Lamination-Based Technology For High Performance Metallic Magnetic Cores

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Outline

- Requirements for passives in multi-watt power converter applications
- Innovations in magnetics
- Highly-laminated magnetic metal cores
  - » Concept
  - » Fabrication approach
  - » Experimental results
- Conclusions

Passive Elements for Ultra-Compact Multi-Watt Power Converters

- Typically comprised of conductors plus optional specialty materials (dielectrics, magnetic cores, etc.)
- In power converters (e.g., your laptop power cord), the magnetic energy storage component is typically the largest device present, and is typically made from ferrite (bulky element)
- Increases in operating frequency can reduce bulk, but potentially increase losses
- What are the technologies that can be exploited to overcome these losses?

Innovations in Magnetics

- At least, 2 innovation approaches can improve the performance of magnetic cores for power applications

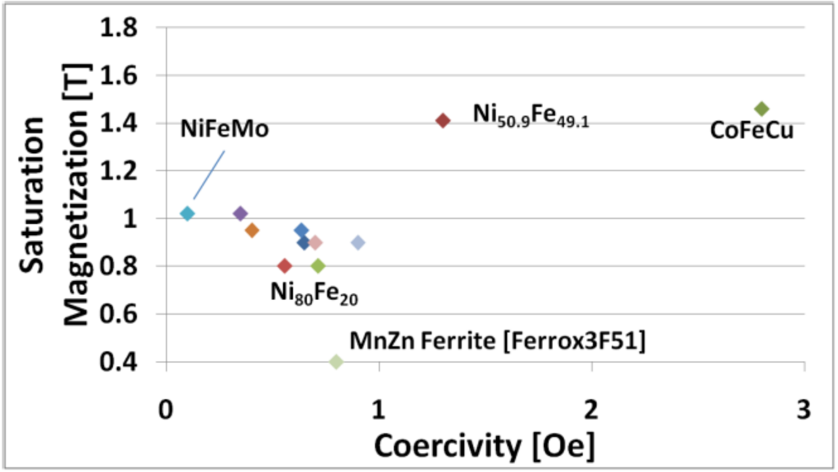
1. Enhance intrinsic properties of magnetic materials

   e.g., nanogranular materials, CoZrTa, CoZrO, enhanced MnZn ferrites…

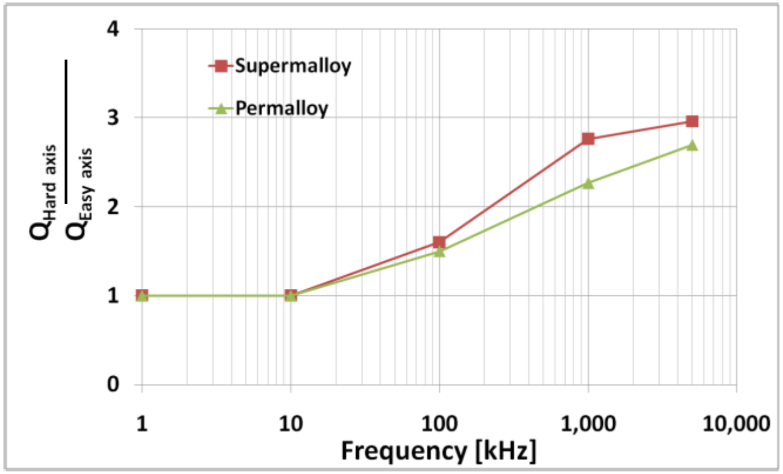
2. Use technological innovations in core manufacturing process to alleviate material limitations

One Solution: Metal Core Inductors

- Advantages of electroplated metallic alloys
  - High saturation (High operating flux density → inductor miniaturization)
  - Low coercivity
  - Ability to electroplate in magnetic field to define easy/hard axis
  - CMOS compatible



