Integrated Magnetic Components for Distributed Power Electronics

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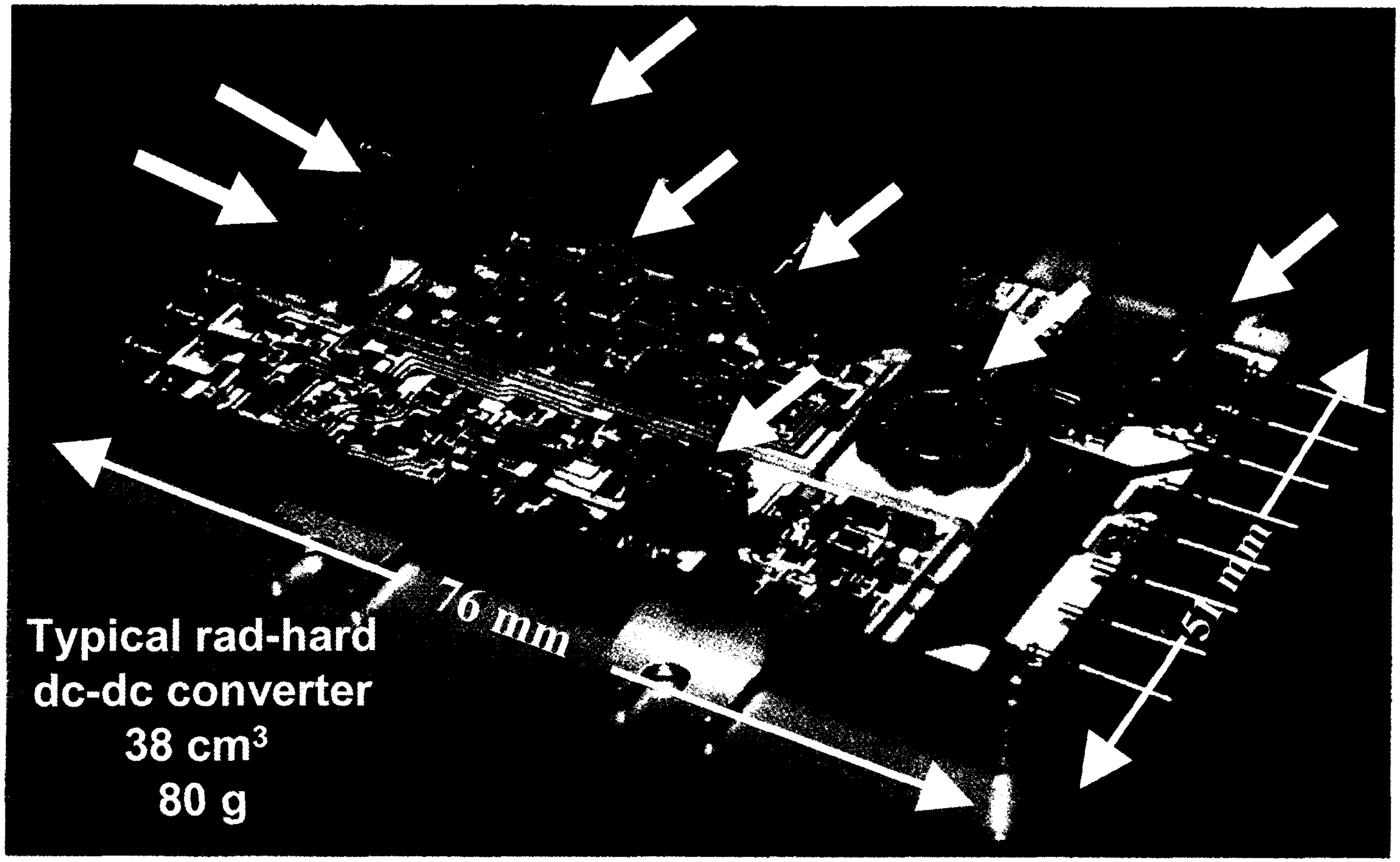
Integral Wave Technologies

Today's Space Power Converter Technology



-magnetic components required for energy storage, filtering and isolation
-still difficult to miniaturize and integrate power magnetics
-power electronics remain a mass/volume burden for spacecraft avionics

Spacecraft power electronics considerations

JPL/NASA Philosophy--*Need design flexibility*

-would rather develop one small (e.g., 10 W) converter

-parallel smaller converters for 20, 30, 100 W (using modular *slices*)

-avoid designing a 100 W converter that is never used again

-looking for methods of high density packaging to cut down on passives

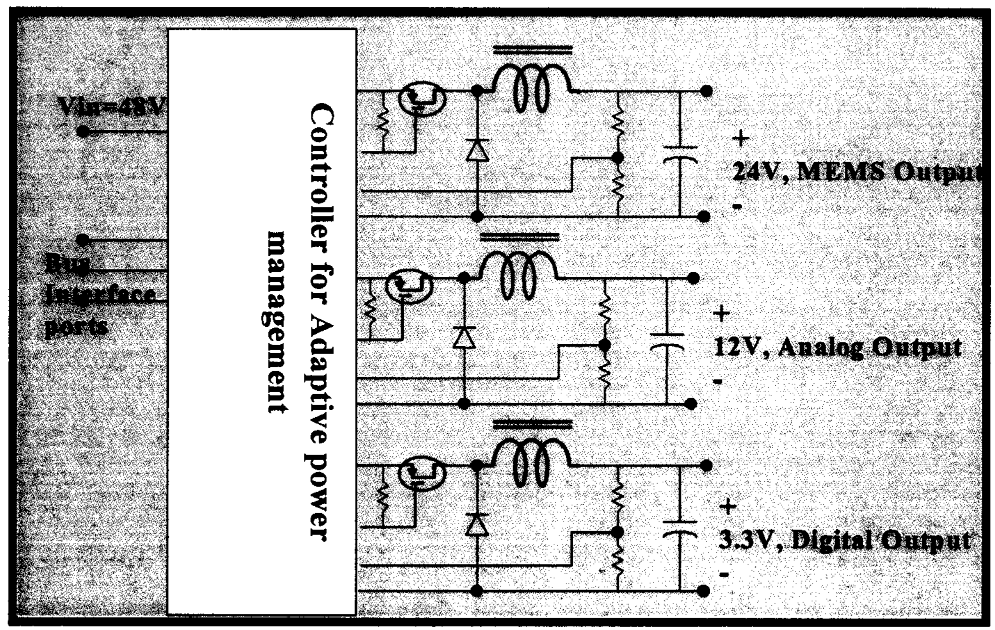
-combine passives/switching/control

-move to distributed power

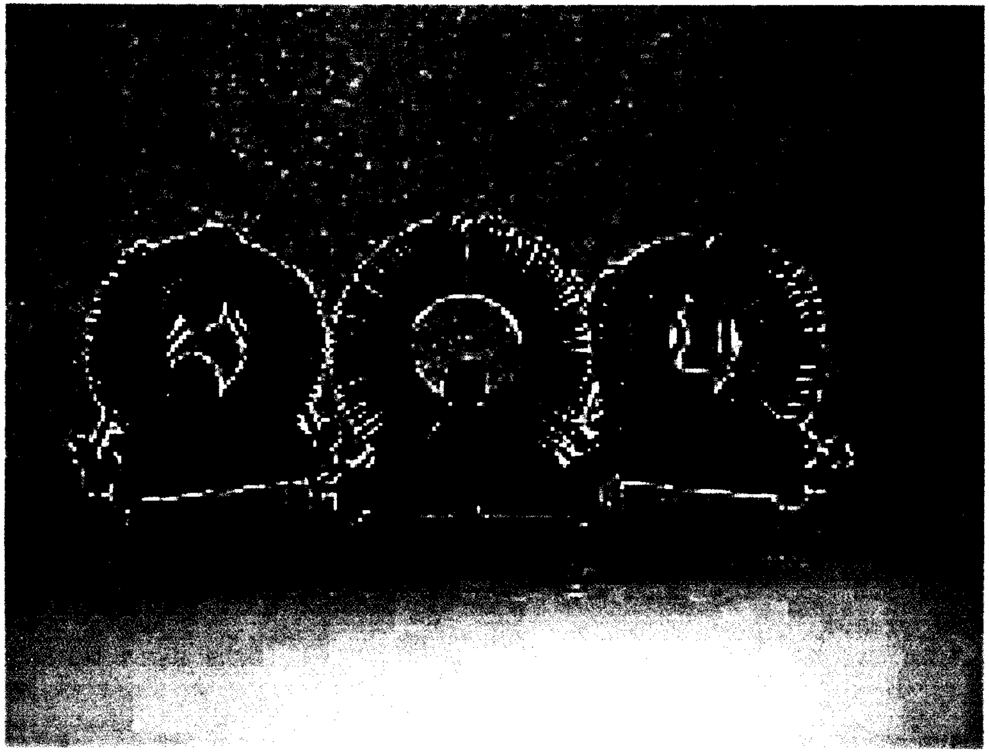
-no longer wind our own magnetics

-batch fabrication would be great

-are *integrated* magnetics the answer?

