Electrodeposition of high permeability films

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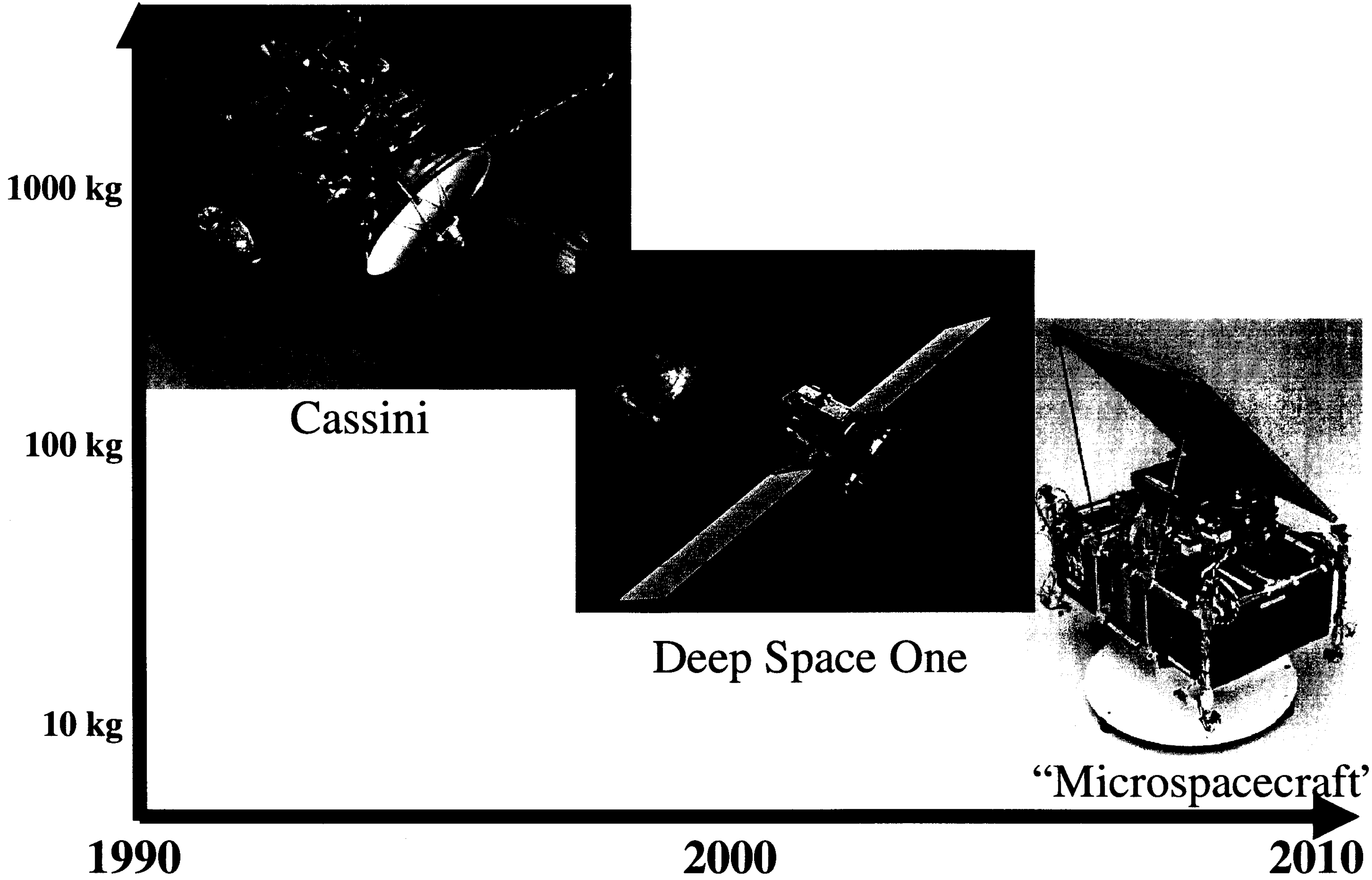
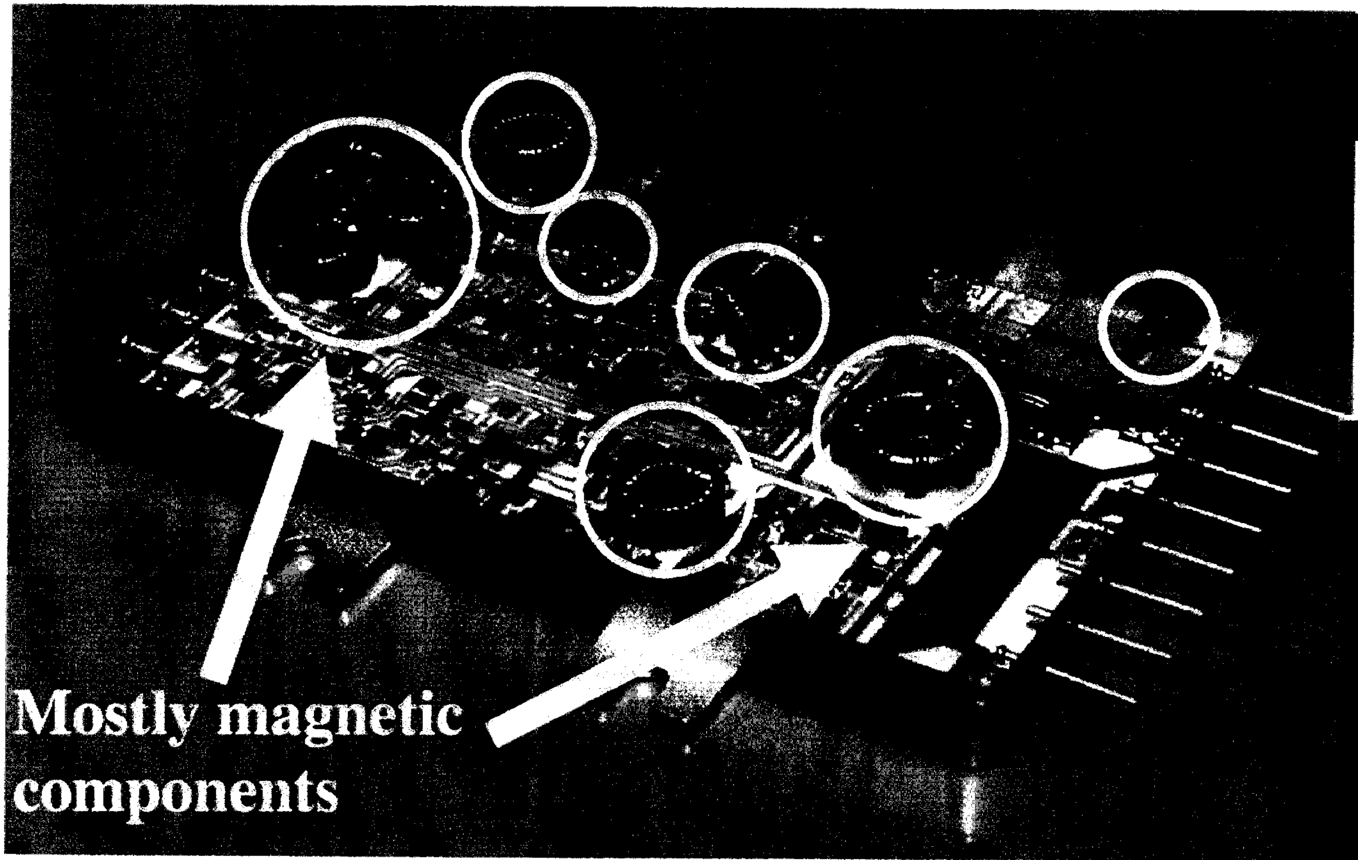
Reduction in spacecraft mass and volume



