Ferromagnetic integrated inductor/noise suppressor

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OUTLINE
1. Thin film permeameter for material evaluation
2. Slit works on thin film inductor
3. Thin film electromagnetic noise suppressor
4. Side channel attack protection
5. Summary
Permeability vs Ferromagnetic Resonance Freq.

\[ \mu = \frac{M_s}{H_k} \]

\[ f_r = \frac{\gamma}{2\pi} \sqrt{\frac{M_s H_k}{\mu_0}} \]

\[ \mu \cdot f_r^2 = \text{const} \]

**Inductor**

**Noise Suppressor**

(a) Real part

(b) Imaginary part

\[ \rho = 500 \, \mu\Omega \text{cm} \]

\[ M_s = 1.2 \, T \]
Development of thin-film permeameter

Shielded loop coil method

Coplanar line method (coming)

M. Yamaguchi et al.

Also
Ryowa Electronics Co.
Model PMM-9G1
9GHz measurement jig

Centered pick-up coil arrangement
Improved EM uniformity at the coil window

Strip line structure (Side-open TEM cell)
Improved EM uniformity throughout the jig

Loaded end:
Yielding TRAVELING EM field

Improved EM uniformity at the coil window
Planar Shielded-loop coil

- 50 Ω signal line
- 1 turn coil with gap
- Hac
- GND line
- Strip line
Voltage transfer along the strip line, I

50 Ω signal line

1 turn coil with gap

Hac

GND line

Strip line
Voltage transfer along the strip line, II

50 Ω signal line

1 turn coil with gap

New calibration point

GND line

Strip line
E-filed Voltage Suppression

Eac

Strip line

GND line
Comparison of E- and M- voltages extracted by simulation & experiments.

Simulated by ANSOFT HFSS Ver. 8.0.21
TDR Profiles

Position [psec]

Impedance [Ω]

lower
middle
upper
Point

Position [psec]
Validity check

1. Comparison with L.L.G. equation

Experimental data
Calculated

2. Int’l cross measurements

Tohoku U, Japan (Yamaguchi)
Frequency domain
TEM cell/Pick-up coil

NIST, USA (Silva)
Time domain
Coplanar line

CEA, France (Acher)
Frequency domain
Microstrip line

FMR frequencies agreed within the error of 15%

FeCoBN:
thickness 978 nm, $4\pi M_s \sim 22 kG$, $H_c \sim 5 Oe$, $H_k \sim 60 Oe$, resistivity $\sim 73.8 \ \mu \Omega \cdot cm$

By Prof. J-R Kim, Hanyang Univ., Korea
Int’l Cross Measurements, I

A jig for the pickup coil method.

A jig for the transmission line method.

Completed System (PMM-9G1, by Ryowa)

Granular films

CoZrO
Thickness 1.82μm, Resistivity 1800μΩcm

Metallic films (FeCo-base system)

FeCoBSi(80 nm)/NiFe(20 nm) bilayer

NiFe/CoFeN/NiFe
(by Prof. Wang, Stanford U)
Spin-Spray ferrite films

A, D : NiZn-Ferrite films, B, C, E : NiZnCo ferrite films

![Graph showing relative permeability vs frequency for Spin-Spray ferrite films, with labels A, D for NiZn-Ferrite films and B, C, E for NiZnCo ferrite films. The graph plots relative permeability on the y-axis and frequency on the x-axis, with distinct curves for each sample type.]
Slit works on magnetic film

\[ H_{k\text{eff}} = H_k + N_d M_s \]

- \( H_k \): anisotropy field
- \( N_d \): demagnetizing factor
- \( M_s \): saturated magnetization

\[ \mu_{\text{eff}} = \frac{M_s}{H_k + N_d M_s} \]

\[ f_r = \frac{\gamma}{2\pi} \sqrt{\frac{M_s H_k + N_d M_s^2}{\mu_0}} \]

- \( \gamma \): gyromagnetic constant

- \( l_m = 4\text{mm} \)
- \( w_m = 20\mu\text{m} \)
- \( t_m = 0.2\mu\text{m} \)
- \( d_m = 2.3 \mu\text{m}, 3.3 \mu\text{m}, 4.0 \mu\text{m} \)

**Diagram:**
- Labeled dimensions: \( l_m, w_m, d_m, t_m \)
- Easy axis indicator
- Graph: Real part of relative permeability vs. Frequency (GHz)

**Equations:**
- \( H_{k\text{eff}} \)
- \( \mu_{\text{eff}} \)
- \( f_r \)

**Intrinsic easy axis**
Test pattern of bi-directional micro wire array

Observed domain structures (1)

(a) 10μm wide micro wire array

(b) 30μm wide micro wire array

Observed domain structure. 0.1mm thick and 2mm long samples.
Hysteresis curves

Horizontally aligned micro wire array

Vertically aligned micro wire array

Broken lines: before annealing
Solid lines: after annealing

0.1 mm thick
10 μm wide
0.6 μm spacing
2 mm long
Frequency profile of complex permeability

Width: varied, 0.1 μm thick, 0.6 μm spacing, 4 mm long
no heat treatment

(a) Real part

(b) Imaginary part
Possible advantages of magnetic thin-film inductors

- **Miniaturization**
  Magnetic film enhances magnetic flux.

- **Low coil loss**
  Coil length reduces with miniaturization.

- **Low eddy current loss in Si and SiGe**
  Magnetic flux is mostly associated with magnetic film.

- **Thin insulator between coil and Si**
  Because low eddy current loss in Si.

