Atomic layer deposition of superconducting films and multilayers for SRF

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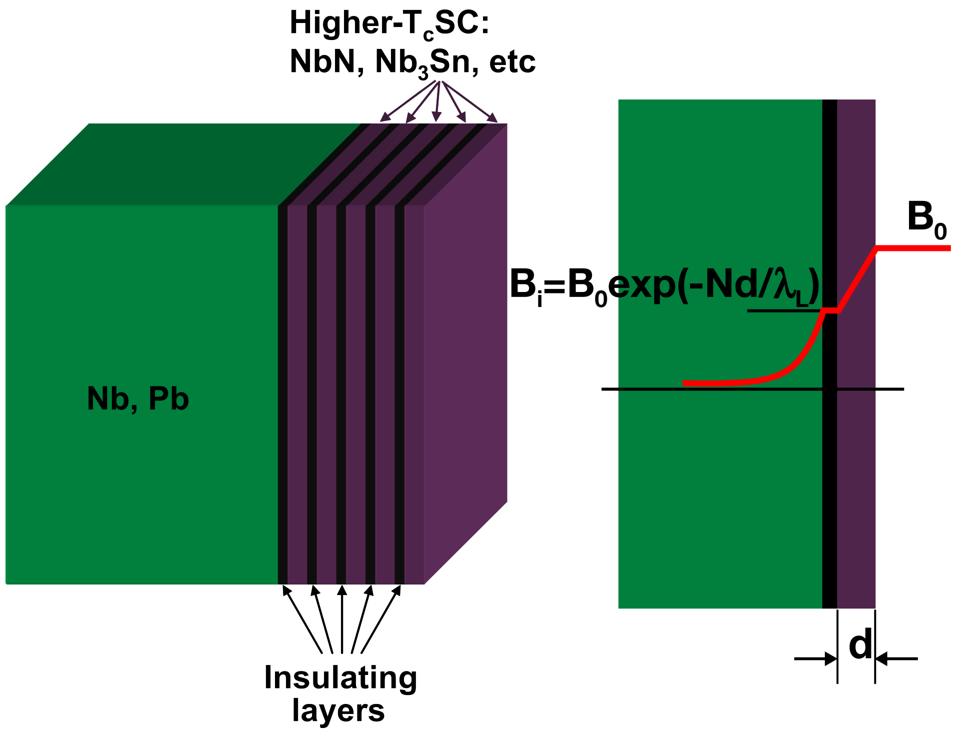
Multilayer thin films for SRF

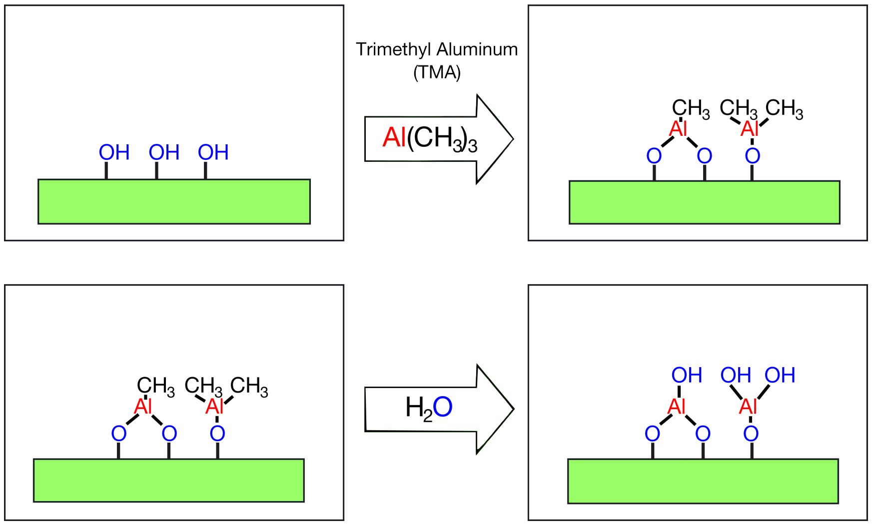
Superconductor-Insulator multilayer [Gurevich, *Appl. Phys. Lett.* **88**, 012511 (2006)]

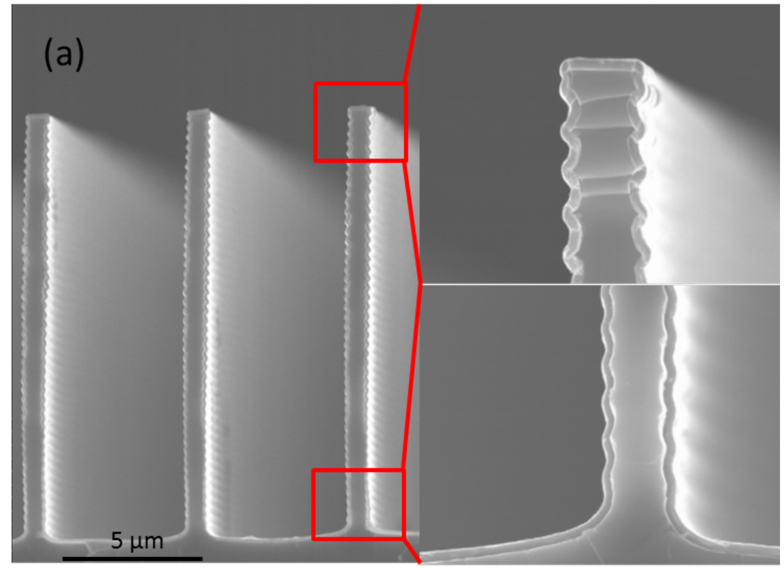


- Potential path to high E_{acc} and high Q_0

Atomic layer deposition (ALD)

A thin film synthesis process based on sequential, self-limiting surface reactions between vapors of chemical precursors and a solid surface to deposit films in an atomic layer-by-layer manner.



