Electrically Detected Magnetic Resonance and Near Zero-Field Magnetoresistance in Wide Bandgap Semiconductors

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This Year

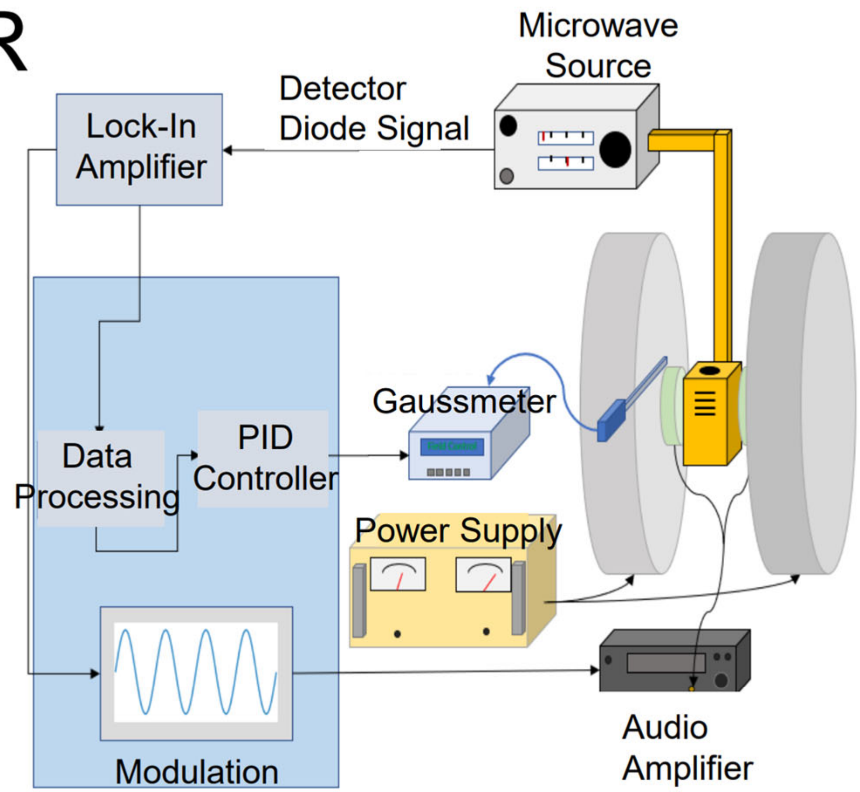
- Mostly overcame NZFRM sensitivity issues on Penn State GaN devices.
- Built in situ NZFMR system for Sandia Ion Beam- it works!
- Demonstrated strong NZFMR/EDMR response for proton bombardment in SiC.
- Michael Flatte group- big advance in interpretation of NZFMR.

This Work:

- We are developing and using a new electron spin related technique called near zero-field magnetoresistance (NZFMR) spectroscopy, and also using a relatively new technique, electrically detected magnetic resonance (EDMR) to identify electrically active defects in GaN and also SiC based devices.
- Our focus is on particle bombardment induced defects. NZFMR and EDMR offer ultra sensitive approaches to identify the chemical and physical nature of electrically active defects.

Conventional EPR

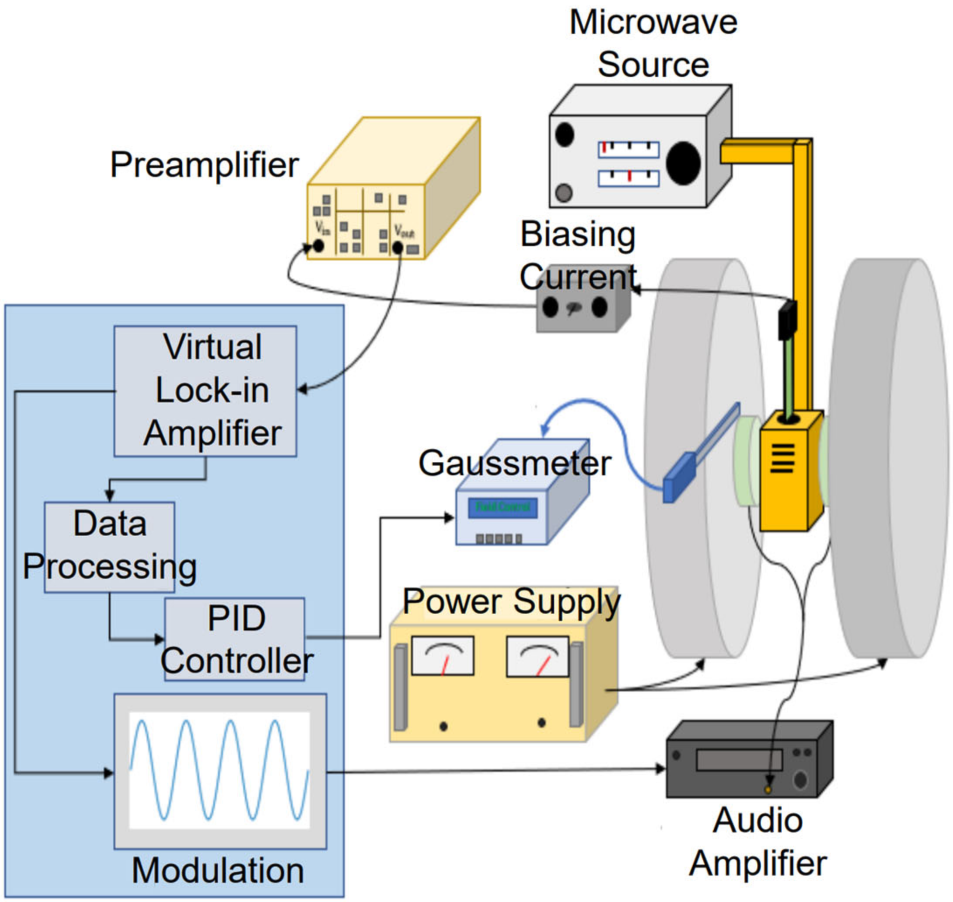
- Sensitivity: 10^{10} total paramagnetic defects.
- Cannot distinguish between defects which do and do not affect device performance



Typically expensive, bulky, high power requiring equipment.

EDMR

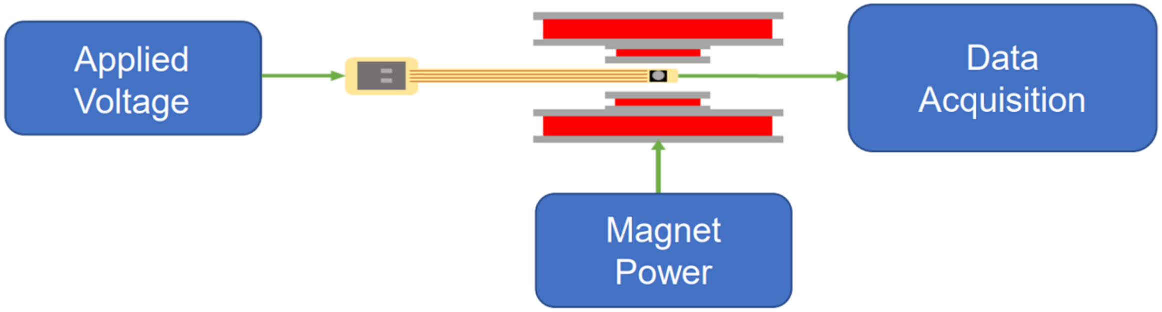
- Greatly improves sensitivity to 10^3 paramagnetic defects in device under study.
- Exclusively sensitive to defects which affect device performance.
- Some capability for identifying the physical location of those defects.



