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MADISON CEC/ICMC 2017

Development of NbTiN based multi-layered structures for SRF applications

Jefferson Lab

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A. Sutter

T. Junginger

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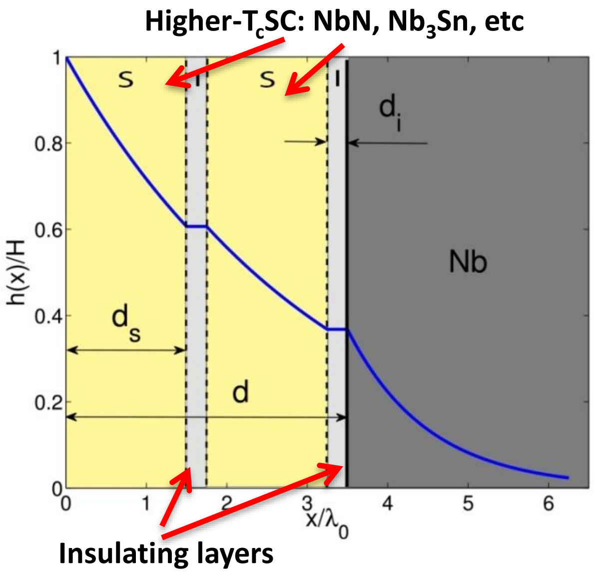
SRF Application beyond Nb: SIS Multilayers

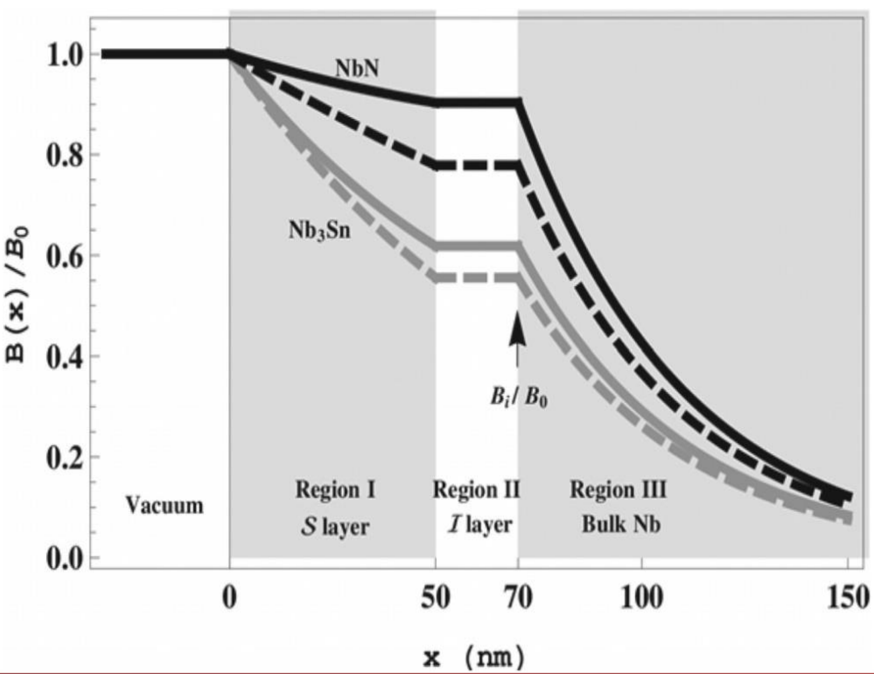


Taking advantage of the high –T_c superconductors with much higher H_c without being penalized by their lower H_{c1}…

Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)
Alex Gurevich, AIP ADVANCES 5, 017112 (2015)
T. Kubo, Applied Physics Letters 104, 032603 (2014)

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

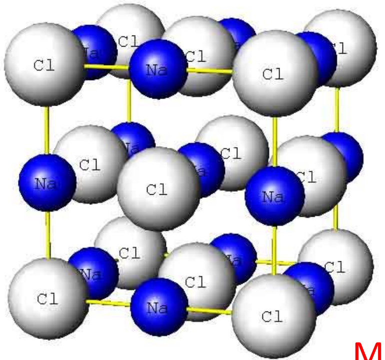
Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration



- Strong increase of H_{fp} 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_{fp} ,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
- SC layers with higher T_c, Δ (Nb_3Sn, NbN, etc.) => Strong reduction of R_{BCS} (ie high Q_0)

Possibility to move operation from 2K to 4.2K

APPROACH



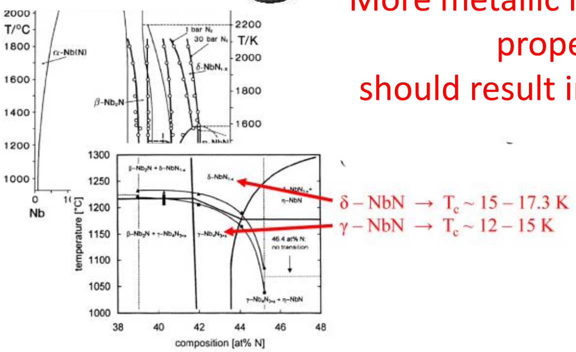
Superconductor

Ternary Nitride **$(Nb_{1-x},Ti_x)N$**

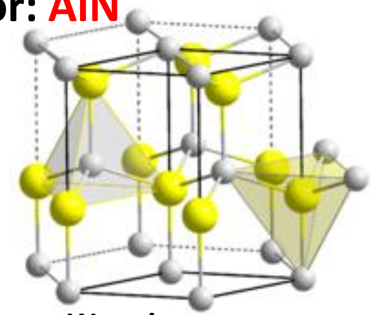
T_c= 17.3 K, a= 4.341 Å for δ-phase

Presence of Ti found to reduce significantly the resistivity

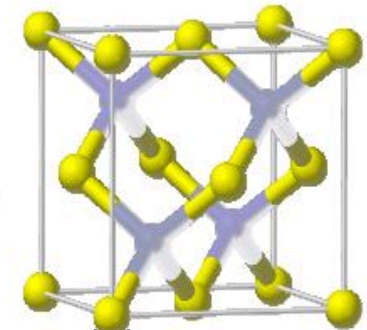
More metallic nature and better surface properties than NbN
should result in better RF performance



Insulator: AlN



Wurtzite structure



Sphalerite structure

- Grown with a wurtzite (hcp, a=3.11Å, c=4.98Å) or sphalerite (B1 cubic, a= 4.08 Å) structure.
- Found to enhance the properties (T_c) for very thin NbN and NbTiN films .
- Large thermal conductivity (3.19W/cm.K at 300K, comparable with Cu, 4.01W/cm.K)