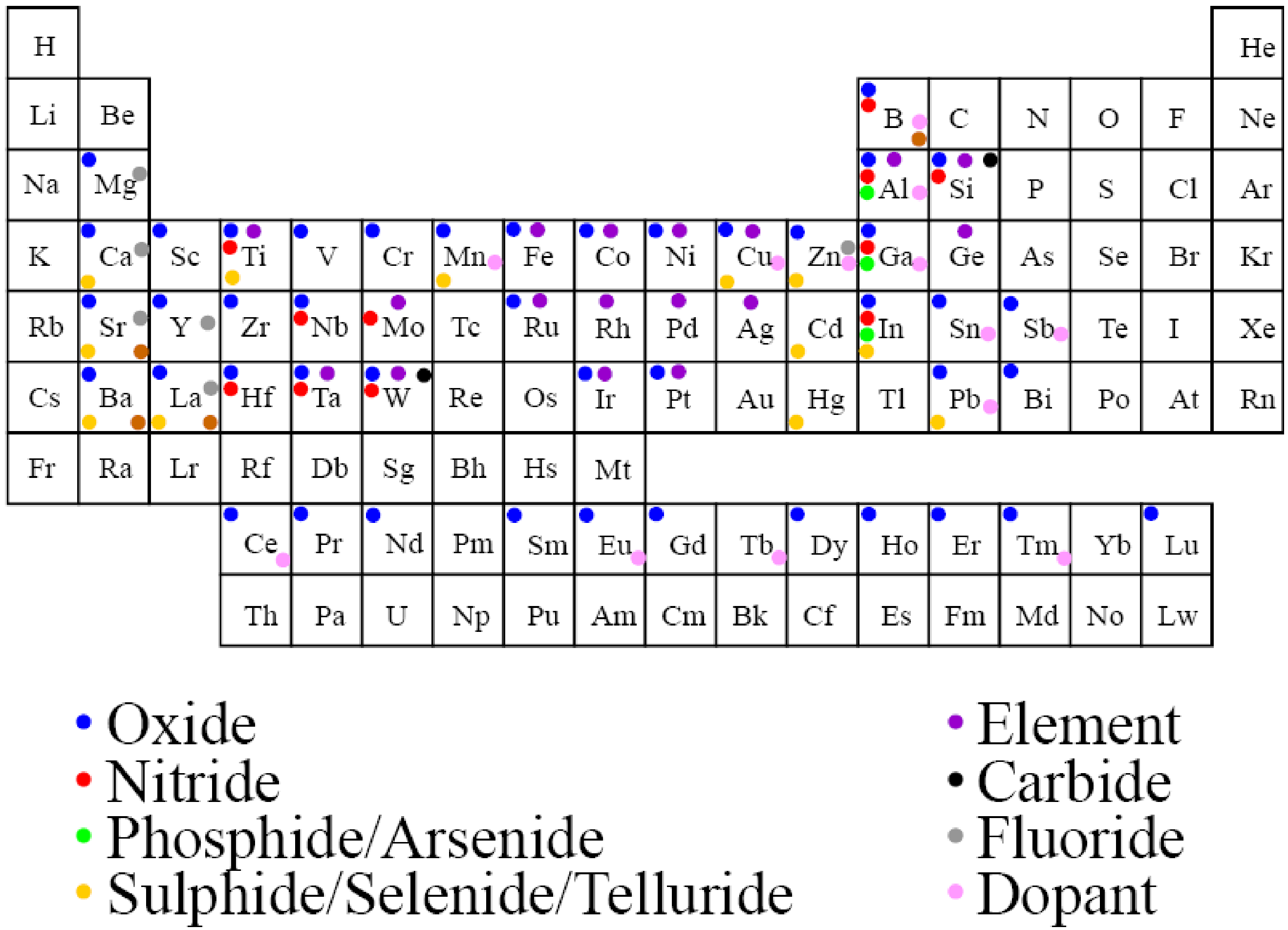


Advantages:

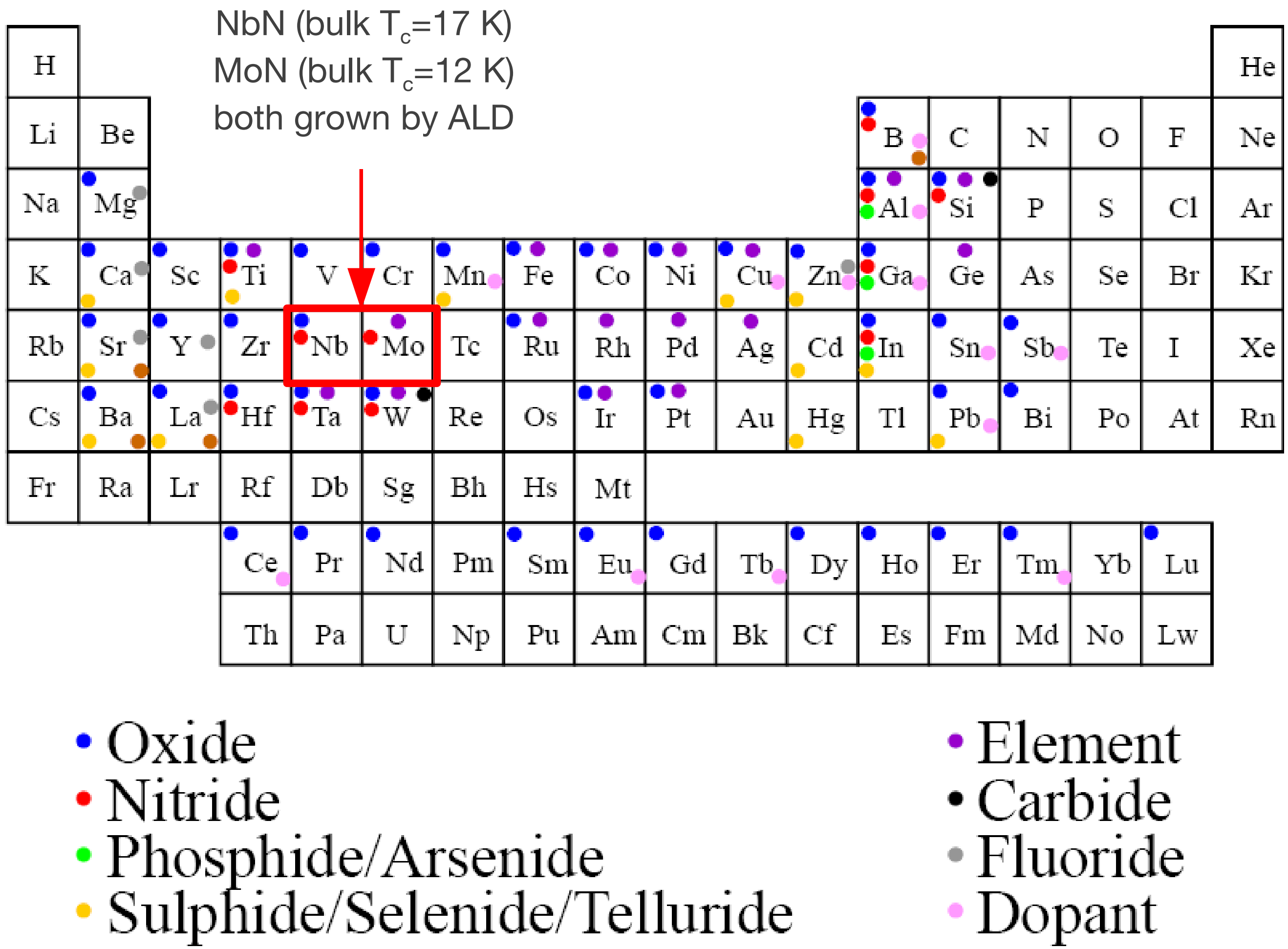
- Atomic-level control of thickness and composition
- Smooth, continuous, pinhole-free coatings on large area substrates
- No line-of-sight limits → excellent conformality over complex shaped surfaces

Coat inside Nb SRF cavity with precise, layered structure → ALD

ALD thin film materials



ALD superconductors?