- **High self-resonance frequency??**
  Size is small but magnetic film can be a electrode of a capacitor...

Toward High efficiency
## Spiral inductor

**Diagram:**
- Magnetic film
- Underlayer
- Polyimide
- Spiral coil
- SiO₂
- Si
- Bi-directional micro wire array structure

### Advantages:
- Enhance the air-core inductance up to 100%
- Post Si process compatible
- by micro wire array structure:
  - Enhance FMR frequency
- by bi-directional wire structure
  - Utilize 100% area of magnetic film

### Table:

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
<td>Spiral: 4 turns</td>
</tr>
<tr>
<td></td>
<td>Width: 11.0 μm</td>
</tr>
<tr>
<td></td>
<td>Spacing: 11.0 μm</td>
</tr>
<tr>
<td></td>
<td>Thickness: 2.6–3.0 μm</td>
</tr>
<tr>
<td></td>
<td>Area: 337 x 337 μm²</td>
</tr>
<tr>
<td>Magnetic thin film</td>
<td>Thickness: 0.1, 0.3 μm</td>
</tr>
<tr>
<td></td>
<td>Wire array patterns:</td>
</tr>
<tr>
<td></td>
<td>None, Parallel or Micro wire array</td>
</tr>
<tr>
<td>Substrate</td>
<td>Thickness: 600 μm</td>
</tr>
</tbody>
</table>
Non-patterned CoNbZr film inductor

- Inductance ($L=10.1 \text{nH (± 50%)}$)
- Resistance ($R=19.2 \Omega$)
- Quality factor ($Q=3.4$)
Sandwich structure thin film inductors

(i) **Air-core**: The slits on magnetic film faces to the coil gap.

(ii) **Plain**: The slits on magnetic film faces to the coil gap.

(iii) **Aligned**: The slits are shifted by a half coil pitch.

(iv) **Shifted**: The slits are shifted by a half coil pitch.

(v) **Closed**: The top and bottom magnetic layers are terminated at the edges.

(a) Cross sectional structure

(b) Magnetic film patterning

(c) Outlook of the completed inductor
Intra-EMI problems of modern IT equipments

**High Freq. operation**
- Signal and communication frequencies conflict.
- Wave length becomes similar to device and Equipment size.

**High Density Packaging**
- For further miniaturization
- For new device installation (camera, et al)

**Noise Suppression Sheet (NSS)**
- To reduce unexpected signal to noise couplings
- By means of FMR loss generation in magnetic materials

**Low Power drive**
- Low S/N ratio
- Radiating wave source (Common Mode Current)
Idea of thin film noise suppressor

**Ideal frequency profile**

- Insertion loss
- Without magnetic film
- With magnetic film
- Signal frequencies
- Noise frequencies

**Schematic diagram**

- Magnetic layer
- Insulator
- Input
- Attenuation

**Reflection, $S_{11}$ Transmission, $S_{21}$**

$$P_{\text{loss}}/P_{\text{in}} = 1 - (|S_{21}|^2 + |S_{11}|^2)$$
Gap length vs. transmission properties

CoNbZr magnetic film
15 mm(L) x 2 mm(W) x 0.5, 1, 2 μm(T)

Sheet resistance

\[ Rs = \frac{\rho}{t} \] [Ω/square]

\( \rho \): Resistivity
\( t \): Film thickness

Current

S. Ohnuma et al: Intermag2005

Size: 35x35mm²
Thin-film shielded-loop coil

Lead portion

Loop portion

$A - A'$

$B - B'$

$C - C'$

$2 \mu m$

Ground gap

$6 \mu m$

$d = 50, 100, 200, 500 \mu m$

$d = 500 \mu m$
Time domain analysis

BG-1
BV-1
BV-2
BG-2

BV-3

+ + +

-150 -100 -50 0 50 100 150

Time [ns]

Current [mA]

BV-1
(BV-2)+(BV-3)
(BV-1)-(BV-2)-(BV-3)

120 130 140 150 160 170 180 190 200 210 220 230 240

Time [ns]

Current [mA]
A variety of side channel attack methods

- Analysis by combining various I/O to the module
  - Nondestructive attack
    - Frequency operation
    - Voltage operation
    - Adding noise
    - Electric field, Magnetic field, and Irradiation
  - Destructive attack
    - Light, EM radiation, and irradiation

- Input in module
- Output from inside of module

- Leakage information
  - EM radiation
  - Current, voltage
  - Processing time

- Side channel attack on cryptographic modules
Electromagnetic radiation analysis system that use micro magnetic field probe.

- Digital oscilloscope
- Micro magnetic field probe
- LSI board
- PC for wave analysis
- Magnetic field probe
- Measurement point
Differential Electromagnetic Analysis (DEMA)

Electromagnetic radiation from CPU depends changes of the data.

...DEMA is attack method that uses change in EM wave radiated from CPU while encryption.

Outline of DEMA

I) Acquire wave form corresponding to various plaintexts (ciphertexts).
II) Assume a part of the key.
III) Assume 1 bit of internal variety from the key assumed.
IV) Classify to two groups according to an internal variable is 0 or 1.
V) Calculate difference between averages of the two groups.
VI) Repeat II)-V) changing assumption of the key.
VII) Consider the one with the maximum peak to be a correct key.
Relation between sampling frequency and analytical accuracy

![Graph showing the relationship between sampling frequency (100MSa/s, 200MSa/s, 400MSa/s, 1GSa/s) and the number of waveform data (x-axis) and the number of error bits (y-axis). The graph illustrates how increasing the sampling frequency reduces the number of error bits.]