Saturation magnetization and coercivity of electroplated films



In-field electroplating for easy and hard axis formation

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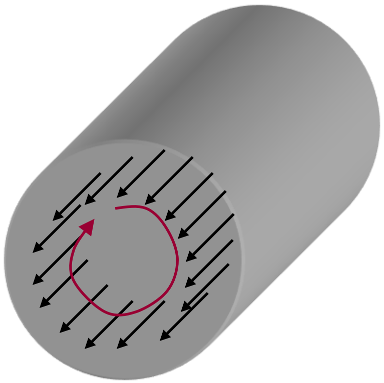
Skin Depth

- Conducting, highly permeable materials will have small skin depths at moderate frequencies
  - » e.g., steels: 60 Hz -> 1-2 mm
  - » 1 MHz -> 1-2 µm
- Current ‘macro’ approach: lamination at low frequency, ferrites at high frequency (but:)
  - » Ferrite saturation flux density limitations
  - » Ferrite temperature limitations
- Opportunity for MEMS-based steel laminations
  - » Ultracompact power converters
  - » High (mechanical) frequency microactuators



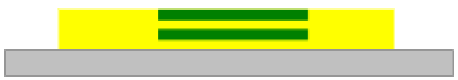
$$\delta = (\pi f \mu \sigma)^{-1/2}$$

Highly-Laminated Metal-Core Inductors for Ultracompact Power Conversion

- Could consider utilization of metallic cores for higher saturation flux density and therefore lower size, low coercivity, high thermal conductivity, but operation in the low MHz region requires a few μm thick film lamination in the case of Ni(80%)Fe(20%) permalloy, AND:
- Large power handling of the device (typically 1-20 W) requires thick cores (i.e., large number of laminations) - how to achieve?

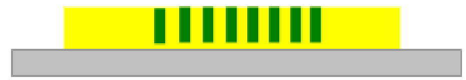
➲ A manufacturing process to realize highly laminated magnetic cores for power applications, and demonstrate integrated magnetic components using the process

Previously Reported Microfabricated Laminations



Electrodeposition of magnetic material

- Multiple deposition steps of seed layer
- Multiple photolithography for plating molds and insulators
- Overall core fabrication time is proportional to the number of layers



Electrodeposition of magnetic material

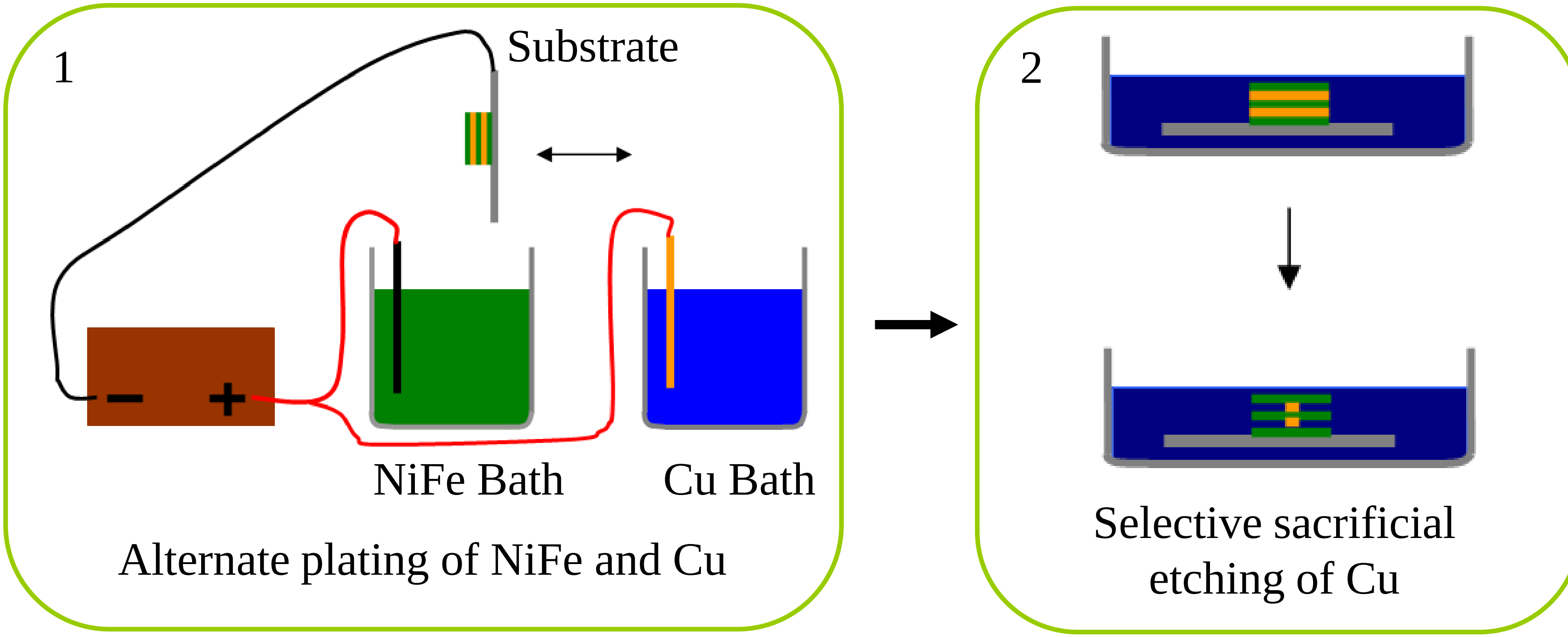
- One deposition of seed layer
- High-aspect-ratio plating mold is required for large cross-sectional core