Except in one paper, superconductivity has been ignored...

- Reported T_c = 10 K for NbN [Hiltunen, *et al.*, *Thin Solid Films* **166**, 149 (1988)]

Superconductors by ALD

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

- Niobium Silicide: NbSi
  - $NbF_5 + Si_2H_6$
  - $NbF_5 + SiH_4$
- Niobium Carbide: NbC
  - $NbF_5 + Al(CH_3)_3$
  - $NbCl_5 + Al(CH_3)_3$
- Niobium Carbo-Nitride: $NbC_{1-x}N_x$
  - $Al(CH_3)_3 + NbF_5 + NH_3$
  - $Al(CH_3)_3 + NbCl_5 + NH_3$
- Molybdenum Nitride: MoN
  - $MoCl_5 + NH_3$
  - $MoCl_5 + Zn + NH_3$
- Niobium Titanium Nitride: $Nb_{1-x}Ti_xN$
  - $(NbF_5, TiCl_4) + NH_3$
  - $(NbCl_5, TiCl_4) + Zn + NH_3$
- Iron Selenide: $FeSe_x$
  - $FeCl_3 + Se(Et_3Si)_2$

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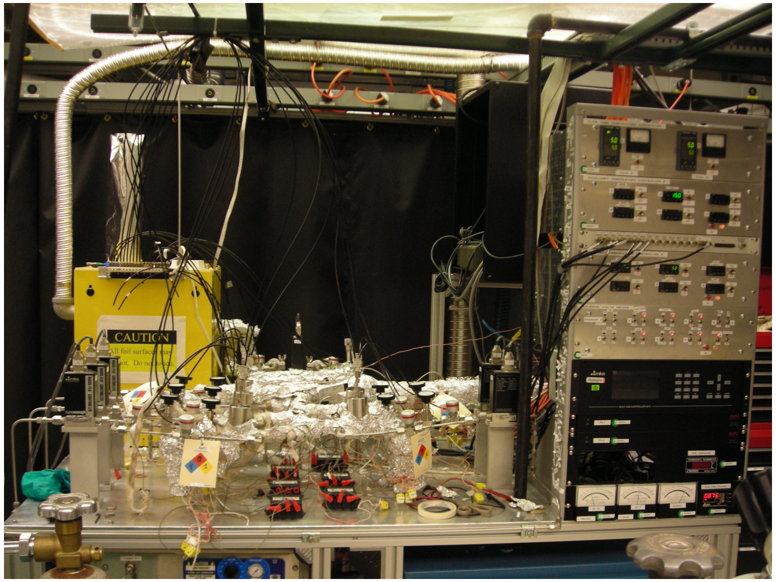
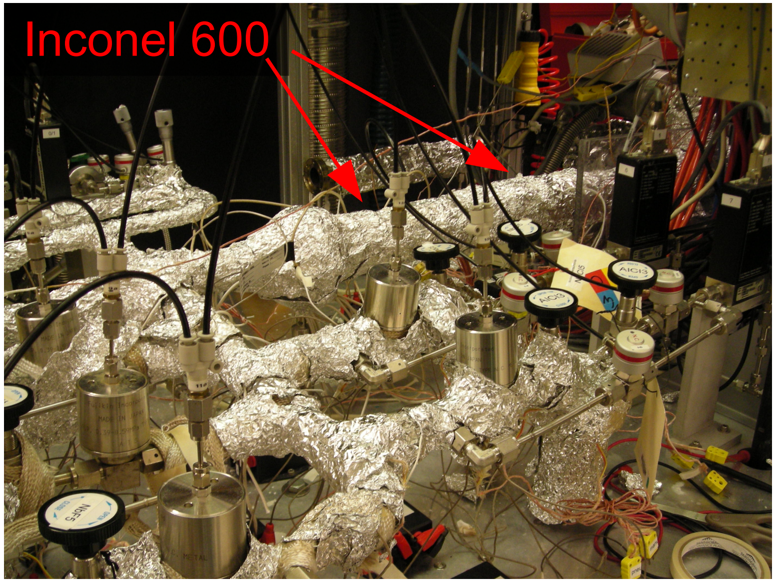
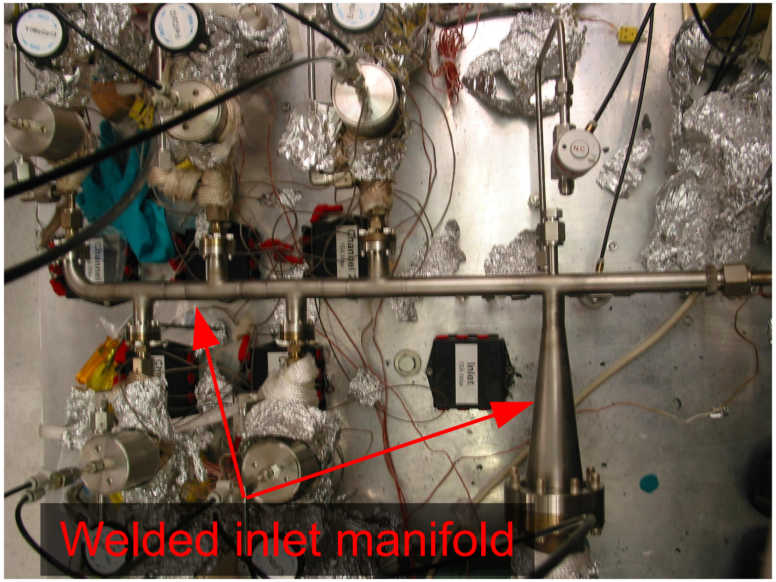
Viscous flow ALD reactor

Key features:

- Inconel 600 reactor tube (superior corrosion resistance)
  - Halide precursors ($NbCl_5$, $TiCl_4$, etc.)
- All-welded precursor inlet manifold (reduced sites for potential leaks)
  - Oxygen contamination in nitride films







Thin film characterization

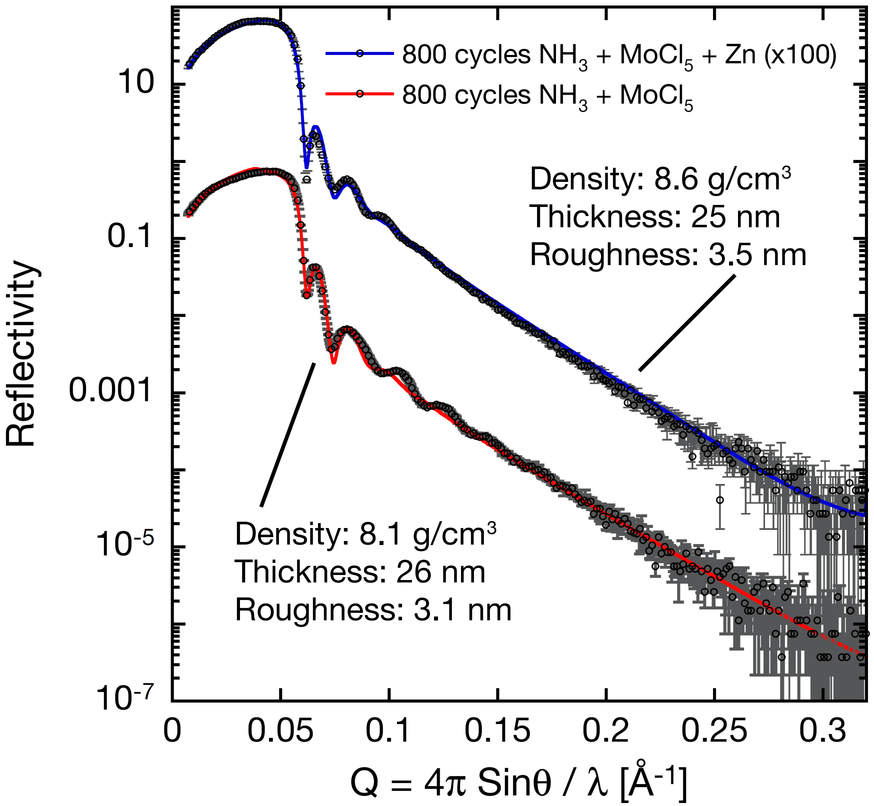
- X-ray photoemission spectroscopy (XPS)
- X-ray reflectivity (XRR)
- X-ray diffraction (XRD)
- Synchrotron grazing-incidence x-ray diffraction (GIXRD)
- Scanning electron microscopy (SEM)
- Transmission electron microscopy (TEM)
- DC electrical transport (down to 1.6 K)
- SQUID magnetometry

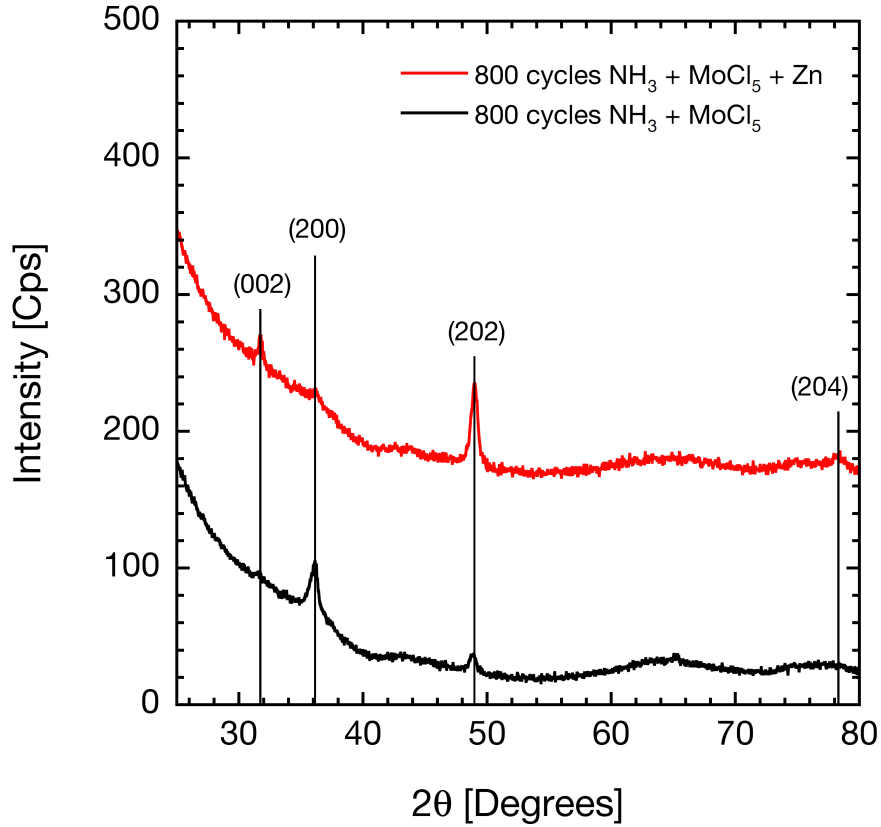
- Atom probe tomography (APT) [Seidman, NU]
- Rutherford backscattering spectroscopy (RBS) [Evans Analytical]

Molybdenum nitride: MoN

Effects of intermittent Zn pulse

- Chemistry: $MoCl_5 + NH_3$ versus $MoCl_5 + Zn + NH_3$ at 450°C
- Hexagonal MoN in both cases, higher density & change in texture with Zn