CHALLENGES

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

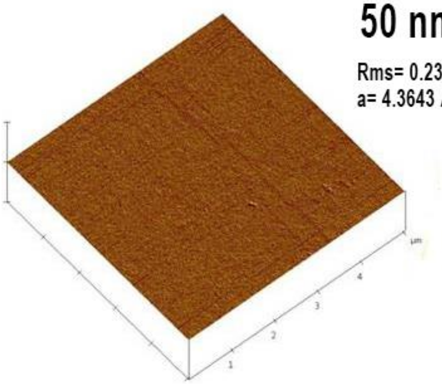
Base pressure range: 10^{-10} Torr

- dc-Magnetron Sputtering (reactive mode)
- HiPIMS (Huettinger 2000 V, 3000 A)
- Central sample stage

Substrates:

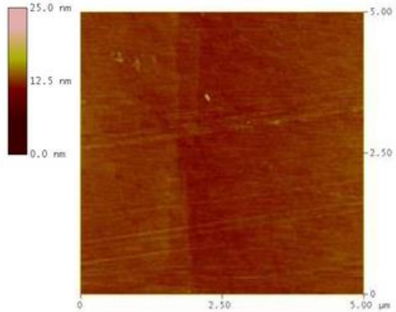
MgO (ideal)
AlN ceramic (worst case)
Bulk Nb
ECR Nb films
(real)

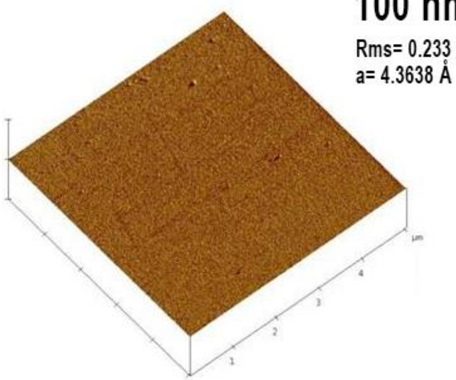
NbTiN Films – Influence of Thickness on Tc



50 nm

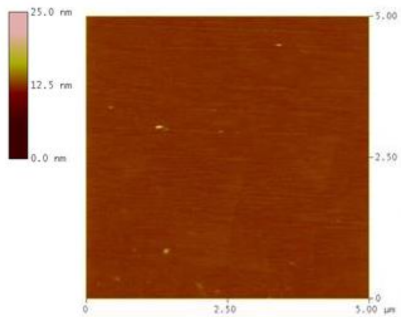
Rms= 0.236 nm
a= 4.3643 Å

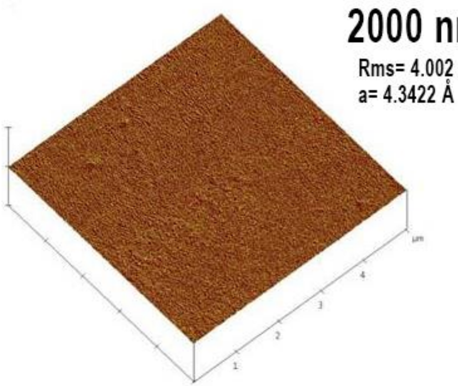




100 nm

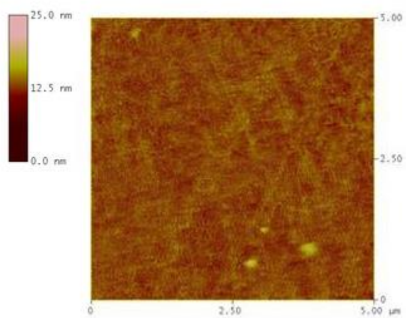
Rms= 0.233 nm
a= 4.3638 Å





2000 nm

Rms= 4.002 nm
a= 4.3422 Å

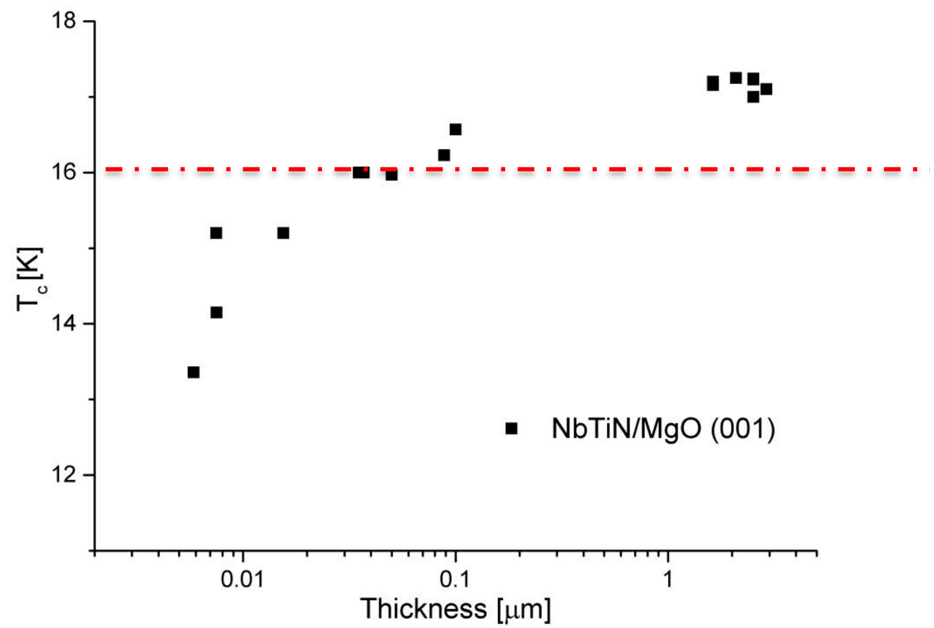


Process Conditions for NbTiN

N_2/Ar	0.23
Total pressure	2×10^{-3} Torr
Sputtering Power	300 W
Deposition rate	~ 20nm/min