Power electronics continue to defy miniaturization



Mostly magnetic components

State-of-the-art, space rated dc-dc converter

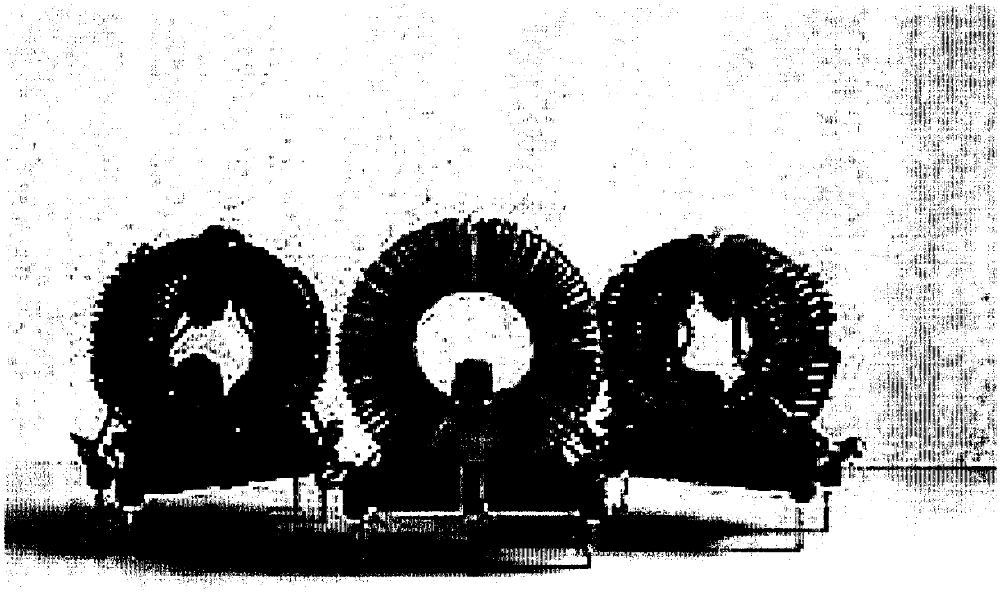
4000 mm^2, 80 g

Integrated, on-chip power converter

4 mm^2, 1 g

Problem: How do we integrated "passive" components?

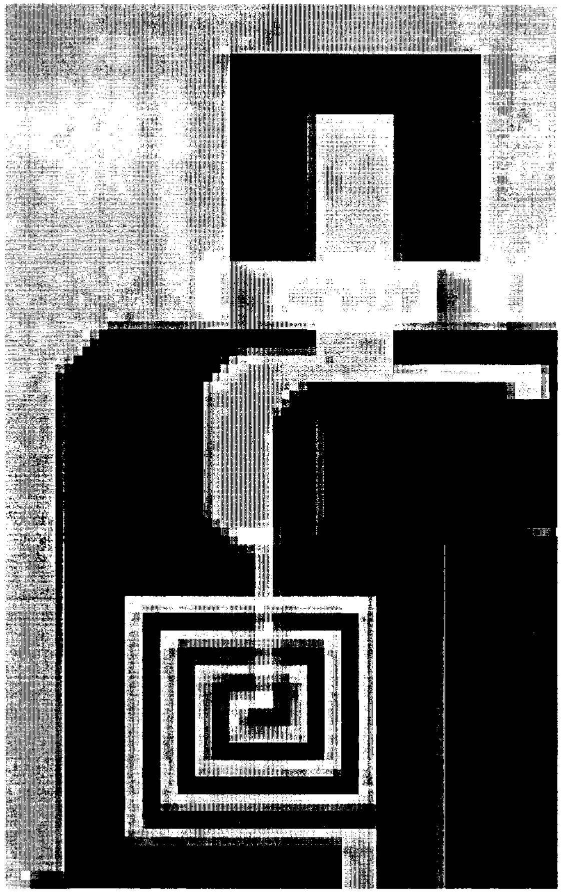
Discrete vs. integrated inductors



Discrete, surface mount inductors

Heavy gauge copper wire wound around a ferrite based core

High inductance *but* high mass and volume

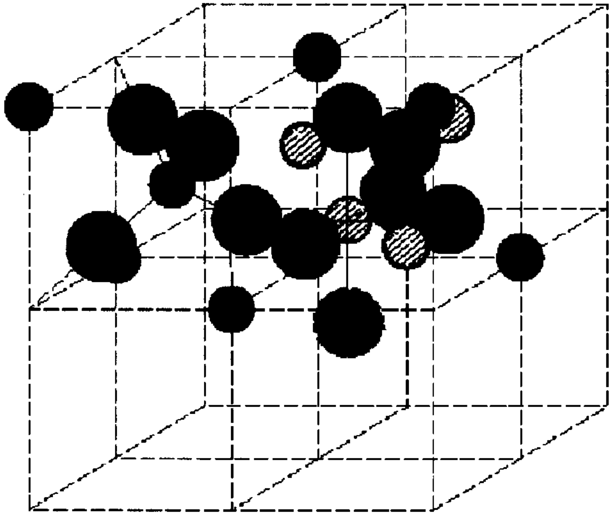


Integrated inductors

Spiral metal trace on silicon

Low mass and volume *but* low inductance

Classic power magnetics are incompatible with silicon based technology



Ferrite Spinel Structure

Ferrites or "Ceramic Magnets"

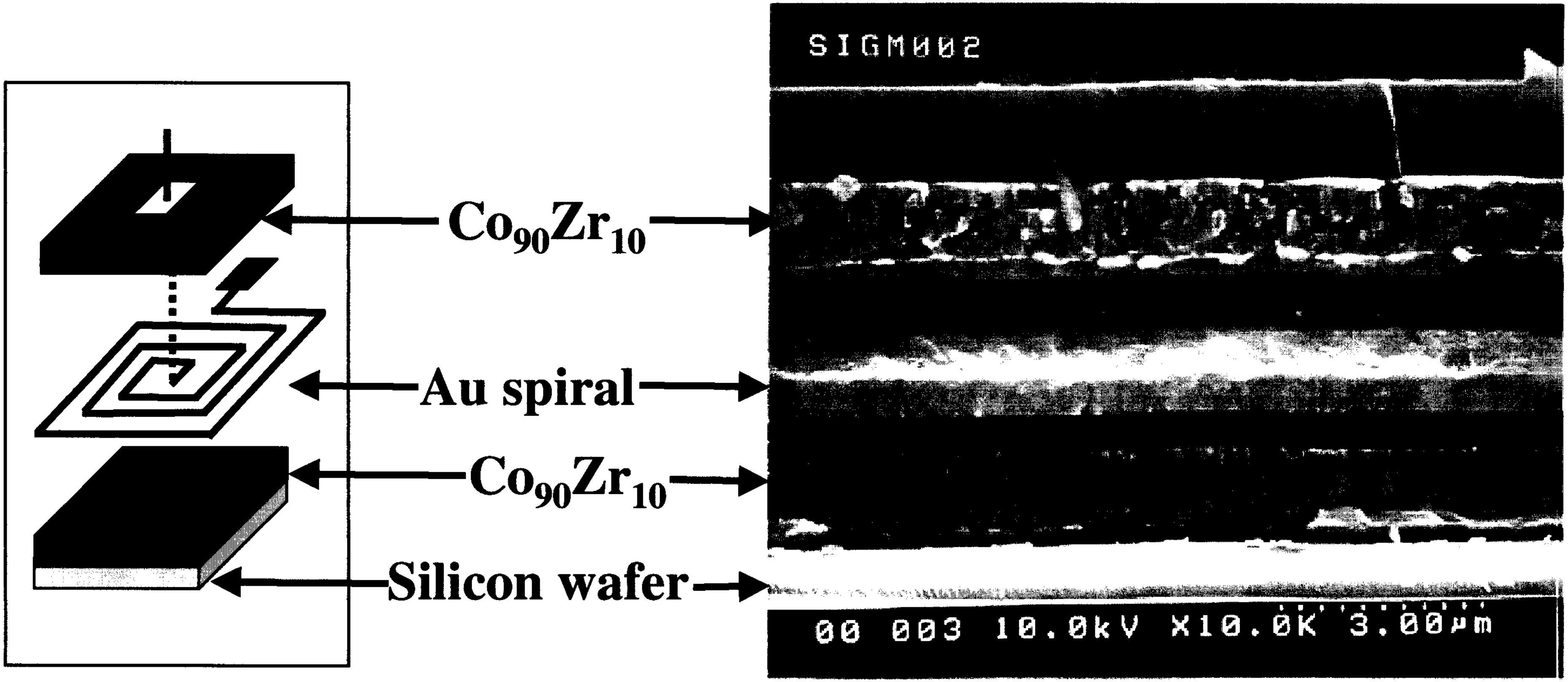
- *classic high frequency material* used for power
- difficult to deposit, require high T processing

Metallic Alloys

- well suited for thick/thin film deposition
- *low temperature*, silicon compatible processing
- *low resistivity* limits high frequency application

Typical Magnetic Properties	B_{max}, G	μ	H_c, Oe	ρ, μΩ−cm	Fabrication Methods
Ferrites	5,000	30	100	**10^7**	Ceramic methods
Metallic Alloys	**20,000**	**1000**	**<0.1**	5 to 50	sputtering, electroplating