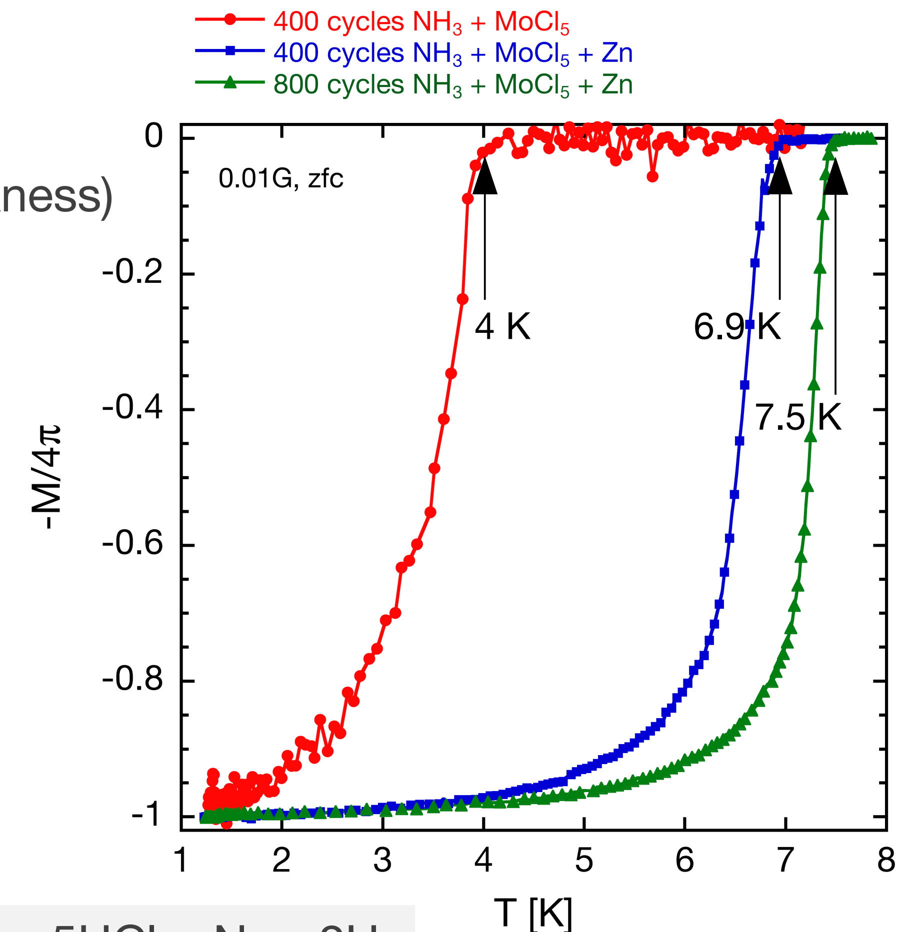




MoN: Superconducting T_c (SQUID)

Addition of Zn leads to:

- ~2x increase in T_c (equivalent thickness)
  - Peak T_c = 7.5 K for 25 nm film
- Decrease in RT resistivity
  - 200 μΩ-cm without Zn
  - 120 μΩ-cm with Zn



- No chlorine, zinc observed by XPS
- Could be related to film density
  - 88-93% of bulk (9.2 g/cm³)
- Could be due to hydrogen:

Without Zn: $MoCl_5 + 3NH_3 \rightarrow MoN + 5HCl + N_2 + 2H_2$

With Zn: $MoCl_5 + Zn + NH_3 \rightarrow MoN + ZnCl_2 + 3HCl$

Niobium titanium nitride: $Nb_{1-x}Ti_xN$

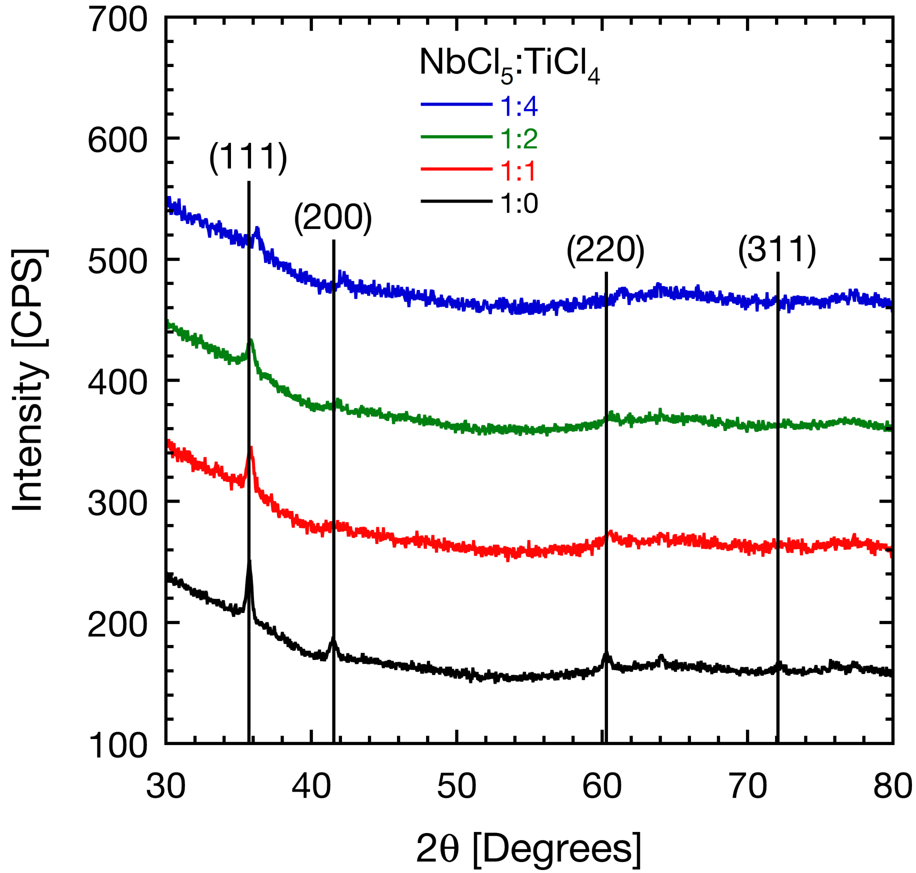
- Chemistry: ($NbCl_5$:$TiCl_4$) + Zn + NH_3 at 450°C, 500°C
- Can vary Ti content with $NbCl_5$:$TiCl_4$ ratio (1:2 ~ 20% TiN)
  - Cubic δ phase in all films

With increasing TiN

- Peaks shift to higher angle
- Density decreases
  - 7.2 g/cm³ (1:0)
  - 5.7 g/cm³ (1:4)
- RT resistivity decreases
  - 380 μΩ-cm (1:0)
  - 130 μΩ-cm (1:4)

