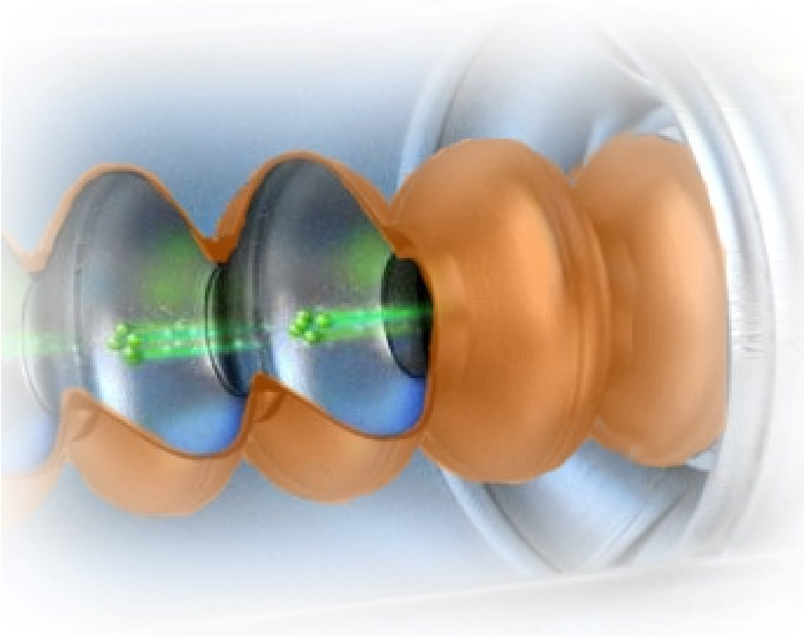
Material & Superconducting Properties of NbTiN/AlN Multilayer Films



A.-M. Valente-Feliciano

D. R. Beverstock, O. Trofimova, J.K. Spradlin, C.E. Reece (JLab)

S. Keckert, D. Tikhinov (HZB)

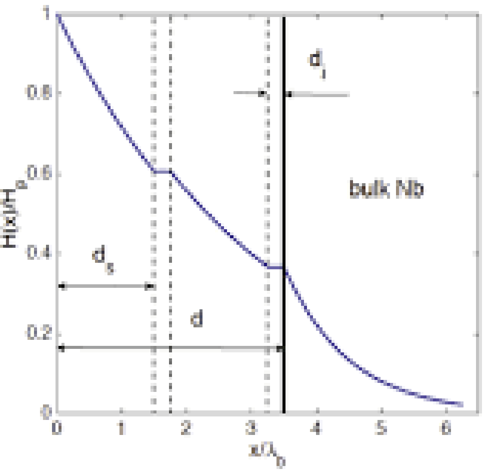
R. Valizadeh (STFC)

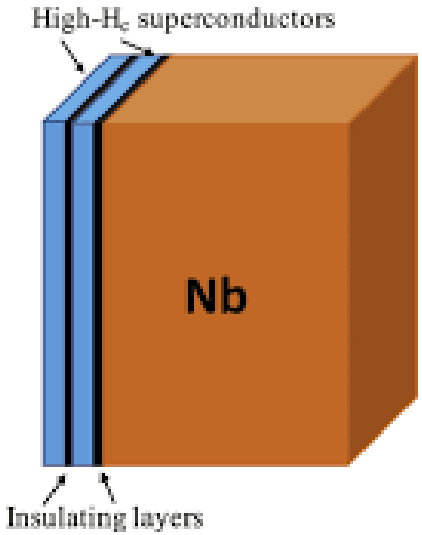
C. Antoine (CEA Saclay)

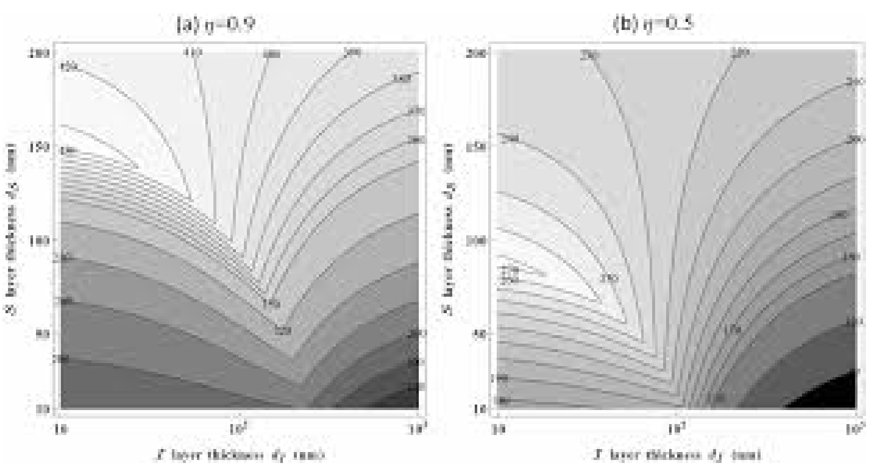
OUTLINE

- Introduction
- Materials choice – reminders
- Experimental Setup
- NbTiN based structures on niobium
- QPR Results – summary
- NbTiN based QPR structures
- Conclusion & Future Work

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

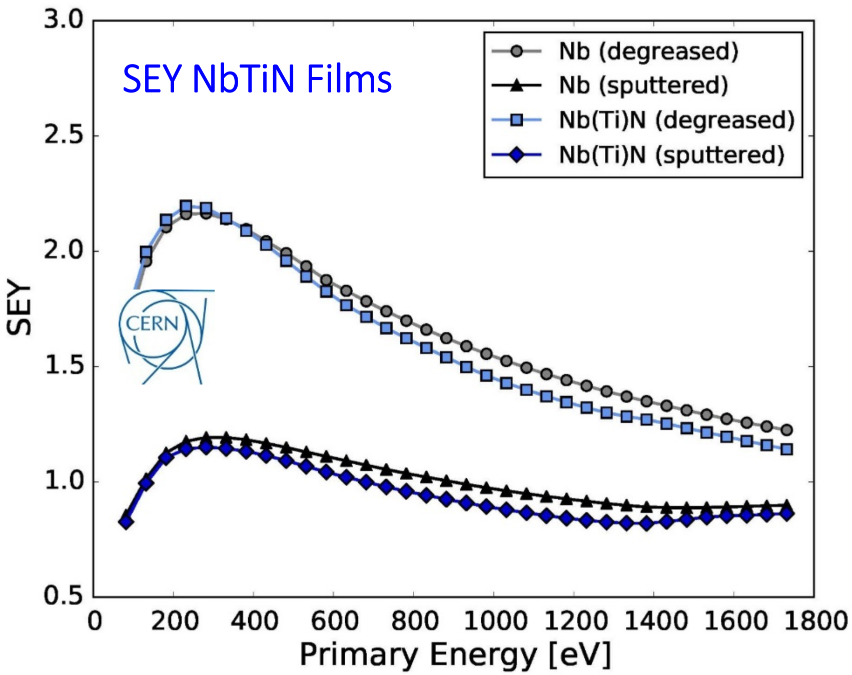
SIS Multilayers: Materials Choice - Reminder

NbTiN

Good superconductor, bulk Tc~17.3 K

δ-phase for T_c> 16 K

Typically more stable and metallic behavior than NbN



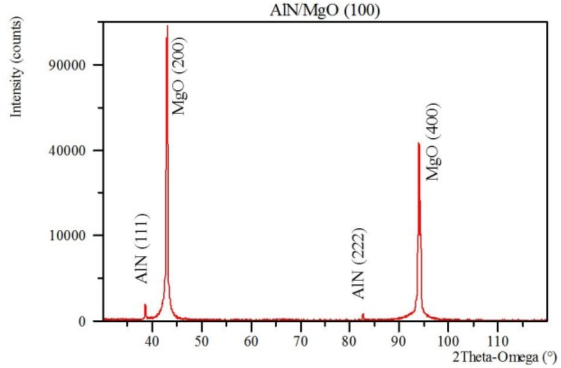
Measurements at room temperature

Max. SEY =2.2 ± 0.1 comparable to EP Nb

After sputtering away ~ 3 nm, SEY down to 1.15

AlN

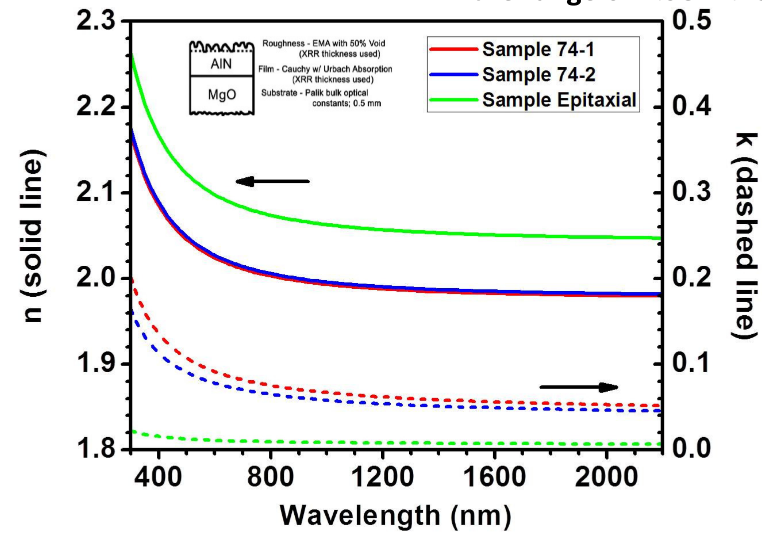
Good Dielectric Behavior



Good quality AlN are readily produced at 600 and 450°C by dc-reactive magnetron sputtering with N_2/Ar ~33%.
The films exhibit the cubic structure (single crystal) at 600 °C and the hexagonal structure (polycrystalline) at 450 °C .

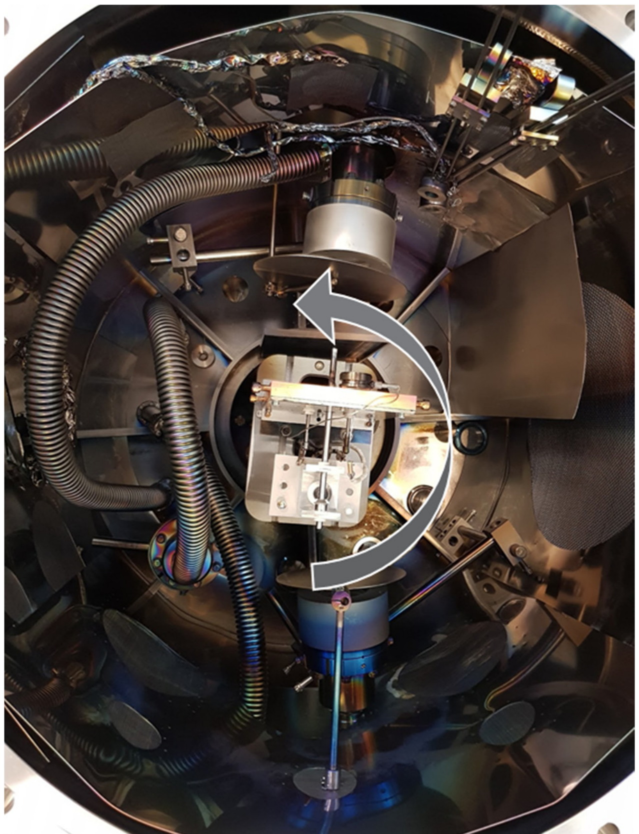
At 450 °C, 30 nm AlN films exhibit dielectric properties of polycrystalline AlN films

n in the range of 1.98- 2.15

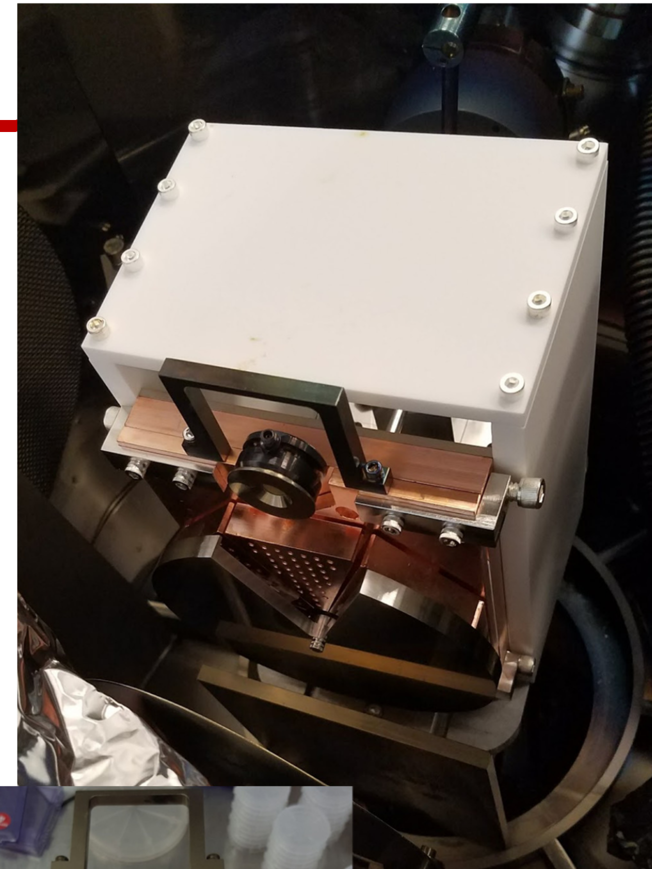


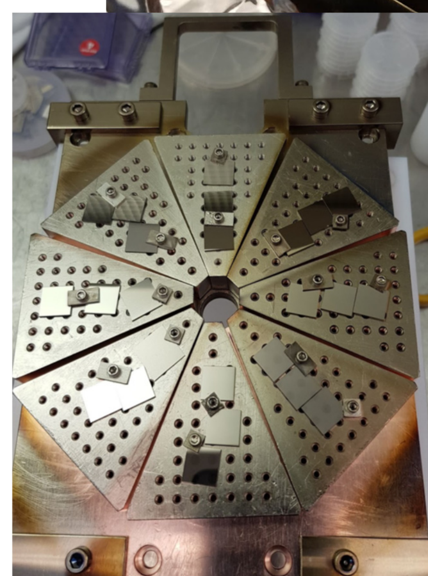
UHV DEPOSITION SYSTEM upgrade

Samples heated up to 600 °C
Base pressure 10^{-10} Torr
3 magnetron sources
DC, RF and HiPIMS capable



