Plasmon Field Effect Transistors for Low Concentration Gas Detection

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Goal and Purpose

Goal

- ➢ Improve the detection of hazardous gases at extremely low concentrations
- ➢ Utilize localized surface plasmon resonance (LSPR) in gold nanoparticles
- ➢ Fabricate and characterize plasmon field-effect transistors (PFETs) for sensing applications

Why It Matters

- ➢ Early detection improves industrial and environmental safety.
- ➢ Hydrogen, ammonia, and methane are widely used and potentially hazardous gases.
- ➢ Higher sensitivity may enable detection below ~0.1% concentration.

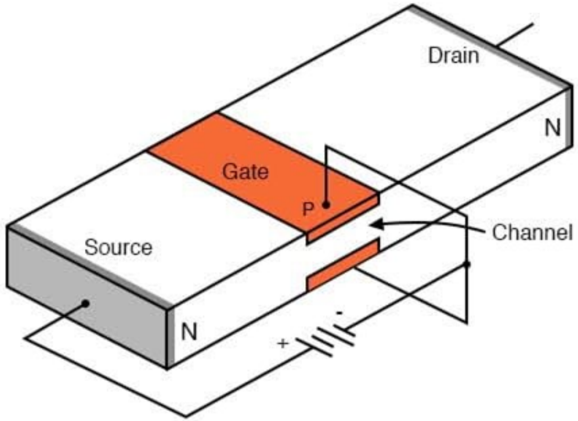
https://intrinsicallysafestore.com/blog/hazardous-materials-how-many-classes-of-hazardous-materials-are-there/

What is a Field-Effect Transistor?

Field-Effect Transistor (FET)

Key Concepts

- ➢ A FET controls the flow of electrical current through a semiconductor channel
- ➢ Current flows between the Source and Drain Electrodes
- ➢ A voltage applied to the Gate creates an electric field that controls how much current flows through the channel
- ➢ FETs are widely used in modern electronics for switching, amplification, and sensing applications



https://www.allaboutcircuits.com/textbook/semiconductors/chpt-2/junction-field-effect-transistors/

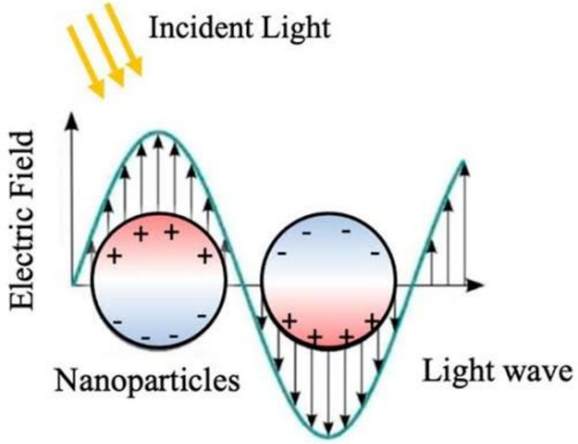
What is Localized Surface Plasmon Resonance?

Localized Surface Plasmon Resonance (LSPR)

- ➢ Occurs when the conduction electrons in metal nanoparticles oscillate collectively in response to incident light.

Key Concepts

- ➢ Incident light causes the nanoparticle's conduction electrons to oscillate collectively
- ➢ When the light matches the nanoparticles natural oscillation frequency, resonance occurs
- ➢ At resonance, a strong localized electromagnetic field is created around the nanoparticle
- ➢ Gas molecules or other nearby materials change the local refractive index, shifting the plasmon resonance



Source: Wu et al., MDPI, 2023.

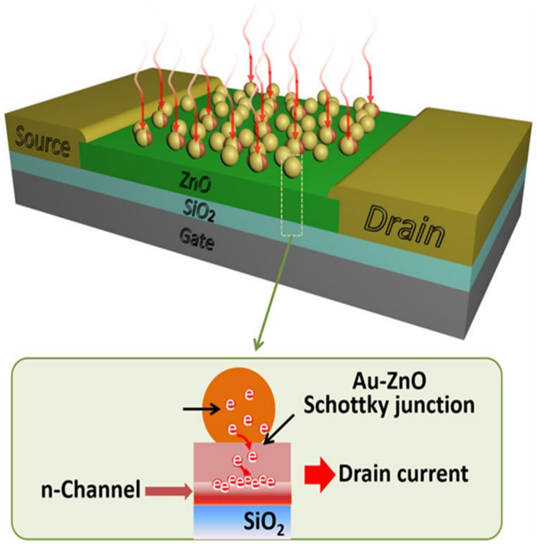
What is a Plasmon Field-Effect Transistor?

