Sandia National Laboratories

Synthesis of Advanced Magnetic Materials for Inductors and Transformers

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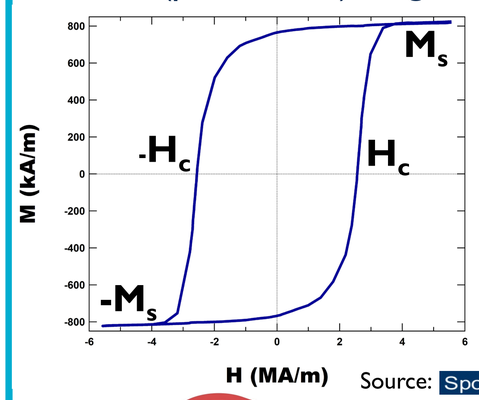
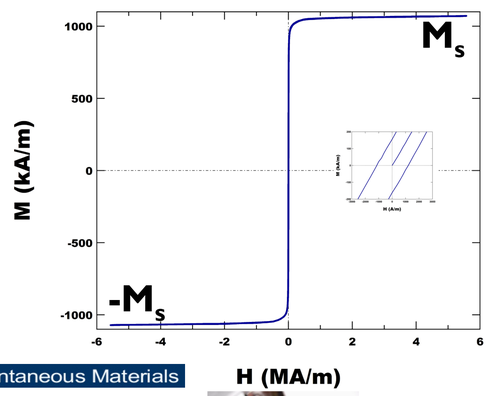
Project Objective

The size requirements of power electronics are determined by the necessary components. Magnetic materials contribute to this significantly, and to maximize efficiency and size, new magnetic materials are required. One of the main challenges has been developing materials that work in conjunction with high frequency semiconductor switches. This year, we sought to fabricate iron nitride/Ni-P layered composite transformer cores and demonstrate decreased losses in comparison to neat iron nitride at frequencies up to 100 kHz and temperatures of 150 °C. To achieve this, we have focused on identifying and optimizing synthetic routes to yield phase pure iron nitrides and then incorporating them into composites. This has resulted in materials with good performance up to 1 MHz.

Hard (permanent) magnet

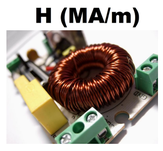


Soft magnet

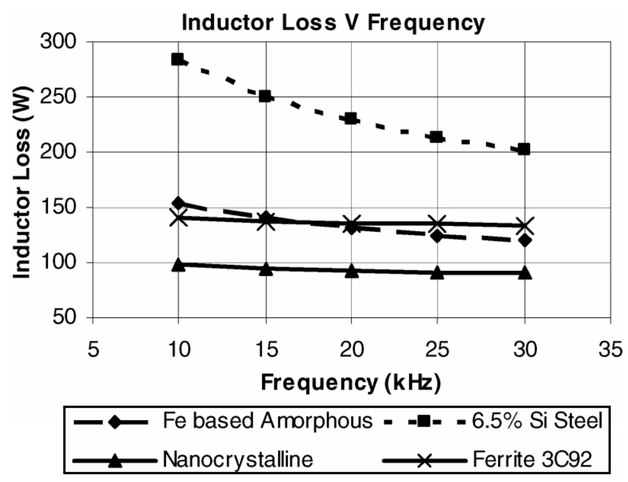


Source: Spontaneous Materials

M_s = saturation magnetization
H_c = coercivity



- Hysteresis and Eddy current losses
- **Develop new soft magnetic materials that work in conjunction with high frequency semiconductor switches**



B.J. Lyons, J.G. Hayes, M.G. Egan, Magnetic Material Comparisons for High-Current Inductors in Low-Medium Frequency DC-DC Converters, *IEEE*, **2007**, 71. Specifications: V_{lv} = 200 V, V_{hv} = 400 V, P_{in} = 40kW.

- Current magnetic materials experience significant loss as frequency is increased

Magnetic Material	J_s (T)	ρ(μΩ·m)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Ferroxcube)	0.52	5×10^6	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	> 200	Low

($J = \mu_0 \cdot M$)

- γ'-Fe_4N has a higher saturation polarization (J_s) and electrical resistivity than Si steel
- Use of abundant elements (Fe and N) will keep costs low

Synthesis and purification of iron nitride

Metathesis- effective for early transition metals

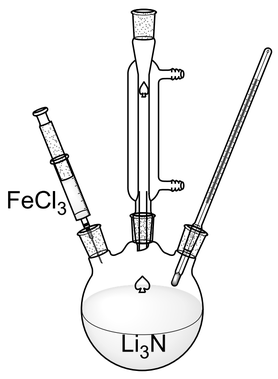
$$MX_n + Li_3N \longrightarrow M_yN + LiX$$

Group	MX_n	Product
4	$TiCl_4$	TiN
	$ZrCl_4$	ZrN
	$HfCl_4$	HfN
5	VCl_3	VN, V_2N
6	$CrCl_3$	Cr, Cr_2N
7	MnI_2	Mn_4N, Mn
8	$FeCl_3$	Fe
10	$NiCl_2$	Ni

- Effective for group 4-7 metals
- Reactions with group 8 – 10 metals generate too much heat
- Decomposition to elemental metal