Sputter deposition of Magnetic material

- Alternate sputtering of magnetic materials and insulation layers
- Stress issues in laminated films
- Some patterning complexity

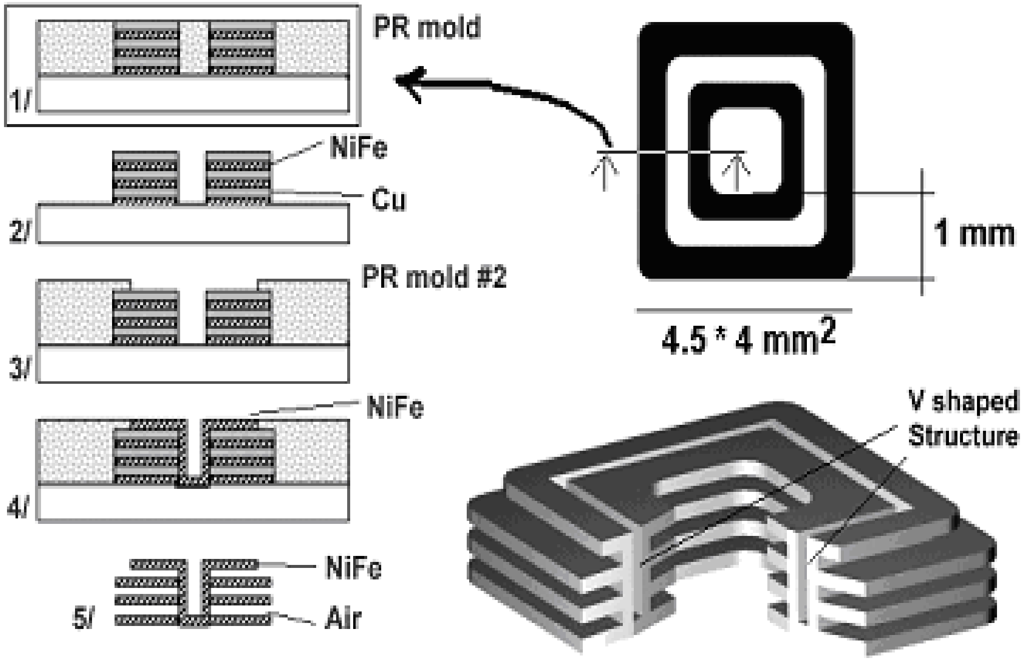
Magnetic material — Insulation material

Proposed Lamination Manufacturing Concept



- Only one vacuum process for the seed layer
- One or two photolithography steps regardless of the number of magnetic film layers
- Highly laminated AND thick core is possible

