Atomic Layer Deposition of Thin Superconducting Films and Multilayers: Coupons and Cavity Tests

Thomas Proslier

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R. McDermott, U. of Madison
Decrease Cost I: Multilayers

Fields in bulk Nb cavities approaching dc depairing limit for Nb, $H_c(0) \approx 200 \text{ mT}$


- Increase performance
  - Move beyond limits of Nb
- Decrease cost (early career award 2011)
  - Higher operating temperature (reduce cryogen costs)
  - Replace bulk Nb with cheaper material (Cu/Al)

- Coat inside Nb SRF cavity with precise, layered structure → ALD
Decrease Cost II: Nb films on Cu

SRF cavities Goals $E_{\text{max}} \sim 70 \text{ MV/m}$ and $Q > 10^{10}$ at $T > 4.2 \text{ K}$

- All thin films
  -> reduce surface preparation.

- High Tc materials:
  $\text{Nb}_3\text{Sn}$, $\text{MgB}_2$, Pnictides, $\text{BaKBiO}_3$ etc…

- But:
  Higher Tc -> Lower $H_{c1}$ -> Lower Gradient
Collaboration: Synergy of expertise

**PHYS-APS**
Processing/Testing

M. Kelly, R. Murphy

**Collab**
Berkeley/Alameda
HIPIMS

A. Anders, M. Krishnan

**HEP**
support-funding

Th. Proslie

**MSD**
ALD-PCT-characterization

J. Klug, N. Groll

**IIT**
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J. Zasadzinski
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**Collab**
JLAB
test coupons/cavities
ECR

A-M. Valente, P. Kneisel, G. Ciovati

**Collab**
FNAL
Processing/testing

A. Grasselino, A. Romanenko,
L. Cooley, A. Rowe, B. Stone,
V. Yakovlev, C. Ginsburg…

**Collab**

M. Kelly, R. Murphy

A. Anders, M. Krishnan

A-M. Valente, P. Kneisel, G. Ciovati
- **Multilayers:**
  Atomic Layer Deposition of superconductors. Coupons & SRF cavities.

- **Niobium on Copper**
  Coupons and RF test.
Sequential pulsing of gas phase precursors (A and B) ... (A, B, C...)
Superconductors by ALD

Goal for SRF is a material with a $T_c$ higher than bulk Nb (9.2 K)

- **Niobium Carbide: NbC**  \[1.7 \text{ K}\]
  - $\text{NbF}_5 + \text{Al(CH}_3\text{)}_3$
  - $\text{NbCl}_5 + \text{Al(CH}_3\text{)}_3$

- **Niobium Carbo-Nitride: NbC$_{1-x}$N$_x$**  \[3.8 \text{ K}\]
  - $\text{Al(CH}_3\text{)}_3 + \text{NbF}_5 + \text{NH}_3$
  - $\text{Al(CH}_3\text{)}_3 + \text{NbCl}_5 + \text{NH}_3$

- **Niobium Silicide: NbSi**  \[3.1 \text{ K}\]
  - $\text{NbF}_5 + \text{Si}_2\text{H}_6$
  - $\text{NbF}_5 + \text{SiH}_4$

- **Titanium Nitride: TiN**  \[3.8 \text{ K}\]
  - $\text{TiCl}_4 + \text{NH}_3$

- **Molybdenum Nitride: MoN**  \[11.8 \text{ K}\]
  - $\text{MoCl}_5 + \text{NH}_3$
  - $\text{MoCl}_5 + \text{Zn} + \text{NH}_3$

- **Niobium Titanium Nitride: Nb$_{1-x}$Ti$_x$N**  \[14 \text{ K}\]
  - $(\text{NbF}_5, \text{TiCl}_4) + \text{NH}_3$
  - $(\text{NbCl}_5, \text{TiCl}_4) + \text{Zn} + \text{NH}_3$

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Th. Proslier et al. Accepted to PRB

M. Mironov et al. submitted to Nature Materials

N. Groll et al. Accepted to APL.

ALD NbN with $T_c = 10$ K reported

Superconductors by ALD

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  - $(\text{NbF}_5, \text{TiCl}_4) + \text{NH}_3$
  - $(\text{NbCl}_5, \text{TiCl}_4) + \text{Zn} + \text{NH}_3$
Growth characterization – NbSi

