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Analysis of Multilayer Devices for Superconducting Electronics by High Resolution Scanning Transmission Electron Microscopy and Energy Dispersive Spectroscopy

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Size and Scope of C3 Presents a Significant Challenge to State-of-the-Art SCE Yield

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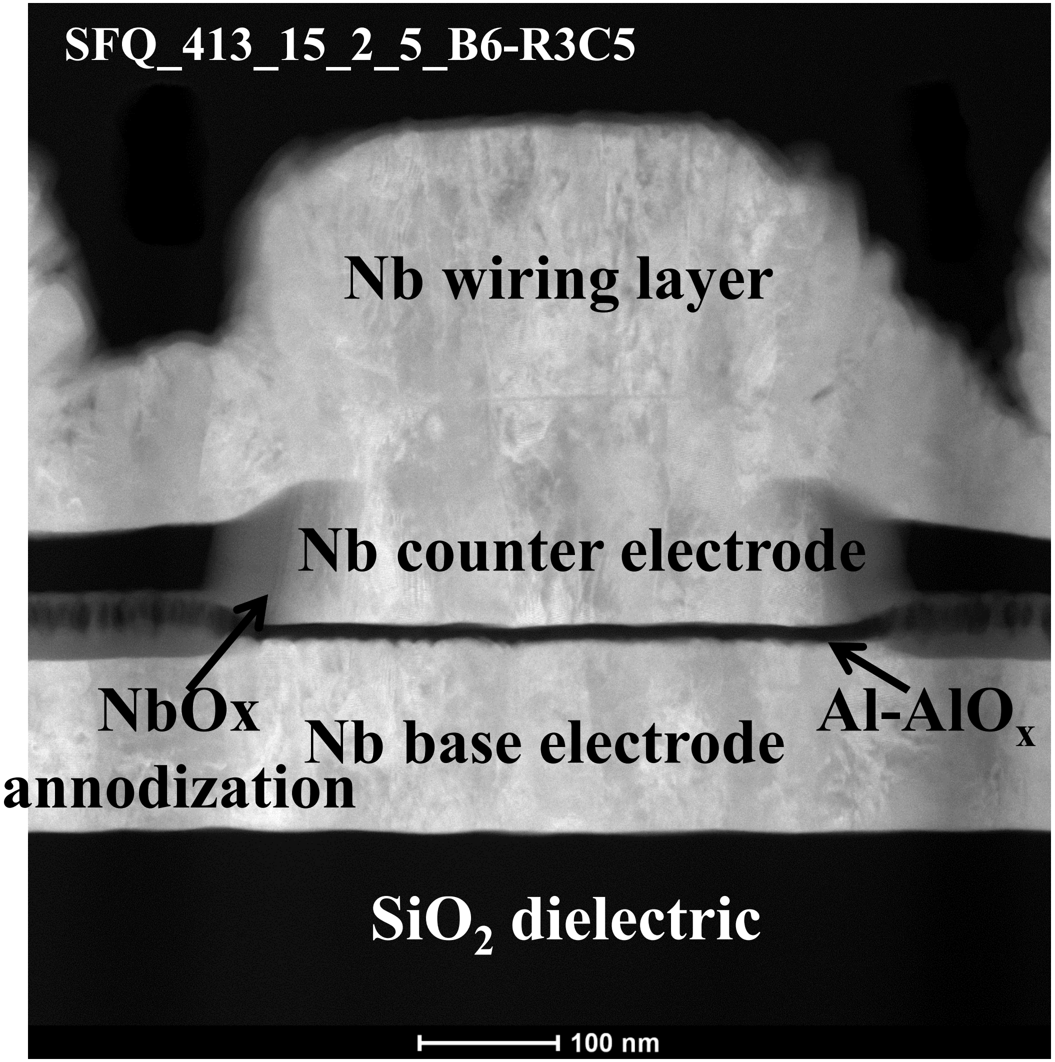
- Scaling of both logic and memory requires high yield fabrication and processing
- High yield requires uniform device characteristics
- Device characteristics depend upon properties of nanometer-scale thin films
- Microanalysis (structure, morphology, chemical composition) at these length scales can provide guidance to fabrication and processing
- Scanning transmission electron-beam microscopy **(STEM)** combined with energy dispersive x-ray spectroscopy **(EDS)** allows characterization of these parameters at the required length scales