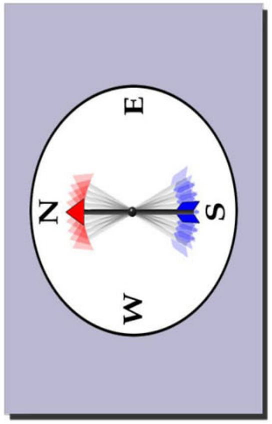
Typically expensive, bulky, high power requiring equipment.

Near Zero Field Magnetoresistance Spectroscopy

- New technique has much of the analytical power of EPR/EDMR but requires a very simple, inexpensive apparatus which can be directly coupled to widely utilized electronic characterization gear.



Background Physics EPR



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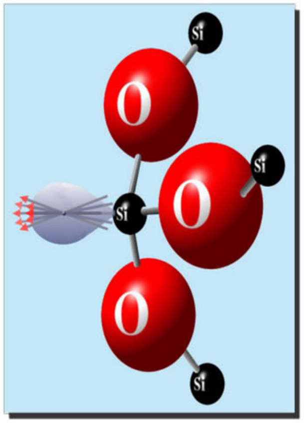

Natural oscillation frequency depends on what field the compass needle sees

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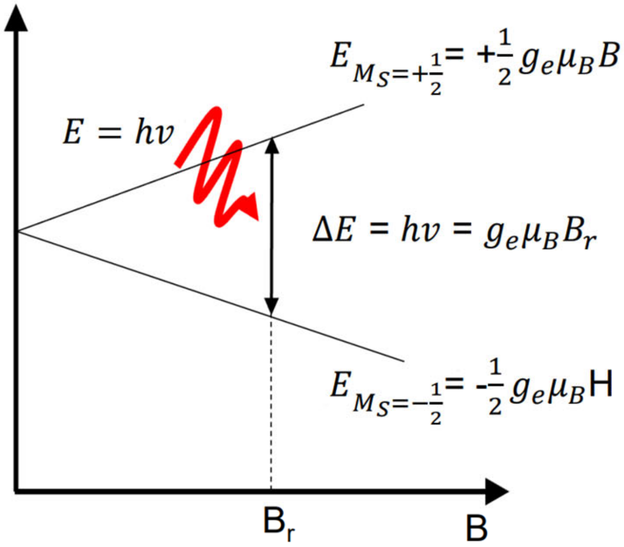
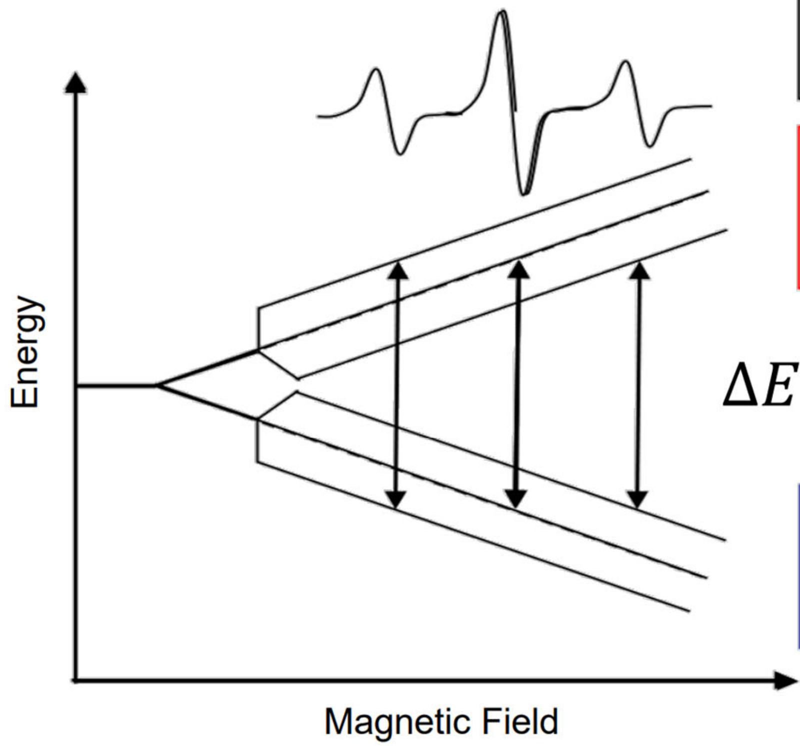
Unpaired electron same story but here local field influenced by surrounding

Spins are "flipped"



Background Physics EPR



Deviations from the resonance condition provide useful information about the nature of specific defects

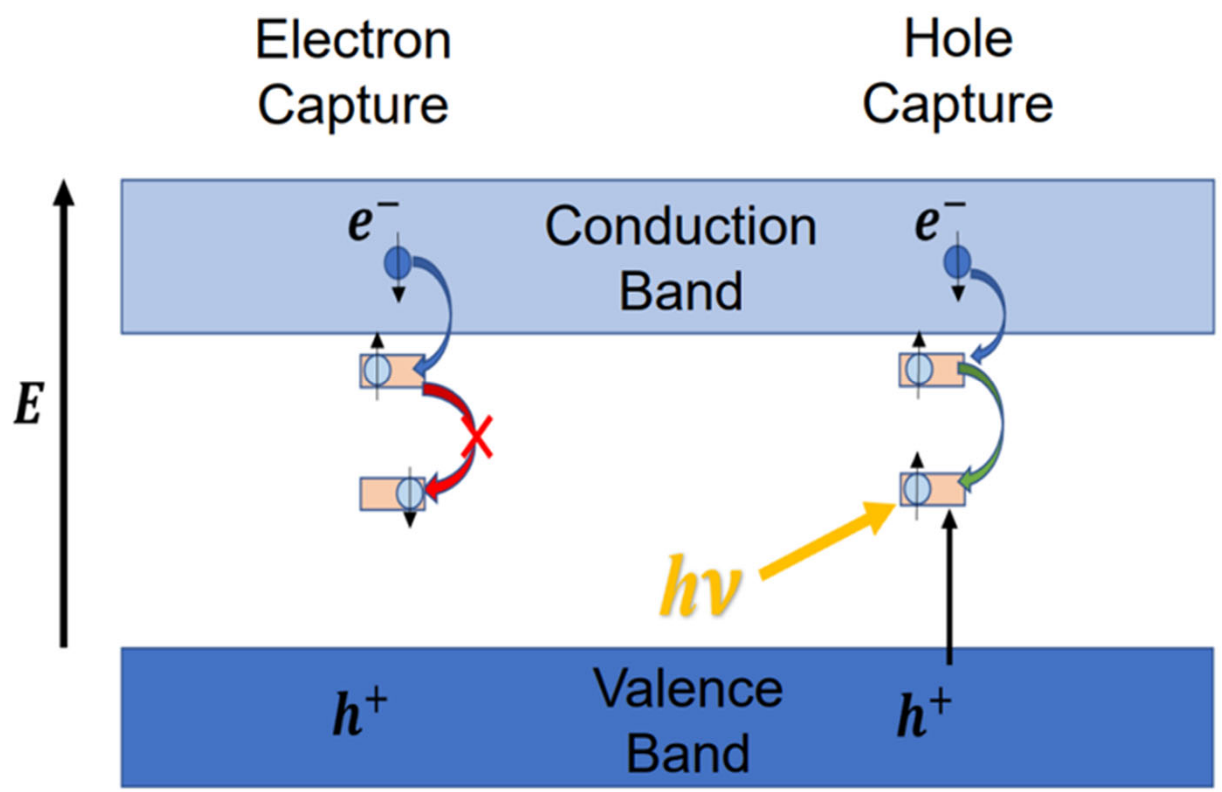
Spin-Orbit Coupling: due to the electron's orbital angular momentum about the nucleus

$$\Delta E = hv = g\,\beta H + m_I A$$

Electron-Nuclear Hyperfine Interaction: due to nearby nucleus with magnetic moment

