Magnesium Diboride Films for SRF Cavity Applications

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I. Introduction and Approach:

The Need to Go Beyond Bulk-Nb Cavities

The T > 4 K Approach: MgB$_2$/\{Cu, Nb\} Films; Thickness $\sim 2\lambda$

Properties, Potential Payoffs, Challenges

II. The Case for MgB$_2$:

Reactive Evaporation

High-quality Thin-film Deposition

$R_s(T, H)$ Data

Power Dependence (Low, High)

Film Passivation

Film stability

System Simulations

Thermal Management

► Energy Gap

Data (IMD, $\lambda(T < 5K)$) and Theory of $\pi$ Energy-Gap Symmetry

III. Summary, Outlook
The T > 4 K Approach: MgB$_2$ Films of Thickness O(2$\lambda$)

- **New** Superconductor (2001); $T_C = 39.5$ K. Advantage: $5K \leq T_{\text{OPERATION}} \leq 20$ K

- **Payoffs:**
  - **Simplified Cryogenics:** Gaseous He vs. Liquid He for Nb
  - **Reduction** in Size, Weight, Power (SWP)
  - **Enhanced Reliability**

**INPUT POWER vs. $T_{\text{OPER}}$ FOR 1 WATT CRYOCOOLER**

**Prime Power: MgB$_2$ vs. Nb**

- 10 PERCENT CARNOT
- 3 PERCENT CARNOT
- 1 PERCENT CARNOT
- 1 WATT CRYOCOOLERS

**REF: AES, Inc. '06**
## The MgB₂ Alternative

### Nb vs. MgB₂ Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Nb (Type I/II)</th>
<th>MgB₂ (Type II)</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Fields (T=0K) (Tesla)</td>
<td>Hₐ = 0.2</td>
<td>Hₐ &gt; 1.55 (.16x15.)^(1/2)</td>
<td>● <strong>Potential for High Gradient</strong></td>
</tr>
</tbody>
</table>
| Operating Temperature (K)                     | 2              | 5-20           | ● **Payoffs:**
|                                               |                |                | Big Cost, SWP Savings                             |
|                                               |                |                | ● Enhanced Reliability                            |
| ξₑₑ(T=0) (nm) (Coherence Length)              | 38             | ~ 4 - 8        | ● Polycrystalline Films: OK                       |
| Oxide Structure                               | Many Oxides    | Only MgO Only B₂O₃ | ● Reduced Potential for Corrosion                 |
|                                               | Some are Magnetic | Only B₂O₃ |                                           |
| Crystal Structure                             | BCC            | AIB₂ (Hexagonal) | ● **Stable, Simple**                             |
| Classification                                | Single Element Metal | Two Elements Ceramic | ● **Challenge:**
|                                               |                |                | Quality SRF Cavity Coating                       |
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Film Deposition: Reactive Evaporation

Solves MgB$_2$ Film-growth Difficulties: Mg Volatility, Oxidation

Advantages:
- Localized source of high-pressure Mg vapor
- Mg and substrate temperatures: Different

Films:
- $T_C \cong 39K$, $\Delta T_C \cong 1K$, Resistivity($T_C$) $\cong 2\mu\Omega$
- 2” Wafers
- RMS roughness = 4.4 nm

Low Power $R_S(T)$
MgB$_2$ vs. Nb Films

- $R_S$(MgB$_2$; $T$) < $R_S$(Nb; $T$) for $T$ > 2 K
- $R_S$(MgB$_2$ /Nb (Polished)): Comparable to MgB$_2$ /Sapphire


 Nb-Bulk: $R_S$ (2K, $f = 2.2$GHz) $\sim R_{\text{RESIDUAL}}$ (2K) $\sim 10^{-2}$ $\mu\Omega$

- $T_c$(Nb) = 9.2 K, $T_c$(MgB$_2$) = 39 K
Higher Power $R_s(T)$
MgB$_2$/(Nb, Sapphire)

- $R_s$(NL Onset)/Sapp. at $H \sim 800$ Oe ($\Leftrightarrow E_{ACC} \sim 20$ MV/m): Material Limited?
- $R_s$(NL Onset)/Nb at $H > 200$ Oe Flat!
- Sample Variability

Passivation
Success at Film-Stabilization

- $\text{MgB}_2$ Degrades in Air
- Passivation with 5 X (2.5 nm $\text{Al}_2\text{O}_3$ and 2.5 nm $\text{ZrO}_2$) by ALD
- Over 6 Months & 5 Temperature Cycles $R_s$ Unchanged. $Q (f = 1. \text{ GHz}) \sim 1. \times 10^8$
  (Measured in a 2” Dielectric Resonator.)

![Diagram showing passivation layers and measurement results]

$Q = 9.59 \times 10^6$
$R_S = 2.3 \times 10^{-5}$

at 10.76 GHz

$R_S(1 \text{ GHz}) = 2 \times 10^{-7} \Omega$
System Simulations
Thermal Management, Power (AES, Inc.)

- Based on Our $R_S$ Data $\Rightarrow$ Simulations Confirmed Feasibility

Two Thermal-management Issues:

1. Gaseous He Cooling: MgB$_2$/Cu Five-Cavity Array
2. Resonance-Frequency Shift: Due to Thermal Expansion

Worst Case Scenario

$\text{He}(T, P) = (30\text{K}, 3 \text{ Atm})$

(Q = $0.608E9$ $f = 703.75 \text{ MHz}$)

- Cooling Load: Not a Problem
- Thermal Expansion: Relatively Small

Feasible

REF: AES, Inc.
Energy-Gap ($\pi$-Gap) Symmetry

● YBCO Work $\Rightarrow$ IMD-Power: Nonlinear Probe of Energy-Gap Symmetry
● Surprise: Low-T IMD-power Upturn: Inconsistent with s-wave $\pi$-Gap

$$P_{S\text{-WAVE}} (T) \propto T^{-5} e^{-2\Delta/(k_B T)}$$

$$\Delta_\pi (T, \varphi) = \Delta_0 (T) \sin (6 \varphi)$$

$$P_{IMD} (T) \propto T^{-2}$$

● Impact of $\pi$-Gap $\ell=6$ Symmetry: Surface-Resistance Variation, NL, at Low-T

$$R_S (BCS) \propto \frac{1}{T} e^{-\Delta/(k_B T)} \iff R_S (\ell = 6) \propto T$$

Accomplishments

- **Materials Science (Reactive Evaporation Deposition):**
  - High-quality, Flat, Ultra Smooth MgB₂/Sapphire, MgB₂/Nb Films
  - Passivation Success with ZrO-AIO Coating

- **Data/Characterization and Analysis:**
  
  \( R_S \) Database: at Low, High Power of Flat MgB2/(SAPPHIRE, Nb) Films

\[
E_{\text{ACC}}: \begin{align*}
&\text{CURRENT RECORD} \sim 20\text{MV/m} \\
&\text{LIKELY that } E_{\text{ACC}} \text{ IS HIGHER}
\end{align*}
\]

Thermal Management Simulation \( \Rightarrow \) OK
\( \pi \) Energy-Gap \( \ell=6 \) Symmetry: Data and Theory

- **Outlook:**

  The 2-\( \lambda \) Thick MgB-Coated Cavity Proposition: Promising
Future Challenges

High-Quality Film **Deposition on Curved Metallic Surfaces**

Demonstrating **Low $R_s$** in those films

Demonstrating a **High Field Gradient** in those Films

**Theory**

**Make a MgB$_2$-based** RF Cavity with High Field Gradient
End Presentation