Core Fabrication

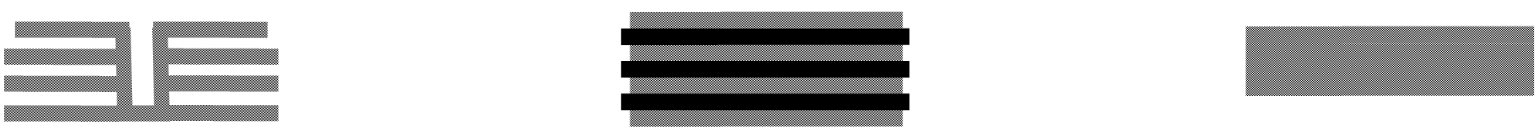


1) A mold is filled with sequential electrodeposition of NiFe(4um) and Cu (6um) layers
2) Mold removal
3) New photo-resist layer and patterning
4) NiFe layer is electrodeposited in a 'V-shape' to support each individual NiFe layers once Cu layer is etched
5) Second mold removal and Cu sacrificial etching

Fabrication of Test Cores

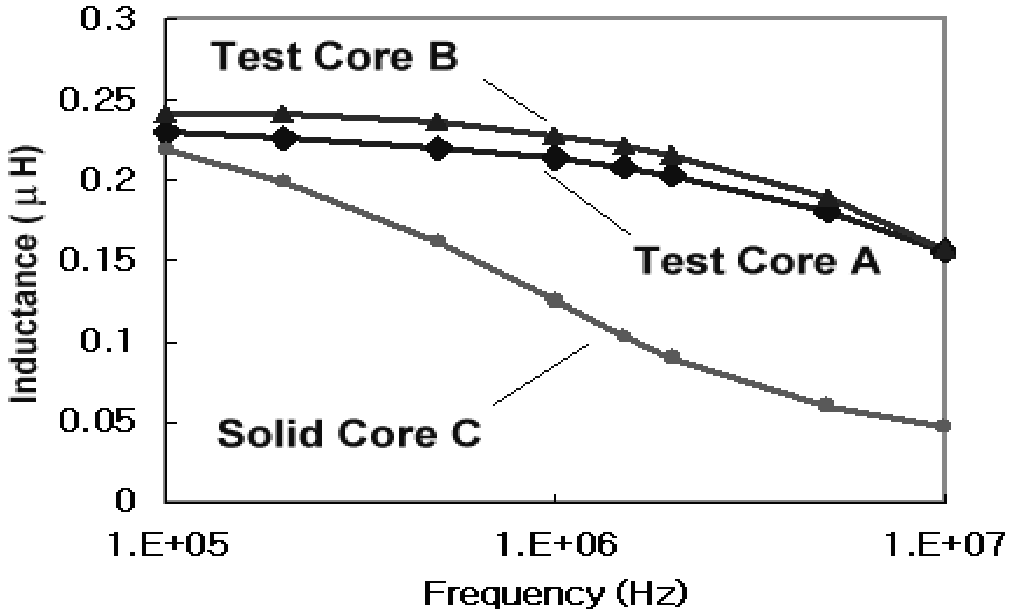
- In order to evaluate usefulness of the proposed lamination technique, three different types of test cores were fabricated
- Core A: fabricated using the proposed technique
- Core B: fabricated by stacking NiFe films and placing insulation films between them (perfect lamination case)
- Core C: solid NiFe core (unlaminated case)