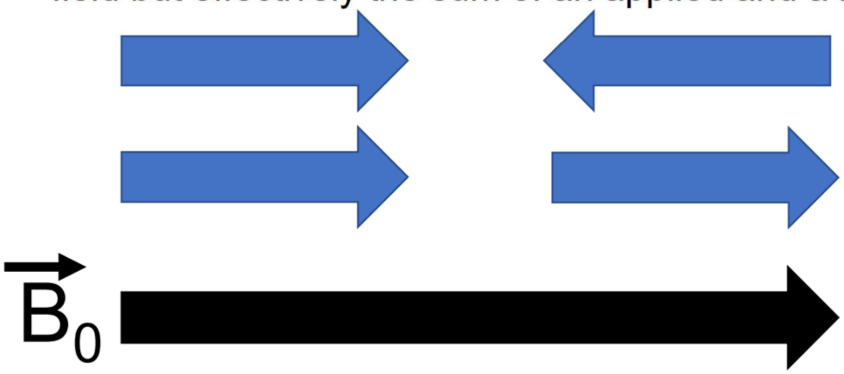
At resonance, <u>spin</u> flips

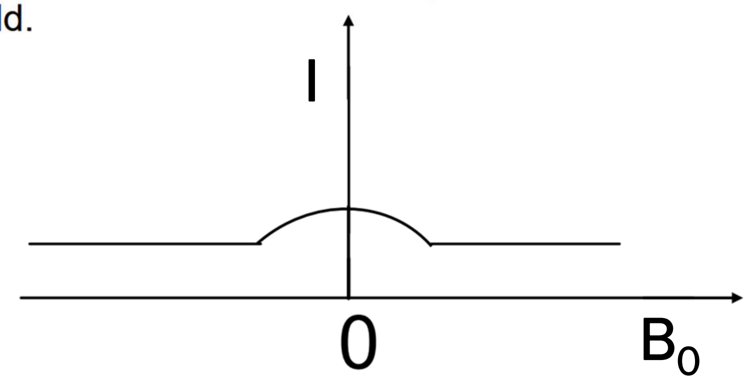
EDMR: Spin Dependent Recombination (SDR)



Basic Physics NZFMR

- The energy of a magnetic moment (u) in a magnetic field (B0) is equal to –μ·B.
- The energy of 2 magnetic moments pointing in the same direction is -2μ·B.
- The energy of 2 magnetic moments pointing in opposite directions is 0.
- The only case in which the 2 possibilities will yield the same energy is when the magnetic field is 0
- When the states have the same energy, they can be mixed.
- This mixing of states has a similar effect to resonance in EDMR (renders forbidden event allowed).
- We need to think about the magnetic field at the site of the spins. This is not simply the applied field but effectively the sum of an applied and a local field.





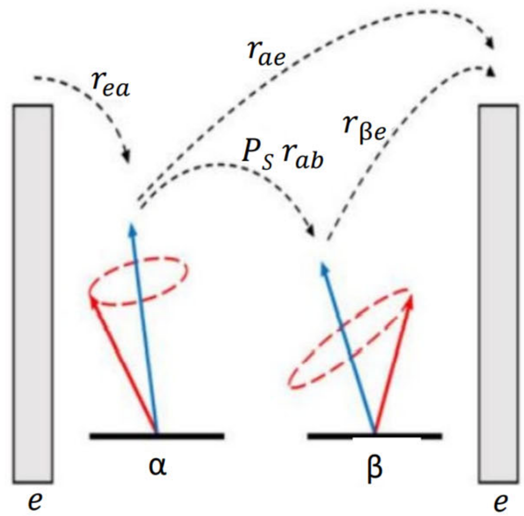
Stochastic Quantum Liouville Equation (SQLE): Interpreting NZFMR

- Most readily understood through Wagemens' two-site model for carrier transport, as adapted by Harmon, Flatte et. al:
- The density-matrix can be expressed as:

$$0 = -\frac{i}{\hbar}[\boldsymbol{\mathcal{H}}, \boldsymbol{\rho}] - \frac{1}{2}(r_{ab} + r_{ae})\{\boldsymbol{\Lambda_S}, \boldsymbol{\rho}\} - \frac{1}{2}r_{ae}\{\boldsymbol{\Lambda_T}, \boldsymbol{\rho}\} + \frac{1}{16}r_{ea}\boldsymbol{\Gamma}$$

- For the steady-state condition, the four spin states can be represented by the Hamiltonian:

$$\boldsymbol{\mathcal{H}} = g\mu_B(\boldsymbol{S_1} + \boldsymbol{S_2}) \cdot \boldsymbol{B} + a_\alpha(\boldsymbol{S_1} \cdot \boldsymbol{I_\alpha}) + a_\beta(\boldsymbol{S_2} \cdot \boldsymbol{I_\beta})$$