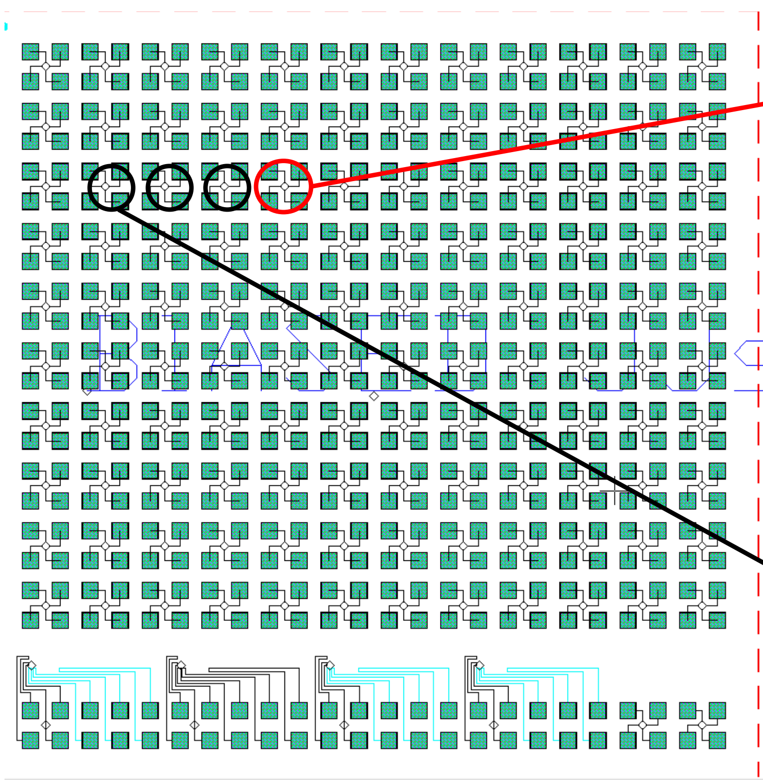
MIT-LL JJs: FIB/STEM/EDS – Differences between JJs with I_c, R_n within design range vs outliers *on same chip*

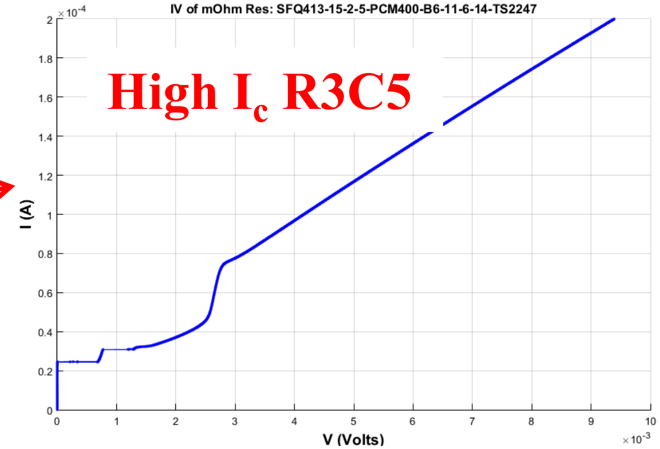


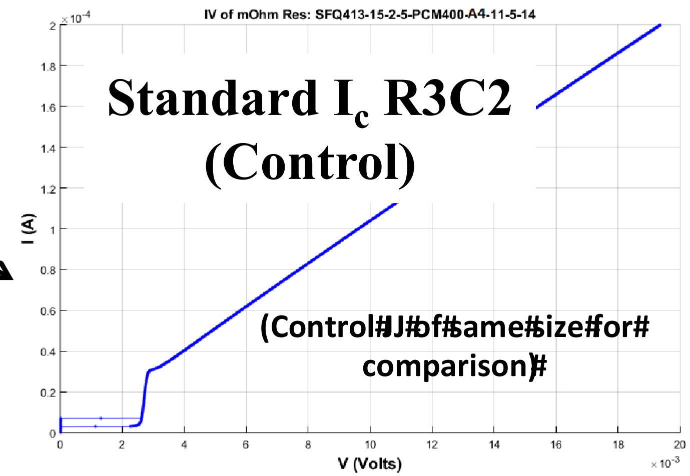
- HAADF STEM imaging – sensitive to Z-contrast: Nb is bright, Al and SiO_2 are darker (less scattering)
- Need thin cross-sections in order to resolve Al-Ox layer
- High resolution imaging – structure/morphology
- Roughness is typical for columnar growth of Nb at ambient temperatures by sputtering
- Anodization on sidewalls defines junction area
- Aluminum incorporated into anodization layer outside junction area shouldn’t affect electrical properties of junction