A magnetic “microinductor” on a silicon wafer



6 mm^2

$$L \propto N^2, A, \mu$$

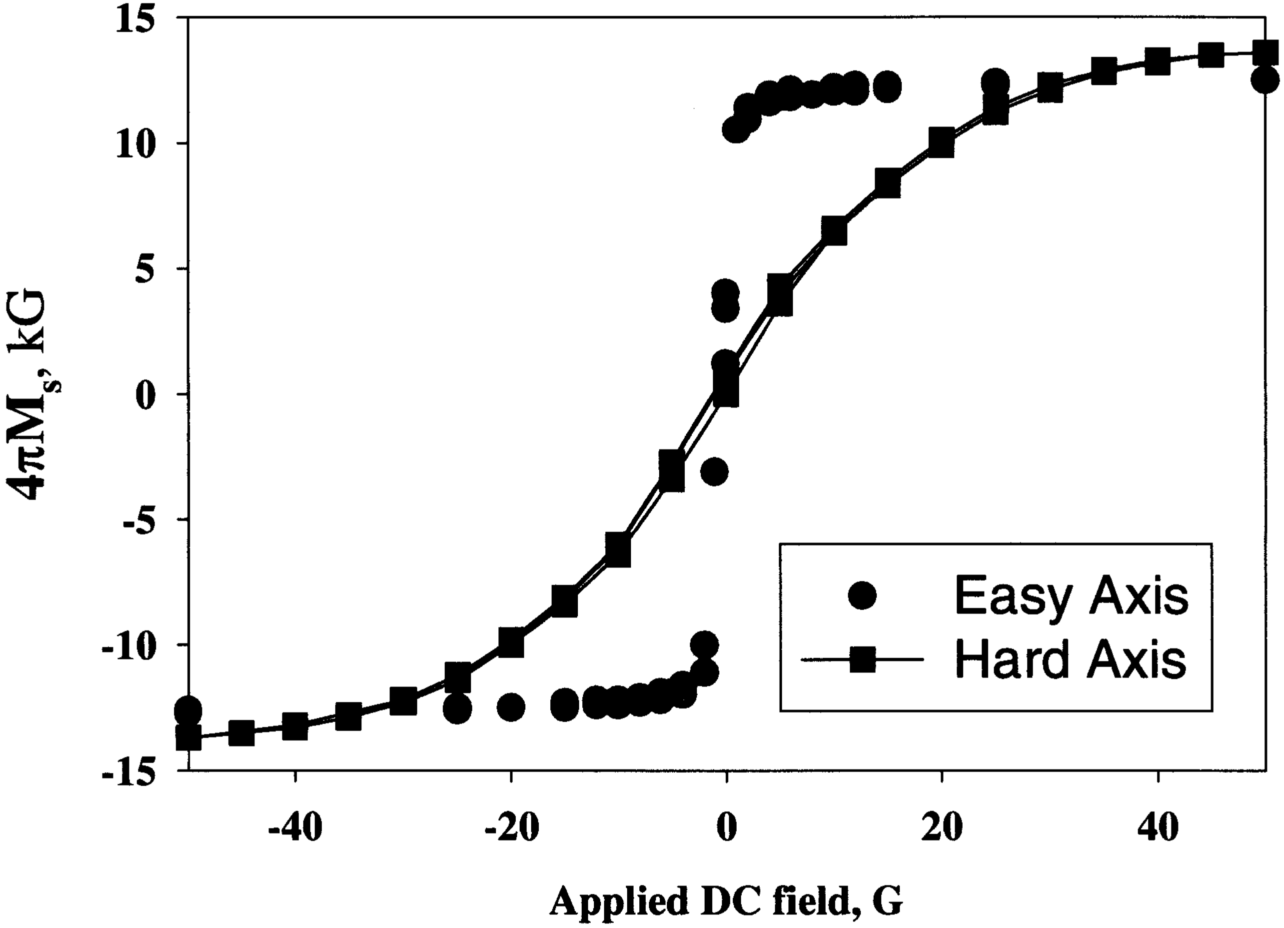
SEM Cross section of a “micro-inductor” with magnetic thin films (1 µm)

