High $T_c$ : New Developments & Progress on Understanding the Mechanisms and Hope for the Future

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Why do we need high-$T_c$ materials study for RF cavities?

- High-purity Nb and cavities are still expensive.
- Refrigeration to get to 4 K or lower is expensive
- Nb cavities have reached close to its theoretical limit and the recipe to get good results such as $E_{acc} > 35$ MV/m repeatedly will be established within ~5 years.

![Level of Interest vs. Time Diagram](image-url)
Outline

1. What are high-$T_c$ materials
2. Mechanisms of Superconductivity in High-$T_c$ materials (Cu oxide and MgB$_2$)
3. Properties of High-$T_c$ materials that are related to the application to SRF cavities
4. Developments in the past 2 years
What are high-$T_c$ materials

- In 1986, Georg Bednorz and Alex Müller discovered a superconductivity at $\sim\text{38 K}$ in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ ceramics.
- In 1987, research groups in Alabama and Houston, coordinated by K. Wu and Paul Chu discovered $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_7$ ceramics with $T_c = \text{92 K}$. For the first time above LN2 temperature.
- The highest $T_c$ so far is $\text{138 K}$ with $(\text{Hg}_{0.8}\text{Tl}_{0.2})\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{8.33}$
- Is room temperature superconductor possible??
- $\text{MgB}_2$ was discovered to be superconductive at $\sim\text{40 K}$ in early 2001. It was a surprise since it is a simple binary intermetallic compound.
2. Mechanisms of Superconductivity in High-\(T_c\) materials - Cuprates (\(\text{Cu}_x\text{O}_y\))

- In general, superconductivity results from the interaction between electrons (holes) and phonons, the quantized lattice vibration.
- The superconductivity occurs when additional oxygen is doped into \(\text{YBa}_2\text{Cu}_3\text{O}_6\) which forms CuO “chains.”
- These oxygen ions attract electrons from CuO\(_2\) plane, which produces holes that become Cooper pairs.

(La,Sr)$_2$CuO$_4$ and YBa$_2$Cu$_3$O$_7$

a) $\text{(La,Sr)}_2\text{CuO}_4$ $T_c=38$ K

b) YBa$_2$Cu$_3$O$_7$ $T_c=92$ K

$\text{Tl}_2\text{Ba}_2\text{Cu}_1\text{O}_6$ (85K), $\text{Tl}_2\text{Ca}_1\text{Ba}_2\text{Cu}_2\text{O}_8$ (105K) and $\text{Tl}_2\text{Ca}_2\text{Ba}_2\text{Cu}_3\text{O}_{10}$ (125K)

Magnesium Diboride (MgB$_2$)

Superconductivity comes from the phonon-mediated Cooper pair production similar to the low-temperature superconductors except for the two-gap nature.

**Compared to cuprates:**

- Cheaper
- Lower anisotropy
- Larger coherence length
- Transparency of grain boundaries to current flows

These makes MgB$_2$ attractive for applications.

2. Properties of High-$T_c$ materials that are related to the application to SRF cavities

- The RF surface resistance ($R_s$), which is proportional of $1/Q_0$, is the most important property for RF cavities.
- The other critical property is RF critical magnetic field ($H_{c, RF}$)
- Here, we focus on the $R_s$ and its power dependence and will not discuss $H_{c, RF}$ since there is no data yet, to my knowledge.
Rs of YBCO shows rapid increase with $H_{RF}$


Nb 1GHz
3. Developments in the past 2 years

• To my knowledge, no efforts to use YBCO or other cuprates for SRF cavities have been made.
• MgB$_2$ has shown in 2003 lower $R_s$ than Nb at 4 K and about 10x lower predicted BCS $R_s$.
• A MgB$_2$ sample was tested up to $H_{RF} \sim 120$ Oe, i.e. equivalent of $E_{acc} \sim 3$ MV/m, with little increase in the $R_s$. (late 2004)
• Here, we focus on the development of MgB$_2$. 
Simple binary compound, but needs high Mg pressure to form MgB$_2$ phase


Pressure-temperature phase diagram for the Mg:B
MgB$_2$ Film Growth, an example at the Superconductor Technologies, Inc. (STI)

*In-situ* reactive evaporation

More details are found in
T. Tajima et al, Proc. PAC05.

B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005
MgB$_2$ on 4" substrates

R-plane sapphire

Si$_3$N$_4$ / Si

B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005
Surface morphology – MgB$_2$ on $r$-plane sapphire

- Typical surface on $r$-plane sapphire
- Growth $T = 550 \, ^\circ C$
- $t = 5500 \, \text{Å}$
- Small, conical grains
- $\sim 1000 – 2000 \, \text{Å}$ diameter
- RMS roughness $= 44 \, \text{Å}$

B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005
Surface morphology – smoother films

- MgB$_2$ on MgO
  - Growth $T = 550$ °C
  - $t = 3000$ Å
  - RMS roughness = 22 Å

- MgB$_2$ on sapphire
  - Low $T$ growth: 450 °C
  - $t = 1500$ Å
  - RMS roughness = 12 Å

B.H. Moeckly, ONR Superconducting Electronics Program Review Red Bank, NJ, February 8, 2005
Microstructure – MgB$_2$ on c-plane sapphire

- Columnar growth
- Clear layer at interface
- Layer looks grown, not reacted

- Grain size ~100 nm
- Numerous threading defects in lower half
- Defects decrease with thickness

Dave Smith

B.H. Moeckly, ONR
Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005
Stability – DI water soak

- Films etch very slowly in water
- Films also seem stable with time

B.H. Moeckly, ONR
Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005
Latest films have shown $R_s$ lower than Nb at 4 K.

Residual resistance still dominates at lower temperatures.

1 cm$^2$ sample on r-cut sapphire
Predicted BCS $R_s$ is $\sim 1/10$ of Nb

Dotted lines are predicted BCS resistance.

$R_s$ does not change much with $H_{RF}$.

First attempt to coat on a Nb substrate (1.5 cm disk).

$R_s$ was higher than Nb possibly due to the rough ($R_a \sim 400 \text{nm}$) substrate.

The highest $H$ was limited by available power.

There was only one test and the result needs to be confirmed with others.

Measurement at Cornell with $TE_{011}$ Nb cavity at 4.2 K.
Summary

• It is important for the SRF community to continue looking for high-\(T_c\) materials that can be applied to SRF cavities.
• YBCO and other cuprates show rapid increase of \(R_s\) with \(H_{RF}\), preventing the use of cuprates for SRF cavities.
• MgB\(_2\) is more complicated than Nb but less complicated and cheaper than YBCO and other higher-\(T_c\) materials and could potentially lead to significant cost reduction.
• Critical parameters such as \(R_s\) power dependence and critical \(H_{RF}\) need to be determined.
• Making a MgB\(_2\)-coated cavity might be easier than you think. Let’s try to coat/make a cavity with MgB\(_2\) and measure the performance.
Thanks for the data and/or discussions and collaborations!

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Backup Slides
Tests at Cornell with 6-GHz Nb TE_{011} Cavity

Measurement by Alexander Romanenko, Hasan Padamsee
MgB$_2$ has two energy gaps

RF response has shown lower energy gap behavior.

A. Floris et al., cond-mat/0408688v1 31 Aug 2004