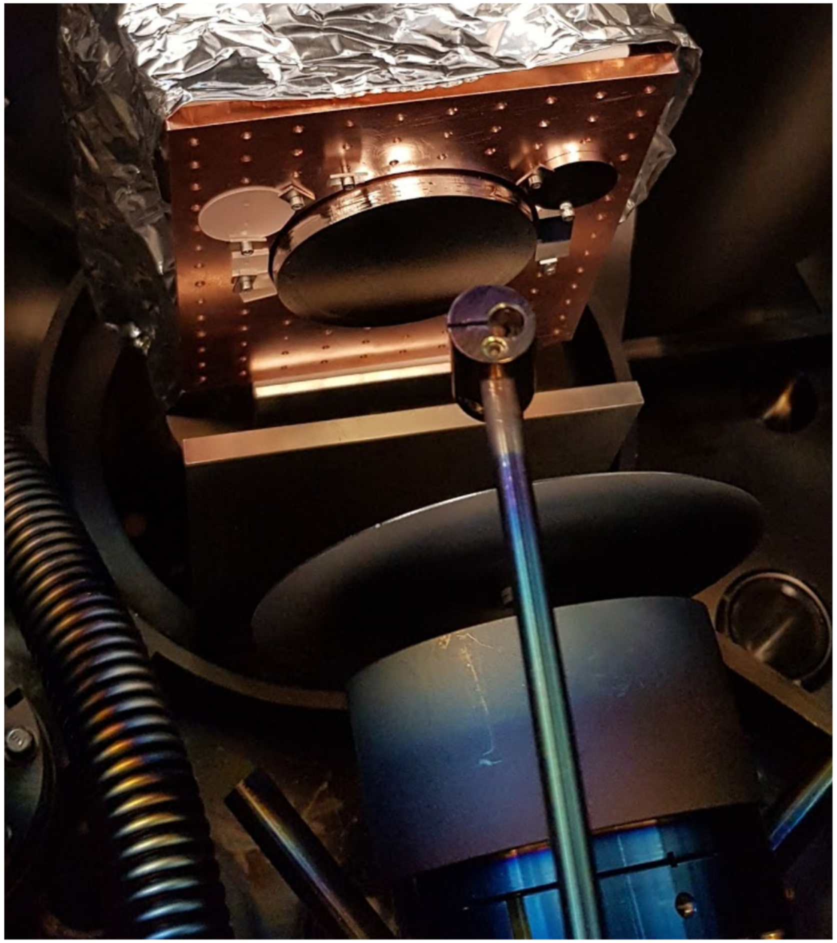
Central stage mounted on differentially pumped CF system to position samples in front of each magnetron source

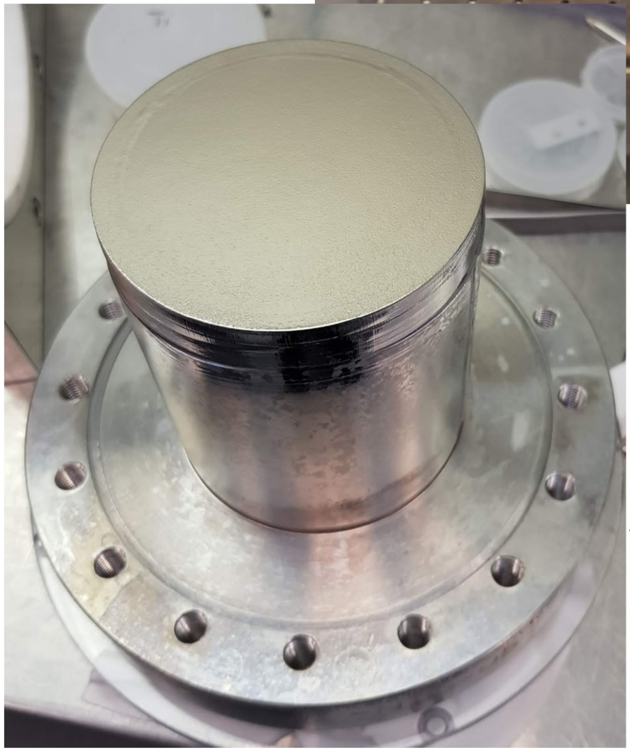




UHV DEPOSITION SYSTEM

QPR Sample Coating Setup

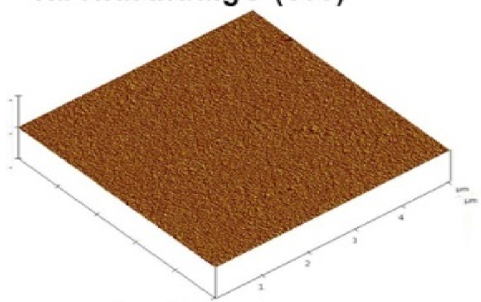




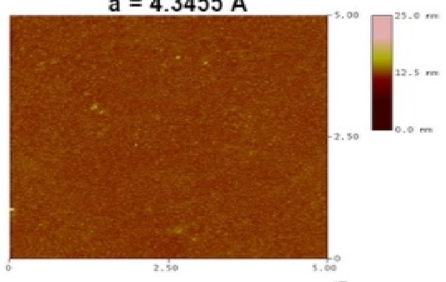
Samples are mechanically polished, heat treated at 800 °C and electropolished

SIS NbTiN/AlN structures on MgO & Nb surfaces

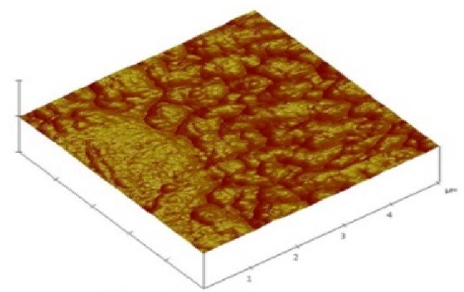
NbTiN/AlN/MgO (100)



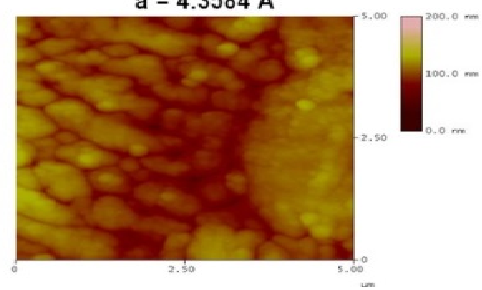
Rms=0.396 nm
a = 4.3455 Å

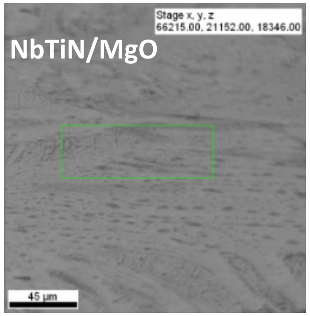


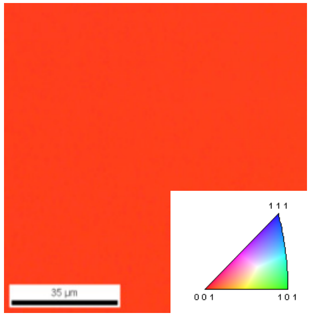
NbTiN/AlN/AN ceramic

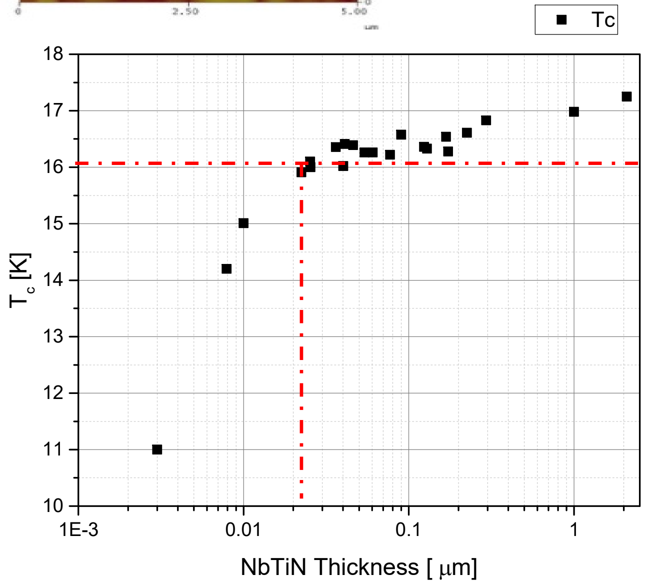


Rms=13.434 nm
a = 4.3584 Å







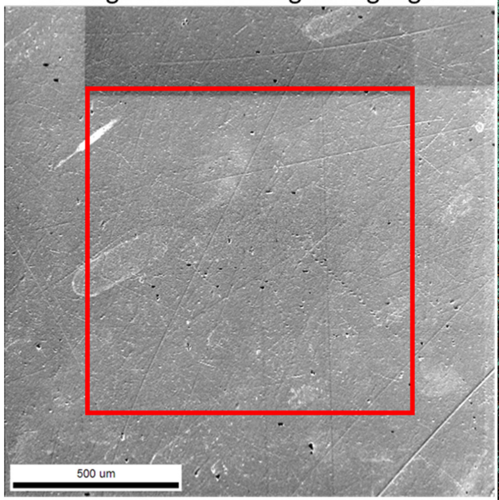


NbTiN/MgO
~ ideal case

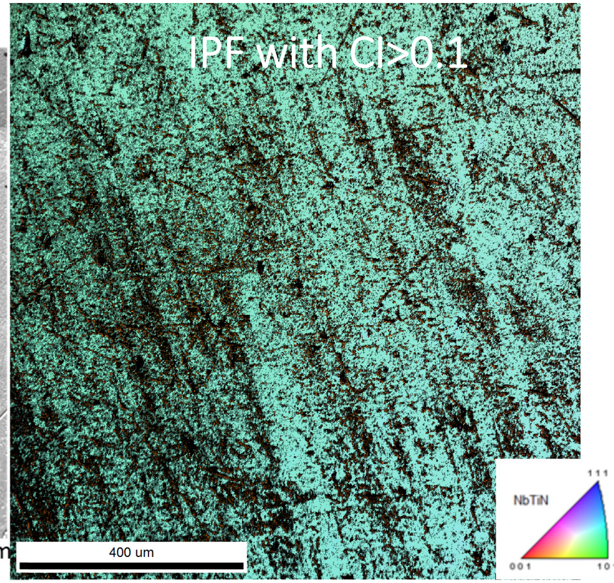
NbTiN, NbTiN/AlN ceramic
Have a T_c slightly depressed in comparison

Microstructure of NbTiN Films on Nb

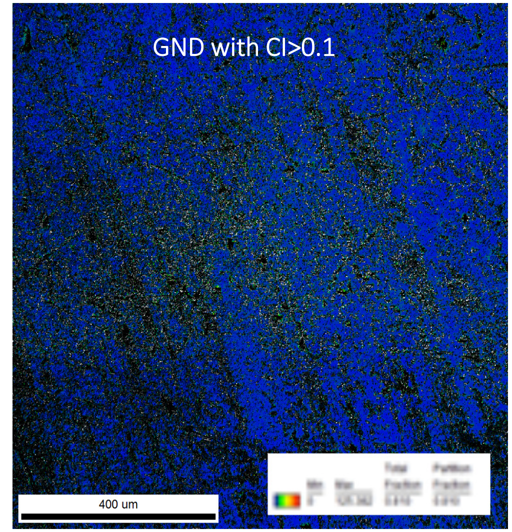
SE Image with EBSD Region Highlighted



1500 µm

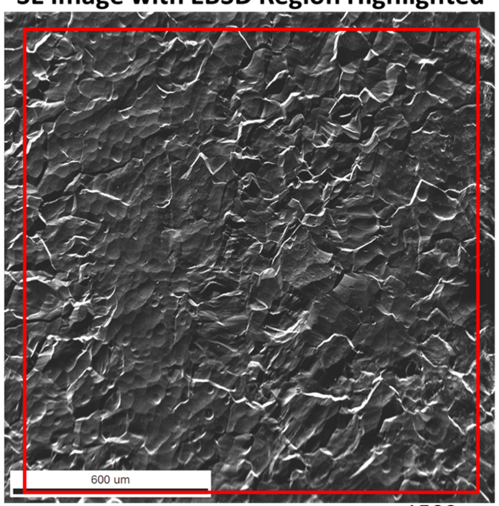


2 µm “bulk” NbTiN/ single crystal Nb

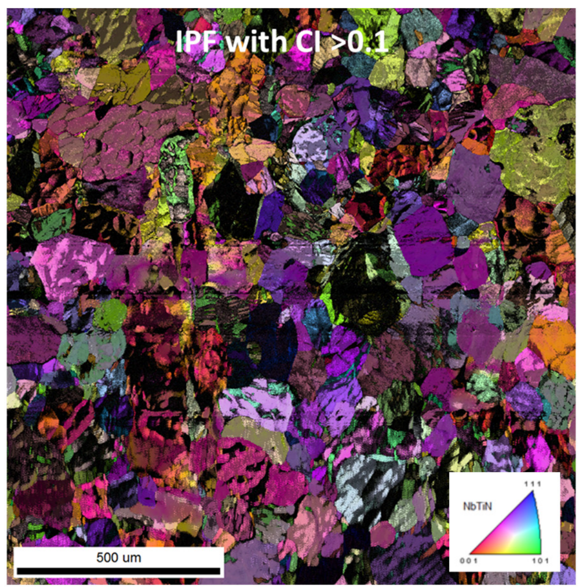


Tc =17 K

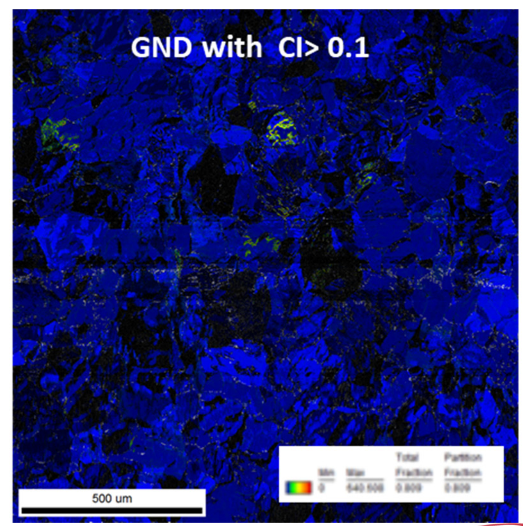
SE Image with EBSD Region Highlighted



1500 µm



200 nm NbTiN/Nb



Tc =14.8K

Film Interface development in SIS Multilayers - Metamaterials

Metamaterial superconductor based on NbTiN (metamaterials synergistic project, DARPA-BAA funded)

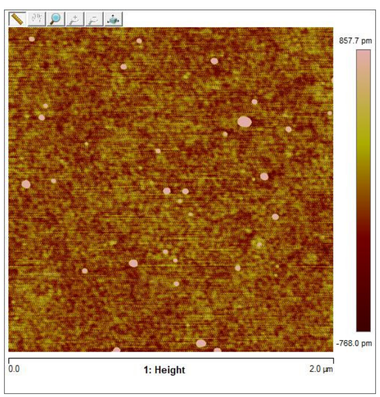
Nature Scientific Reports 6, Article number: 34140 (2016)

- Multilayer structure of NbTiN = 3 nm and AlN = 2/1.5/1 nm. Series of 16-, 8-, 4-, 2-, 1- bilayers deposited on NbTiN/MgO
- Metamaterial layered superconductor of NbTiN and AlN can enhance T_c compared to NbTiN single layer.
- Low roughness of sequential films is necessary to accomplish sharp interfaces.

