A15 Superconductors: Alternative to Nb for RF Cavities

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Outline

• **Theory:** *Surface Resistance*

  - **Mo-Re system:** *Deposition Technique and Results*
  - **V₃Si:** *Thermal Diffusion in Reactive SiH₄ Atmosphere*
  - **Nb₃Sn:** *Liquid solute diffusion technique*
  - **6 GHz cavities:** *RF Measurements*

• **Conclusions and future plan**
Surface Impedance and Surface Resistance

For a normal metal in the normal regime:

\[ Z_n = \frac{1 - i}{\sigma_n \delta} = \left(1 - i\right) \frac{\rho_n}{\delta} \]

- \( \sigma_n = 1 / \rho_n = \) dc conductivity at T
- \( \delta = \) skin depth

Extension to Superconductors:

\( \sigma_1 - i\sigma_2 \) in place of \( \sigma_n \)

As derived by Nam, for \( T < T_c / 2 \), \( R_s \) can be approximated by:

\[
\frac{R_s}{R_n} = \frac{1}{\sqrt{2}} \frac{\sigma_1}{\sigma_n} \left(\frac{\sigma_2}{\sigma_n}\right)^{3/2}
\]
Mattis and Bardeen Integrals

In the framework of the BCS theory, for $\omega < 2\Delta$, the complex conductivity of a superconductor is:

\[
\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar \omega} \int_{\Delta}^{\infty} \left[ f(E) + f(E + \hbar \omega) \right] g^+(E) dE
\]

\[
\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar \omega} \int_{\Delta - \hbar \omega, -\Delta}^{\Delta} \left[ 1 - 2f(E + \hbar \omega) \right] g^-(E) dE
\]

The two integrals $\sigma_1/\sigma_n$ and $\sigma_2/\sigma_n$ are easily numerically calculated.

\[
\frac{\sigma_1}{\sigma_n} = \left[ \frac{2\Delta}{K_B T} \right] \frac{e^{-\Delta/K_B T}}{\left( 1 + e^{-\Delta/K_B T} \right)^2} \ln \frac{\Delta}{\hbar \omega}
\]

\[
\frac{\sigma_2}{\sigma_n} = \frac{\pi \Delta}{\omega} \tanh \frac{\Delta}{2K_B T}
\]

In the normal skin effect regime, for $\hbar \omega \ll 2\Delta$
Then, if \( T < T_c / 2 \)

\[
R_{\text{BCS}} \approx \frac{R_n}{\sqrt{2}} \left( \frac{\hbar \omega}{\pi \Delta} \right)^{\frac{3}{2}} \frac{\sigma_1}{\sigma_n} = A \sqrt{\rho_n} e^{-\frac{\Delta}{K_B T}} (1 + O(\Delta, \omega, T))
\]

Empirically, \( R_{\text{res}} \) is found to be dependent on \( \rho_n \) too.
Essence of the previous slides

For low rf losses,
a high $T_c$ value is not sufficient

A metallic behaviour
in the normal state is mandatory
Literature: Mo-Re system

$\text{Mo}_{38}\text{Re}_{62}$

Testardi, 1975
Literature: Mo-Re system

A - Sputtering $v \sim 500$ Å/min, deposition $T = 1000$ °C, B - Sputtering $v \sim 1000$ Å/min, deposition $T = 1200$ °C, C - Mo-Re bulk samples

Gavaler et al.
Mo-Re system: deposition technique

Magnetron Sputtering at high T

3 Target Compositions

$\text{Mo}_{75}\text{Re}_{25}$

$\text{Mo}_{60}\text{Re}_{40}$

$\text{Mo}_{38}\text{Re}_{62}$
Mo$_{75}$Re$_{25}$

26 SPUTTERING RUNS

More than 60 samples

11 samples SETS

Annealing treatment
Mo$_{75}$Re$_{25}$: XRD Spectra

Target XRD Spectrum

Deposition $T = 633^\circ C$, Annealing $t = 15$ minutes
Mo$_{75}$Re$_{25}$: A Superconductive Transition Curve