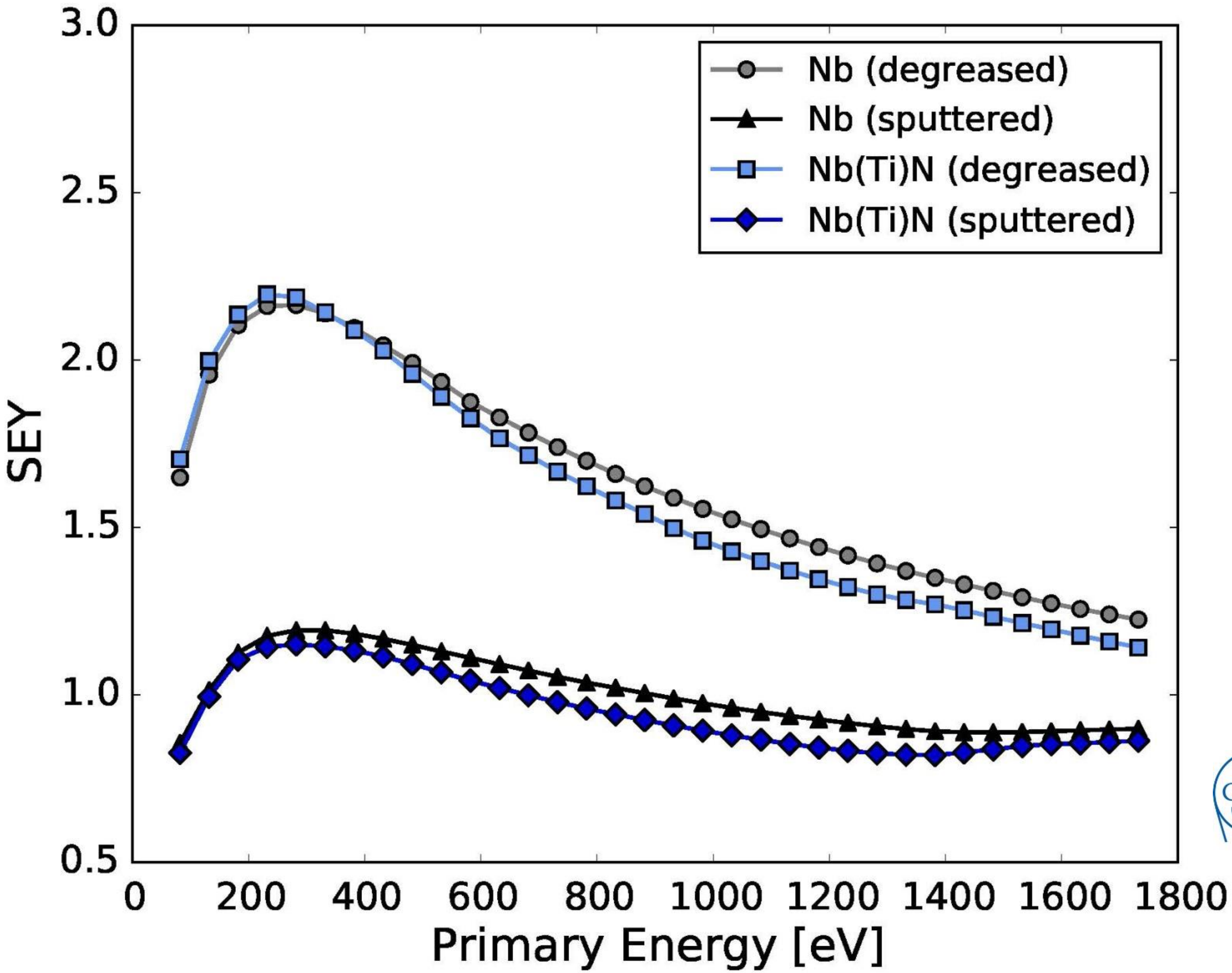
Single crystal NbTiN/MgO films (XRD/EBSD)

Very smooth films (~ substrate)



T_c ≥16 K for film thickness > 35 nm

Secondary Electron Yield of NbTiN Films



Measurements at room temperature

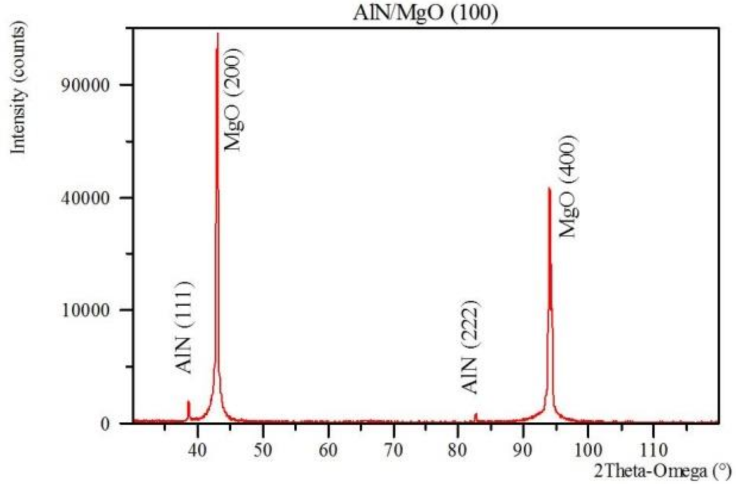
Max. SEY =2.2 ± 0.1 comparable to EP Nb

After sputtering away ~ 3 nm,
SEY down to 1.15

Process Conditions for AlN

N_2/Ar	0.33
Total pressure	2x10^{-3} Torr
Sputtering Power	50 -100 W
Deposition rate	~ 4nm/min