Example of JJs chosen for comparison on same chip, to date 3 chips, 7 JJs (one control JJ from each chip)

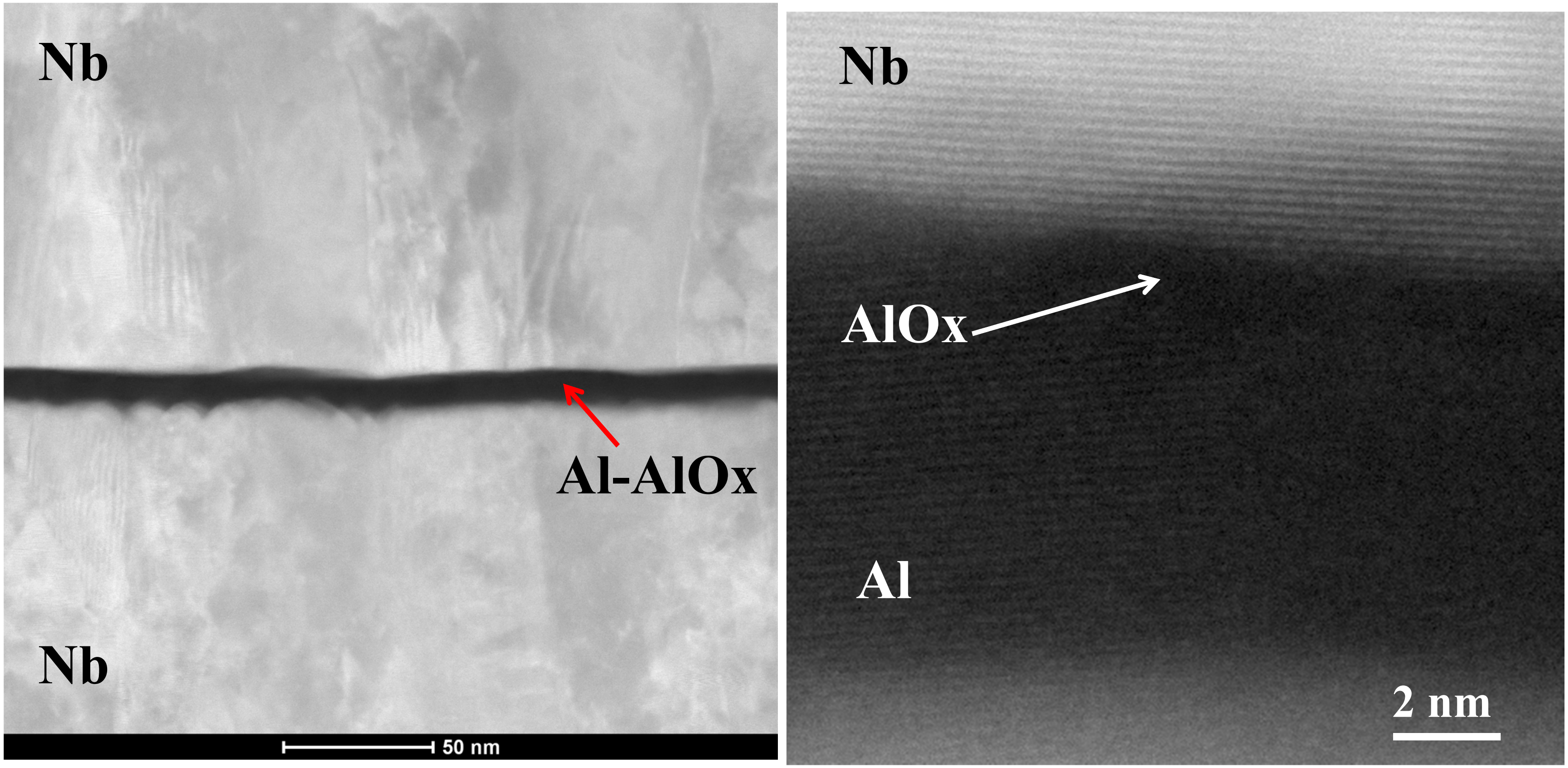
PCM