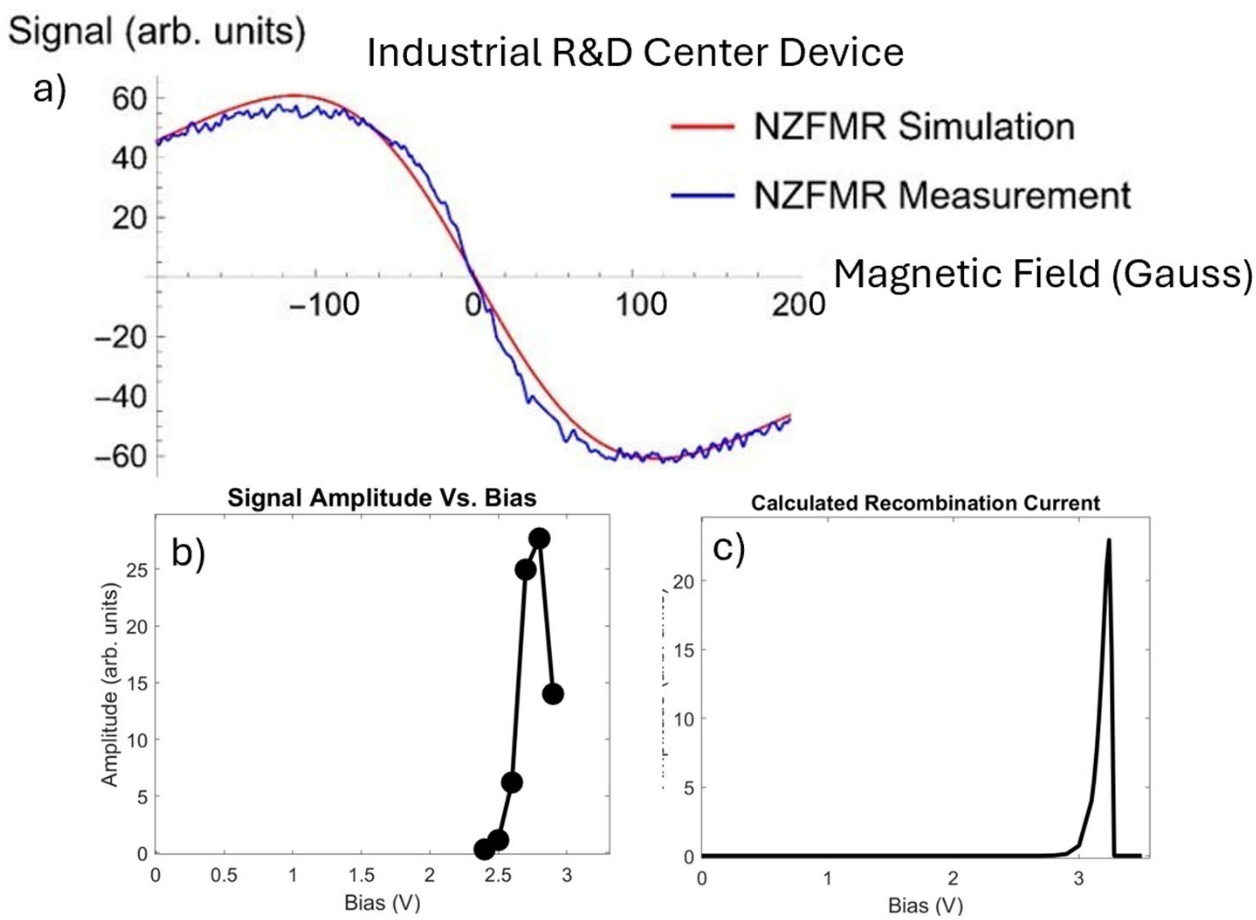


W. Wagemans, F. L. Bloom, and P. A. Bobbert, "A two-site bipolaron model for organic magnetoresistance," *J. Appl. Phys*. vol. 103, no. 7, Sep. 2007.

N. J. Harmon and M. E. Flatté, "Spin-Flip Induced Magnetoresistance in Positionally Disordered Organic Solids," Phys. Rev. Lett., vol. 108, 186602, 2012.

N. J. Harmon, M. E. Flatté, "Effects of Spin-Spin Interactions on Magnetoresistance in Disordered Organic Semiconductors," Phys. Rev. B, 245213, 2012.

Last year's results



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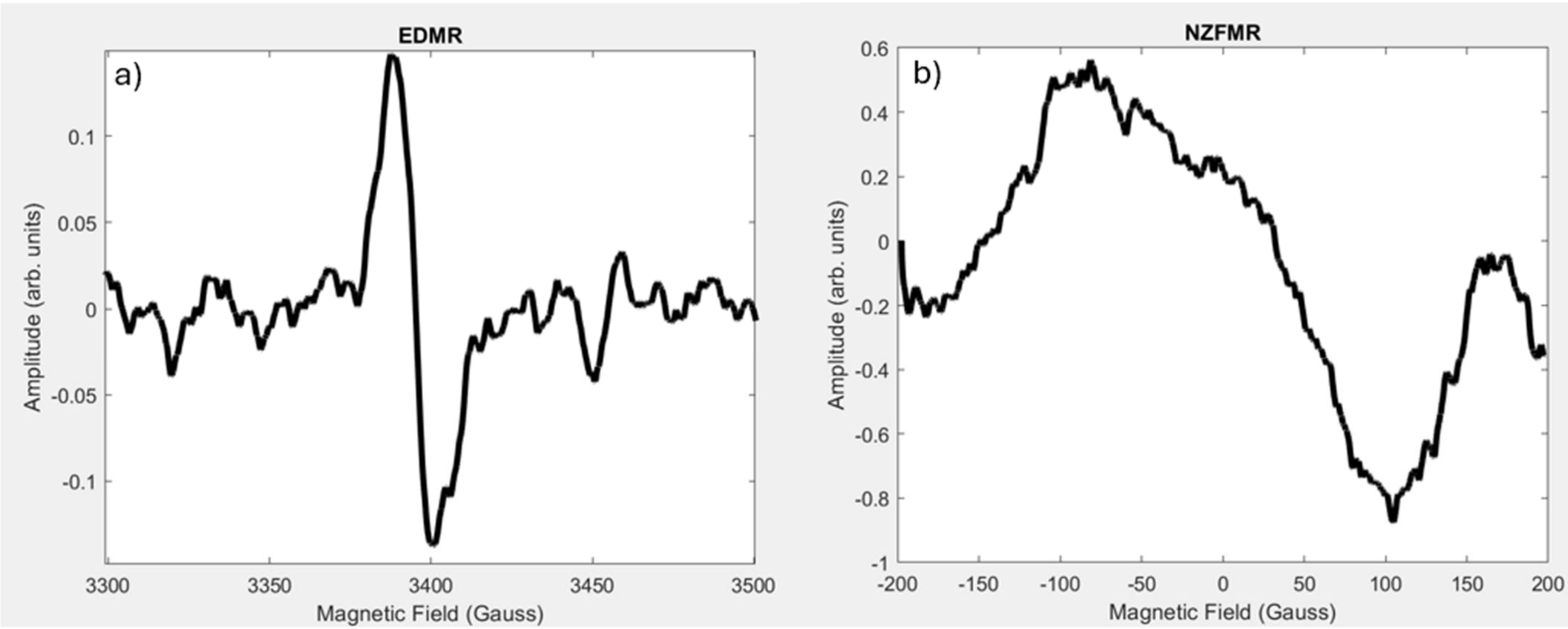
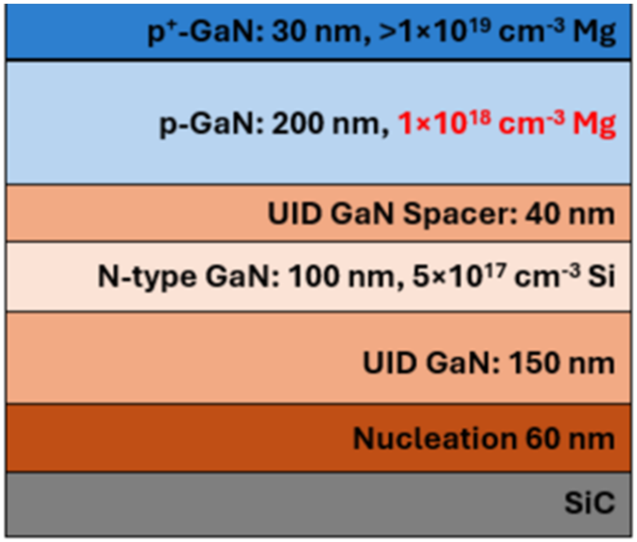
Earlier Penn State Devices



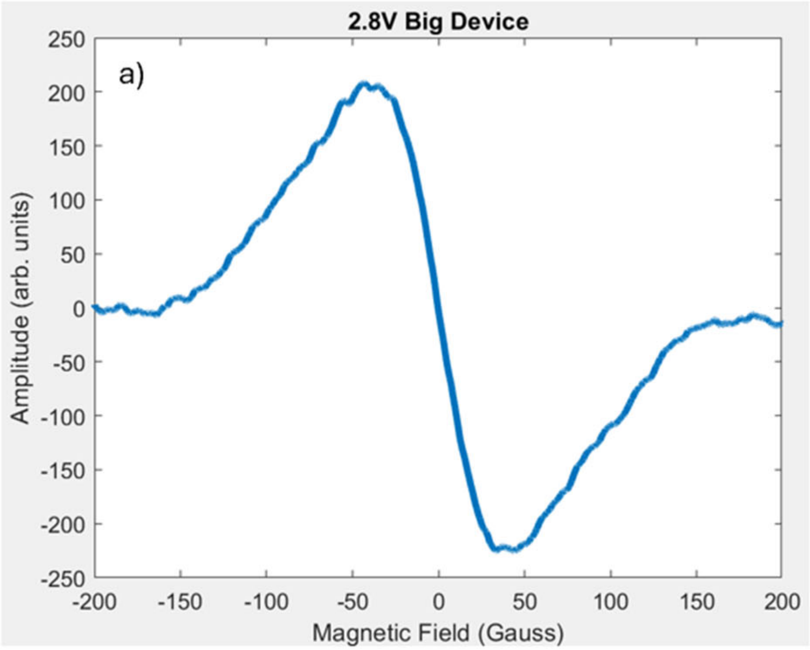
We show a) an EDMR response and b) an NZFMR response on a GaN pn junction diode fabricated by Dr. Chu's group.

