Microwave Assisted Magnetic Recording for 2Tb/Sqin
9-17-12

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Presented at IEEE Santa Clara Valley Magnetics Society Meeting, September 18, 2012
Acknowledgements

- **Western Digital**: Ramamurthy Acharya, Gerardo Bertero, Michael Chapline, Carl Eliot, Christian Kaiser, Qunwen Leng, Steven Lambert, Mahendra Pakala, Kumar Srinivasan, Shawn Tanner

- **Data Storage Systems Center**: Prof. Jimmy Zhu; Yiming Wang, Choew Him Sim

- **NIST Bolder**: Tom Silva, Justin Shaw

- **Colorado State U., Ft Collins**: Prof. Mingzhong Wu, Lei Lu
MAMR Topics

- Magnetic Recording Super Paramagnetic Limit
- MAMR with a Spin Torque Oscillator in the writer gap architecture
- Loop simulations
- Write/read simulations
- STO fabrication and test
- STO simulations
- Ferromagnetic Resonance media measurements (NIST Bolder & CSU)
- Microloop marks on media (Colorado State University, Ft Collins)
- Recent Jimmy Zhu MAMR talk
What can we do to extend recording?

- **Conventional PMR**
  - Exchange Coupled Composite media
  - Reduced switching field variability (+1dB/% $\sigma_{H_k}$)
  - Reduced Inter Layer in media with granular Soft Under Layer
  - Shingled Magnetic Recording
    - Reduce track pitch ~35% ultimately
    - Increased write field from wide pole (higher $H_k$ allows finer grains)
    - **System challenges to preserve performance** (fast access to data)

- **Bit Pattern Media** allows 1 grain/bit vs ~15 **but:**
  - 75% dead space between islands
  - Inadequate write field from very narrow pole (might require Shingling)
  - Requires good write timing to islands and perhaps read after write
  - **Expensive process to get flyable media**

- **Heat Assisted Magnetic Recording** can write $H_k > 90$ kOe **but:**
  - Many changes in heads and media need debug time
  - Perfecting L10 FePt media needs time
  - Could use an insurance policy

- **Microwave Assisted Magnetic Recording** could
  - **Gain x2** in data density or it may buy only a little (media properties?)
  - Only a small change to the head is required (media can be evolved to optimum)
  - **Will it work better than PMR?**
Heat Assisted Magnetic Recording for High $K_u$

scaling strategy: tall grains with small core size $D_p$!

Basic assumption: $K_u V_p / k_B T \sim \text{const}$

Plot is based on bulk materials properties ($K_u, M_s$); small grains have a lot of surface causing properties to change!

Major efforts worldwide to fabricate such $L1_0$ structures
MAMR Switching Driven by a Spin Torque Oscillator Field

- Microwave field of the STO causes media magnetization to precess at ever larger angles until it switches.

- The magnetization of the Field Generating Layer in the STO precesses due to a spin polarized current flowing into it.

Pole Tip field is insufficient to switch by itself.

Magnetization of the Field Generating Layer of the Spin Torque Oscillator precesses.

Circular MAMR field pumps in energy.

Magnetization precesses to larger angles until it switches.

Rest position due to pole field before MAMR field starts.

Magnetization after switching.

Circular AC Field.
WD Simulated Loops with circular $H_{rf}$ to understand Bf-09 MMM2012, Bruce Terris, HGST (sees significant $H_n$ reduction; little $H_c$ effect with ~500 Oe rf with linear polarization)

$H_{rf} \Rightarrow 1$ kOe needed to get $M = M_s$
WD Simulation gives $H_{dc} \Rightarrow 8$ kOe to get $M=M_s$ with $H_{rf} = 1$ kOe (note that $H_{sat} = 14$ kOe for no RF)

$H_{dc} = 4, 5, 6, 7, 8$ kOe

circular rf

$H_{dc} = 5$ kOe rf linear
Spin Torque Oscillator in the Writer Gap

- Field Generating Layer precesses due to the spin polarized current from the polarization layer.
- The direction of precession reverses when the pole tip field reverses and flips the polarization layer and the bias layer.

Orange arrows are magnetization direction.

Write Pole

Current Source

Trailing Write Shield

Polarization Layer

Field Generating Layer

Bias Layer

FGL Thickness

Write Shield

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STO width sets Magnetic Write Width (ABS View)

- Wide write pole with no Side Shields gives ~30% more field
- MAMR field lowers required \((\text{pole field})/\text{Hk}\) by ~40%
- Net \((\text{pole field})/\text{Hk}\) increases ~x2 for ~x2 AD gain
- Just right pole field, media properties, and FGL Mr*T give FGL defined track width
400 kfcı written 36 nm (700 ktpi) off 1000 kfi (jitter 6.5% → 7%)

Hk=16 & 8 kOe bop/top
Simulated Single Layer Media Sigma Hk Sensitivity – 3%

- MWW ~ 32 nm (635 kTPI for MWW=80% of pitch)
- 3.33 MFCI for 10% jitter on ~2T pattern

