RF Magnetic Films and Their Applications in Integrated Magnetic Devices

Nian X. Sun
Electrical and Computer Engineering Department, Northeastern University, Boston, MA, USA
Group Introduction

Visiting Prof.
- Shandong Li

Post docs:
- Ming Liu
- Jing Lou

PhD students:
- Shawn Beguhn
- Andrew Czarnecki
- Ming Li
- Jing Wu
- Yunume Obi
- Zhijuan Su
- Qi Wang
- Xing Xing
- Xi Yang
- Ziyao Zhou

Research Areas:
- Magnetic, ferroelectric and multiferroic materials for RFIC and MMIC
- RF/microwave devices and subsystems
- Magnetic sensors, spintronics, energy harvesting technologies, solar cell materials, etc.

Financial Supports:
- NSF, ONR, AFOSR, MIT/LL, Draper Lab, Analog Devices, Northrop Grumman

12/6/2010
Outline

- Challenges of integrated magnetic inductors and RF magnetic materials
- Loss mechanisms and micromagnetics of:
  - Metallic magnetic films and multilayers
  - Ferrite films and multilayers
- Recent progress of RF metallic magnetic films and ferrite films and multilayers
- Summary
Status and Challenges on Integrated Magnetic Power Inductors

- Five types of magnetic inductors.
- Hundreds of magnetic material compositions and microstructures
- Performance of integrated power inductors are limited by magnetic materials.
Integrated Magnetic Inductors for Power: SOA and Challenges

Inductor challenges: high Q, high L (10~200nH) and L/area (or large ∆L/L) at 10~100 MHz!

Magnetic materials challenges: high $\mu_r$, large t, low tan$\delta$<2%, high $M_s$, and high $\rho$.


Loss Mechanisms and Thickness Effects on Permeability Spectrum of Magnetic Films

Ferromagnetic resonance
Eddy current loss
Domain wall resonance
Thick films lead to excessive eddy currents
Out of plane anisotropy grows with film thickness
Magnetic multilayers!
Micromagnetics of Magnetic/Non-magnetic Multilayers: Enhanced RF Magnetism

How to achieve the easy axis state:
- Low b and low D
- High b so that no-pinhole
- High D for high average permeability


Northeastern University
College of Engineering
Permeability Spectra of 2µm Thick Metallic Magnetic films: Single Layer and Multilayer

- Eddy current dominated permeability of single layer film
- Ferromagnetic resonance dominated permeability spectrum for the multilayer!
Edge Closure Domain Walls in Patterned Magnetic/Non-magnetic Islands

Magnetic/non-magnetic insulator multilayers:
- Thicker film with significantly reduced eddy current loss
- Improved soft magnetism:
  - Significantly reduced Hc
  - Less out of plane anisotropy
  - Lower Gilbert damping.
Novel FeGaB Films: Microstructure, Soft Magnetism and Magnetostriction


Graphs showing the relationship between intensity, 2 theta, 4πMs, Hc, Hk, boron content, and applied field with magnetic field and magnetostriction constant.
High E-field tunable FMR frequency range from 1.75 to 7.57 GHz, or $f_{\text{max}}/f_{\text{min}} = 4.3$ at 0Oe.

Dramatic changes in hysteresis loops, ~750 Oe change in anisotropy.

Soft Magnetic FeCoHf Films with High Uniaxial Magnetic Anisotropy

- High uniaxial anisotropy induced by composition gradient
- Excellent RF magnetic properties!

High Quality RF Ferrite Films by Low-Temperature Spin Spray: Process Introduction

- Low process temperature of 90°C, high crystalline quality, high deposition rate 50~100nm/min, low RF loss tangent.
- Compatible with RFIC and MMIC, even organic substrates.

Permeability Spectra for Thin Film Magnetic Materials: the Modified Snoek’s Limit

\[ \mu_r = \frac{4\pi M_s}{H_{total}} + 1 \]

\[ f_{FMR} = \gamma \cdot \sqrt{H_{total} \cdot (4\pi M_s + H_{total})} \]

\[ f_{FMR} = \gamma \cdot H_{total} \cdot \sqrt{\mu_r} \]

\[ \mu_r \cdot f_{FMR} = \gamma \cdot 4\pi M_s \cdot \sqrt{\mu_r} \]

- Snoek’s limit boosted by \( \sqrt{\mu_r} \)
- 0.5~1 order of magnitude enhanced FMR frequency.