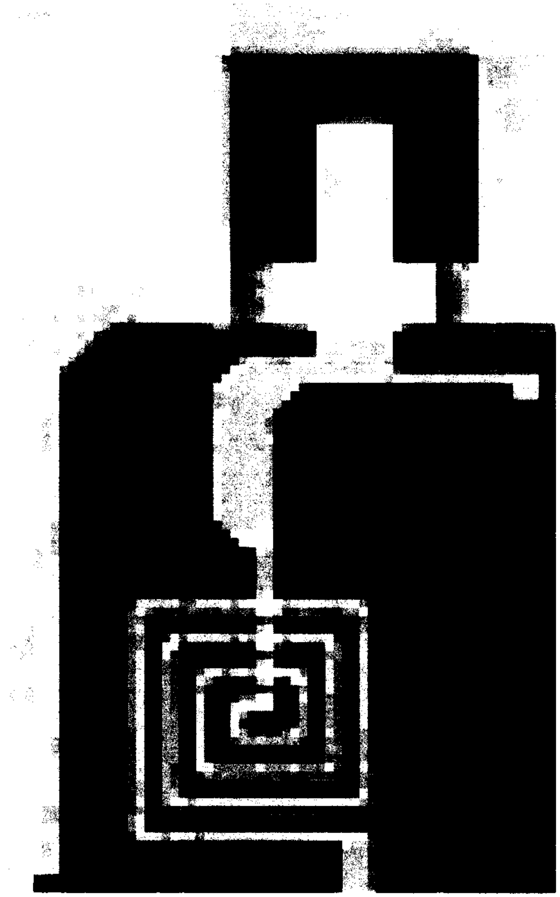


Discrete vs. integrated inductors



Discrete, surface mount inductors
Heavy gauge copper wire wound around a ferrite based core

High inductance *but* high mass and volume

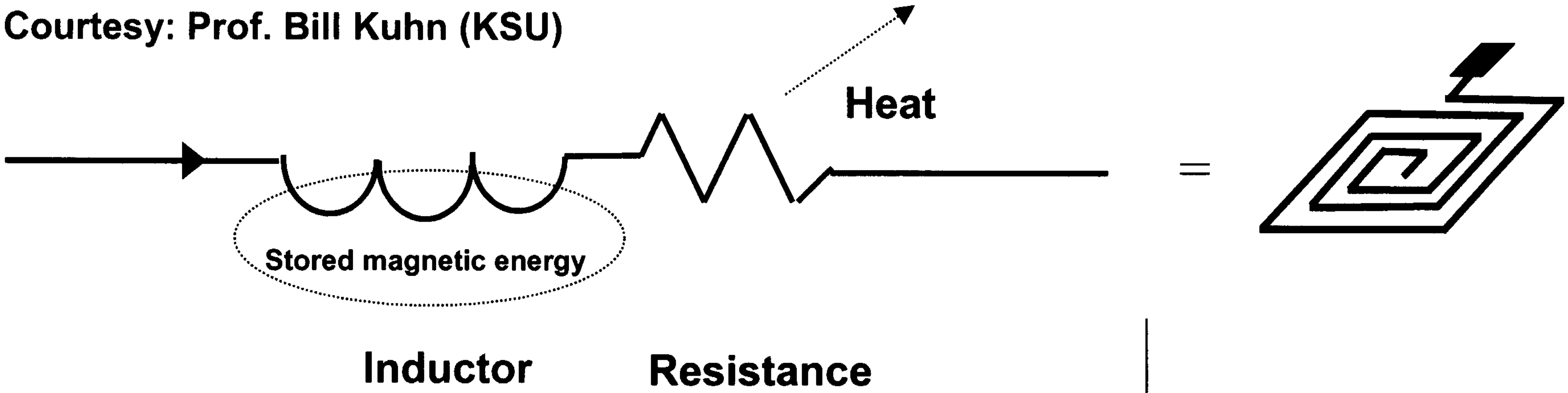


Integrated inductors
Spiral metal trace on silicon

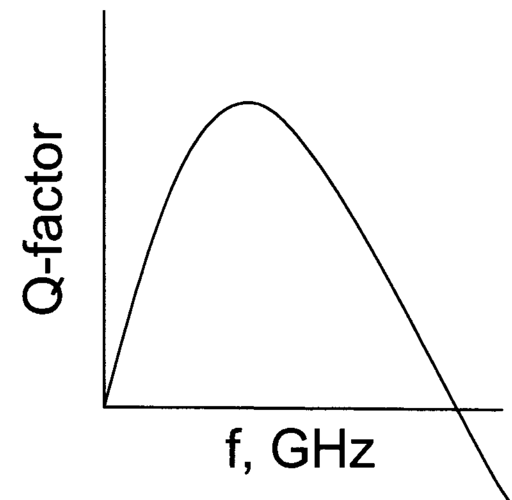
Low mass and volume *but* low inductance

Integrated Microinductor Approximated By a Metal Spiral

Courtesy: Prof. Bill Kuhn (KSU)



$$Q = \frac{2\pi \text{ Energy Stored}}{\text{Energy Dissipated}} = \frac{fL}{R}$$



- Increasing *N* means increasing *R*, thereby decreasing *Q* and SRF
- Could operate at a higher (>500 MHz) frequency, but not optimal for power
- Enhance L by adding magnetic materials; keep R low by using thick Cu lines
- Important to have Q peak in key power region of 1-10 MHz

Microinductor challenges

- Small volume of core
  - t= film thickness, effective cross section area of core limited
  - $\mu \bullet t$ is critical parameter (permeance)
- Frequency response
  - -reduce losses at 1-10 MHz (smaller size, but less efficient)
  - -need new "power materials" that can be readily integrated
  - -don't have access to hundreds of core materials and shapes
- Packaging/Integration
  - -minimize footprint
  - -thermal management (can be benefit)
  - -performance (parasitics, sensitivity to environment)
- Need the proper combination of:
  - -inductance
  - -resistance
  - -area
  - -Q (1-10 MHz)
  - -current handling

“Micro-fabricated” inductors

-Earliest investigations in the 1970’s (sputtered/evaporated alloys as the “core”)

-Honeywell investigated electroplated inductors in the early 1980’s

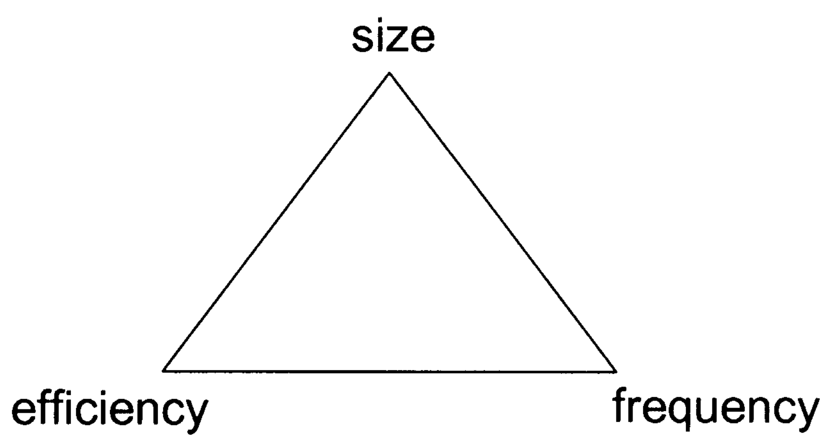
-Lucent and others investigated in the 1990’s

-More recently various academic groups (Japan, Europe, U.S.)

-Still no real application of a microinductor for power

Need the right balance of (conflicting) characteristics

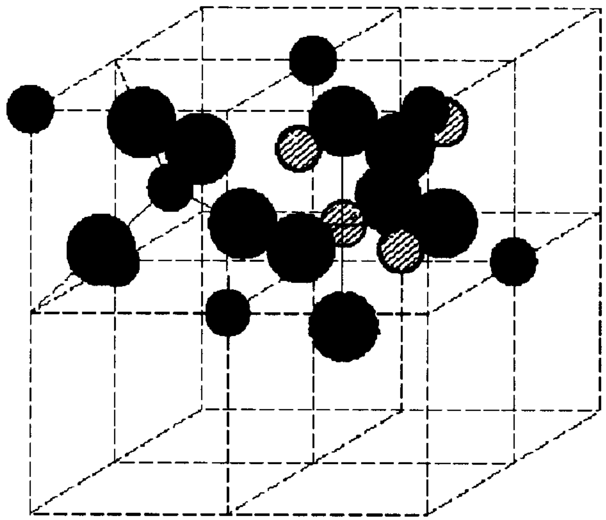
- Inductance (favored by more turns, which increases R)
- Resistance (favored by less turns, which decreases L)
- Size (very restricted)
- Low loss and high Q (difficult between 1-10 MHz)
- Frequency of operation (sufficient Q difficult)
- Current handling and power (less volume, easy saturation)
- Ease of fabrication (annealing? magnetic fields? materials costs? laminations?)



NASA

Candidate Magnetic Materials

JPL



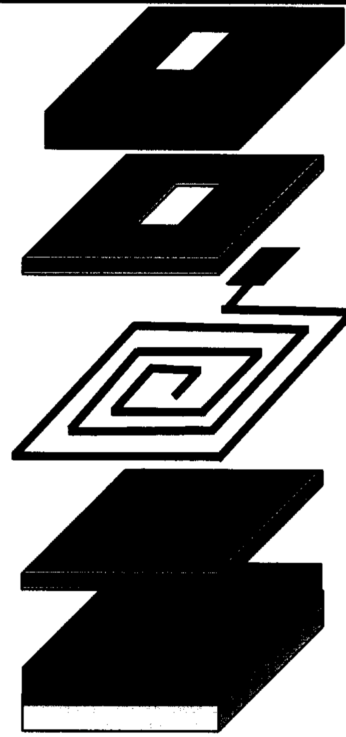
Spinel Ferrite structure

Ferrites
- classic high frequency material
- low saturation magnetization
- difficult to deposit, require high temp. processing

Ferromagnetic metals
- well suited for thin film deposition
- high permeability leads to enhanced inductance
- low resistivity limits high frequency application

Material	B_{max}, G	μ	H_c, Oe	ρ, $\mu\Omega$–cm	Deposition Methods
Ferrites	5,000	1000	1	**10^7**	sputtering, stencil printing
Ferromagnetic metals	**24,000**	**3500**	**<0.05**	10^2	sputtering, **electroplating**