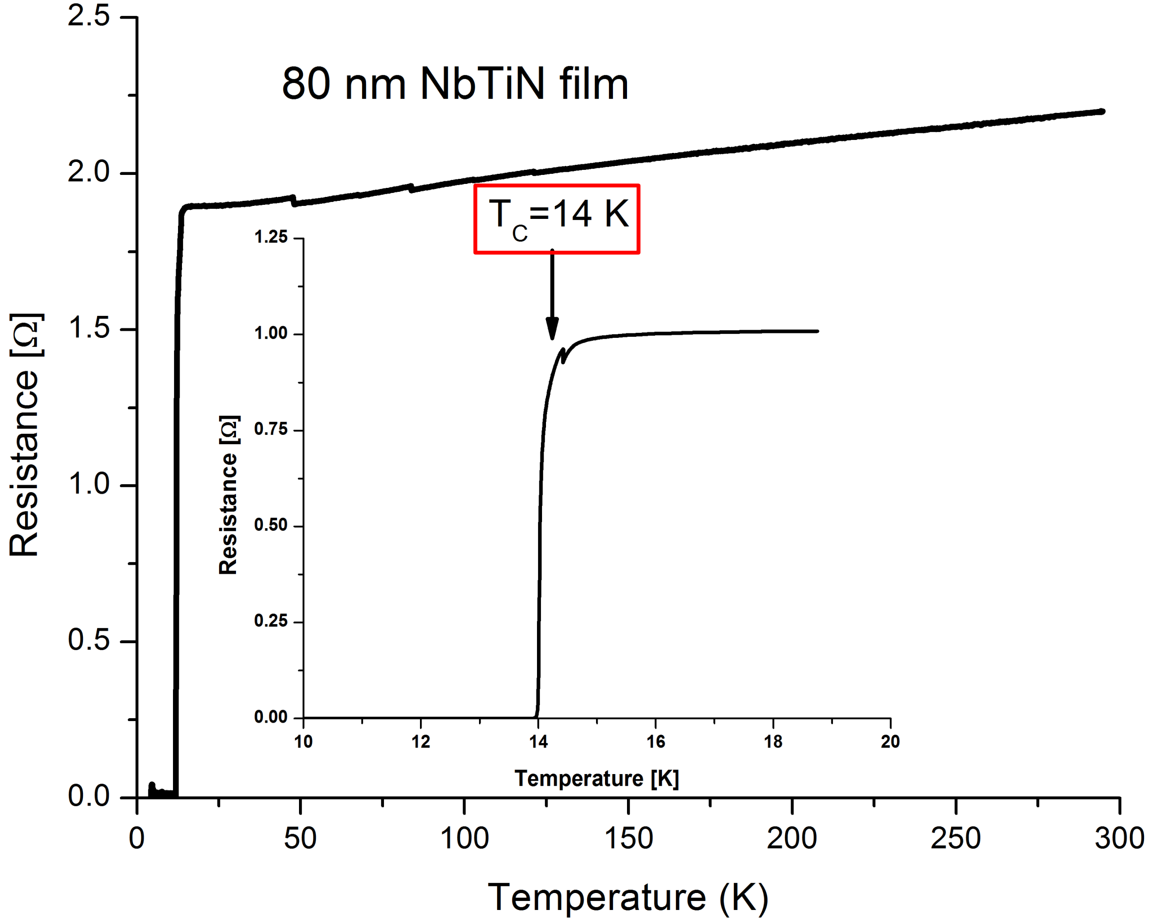
Impurity content: 0.05 atom % Cl

Are they good superconductors?



Optimized growth of $Nb_{1-x}Ti_xN$

- Achieved superconducting T_c=14 K, ***40% higher than any other ALD film***
- Nearly 5 K higher than Nb



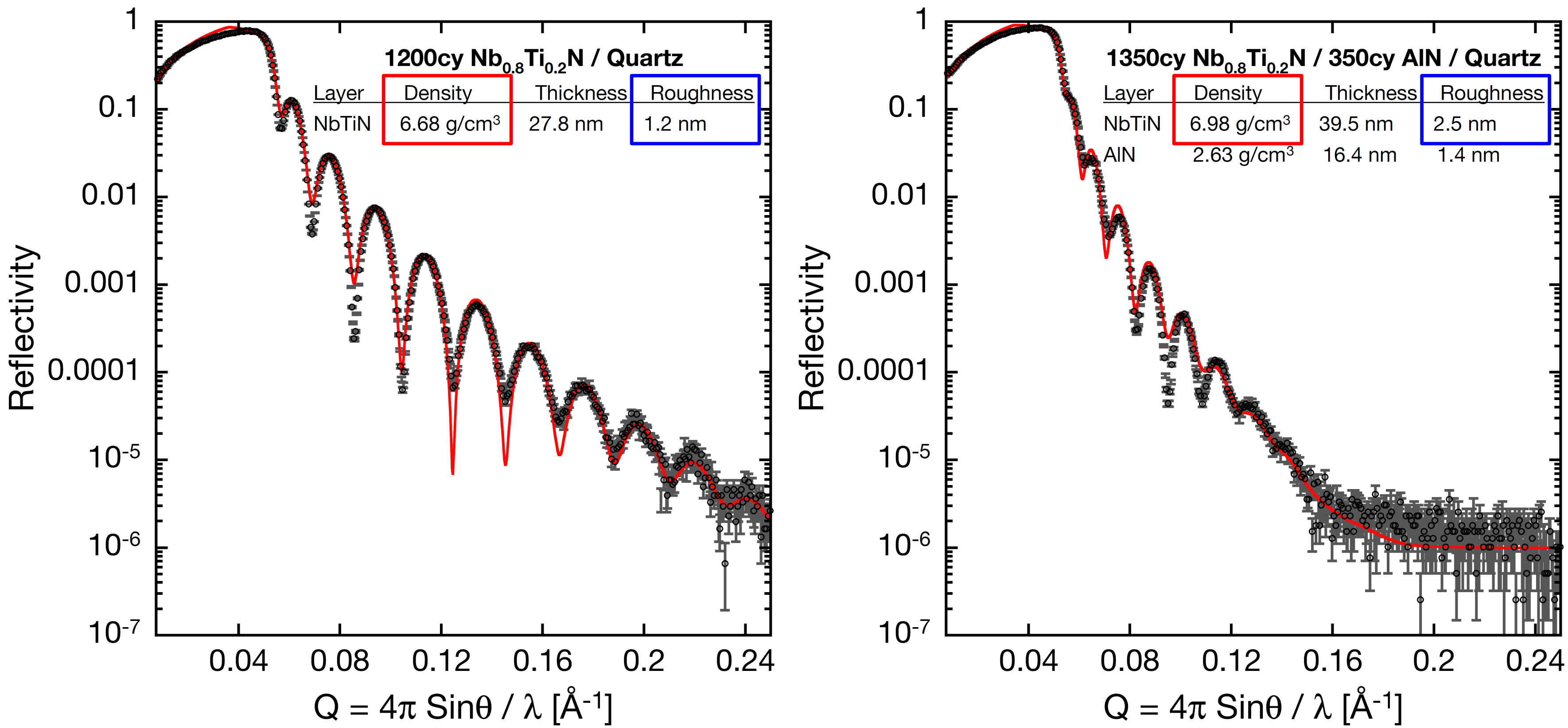
$Nb_{1-x}Ti_xN$-based superconductor-insulator structures