SFQ_413_15_2_5_B6 – 485 nm JJ





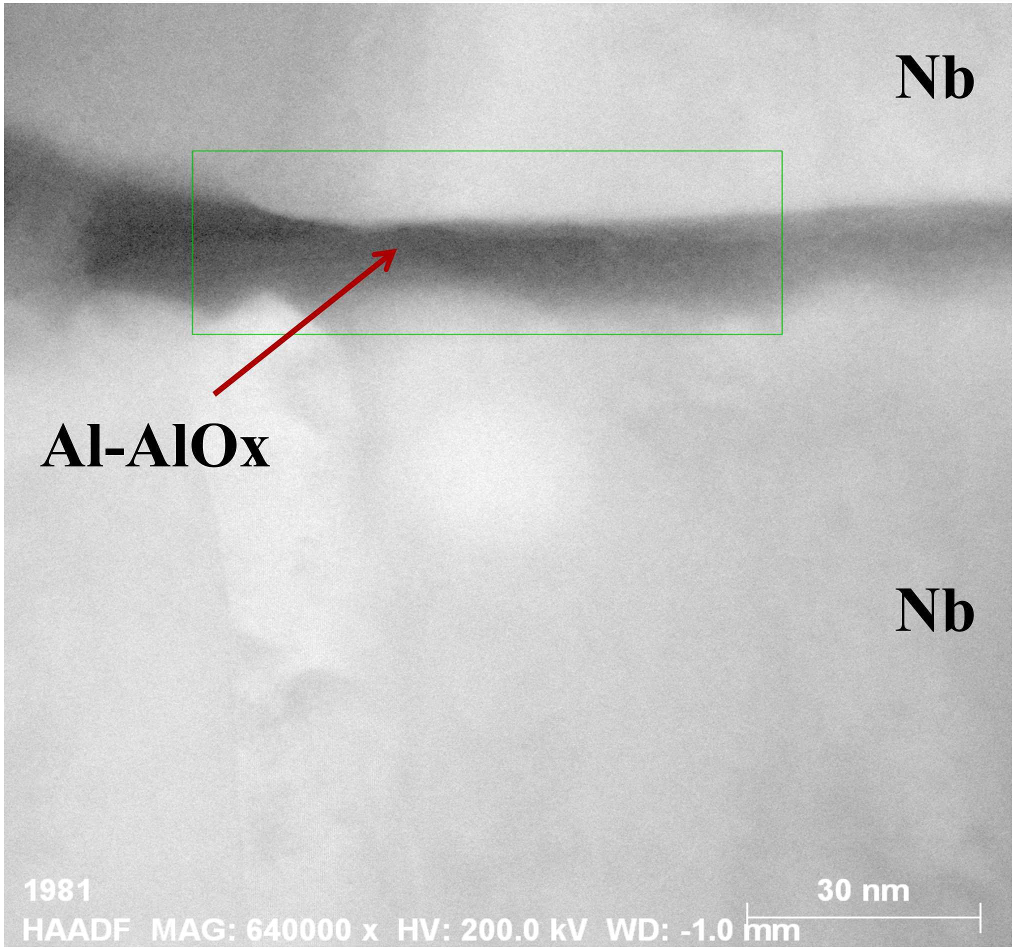


Higher magnification STEM imaging across JJ shows Nb lattice fringes and Al lattice fringes