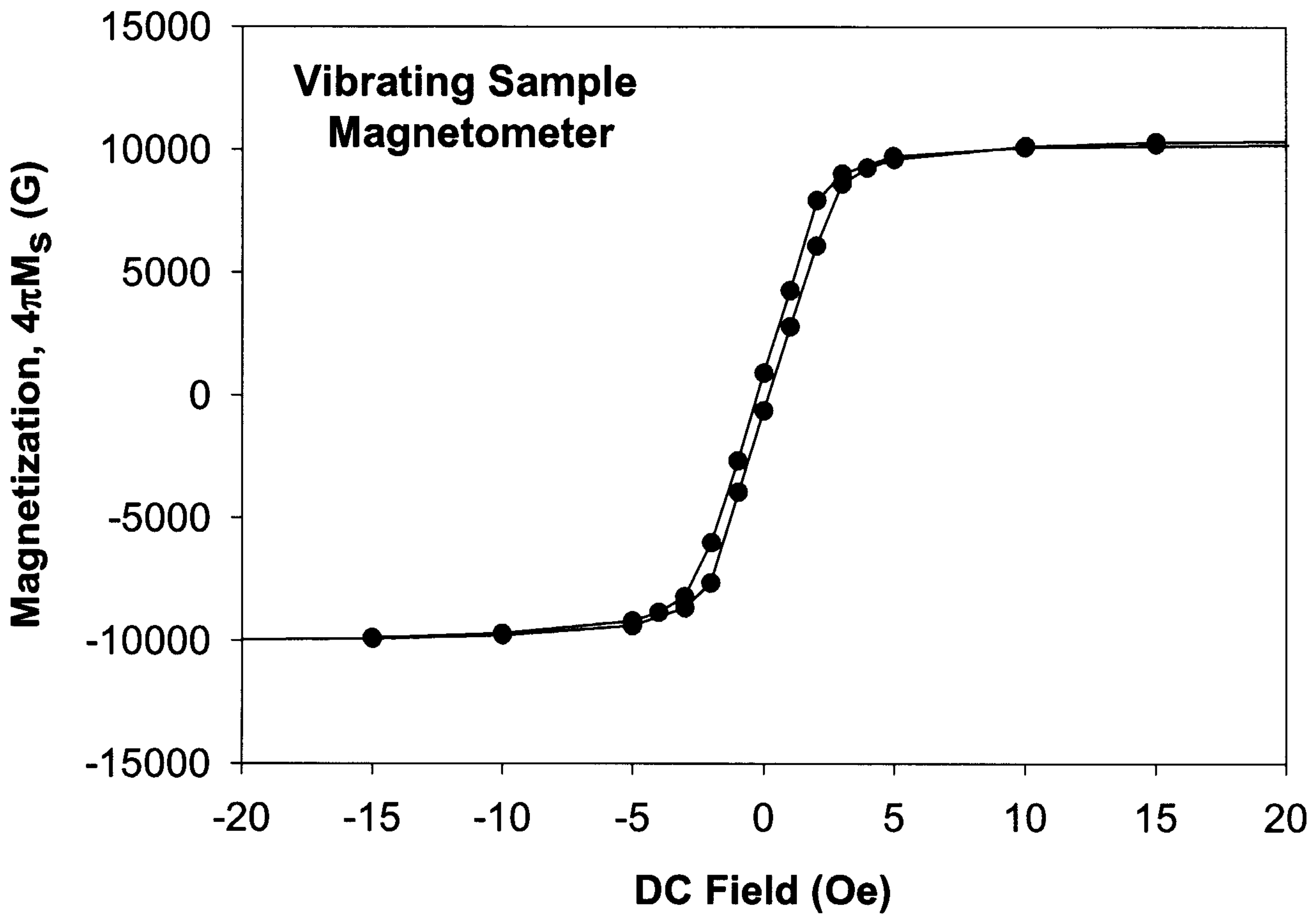
Microfabricated "Micro-inductors"



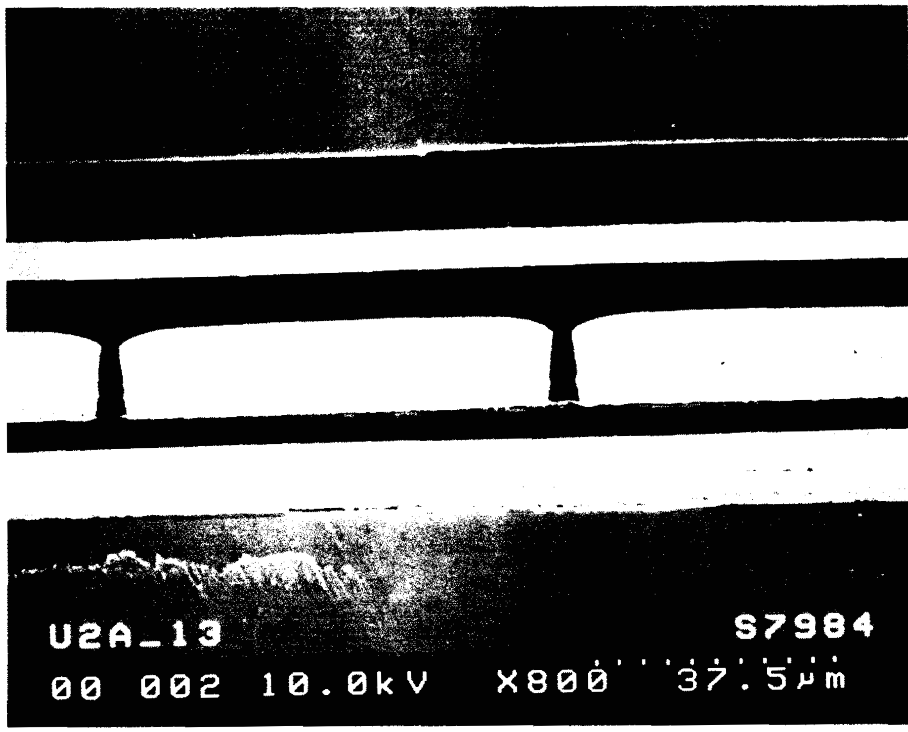
Permalloy:	electroplated, using SJR 5740 photoresist
SU-8:	applied with multiple spin coats
Copper:	plated, using SJR 5740 photoresist
Polyimide:	photo-imaged, PPI

Permalloy vibrating sample magnetometer data

Electroplated NiFe using standard Permalloy Bath
composition ≈ 80% Ni 20% Fe



Cross-sectional SEM of a typical microinductor

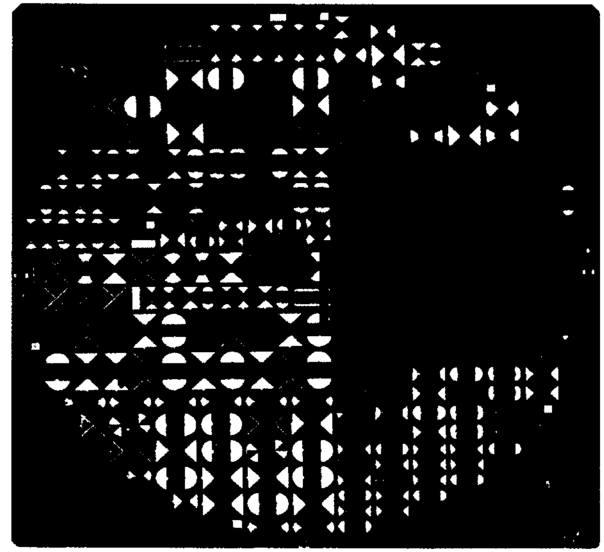


-resembles “pot core” geometry in which windings are buried in magnetics

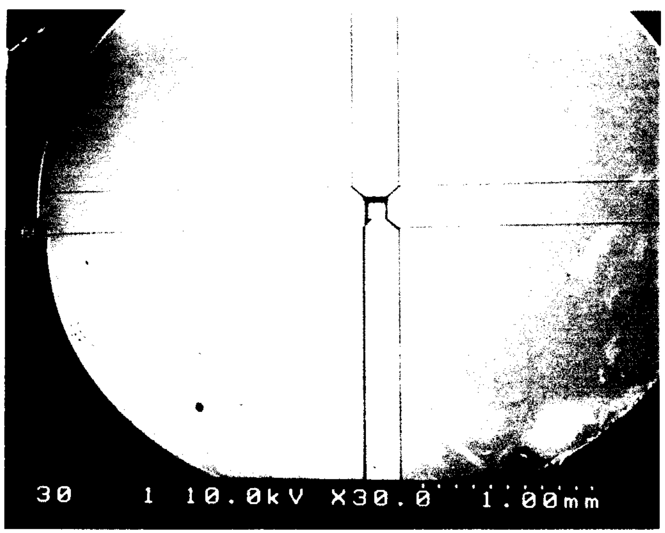
-should be better for shielding of EMI

JPL Batch Fabrication of Microinductors

Silicon wafer with 284 microinductors



Close-up of microinductors



Top view of microinductor

Example test structure on glass:

N = 30 turns

Area = 13 mm^2 (round)

Line width = 58 μm line widths

Line spacings = 6 μm

Copper thickness = 11.4 μm

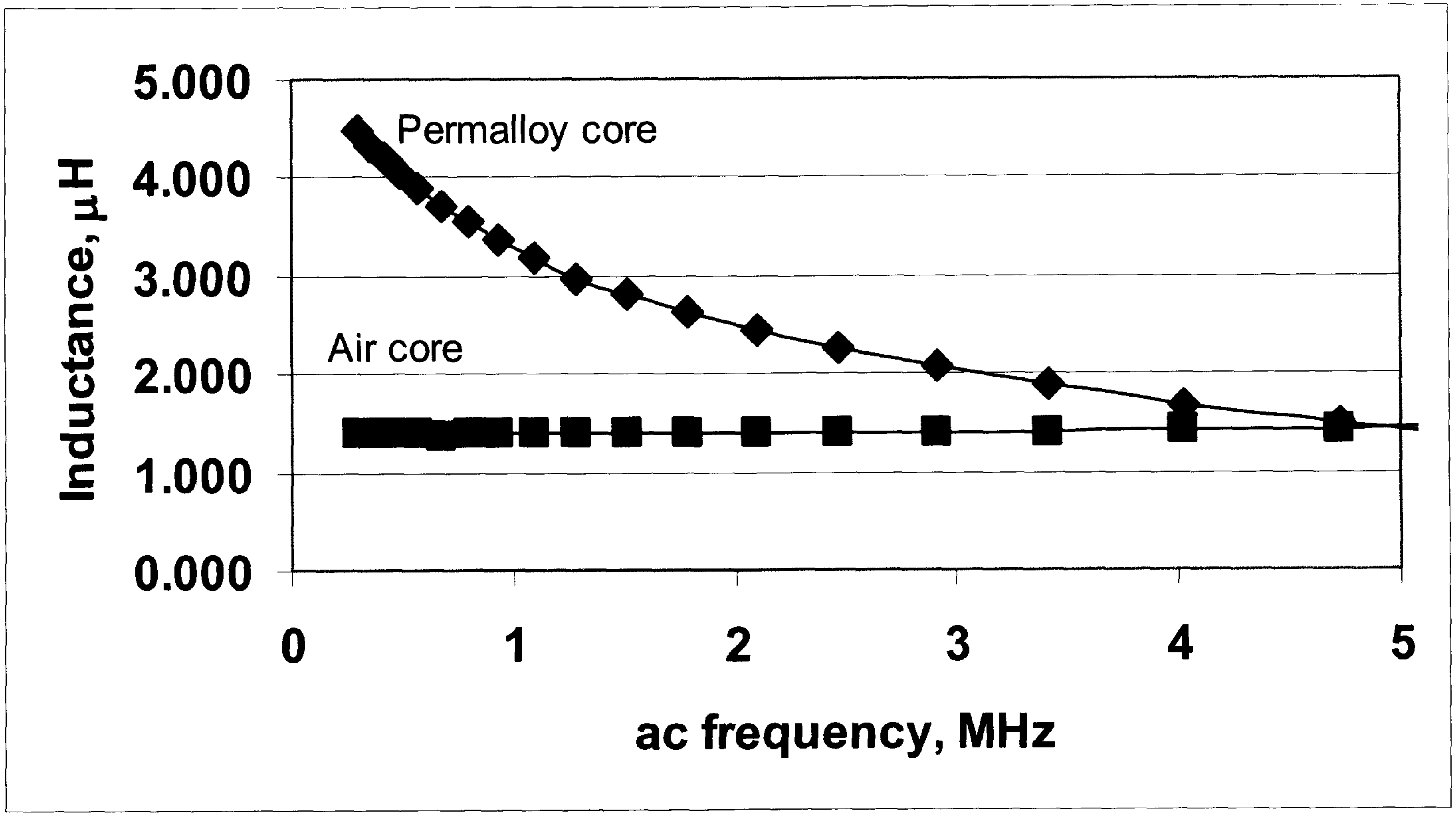
Lower Permalloy thickness = 2.3 μm

Upper Permalloy thickness = 3.5 μm

Enhancement over air core values

L = 3.2 μH at 1 MHz

R = 16.3 Ω at 1 MHz (DCR = 5.1 Ω)



