Flexible Media Research

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for

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and

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Magnetic Tape

Made by a double slot-die coating process:

- Magnetic layer: 150 nm
- Under layer: 1.5 µm
- Base film: 6.8 µm
- Back coat: 500 nm

The magnetic layer contains iron particles oriented parallel to the length of the tape:

\[ H_c \approx 1,800 \text{ Oe} \]
\[ M_r \delta \approx 7 \text{ to } 8 \text{ memu/cm}^2 \]
\[ SQ \approx 0.76 \text{ to } 0.81 \]

The under layer contains TiO_2 or α-Fe_2O_3 particles.

The back coat contains carbon black for anti-static.
Magnetic tape remains the primary medium for archival data storage.

However, the future of magnetic tape relies on a continuing rate of increase in data density while maintaining the current (or better) competitive advantage in cost.

The current limiting factors are track density, bit density, and tape thickness.
### INSIC Magnetic Tape Storage Roadmap

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>2006</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track density (tpi)</td>
<td>900</td>
<td>2,700</td>
<td>9,800</td>
</tr>
<tr>
<td>Bit density (kbpi)</td>
<td>125</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Tape Thickness (µm)</td>
<td>8.8</td>
<td>5.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Length (m)</td>
<td>600</td>
<td>1,000</td>
<td>1,400</td>
</tr>
<tr>
<td>Areal Density (Gb/in²)</td>
<td>0.11</td>
<td>0.68</td>
<td>4.9</td>
</tr>
<tr>
<td>Volumetric Density (TB/in³)</td>
<td>0.03</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Tape cartridge capacity (TB)</td>
<td>0.10</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
Particulate Magnetic Tape in the Year 2015

Data cartridges with storage capacities approaching 100 terabytes - more than 20 TB/in^3

Particle sizes less than 50 nm with polydispersity less than 5%

Highly ordered, self-assembled particles with particle volume fractions exceeding 50%

Magnetic film thickness less than 50 nm

New particles, beyond iron

Base films with thickness of one micron or less

Solventless coating processes that eliminate air pollution

Sustainable manufacturing and materials packages
Track density and bit density are limited by noise.

Need thinner, smoother, more ordered magnetic layer containing smaller particles.
Heart of the Matter:
Dispersions of Magnetic Particles

- Reverse micelle / association colloid templates to synthesize monodisperse particles.
- Block co-polymer *nanoreactors* to synthesize monodisperse particles.
Interdendrimer Magnetic Nanoparticles

Monodisperse, acicular, metallic Cobalt nanoparticles obtained in aqueous media by photochemical reduction in the presence of dendrimer.
Dispersion Characterization

Probes the particle moments in an AC field with a perpendicular DC field.

- DC field amplitude sweep
- Transient response to DC field
- AC frequency sweep
- AC field amplitude sweep
- Drying over time
- Gelling over time

AC Susceptibility

\[ \chi' \quad \chi'' \]

0 \quad 4 \quad 8

\( \omega \) (Hz)

Steady Shear Flow

Rheology

\[ \eta \] (Pa s)

\[ \dot{\gamma} \] (s\(^{-1}\))

0.0001 0.001 0.01 0.1 1 10 100 1000

Small Amplitude Oscillatory Shear

\[ G' \quad G'' \]

10 100 1000

\( \omega \) (s\(^{-1}\))
Dispersion Characterization

Shear thinning in viscosity a consequence of network reformation time being greater than characteristic time of flow.

The network is weaker, but re-forms more rapidly, at lower particle volume fractions.

Using rheology to probe structure
Order and Self-Assembly—Simulations

Order and Self-Assembly

Order Parameter:

\[ S = \left\langle uu - \frac{1}{3} \delta \right\rangle \quad \rightarrow \quad S = 3\sqrt{\frac{9}{2} \text{tr}(S \cdot S \cdot S)} \]

\[ S = 1 : \text{perfect prolate order} \quad S = -1/2 : \text{perfect oblate order} \]
Order and Self-Assembly — Model

Assume:
- Anisotropic Hydrodynamic Drag
- Maier-Saupe Steric Interaction
- Magnetic Mean Field

Evolution of $S$:
$$\frac{\partial S}{\partial t} + \mathbf{v} \cdot \nabla S = \ldots$$