rf sputtered $Co_{90}Zr_{10}$ films display excellent soft magnetic properties

-low coercivity

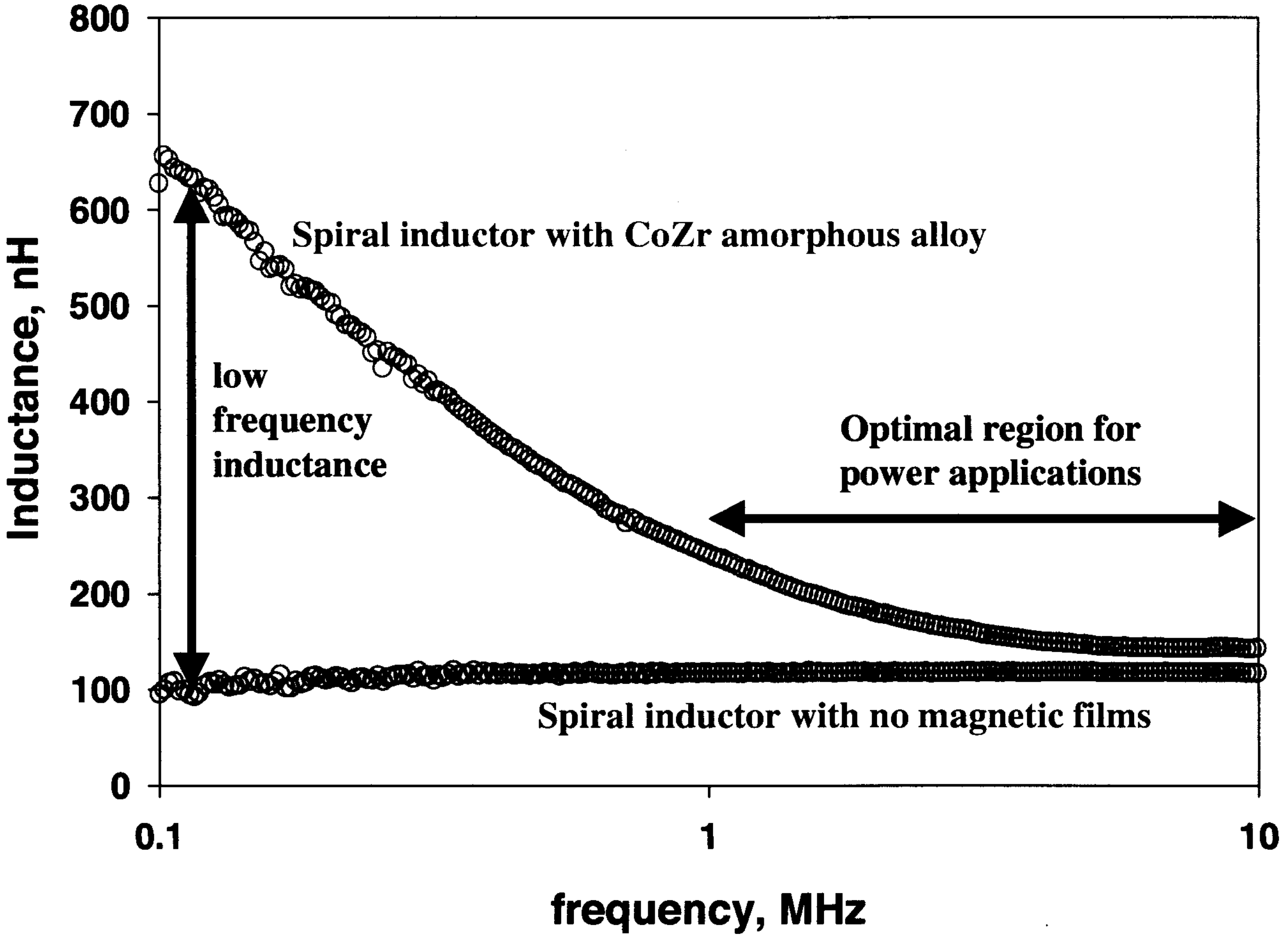
-high saturation magnetization

-difficult to deposit films over 1 μm



Spiral microinductors with $Co_{90}Zr_{10}$ magnetic layers

eddy currents in the magnetic material degrade inductance at high frequencies

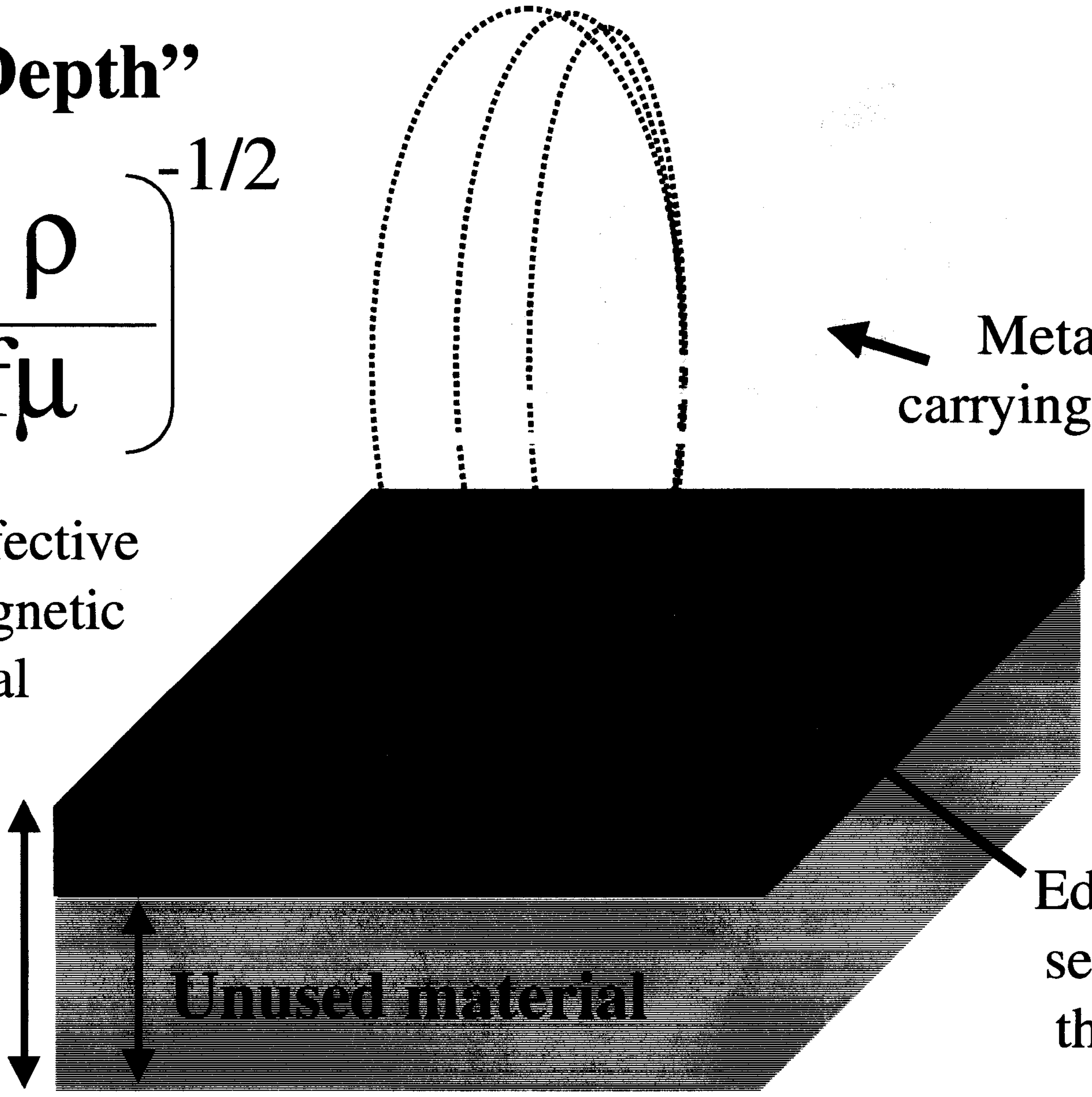


Eddy currents and skin depth

"Skin Depth"

$$\delta \propto \left(\frac{\rho}{f\mu}\right)^{-1/2}$$

Reduces effective area of magnetic material



Metal spiral carrying ac current

Magnetic film thickness

Unused material

Eddy currents set up flux in the *opposite* direction

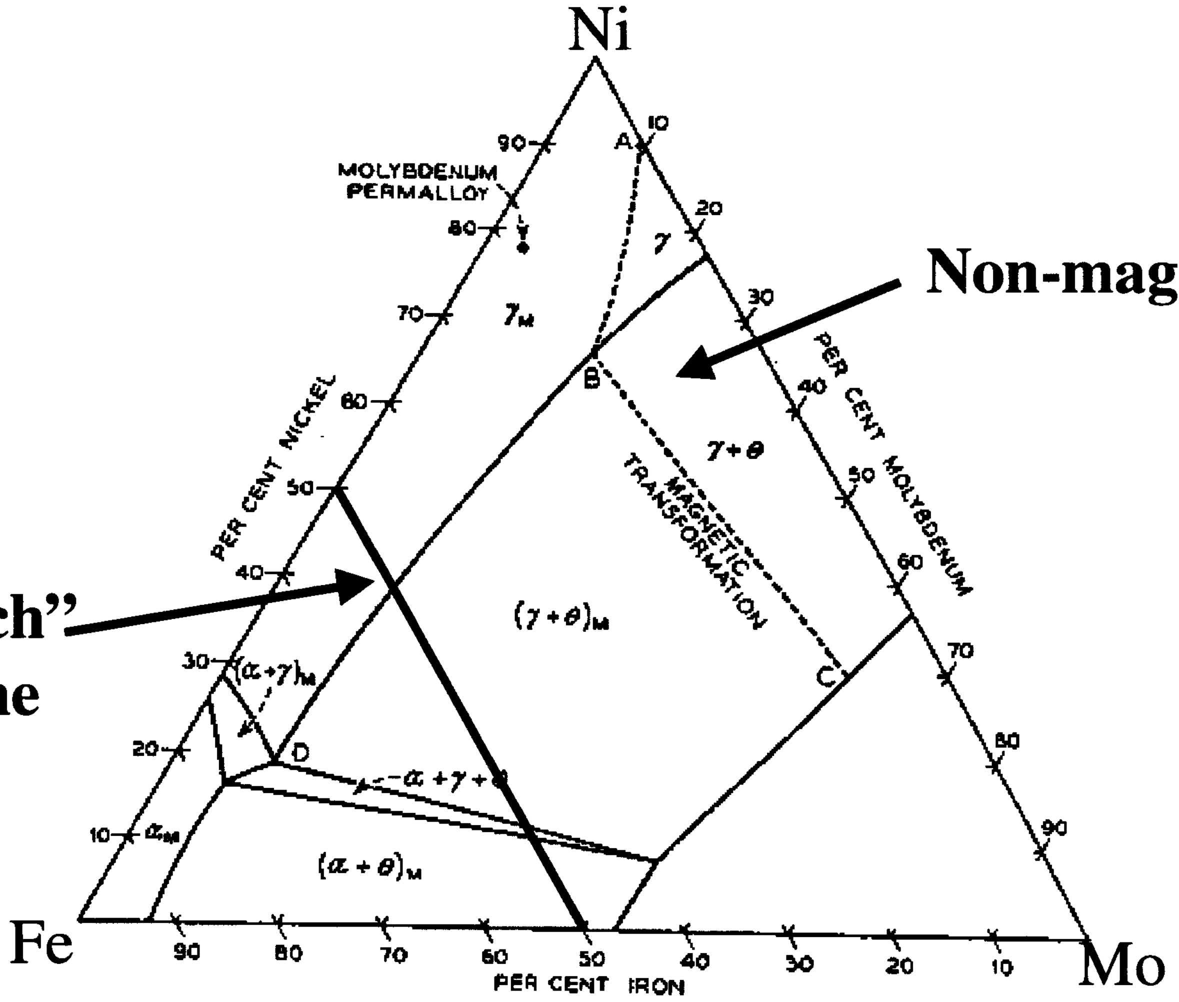
Alternative Magnetic Materials

Skin depth and eddy currents are dictated by the resistivity

	Permeability	H_c Oe	$4\pi M_s$ Oe	Resistivity, $\mu\Omega$-cm
Permalloy (80 Ni, 20 Fe)	8,000	0.05	10,800	16
45 Ni, 55 Fe	2,500	0.3	16,000	45
4 Mo, 79 Ni, 17 Fe	20,000	0.05	8,700	55
3 Mo, 47 Ni, 50 Fe	2,000	0.1	14,500	80

