Sapphire & Integrated Photonics

Problem: The road block for high frequency silicon photonics is a missing monolithic on-chip laser due to thermal expansion mismatch between film and substrate.

New idea: Develop sapphire, which is thermal expansion matched to III-V semiconductors as a photonic platform.







Deliverable: Growth of high quality InAs/GaAs quantum well structure fabricated on a sapphire substrate. The quantum well will emit high intensity, narrow bandwidth, photoluminescence.

Objective: Demonstrate:

1. Growth of high quality III-V materials, such as GaAs, AlAs, and InAs, epitaxially grown on sapphire substrates.
2. Sapphire as a new photonic platform to integrate silicon electronic circuits together with active optoelectronics, such as lasers and detectors, and low loss passive devices for integrated photonics.

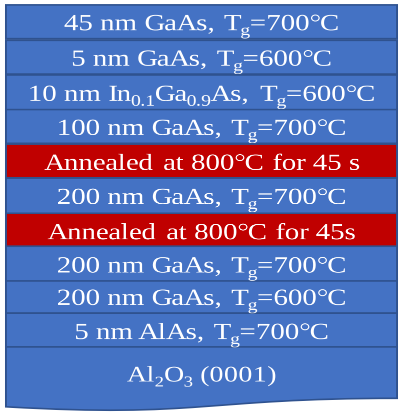
What is new here?

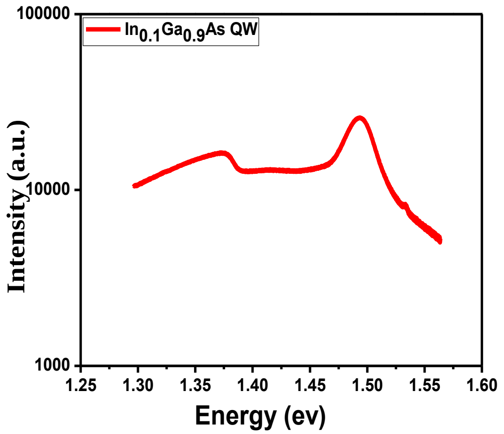
- Achieved growth of beautiful, faceted GaAs semiconductor nanoscale crystals on a sapphire platform.
- Fabricated an InAs/GaAs quantum well on a sapphire substrate with excellent photoluminescence.

Example of what we want to do: Grow Semiconductor laser, detector, waveguide, modulator on a Sapphire Platform to Advance Photonics.

Problem: The road block for high frequency silicon photonics is the difficulty of fabricating laser, detector, waveguide, modulator, and electronics on one platform.

New idea: Develop sapphire, which is thermal expansion matched to III-V semiconductors as a photonic platform. Sapphire also has a low refractive index (1.76-1.77) making possible low loss in optical waveguides on the semiconductor sapphire system.





Deliverable: Photonic system on sapphire with RF-in and RF-out

Objectives: (1) Using AlAs as a wetting layer we will improve the GaAs buffer quality and for InGaAs quantum wells.

(2) We will explore different InGaAs quantum wells and investigate InSb as an alternative quantum well since the it has a lower lattice mismatch.

(3) As a result we will first develop a laser on sapphire. Followed by a detector and waveguides, and than adding a modulator and driving electronics.

What is new here? Demonstrate:

- Year 1 - Quality semiconductor laser on sapphire operating near room temperature with mw intensity levels
- Year 2 - Semiconductor detector, waveguide modulator and driving electronics on sapphire.
- Year 3 – Photonic system on sapphire with RF-in and RF-out

Completed Project: Modeling of Perimeter Gated Single Photon Avalanche Diodes

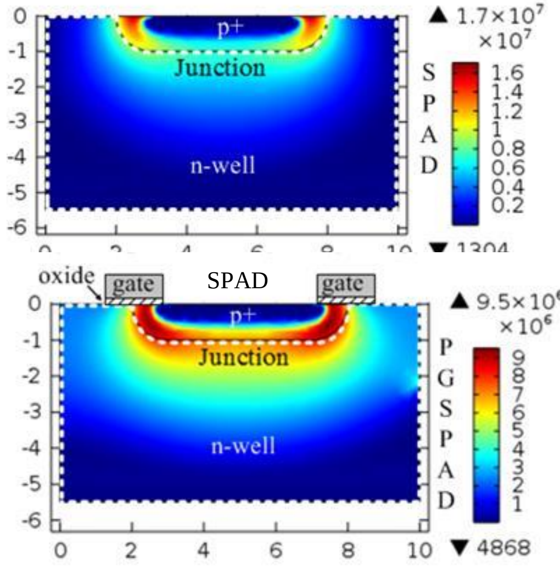
Problem: photomultiplier tubes are bulky, sensitive to magnetic fields, expensive, and use high bias voltages

New idea: Semiconductor based avalanche diodes are compact, insensitive to magnetic fields, relatively cheap and have low bias voltages.

CMOS single avalanche photodiodes are planar and suffer from premature edge breakdown. Modification to 3-terminal device modulates field and carrier concentration.

Deliverable:

- ❖ PGSPADs have uniform electric field distribution
- ❖ Controls device breakdown voltage
- ❖ Tunes noise floor



PGSPAD

Objective:

1. Demonstrate the effect of the polysilicon gate on the new device: perimeter gated single photon avalanche diodes (PGSPADs).
2. Model the device and develop a SPICE model for simulation.
3. Integrate with readout electronics

What is new here?