AlN Films



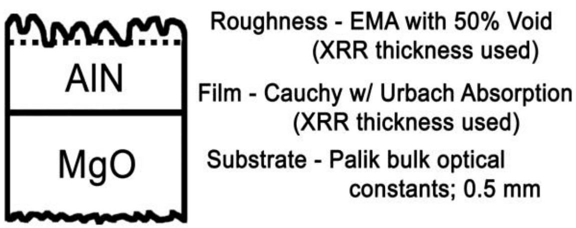
Structure

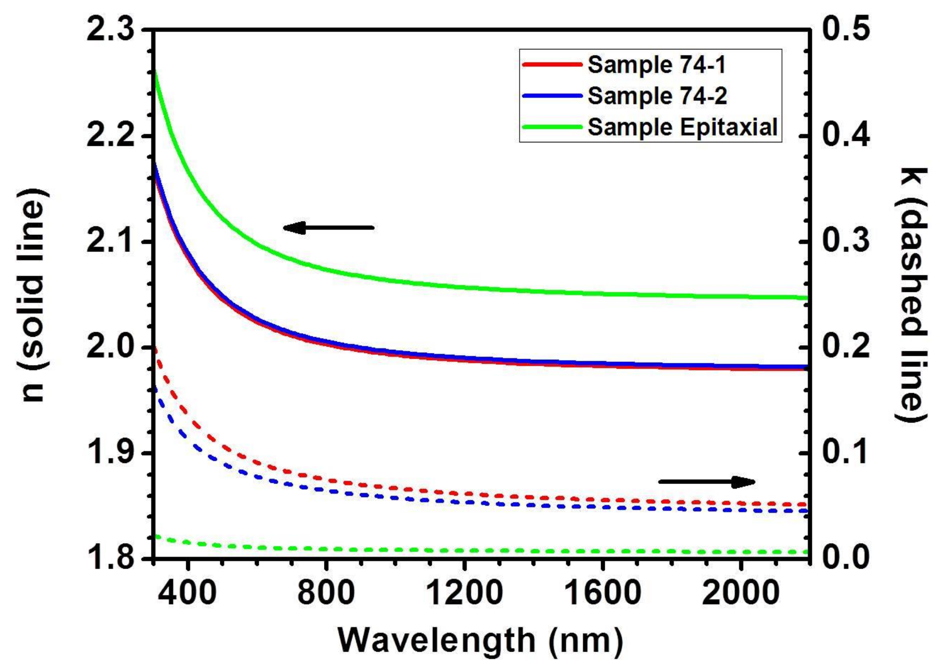
AlN films were coated by reactive sputtering with different parameters. They were found to become fully transparent for N_2/Ar ratios of ~33%.

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 .

Dielectric Behavior

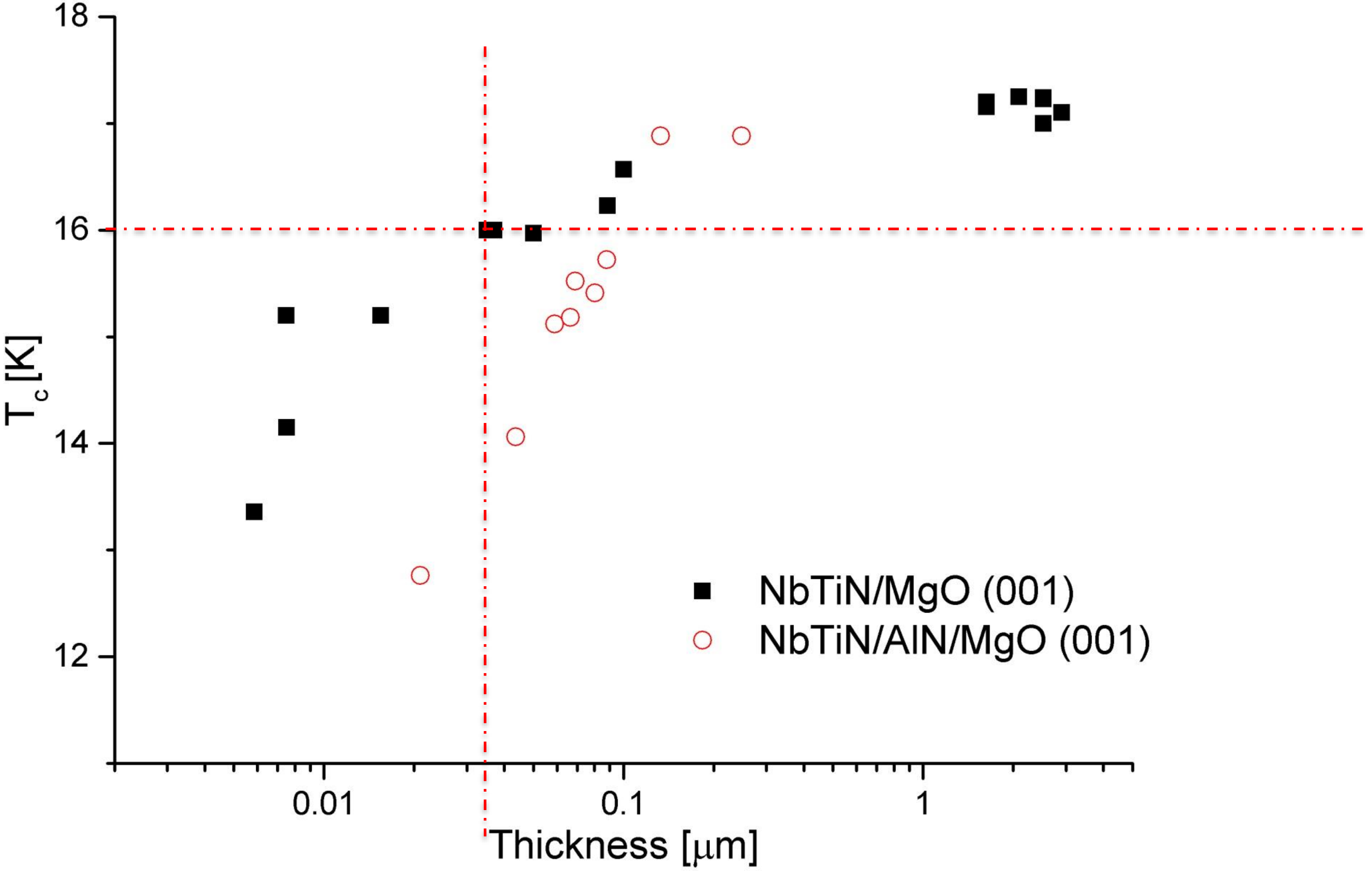




At 450 °C, 30 nm AlN films exhibit dielectric properties of polycrystalline AlN films