V. Smolyaninova

Bilayers deposited on NbTiN/MgO.

# bilayers	NbTiN [nm]	AlN [nm]
16	3	2.5
8	3.3	2.4
4	4.3	2.5
2	3.4	2



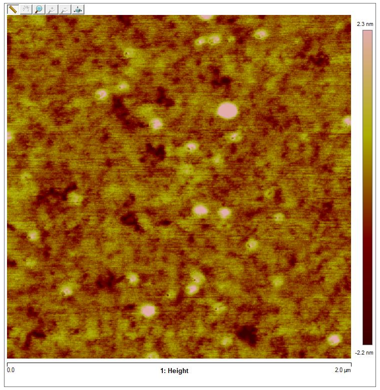
8 layers of NbTiN/AlN on NbTiN/MgO

RMS = 0.389 nm,

Ra = 0.19 nm

NbTiN = 3.3 nm,

AlN = 2.5 nm



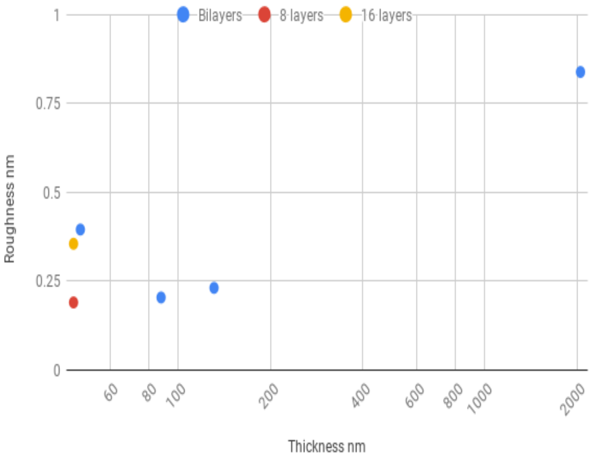
16 layers of NbTiN/AlN on NbTiN/MgO

RMS = 0.556 nm,

Ra = 0.355 nm

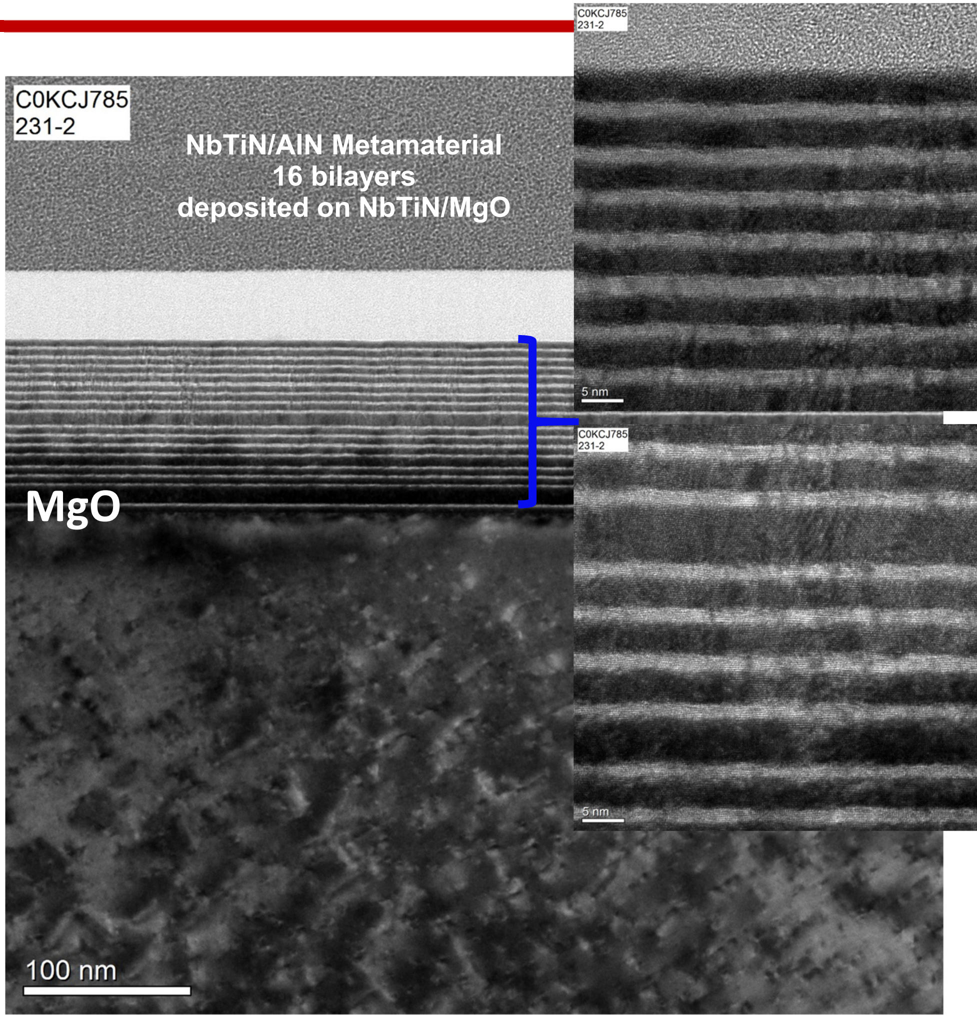
NbTiN = 3 nm,

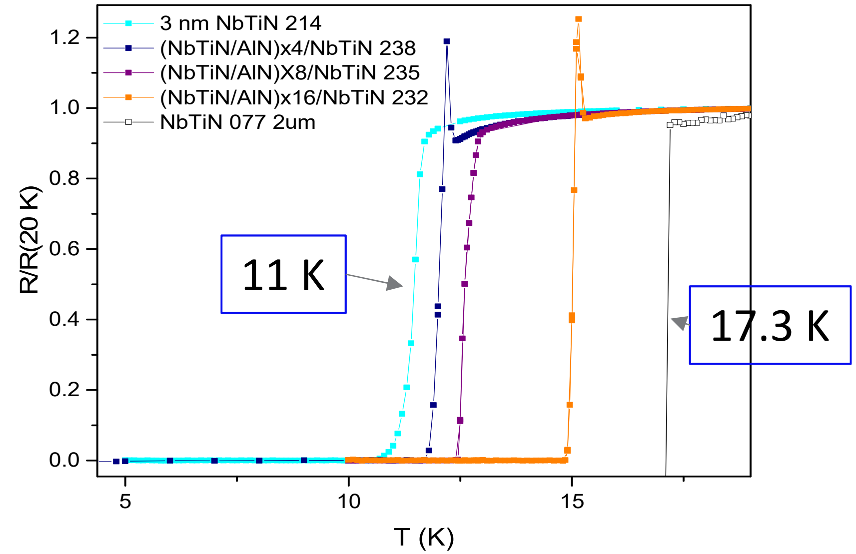
AlN = 2.4 nm

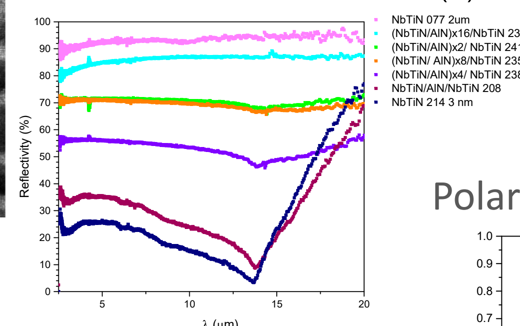


No significant increase of film roughness with additional layers.
Preserving the potential for sharp interfaces

Metamaterial superconductor based on NbTiN

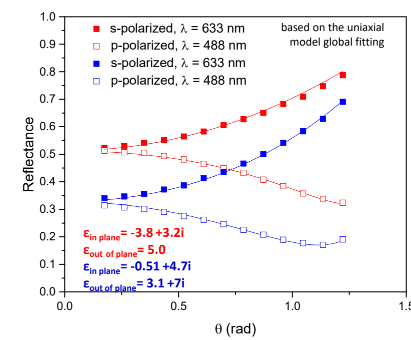






FTIR Reflectivity of multilayers & monolayers

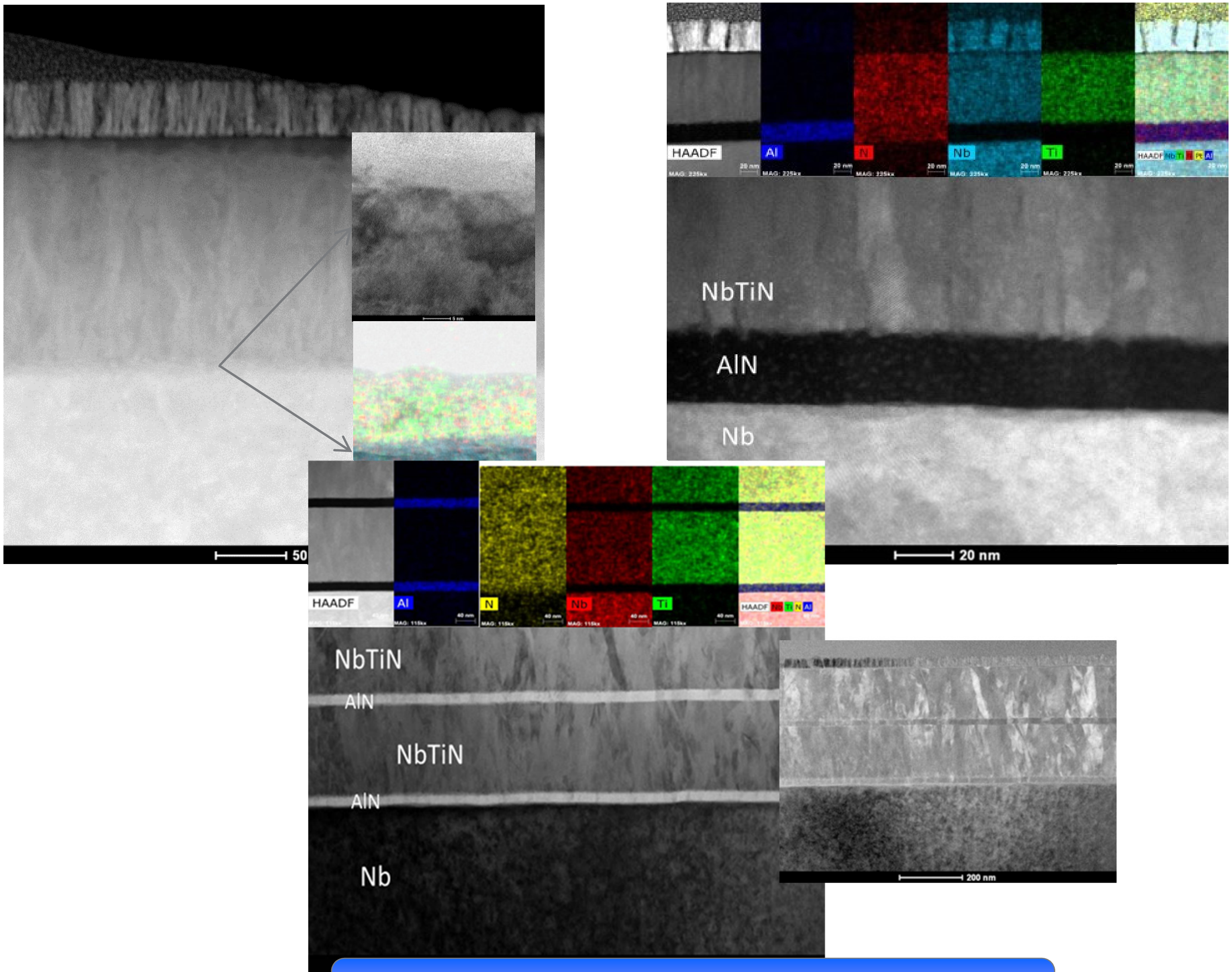
Polarization reflectometry



Hyperbolic metamaterial properties demonstrated

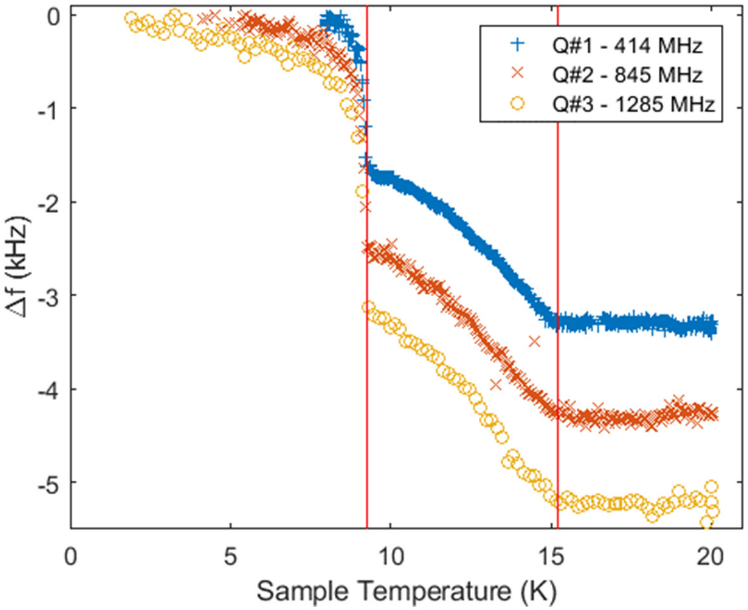
T_c enhancement with increased number of bi-layers but not yet above bulk value as predicted by theory