*Values based on bulk material

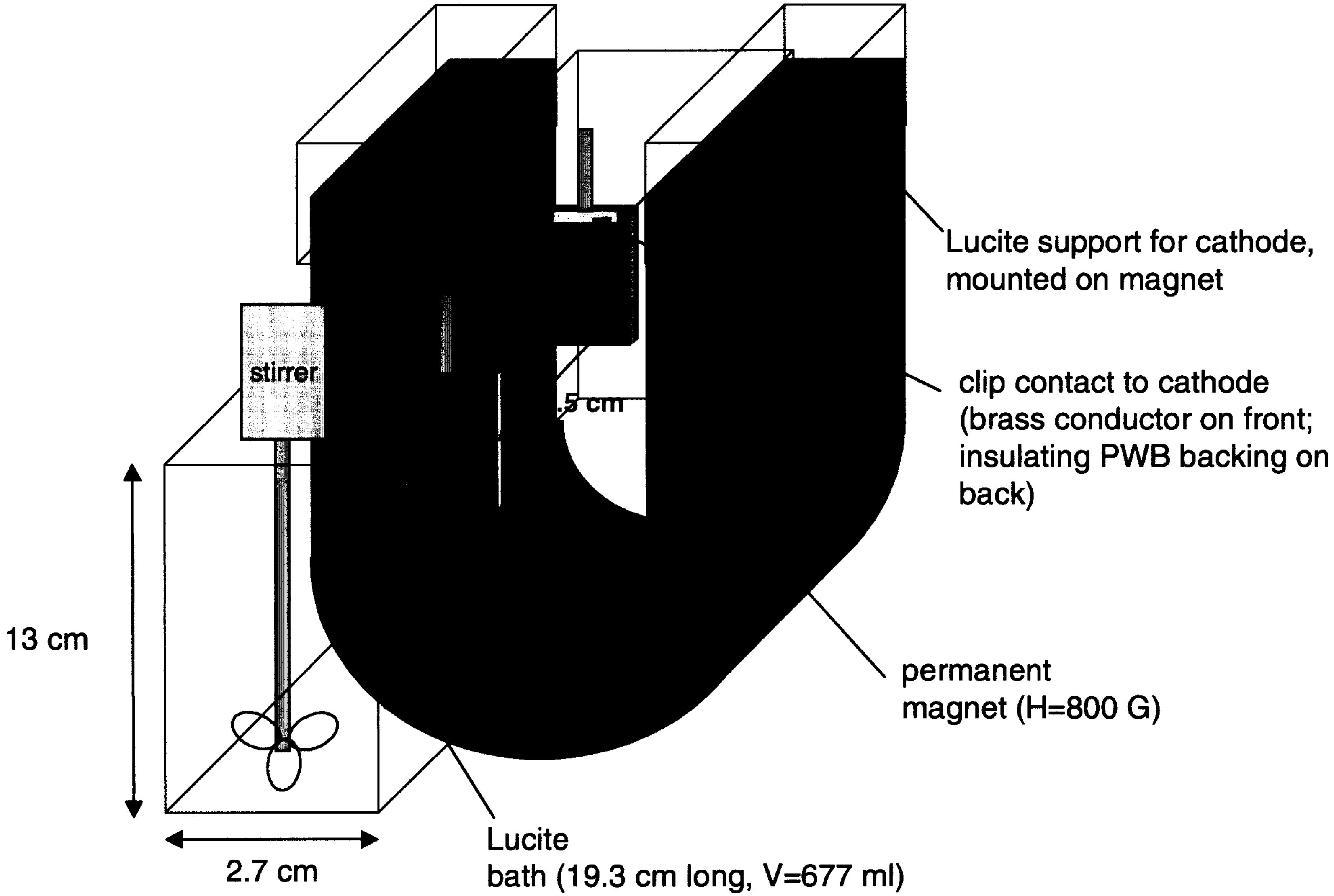
Ni-Fe-Mo phase diagram



Non-magnetic phases

“Fe rich” tie line

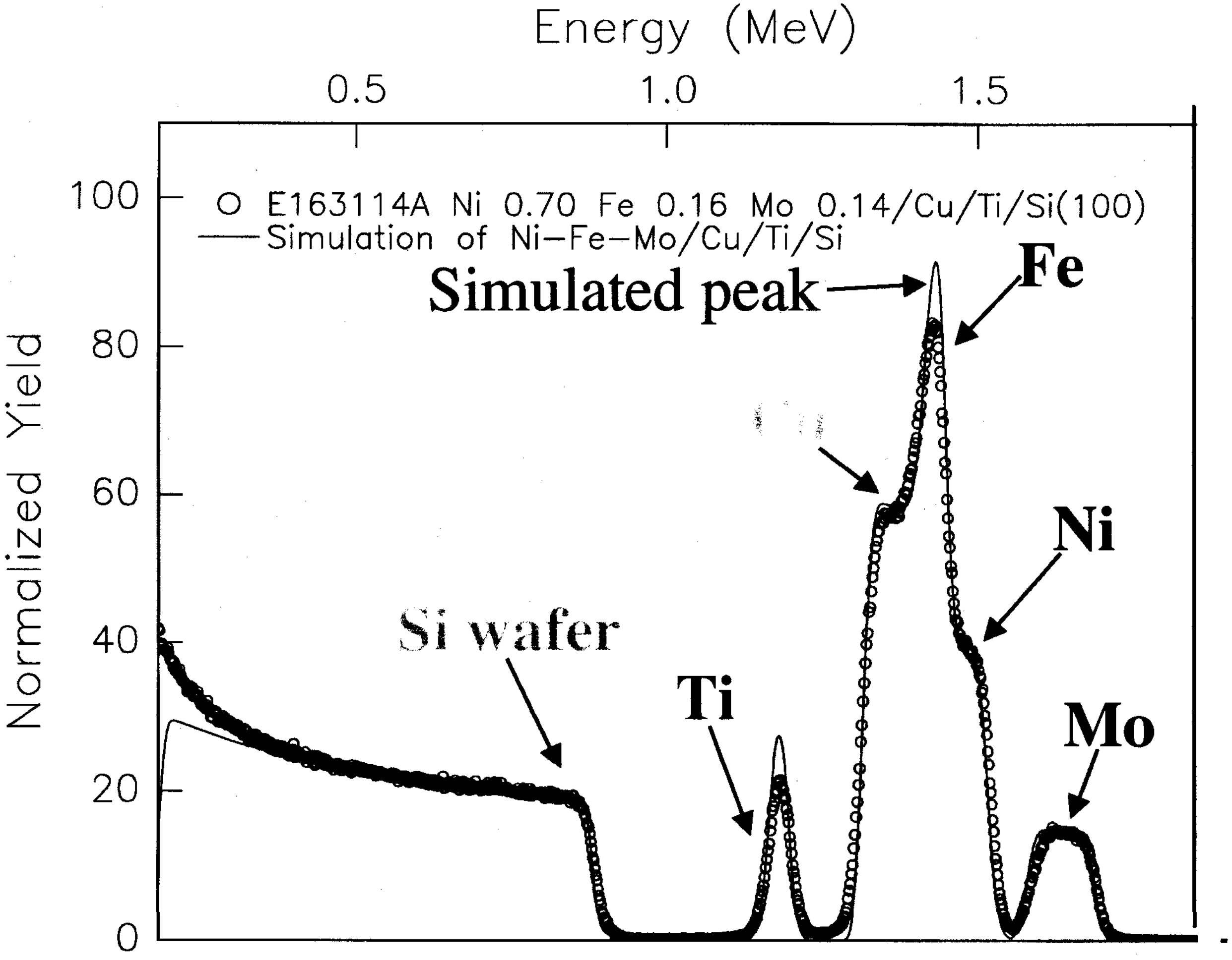
Electrodeposition Bath

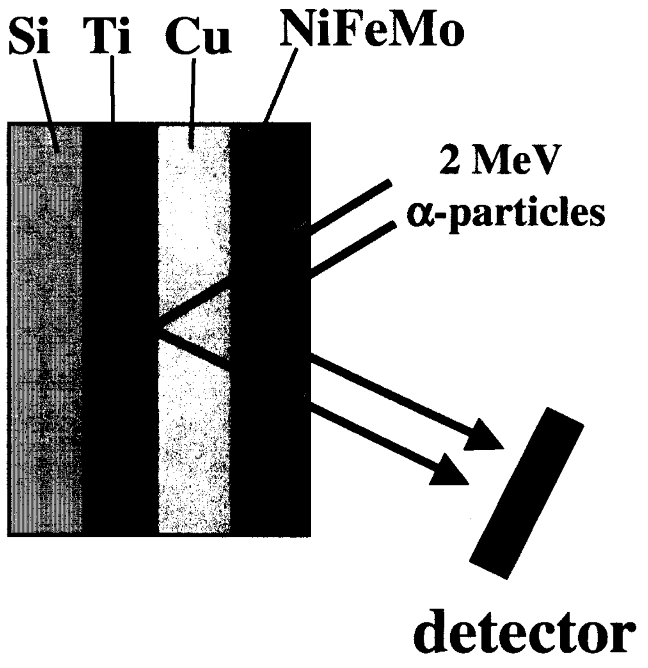