n in the range of 1.98- 2.15

NbTiN/AlN bi-layers – Influence of thickness on Tc



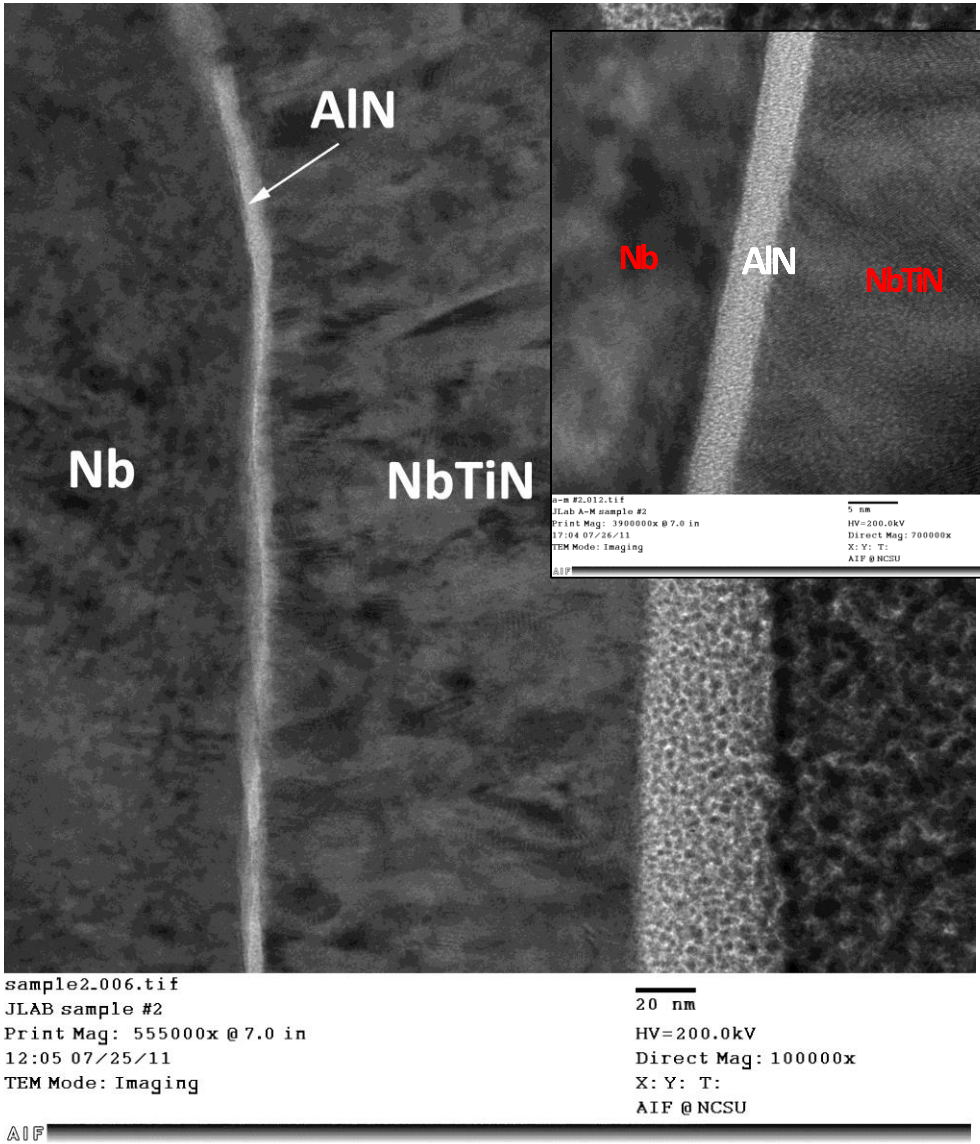
SRF Multilayer Structures Based on NbTiN
Influence of coating temperature

NbTiN/AlN/Nb film at 600 °C

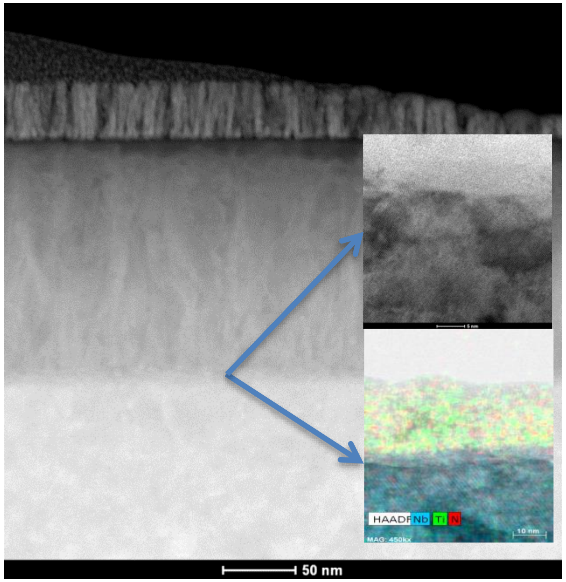
	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	2x10^{-3}	2x10^{-3}
Sputtering Power [W]	100	300
Deposition rate [nm/min]	~ 2.5	~ 18
Thickness [nm]	5	100
T_c [K]	N/A	14

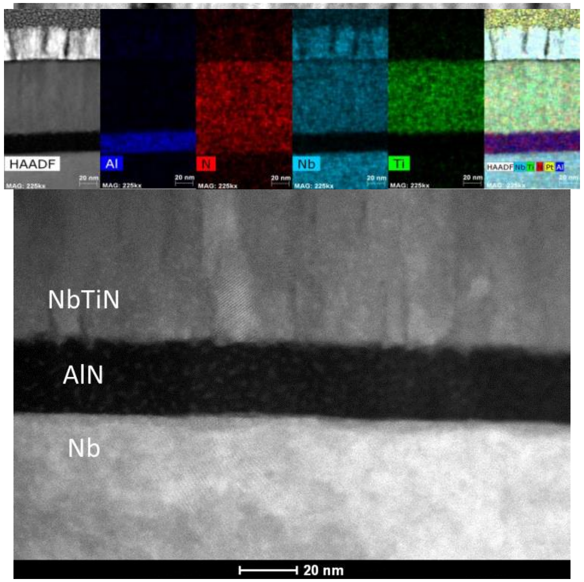
TEM cross-section (FIB cut) of NbTiN/AlN/Nb/Cu structure

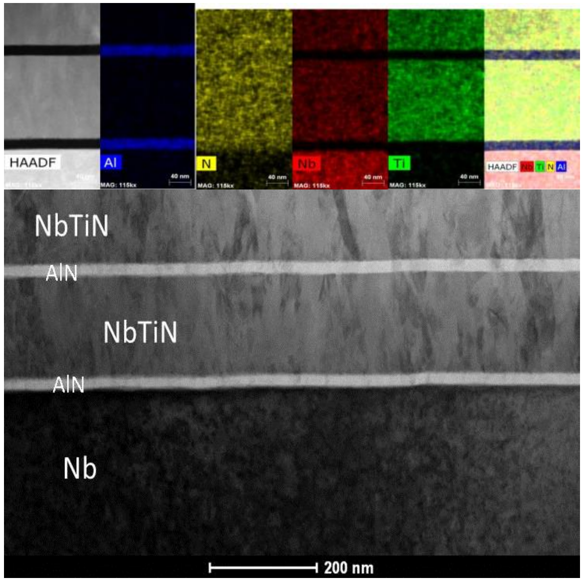
Miscibility of AlN into Nb and NbTiN at 600 °C

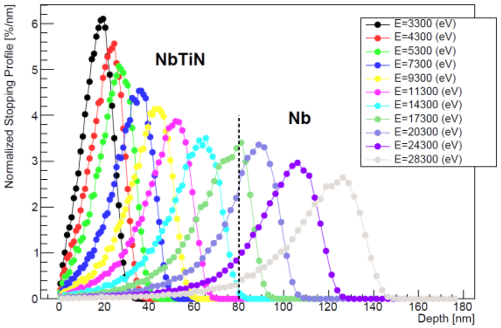


Development of SIS NbTiN/AlN structures on Nb surfaces







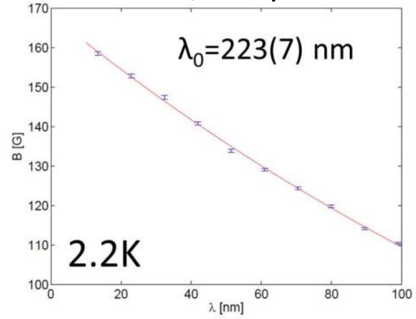


Single exponential decay with λ_0=223(7) nm
Proximity effect? Dirty Nb due to diffusion?

