Device-Level Electrical Characterization Using Ferromagnetic Resonance of Magnetic Multilayers

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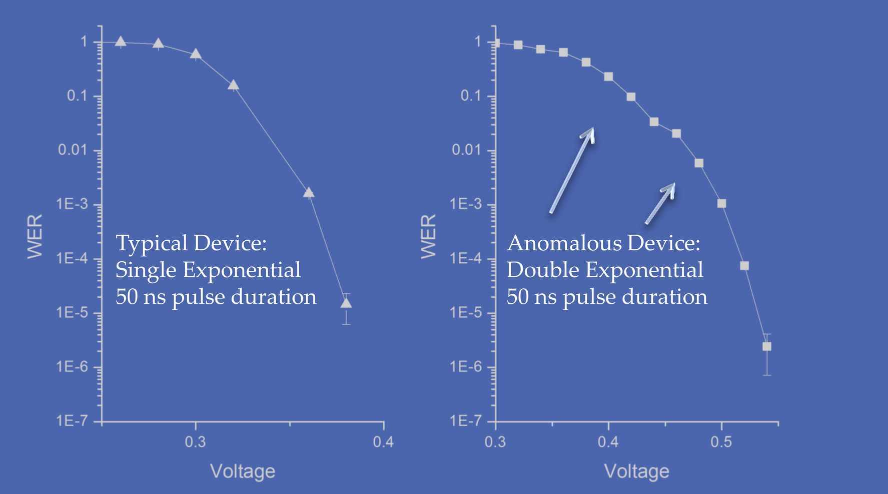
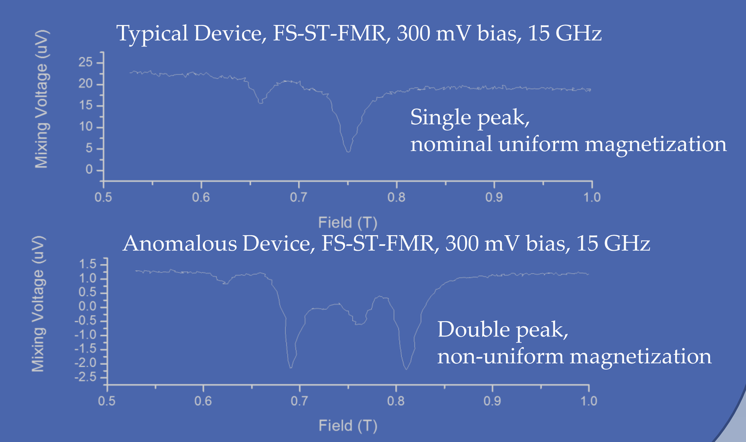
Problem:

- Small fraction of MRAM devices have anomalous or ballooning write error rate (WER)
- Previously could only be identified by switching devices millions of times
- Physics that causes anomalous WER tail not understood



Solution:

- Use rapid FMR spectra to identify candidate devices
- Spend time thoroughly studying devices that help understand new physics
- FMR spectra indicate that anomalous devices strongly deviate from uniform magnetization reversal