In situ monitoring:
- Quartz crystal Microbalance (QCM)
  <300 °C: Mass gain (ng/cm²)
- Residual Gas Analyzer (RGA):
  reaction products
  -> Growth mechanisms

\[
\text{NbSi} = \text{NbF}_5 + \text{Si}_2\text{H}_6
\]
Growth characterization – NbSi

In situ monitoring:
- Quartz crystal Microbalance (QCM):
  <300 °C: Mass gain (ng/cm²)
- Residual Gas Analyzer (RGA):
  reaction products
  -> Growth mechanisms

Superconducting NbSi grown by ALD
4.5 Å/cycle

\[ \text{NbF}_3^* + \frac{11}{6} \text{Si}_2\text{H}_6 \rightarrow \text{NbSi}_3\text{H}_4\text{F}^* + \frac{2}{3} \text{SiHF}_3^* + \frac{19}{6} \text{H}_2 \]

\[ \text{NbSi}_3\text{H}_4\text{F}^* + 2 \text{NbF}_5 \rightarrow (\text{NbSi})_2\text{NbF}_3^* + \text{SiF}_4 + 4\text{HF} \]

500 nm
Niobium silicide: NbSi

X-ray reflectivity (XRR)
- Constant GR between 150-275°C
  - CVD above 275°C
- Low roughness, increases with T
  - Amorphous-crystalline transition?
  - No peaks in XRD
- Density constant up to 350°C

Composition
- No fluorine detected
- RBS: Nb:Si ratio 1:1
- XPS: Nb, Si chemically bound

Resistivity
- 145-165 μΩ-cm in ALD regime

Do not grow on oxides!

Molybdenum Nitride (MoN)

Growth temperature: 450 °C
MoCl$_5$ + NH$_3$

Preferred orientation: (002) / $T_C = 11.5$ K
XRR: Thickness study

450 °C

Linear, well controlled growth with fine thickness control
Bulk-like density, roughness ~ 25-35 Å

Graphs showing:
- Linear relationship between thickness (Å) and number of ALD cycles with a slope of 0.31 ± 0.02 Å/cycle.
- Density (g cm⁻³) and roughness (Å) plotted against number of ALD cycles.
GIXRD: Evolution of structure with thickness

Mo$_2$N as a nucleation confirmed by XPS

MoN phase grain size increase with thickness
Mo$_2$N does not

Confirmation of Mo rich nucleation
Transport: Evolution with thickness

450 °C / H=0T

Resistivity bulk ~ 100 \( \mu \Omega \cdot cm \)

Tc bulk ~ 11.5 K

d>30 nm
Tunneling spectroscopy

$T = 1.8K - 27\text{ nm}$

$\Delta = 1.93 \pm 0.15\text{ mV}$

$\Delta_0 = 1.89 \quad T_c = 11.00$
MoN: $\Delta$, $T_c$ vs thickness

Bulk Limit for $T_C$ and $\Delta > 30$ nm

$2\Delta/k_BT_C = 4.5 \pm 0.1$, strong coupling.
Magnetic field dependence: Transport

Coherence length, $\xi_{GL} \sim 5.5$ nm
Magnetic field dependence: Transport

Thickness control -> 3D to 2D transition
\( \lambda_{\text{MoN}} \geq 150 \text{ nm} \)
Critical current

\[ j_c = H \frac{\pi r}{\ln(8r/d - 0.5)} / w \cdot d \]

50 μm Cu wire / 60 nm MoN @ 2K -> I ~ 1 Amp
Scalability by ALD (magnets?)

- MoN(1000cy)/AlN(300cy) @ 450°C on Cu coils: **266 wires/ 50 μm diameter**

Conformal deposition.