Typical Electroplating Bath

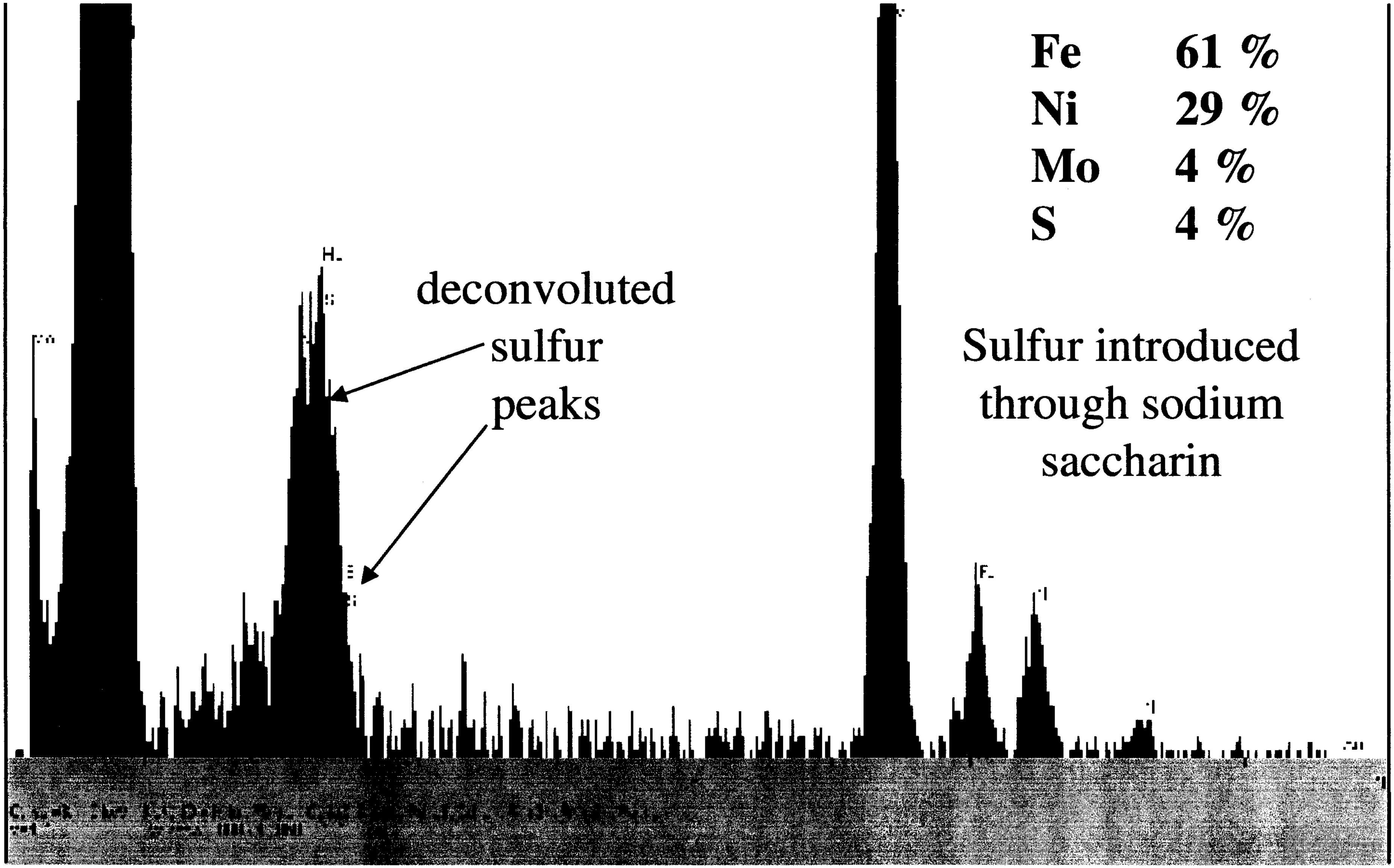
$NiSO_4 \cdot 6H_2O$	60 g/L
$FeSO_4 \cdot 7H_2O$	3-15 g/L
Na_2MoO_4	0.2-1 g/L
ammonium chloride	20 g/L
citric acid monohydrate	60 g/L
sodium saccharin dihydrate	1.5 g/L
sodium dodecyl sulfate	0.1 g/L