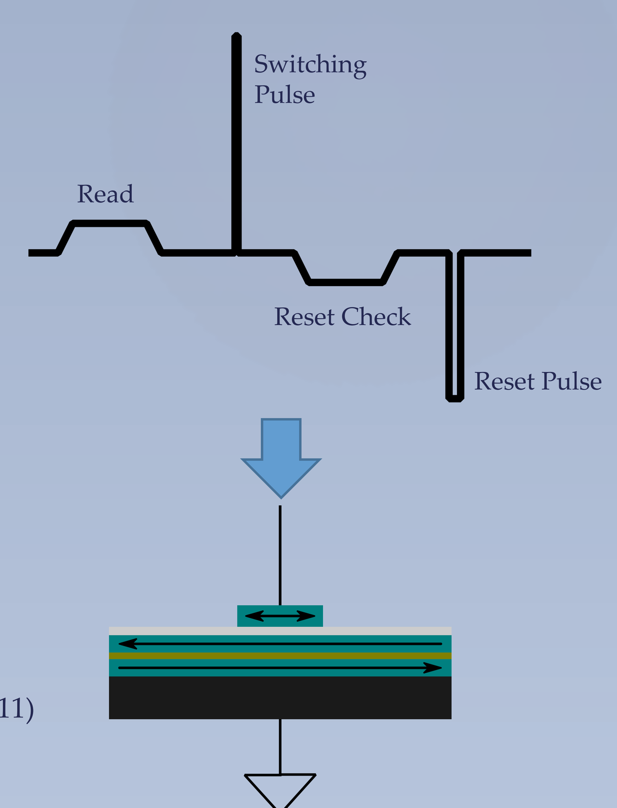


Write Error Rate (WER) Measurements

- Reset nanopillar to known state with long pulse (typical 400 ns, 0.4 V)
- Read state with small bias voltage (test for bad reset)
- Attempt to switch nanopillar with 5-100 ns long pulse at voltages ranging 0.2-0.7 V
- Read state with small bias voltage (test for switching/no switching)
- Generate WER at each voltage/duration pair:

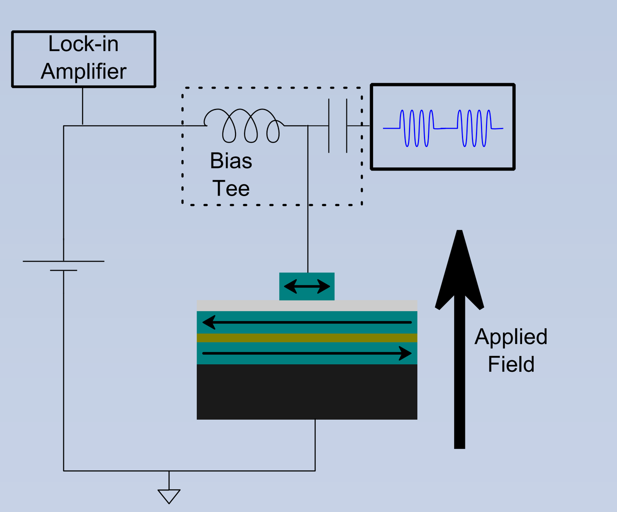
$$WER = 1 - \frac{\#\,Switched}{\#\,Trials}$$

- Typical data set down to ~10^{-6} error rate takes ~6 hours to collect



R. Heindl, W.H. Rippard, S.E. Russek, and A.B. Kos, PRB, **83**, 054430 (2011)

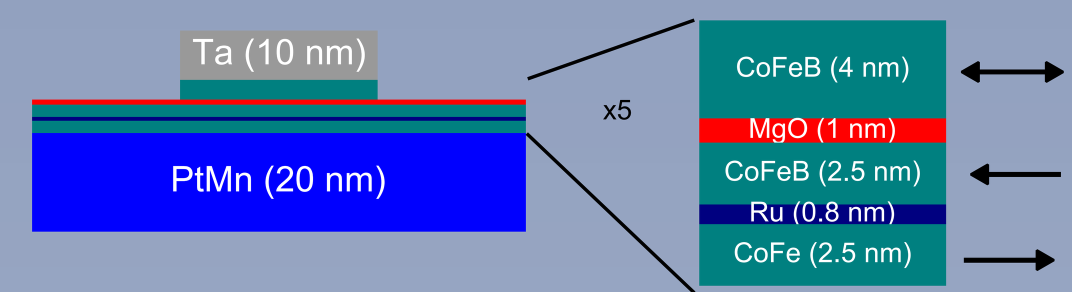
Field-Swept Spin-Torque Ferromagnetic Resonance Measurements (FS-ST-FMR)



- Inject chopped microwave signal at fixed frequency
- Measure rectification voltage as a function of applied magnetic field with lock-in amplifier
- Adjust output microwave amplitude to deliver constant microwave power to the device with frequency
- Repeat at various DC bias currents
- Full bias dependence shown below takes ~50 minutes to collect

E.R. Evarts, M.R. Pufall, and W.H. Rippard, JAP, **113**, 083903 (2013)