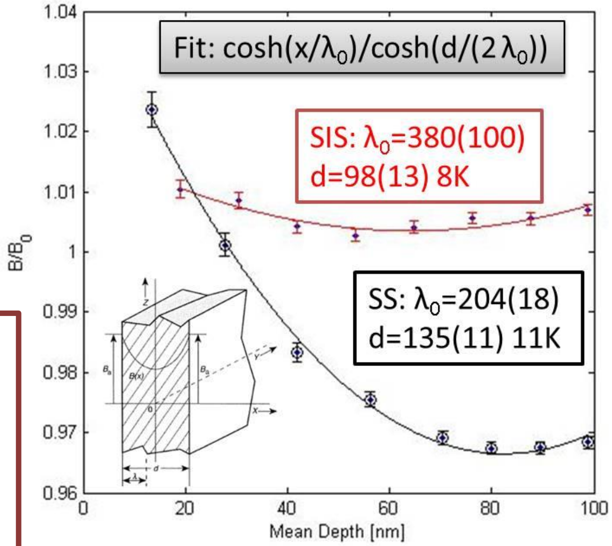
μ SR measurement (T. Junjinger,A. Sutter) on NbTiN/Nb (SS) & NbTiN/AlN/Nb (SIS)

- Measure above T_c of Nb
- Field enters from both sides
- **Significantly different λ_0 and d for SS**

Suggest potential proximity effect for the SS structure, not present for SIS structure



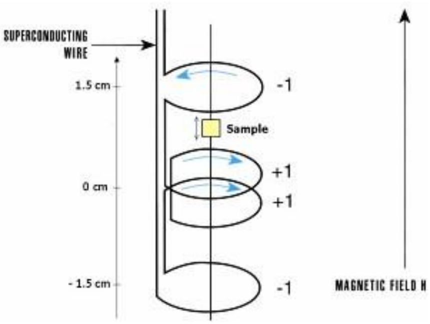
To benefit from the counter current flow an insulating layer is essential at least for the NbTiN/Nb system

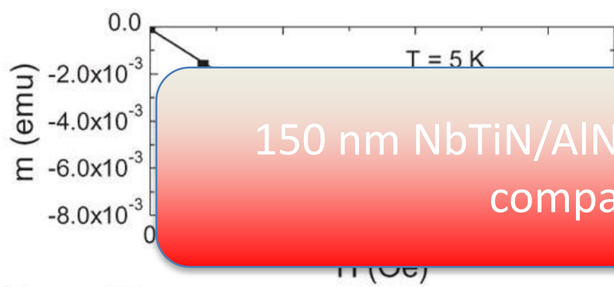


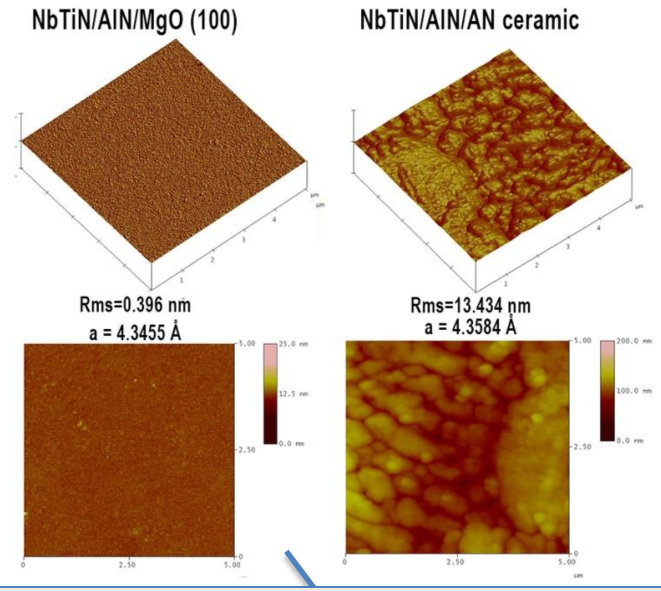
NbTiN/AlN Films (SI) – Flux penetration

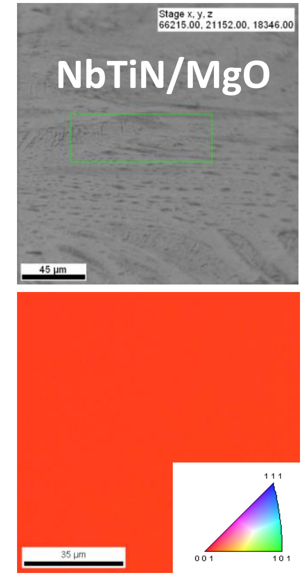
SQUID Magnetometry

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

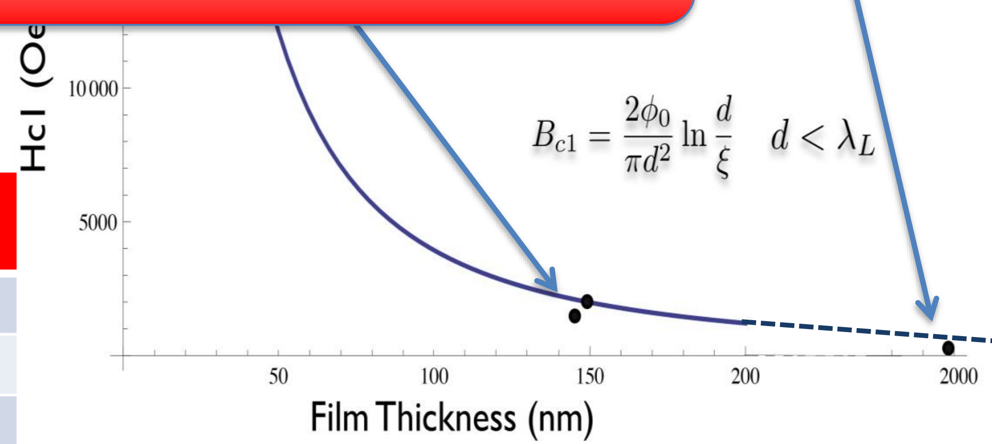








150 nm NbTiN/AlN SI structures exhibit **H_{fp} enhancement** compared to bulk-like NbTiN film