- **Deposition:** $T = 633^\circ C$
- **Annealing:** $t = 15$ min

$T_c = 11.398$ K
$\Delta T_c = 0.009$ K
$RRR = 1.57$
Mo$_{75}$Re$_{25}$: $T_c$ vs Annealing Time

$T = 750^\circ C$

$T = 800^\circ C$
**Mo$_{75}$Re$_{25}$: $R$ vs $T$ at Increasing $H$**

Deposition $T = 633^\circ C$, Annealing $t = 15$ minutes

- 40,000 Gauss
- 0 Gauss

![Graph showing $R$ vs $T$ at increasing $H$.]
A Mo$_{75}$Re$_{25}$ Film Deposited on Cu

Mo$_{75}$Re$_{25}$, Cu: Deposition $T = 680°C$, no annealing

$T_c = 11.18K$

$\Delta T_c = 0.08K$
A Mo$_{75}$Re$_{25}$ Film Deposited on Nb

Mo$_{75}$Re$_{25}$, Nb: Deposition T = 725°C,
Annealing t = 15 min

$T_c$ = 11.03K
$\Delta T_c$ = 0.08K
Mo$_{60}$Re$_{40}$: A Superconductive Transition Curve

- **Deposition:** $T = 750^\circ C$
- **Annealing:** $t = 60$ min

$T_c = 12.00 K$
$\Delta T_c = 0.041 K$
$RRR = 1.88$
Mo$_{60}$Re$_{40}$: $\Delta T_c$ vs Annealing Time

- **Deposition $T = 800^\circ$C**
- **Deposition $T = 850^\circ$C**
Lines of equal $R_{BCS}$. At $T = 4.2$ K, $f = 500$ MHz, $s = 4$

$R_{BCS}$ depends on $\Delta$ and $\rho_n$

- $\text{Mo}_{60}\text{Re}_{40}$ ($T_c = 12.13$, $\text{RRR} = 1.3$, $\rho_n \sim 30 \mu\Omega\text{cm}$)
- $\text{Mo}_{75}\text{Re}_{25}$ ($T_c = 11.82$, $\text{RRR} = 1.71$, $\rho_n \sim 10 \mu\Omega\text{cm}$)
$\text{Mo}_{38}\text{Re}_{62}$: A Superconductive Transition Curve

Deposition $T = 750^\circ C$, Annealing $t = 60$ minutes

$T_c = 9.47K$
$\Delta T_c = 0.029K$
$\text{RRR} = 1.11$
Annealing treatments give surprising results:

- $T_c$ is higher than 12K ($\text{Mo}_{60}\text{Re}_{40}$)
- $\Delta T_c$ becomes one of the most meaningful parameters.
- A sharp superconducting transition corresponds to a high $\xi_0$.

Essence of the previous slides:

- We deposited more than 100 films
- $R_{\text{BCS}}$ is around 16 nΩ ($\text{Mo}_{75}\text{Re}_{25}$, $\text{Mo}_{60}\text{Re}_{40}$)

of the most meaningful parameters. A sharp superconducting transition corresponds to a high $\xi_0$. 
$V_3Si$: RRR vs Silicon content
Preliminary results on cosputtering of $V_3Si$ films by the facing-target magnetron technique

Y. Zhang, V. Palmieri, R. Preciso, W. Venturini, Legnaro National Laboratory, ITALY

Schematic diagram of the facing-target magnetron.