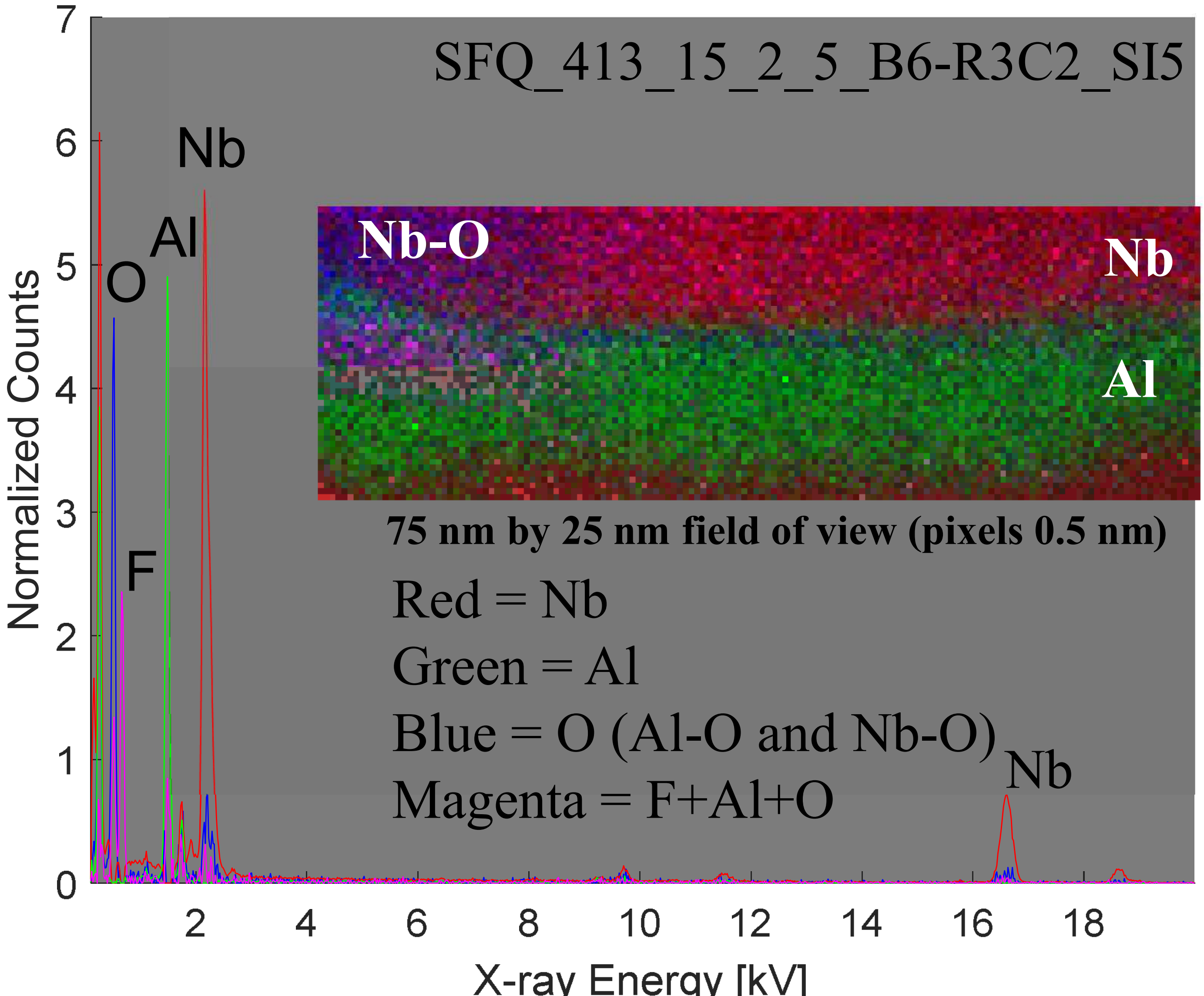
- Lattice fringes observed only for favorably oriented grains
- In this sample, a couple of Al grains were favorably oriented
- ~1.5 nm oxide is amorphous region between them
- No consistent differences between control and outlier JJs

EDS spectra collected at each pixel within green rectangle allows phase mapping: left edge of control junction