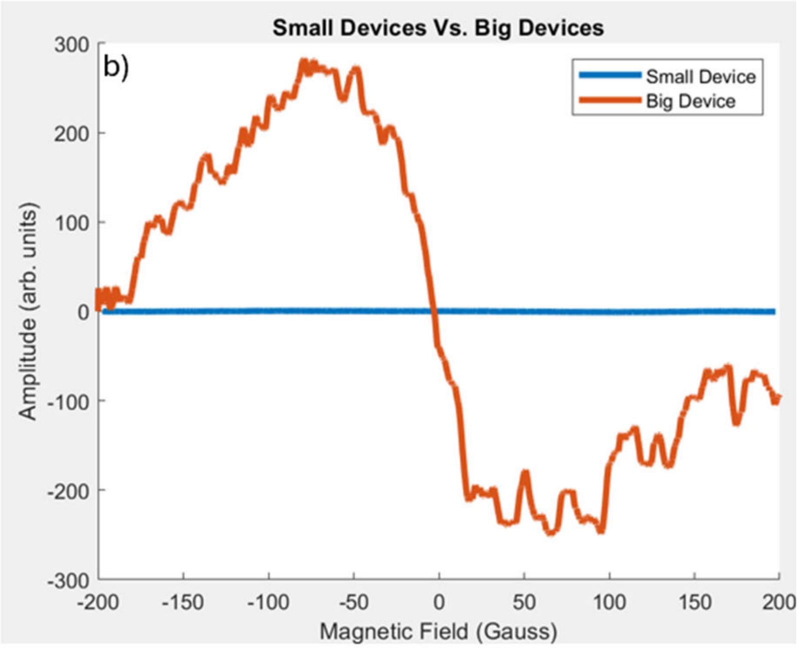
New Penn State Devices



A block diagram schematic of the layers of the structure under test. There are also doping concentrations and thicknesses listed,.

New Penn State Devices

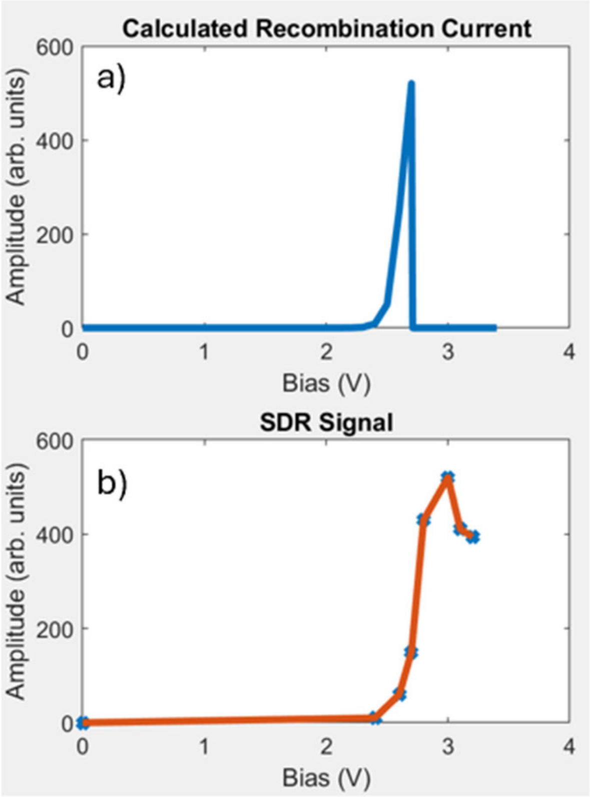




In a), we show an NZFMR response on a much larger device recently provided by Dr. Chu's group. The cross-sectional area of this device is about 1mm^2. In b), we illustrate a comparison between the measurements in the new larger devices and the earlier smaller device provided by Dr. Chu's group.

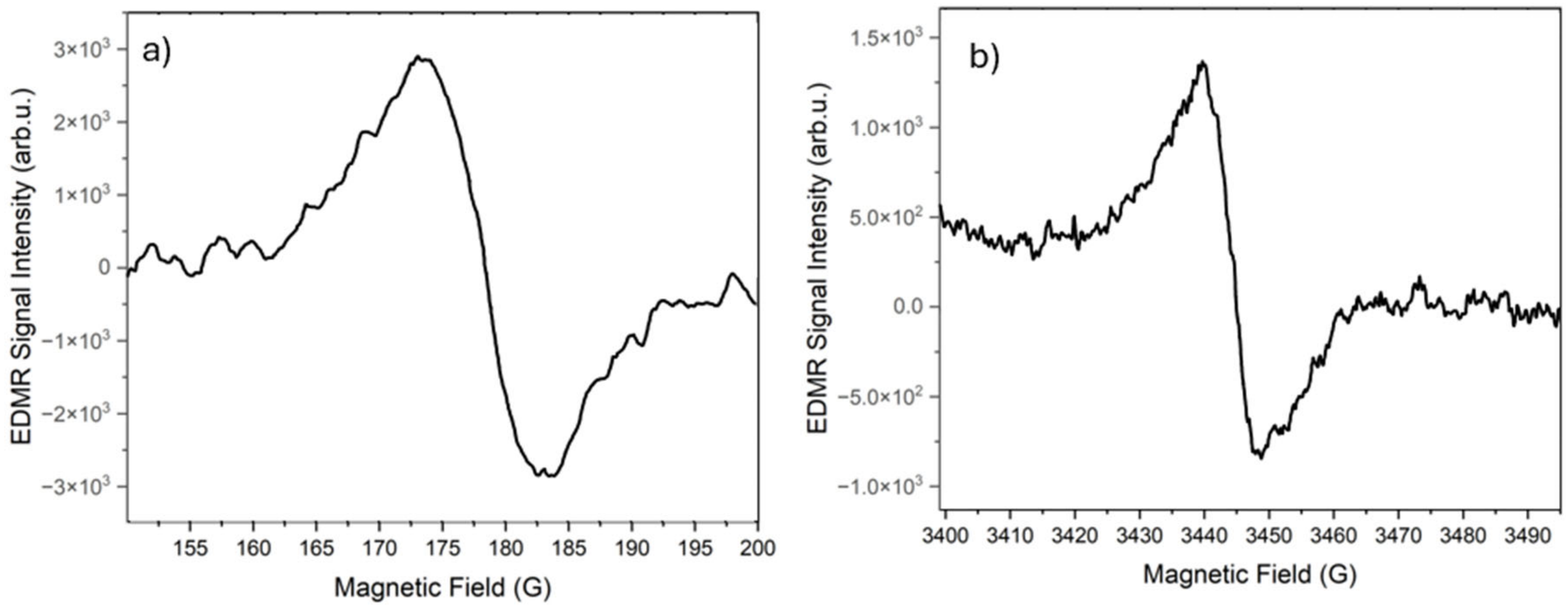
The two traces were chosen to match as closely as possible spectrometer settings and device biasing conditions.