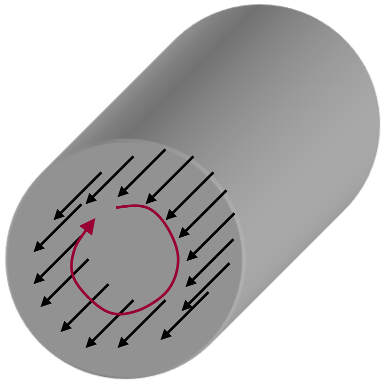
Cross-sectional view of cores



Core A   Core B   Solid core C

Performance Comparison of Test Cores

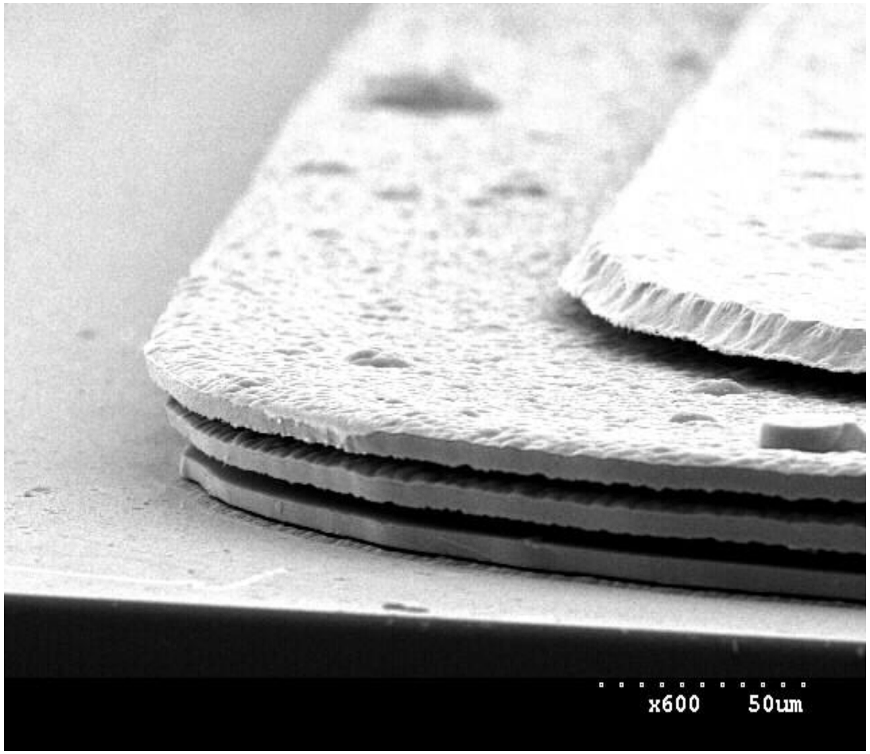




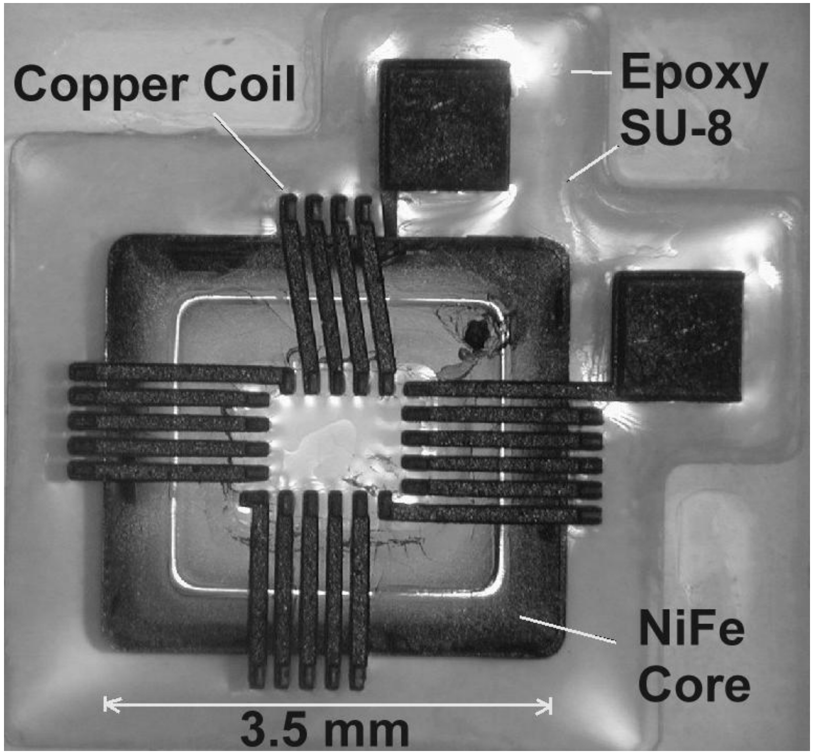
reduced effective cross-sectional area results in reduced inductance