Plasmon Field-Effect Transistor (PFET)

- Combines a conventional FET with metal nanoparticles integrated onto the semiconductor channel

Operating Principle

- Light excites LSPR in metal nanoparticles
- LSPR generates energetic, or hot, electrons
- These electrons are injected into the ZnO channel
- The drain current changes in response to this electron transfer
- Gas molecules modify this response, enabling gas detection



Source: Kojori et al., Nano Letters, 2016.

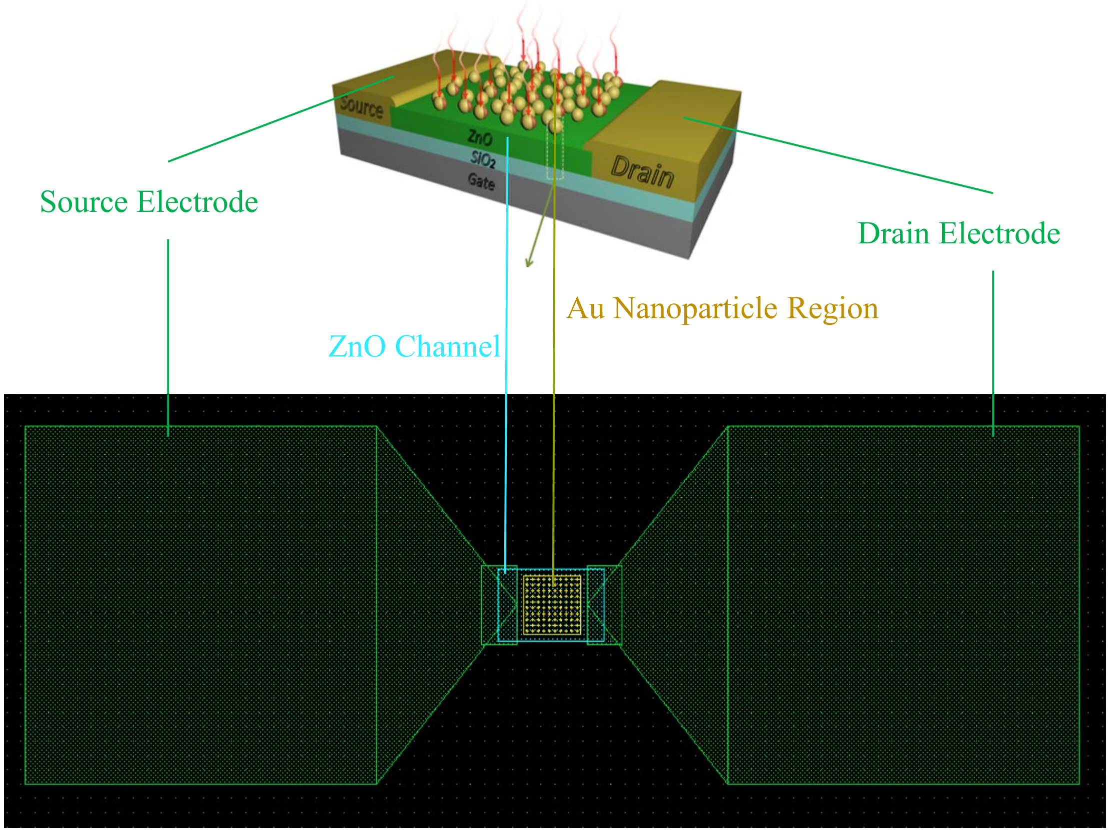
Device Design

Design Objectives

- ➢ Create source and drain electrode geometry.
- ➢ Define the active sensing region.
- ➢ Prepare the device layout for microfabrication.

Design Tool

- ➢ Layout designed using Layout Editor software.
- ➢ Geometry converted into lithography mask patterns.