~ 250 Amps per layer of MoN
4 layers AlN/MoN -> 1kAmps!
Epitaxy

<table>
<thead>
<tr>
<th>Film</th>
<th>Substrate</th>
<th>Epitaxial relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoN</td>
<td>c-Al₂O₃</td>
<td>(0001)(1010)MoN</td>
</tr>
<tr>
<td>NbN</td>
<td>c-Al₂O₃</td>
<td>(111)[110]NbN</td>
</tr>
<tr>
<td>TiN</td>
<td>c-Al₂O₃</td>
<td>(111)[110]TiN</td>
</tr>
<tr>
<td>MoN</td>
<td>m-Al₂O₃</td>
<td>(1120)[1100]MoN</td>
</tr>
<tr>
<td>Nb₀.₈Ti₀.₂N</td>
<td>a-Al₂O₃</td>
<td>(111)[110]Nb₀.₈Ti₀.₂N</td>
</tr>
<tr>
<td>MoN</td>
<td>r-Al₂O₃</td>
<td>[1212][1010]MoN</td>
</tr>
<tr>
<td>TiN</td>
<td>r-Al₂O₃</td>
<td>(135)[121]TiN</td>
</tr>
</tbody>
</table>

(a) 60 nm MoN
(b) 15 nm Nb₀.₈Ti₀.₂N
(c) MoN(0002)
(d) MoN(2022)
(e) TiN(111)
(f) TiN(200)
(g) MoN(2240)
(h) Nb₀.₈Ti₀.₂N(111)

Intensity (A.U.)

Q = 4π Sinθ / λ (Å⁻¹)
MoN: High Res. Cross section TEM

From this direction with the film very thick we can confirm that we have the hexagonal phase throughout the majority of the film.

By addition gentle ion milling we can thin the sample and focus on the interface.
Nucleation of MoN

C axis Sapphire

[110] of Mo$_2$N

[110] of MoN
MgO(001)-MoN (211)

Grown at 450 °C

MoN

MgO

$\phi$ (°)

0  60  120  180  240  300  360

Intensity (A.U.)

(022)  (202)  (022)  (202)

a = 4.217 Å

2.982 Å

Mg

O
MgO-MoN

- MgO is a good tunnel barrier (for Josephson junctions etc)
- Good lattice match with Nb: attractive for SRF cavity
- We have high, sharp $T_c$ for MoN on (001)MgO

![Graph 1](image1)

- $T_c$: 11.89 K
- $\Delta T_c$: 0.09 K
Can we grow MgO by ALD?  OUI!

- 200 cycles Mg(Cp)₂/H₂O at 300 °C  -- 10nm thick
- OP/IP epitaxy: \((111)[110]\text{MgO} \parallel (0001)[1010]\text{Al}_2\text{O}_3\)
  \((111)[110]\text{MgO} \parallel (0001)[1010]\text{Al}_2\text{O}_3\)

- OP/IP alignment (FWHM): \(\Delta \omega: 0.017 \pm 0.003^\circ, \Delta \phi: 2.1 \pm 0.4^\circ\)

- Same epitaxy as observed for NbN and TiN \textit{at much lower temperature}

- Many materials haven't been deposited epitaxially by ALD simply because no one has tried.
Titanium Nitride (TiN) and NbTiN

- Chemistry: \((\text{NbCl}_5:\text{TiCl}_4) + \text{NH}_3\) at 350°C and 450°C
  - TiN and NbN GR < 1 unit cell ~ 0.3 and 0.2 Å/cy respectively
- Can vary Ti content with NbCl\(_5\):TiCl\(_4\) ratio (1:2 ~ 20% TiN)
  - Cubic δ phase in all films

With increasing TiN
- Peaks shift to higher angle
- Density decreases
  - 7.2 g/cm\(^3\) (1:0)
  - 5.7 g/cm\(^3\) (1:4)
- RT resistivity decreases
  - 380 µΩ-cm (1:0)
  - 130 µΩ-cm (1:4)