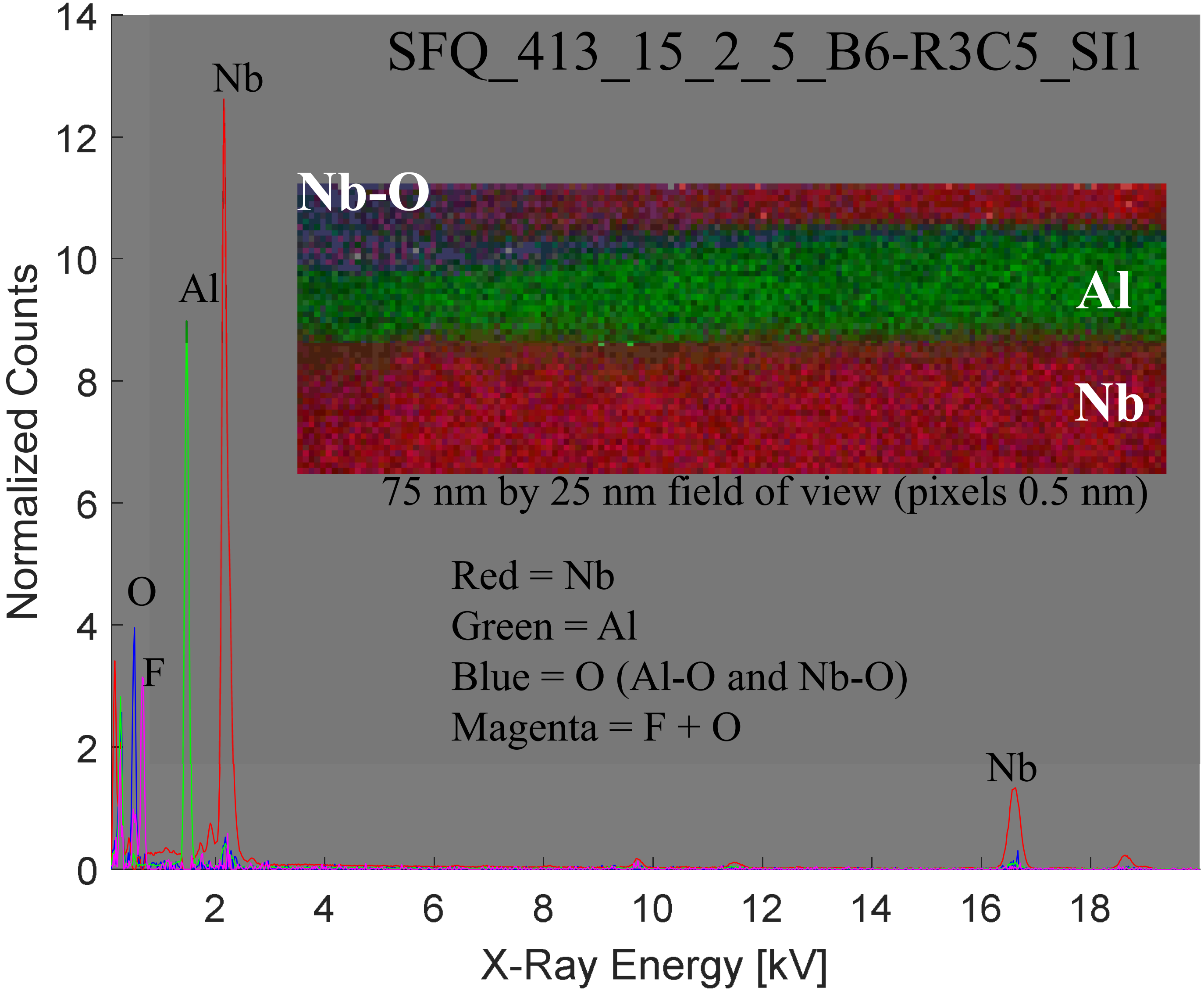
- STEM excites x-ray spectrum at each 0.5 nm pixel
- Multivariate statistical analysis of all spectra identifies pixels with same spectra – color codes them
- Create a phase map (multiple elements) with different colors at 0.5 nm/pixel