Sigma Hk=3% gives very good recording
Simulated Single Layer Sigma Hk Sensitivity

- 2Mfci all ones, 23 transitions/run
- 36% grain area sigma (pseudo-Voronoi)
- Hperp (13, 15, 15kOe for 3, 6, 9% Hk sigma, respectively)
- Hk=27 kOe and Ms=500 emu/cc
- KuV/kT=53 (5 nm dia, 15 nm thk)
- No grain boundaries yet
- 3 nm pole-media surface
- 15x25x25 Field Generating Layer
- 41 GHz rf (1.2x10^8A/cm^2 oscillator current density
- 1 sigma error bars on figure
- Pitch = 1.25*MWW

Sigma Hk = 9% is N.G. (Note that there is a -2/3 dB loss per 1% increase in sigma Hk for PMR so MAMR is similar to PMR for this)
Sigma Hk = 3% gives low DC noise and narrow tracks
(MWW~ 32 nm for H_{perp} =13 kOe)
 Sigma Hk=9% needs $H_{\text{perp}} = 15$ kOe to reduce DC noise resulting in wide (MWW~ 45 nm) tracks

~ 45 nm MWW
Overwrite Simulations (pessimistic .. short sequences)

![Graph showing OVW (dB) vs kBPI for Series 1](image-url)
STO & CPP-GMR in the Reader Gap

DC Current

Bias Layer

CPP-GMR

Field Generating Layer

STO

Polarization Layer =
WD on Wafer Spin Torque Oscillator  9 GHz line

2.3 mA (1.5 mA ref. subtracted)

40k1

Vrms in 8 MHz RBW

Freq. (GHz)
High resistance lapped bars with 8→10GHz lines
Progressively ion milled bar level STO tests

Freq. = 14.5 GHz
0.14 Volts max.

Freq. = 8 GHz → 9.8 GHz
0.16 Volt max.
Latest lapped bars with high resistance from ABS ion milling
Latest lapped bars (R~110 Ohms)

K271  R=125Ω  10GHz  17.5→17 GHz
Latest lapped bars (ABS ion milled)

- 11 GHz
- 21.5 → 20 GHz for V > 130 mV

0 < volts < 140 mV (ignore scale)
Large Shield to Shield Passive Gap for Large $H_{\text{perp}}$

- Simulations show increase in frequency for $H_{\text{perp}} > 5$ kOe
- $H_{\text{perp}} = H_{\text{applied}} \left( \frac{G_{\text{passive}}}{G_{\text{active}}} \right)$
- $F_{-3\text{dB}} = \frac{1}{2\pi R_{\text{sto}} C_{\text{passive}}} \sim 5$ Ghz
~2.5 kOe perpendicular to film

Weak current (vert) dependence of freq (horiz) as seen in simulations

M19H and M19J have strong narrow lines at 14 and 16 GHz in 2.8 kOe perp. to film and 1.6 kOe perp. to ABS
Neighboring parts are very similar

- Weak current dependence on frequency and strong dependence on field
- Slope break at ~ 2.8 kOe is expected from saturation of the read shields resulting in the loss of the x3 gain from the gap ratio(x4) and proximity to the ABS (x.75)
Simulation of Frequency vs Current and Field

- **Strong field dependence**
- **Weak current dependence causes tuning problem**

**Diagrams:**
- **Freq vs Cur. for**: $\alpha=2\%$ (FGL&BL); FGL=6, BL=9; $H_{\text{perp}}$=0 to 15kOe
  - Graph showing frequency vs current with different field values (0kOe, 5kOe, 10kOe, 15kOe).
  - Current values: 2 mA, 3 mA, 4 mA.
- **Frequency vs Field for**: $2\leq I \leq 4$; damping=2%; FGL=6nm; BL=9nm.
  - Graph showing frequency vs field with different current values (2 mA, 3 mA, 4 mA).
  - Field values: 0 to 15kOe.
Some STO Simulation Results

- **For thin Bias Layers**
  - Freq. ~ $H_{\text{perp}}$
  - Unstable for $H_{\text{perp}} = 0$

- **For thick bias layers**
  - Freq. constant for $H_{\text{perp}} < H_{\text{threshold}}$
  - $H_{\text{threshold}}$ increases with Bias Layer thickness

**Bias Layer Thickness = 5 nm**

Freq. vs Hz for $I=12$ mA, $T_s=6\text{nm}, T_h=5\text{nm}, M_{\text{sH}}=240, K_h=2\times10^6, a_s=.005, a_h=.01, 40\times40 \text{nm}$

**Bias Layer Thickness = 1 nm**

Freq. vs Hz for $I=8\text{mA}$, $a_s=.005$, $a_h=.01, K_h=3\times10^6, T_s=3\text{nm}$, $T_h=1, M_{\text{sH}}=401, 40\times40 \text{nm}$
STO magnetization at two currents (3 and 5 mA)

- As current increase
  - Frequency increases
  - Curling increases
  - A point of gross instability is reached eventually
There are many ways to be wrong
Unstable STO oscillation from highly curled magnetization