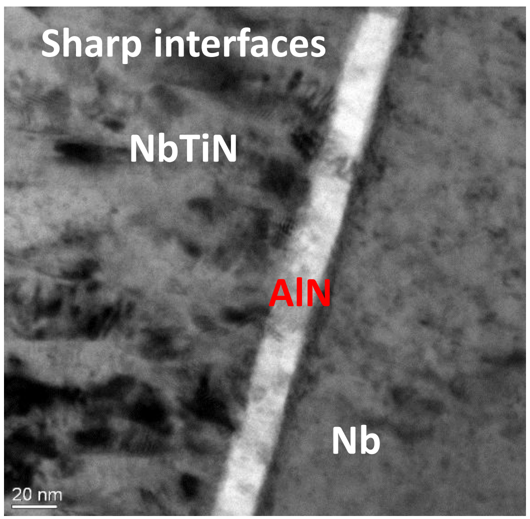
$$B_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\xi} \quad d < \lambda_L$$

	Thickness [nm]	H_{c1} [mT]	T_c [K]
NbTiN/MgO	2000	30	17.3
NbTiN/AlN/AlN ceramic	145	135	14.8
NbTiN/AlN/MgO	148	**200**	16.7

RF characterization of NbTiN/AlN/Nb structures

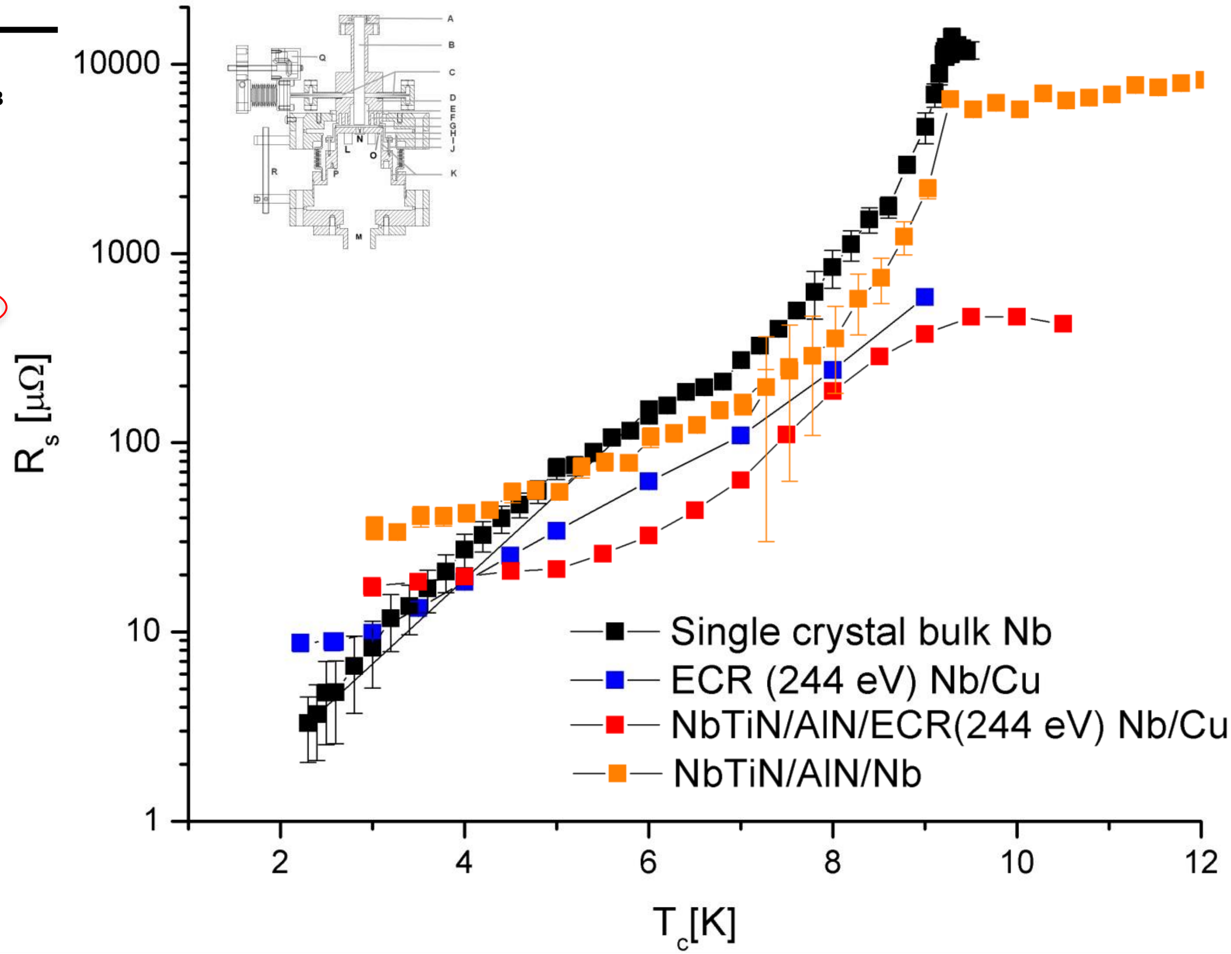
SIS structures coated on ECR Nb/Cu film: 24h-bake, coating and annealing for 4 h at 450°C.

	AlN	NbTiN
N_2/Ar	0.33	0.23
Total pressure [Torr]	2×10^{-3}	2×10^{-3}
Sputtering Power [W]	100	300
Deposition rate [nm/min]	~ 2.5	~ 18
Thickness [nm]	20	150
Tc [K]	N/A	16.9



