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Sandia National Laboratories

# Synthesis of Advanced Magnetic Materials for Inductors and Transformers

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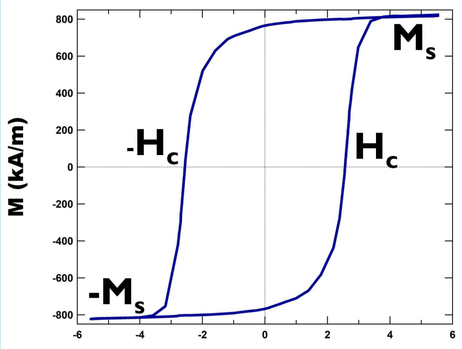
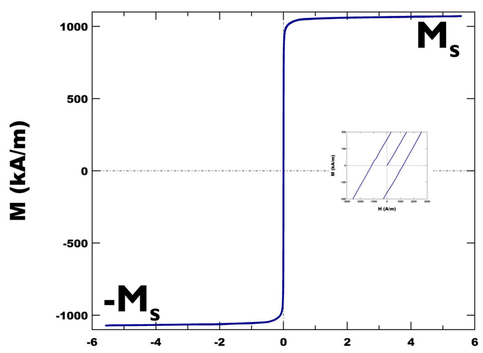
## Project Objective

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 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

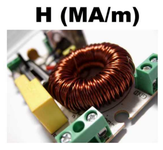



### Soft magnet

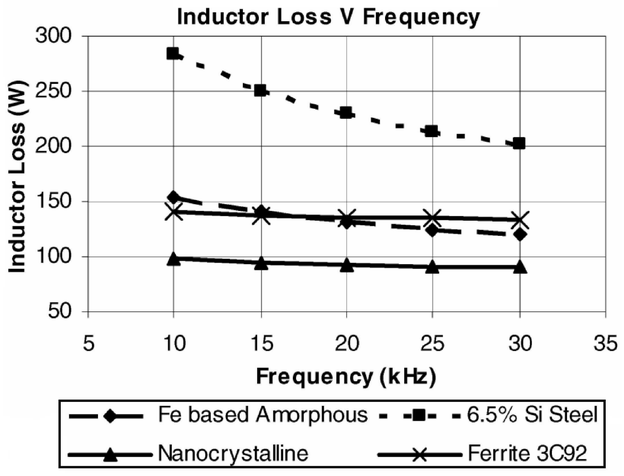



Source: Spontaneous Materials

$M_s$ = 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.

- Current magnetic materials experience significant loss as frequency is increased

| Element | Mass fraction (ppm) |
|---|---|
| Hydrogen | 739,000 |
| Helium | 240,000 |
| Oxygen | 10,400 |
| Carbon | 4,600 |
| Neon | 1,340 |
| Iron | 1,090 |
| Nitrogen | 960 |

From Croswell, Ken (February 1996). Alchemy of the Heavens. Anchor. ISBN 0-385-47214-5.

- $\gamma'$-$Fe_4N$ 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

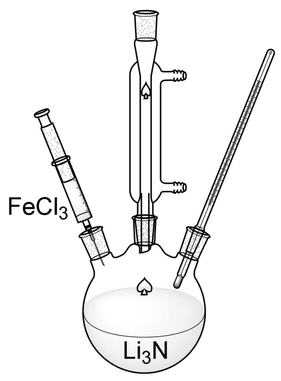
$$MX_n + Li_3N \longrightarrow M_yN + LiX$$

| 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

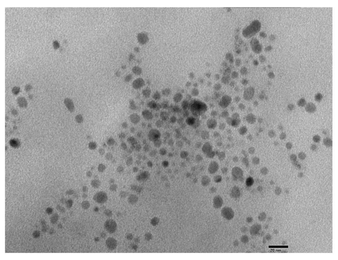


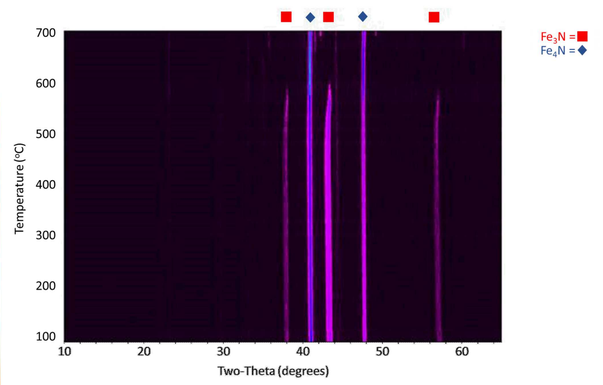

Excess solvent should act as heat sink and allow for isolation of desired product

Results

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

- 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)





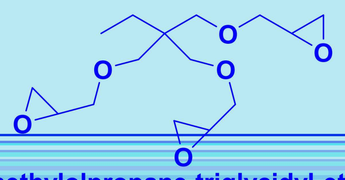

- Using a heat treatment, commercial $Fe_{(2-4)}N$ can be converted to 95 % phase pure $Fe_4N$

## Incorporation of iron nitride into soft magnetic composites

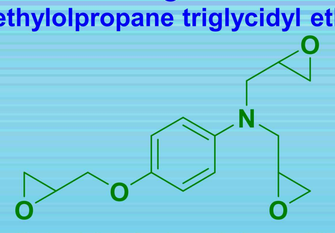
**Iron nitride + $H_2N(CH_2)_6NH_2$**

- 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 $T_g$

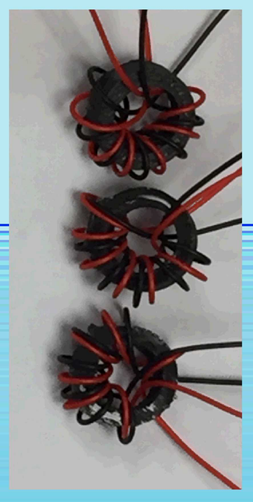
neopentyl glycol diglycidyl ether

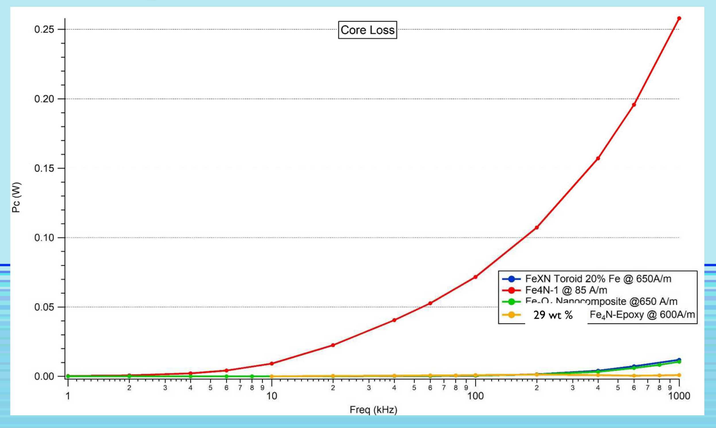


trimethylolpropane triglycidyl ether



*N,N*-diglycidyl-4-glycidyloxaniline






- Preliminary data indicate low core loss at high frequency

## Acknowledgements

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