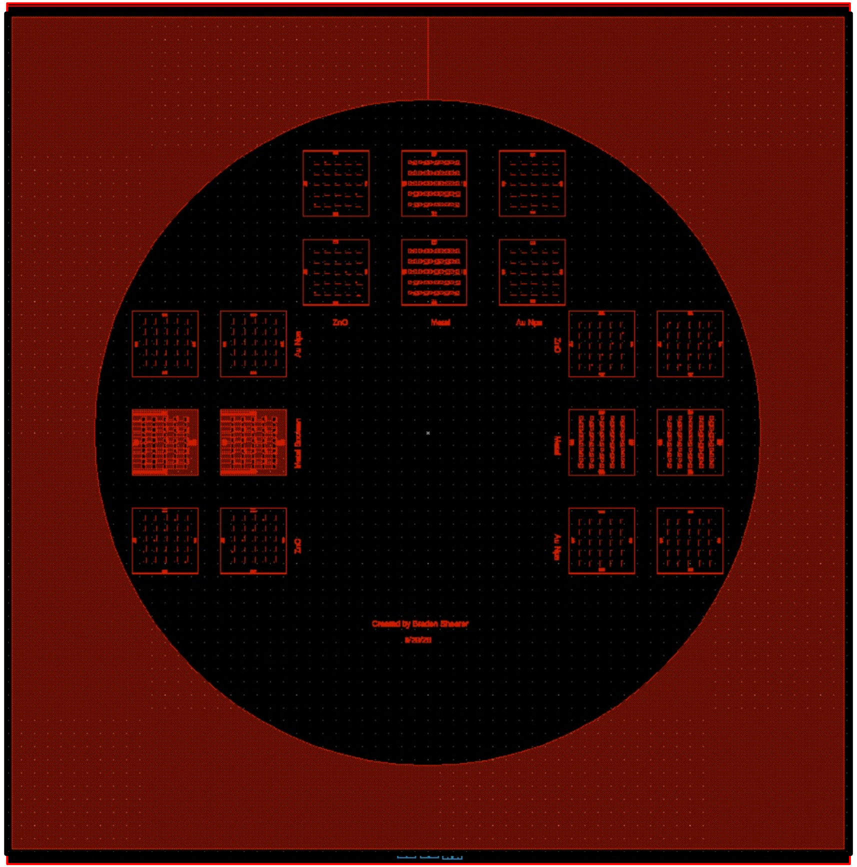
Device Design Cont.

Layout Optimization

- Multiple PFET geometries included with ZnO channel lengths varying from 5-100 μm

Mask Layout

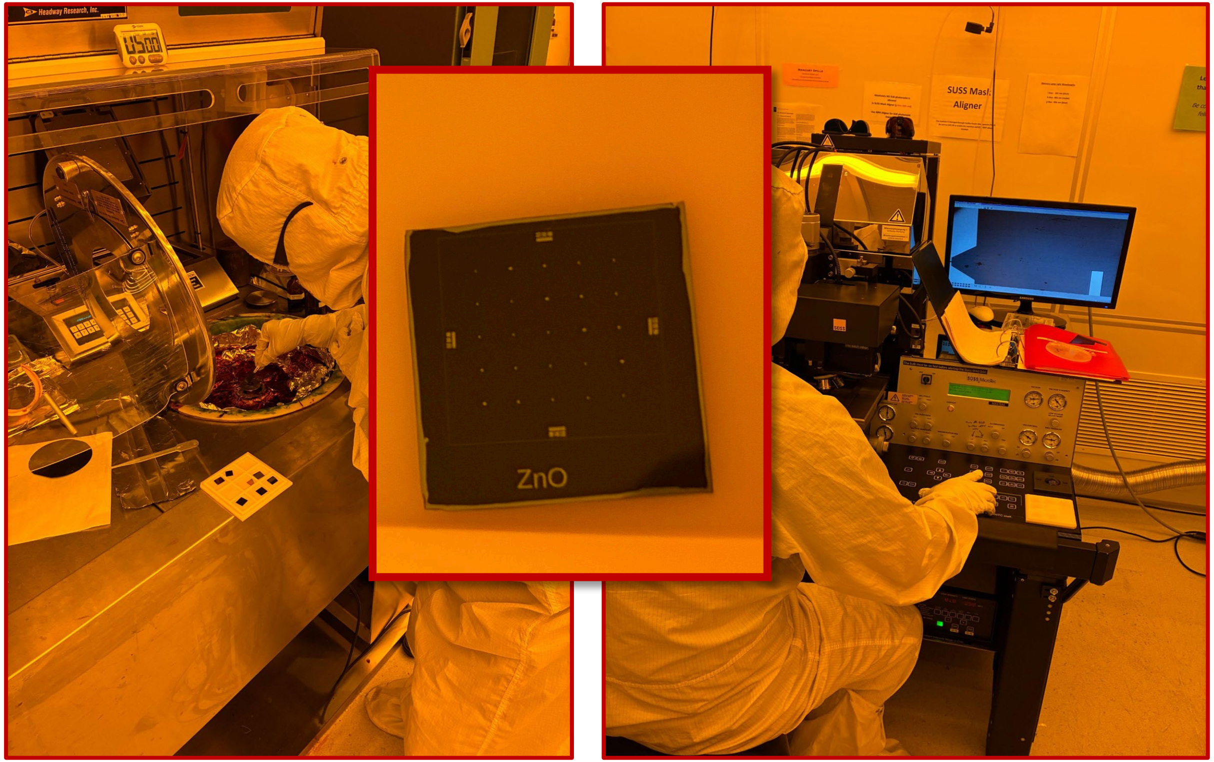
- Source/Drain electrodes, ZnO channels, and Au Nanoparticle regions were modeled separately on their own die