Stress:
$$\tau = \ldots$$

$S$ vs $H$ and $\dot{\gamma}$

$n$ vs $\dot{\gamma}$
Order and Self-Assembly — Model

Problems with model:

• Polydispersity
• Fixed Magnetic Moments
• Mean Fields
• Spatial Inhomogeneity
• Equilibrium Network Structure
• ???
Cryo-VSM: Angular Dependence of Remanence

Angular dependence of parallel remanence ($M_p$) and transverse remanence ($M_t$)
Cryo-VSM: Angular Dependence of Remanence

\[ f(\theta) = \frac{(M_p + \frac{\partial M_t}{\partial \theta})}{2} \]

Small Angle Neutron Scattering in Shear and Magnetic Field  
(Gary Mankey et al.)

Measurements made at the Center for Neutron Research at NIST
SANS Data

- a) Fe 4.4% Nanoparticles in Cyclohexanone
  - ▲ Increasing
  - ▼ Decreasing
  - H = 0 Oe

- b) H = 90 Oe

- c) H = 180 Oe

Model Predictions

- a) \( \overline{H} = 0 \)

- b) \( \overline{H} = 1 \)

- c) \( \overline{H} = 2.5 \)

Order Parameter S vs. Dimensionless Shear Rate G
Co-axial Shear Magnetometry
(Duane Johnson)

Measure susceptibility in flowing dispersion (with or without constant magnetic field in flow direction) to infer order parameter.
Coating Simulation

Goal: Thinner, Smoother Magnetic Layer
Tape Characterization

Particle Orientation Distribution

Angle
Tape Characterization

Orientation Distributions in Fuji Ultrium LTO Tape

Angular dependence of parallel remanence ($M_p$) and transverse remanence ($M_t$)

Orientation Distribution

\[ f = \frac{(M_p + dM_t/d\phi)}{2} \]
# Tape Characterization

Summary of Results for DLT IV Tapes

<table>
<thead>
<tr>
<th>Sample</th>
<th>H$_{c}$ (Oe)</th>
<th>SQ</th>
<th>$M_r t$ (memu/cm$^2$)</th>
<th>S</th>
</tr>
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<tbody>
<tr>
<td>UA-DLT IV-001</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>1768</td>
<td>0.779</td>
<td>7.61</td>
<td>0.643</td>
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<tr>
<td>2</td>
<td>1835</td>
<td>0.785</td>
<td>7.62</td>
<td>0.639</td>
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<tr>
<td>UA-DLT IV-003</td>
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<tr>
<td>1</td>
<td>1826</td>
<td>0.753</td>
<td>7.21</td>
<td>0.627</td>
</tr>
<tr>
<td>2</td>
<td>1894</td>
<td>0.764</td>
<td>7.11</td>
<td>0.595</td>
</tr>
<tr>
<td>3</td>
<td>1864</td>
<td>0.828</td>
<td>6.17</td>
<td>0.581</td>
</tr>
<tr>
<td>UA-DLT IV-004</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1746</td>
<td>0.817</td>
<td>7.98</td>
<td>0.673</td>
</tr>
<tr>
<td>2</td>
<td>1813</td>
<td>0.810</td>
<td>7.75</td>
<td>0.657</td>
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<tr>
<td>3</td>
<td>1779</td>
<td>0.818</td>
<td>8.03</td>
<td>0.663</td>
</tr>
</tbody>
</table>

A lot of room for improvement!
Dimensional Stability

Thinner, smoother tape composed of smaller, better oriented particles must be able to withstand increasingly demanding conditions in drives and libraries — without loosing (literally) the data.
Mechanical Behavior of Magnetic Tape

Thinner, smoother tape composed of smaller, better oriented particles must be able withstand increasingly demanding conditions in drives and libraries.

This requires understanding the mechanical properties of the tape and how those properties are influenced by the materials package — the constitutive behavior of the tape and how it depends on tape structure.

\[ \pi - \rho \delta = \left( \frac{2}{3} G - K \right) \left( \gamma^{(0)} \right) \right) \]

\[ -G \gamma^{(0)} \left( S + \frac{1}{3} \delta \right) \]

\[ + G \left( N + B - \frac{3}{2} S \right) + G \left( N + B \left[ S \cdot S - S \cdot S \left( S + \frac{1}{3} \delta \right) \right] \right) \]

Particle Order  Constitutive Relations

Tape Guiding, Wear, & Aging Studies
GMR Heads

Thinner, smoother, more ordered magnetic layers reduce noise, but they also result in smaller signal.

