Multilayer Approach to Increase the Performance of SRF Accelerating Structures beyond Bulk Nb
Outline

- Theoretical Proposal: SIS Concept
- Choice of Materials
- Experimental Setup
- NbTiN films
- AlN Films
- SRF NbTiN/AlN SIS Structures
- Concluding Remarks
Beyond Nb: SIS Multilayers

Taking advantage of the high –T_c superconductors with much higher H_c without being penalized by their lower H_{c1}...

Alex Gurevich, AIP ADVANCES 5, 017112 (2015)

Multilayer coating of SC cavities: alternating SC and insulating layers with d < \lambda

Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration

- Strong increase of H_{c1} in films allows using RF fields > H_c of Nb, but lower than those at which flux penetration in grain boundaries may become a problem => no transition, no vortex in the layer
- High H_{c1}, applied field is damped by each layer
- Insulating layer prevents Josephson coupling between layers
- Applied field, i.e. accelerating field can be increased without high field dissipation
- Strong reduction of BCS resistance (ie high Q_0) because of using SC layers with higher T_c, \Delta (Nb_3Sn, NbN, etc)

Possibility to move operation from 2K to 4.2K
Choice of Materials for S-I-S structures

Ternary Nitride \((\text{Nb}_{1-x}\text{Ti}_x)\text{N} (T_c=17.3\text{ K, } a = 4.341\text{ Å})\)

Presence of Ti found to reduce significantly the resistivity and facilitate formation of a pure cubic structure. The \(\delta\)-phase remains thermodynamically stable even at RT. \(T_c\) as high as for good quality NbN, for Nb fraction \((1-x)>0.5\)

More metallic nature and better surface properties than NbN should result in better RF performance.

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- extreme hardness, excellent adherence on various substrates, very good corrosion and erosion resistance, high sublimation temperature, and relative inertness
**Choice of dielectric for S-I-S structures**

AlN is an insulator that:
- can be grown with a wurtzite (hcp, $a=3.11\text{Å}$, $c=4.98\text{Å}$) or sphalerite (B1 cubic, $a= 4.08 \text{ Å}$) structure.
- has been found to enhance the properties ($T_c$) of NbN and NbTiN, in particular for very thin films.
- has a large thermal conductivity ($3.19\text{W/cm.K at 300K}$, comparable with Cu, $4.01\text{W/cm.K}$)

![Wurtzite structure](image1.png)

![Sphalerite structure](image2.png)
**Experimental Setup**

- **Substrates:** MgO, AlN ceramic, Bulk Nb, ECR Nb films

- **Base pressure range:** $10^{-10}$ Torr

- **Equipment:**
  - 3 x 2” DC/RF Magnetrons
  - Ion source
  - dc-Magnetron Sputtering (reactive mode)
  - HiPIMS (Huettinger 2000 V, 3000 A)

**CHALLENGES**

- Develop good quality and uniform thin layers
- Sharp interfaces
- Growth of equally performing S/I and I/S layers
**NbTiN film**

NbTiN are grown on various substrates at 600°C by reactive sputtering with targets of different Nb/Ti weight ratios. Films exhibit good crystalline structure in general. Best results at 600 °C on MgO.

*Bulk-like film*

- **NbTiN grown at 600°C on MgO**
  - Thickness = 2μm
  - High quality single crystal
  - $T_c = 17.25$ K
  - $H_{c1} = 30$ mT
NbTiN Films – Influence of Thickness on Tc

Single crystal NbTiN/MgO films (XRD/EBSD)
Very smooth films (~ substrate)

$T_c \geq 16 \text{ K for film thickness } > 35 \text{ nm}$
Measurements at room temperature
Max. SEY = 2.2 ± 0.1 comparable to EP Nb
After sputtering away ~ 3 nm, SEY down to 1.15
Secondary Electron Yield of NbTiN Films

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sputtering away ~3 nm, SEY down to 1.15

TUPB050 - Secondary Electron Yield of SRF Materials
Sarah Aull et al., CERN
Good quality AlN are readily produced at 600 and 450°C by dc-reactive magnetron sputtering. The films exhibit the cubic structure (single crystal) at 600 °C and the hexagonal structure (polycrystalline) at 450 °C.