Chlorine content: 0.05 atom %

Are they good superconductors?
Controlled composition

Atomic control of Composition -> Tune Tc
**Nb_{1-x}Ti_xN: Superconducting T_c**

- Achieved superconducting $T_c = 14$ K 4:1
  - 40% higher than previously reported value for ALD NbN
  [Hiltunen et al., Thin Solid Films 166, 149 (1988)]

\[ \Delta = 2.3 \text{ meV} \pm 0.1 \]
Synergy

Jlab
Single Cell Nb Cavities Testing

MSD/HEP

FNAL
Single Cell Nb Cavities Testing

PHYS/APS/HEP

Clean room
Oven
Remote control
ALD

Material science fundamentals

Surface treatments
RF testing
Cavity test Results: NbTiN/AlN coating

PAV002 After coating by ALD (15 nm AlN/ 60 nm NbTiN)

Thermal Q switch of the cavity ~ 3 MV/m
-> does the multilayer quench?
-> Is the Tc of NbTiN what we anticipated (14K)?

Temperature mapping will give us answers !!

Reprocessing:
- Tumbling
- Chemical etching
- Baking
- Baseline testing

Other Materials to try: MoN/AlN
- Multilayers:
  Atomic Layer Deposition of superconductors. Coupons & SRF cavities.

- Niobium on Copper
  Coupons and RF test.
Nb onto Cu Initial surface roughness?

- Cu surface: Surface roughness, Sticking onto Cu

μm Sup films <-> roughness
4/HPR, All
3/EP (Able Electro)
2/Mechanical polish
(mirror-intermediate(5μm))
1/Machining

10 coupons

~1μm

>30μm

1 Cu cavity EP
1 Cu cavity Pol + EP

Nb/ Cu cavity
Alameda/Jlab

APS optic shop
Sticking/diffusion barrier

High RRR for T \( \gtrsim \) 400 C
BUT! delamination occurs

Solution: seed layer/diffusion barrier
ALD can Help:
Nitrides

- AlN/MoN/AlN 900 nm
- HPR 2000 ps

- Send coupons to HIPIIMS/Alameda/Jlab
- RF tested @ Jlab (end of March)
- Send EP Cu Cavity to Alameda
  Dep of Nb @ 450°C and above.

Nb sputt @ 450°C

TiN, MoN/TiN coating works
Cavity Coating test

Cu Cavity AES

Mechanical/Chemical Polishing

ALD coating TiN
20 nm @ 450 °C

Nb coating - 5μm Iris
~ 25 μm Beam Tube
375 °C
Cavity Coating test

AES cavity / HPR ANL

Nb Coating 2 μm Iris / 5 μm beamtubes
350 °C

Q ~ 1-2 \(10^7\) 4K, no improvement upon cooling
Summary

- Tune Tc and transport properties by controlling film thickness
- Tune Tc and transport properties by controlling composition: \( \text{Nb}_{1-x}\text{Ti}_x\text{N}, \text{TiN}, \text{MoN}, \text{NbSi}, \text{NbC}, \text{NbCN} \ldots \) and thickness.
- Growth temperature: lower Temp for High quality nitrides
- Fundamental interest for Quasi 2D limits + applications: Bolometers, High energy physics accelerators, magnets...
- Future work: \( \text{MgB}_2 \) (40K), \( \text{FeSeTe} \) (15K), \( \text{K(FeSe)}_2 \) (31K) etc...
  
  More cavity coating/Testing
  
  Nb onto cu cavities
Goal

Our research is directed towards depositing MgB$_2$ films onto cooper or other high thermal conductivity metals which would allow future superconducting rf cavities to be fabricated as film-coated structures.

Challenges

- **Material synthesis: atomic layer deposition**
  - Low-temperature growth (<500 C) of high-quality MgB$_2$
  - Create new chemistries and precursors (more reactive precursor for magnesium is needed).
  - ALD systems for cavity scale up and coupons research available and working

- **Materials synthesis: hybrid physical chemical vapor deposition (HPCVD)**
  - High-temperature growth (> 600 C)
  - Growth on copper challenging: Sticking and diffusion can be an issue.
  - Thickness control and conformality limited -> bulk films (> 10 λ).

Synergy

- Nucleation/diffusion layer by ALD can mitigate contamination @ high temp. in HPCVD
- Bulk HPCVD + Multilayer ALD of MgB$_2$ can further increase performance @ 10° K and increase $E_{\text{max}}$. 
Cavity and cryomodule concept

Typically superconducting Nb CW cavity designs require about 20 to 60 W at 4 K. MgB2 films can achieve similar surface resistance at 8-12 K. It makes it possible to use cryocoolers for heat removal.