Rutherford Backscattering Spectrometry





Compositional Analysis by EDS



Fe	**61 %**
Ni	**29 %**
Mo	**4 %**
S	**4 %**

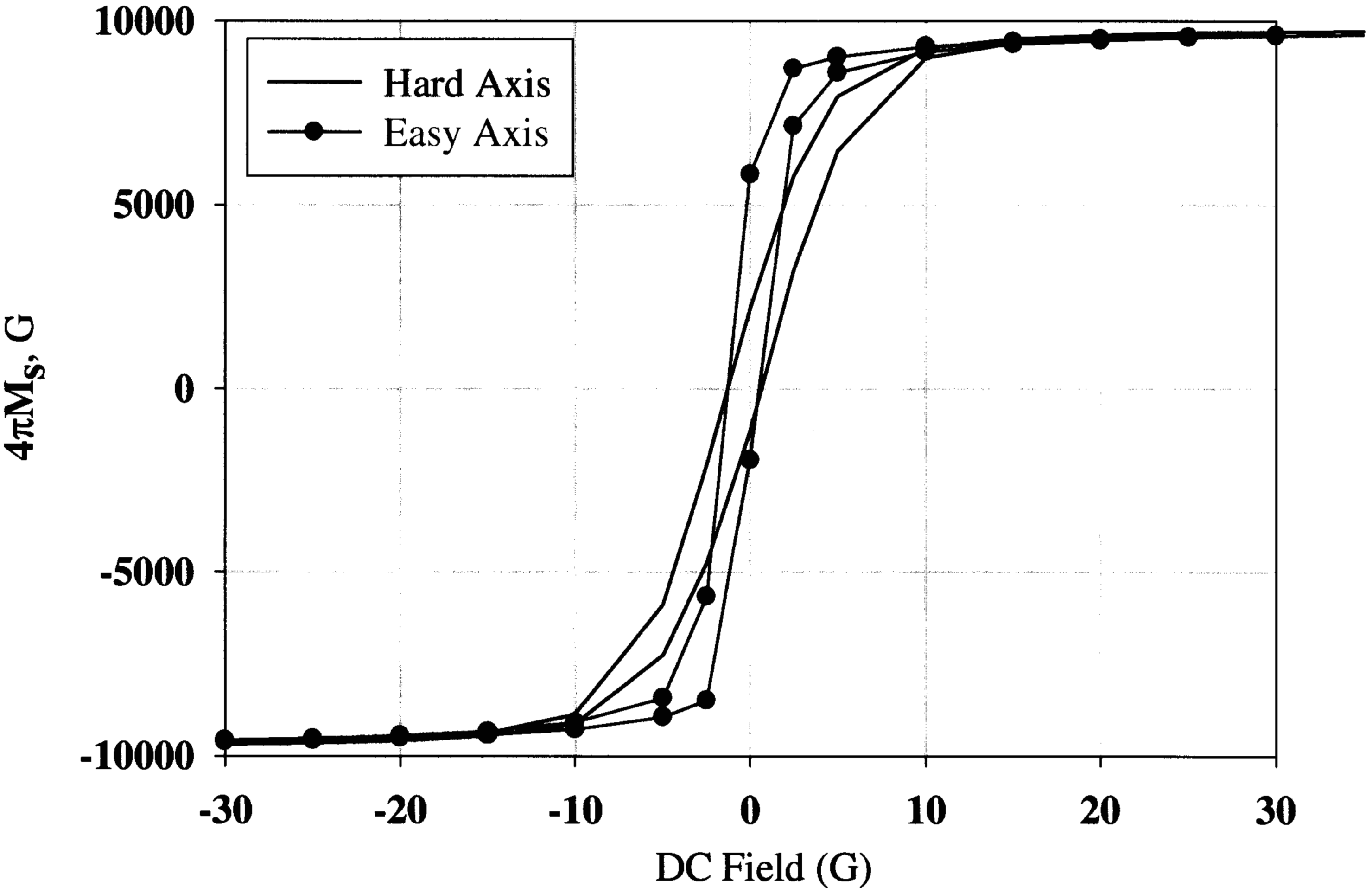
deconvoluted sulfur peaks

Sulfur introduced through sodium saccharin

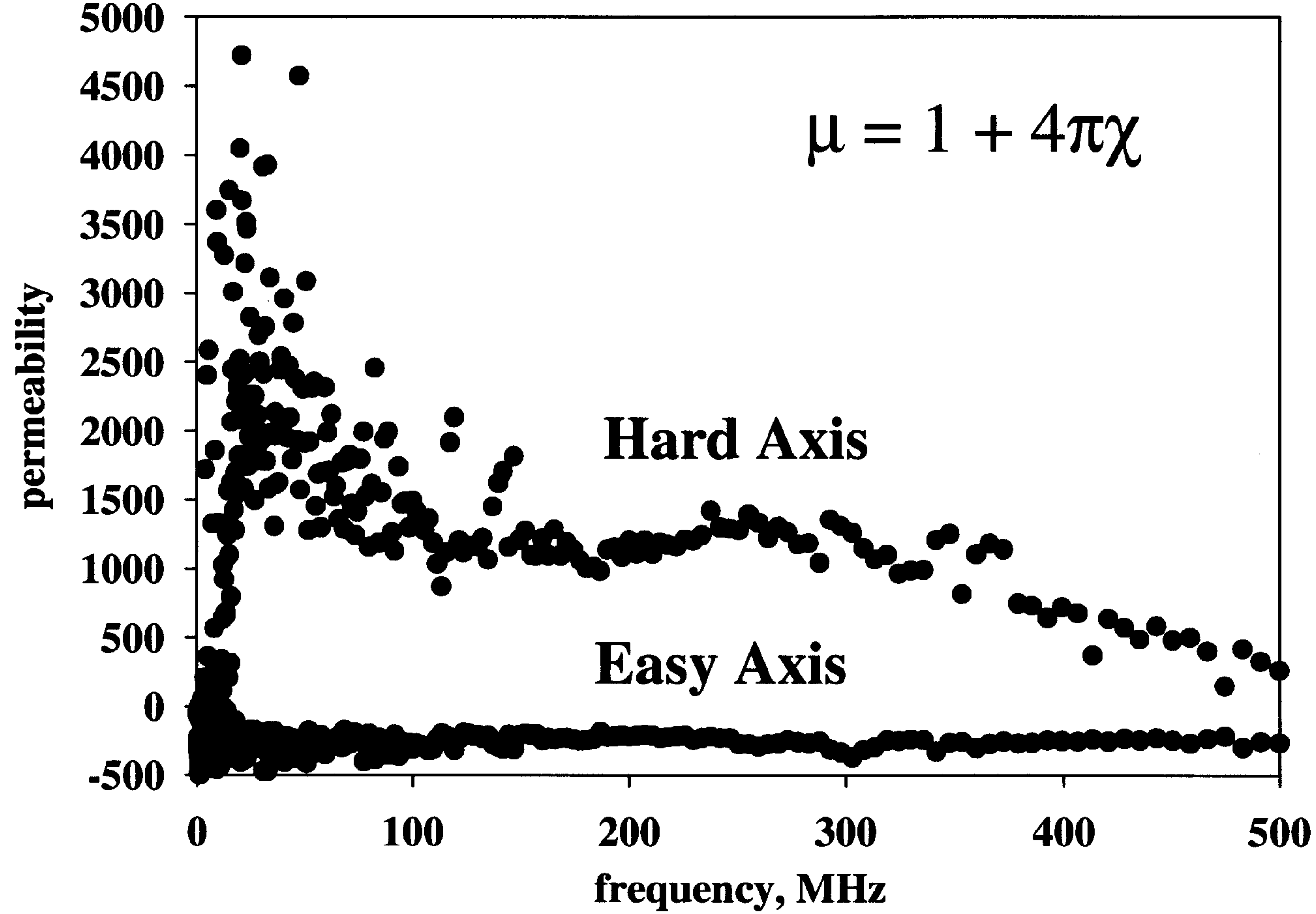
Electroplated Ni-Fe-Mo films

-Anisotropy introduced by plating in a field

-Excellent soft magnetic properties

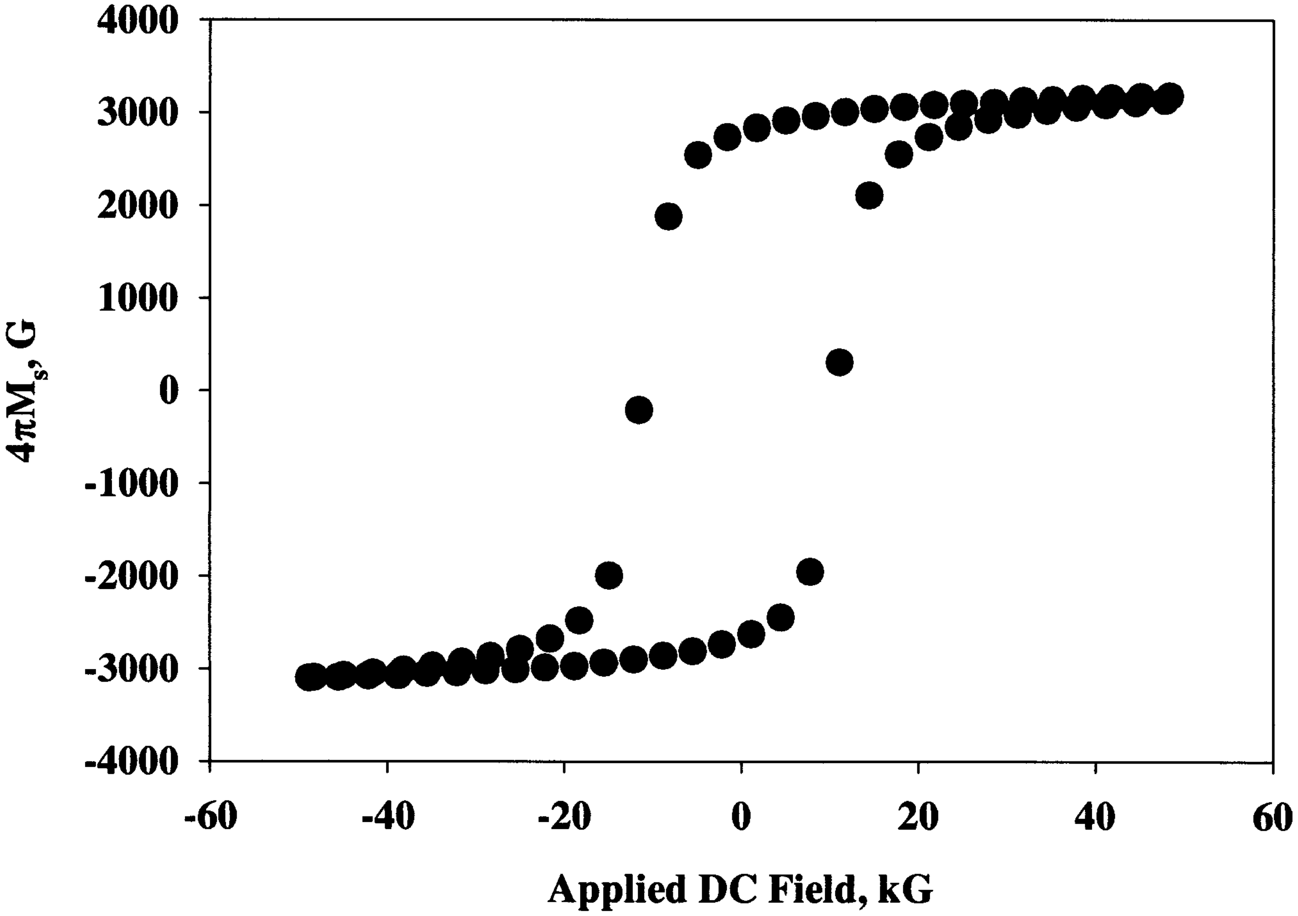


Hard and Easy Axis Permeability



Influence of bath composition on magnetic properties

Films deposited with high Fe^{+2} and Mo^{+6} concentration often result in films with poor magnetic properties