Aluminum nitride: AlN

- Oxygen-free insulator, stable interface with Nb(Ti)N
- Good thermal conductivity (285 W/m-K)
- 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
  - ALD previously demonstrated [K.-E. Elers, et al. *J. de Phys. IV* **5** (1995)]

- NbN/AlN multilayers grown previously by sputtering
  - Enhanced J_c at high fields [J.M. Murduck, et al. *Appl. Phys. Lett.* **62** (1988)]
  - Model system for vortex matter in HTS [E.S. Sadki, et al. *Phys. Rev. Lett.* **85** (2000)]

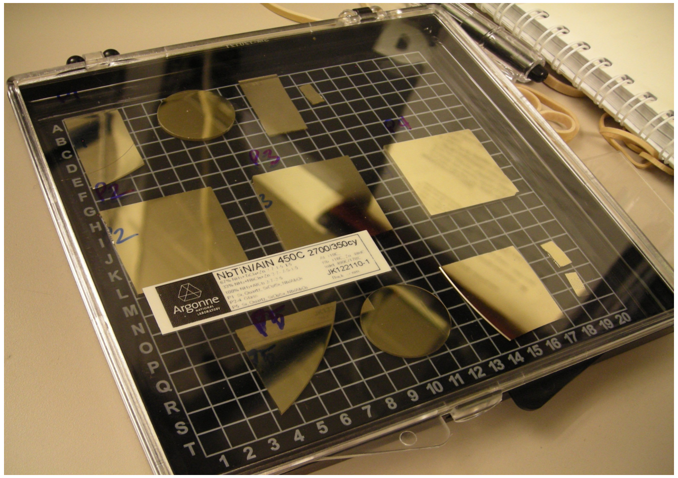
$Nb_{1-x}Ti_xN$ / AlN: X-ray reflectivity

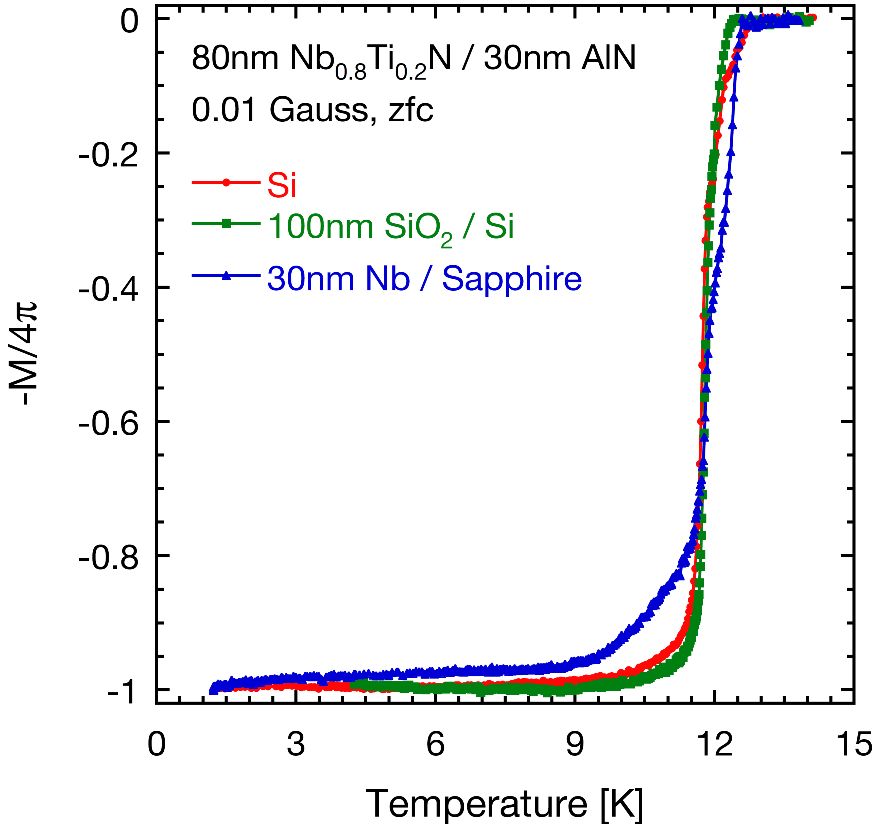


- Density ~5% higher with AlN
- Roughness ~2x higher with AlN
- Change in thickness/cycles (difference in nucleation delay)

$Nb_{1-x}Ti_xN$ / AlN multilayers

- 40 nm $Nb_{0.8}Ti_{0.2}N$ / 15 nm AlN (single bilayer and 2x stack)
- 80 nm $Nb_{0.8}Ti_{0.2}N$ / 30 nm AlN (single bilayer and 2x stack)
  - Quartz, Si(001), 100 nm SiO_2/Si(001), 30 nm Nb/Sapphire, and cavity-grade Nb