- ❖ Successfully simulated the underlying physics and developed SPICE models for PGSPADs
- ❖ Quantified the effect of the gate on the device (lowers noise floor through band to band tunneling)

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Example of what we want to do: Modeling New High Frequency Devices

Problem: The proposed new devices need simple models to understand and improve performance in order for wide adoption by designers.

New idea: Model the physics of the novel devices using Matlab and device simulators. Extend to black box circuit models to enable electronics integration.

Deliverables:

- ❖ Modeling for the proposed devices by our team
- ❖ Antenna properties for nanoparticle-decorated graphene antenna.
- ❖ Communication parameter performance Correlation

Objective: Demonstrate:

1. Use nanoparticle-decorated graphene for wireless communication device.
2. Measure the nanoparticles on the properties of wireless communication device

What is new here?

- ❖ Nanoparticles incorporated in graphene-based wireless device.

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Deliverables from the Center Based on Innovative Materials

- ***Ultrafast electronic circuits*** that can tolerate harsh environments, a new era for photonics, and students capable of developing the next generation electronic systems.

- ***New 2D materials*** for high-resolution security imaging systems, improved collision-avoidance radar, communications networks with higher capacity, and spectrometers that could detect potentially dangerous chemicals and explosives with much greater sensitivity.

- ***THz circuits*** that will reduce the size, weight and power consumption of current technology on atmospheric sensing, radio astronomy and medical imaging systems while improving the range and portability of these systems.

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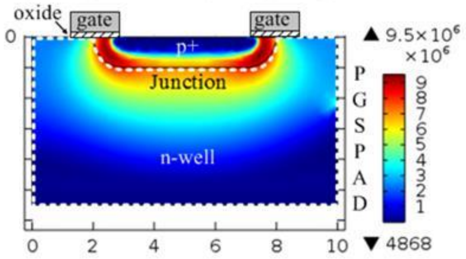
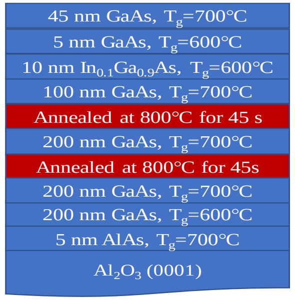
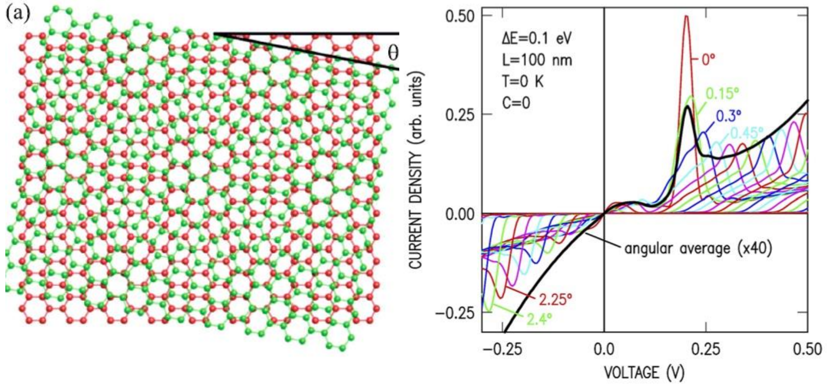
Deliverable: Modeling for the proposed devices by our team



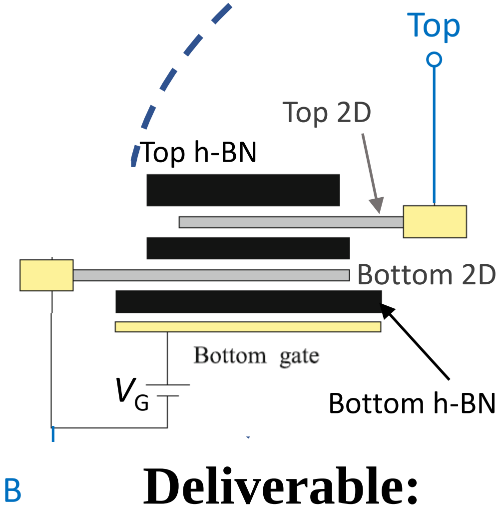
Deliverable: Highly trained Students



Deliverable: Photonic system on sapphire with RF-in and RF-out



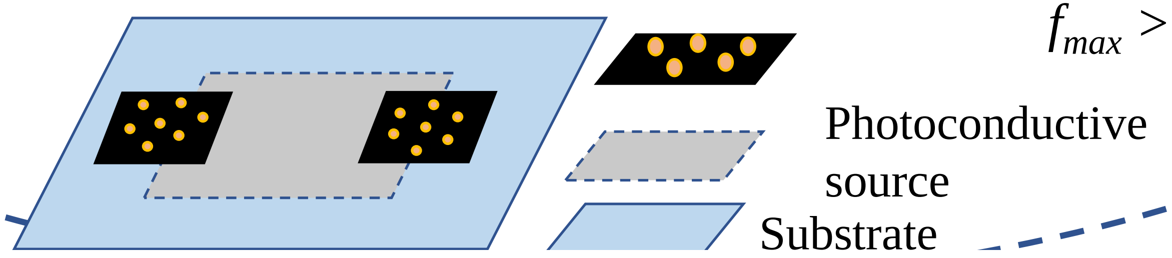
Deliverable: Graphene RTDs with f_{max} > 2 THz and high output power



Deliverable: Integrated RTDs with f_{max} > 2 THz and high output power

In Summary

Team will Innovate 2D Materials to Achieve Efficient High Frequency (GHz to THz) Devices



Deliverable: Fabricated nanoparticle-decorated graphene antenna

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