Microwave Measurements of Spintronic Devices

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Outline

Ferromagnet-based Spintronics.
  • **Ferromagnets**: Spin filters
  • **Spin torque**: Fundamental interaction between spin current and ferromagnet

Device-level microwave measurements: Probe of structure/function.
  • **Spin torque MRAM**
    • Correlate error rates to spectral behavior
  • **Spin Torque Oscillators**
    • Phase locking, frequency noise
    • STOs as local probes of magnetization

Outlook & Future Challenges.
Spin Transfer: Angular Momentum Absorption

Incident $e^-$ current

Absorbed angular momentum: **Torque**

Polarizing layer (thick): “Fixed”

Active layer (thin): “Free”

Transmitted $e^-$ spins

Newton’s Third Law: Reaction torque on $\mathbf{M}$; Depends on sign of $I$

Complementary effect: GMR
Magnetization Dynamics: Spin Torque

\[ \frac{d\vec{m}_1}{dt} = T_{\text{Larmor}} + T_{\text{Damping}} + T_{\text{Spin Transfer}} \]

- Larmor term: precession
- Damping term: aligns \( M \) with \( H \)
- Spin torque can counteract damping!

Spin torque can counteract damping!

Nanoscale effect: larger at smaller length scales

\[ T_{\text{Spin Transfer}} \approx T_{\text{Damping}} \]

\[ J \sim 10^7 \text{A/cm}^2 \]

Slonczewski, 1996
What does Spin-torque do?

Sign of torque depends on direction of current flow: causes **motion of the magnetization**, depending on the magnetic configuration.

Bistable device (small fields): **Current-induced switching**

Monostable device (high fields): **Current-tunable Coherent magnetization precession**

...fundamentally new way to manipulate magnetization
Spin torque Magnetic RAM.

...Potential nonvolatile RAM: Need to determine details of switching

"Nanopillar" Schematics:

- Free layer
- Fixed layer (SAF)

Current

- CoFeB (4 nm)
- MgO (1 nm)
- CoFeB (2.5 nm)
- Ru (0.8 nm)
- CoFe (2.5 nm)
- PtMn (20 nm)

- Tunnel junctions: large MR (70%) & spin polarization
- Measure write error rate (WER) for large numbers of events: compare to two state (single domain) model
- Also can measure real-time switching trajectory ($R$ vs. $t$)
ST-MRAM: Write Error Rate Variations

Typical Device

• Largely follows single exponential expected from single domain
• Shorter pulses require higher voltage to achieve same error rate

‘Anomalous’ Device

• Deviates from single exponential at higher biases
• Evidence of non-single domain behavior?
ST-MRAM: Resonance Spectra

**ST-ferromagnetic resonance (ST-FMR):**
- Inject AC current, measure device response vs. $f, H$
- Determine resonant modes of device

**Typical Device**

```
-69
-61
-54
-46
-39
-32
-24
-17
-9.4
-2.0
5.4
```

**Anomalous Device**

```
-17
-15
-13
-11
-9.4
-7.5
-5.6
-3.7
-1.8
0.10
```

- ‘Typical’ and ‘anomalous’ devices have similar spectra at low bias
  - Implies similar physical structures

*Mode patterns determined with OOMMF micromag. simulator (oommf.nist.gov)*
ST-MRAM: Spectra vs. Voltage Bias

Spectra of anomalous devices are function of voltage bias

- Higher order modes excited at high bias: become similar in magnitude to fundamental mode
- Deviation from single domain spectra: deviation of WER

*Linear response not solely responsible for variations: Requires measurements of full devices*

*Mode patterns determined with OOMMF micromag. simulator (oommf.nist.gov)
Spin Torque Oscillators

Current concentrated by electrical lead: Magnetization is unpatterned

Top electrical contact

Spin valve mesa

Applied field

θ

Applied field

“Free” layer

“Fixed” layer

Cu

~60 nm
Spin Torque Oscillators

Current concentrated by electrical lead: Magnetization is unpatterned

Top electrical contact

Spin valve mesa

- DC current induces microwave precession
- Frequency tunable with current
- Line widths in 1-100 MHz range

...STOs are nonlinear, current tunable oscillators
STOs: Metrology Challenges (i.e., Why?)

Quantifying **nonlinear coupling** of STOs via currents, fields, and spin waves, to enable **large-scale arraying**—e.g., bio-inspired NonBoolean architectures*

Understanding details of oscillations (line width, frequency, **phase noise**): dependence on **nanoscale** (magnetic) **structure**, defects, effects on phase locking

Measurements are of **magnetic devices** at nanometer scales, at frequencies >10 GHz

* Collab. with Intel, Notre Dame, Pitt., others
Injection Locking—CW microwaves

Inject AC spin current at \( f = 20.96 \) GHz, tune \( f_{osc} \): 

- Device locks to \( f/2 \) (= 10.48 GHz)
- Width of locking range (in frequency) depends on drive amplitude
Injection Locking: Time domain

- Scope trigger coherent with microwave source:
  - Any signal not coherent with microwaves will average to zero...
  - determine phase vs. frequency difference
Phase and Amplitude vs. Frequency Difference

- Phase changes as a function of DC bias
- Amplitude $\propto$ time device is locked.
- Even when partially “locked” the STO maintains well-defined phase with the injected signal: *Stochastic process*
Use a “pulse picker” to trigger scope and gate RF source
Microwaves are pulsed: 100 ns on and 900 ns off, to allow device decoherence (≈ 80 ns required)
**Time Required for Locking**

**Locking to Pulsed Microwaves**

- Consider “locked” when envelope reaches 90% of steady-state amplitude.