Superconducting transition of a $V_3Si$ sample
Thermal diffusion of $V_3Si$ films

Y. Zhang, V. Palmieri, W. Venturini, F. Stivanello, R. Preciso, Legnaro National Laboratory, ITALY

Diffusion Parameters:

<table>
<thead>
<tr>
<th>Silane pressure</th>
<th>Heat power</th>
<th>Temperature</th>
<th>Diffuse in silane</th>
<th>Anneal in vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.2 \cdot 10^{-4}$mbar</td>
<td>300W</td>
<td>900°C</td>
<td>20h</td>
<td>40h</td>
</tr>
</tbody>
</table>

There is room to improve the film quality by higher thermal diffusion temperature or by longer annealing time in vacuum.

AC inductive measurement:

$T_c \sim 16.0K$

$\Delta T_c < 0.4K$
Reactive sputtered $V_3Si$ films
Y. Zhang, V. Palmieri, W. Venturini, R. Preciso, Legnaro National Laboratory - INFN, Italy

Surface of two annealed samples under SEM: Grain size, (a) 0.2µm, (b) 0.5µm

Before annealing

After annealing

Temperature vs. Silicon content graph:
- 800°C
- 500°C

$T_c$ (K) vs. Silicon content (% at.)
Essence of the previous slides

No matter how good the initial superconductive properties of the film are

$T_c$'s of 17 K and RRR values of 18 have been recovered by annealing in SiH$_4$ atmosphere

We are ready to apply the thermal diffusion method to 6 GHz cavities
Wuppertal: Nb$_3$Sn cavity (1.5 GHz) obtained through Sn vapour phase diffusion (’90s)

Q vs. E_{peak} of the first two Nb3SN-coated 1.5 GHz single-cell cavities in comparison to pure Nb at 4.2 K and 2 K from CEBAF.
Nb$_3$Sn: Liquid solute diffusion
**Nb$_3$Sn: Used System**

- Linear feed trough
- Cooling water jacket
- Furnace
- Liquid Sn
$\text{Nb}_3\text{Sn}$: Phase Diagram

$T_c$ phases $\approx 930^\circ\text{C}$
Nb$_3$Sn: Sn at.% vs Depth

Nb$_3$Sn n°4: 970°C, 30min+6h
**Nb$_3$Sn: XRD**

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- **Nb$_3$Sn n°4:** T=970°C, 30min+6h
$\text{Nb}_3\text{Sn}: \text{A Superconductive Transition Curve}$

$T_c = 17.3 \text{ K}$

$\Delta T_c = 0.1 \text{ K}$
**Nb$_3$Sn Process Parameters:**

- $T = 970^\circ$C
- Dipping time = 1h
- Annealing time = 1h

**Nb$_3$Sn Surface Treatment:**

- Pure HCl (55-66°C) for 15 minutes
Essence of the previous slides

- Uniformity of Nb$_3$Sn film ensured and stoichiometry maintained

- We can avoid Nb-Sn low $T_c$ phases:
  - maintaining $T > 930^\circ C$ during the experiment
  - reducing $T$ very fast at the end of the process

- A possible Sn outer layer has to be removed: we are able to get rid of it by prolonged post annealing
6 GHz seamless cavities
obtained by the spinning technique:

- are made from scrap material
- do not need welding (even for flanges)
- are directly measured inside a Liquid He dewar
6 GHz Cavities

1. Spinning Technique

2. Surface Treatments
   - Mechanical polishing
   - Chemical polishing
   - A15 obtainment

3. Q Factor Measurement
6 GHz Cavities: Q Factor Measurement

$\text{Nb}_3\text{Sn}$
Conclusions
From scrap material and by a seamless technique we are planning a 6 GHz cavities mass production to investigate A15 intermetallic compounds.
A atoms form **linear chains**: they are parallel to the 3 crystallographic directions [100], [010], [001]
Mo$_{75}$Re$_{25}$ Cavity (MIT 1978)

K. Agyeman, I. M. Puffer, J. A. Yasaitis and R. M. Rose, “Superconducting Mo$_{0.75}$Re$_{0.25}$ cavities at X-band”
Literature: Mo-Re system

6 GHz Cavities: Mechanical Polishing
6 GHz cavities: Chemical Polishing