Fabrication

Step 1: Photolithography

- Used to pattern the ZnO channels
- Patterned using AZ5214
- Developed using AZ300MIF
- Etched using HCl



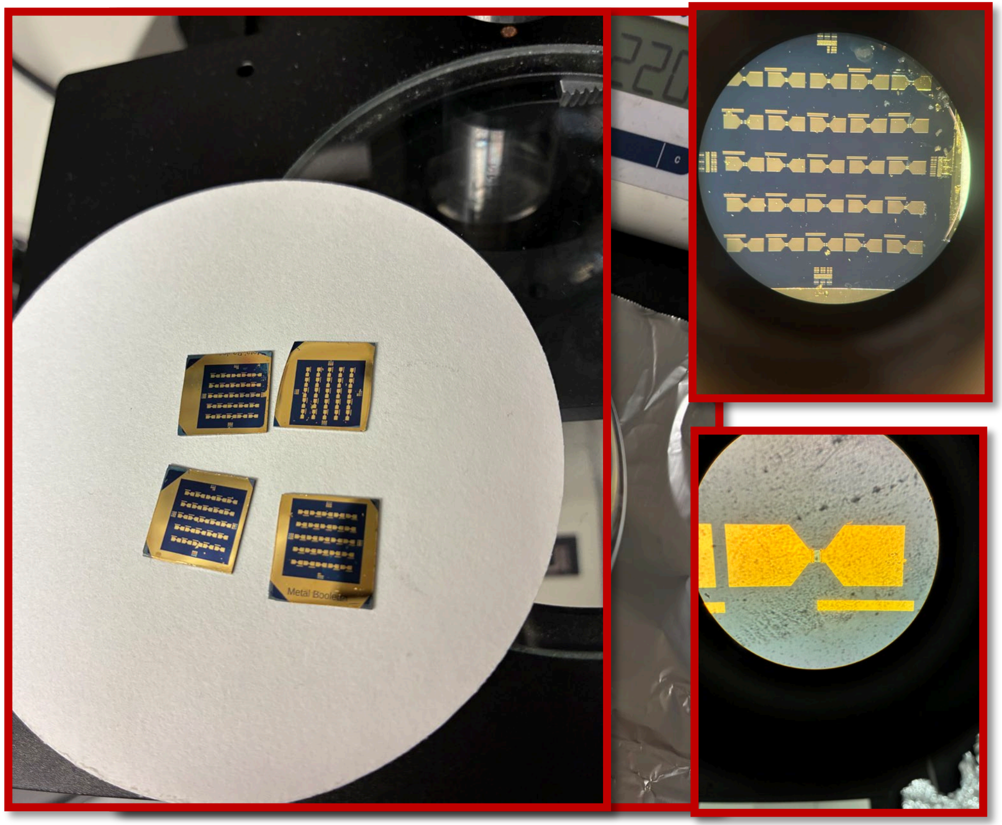
Fabrication Cont.