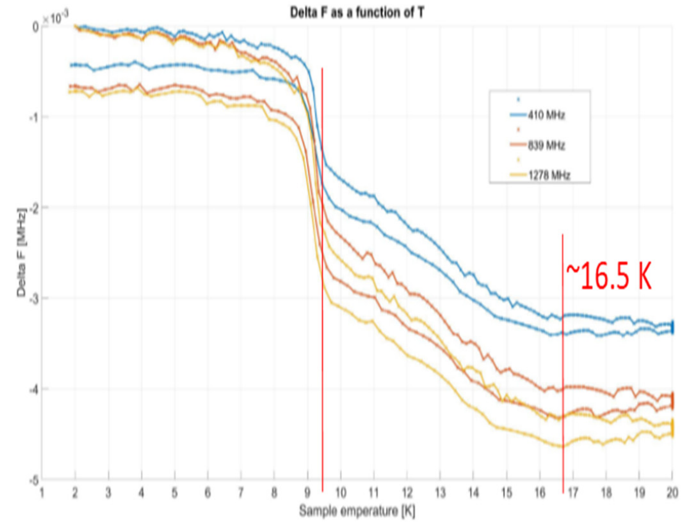
SIS NbTiN/AlN structures on MgO & Nb surfaces



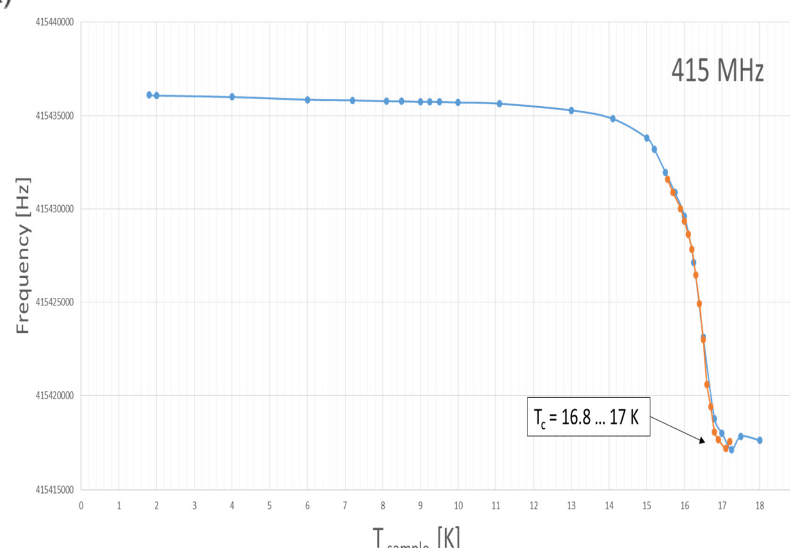
Good quality structures with sharp interfaces on Nb surfaces

NbTiN based QPR Samples – Critical Temperature

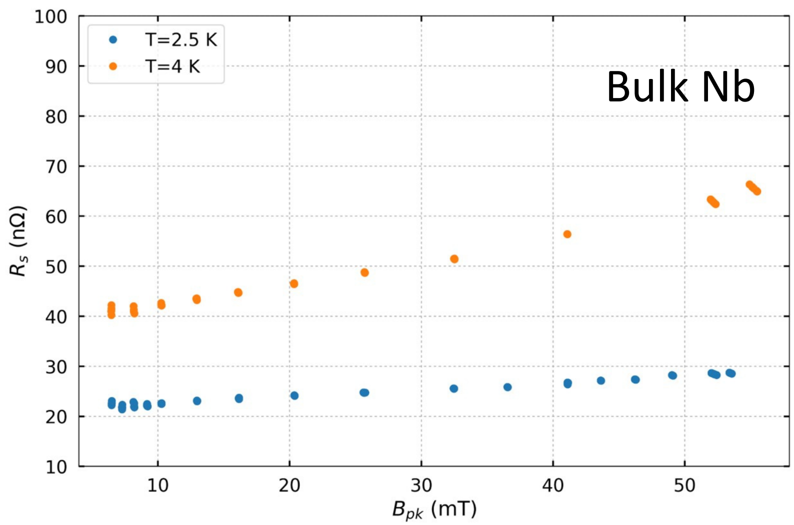


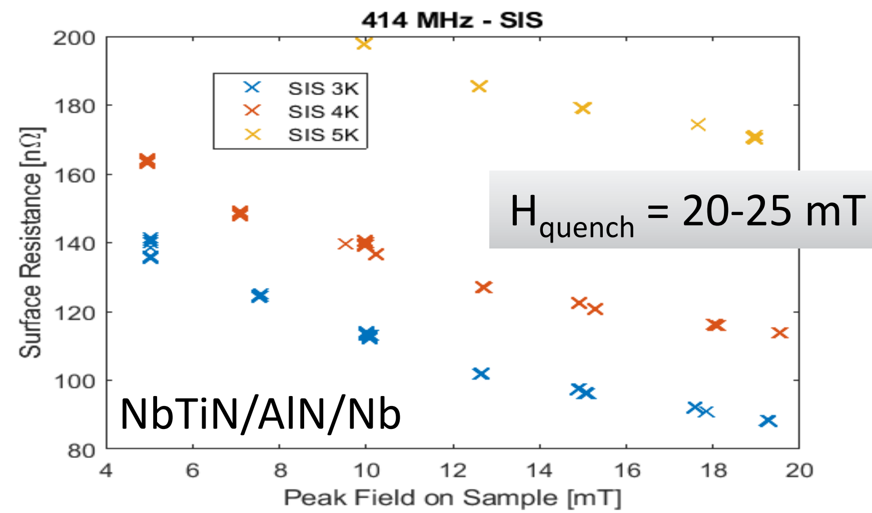


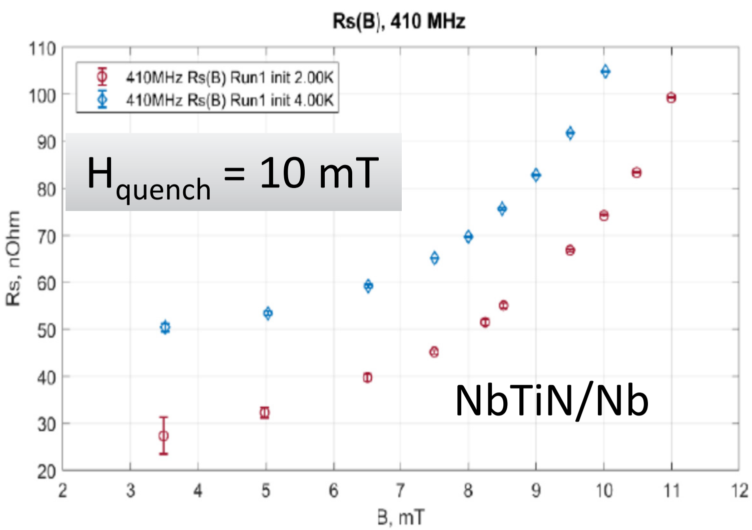
QPR measurements @ HZB
S. Keckert (THFUA1)
D. Tikhinov (TUP073)

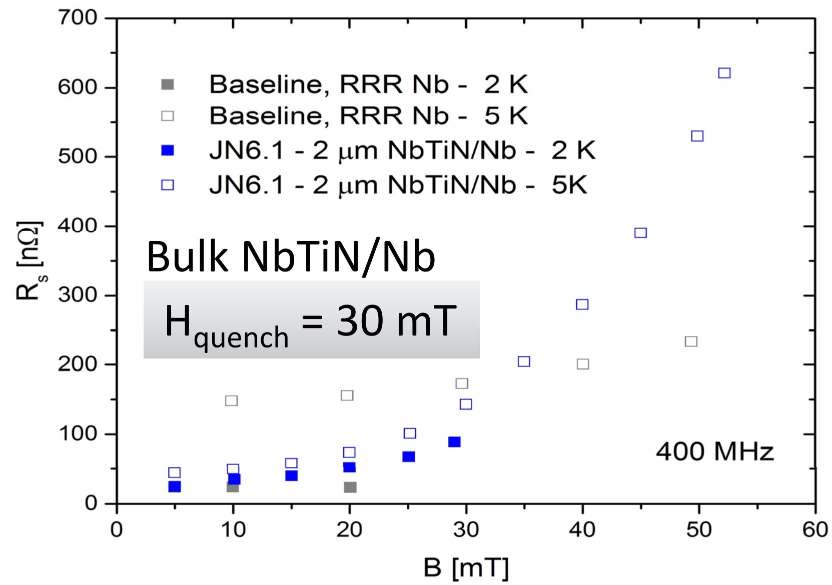


NbTiN Structures on QPR vs. Bulk Nb Baseline (415 MHz)

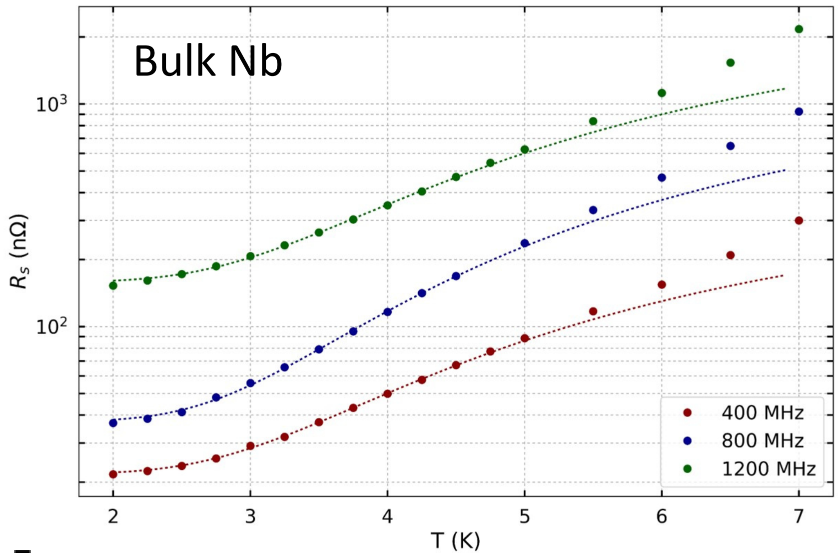


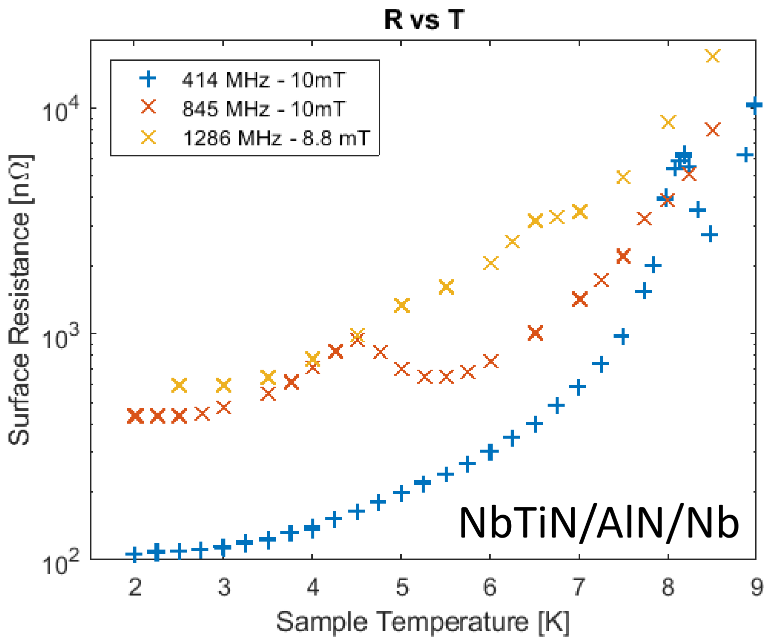


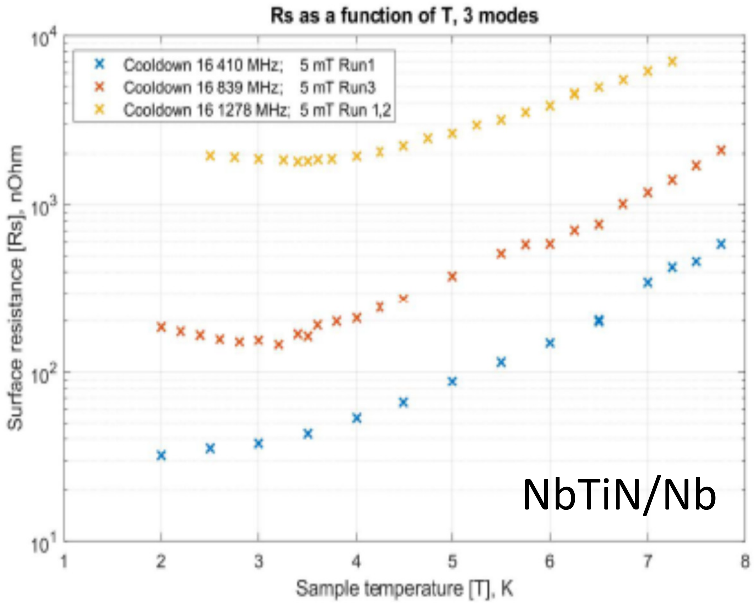




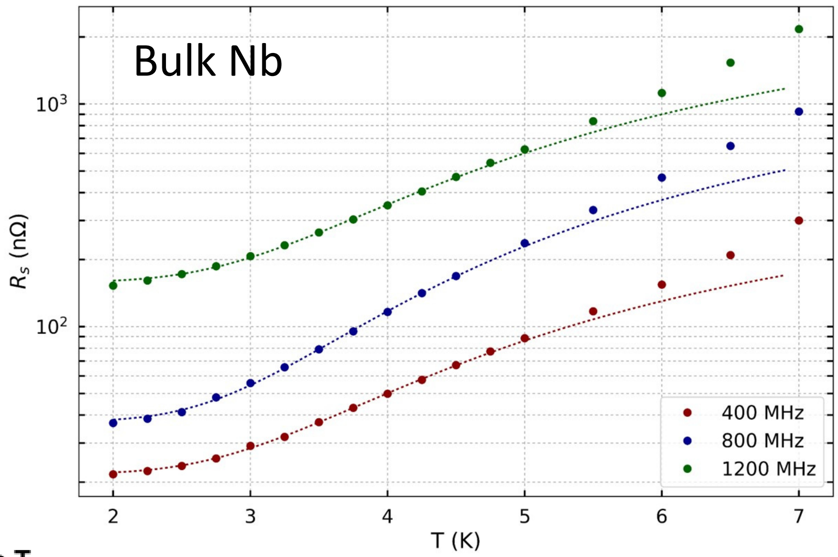
NbTiN Structures versus Bulk Nb Baseline – $R_s(T)$