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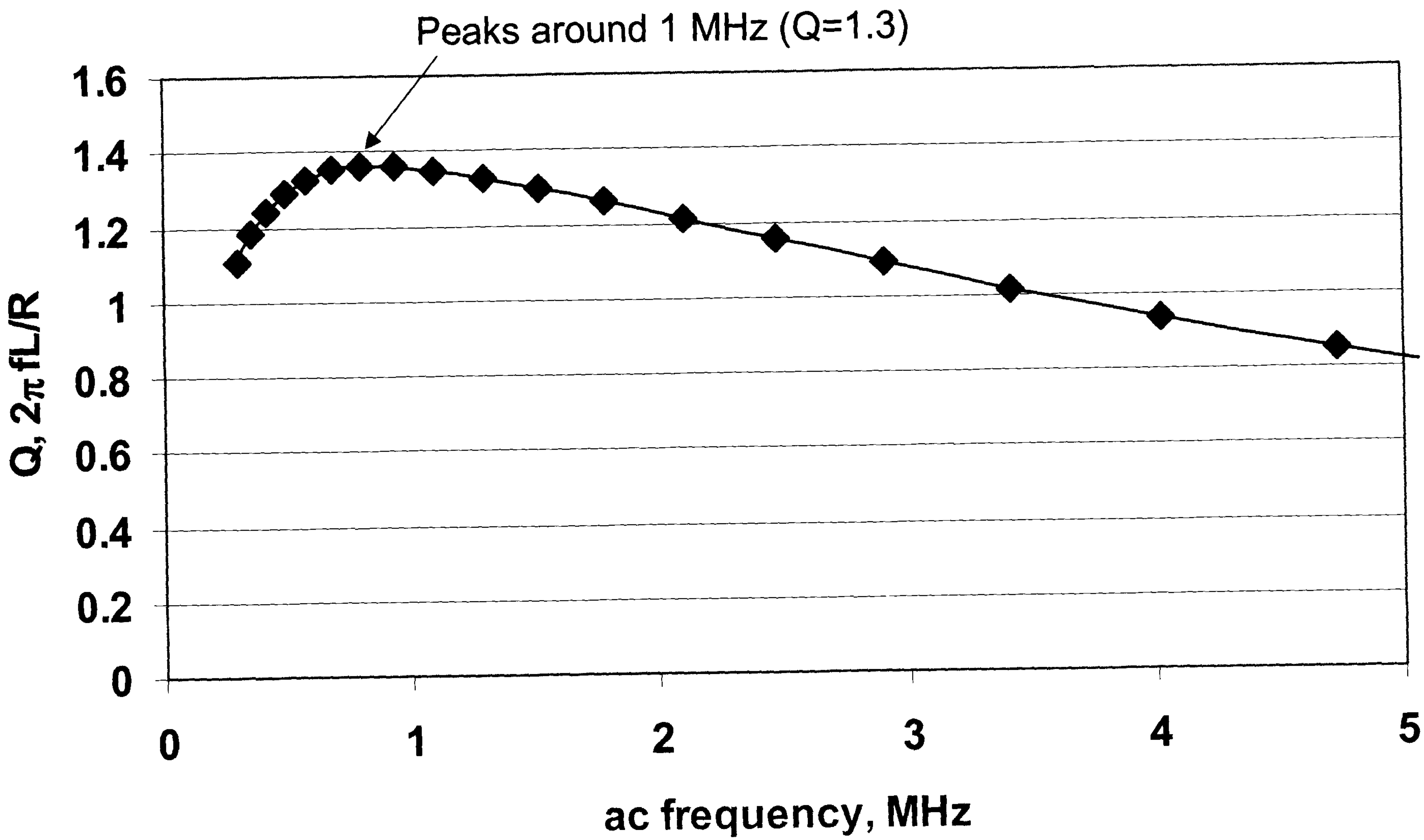
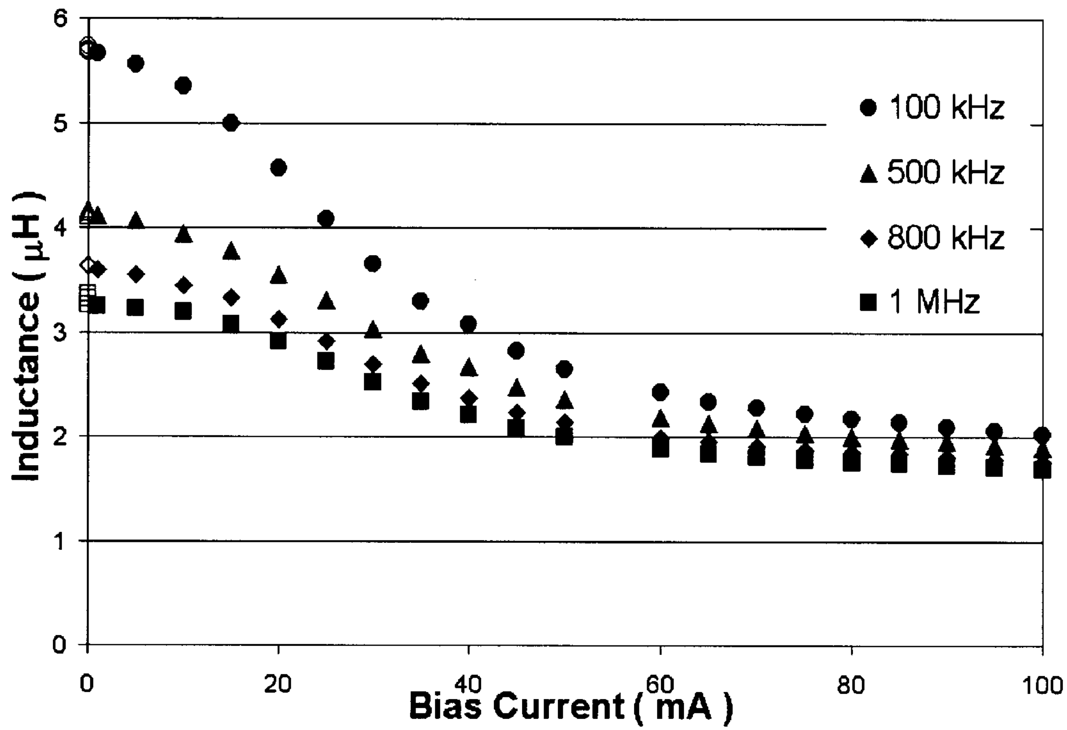
Q peaks in the critical power region

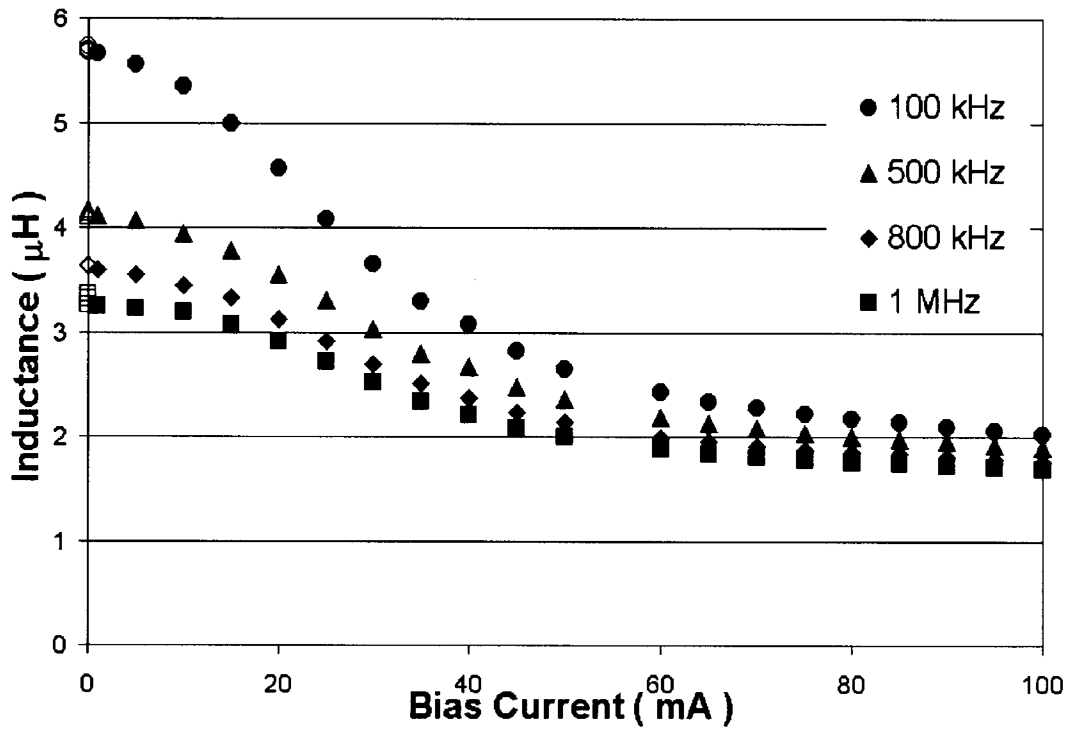


Current response



Inductance vs. bias current with 7.5 mA RMS alternating current at 100 kHz, 500 kHz, 800 kHz, and 1 MHz