**Locking Time vs. RF Voltage**

- Locking can occur in a few 10’s of cycles.
- Locking time varies quasi-linearly with RF.
- Consistent with Adler $\sim 1/V_{RF}$.
- Minimum $V_{RF}$ required to lock agrees with CW measurements.
Quantifying Oscillator Performance

\[ V(t) = \left[ V_0 + \varepsilon(t) \right] \sin \left[ 2\pi v_0 t + \phi(t) \right] \]

- **Simple method:** Spectrum analyzer
  - Measures power spectrum of \( V(t) \)
  - But, cannot separate \( \varepsilon(t) \) and \( \phi(t) \)
  - May depend on measurement time

- **Better method:** Direct measurement of \( \phi(t) \) or \( v(t) \)
  - Not affected by \( \varepsilon(t) \)
  - Power spectrum of \( \phi(t) \) or \( v(t) \)
  - Easy to compare with theory

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**Refs:**
- Allan variance James Barnes and David Allan, 1964 (NIST)
- Collected papers NIST Technical Note 1337 (http://tf.nist.gov/general/publications.htm)
- Phase noise tutorial http://tf.nist.gov/timefreq/phase/Properties/toc.htm
• Resonance is in 5-30 GHz range: directly digitize, or mix down to low frequency—use SA IF (70 MHz+/-30 MHz)
• Amplify, digitize at 1 GS/s (low pass filter @ 150 MHz)
Measurement of $f(t)$: Sliding DFT

Discrete Fourier transform segments $\Delta t$ in length, overlapping $\Delta t/2$ to generate $\nu(t)$:

...DFT to get $S_\nu(f)$
Frequency Noise Spectra

NiFe free layer

\[ f = \frac{1}{2\pi} \times \frac{1}{R} \]

\[ \theta_H = 10^\circ \]

CoFe/Ni multilayer F.L.

\[ f = \frac{1}{2\pi} \times \frac{1}{R} \]

\[ \theta_H = 1^\circ \]

- 1/f variation dependent on details of free layer: Unknown relationship
STO: Probe of local magnetic environs

STOs respond to local (nanoscale) **net effective field**: Sum of external, current- and spin-induced, and local anisotropy fields

...Device/materials physics challenge: Controlling these fields to produce desired functional behavior
STOs: Mutual Phase Locking

Spin current induces local oscillation of $\mathbf{M}$: couples to surrounding medium → “spin waves”

• Mechanism for coupling oscillators without additional wiring layer
• Additional source/sink for dynamics: Larger effective volume

$I_{c1}$, sweep $I_{c2}$...

Magnetic interaction

precessional excitation

nanocontact radiating spin-waves
STOs: Mutual Phase Locking

Spin current induces local oscillation of $M$: couples to surrounding medium $\rightarrow$ “spin waves”

- Contacts phase lock when $f_1$ approaches $f_2$
- Combined power increases: phase coherence
- Line width narrows when locked: Larger effective volume
Future directions.

Metrology of **spin currents & transport** in multilayered/heterogeneous systems:
- Spin orientation is not conserved: Many sources and sinks, transport is 3D
- Spin pumping
- Spin relaxation
- Spin accumulation

Metrology of novel spin current sources:
- **Spin Hall Effect**—spin currents from **nonmagnetic** materials
- **Spin Seebeck effect**—spin currents driven by thermal gradients

Need to be understood for efficient spin circuit design
Other Spintronics Efforts at NIST-Boulder.

**RF-STM project** (*Mitch Wallis and Pavel Kabos*)
- Calibrated RF-STM measurements at variable temperatures, high frequencies, with magnetic contrast: Potential to image spin waves, spin currents, doping profiles...

**Nanomagnetism project** (*Justin Shaw, Hans Nembach, Tom Silva*)
- FMR measurements of arrays and individual isolated magnetic elements
- Measurements of spin pumping, spin diffusion
Summary.

• Spin-based devices have unique metrology challenges

• Reliability and speed of ST-MRAM devices depend on magnetization dynamics
  • Potentially complicated dependence on device nanostructure

• STOs are current tunable, nonlinear, microwave oscillators
  • Potential applications in NonBoolean architectures, microwave circuits
  • Development depends on understanding nonlinear device dynamics, coupling, & noise

• Future devices will employ pure spin currents: New metrology challenges?
Bonus Slides!
STOs: Mutual Phase Locking

Spin current induces local oscillation of M: couples to surrounding medium → “spin waves”

- Mechanism for coupling oscillators without additional wiring layer
- Additional source/sink for dynamics
Detection of Spin Waves Using Nanocontact as Detector

Output from precessing (emitter) contact

Measured output from detector contact

Spin waves radiated from one contact to the other: coupling mechanism?

Detection Current (mA)

Emitter Output

Detector Output

Freq. (GHz)

Detector Current (mA)

\( I_{\text{Emitter}} = 6.5 \text{ mA} \)

3.5 0.01 pW/MHz (log scale)

5.000E-13 1.580E-10

0.16 0.0005 pW/MHz (log scale)
Individual Contact Outputs:

contact c1 alone

contact c2 alone

Bias point

...bias contact c1, sweep current through c2

⇒ Look for interactions between oscillators
Mutual Phase Locking: Spectra

Both contacts measured

- Devices lock outputs from 9+ to 10 mA
- Powers combine coherently:
  Need to understand mechanisms setting relative phases

STOs: Probes of local magnetism

Oscillator response is a function of field direction
STOs: Probes of local magnetism

Oscillator response is a function of field direction

\[ \mu_0 H = -0.621 \, T \]

\[ \mu_0 H = 0.62 \, T \]

\[ \mu_0 H = 0.62 \, T \]

- ST-FMR shows only small variations with field direction