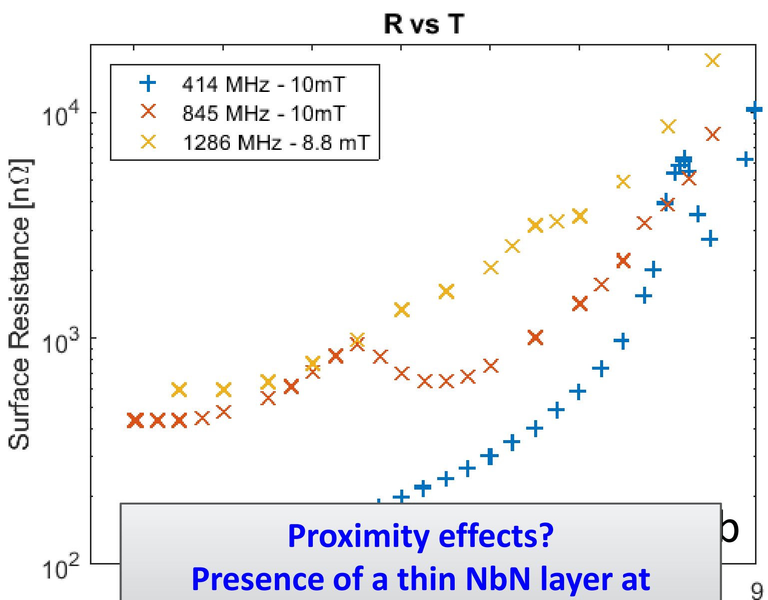




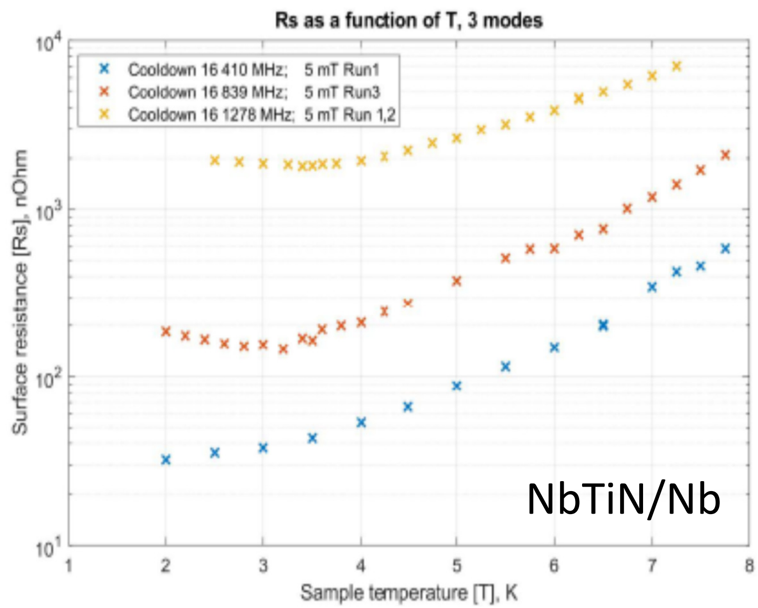


NbTiN Structures versus Bulk Nb Baseline – $R_s(T)$





Proximity effects?
Presence of a thin NbN layer at interface AlN/Nb?



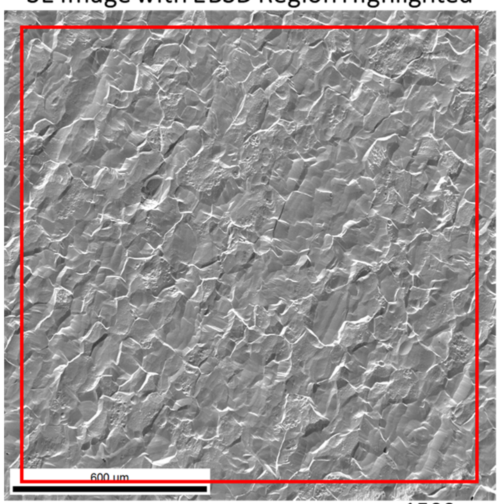
NbTiN based QPR samples structure

75 nm NbTiN/AlN/Nb

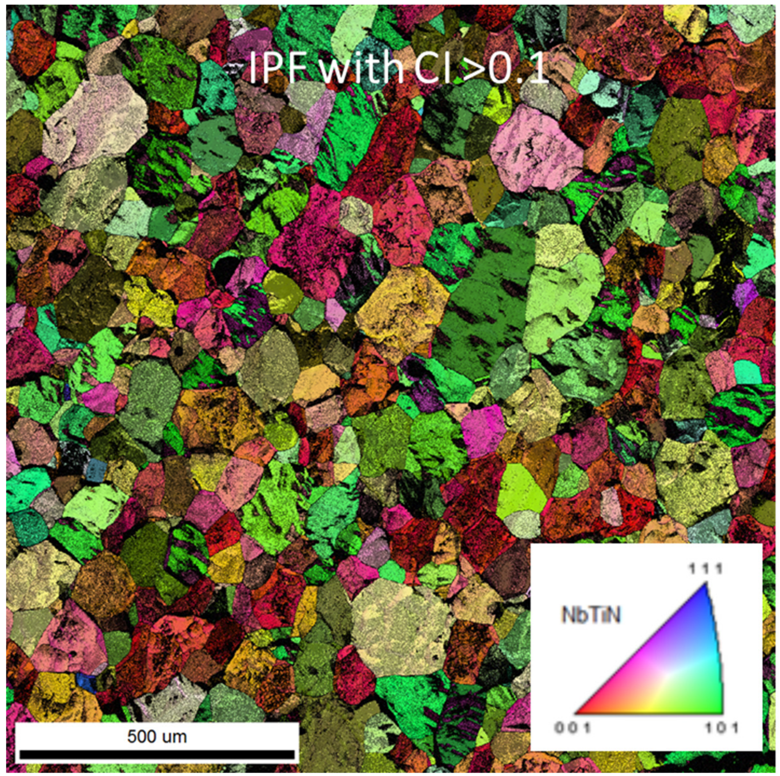
Not able to acquire EBSD map (only a few Kikuchi pattern here and there)

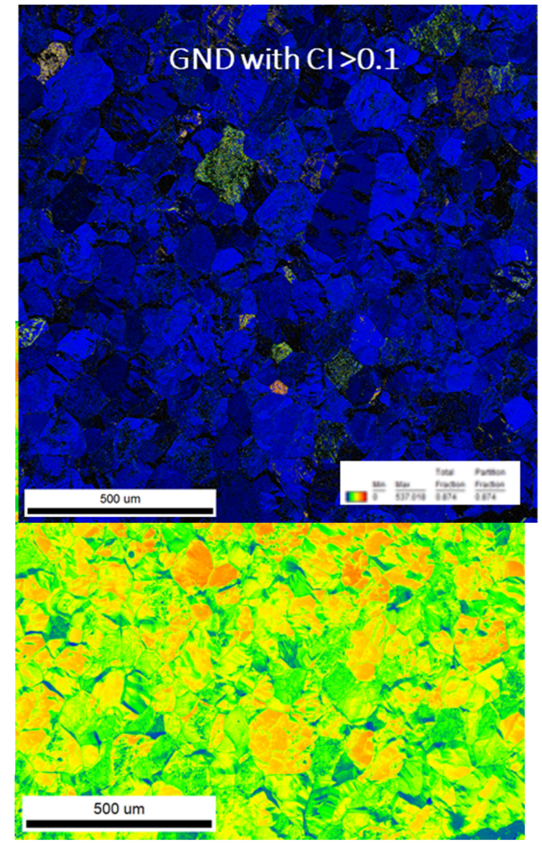
75 nm NbTiN/Nb

SE Image with EBSD Region Highlighted



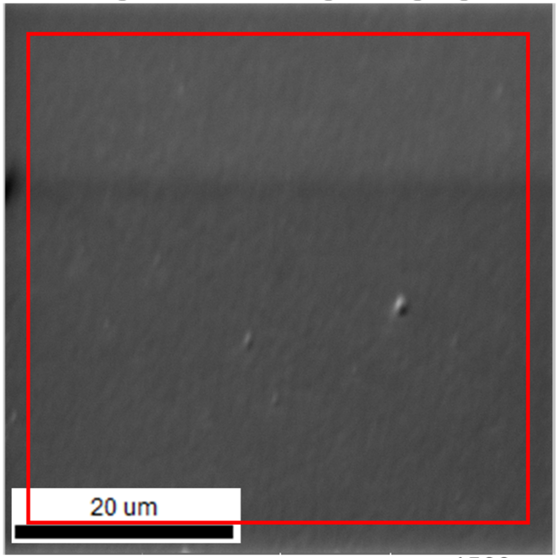
1500 µm



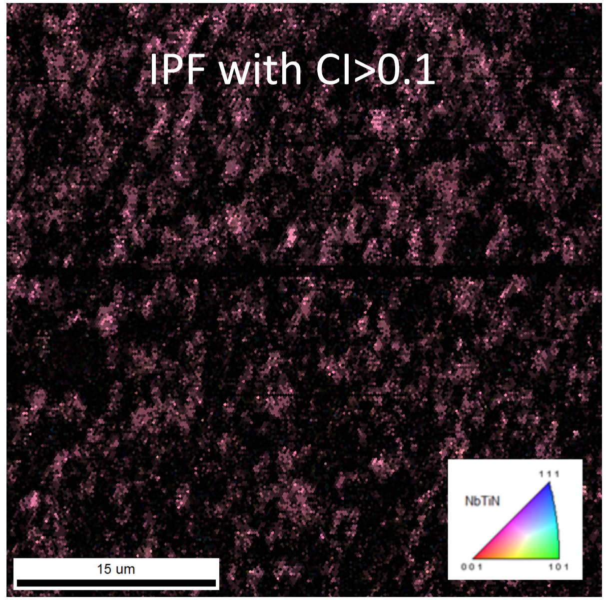


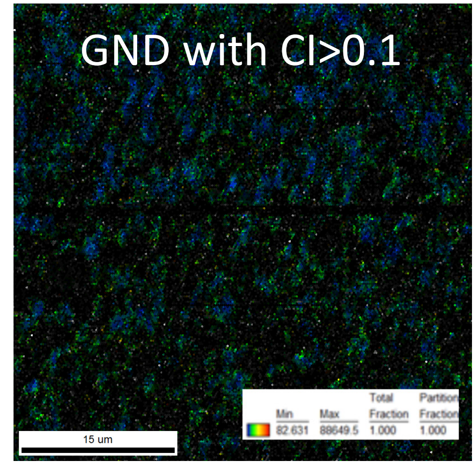
Bulk NbTiN/Nb (2µm)

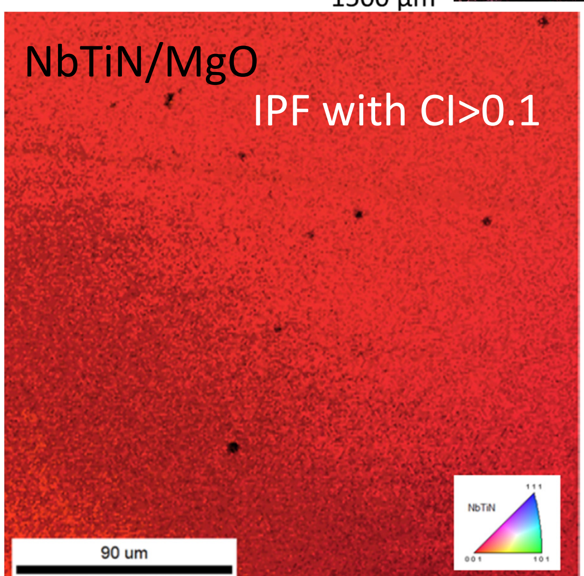
SE Image with EBSD Region Highlighted

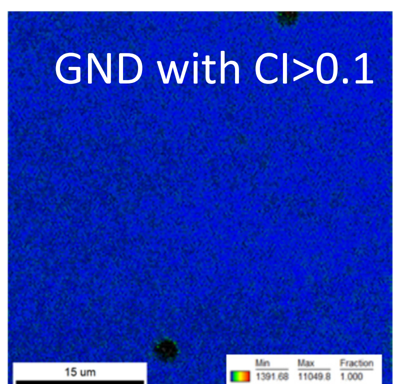


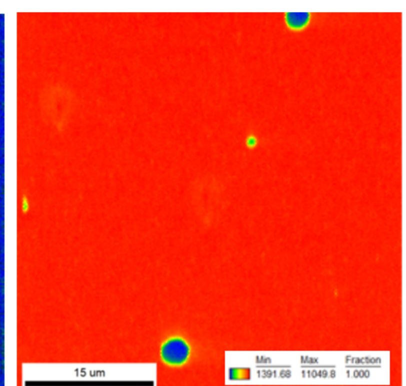
1500 µm





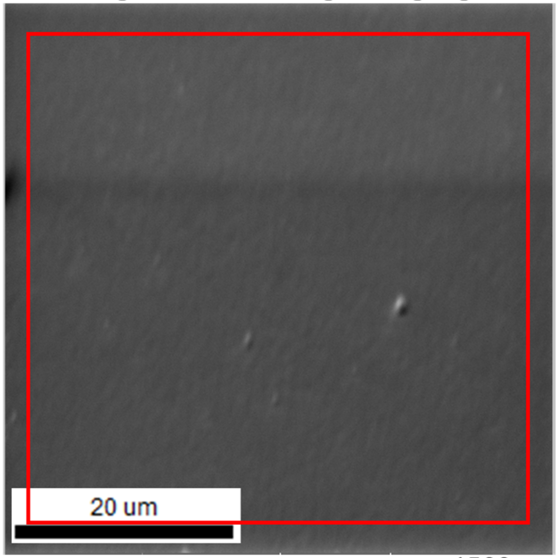




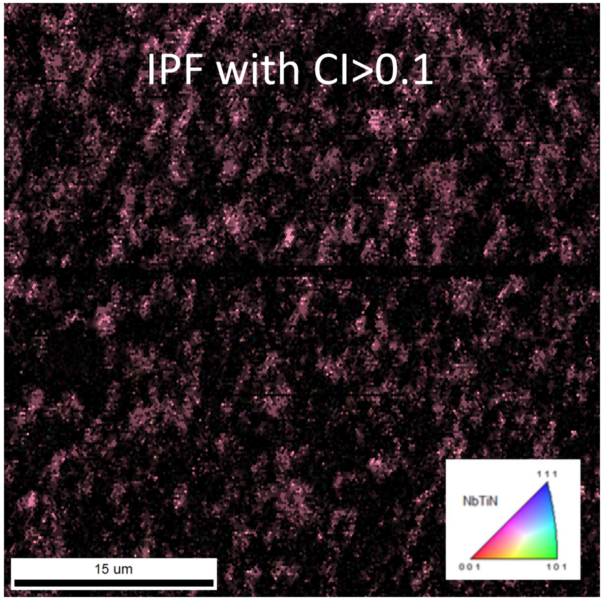


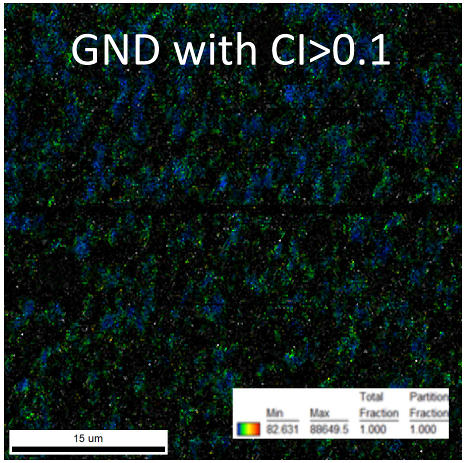
Bulk NbTiN/Nb (2µm)