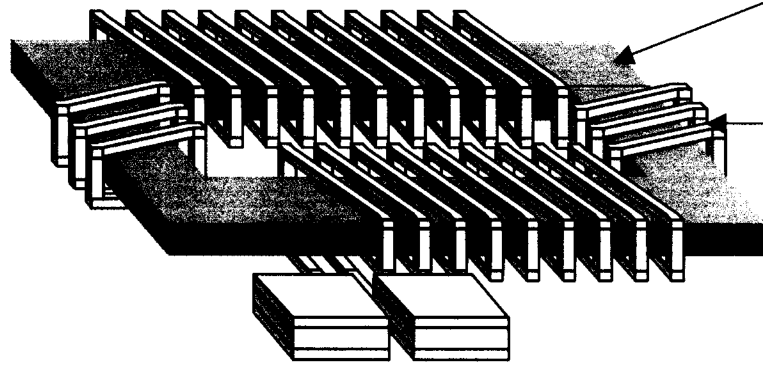
Current response



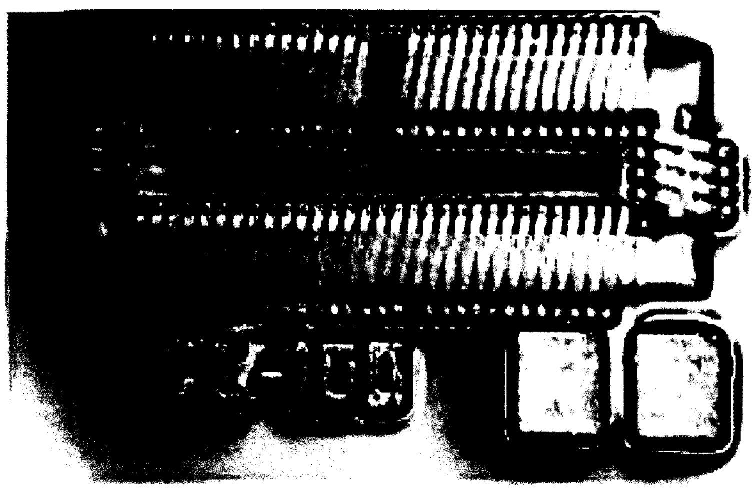
Inductance vs. bias current with 7.5 mA RMS alternating current at 100 kHz, 500 kHz, 800 kHz, and 1 MHz

University of Cincinnati-Toroidal Approach

UNIVERSITY OF Cincinnati

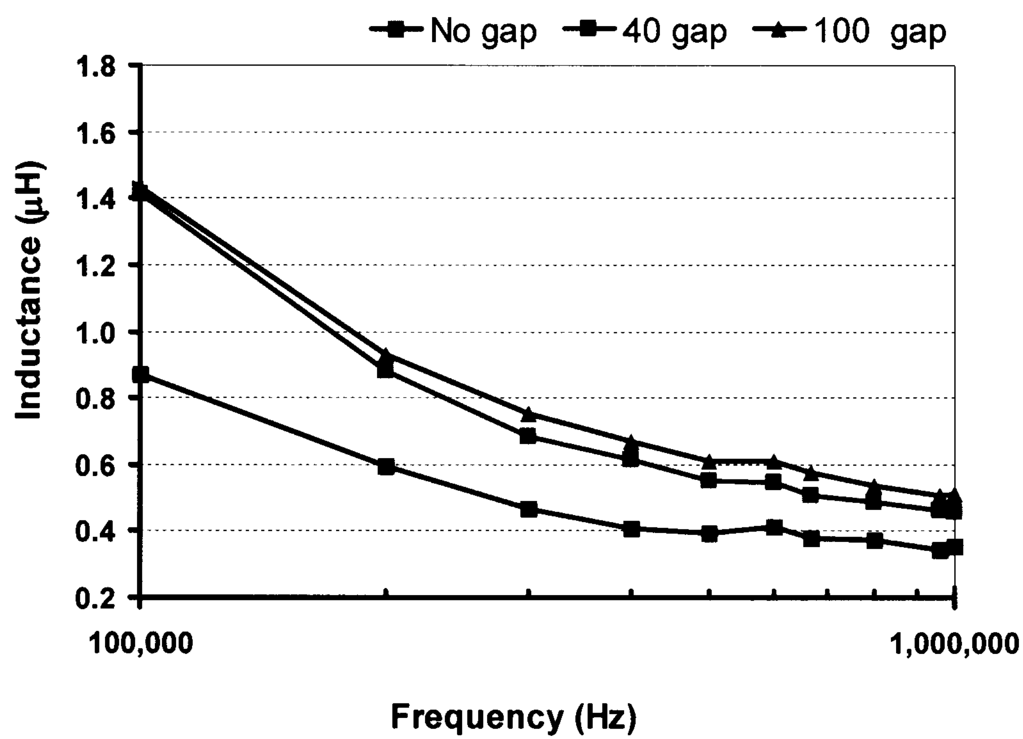


(a)



Courtesy: Prof. Chong Ahn (UC)

(From Final Report to JPL)



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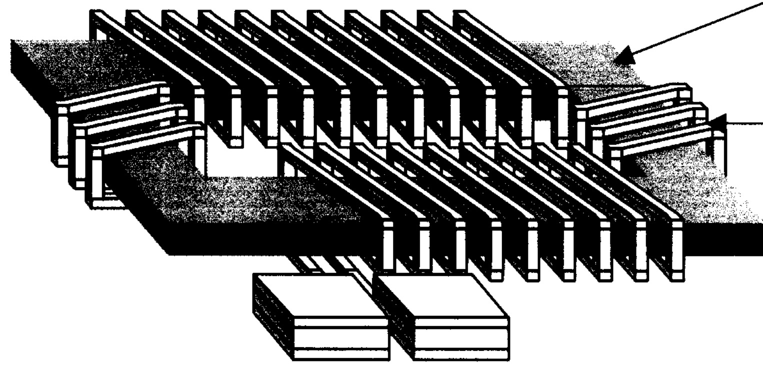

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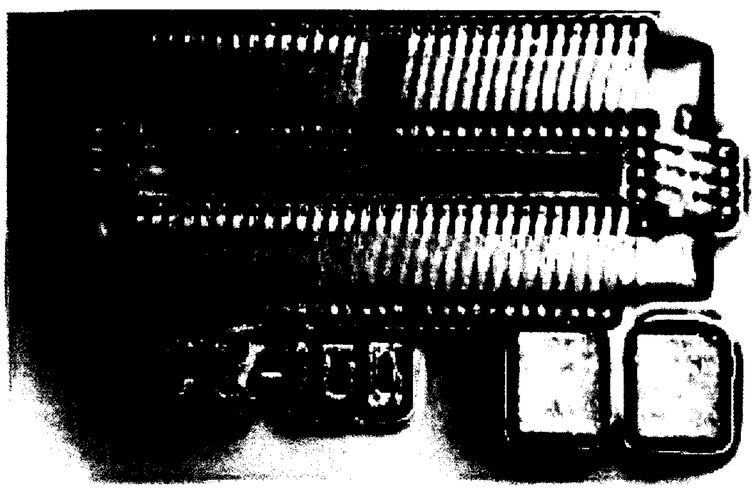
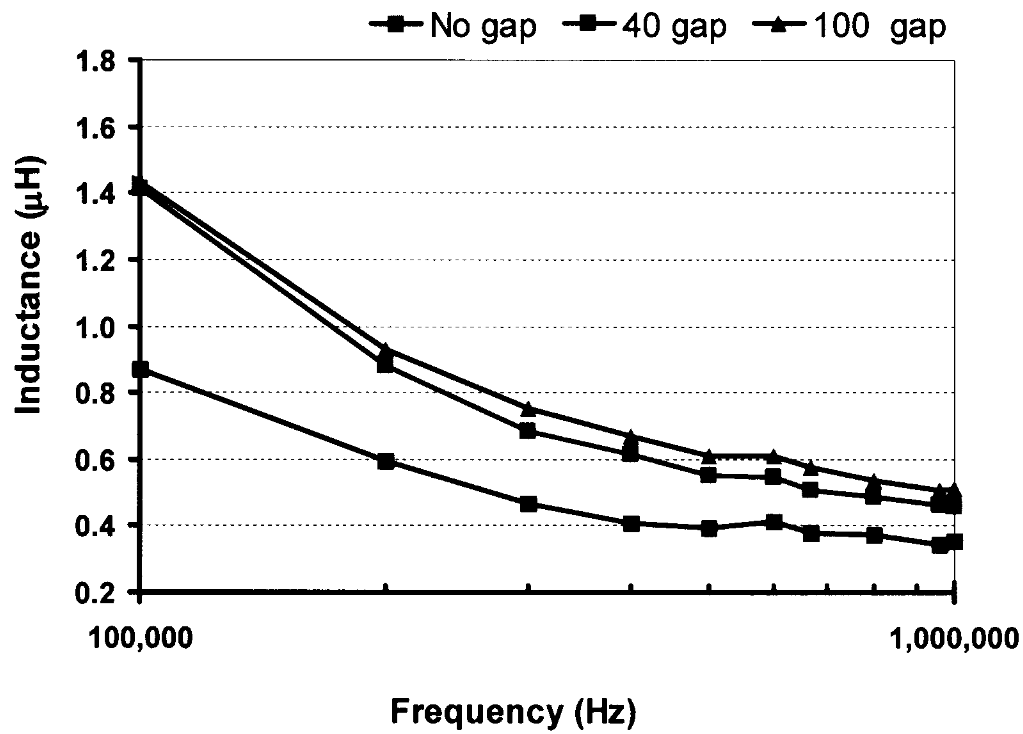




Courtesy: Prof. Chong Ahn (UC)

(From Final Report to JPL)

Improving Microinductor Performance

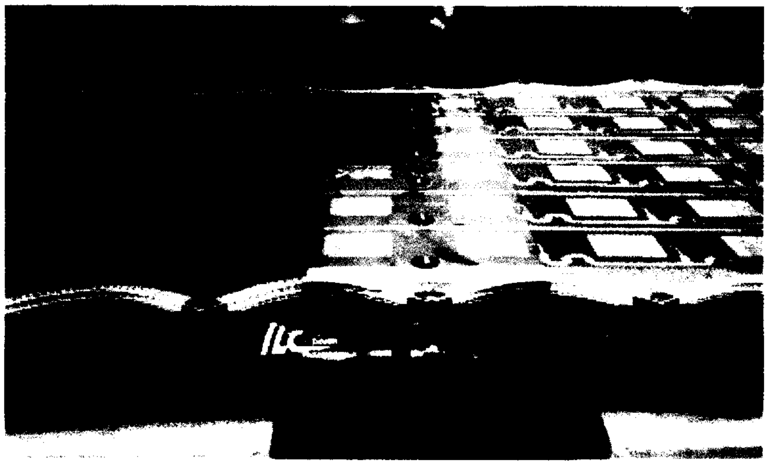
Frequency response
- -add laminations (costly and more processing)
- -new materials (ternary and quaternary alloys, ferrites)
- -control anisotropy (how much does this help?)