The cryomodule without liquid cryogens is considerably simplified. No liquid filling ports or internal piping, liquid reservoirs, or internal gas piping is required. Cryocoolers.

Ideally, a high thermal conductivity material like copper would be best for the cavity. The thermal conductivity of Nb is about 200 W/mK, so even Nb would be usable as a substrate.
MgB$_2$ Film on 2” Sapphire Substrate

Surface Morphology: AFM

Center: Rq=10.4 nm  
Edge: Rq=10.1 nm

Film thickness vs location  
$T_c$, $\rho_0$ distribution  
Typical $\rho$-T curve
End
Super-insulating transition

UofC-ANL collaboration

NbTiN is: $2\times(\text{TiCl}_4 + \text{NH}_3)$ and $1\ (\text{NbCl}_5 + \text{NH}_3)$.

Grown @ 350°C

Nb$_{0.8}$Ti$_{0.2}$N – 2% Cl. ~ 5 nm

Possible super-insulating new compound higher $T^*$
NbSi-TEM

Polycrystalline - $d = 2.174 \pm 0.03\,\text{Å}$
Titanium Nitride (TiN) (1:0)

2 % Cl Impurities @ 350 °C
Lower densities (87%)
Titanium Nitride (TiN) (1:0)-transport

450 °C

Resistivity bulk ~ 70 $\mu\Omega$·cm
Tc bulk ~ 3.9 K

350 °C

Resistivity bulk ~ 200 $\mu\Omega$·cm
Tc bulk ~ 2.8 K
Titanium Nitride (TiN) (1:0)-transport

![Graph showing the effect of thickness and sheet resistance on Tc for 350 °C and 450 °C.](image)

- **Thickness [nm]** vs. **Tc [K]**
  - Black squares: 350 °C
  - Red squares: 450 °C

- **Sheet Resistance, R_{\|} (\Omega)** vs. **Tc [K]**
  - Red line: 450 °C
  - Black line: 350 °C
Niobium Titanium (Nb$_{1-x}$Ti$_x$N) 2:1

(NbCl$_5$ + Zn + NH$_3$)$_N$ + (TiCl$_4$ + Zn + NH$_3$)

$\rightarrow$ ZnCl$_2$ (> 410°C)

Decrease temp:
lower density
more impurities ~ 2% Cl @ 350°C
Niobium Titanium ($\text{Nb}_{1-x}\text{Ti}_x\text{N}$) 2:1

Resistivity bulk ~ 250 $\mu\Omega$.cm
Tc bulk ~ 7.8 K

Resistivity bulk ~ 630 $\mu\Omega$.cm
Tc bulk ~ 4.5 K
Point contact tunneling on hot spots from Nb SRF cavities

X. Zhao et al. PRSTAB 13, 124701 (2010)
Cold spots vs Hot spots Medium Field Q slope

BTK Fit ($\Delta$, $\Gamma$, Z)
High quality spectra, $\Gamma/\Delta < 6\%$

**Cold spot**
- $\Delta = 1.55$
- $\Gamma = 0.09$
- $Z = 20$

**Hot spot**
- $\Delta = 1.09$
- $\Delta = 1.31$
- $\Delta = 1.55$
surface paramagnetism on Nb

Pair breaking parameter

\[ \alpha \square \frac{c}{4} N(0)S(S+1)J^2 = \frac{\Gamma}{\Delta} \]

Homogenous Mag Moments concentration on \( \xi \)

\[ \Gamma/\Delta \sim 0.1 \text{ to } 0.3 \]
Concentration \( \sim 800 \text{ ppm on } \xi \)
\( 2 \times 10^{17} \text{ Spin/m}^2 \)
SQUID \( \rightarrow 5 \times 10^{17} \)

Hot Spots
Zero bias peaks

Normalized conductance

Voltage (mV)

$dldV$ (S)

Voltage (mV)
- $T_c$ tunable with film thickness (0.25-3.1 K)
  - ALD NbSi suitable for ultra-low temperature (down to 10 mK) transport/2D superconductivity studies (in progress)