Self-biased ferrite films by spin spray deposition at 90°C
High permeability (10~200) and high permittivity (~10) and low loss at GHz.
RF Magnetic Devices with Spin Spray Deposited Ferrite Films Exhibiting Enhanced Performance

Monolayer ferrite films

Need for Thick Ferrite/Non-Magnetic Films for RF Devices

- Hard to achieve thick RF ferrite monolayer films > 3~5 um by spin spray, which also exhibit degraded RF performance.

- Need ferrite/non-magnetic insulator multilayers!

- No demonstration showing improved RF performance in ferrite/non-magnetic insulator multilayers!

Spin spray deposited \([\text{NiZn-ferrite/Dextrar}]_n\), failed in achieving improved RF performance!

- Enhanced coercivity, which went up with the number of periods.
- Degraded RF performance with much higher FMR linewidth.
Improved Microwave Magnetic Properties in Spin Spray Deposited Ferrite/Insulator Multilayers

Ferrite/insulator multilayer leads to reduced FMR linewidth and enhanced permeability!
Spin Spray Deposited Ferrite Monolayers and Ferrite/Non-Magnetic Multilayers
Improved RF Magnetics in Spin Spray Deposited Ferrite/Non-Magnetic Multilayers

<table>
<thead>
<tr>
<th>Film Structure</th>
<th>Thickness (μm)</th>
<th>$M_s$ (emu/cm$^3$)</th>
<th>$H_c$ (Oe)</th>
<th>$\mu_r'$</th>
<th>$f_r$ (GHz)</th>
<th>$\Delta H$ (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_3$O$_4$ Single Layer</td>
<td>10</td>
<td>318</td>
<td>111</td>
<td>8</td>
<td>1.2</td>
<td>618</td>
</tr>
<tr>
<td>Fe$_3$O$_4$/PR/Fe$_3$O$_4$</td>
<td>10</td>
<td>318</td>
<td>96</td>
<td>10</td>
<td>1.3</td>
<td>589</td>
</tr>
<tr>
<td>(Fe$_3$O$_4$/PR)$\times$4</td>
<td>10</td>
<td>302</td>
<td>140</td>
<td>5</td>
<td>2.1</td>
<td>1398</td>
</tr>
<tr>
<td>Fe$_3$O$_4$ Single Layer</td>
<td>1.4</td>
<td>398</td>
<td>134</td>
<td>9</td>
<td>1.1</td>
<td>528</td>
</tr>
<tr>
<td>Fe$_3$O$_4$/PR/Fe$_3$O$_4$</td>
<td>1.4</td>
<td>398</td>
<td>118</td>
<td>10</td>
<td>1.2</td>
<td>464</td>
</tr>
<tr>
<td>NZFO Single Layer</td>
<td>1.2</td>
<td>263</td>
<td>23</td>
<td>19</td>
<td>0.9</td>
<td>292</td>
</tr>
<tr>
<td>NZFO/Al$_2$O$_3$/NZFO</td>
<td>1.2</td>
<td>279</td>
<td>21</td>
<td>20</td>
<td>1.0</td>
<td>248</td>
</tr>
</tbody>
</table>

- Improved RF magnetics in ferrite/insulator multilayers, lower $H_c$, higher $\mu$, narrower $\Delta H$!
New Electrostatically Tunable Inductors with Giant Tunable Range

- A new class of electric field tunable inductors
- Giant tunable inductance range
- Novel applications in power electronics!
Summary

- Eddy currents in magnetic film limit the performance of integrated magnetic inductors and transformers.
- Thick magnetic/non-magnetic multilayer films are the key to achieving better performance in power inductors and transformers.
- Open for collaborations!
  - Email: Nian@ece.neu.edu
  - Phone: +1-617-373-3351
  - www.northeastern.edu/sunlab