New Penn State Devices



Calculated recombination current (a)) compared to measured SDR response (b)).

GaN Schottky Diode EDMR (from Suzanne Mohney)



We show EDMR responses on a GaN Schottky diode at a) low field (498MHz) and b) high field (9.626GHz).

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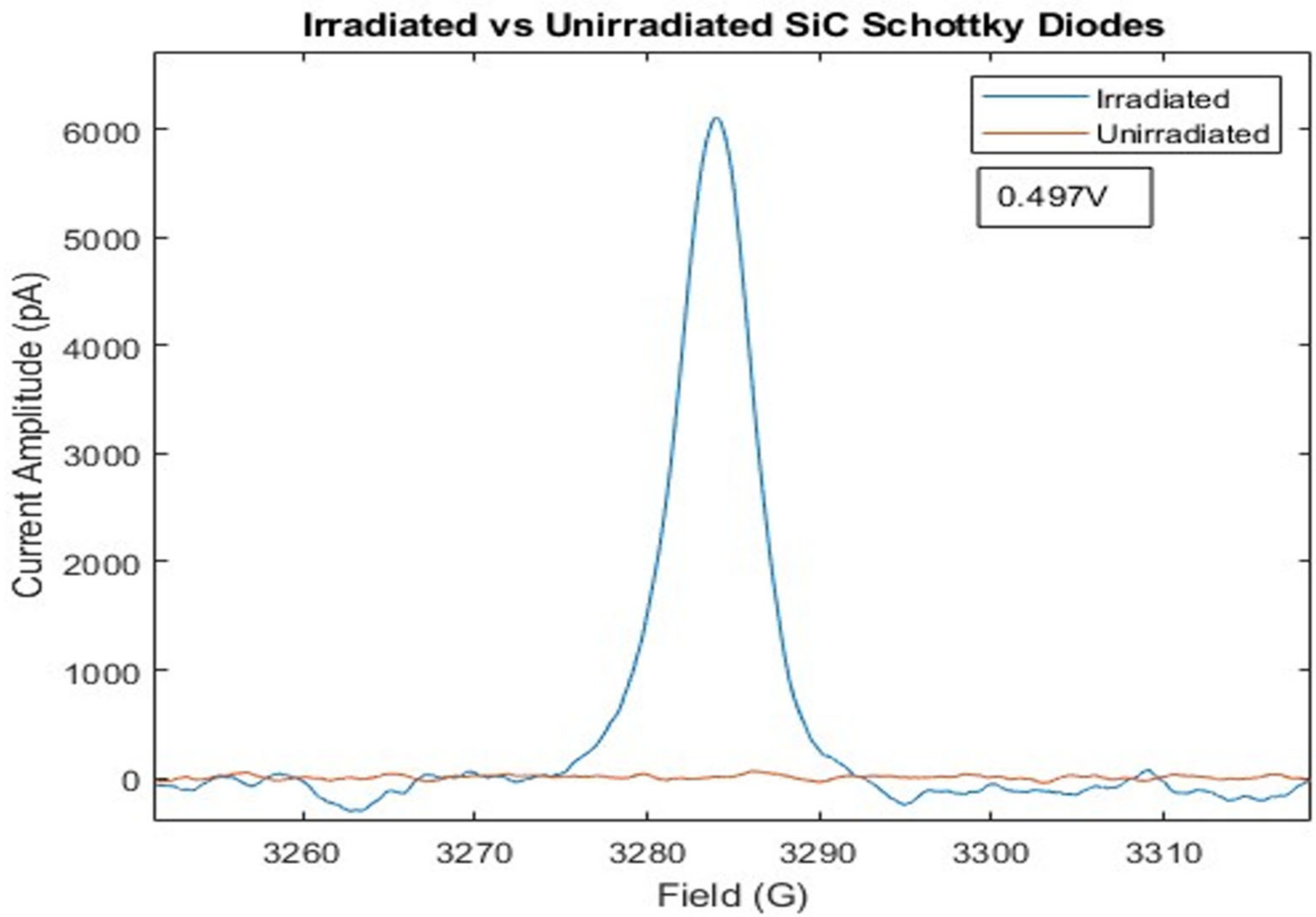
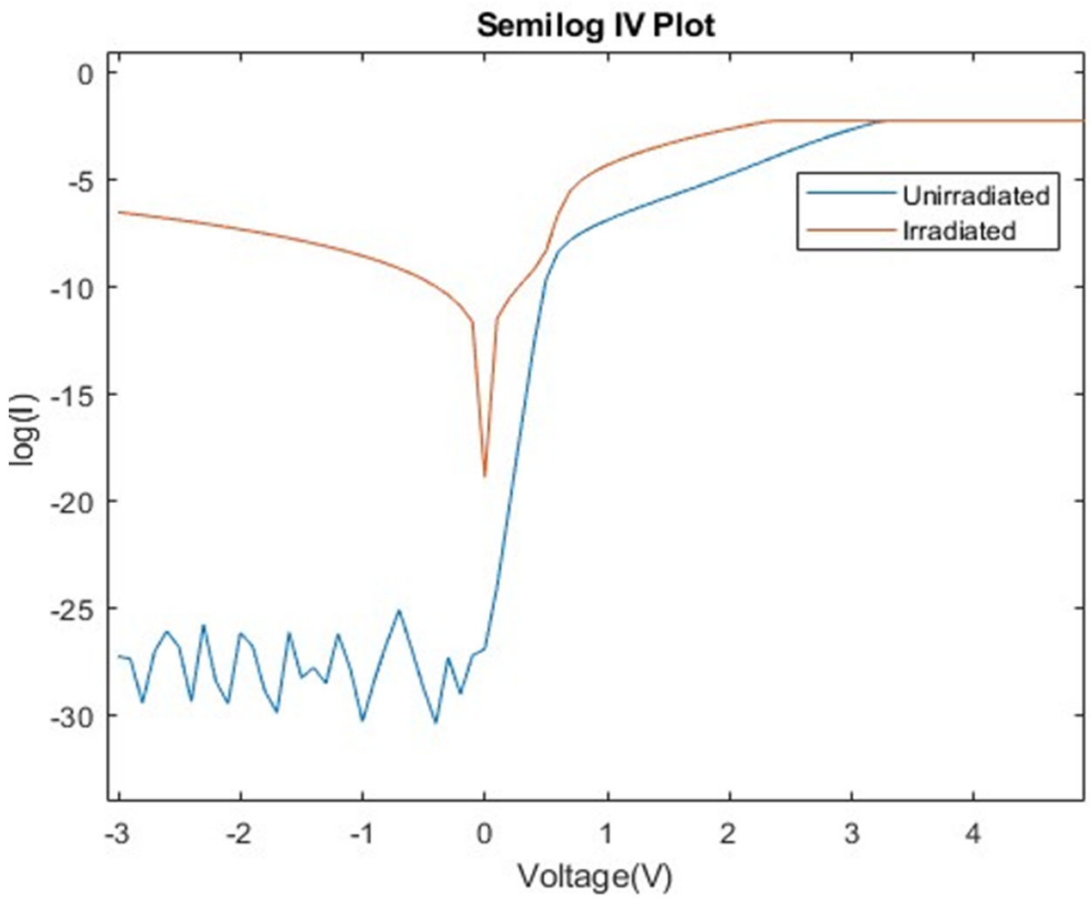
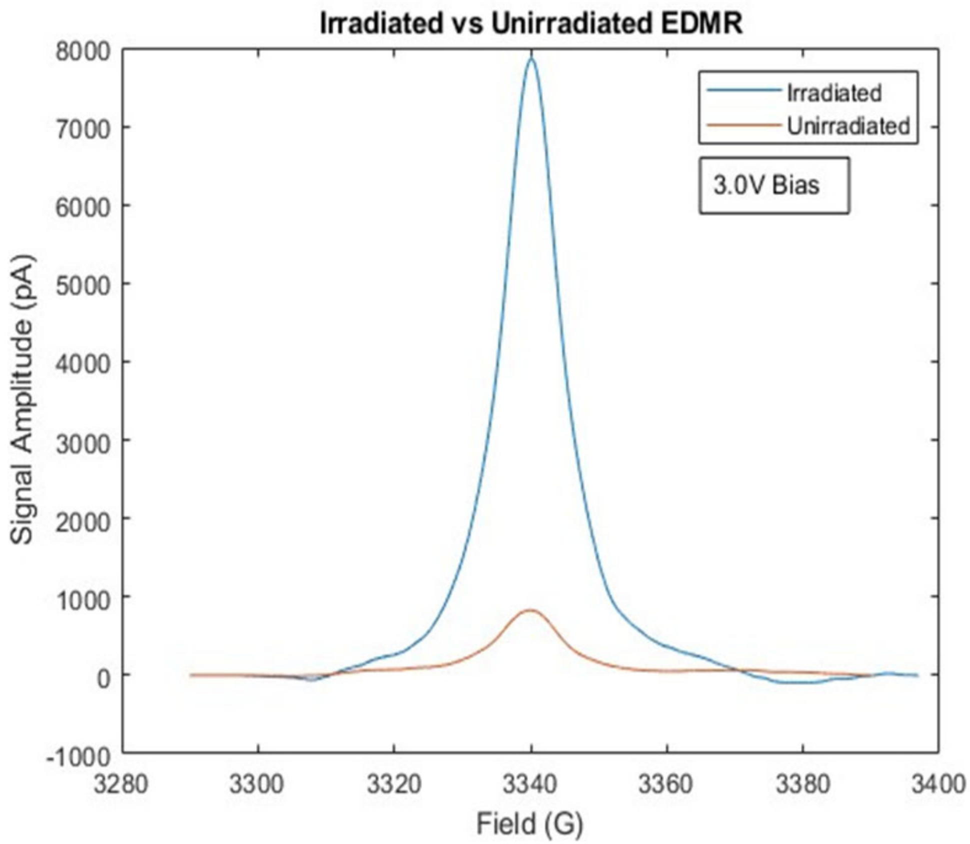
EDMR comparison. Note the very high signal to noise ratio