- Current methods don't work for Fe and Ni
- Need new method

Possible Method

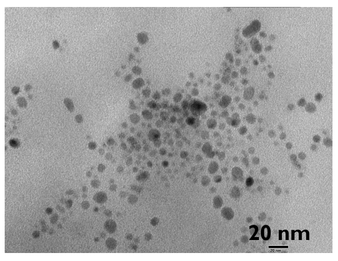


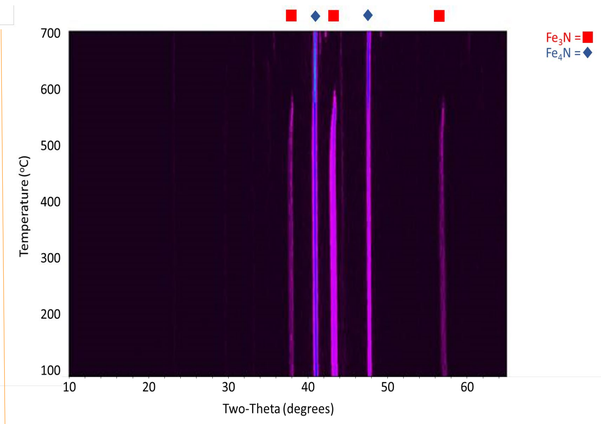
Excess solvent should act as heat sink and allow for isolation of desired product

Results

$$FeCl_3 + Li_3N \xrightarrow[\text{oleylamine -LiCl}]{350\ °C} \text{mixture of } Fe_2N/\ Fe_3N$$

- Mixed product if all materials are combined at beginning
- Fe_2N is only product if $FeCl_3$ is added at 80 μL/min
- Fe(II) precursor results in Fe_3N (higher Fe concentration)



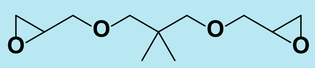


- Using a heat treatment, commercial $Fe_{(2-4)}N$ can be converted to 95 % phase pure Fe_4N

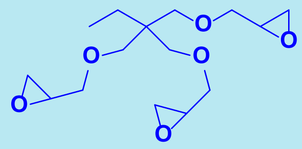
Incorporation of iron nitride into soft magnetic composites

Iron nitride + $H_2N(CH_2)_6NH_2$

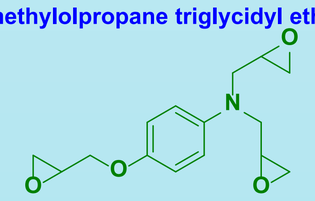
- Ball milling was used to generate a fine mixture of iron nitride and hexamethylenediamine
- Composites have successfully been formed using a 1:1and 1:0.75 molar ration of Iron nitride/ hexamethylenediamine and combining the mixture with an epoxy
- Several systems are being evaluated based on molecular weight and T_g



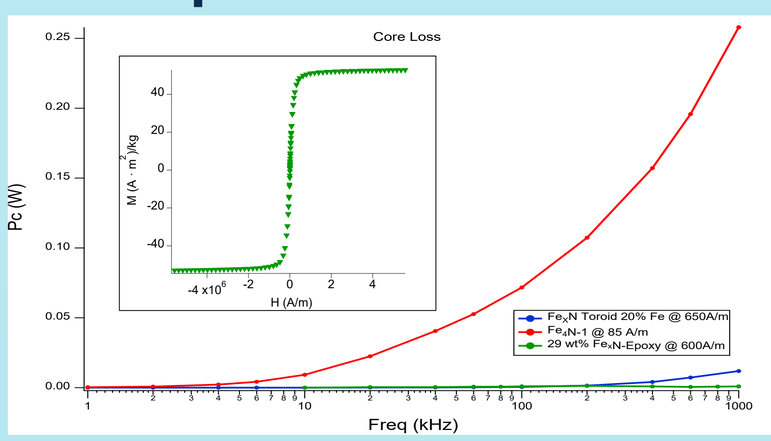
neopentyl glycol diglycidyl ether



trimethylolpropane triglycidyl ether



N,N-diglycidyl-4-glycidyloxaniline



- Preliminary data indicate low core loss at high frequency

Output

- "Soft magnetic materials for a sustainable and electrified world" J. M. Silveyra, E. Ferrara, D. L. Huber, and T. C. Monson *Science* **2018**, *362*, 0195.
- "Soft Magnetic Multilayered FeSiCrB-Fe_xN Metallic Glass Composites Fabricated by Spark Plasma Sintering" T. C. Monson, B. Zheng, R. E. Delany, C. J. Pearce, E. D. Langlois, S. M. Lepkowski, T. E. Stevens, Y. Zhou, S. Atcitty, and E. J. Lavernia *IEEE Magnetics Letters* **2019**, *10*, 7102505.
- "Synthesis and Magnetic Properties of Iron Nitrides," T. E. Stevens, R. E. Lewis, C. J. Pearce, M. A. Rodriguez, S. Dickens, B. B. McKenzie, S. Atcitty, T. C. Monson, American Chemical Society National Meeting 2019, Orlando, FL, March 31 – April 4, 2019.
- "Synthesis of Nanostructured Ferroic Materials for Energy Conversion," T. C. Monson, T. E. Stevens, D. A. Vargas, R. M. Van Ginhoven, B. Zheng, Y. Zhou, M. Fraga, E. Lavernia, Materials Science & Technology 2018, Invited Presentation, Columbus, OH, Oct. 14 -19, 2018.

Acknowledgements

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