- Frequency variation from 19 to 23 GHz
- Amplitude modulation of 55% full range
STO must be well tuned to the media
NIST VNA-FMR (10MHz to 67GHz)

- 10 MHz < f < 67 GHz
- Maximum field: 2.4 T
- Coplanar waveguides with 100 μm wide center conductor

Vector network analyzer

Port 2

$V_{in} = |V_{in}| e^{i\phi_{in}}$

sample

Port 1

$V_{out} = |V_{out}| e^{i\phi_{out}}$

50 Ohm coplanar waveguide

$S_{21} = \frac{|V_{in}| e^{i\phi_{in}}}{|V_{out}| e^{i\phi_{out}}}$

H \perp "perpendicular FMR"

H \parallel "in-plane FMR"
CSU Frequency vs Field Results

\[ \gamma = 3.16 \text{ MHz/Oe}, \quad H_k = 14862 \text{ Oe}, \quad 4\pi M_s = 7738 \text{ G} \]
CSU Line Width Results

$\Delta H_{FMR}$ vs. Frequency

$38 \text{ GHz} \sim 49.5 \text{ GHz}, \ \alpha = 0.079, \ \Delta H_0 = 479.5 \text{ Oe}$
NIST Bolder FMR spectra for media sample

- Simultaneous fit of real and imaginary parts of susceptibility.
- 2000 – 3000 Oe linewidths. (Huge!)
- Excellent fit to LL spectral shape.
NIST Bolder Extracted spectroscopic parameters

- Extremely precise determination of effective anisotropy and orbital contribution to moment.
- Large $g$ is not unexpected for films with large perpendicular anisotropy.
- Exact determination of zero-field resonance frequency.

\[ \mu_0 M_{\text{eff}} = -0.725 \pm 0.002 \, \text{T} \]
\[ g = 2.236 \pm 0.007 \]
• Huge linewidths. (Largest we’ve ever measured!)
• Slight increase over measured frequencies: Most of linewidth due to inhomogeneous broadening, not damping.
WD FMR Line Width Simulation with $\alpha=1\%$ and $\sigma_{Hk}=12\%$

- Intern-granular exchange coupling strongly suppresses $\sigma_{Hk}$ at positive fields

![Simulated Half Line Width vs Frequency for alpha=1\% and SigHk=12\%](image)
Ferromagnetic resonance analysis of internal effective field of classified grains by switching field for granular perpendicular recording media
Shintaro Hinata, Shin Saito, and Migaku Takahashi

Citation: J. Appl. Phys. 111, 07B722 (2012); doi: 10.1063/1.3679466

Width gives $\alpha + \sigma H_k = 2.3\%$

FIG. 4. FMR signals for the media II. Right vertical axis shows $M_{rt}$ of the medium. Dash-dotted line indicates envelope of $H_{DC}^{crit}$. a–d: switching field distribution histograms when $M_{rt}$ is equal to $M_s$, nearly 0, and $-M_s$, respectively.

MMM2012- GU-06, JApplPhys_111_07B722
Media FMR Study Preliminary Conclusions

- FMR will ultimately be able to get sound measurements of damping, anisotropy field and anisotropy field dispersion but more work needs to be done with high intergranular exchange coupling.

- CSU and NIST measurements on the same sample (C152) disagree significantly:
  - CSU $\alpha = 7.9\%$
  - NIST $\alpha = 2.5\% \pm 0.5\%$

- Tohoku U. FMR result on CoPtCr line width gives $\alpha = 2.3\%$

- All the above have sigma Hk contamination.
Experimental Setup

- Rf-probe contact
  - Signal line width: 100 μm

- CPW zoom in

- Magnetic Field
- Substrate
- Ground Plane

- MAMR measurements
  - Signal line width: 5 μm
  - Signal line length: 100 μm

- Signal line width changing part:
  - from 100 μm to 5 μm
MAMR Effects

Magnetic Force Microscopy (MFM) Images

- End of CPW
- Changing part of CPW

Microwave frequency: 13 GHz, Microwave power: 31 dBm,
Pulse repetition rate: 100 kHz, Pulse duration: 98 ns.
Switch field is 3200 Oe for all the MAMR measurements.
Different Microwave Frequencies

Microwave Power: 31 dBm, Pulse repetition rate: 0.1 kHz, Pulse duration: 11 ns.

We observed MAMR effects with a frequency range from 8 to 15 GHz.
Conclusions

- MAMR can provide an insurance policy for the performance and reliability issues of competing approaches
  - Much smaller heads and media change
  - Buy time to debug other technologies
  - Can probably do >2 Tb/Sq”
    - Reduce required head field ~40%
    - Increase head field ~30% with wide write pole and no side shields
    - x2 increase in writeable Hk → ~x2 AD increase

- MAMR has to be done just right (it is a Goldilocks technology)
  - STO optimized to media
    - frequency matched to media with the right deep gap field
    - Right Ms*Thickness for the FGL
  - Essential media modifications
    - Higher anisotropy with smaller grains while maintaining low sigma Hk
    - Other proprietary refinements

- Critical mass of industrial investment is needed for MAMR to happen