- Inductances of three different types of cores were measured after hand-winding of magnet-wires
- Solid core C shows rapid decrease of inductance
- Core A fabricated with proposed technique shows very close inductance behavior to core B (perfect lamination case), demonstrating effectiveness of reducing eddy current

Fabricated Cores and Integrated Inductors

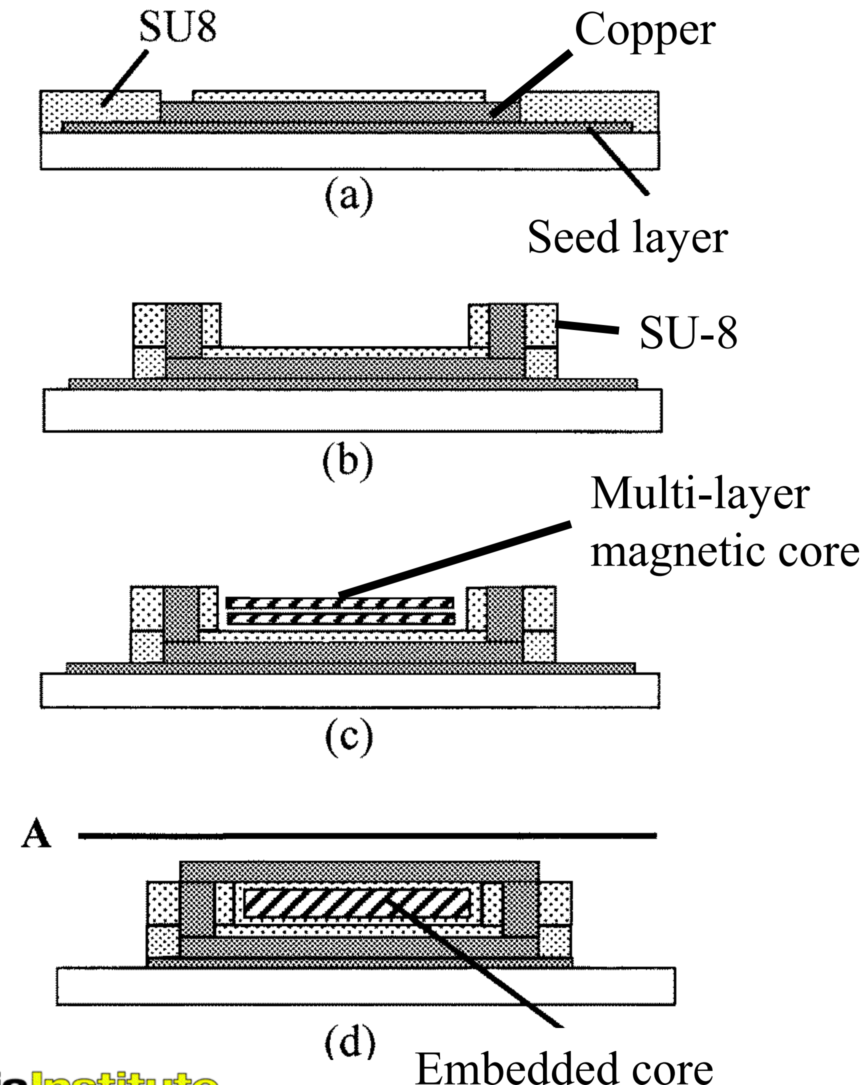


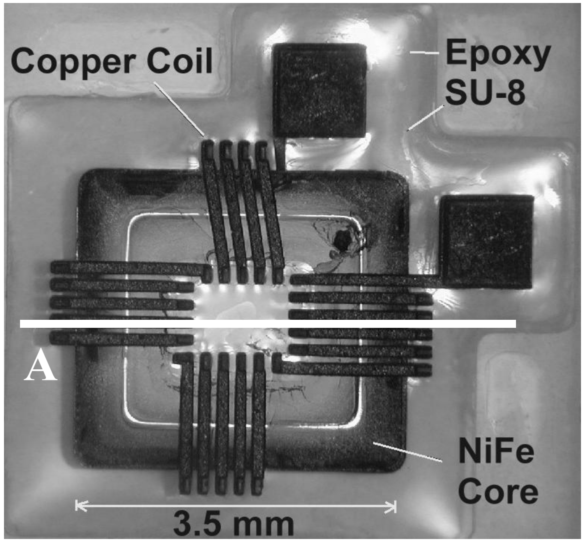
SEM of laminated NiFe core structure after Cu removal (Detail)



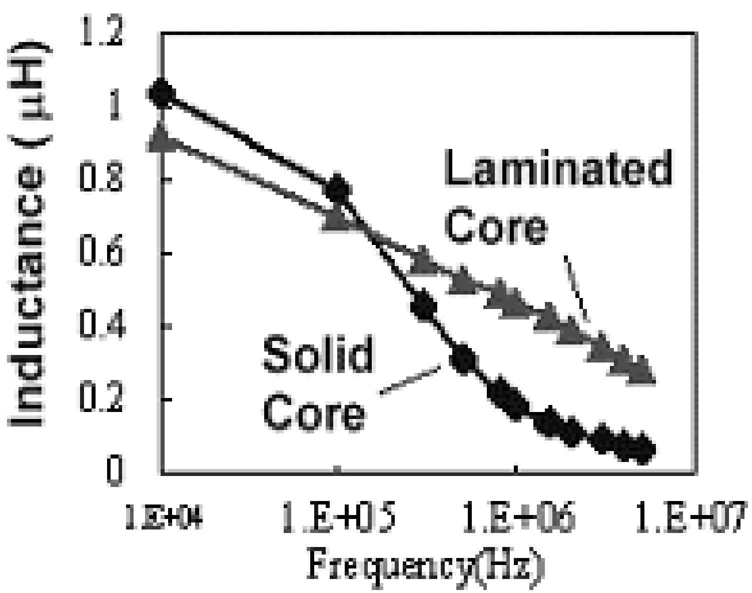
Photomicrograph (top view) of integrated inductor with laminated NiFe core