2D quantum correction start appearing for $\leq 7$ cycles

*Th. Proslier, T. Baturina et al. To be published*
Spin Flip (Kondo) Tunneling Channel

Temperature dependence

\[ G(T) = G_0 \left( \frac{T_K^2}{T^2 + T_K^2} \right)^S \]

\( S = 0.21 \rightarrow \text{Spin } \frac{1}{2} \rightarrow g \sim 2 \)

\( T_K > T_C \rightarrow \text{depairing superconducting state} \)
Field dependence statistic

\[ \Delta E = 2g\mu_BH \]
Magnetic impurities on Surface resistance

Concentration of Mag. Imp: 300 ppm $\rightarrow$ $6.10^{16}$ spins/m$^2$

RF probing few $\lambda \sim 40$ nm $\rightarrow$ 100 nm
Tunneling probing Few $k_f$ or $\xi$ from the insulating interface?

M. Kharitonov, Th. Proslier, A. Glatz, PRB 024514 (2012)
How to improve Nb?

**Coupons test**

(a) Norm. conductance vs. Voltage (mV)

(b) Binding energy vs. Nb and NbO

**Cavity test**

Room Temp 250 °C/2h 380 °C/24h 450-500 °C/24h

(c) Atomic Layer Deposition (10 nm Al₂O₃ + 3 nm Nb₂O₅)

Dc field at Eacc = 3.29 MV/m

Higher Q reproducible
Origin of magnetism?

- Oxygen vacancies? Not enough
- Surface chemical composition:
  - SEM shows a lot of Carbon
  - Raman shows NbC$_x$, Amorphous, Graphite…
- Still unclear.
Conclusions

- Tunneling spectroscopy data correlate with RF cavities performances
  Predictive tool.
  ALD superconducting layers.

- Presence of Magnetic impurities -> Origin? (Q-bits, super-Q dots)
  Oxygen vacancies
  Raman shows C (NbC and Amorphous)

- Future:
  - Scanning x,y -> Piezo stage (tip)
  - new electronic -> Higher $R_J$
  - Other dielectric ALD capping
MoN: TEM

500 cy = 22 nm @ 450C

Grain size ~ 12 to 20 nm / Tc = 9.2 K
Niobium Titanium (Nb$_{1-x}$Ti$_x$N)
XPS: Composition Evolution with thickness

Composition: MoN 1:1 + Nucleation as Mo$_2$N

Sputtering change stoichiometry from MoN to Mo$_2$N
Multilayer structure: Which Dielectric?

- MgB$_2$ deposition at 600 °C ~ 80 nm
- ALD insulator at 300 °C ~ 10 nm
- Inter-diffusion!

T. Tsuyoshi and al. to be published
Hall measurement

 Carrier concentration

\[ k_F = \left(3n\pi^2\right)^{1/3} \]
\[ l = \frac{k_F \cdot \hbar}{(n e^2 \rho)} \]
\[ D = -4k_B \frac{dT_c/dH}{\pi e} \]

\[ V_F = \frac{l}{\tau} \]
\[ \tau = \frac{l^2}{3D} \]

Dirty limit: \( \xi > l \)
Transition:
Strong disorder \( k_F l \sim 1 \) to \( k_F l \gg 1 \)
\[ m_{\text{eff}} = m_e \frac{\hbar \cdot k_F}{V_F} = 6.4 \, m_e \]
Multilayer structure: Which Dielectric?

MgO and Al₂O₃ are amorphous
Y₂O₃ is crystalline and more stable

T. Tsuyoshi and al. to be published
**Nb$_{1-x}$Ti$_x$N-based superconductor/insulator heterostructures**

**Aluminum nitride: AlN**
- Oxygen-free insulator, stable interface with Nb(Ti)N
- Similar structure to Nb(Ti)N
  - 0.27% mismatch between in-plane spacing of (0001)-oriented AlN and (111)-oriented NbN
- Can be grown with AlCl$_3$ and NH$_3$ at same temperature as Nb(Ti)N
  - No thermal cycling between deposition steps
- NbN/AlN multilayers grown previously by sputtering
**Nb$_{1-x}$Ti$_x$N / AlN: X-ray diffraction**