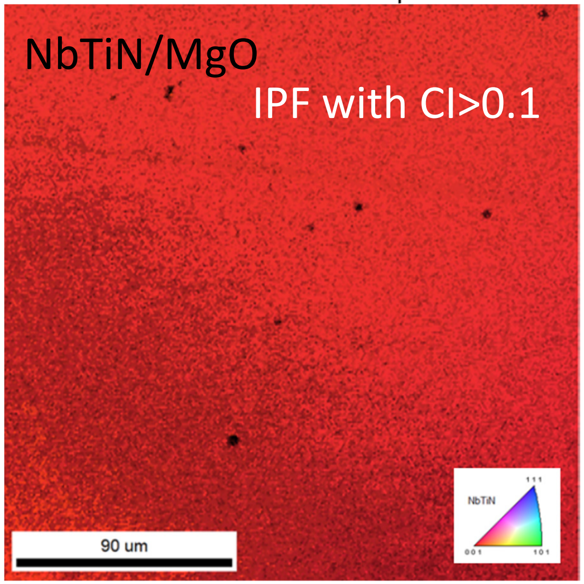
SE Image with EBSD Region Highlighted

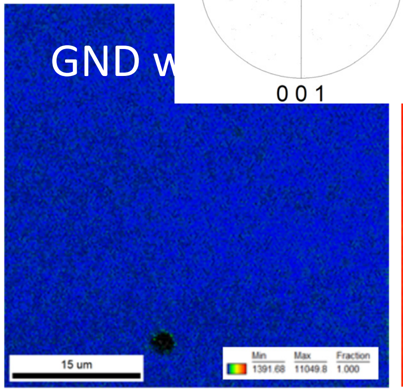


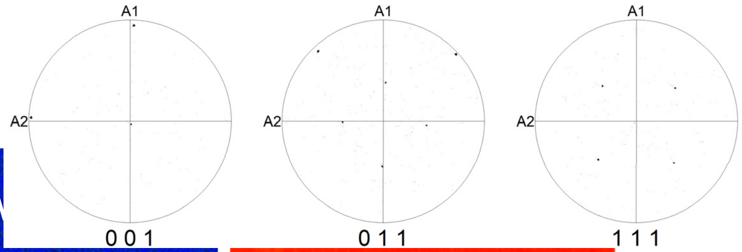
1500 µm

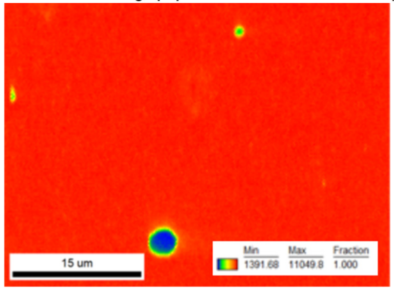




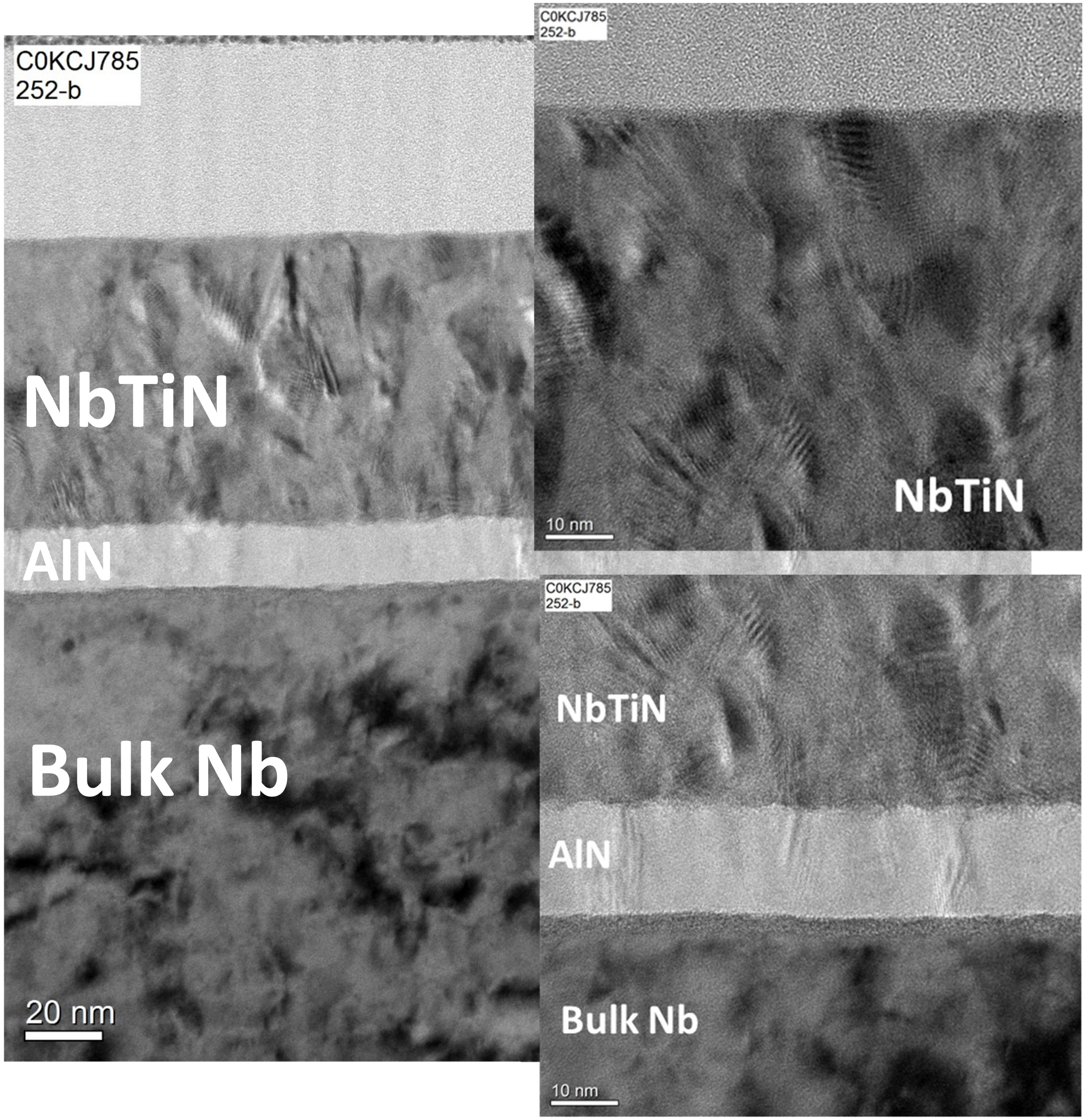




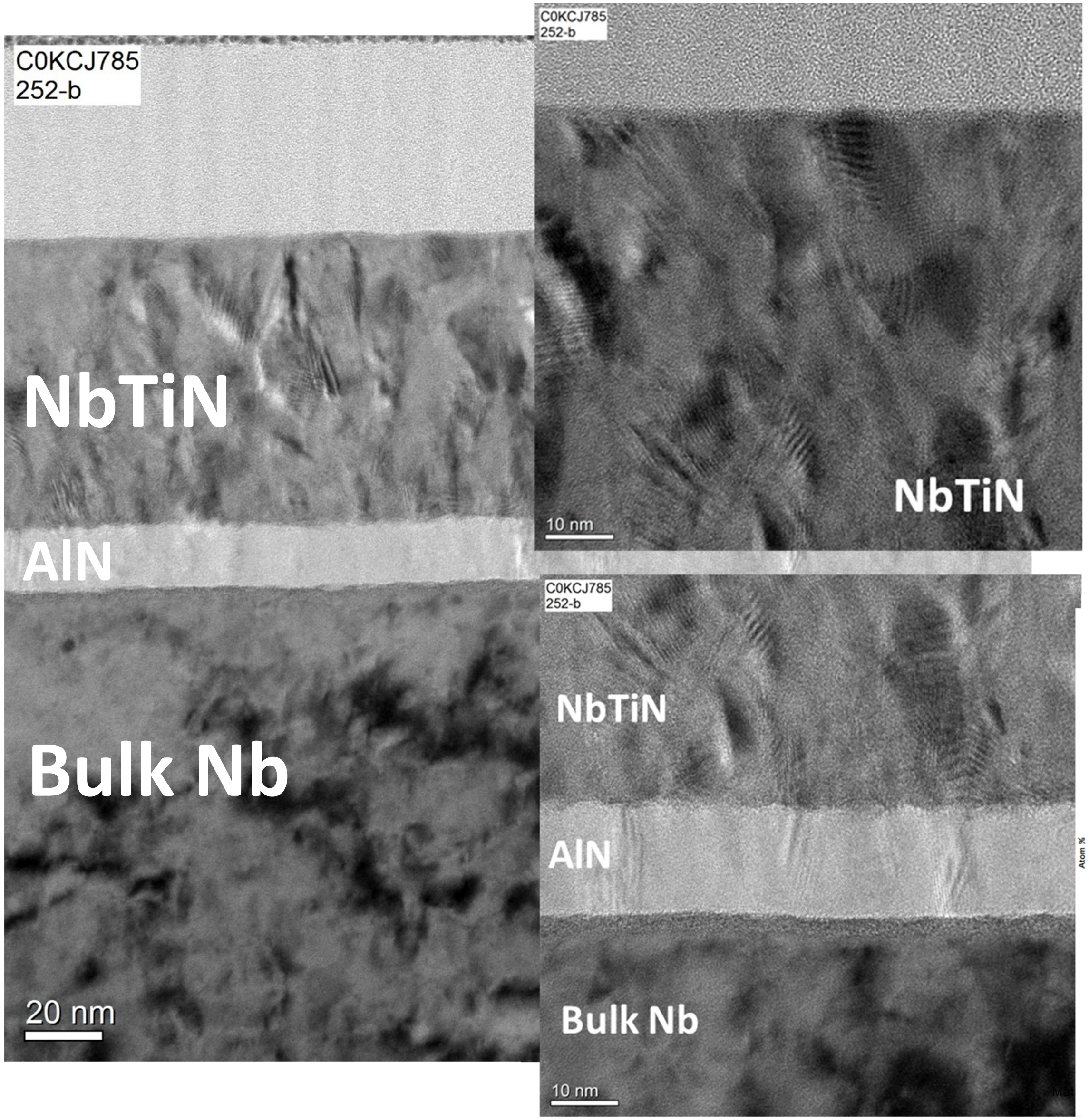


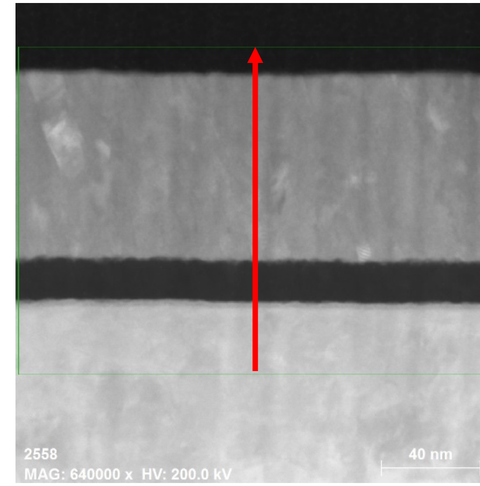


S-I-S' (75 nm NbTiN/AlN/Nb)

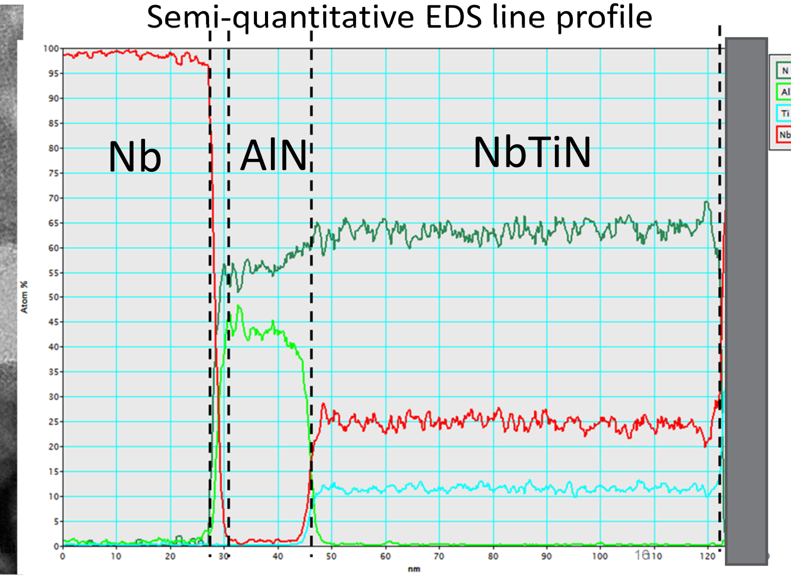


S-I-S' (75 nm NbTiN/AlN/Nb)