At 450 °C, 30 nm AlN films exhibit dielectric properties of polycrystalline AlN films with a refractive index in the range of 1.98-2.15.
SRF Multilayer Structures Based on NbTiN
Influence of coating temperature

### NbTiN/AlN/Nb film at 600 °C

<table>
<thead>
<tr>
<th></th>
<th>AlN</th>
<th>NbTiN</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂/Ar</td>
<td>0.33</td>
<td>0.23</td>
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<tr>
<td>Total pressure [Torr]</td>
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<tr>
<td>Sputtering Power [W]</td>
<td>100</td>
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<tr>
<td>Deposition rate [nm/min]</td>
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<tr>
<td>Thickness [nm]</td>
<td>5</td>
<td>100</td>
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<tr>
<td>Tc [K]</td>
<td>N/A</td>
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</table>

TEM cross-section (FIB cut) of NbTiN/AlN/Nb/Cu structure

Miscibility of AlN into Nb and NbTiN at 600 °C
NbTiN/AlN on bulk Nb

TEM cross-section (FIB cut) of NbTiN/AlN/bulk Nb structure
SRF Multilayer Structures Based on NbTiN
Influence of roughness & interlayer on $T_c$

Quality of underlying AlN dictates quality of the NbTiN film
Roughness of substrate not detrimental to $T_c$

SI layers on MgO and AlN coated simultaneously

Rms=0.396 nm $a = 4.3455 \text{Å}$

Rms=13.434 nm $a = 4.3584 \text{Å}$
**NbTiN Films (SI) – $H_{c1}$ measurement**

**SQUID Magnetometry**
(Prof. A. Lukaszew group, College William & Mary)

150 nm NbTiN/AlN films exhibit **$H_{c1}$ enhancement** compared to bulk-like NbTiN film

*Thickness series study under progress*

<table>
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<tr>
<th>Thickness [nm]</th>
<th>$H_{c1}$ [mT]</th>
<th>$T_c$ [K]</th>
</tr>
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<tbody>
<tr>
<td>NbTiN/MgO</td>
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<td>30</td>
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<tr>
<td>NbTiN/AlN/AlN ceramic</td>
<td>145</td>
<td>135</td>
</tr>
<tr>
<td>NbTiN/AlN/MgO</td>
<td>148</td>
<td><strong>200</strong></td>
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</table>

$H_{c1}$ at 5 K for coherence length ~ 5 nm
Bulk $H_{c1}$ ~ 300 Oe

$$B_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\xi} \quad d < \lambda_L$$
**R_s of NbTiN/AlN structures on Nb surfaces**

SIS structures coated on ECR Nb/Cu film: 24h-bake, coating and annealing for 4 h at 450°C.

Lower BCS resistance beyond 4 K for SIS coated Nb/Cu film compared to standalone film & bulk Nb. Similar effect observed for NbTiN/AlN/bulk Nb.

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<td>150</td>
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<tr>
<td>Tc [K]</td>
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**Graph:**

RF Measurement in 7.5 GHz sapphire-loaded TE_{011} cavity.
Summary

- Good quality standalone NbTiN deposited by reactive DC magnetron sputtering.
  - Bulk, i.e. thicker than 1 micron, NbTiN films readily produced with a $T_c$ of 17.3 K and $H_{c1}$ of 30 mT.
  - Cubic $\delta$-phase and $T_c$ above 16 K for thicknesses larger than 30-50 nm and coating temperatures of 450 °C or higher.

- AlN dielectric films with good dielectric properties.

- Good quality SIS NbTiN/AlN layers with a $T_{c, NbTiN}$ between 16.6 and 16.9 K.
  - **Growth conditions for SIS structures** need to be a compromise between optimum conditions for standalone films and minimizing interaction between layers.
  - If the dielectric can be grown as an adequate template, the substrate macro-roughness is not necessarily detrimental to the $T_c$ of the superconducting film.

- $H_{c1}$ enhancement (SQUID magnetometry) observed for 150 nm NbTiN films. Further studies under way to determine /verify optimum layer thickness.

- **RF characterization of NbTiN/AlN structures coated on Nb surfaces** reveal a promise of delaying flux penetration and lower RF losses for SIS coated Nb surfaces, both bulk and thick film (along with other experiments: cf Antoine C. –CEA, Lukaszew A. - W&M).
On-going & Future Work

- Thickness series to determine/verify optimum layer thicknesses with $H_{c1}$ measurements
- Implementing energetic condensation via HiPIMS (High power impulse magnetron sputtering) will allow to lower the coating temperature while maintaining a good quality $\delta$-phase for NbTiN.

*First depositions of NbTiN films with HiPIMS with reasonable results.*

- RF measurement for SIS NbTiN/AlN structures on previously characterized bulk Nb QPR samples.

A concept to deposit SIS structures on Nb cavities (bulk of thick Nb/Cu) has already been developed. This will allow the implementation of the SIS proof of concept in form of elliptical cavities using existing infrastructure.

Concept for SIS structure coating on Nb & Nb/Cu cavities
Thank You for your Attention
$R_s$ of bulk NbTiN film (2 μm)
 NbTiN Films with HiPIMS

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</table>

0-20 scans of the first films produced by HiPIMS reveal that only the films produced with an average power of 400 W and repetition rate of 200 Hz have the δ-phase. The measured $T_c$ is 16.6 K for a 250 nm thick film.

Typical pulse for reactive HiPIMS of NbTiN

250 nm thick

$T_c = 16.6$ K