Step 2: Image Reversal

- Used to pattern the source/drain electrodes
- Patterned using AZ5214
    - Flood exposure used to change properties from positive PR to negative PR
- Developed using AZ300MIF

Step 3: Lift Off

- Electron Beam Evaporation used to deposit metal onto pattern
- Deposited a layer of titatnium and then a layer of gold.
- Lift-off occurs using Acetone



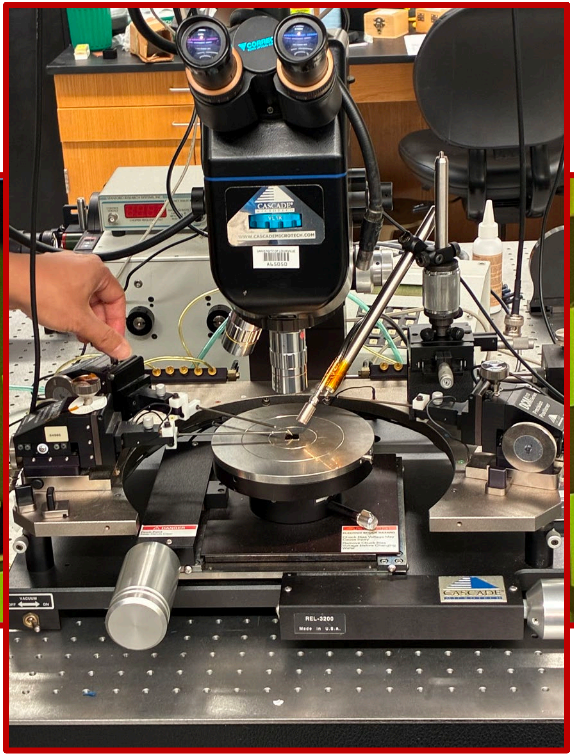
Electrical FET Characterization

Purpose

- Verify the fabricated device operates as FET before PFET fabrication
- Establish baseline electrical performance for comparison after nanoparticle deposition

Measurement

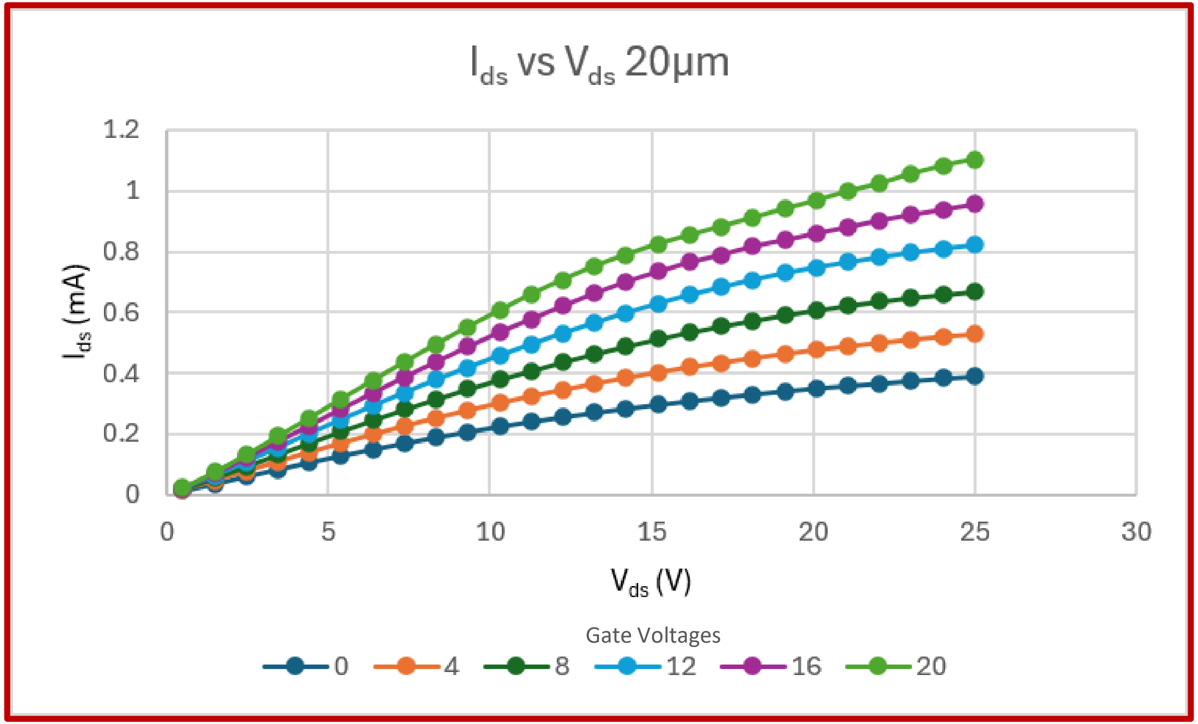
- Devices were characterized using Cascade Microtech probe station and Keithley SourceMeters
- SourceMeters applied gate and drain voltages while measuring the resulting drain current