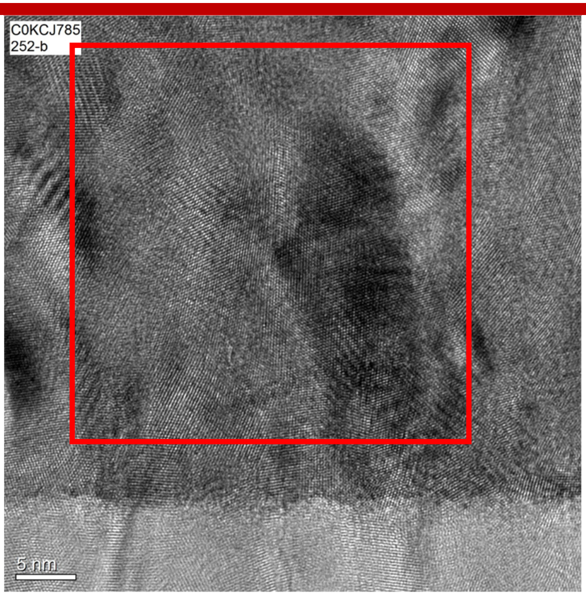


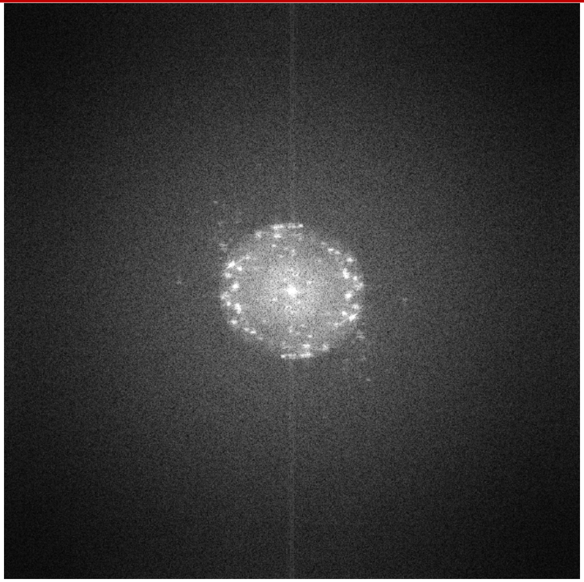


Semi-quantitative EDS line profile

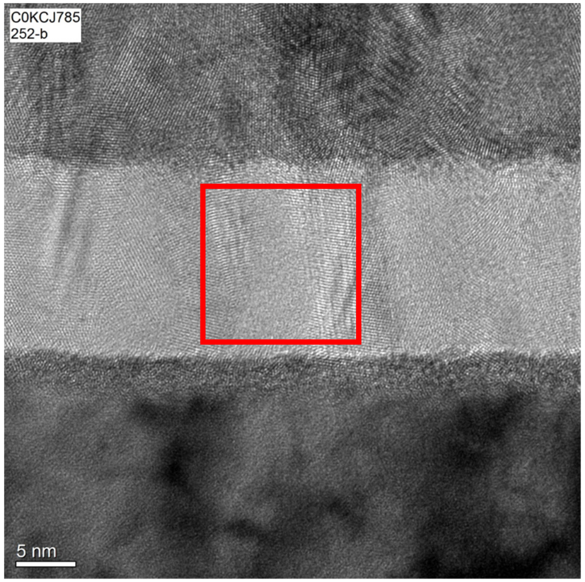


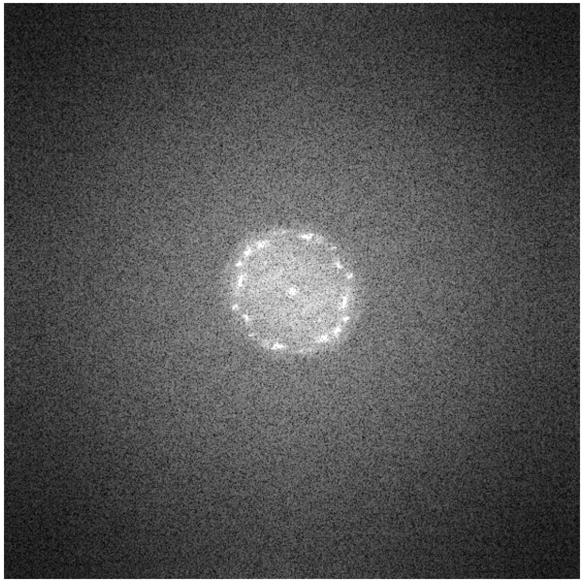
S-I-S' (75 nm NbTiN/AlN/Nb)





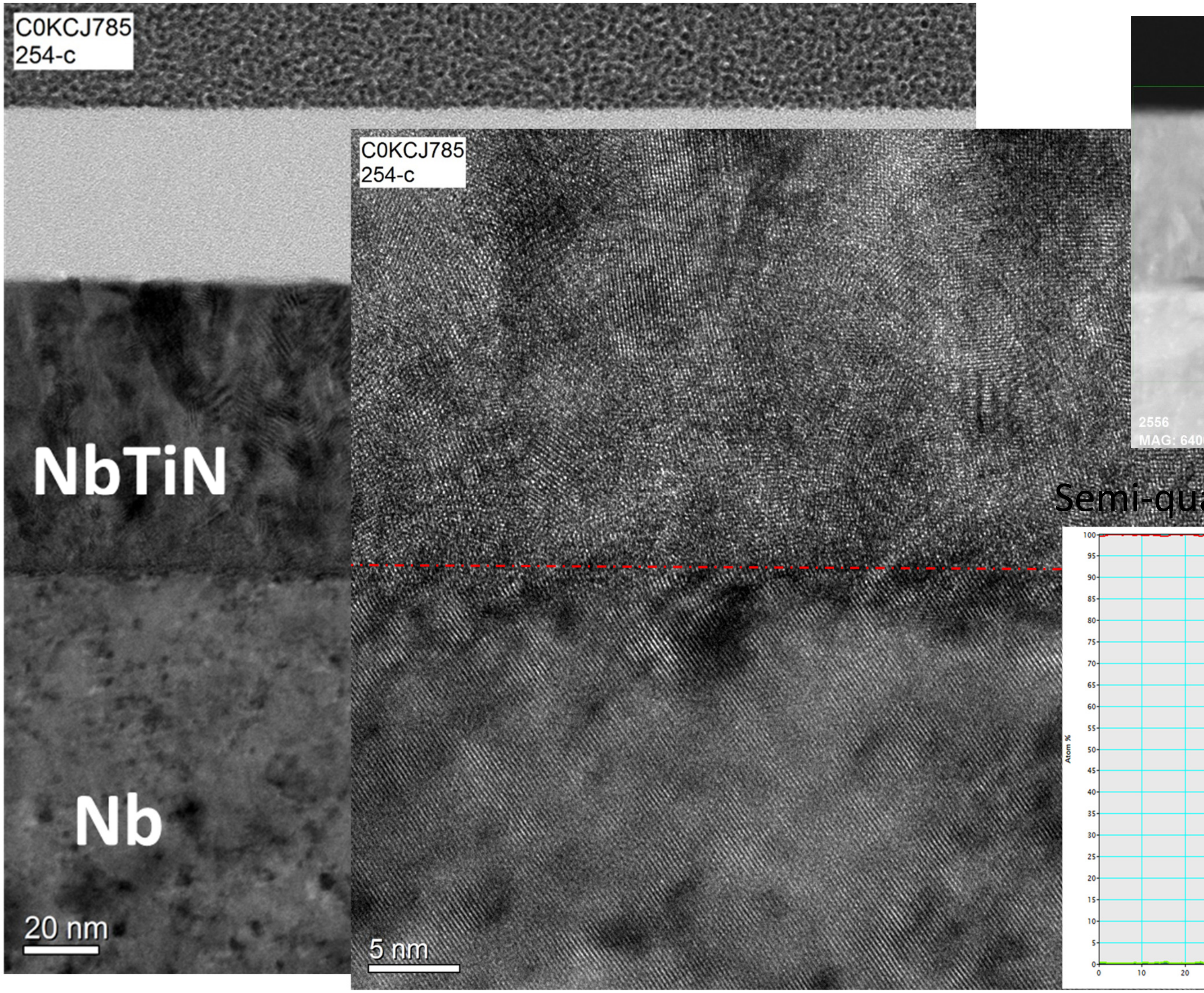
Fourier Transform (FT)

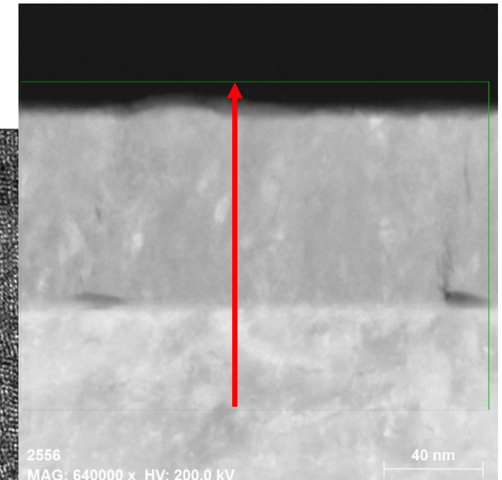




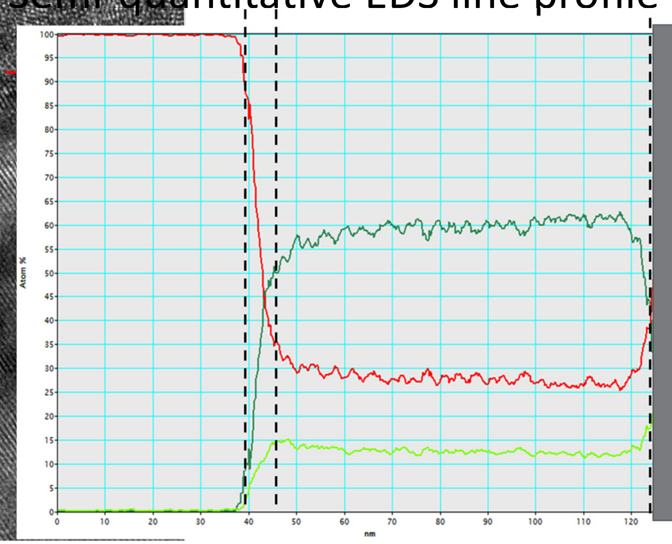
*The layers are too thin for SAED. Fourier transform is used to determine the crystallinity. Both layers are nanocrystalline.

S-S’ (75 nm NbTiN/Nb)

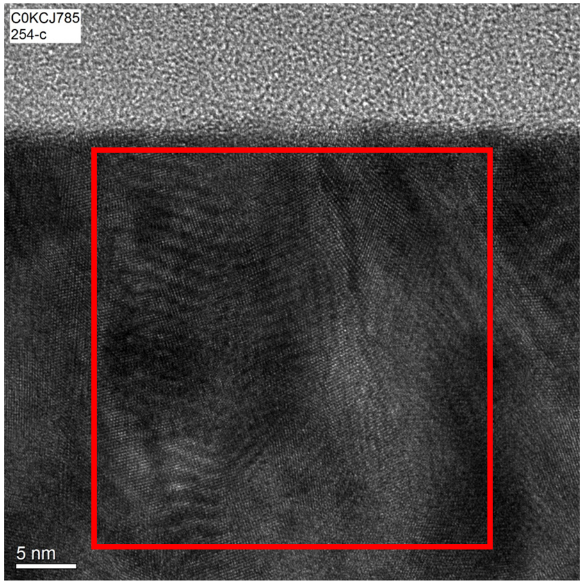


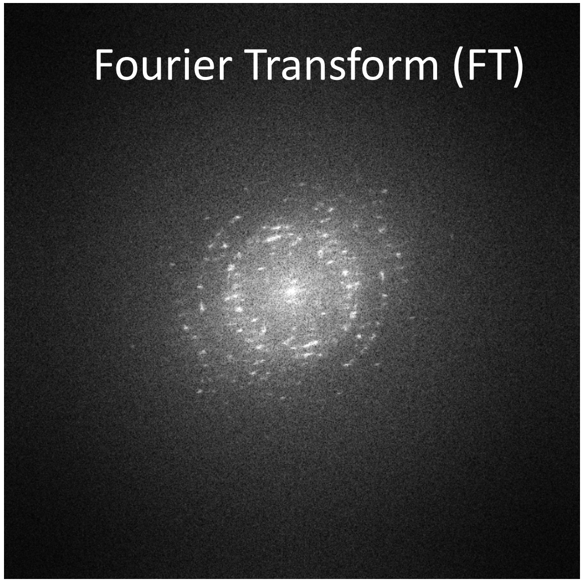


Semi-quantitative EDS line profile



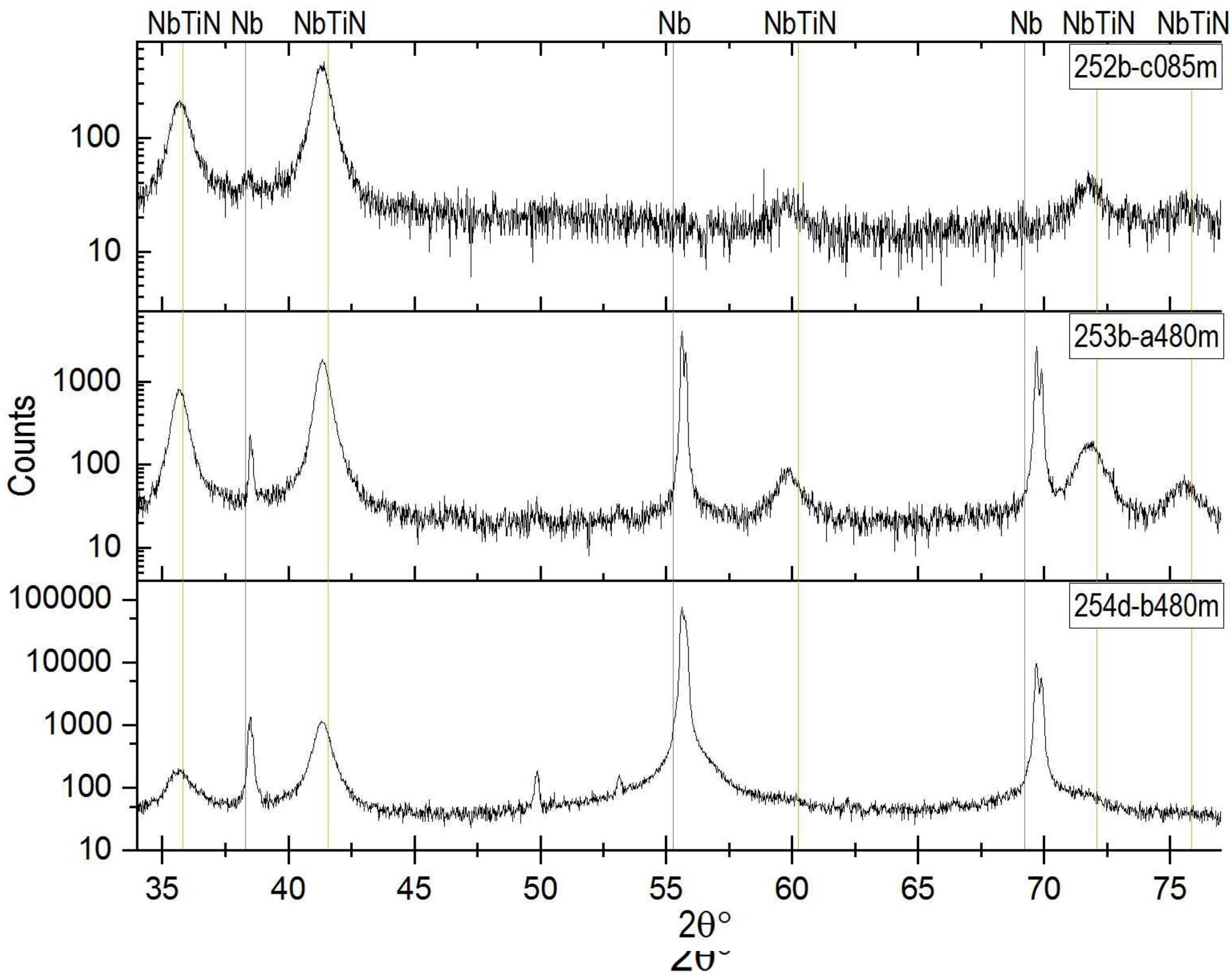
S-S' (75 nm NbTiN/Nb)