Low noise does no good if you lose the signal, too!

Challenge for tape drive designers is how to implement GMR heads.
GMR Heads Require GMR Friendly Tape

In addition to *thinner, smoother, more ordered magnetic layer*

GMR head issues for tape:

- Corrosion (binder chemistry)
- Thermal stability
- Electrostatic Discharge
- Head wear
New Binder Polymers

- Polymers must prevent particle flocculation in dispersions.
- Polymers must protect particles against corrosion.
- Polymers must not corrode head materials (eliminate PVC, a source of inorganic chloride that may corrode the heads).
- Binder thermal properties will be more important (increase $T_g$ to resist deformation due to hot GMR heats).

<table>
<thead>
<tr>
<th>Sr #</th>
<th>POLYURETHANES</th>
<th>HO-R-OH</th>
<th>$M_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AQPUDA-1</td>
<td>HO(CH$_2$CH$_2$O)$_n$H</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(PEG 400)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>AQPUDA-2</td>
<td>HO(CH$_2$CH$_2$CH$_2$O)$_n$H</td>
<td>650</td>
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<tr>
<td></td>
<td></td>
<td>(Terathane 650)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>AQPUDA-3</td>
<td>H[OCH$_2$C(=O)$_n$OCH$_2$CH$_2$OCH$_2$CH$_2$O(=O)(CH$_2$)$_n$OH</td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Polycaproactone diol)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>AQPUDA-4</td>
<td>HO(CH$_2$CH$_2$O)$_n$OH</td>
<td>404</td>
</tr>
</tbody>
</table>
New Binder Polymers

Comparative Corrosion Studies

Tape samples containing commercial iron particles

Exposed to pH 2.0 aqueous buffer

The samples having AQPUDA-1 showed no corrosion by pH 2.0 aqueous buffer

Radiation curable amine-quinone polymer protect commercial iron particles against corrosion
Cold tape does not like hot (e.g., GMR) heads!

\[ \rho \hat{C}_p \left( \frac{\partial T}{\partial t} + \nu \cdot \nabla T \right) = -\nabla \cdot \mathbf{q} \]

\[ \mathbf{q} = - \left\{ \begin{array}{l} \kappa_{\text{magnetic}} \\ \kappa_{\text{undercoat}} \\ \kappa_{\text{substrate}} \\ \kappa_{\text{backcoat}} \end{array} \right\} \cdot \nabla T \]
Some ‘Crazy Ideas’

• Self-assembled acicular particle arrays (requires monodisperse particles).

• Eliminate milling (pre-dispersed particles).

• There’s a lot of room in the undercoat — use it! (e.g., mechanical properties, heat management, ESD)

• Do away with the substrate (simultaneous coating of substrate monomer).

• Do away with the solvent (solvent = binder monomer).

• Self-assemble FePt nanoparticles on a flexible substrate.
A ‘Crazy’ Idea:
Self-assemble FePt nanoparticles on a flexible substrate

(FePt)_{80}Au_{20}
Ferromagnetic FePt Nanoparticles
After Heat-treatment at 500°C for 60 min in a pressure reactor
## Portfolio of Research Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Chemistry</td>
<td>Nikles, Mays, Street</td>
</tr>
<tr>
<td>New Binder Polymers</td>
<td>Lane and Nikles</td>
</tr>
<tr>
<td>Magnetic Dispersions</td>
<td>Nikles, Wiest, Johnson, and Lane</td>
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<tr>
<td>Order and Self Assembly</td>
<td>Johnson, Mankey, Nikles, and Wiest</td>
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<tr>
<td>Coating and Coating Stability</td>
<td>Johnson and Wiest</td>
</tr>
<tr>
<td>Tape Characterization</td>
<td>Nikles, Wiest, and Harrell</td>
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<tr>
<td>Tape Mechanical Stability</td>
<td>Wiest and Nikles</td>
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<tr>
<td>Pollution Prevention and Sustainable Technology</td>
<td>Nikles</td>
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