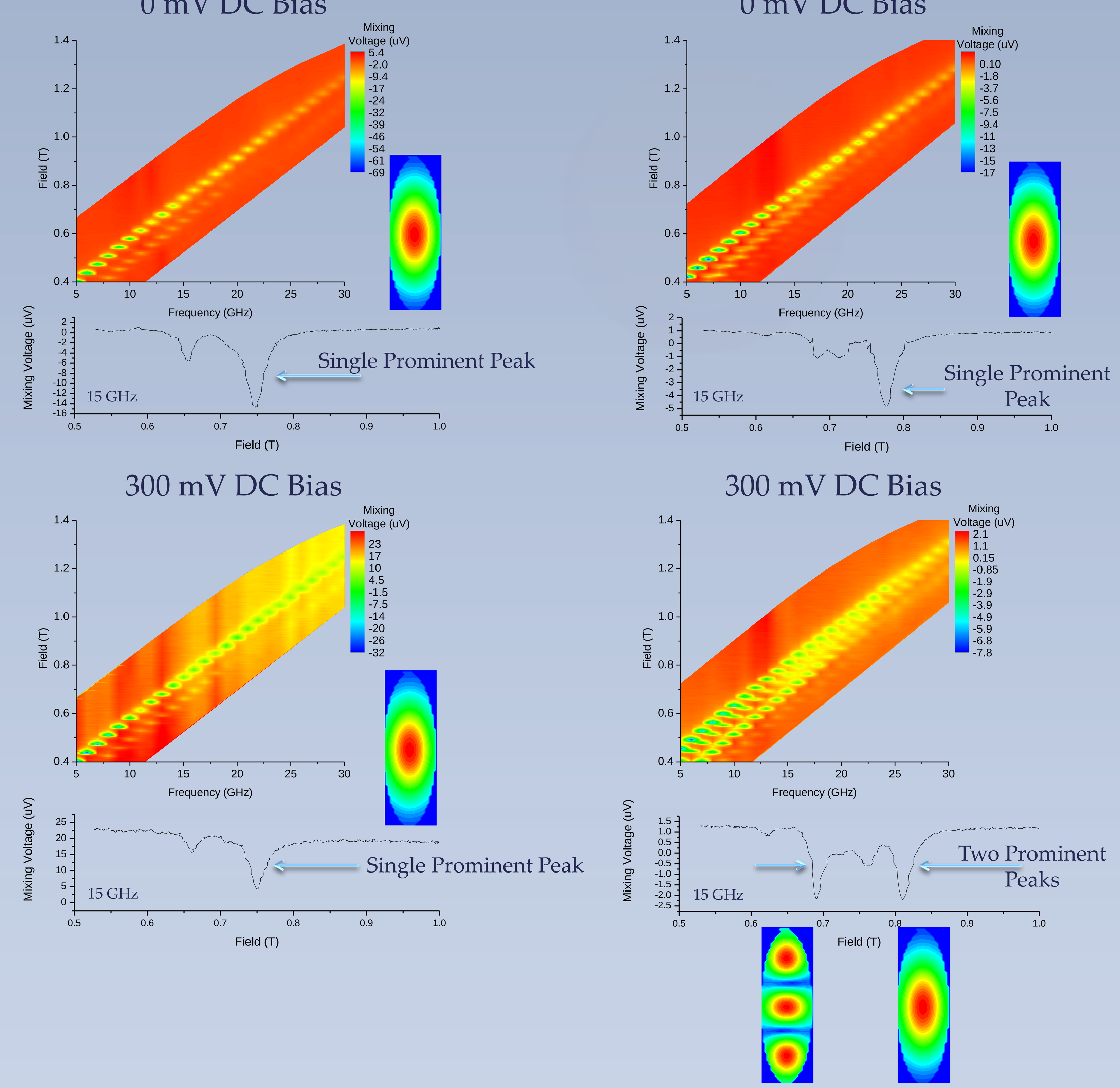
Device Details



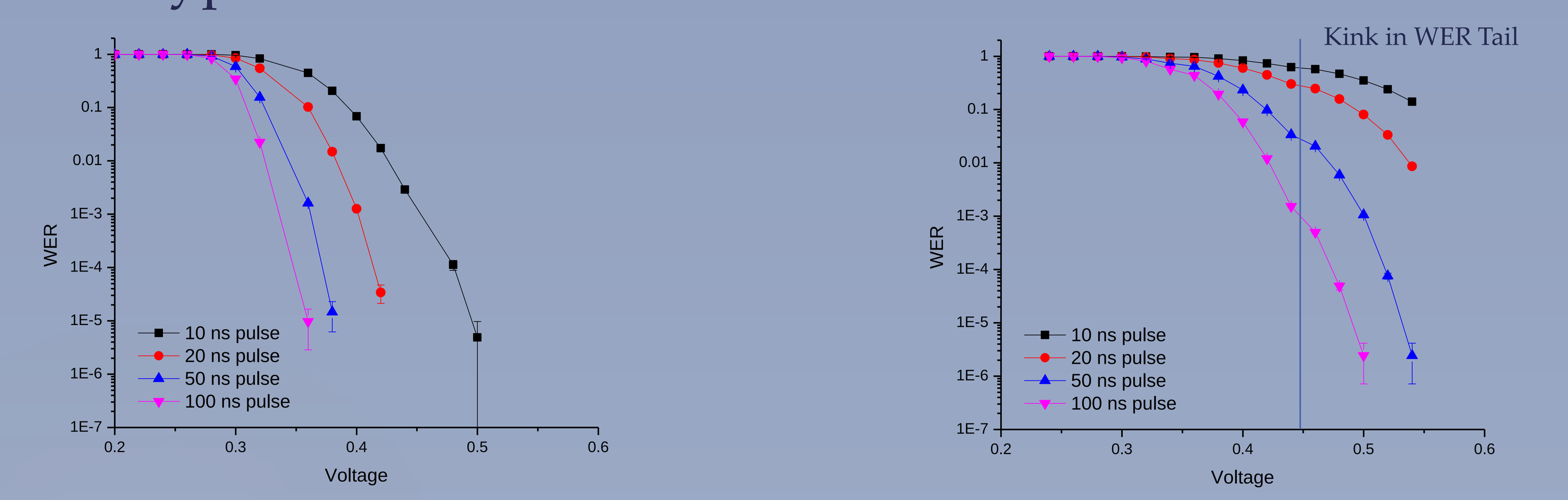
- RA = 3 Ω-μm^2
- TMR = 70%
- Quasi-DC switching voltage = 0.4 V
- Nanopillars etched down to tunnel barrier via argon ion milling
- Typical dimensions:
  - 50 nm x 150 nm
  - 60 nm x 180 nm
  - 70 nm x 210 nm
  - 100 nm x 200 nm
- Results tested on over 20 devices
- Similar results from 7 different films

FS-ST-FMR Spectra

- FS-ST-FMR spectra recorded at different DC bias currents
- Bias current chosen corresponding to bias voltages in the parallel state at $\mu_0 H = 0$ T
- At bias near onset of anomalous behavior, unique signature observed