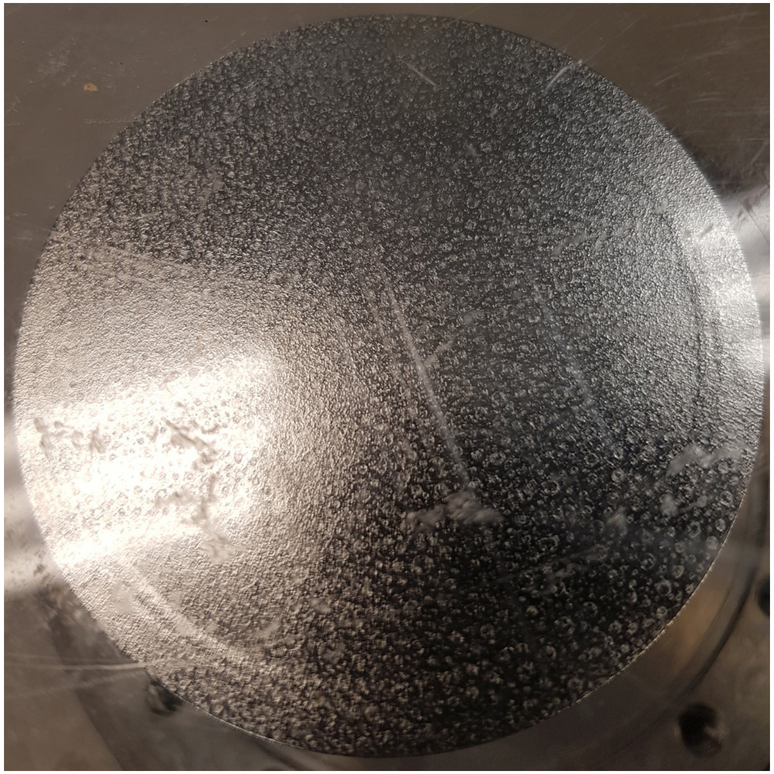


Layer is too thin for SAED. Fourier transform used to determine the crystallinity. This layer is nanocrystalline.

NbTiN based QPR samples structure



Known Issues



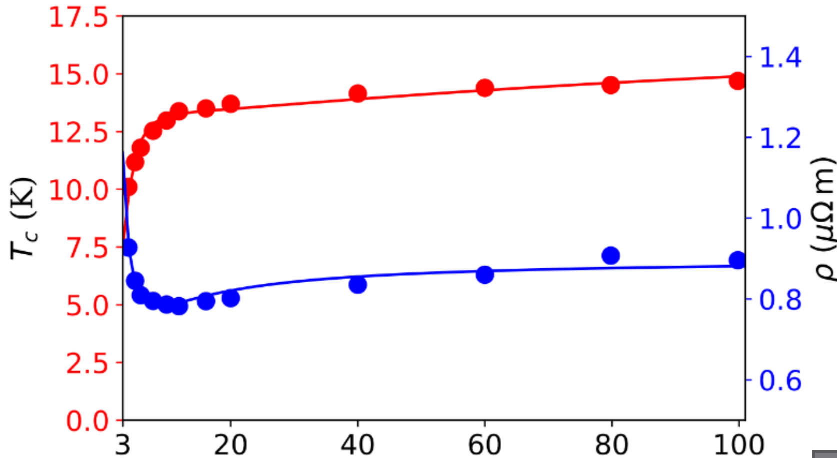
QPR sample after AlN removal and EP

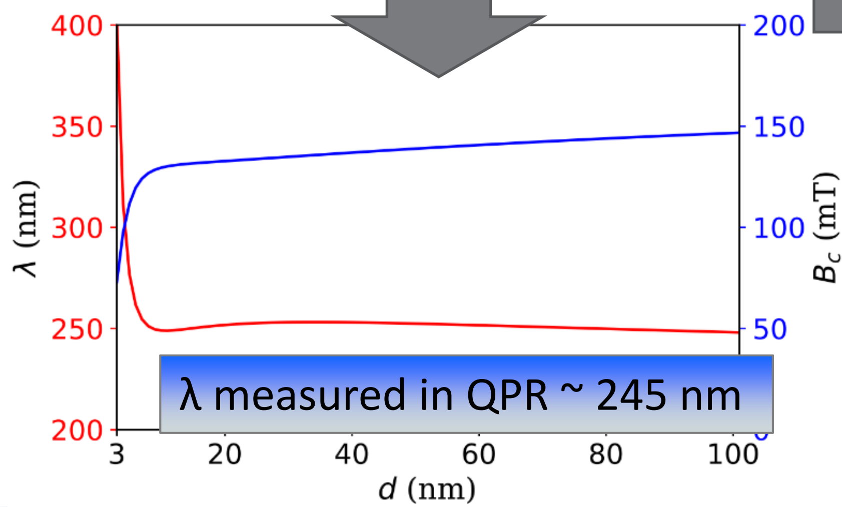
- ❑ 1^{st} coating cycle aborted due to short in NbTi Magnetron source
- ❑ AlN removal with KOH
  (Need to establish new chemistry for alternative materials)
  AlN residues still present?
- ❑ Features appeared on the Nb surface, only removed with extensive EP

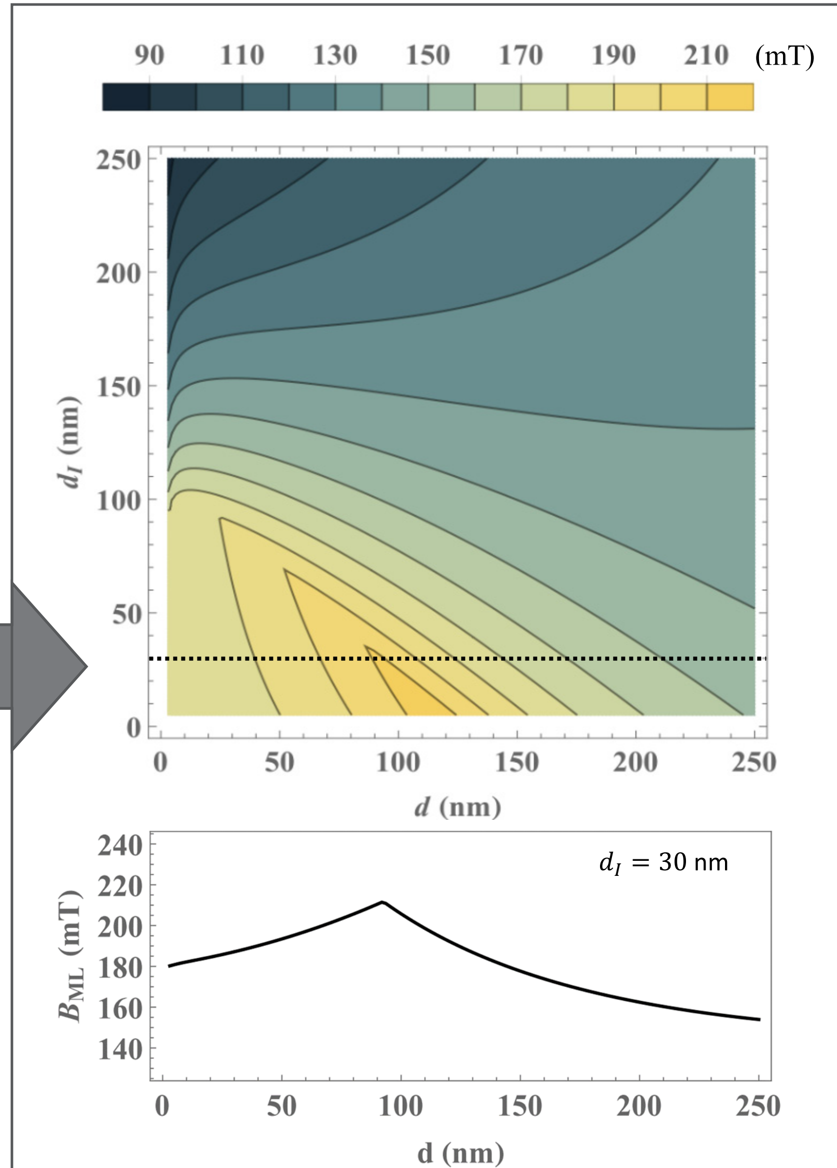
Potential H_{max} for NbTiN

Courtesy T. KUBO

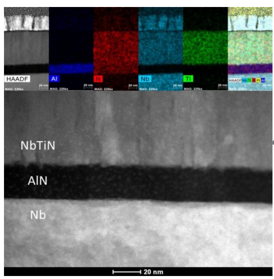
T_c and ρ from L. Zhang et al., Appl. Phys. Lett. 107, 122603 (2015)
$\Delta = 1.86\ k_B T_C$ from T. Hong et al., J. Appl. Phys. 114, 243905 (2013).
$N_0 = 1.17 \times 10^{47}\ J^{-1} m^{-3}$
from D. Hazra et al., Phys. Rev. B 97, 144518 (2018)



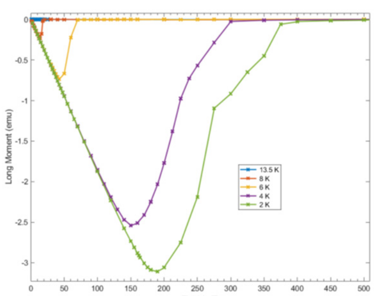


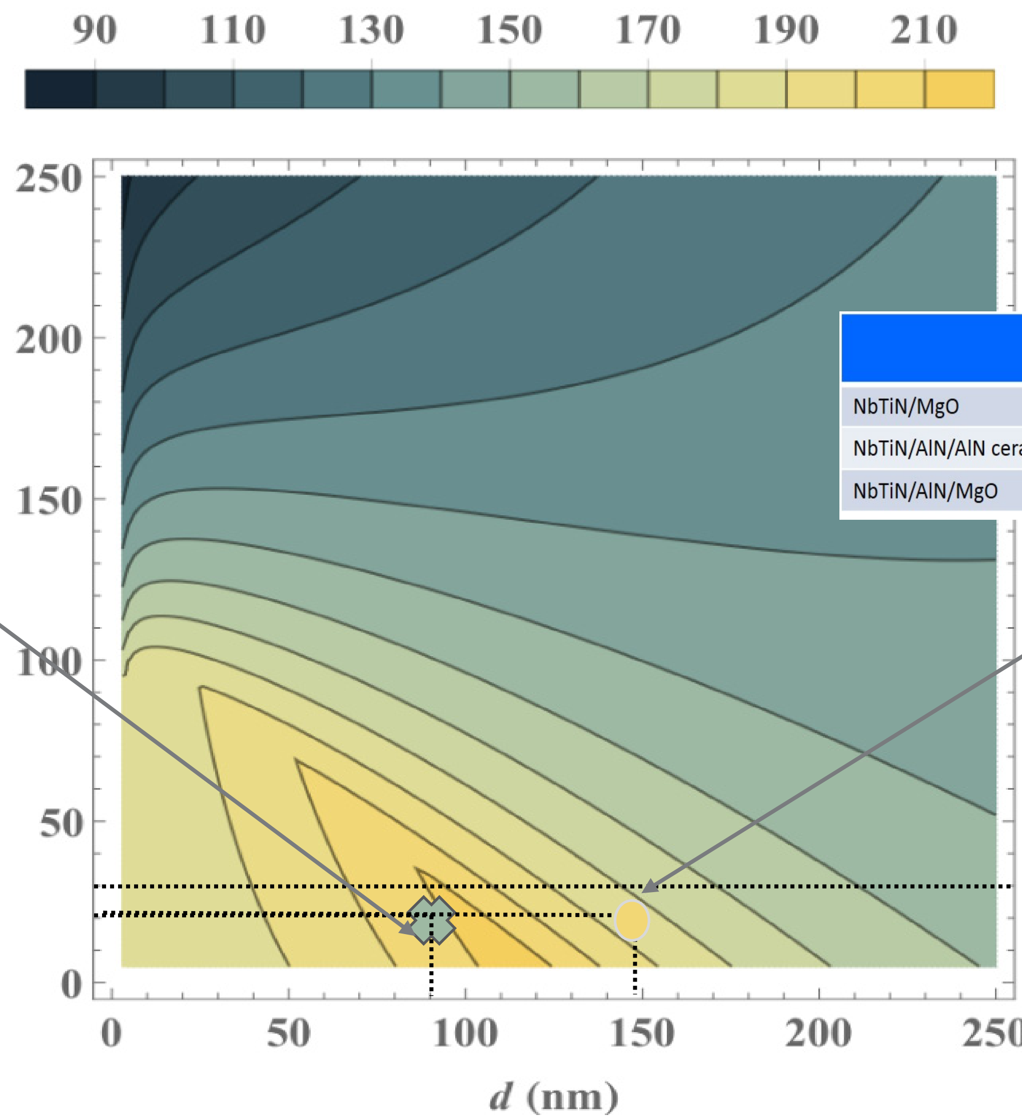


Potential H_{max} for NbTiN



T_c=14.2 K
H_{fp} ~155 mT





	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

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

CONCLUSION & FUTURE WORK

In depth analysis of RF behavior ongoing across frequencies, cooling and applied magnetic field condition

3rd harmonic measurements for first penetration field measurements ongoing (CEA Saclay, KEK)

- **Thickness and T_c on large sample are consistent with small sample studies**
- **Quench field are limited to lower values than predicted**
- **Films and structures follow substrate topology**

- ❑ Refine the contour plot for actual films coated
- ❑ Repeat the S-I-S' on QPR sample with no surface weld
- ❑ Continue exploring the NbTiN/AlN thickness with QPR and 3rd harmonic measurements
- ❑ Reactive HiPIMS to densify the films and get relaxed structure at earlier growth stage
- ❑ Explore other superconductors matched with adequate dielectric