Electrical FET Characterization Results

Results

- Drain current increase with drain voltage
- Higher gate voltages produce larger drain currents
- Confirms successful FET operation



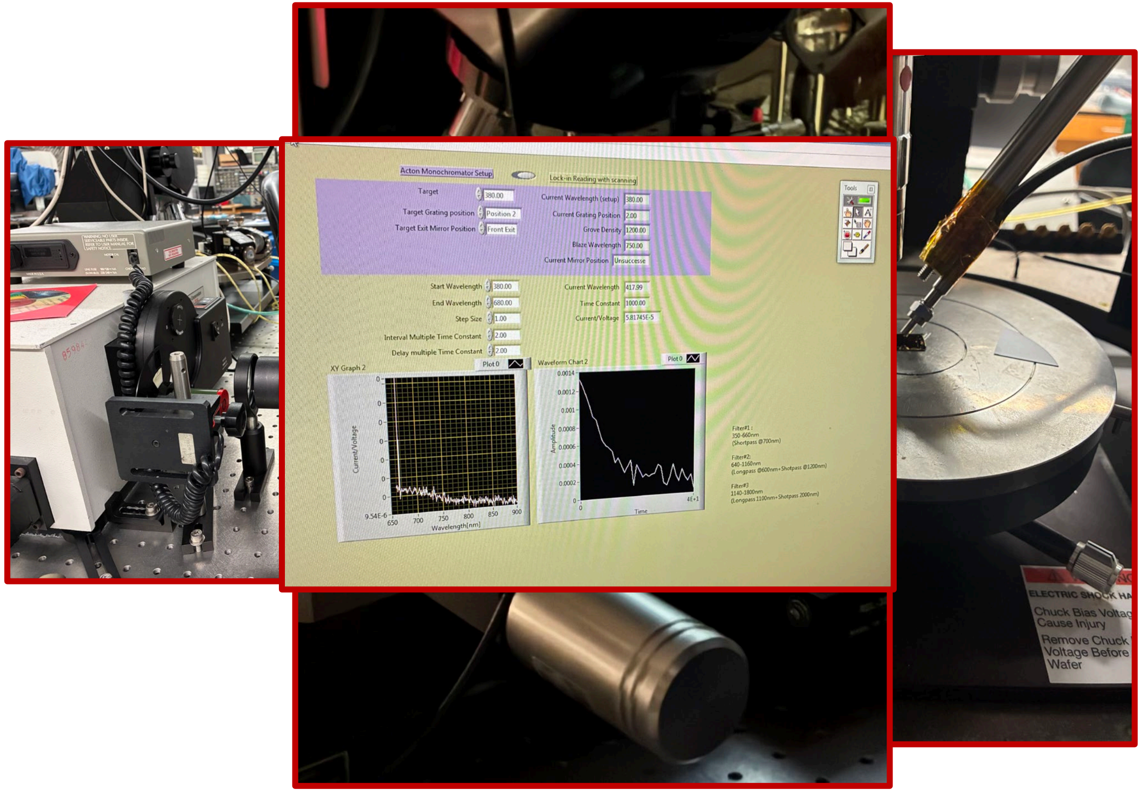
PFET Optical Characterization

Purpose

- Measure the wavelength-dependent electrical response of PFET
- Evaluate the optical response after nanoparticle formation