- **AlN changes Nb$_{1-x}$Ti$_x$N orientation**

![X-ray diffraction graphs](image)

- **With AlN, total integrated intensity increases by $\sim 2x$**
- **Film thickness/growth rate?**
Nb$_{1-x}$Ti$_x$N / AlN: X-ray reflectivity

- Density ~5% higher with AlN
- Roughness ~2x higher with AlN
- Change in thickness/cycles
**Nb$_{1-x}$Ti$_x$N / AlN: Growth rate**

- Thickness/cycle change → difference in nucleation delay
  - G.R. ~0.27 Å/cycle in both cases
  - Delay 100-200 cycles on bare quartz

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**Without AlN**

**With AlN**

<table>
<thead>
<tr>
<th>y = M1*(M0-M2)</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>0.26572</td>
<td>0.021981</td>
</tr>
<tr>
<td>m2</td>
<td>154.02</td>
<td>86.272</td>
</tr>
<tr>
<td>Chisq</td>
<td>0.4185</td>
<td>NA</td>
</tr>
<tr>
<td>R</td>
<td>0.99857</td>
<td>NA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>y = M1*(M0-abs(M2))</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>0.28823</td>
<td>0.02557</td>
</tr>
<tr>
<td>m2</td>
<td>-10.877</td>
<td>114.99</td>
</tr>
<tr>
<td>Chisq</td>
<td>3.5664</td>
<td>NA</td>
</tr>
<tr>
<td>R</td>
<td>0.98495</td>
<td>NA</td>
</tr>
</tbody>
</table>
Transport: Evolution with thickness

400 °C / H=0T

Resistivity bulk ~ 110 μΩ.cm
Tc bulk ~ 8.6 K
$\text{Nb}_{1-x}\text{Ti}_x\text{N} / \text{AlN}: \text{Grain size}$

- No significant difference in XRD grain size (Scherrer)

- TEM studies are underway
\( \text{Nb}_{1-x} \text{Ti}_x \text{N} / \text{AlN}: \text{Superconducting } T_c \)

\[80\text{nm } \text{Nb}_{0.8} \text{Ti}_{0.2} \text{N} \]
\[0.01 \text{ Gauss, zfc} \]

- Red: Si
- Green: 100nm SiO\text{2} / Si
- Blue: 30nm Nb / Sapphire

\[80\text{nm } \text{Nb}_{0.8} \text{Ti}_{0.2} \text{N} / 30\text{nm AlN} \]
\[0.01 \text{ Gauss, zfc} \]

- Red: Si
- Green: 100nm SiO\text{2} / Si
- Blue: 30nm Nb / Sapphire

\(\text{J. Klug, T. Proslieer et al. to be published}\)
Nb$_{1-x}$Ti$_x$N: Ongoing work

- Synchrotron grazing incidence XRD measurements
  - Depth dependence of structure, texture, and strain.

- Comprehensive compositional analysis
  - RBS, XPS
  - Study effects of deposition temperature, etc.

- High resolution TEM studies of S-I multilayers
  - Grain structure
  - Interface morphology

J. Klug, T. Proslie et al. to be published
- Construction of UHV ALD chamber for coating single-cell Nb SRF cavities
- Plasma ALD system.
Extra slide 1: Nb$_{1-x}$Ti$_x$N GIXRD

No AlN

With AlN

(111) (200) (220)
Extra slide 2: Molybdenum nitride

Effects of intermittent Zn pulse at 450°C
- 6% higher density with Zn
- No significant change in growth rate
- Larger roughness with Zn

Without Zn
Density: 8.1 g/cm³
Thickness: 26 nm
Roughness: 3.1 nm

With Zn
Density: 8.6 g/cm³
Thickness: 25 nm
Roughness: 3.5 nm
Extra slide 3: MoN XRD

Effects of intermittent Zn pulse at 450°C

- Hexagonal δ-MoN in both cases (small trace of cubic γ-Mo₂N)
  - Zn leads to change in texture, (200) → (202), (002)