Current
- -gaps (difficult to model)
- -new materials (Co alloys)

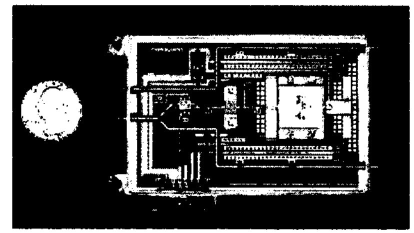
DC resistance
- -thicker copper (at the sacrifice of higher ac resistance?)
- -larger area (sacrifice miniaturization)

Inflatable and Deployable Structures

Active membrane synthetic aperture radar (SAR) antennas including flex-compatible T/R modules (for mapping, surface monitoring and change detection of Earth)

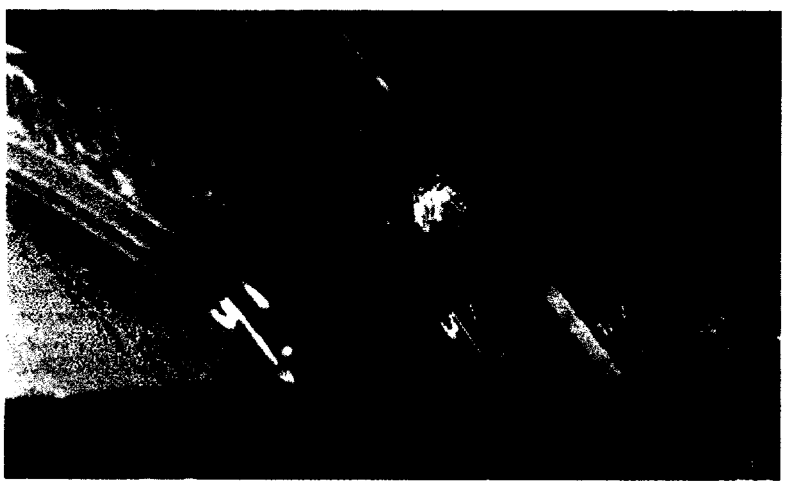


Courtesy: Dr. Alina Moussessian (JPL)



T/R module

Current passive inflatable membrane antenna



Benefits of an active antenna:

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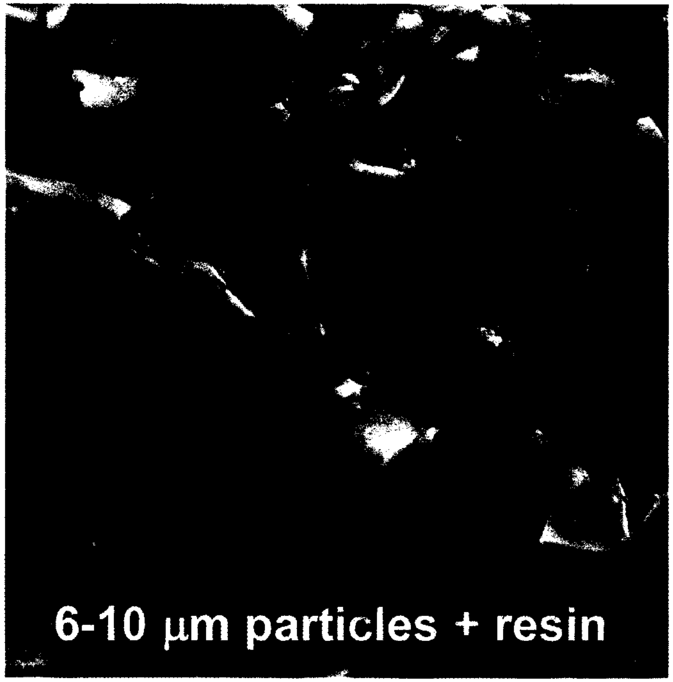
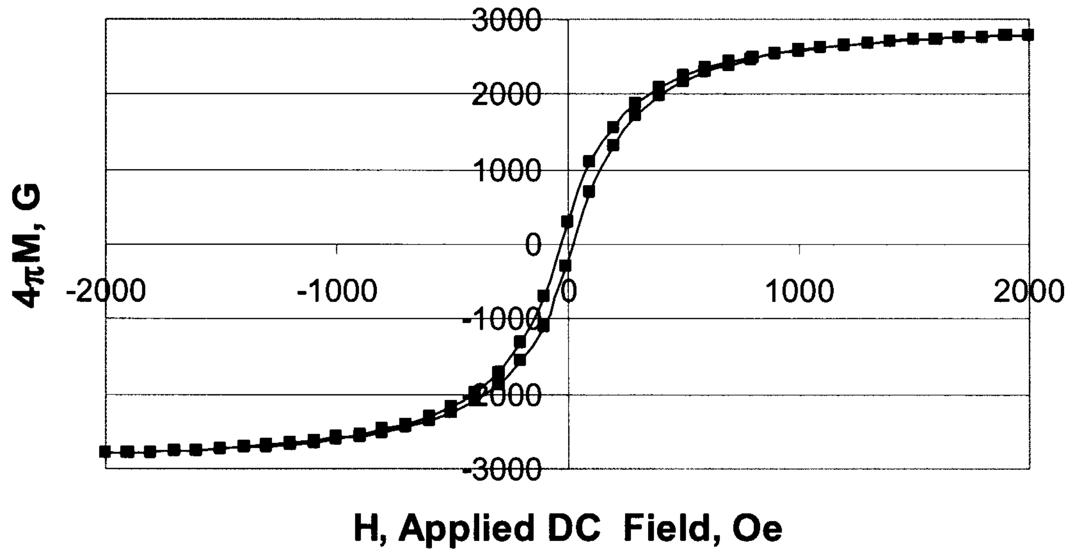
Ferrite polymer composite thick films



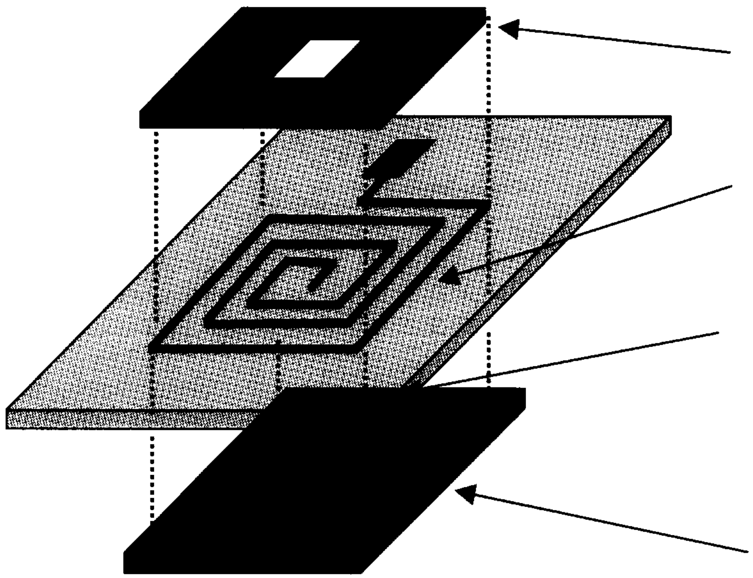
SEM of stencil printed
Ferrite-polymer composite film

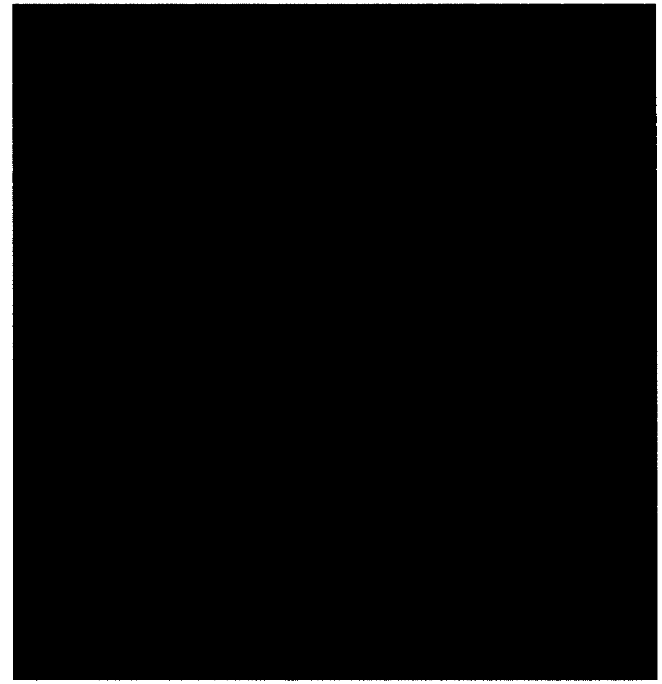


Magnetization curve for printed magnetic film

-Developing novel stencil printed ferrite-polymer composite films
-Stencil and screen printed inks with solvent + resin + ferrite
-Cured at low temperatures-easy integration with heat sensitive substrates
-Enable thicker films to be deposited
-Provide higher frequency operation and higher current handling
-Lower magnetization due to use of ferrites