Experiment Setup

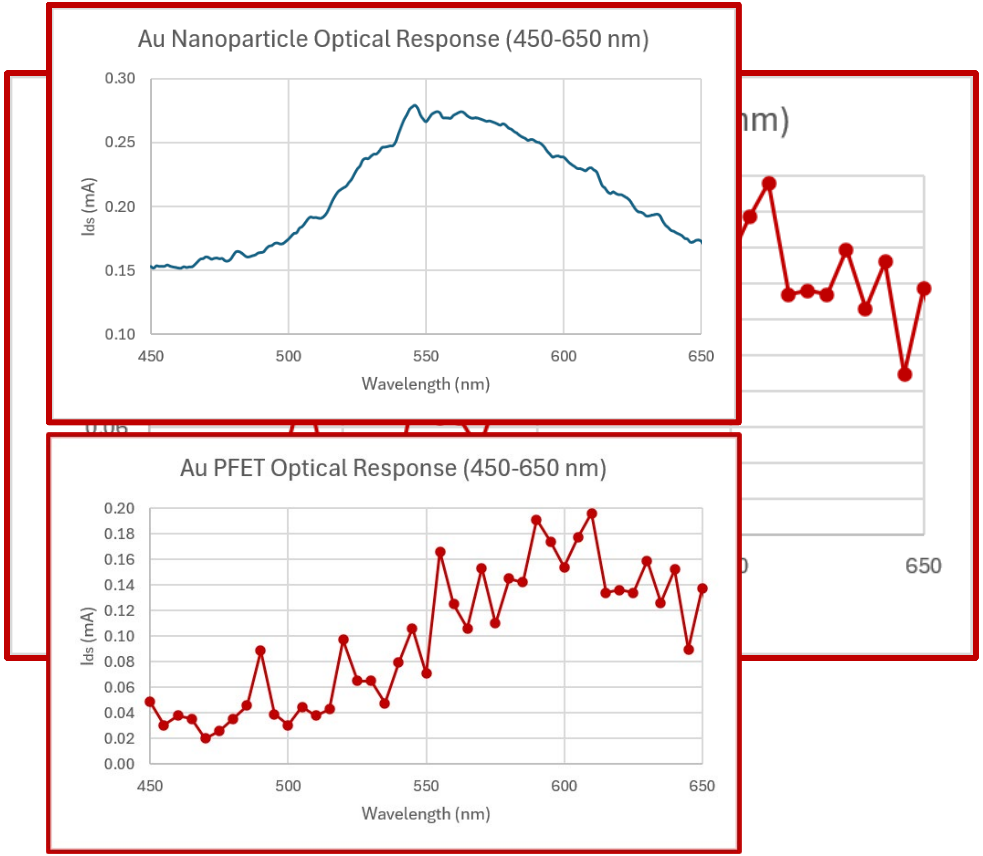
- Broadband light generated using a Tungsten-halogen lamp
- Monochromator selected individual wavelengths
- Fiber optic delivered light to the PFET
- Electrical response measured using the probe station and source meters



PFET Optical Characterization Results

Results

- Electrical response varied with incident wavelength
- A wavelength-dependent response was observed after Au nanoparticle formation
- Optical response shift due to different refractive indices of Glass and ZnO
- Optical characterization confirmed successful PFET photo response



Au/Pd Nanoparticle Optimization

Purpose

- Optimize Au/Pd nanoparticle films for future hydrogen sensing
- Palladium enhances interactions with hydrogen while gold provides the plasmonic response

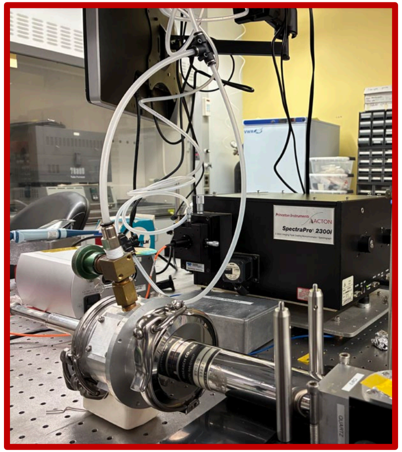
Sample Preparation

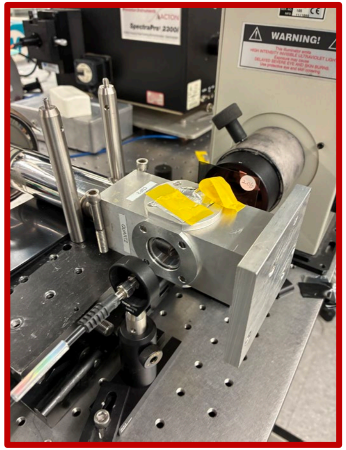
- Au thickness: 5-10nm
- Pd thickness: 2-3nm
- Deposited using electron beam evaporation
- Heated in glove box to minimize oxidation: 200-475°C / 8-35 mins

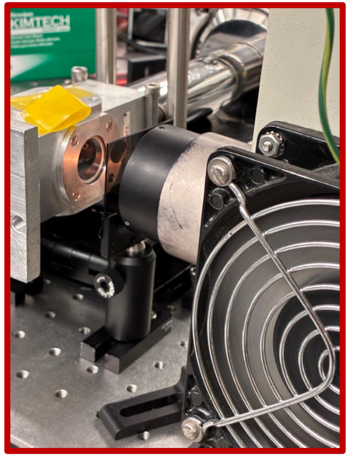
Au/Pd Optical Testing

Setup

- ➢ Au/Pd-coated glass slide placed inside vacuum chamber
- ➢ Nitrogen and hydrogen introduced into chamber
- ➢ Monochromated light transmitted through sample
- ➢ StellarNet spectrometer used to measure, absorbance, transmittance, and scope