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

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

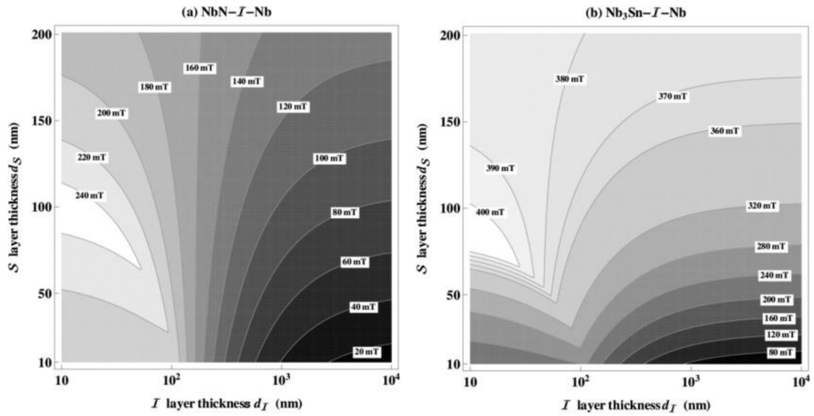


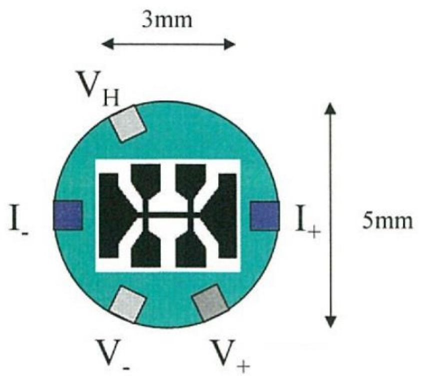
Lower BCS resistance beyond 4 K for SIS coated surfaces compared to standalone ECR film & bulk SC Nb.

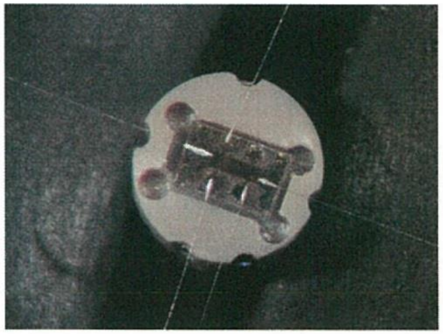
NbTiN based SIS Optimization

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

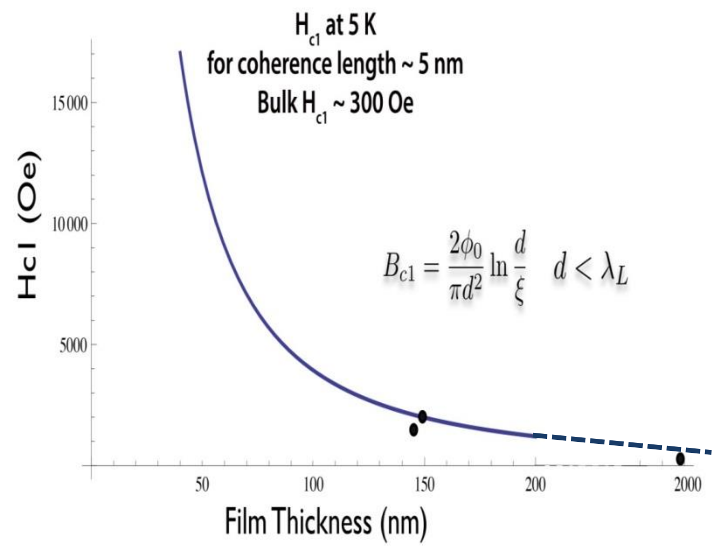
T. Kubo, SRF 2015



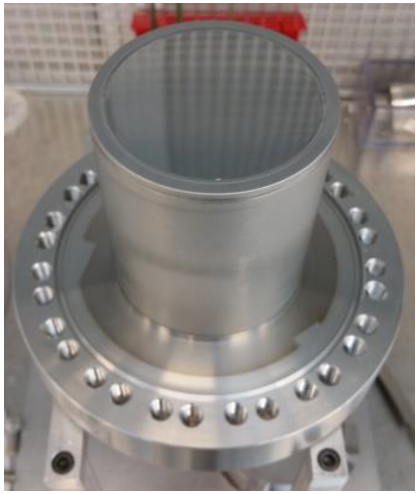




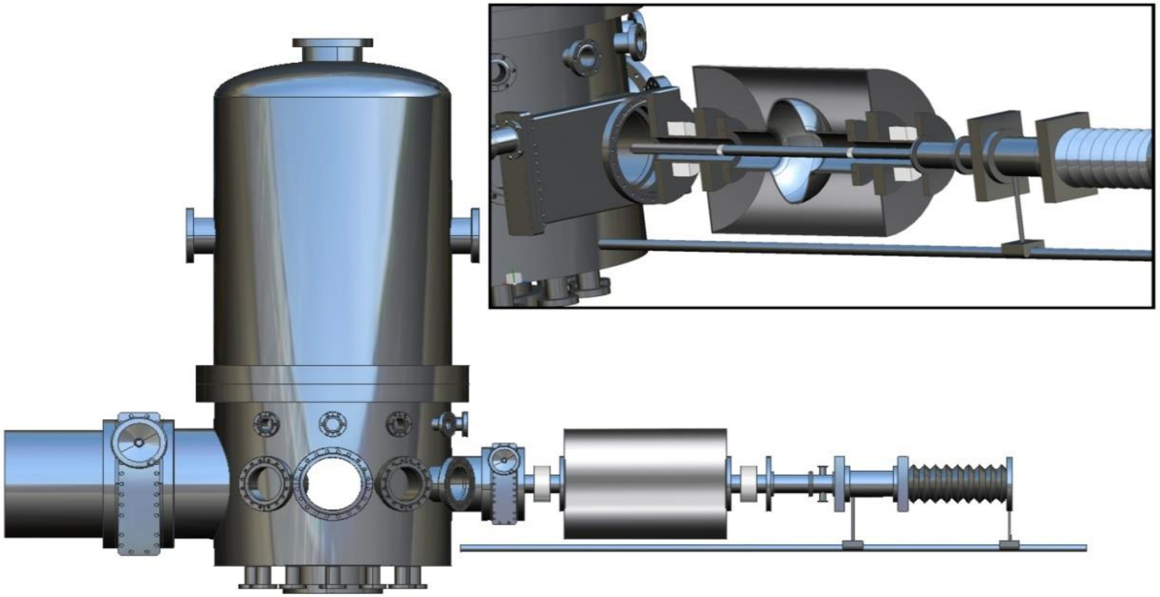
H_{C2} measurements via constrains MR in pulsed field - KU Leuven



NbTiN based SIS Optimization



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



SIS structure coating on Nb & Nb/Cu cavities concept

Conclusions

- ✓ Good quality standalone NbTiN & AlN layers
- ✓ 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 .
- ✓ $\mathbf{H_{fp}}$ **enhancement** (SQUID magnetometry) observed for 150 nm NbTiN films.
- ✓ Completion of $\mathbf{H_{fp}}$ **enhancement versus** thickness under way (Kubo curves)

- ✓ **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**.