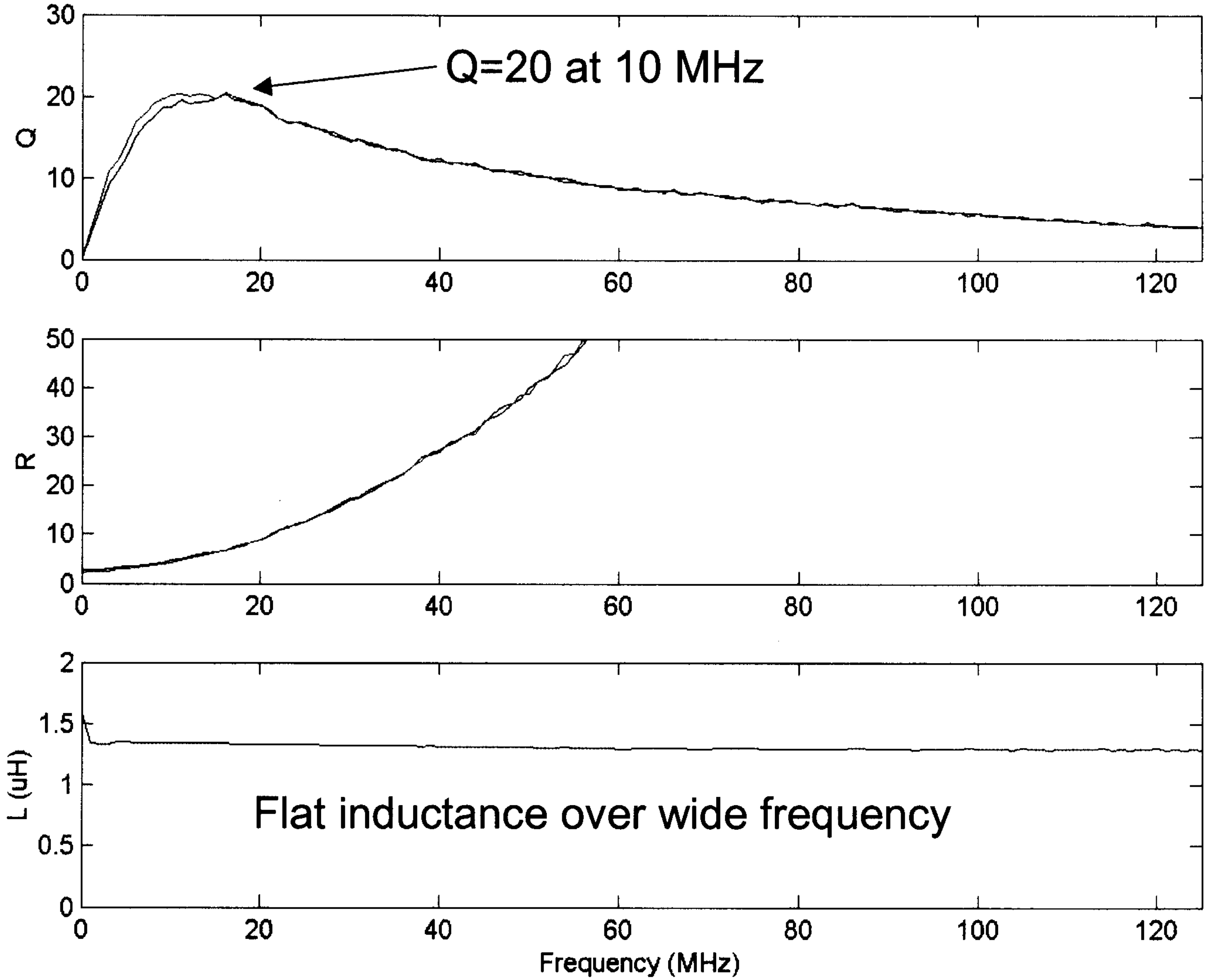
Screen printed inductors





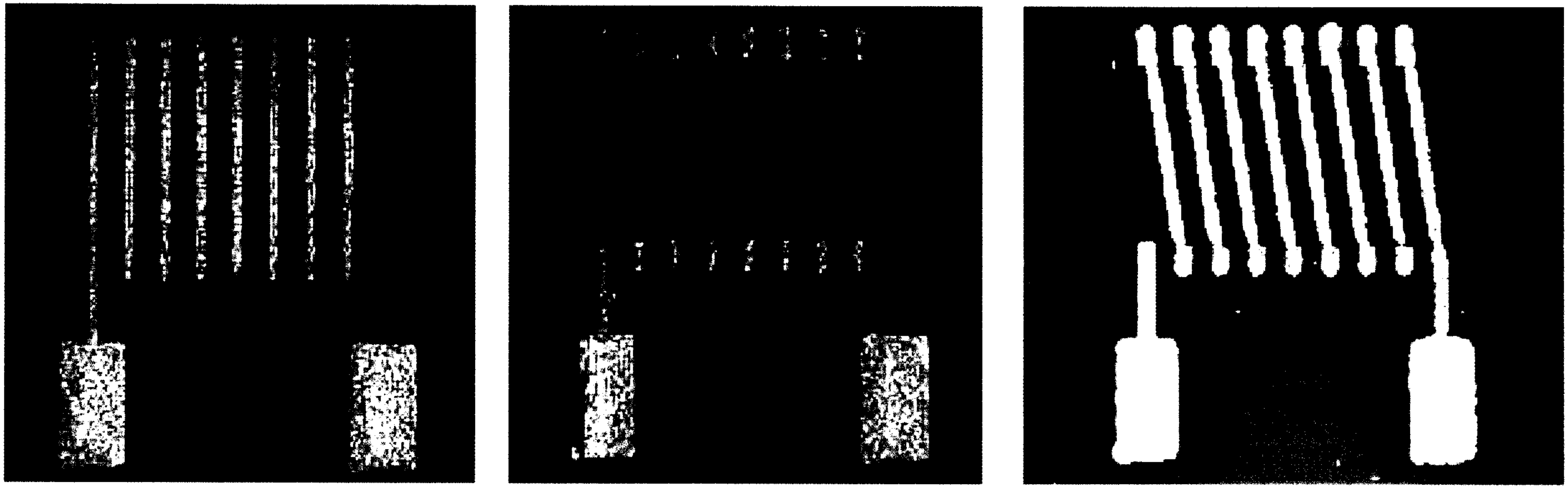
5 mm x 5 mm, 11 turn
coil-on-flex
Mn-Zn composite

Q peaks between 1-10 MHz, flat inductance



Data courtesy of Bill Kuhn (KSU)

Low Temperature Direct Write of Electronic Components



Multilayer, mH inductor coil drwan by printing bottom silver lines, overcoating ferrite layers, and Connecting the botton over the ferrites to complete a spiral coil.

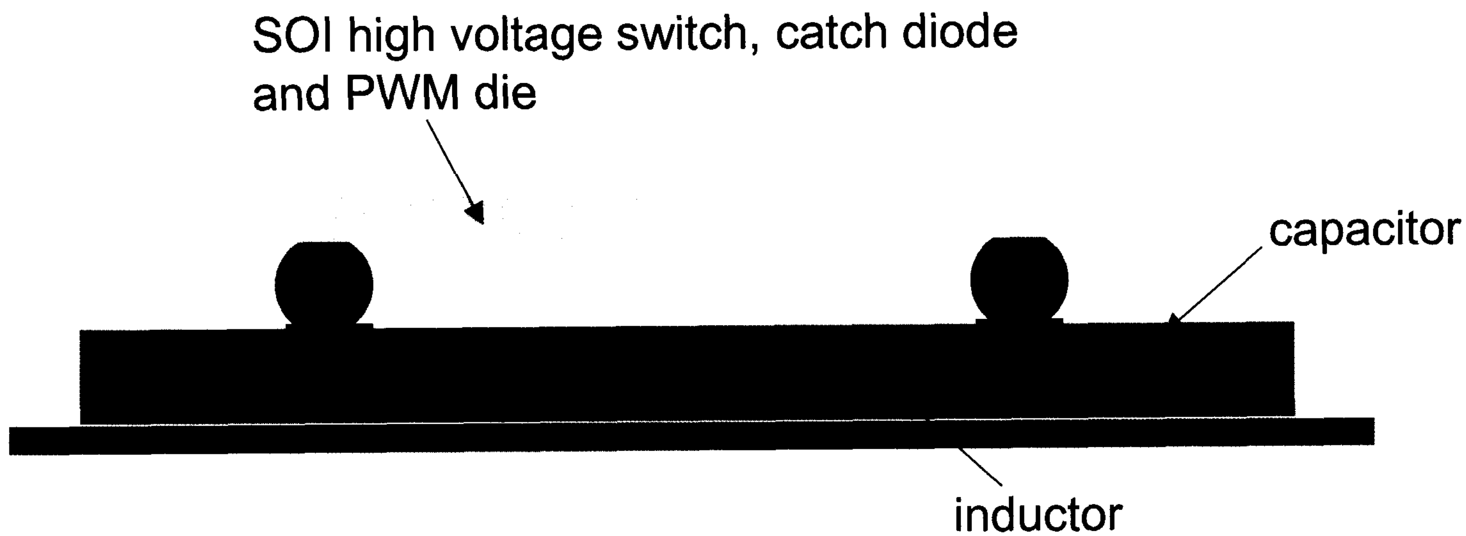
pgclem@sandia.gov

Courtesy: Paul Clem, Sandia National Labs

(505) 845-7544,

http://www.sandia.gov/materials/sciences/factsheets/LoTempWrtElcCom2.html

Packaging and integration of a dc-dc converter



Multi-layer passive test structure (capacitors, resistors)