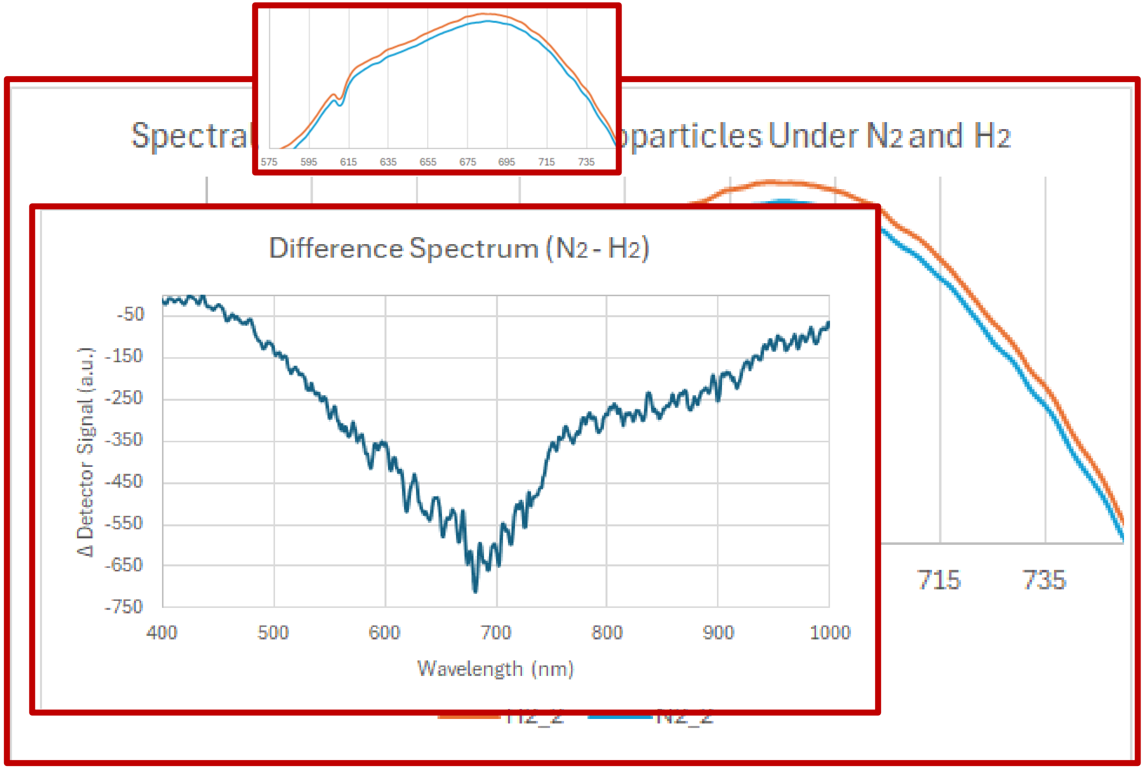




Preliminary Au/Pd Nanoparticle Results

Results

- Optical spectra were collected under both N_2 and H_2 environments.
- The difference spectrum revealed reproducible changes near the plasmon resonance region.
- Continued optimization of Au/Pd thickness and annealing conditions is expected to improve hydrogen sensitivity.



Conclusion and Future Work

Conclusions

- Successfully fabricated ZnO-based PFET devices
- Confirmed FET operation
- Demonstrated wavelength-dependent PFET photo response
- Established optical characterization methods for Au/Pd nanoparticle films

Future Work

- Optimize Au/Pd thickness
- Optimize baking temperature and duration
- Integrate optimized Au/Pd nanoparticles into PFET devices

https://materialsmodeling.org/theses/2016-Thermodynamics-and-Optical-Response-of-Palladium-Gold-Nanoparticles/

Acknowoledgements and References

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KY MULTISCALE
The NSF NNCI Multi-Scale Manufacturing & Nano Integration Node

National Nanotechnology Coordinated Infrastructure

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All About Circuits "Junction Field-Effect Transistors" https://www.allaboutcircuits.com/textbook/semiconductors/chpt-2/junction-field-effect-transistors/