Molybdate Equilibria in Acidic Solution

$$MoO_4^{2-} + H^+ \rightleftharpoons HMoO_4^- \qquad K_1 = 10^{3.7}$$

$$HMoO_4^- + 2\,H_2O + H^+ \rightleftharpoons Mo(OH)_6 \qquad K_2 = 10^{3.7}$$

-Typical Permalloy baths operate at pH = 3.0

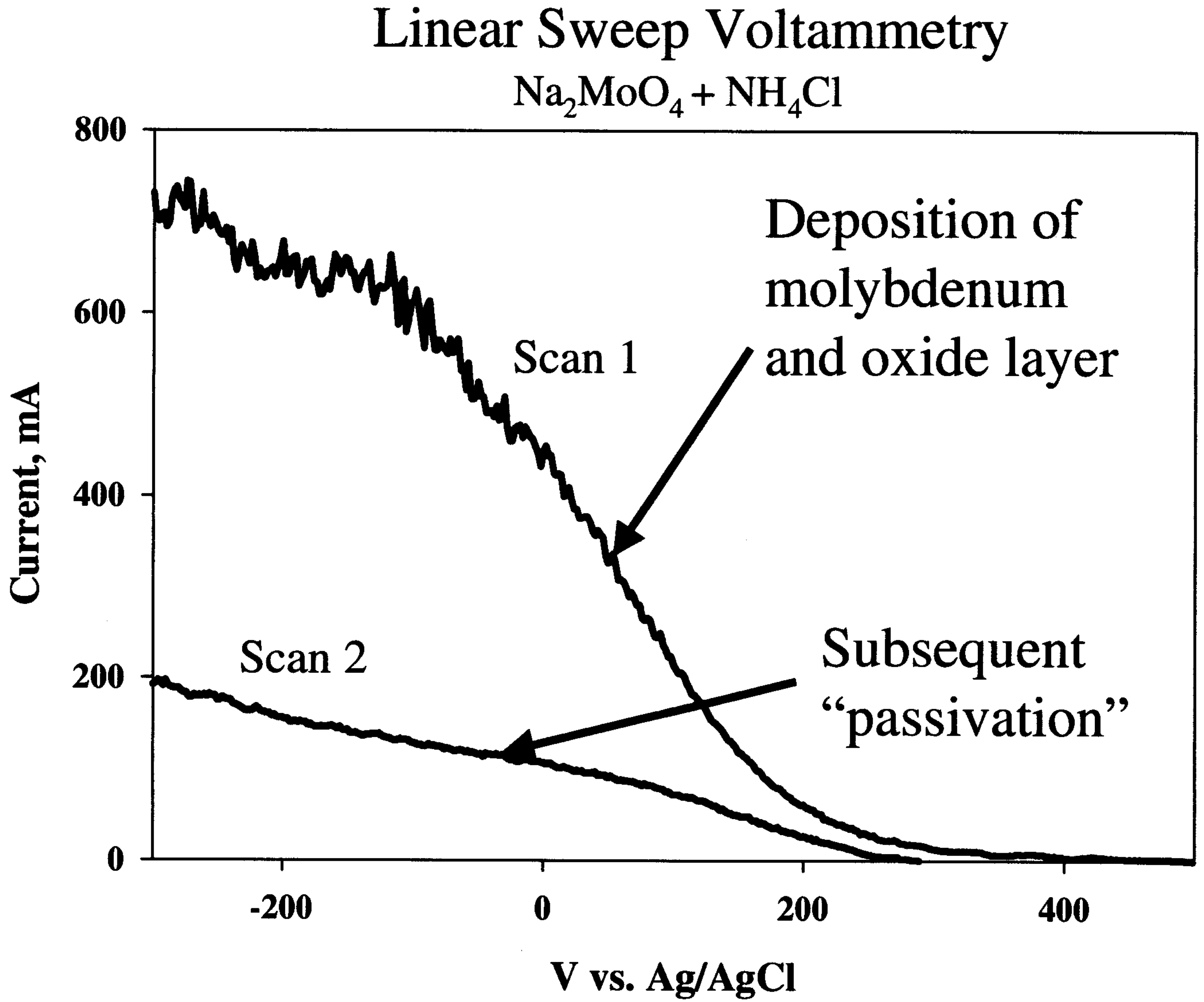
-Acidic baths favor molybdenum hydroxide formation

-Causes incorporation of oxides into the film

-Basic baths result in precipitation of iron hydroxides

-Optimal films deposited at pH of about 5.0

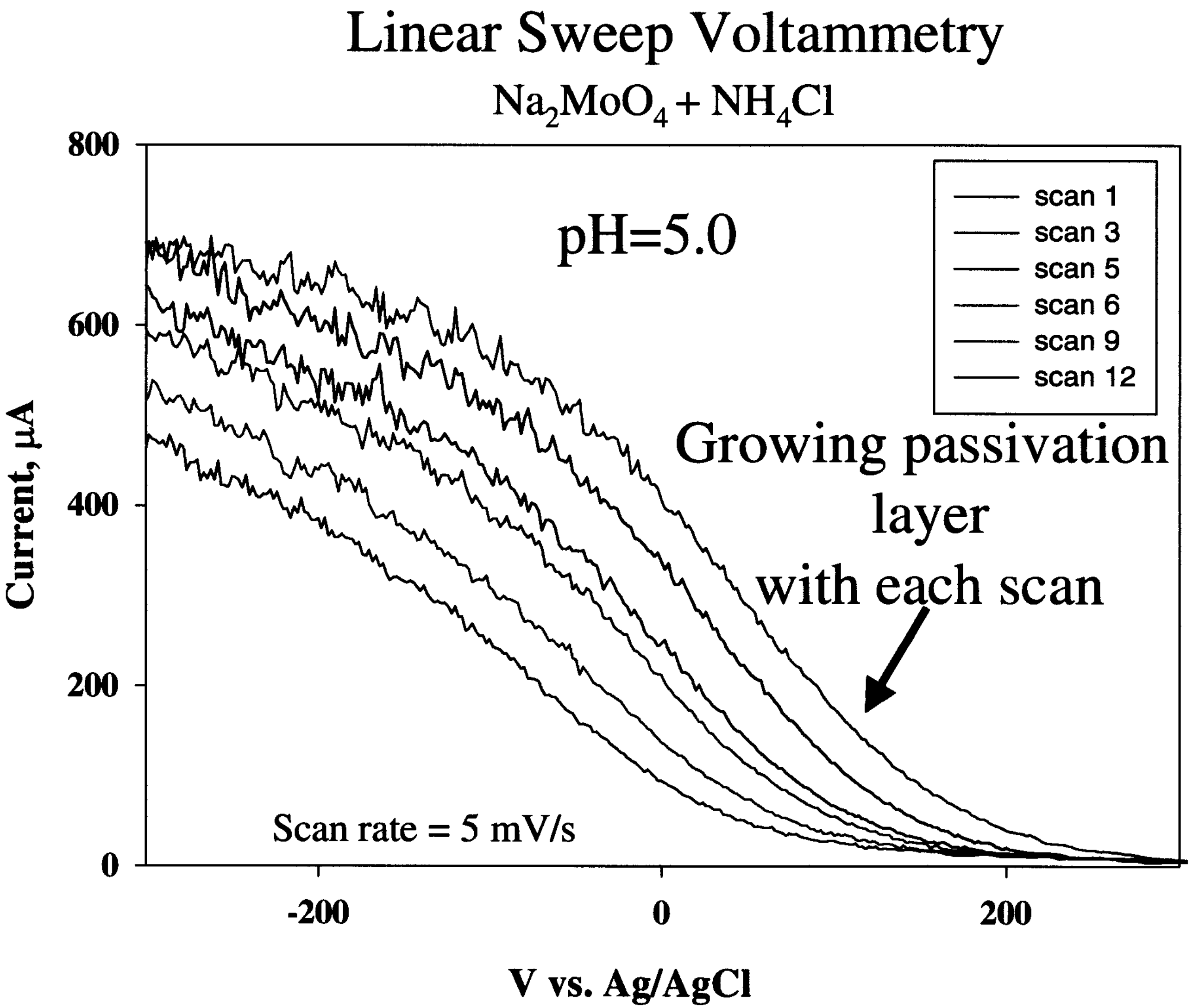
Electrodeposition of Mo at pH = 3.00



Deposition of molybdenum and oxide layer

Subsequent "passivation"

Electrodeposition of Mo at pH = 5.00



Conclusion

Ni-Fe-Mo

- Periodic application of reverse or anodic current (Pulse plating)
- Boric acid buffers to reduce surface pH
- Use another metal (i.e., Cr vs. Mo)

Combine with other energy storage elements

- High dielectric anodized Ta_2O_5 capacitors
- Solid state, thin film lithium ion microbatteries
- *Build up entire power circuits on silicon*

Acknowledgements

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