Typical vs. Anomalous WER



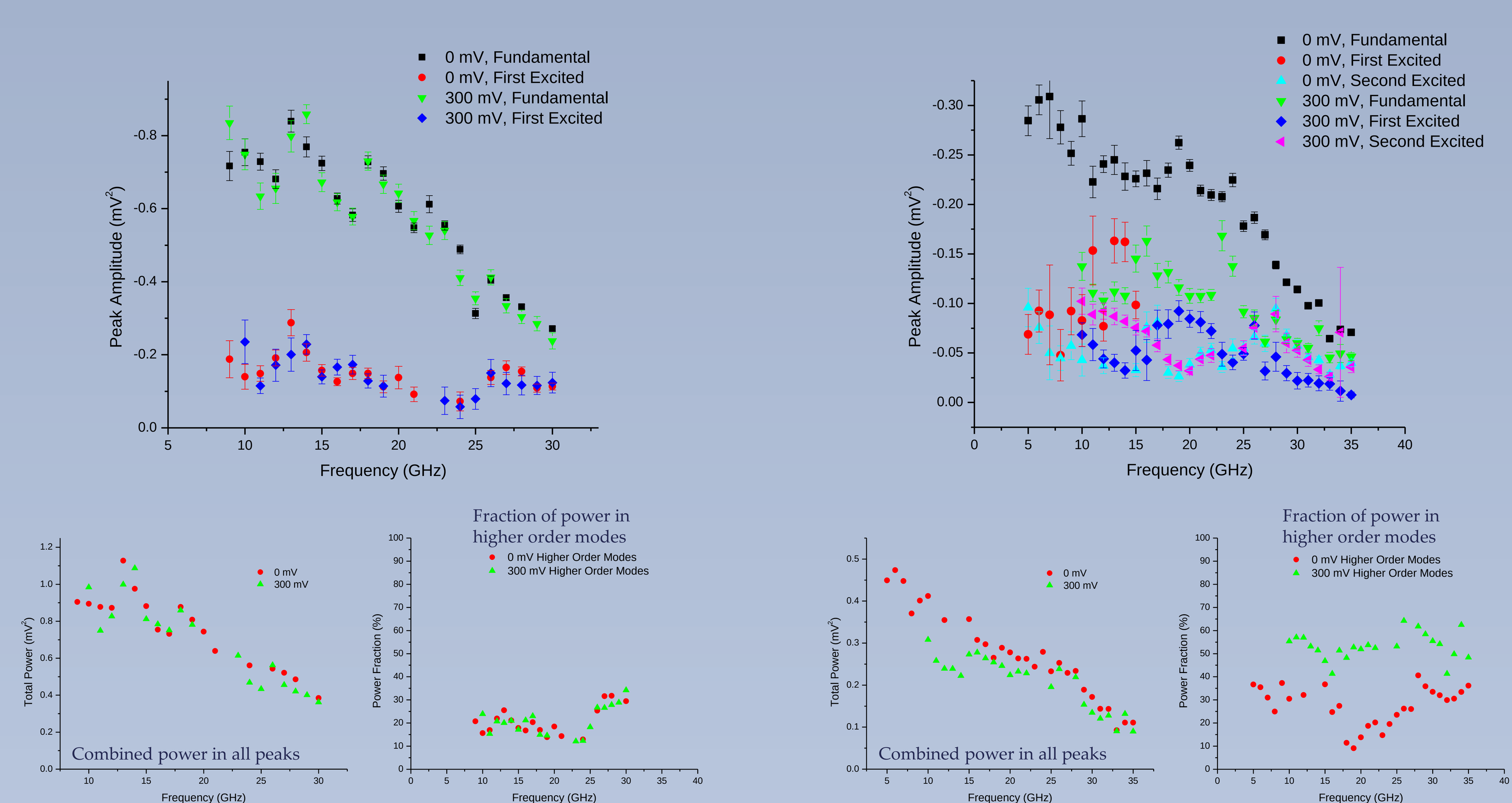
Typical Device

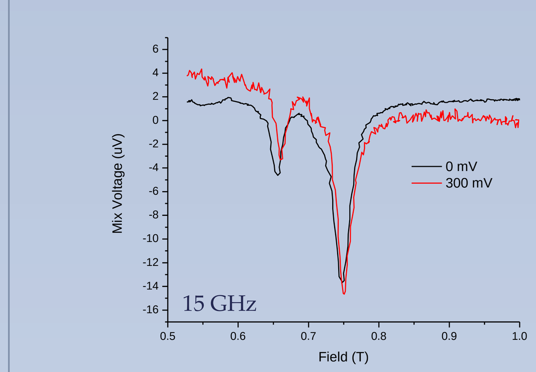
- For each pulse duration, WER decreases (single) exponentially with increasing pulse voltage
- Shift towards quasi-static switching voltage with longer pulse duration

Anomalous Device

- For each pulse duration, WER decreases with double exponential or more complex character
- Typically appears as kink in WER tail
- Overall, shallow slope compared to typical devices

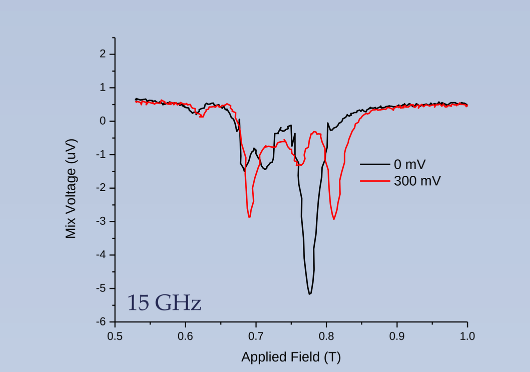
Resonance Peak Analysis





In anomalous devices as bias increases:

- Power shifts into higher order modes
- Resonance fields increase



Conclusions

- Anomalous WER seen in ≈10% of devices
- Devices with anomalous WER tails can be predicted using FS-ST-FMR with DC bias near the onset conditions for the WER anomaly
- FS-ST-FMR measurements (minutes) are orders of magnitude faster than WER measurements (hours)
- Prominent second peak detected in FS-ST-FMR spectra for anomalous devices
- Second peak suggests non-uniform magnetization reversal
- Higher order resonances can account for up 70% of the total power in anomalous devices

Acknowledgments

Special thanks to Everspin Technologies for providing the thin films used in this work. Thanks to S. Russek and A. Kos for fruitful discussions.