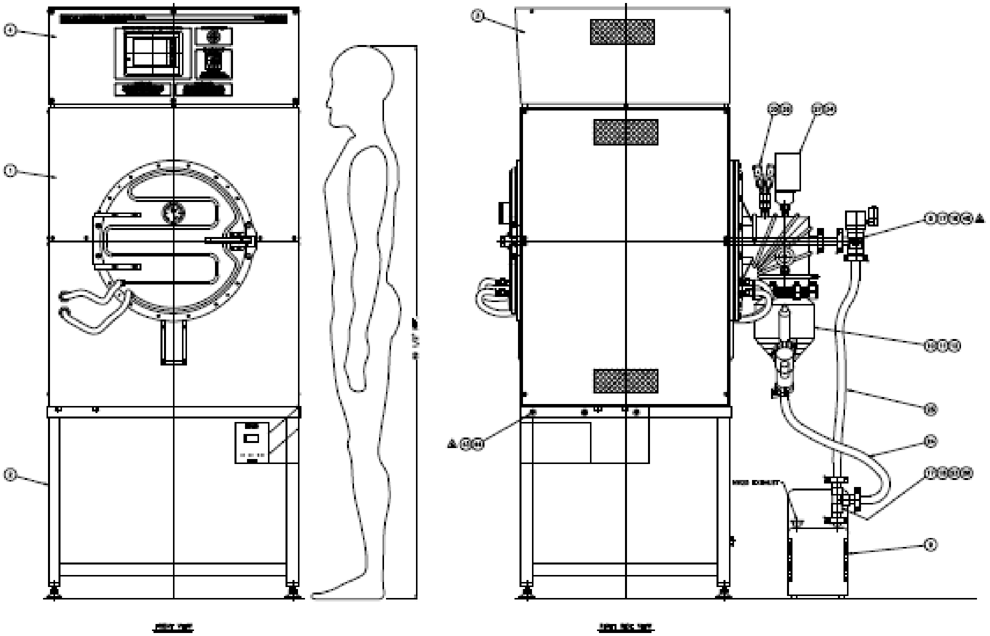


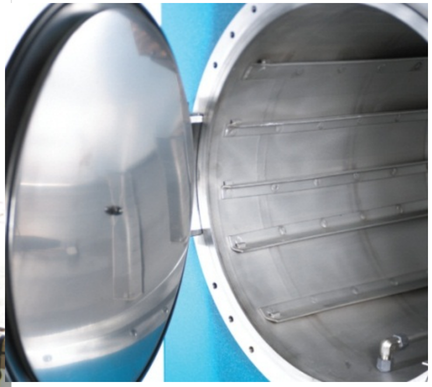


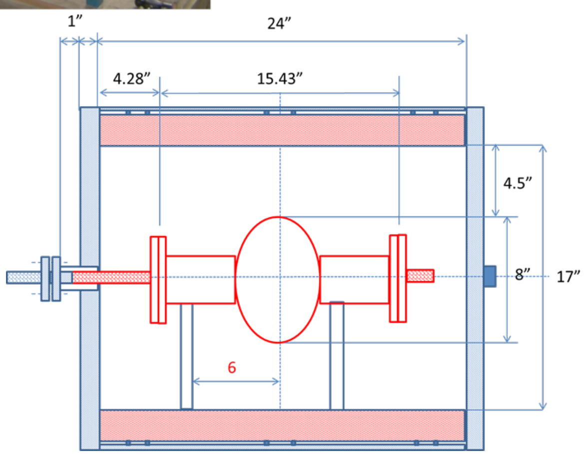
Optimized $Nb_{1-x}Ti_xN$/AlN ALD growth process (T_c = 14 K) is now ready for coating Nb SRF cavities

- Will enable testing the effects of S-I multilayer on cavity performance

Scaling ALD to coat cavities







New ALD system currently being assembled

- Clean room 100 environment
- Up to 650°C in UHV (10e-8 Torr)
- *In situ* processing
- Accommodate single-cell ILC cavities

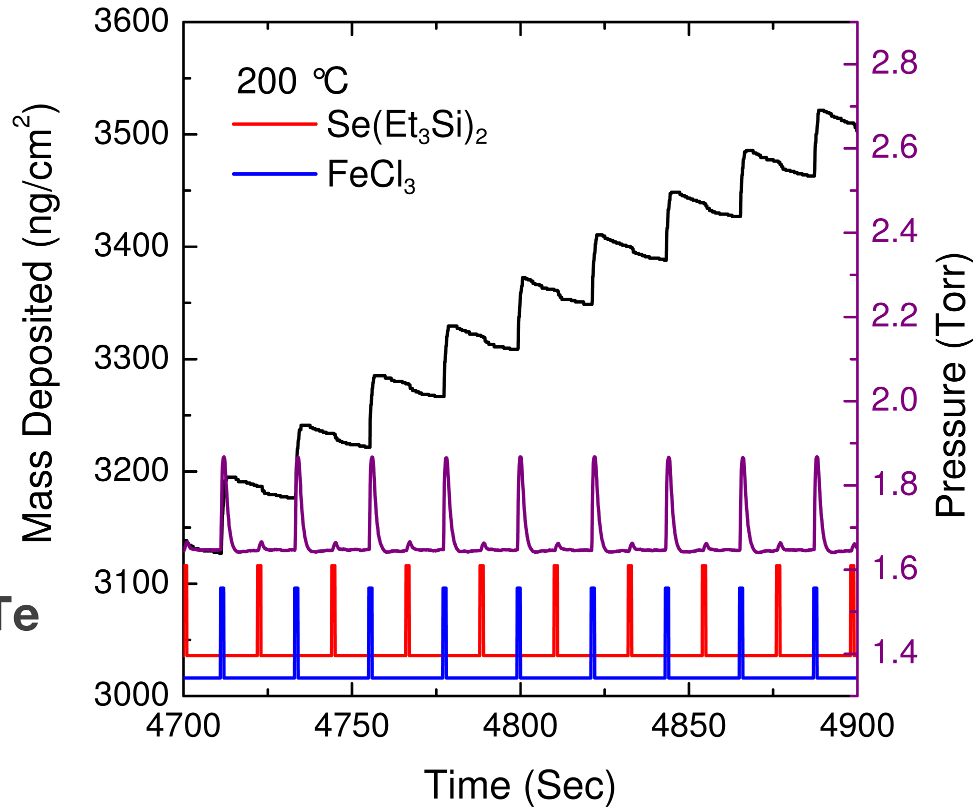
Fe-based superconductors: Initial studies of $FeSe_x$

Promising new Fe-based superconductors ($FeSe_{1-x}Te_x$)

- T_c reported up to 37 K
- Remain superconducting in high magnetic fields (>45 T)

New custom precursors for Se, Te
(J. Schlueter, S. Sullivan ANL)

- $(Et_3Si)_2Te$ / $(Et_3Si)_2Se$
- $(^tBuMe_2Si)_2Te$ / $(^tBuMe_2Si)_2Se$



$$(R_3Si)_2Te(g) + MCl_2(g) \rightarrow MTe(s) + 2R_3SiCl(g)$$

Summary

- Growth of single-phase hexagonal-MoN at 450°C
- Demonstrated ~2x increase in T_c in MoN with intermittent Zn dose ($MoCl_5$ + Zn + NH_3)
- Optimized growth of $Nb_{1-x}Ti_xN$ to achieve superconducting T_c = 14 K, 40% higher than any other ALD film and ~5 K higher than Nb
- Demonstrated successful ALD growth of $Nb_{1-x}Ti_xN$/AlN S-I multilayers on flat substrates (Si, SiO_2, Sapphire, Nb)
- Assembly of new UHV ALD system for coating 1-cell ILC cavities
- New precursors for Fe-based superconductors ($FeSe_{1-x}Te_x$)
- Plasma-enhanced ALD system now online and in use

Thank you for your attention