SiC Shottky


Semilog IV Plot
0
-5
-10
-15
-20
-25
-30
log(I)
-3
-2
-1
0
1
2
3
4
Voltage(V)
Unirradiated
Irradiated

Proton bombarded pin (from NASA)



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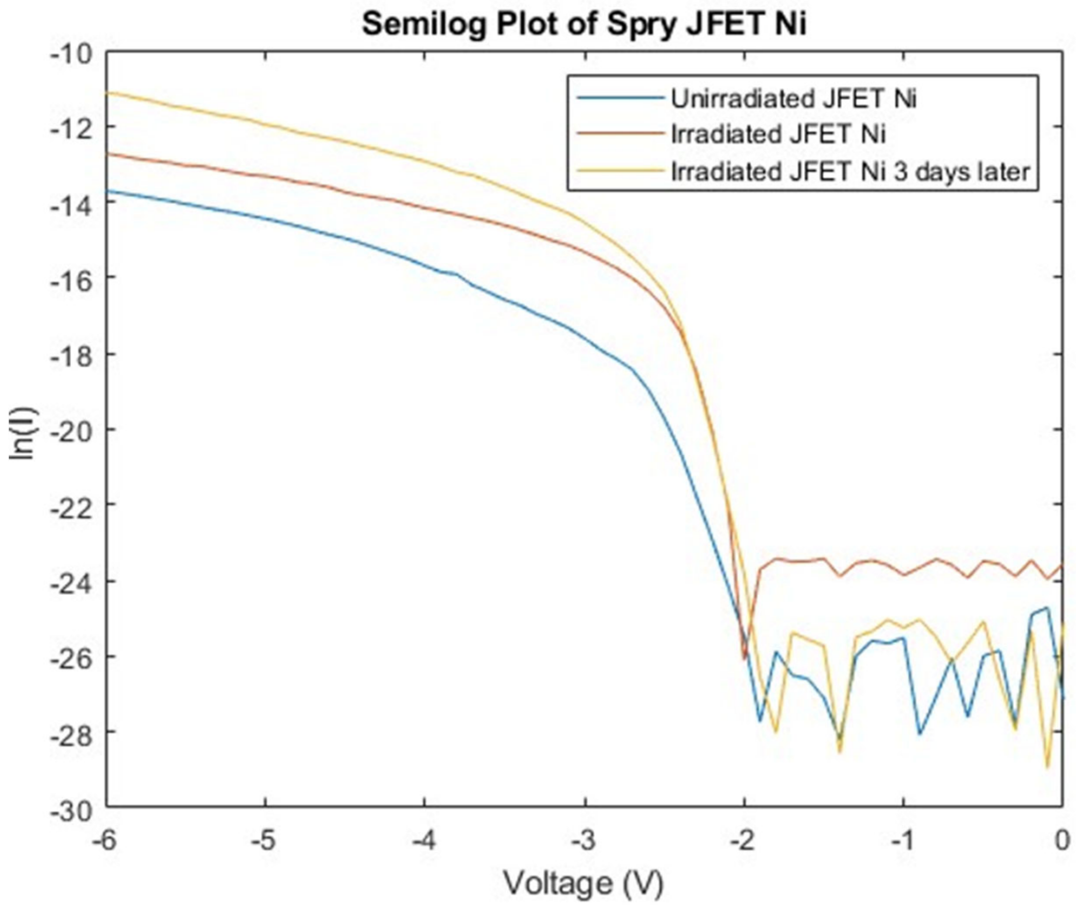
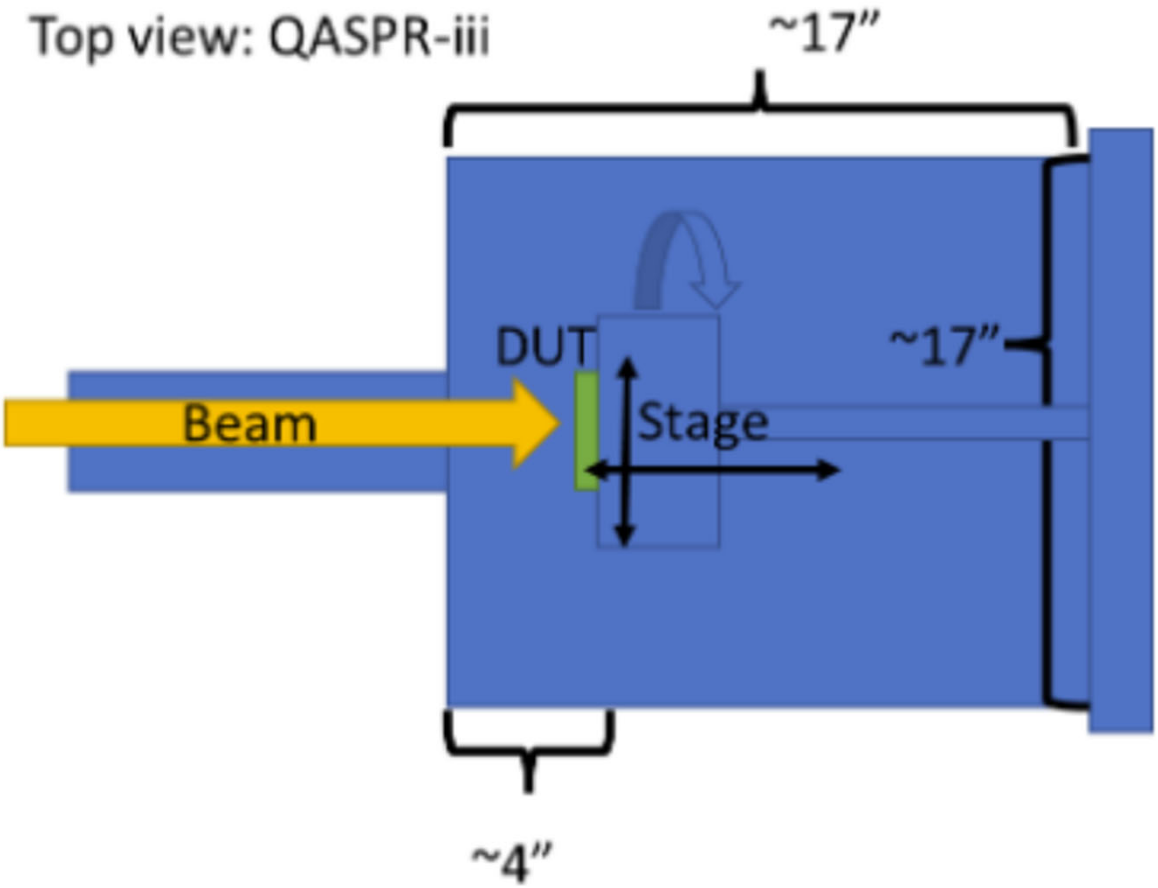
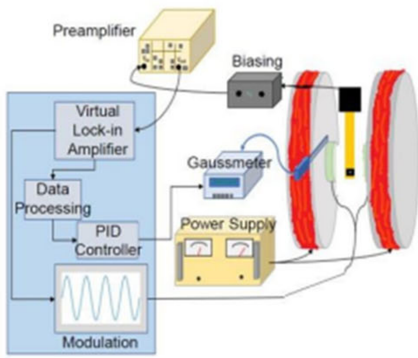
Proton bombarded pin (from NASA)