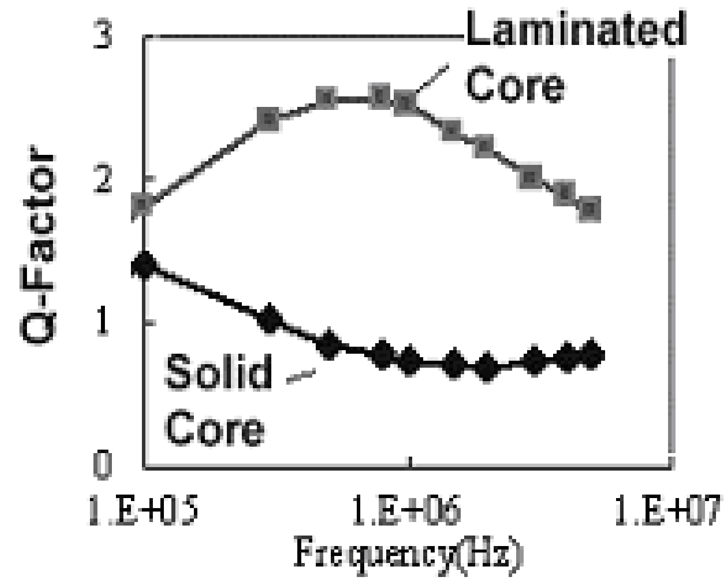
Windings-Core Co-Fabrication Process





Characterization of Micro-fabricated Inductors

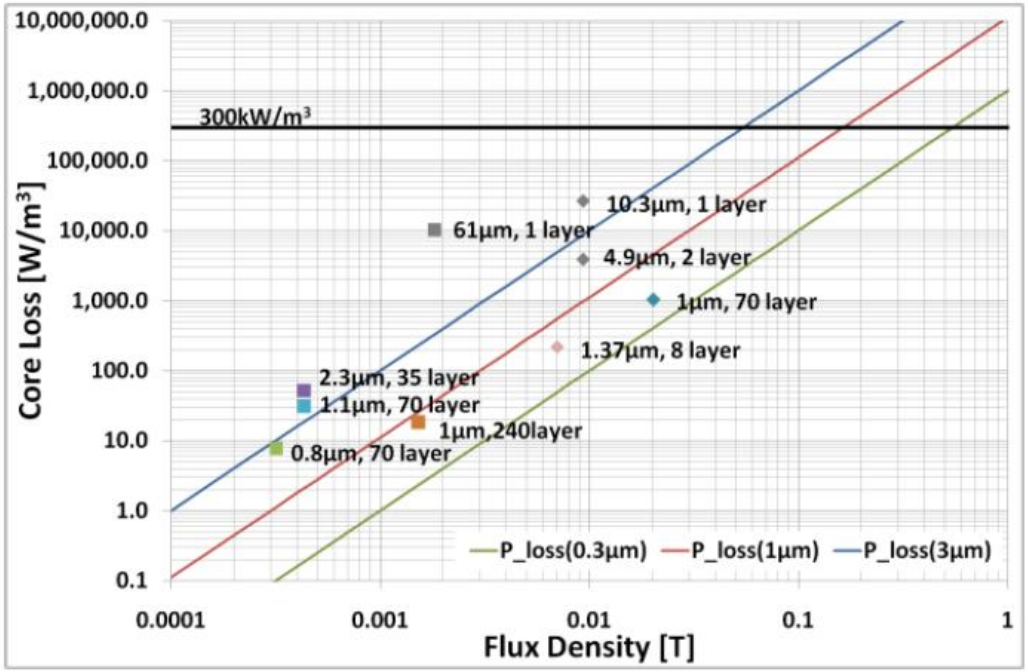




- Solid (unlaminated) core integrated inductors were fabricated as a comparison on the same wafer with the laminated core devices
- Laminated inductors show improved performance over solid-core devices : 2~3times higher Q-factor

Eddy Losses in Laminated Cores

- Eddy current losses vs. operating flux density at 1 MHz
- Lines are calculated values for 3 (blue), 1 (red), and 0.3 μm (green)
- Points represent experimental data



Conclusions

- Highly Laminated Metallic Cores: Technology-driven approach
  - Suppressed (low) eddy current losses
  - High Saturation flux densities
  - Low hysteresis losses
  - Electroplating-based technology compatible with thick magnetic core fabrication and CMOS manufacturing
  - Compatible with monolithic inductor fabrication
- Technological innovation is complementary with material advances.
- Multi-layer metal scaffold demonstrated for high-surface-area electrolytic capacitors (MEMS 2010 conference) and Zn-Air batteries (upcoming PowerMEMS 2010 conference)

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