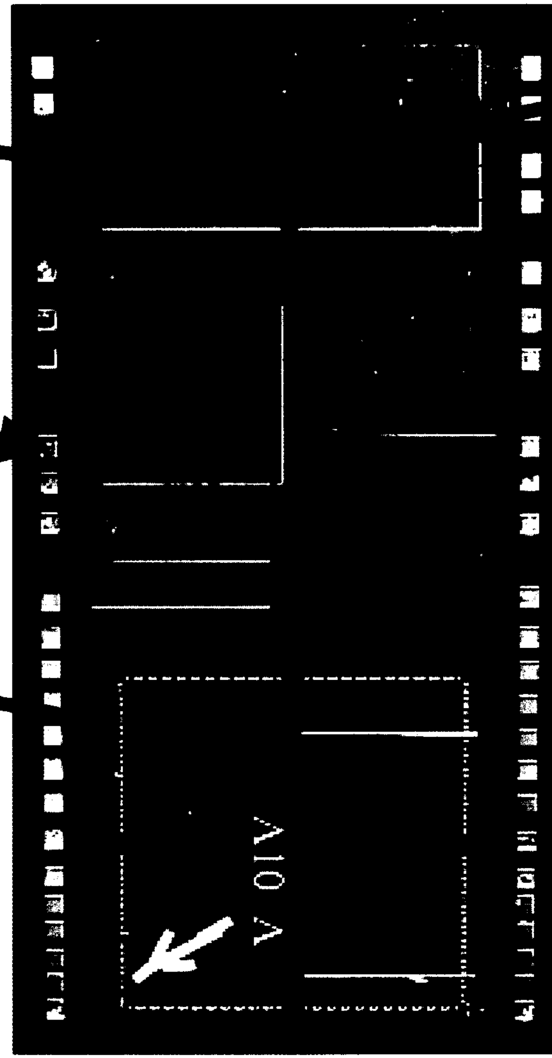
Anodized tantalum oxide capacitors

sputtered Cr-Si resistor

Gold test pads

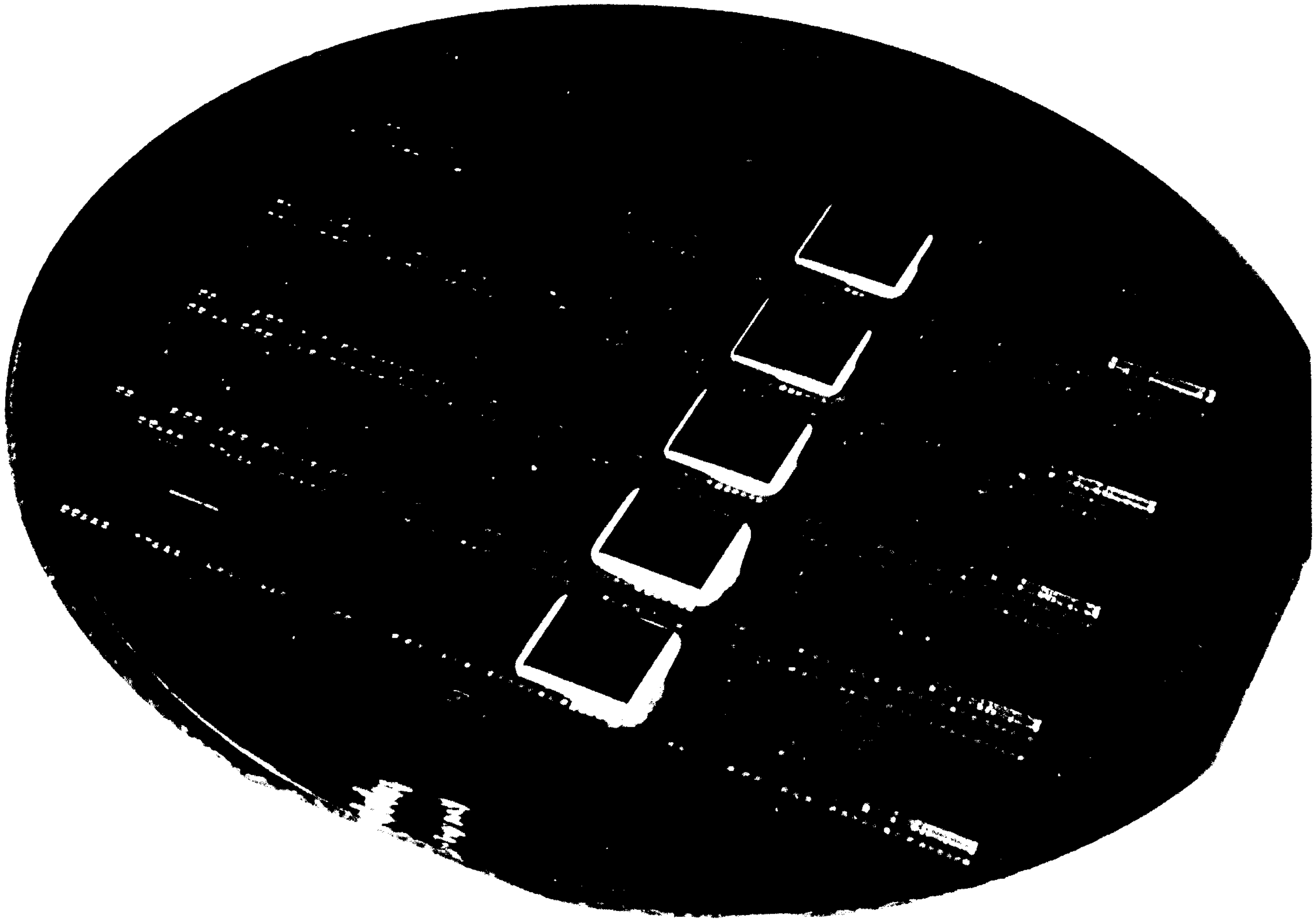
Spin-on BCB capacitors

Ni-Au metallization trace for flip-chip bonding of daisy chain test die



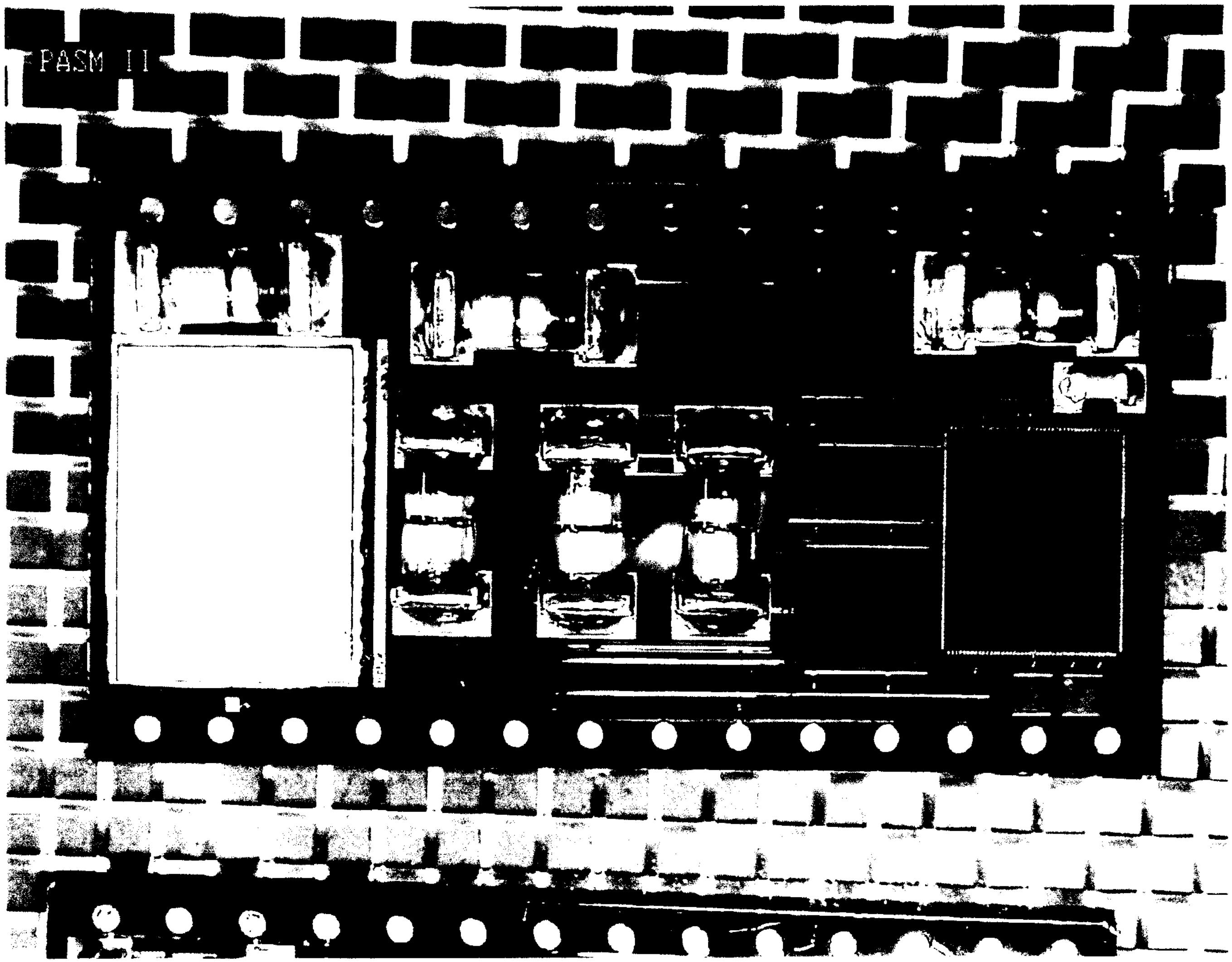
Fabricated by Integral Wave Technologies (Arkansas)

Integrated passives modules



Fabricated by Integral Wave Technologies, Flip Chip at Auburn University

Power switching circuit with integrated passives

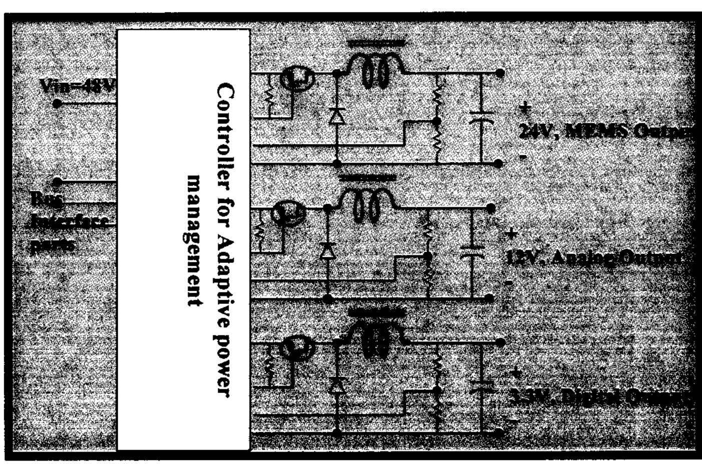


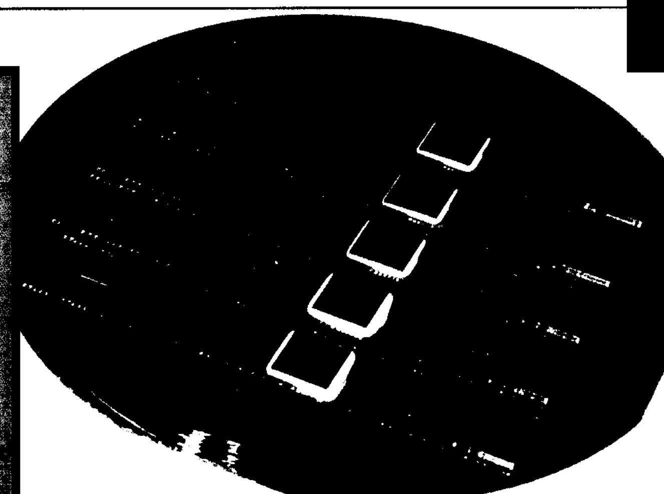
Integrated Magnetic Components for Distributed Power Electronics

• Integration of passive components can play a key role in the miniaturization of spacecraft avionics

• Reducing the mass and volume of spacecraft power electronics will require advances in integrated passives, particularly magnetic components

• Significant challenges remain, including choosing proper materials, as well as addressing design, layout and test and re-work issues





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