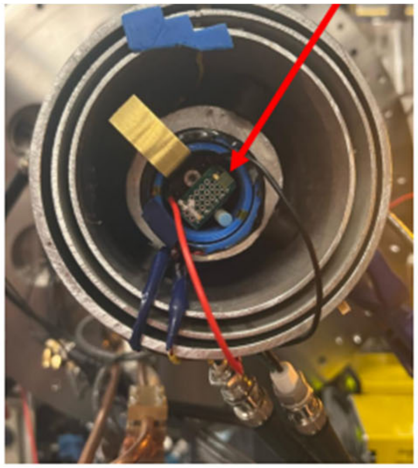
In situ NZFMR



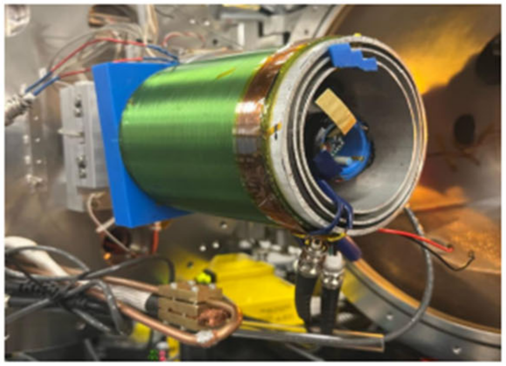
In situ NZFMR



Schematic for NZFMR Spectrometer



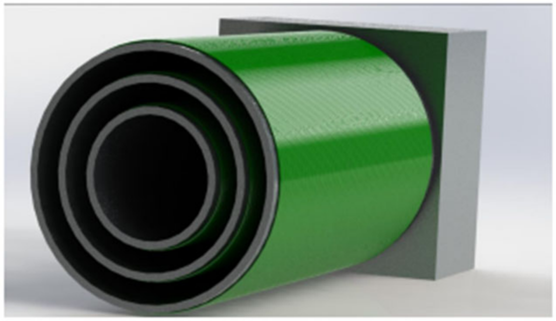
Diode in Spectrometer



Solenoid Spectrometer on Chamber Door

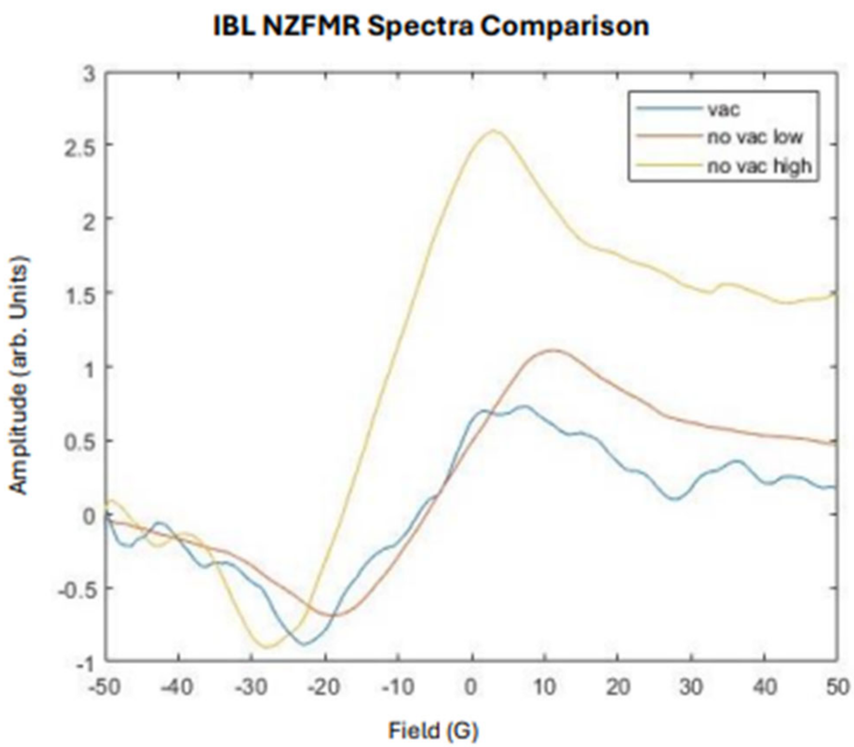
Diode Under Microscope

In situ NZFMR



Early rendering of new solenoid spectrometer used in CFD simulation.
Base 2.5”
Length 5.5”

Preliminary Results from In Situ Spectrometer



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Conclusion:

NZFMR approach works!