STEM/EDS phase image of control JJ – left side



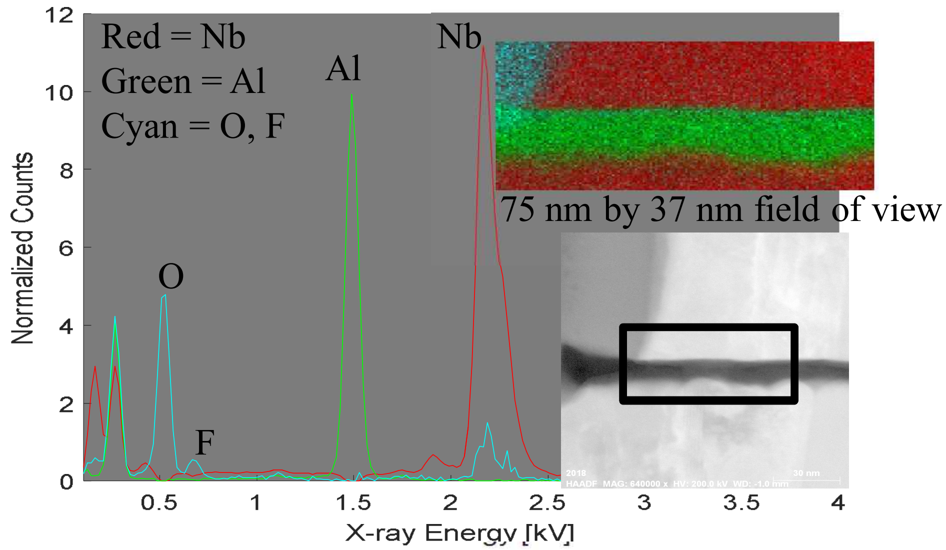
- AlOx layer is observed: 1-1.5 nm
- Al-F observed at edge of junction – appears to coincide with anodization layer

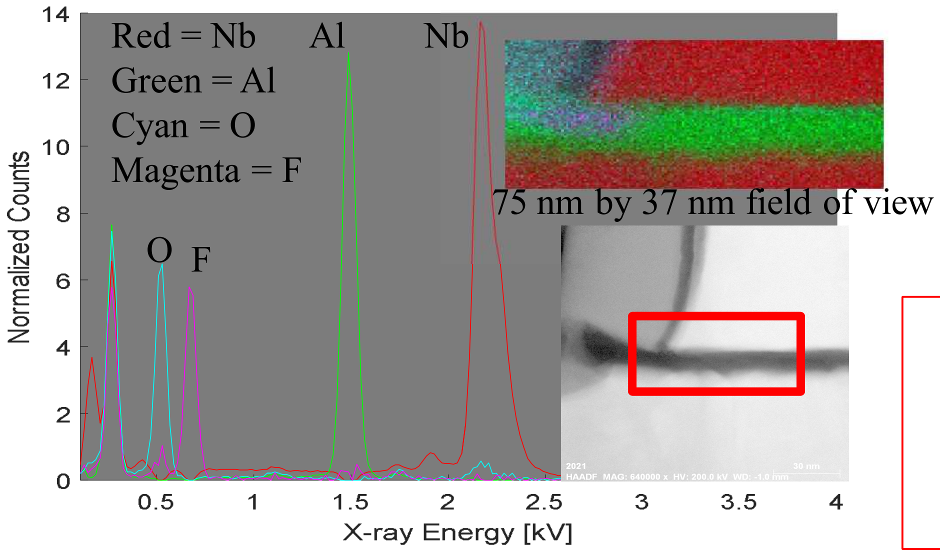
STEM/EDS phase image of high I_c JJ – left side



- AlOx layer is observed: 1-1.5 nm
- F observed at edge of junction – appears to penetrate JJ area beyond anodization area

EDS mapping again shows strong F peak in active area of high I_c junction R2C11





Standard I_c R1C11: left side

- Small F shoulder is detected in same areas as oxygen-anodization layer
- Absence of strong F peak in active junction area

High I_c R2C11: left side

- Strong F spectrum is detected in anodization layer and penetrating ~ 10 nm into active junction area
- Again, suggests I_c may be affected by presence of F in barrier layer
- Also see "gap" between anodization layer and Nb counter

Three sets of control vs high I_c or low R_N JJs and three additional low R_n JJs show F penetrating active JJ area – may explain variation in electrical properties

Nb base electrode roughness propagates up through magnetic multilayer stack, influencing magnetic coupling :NYU-COST F4

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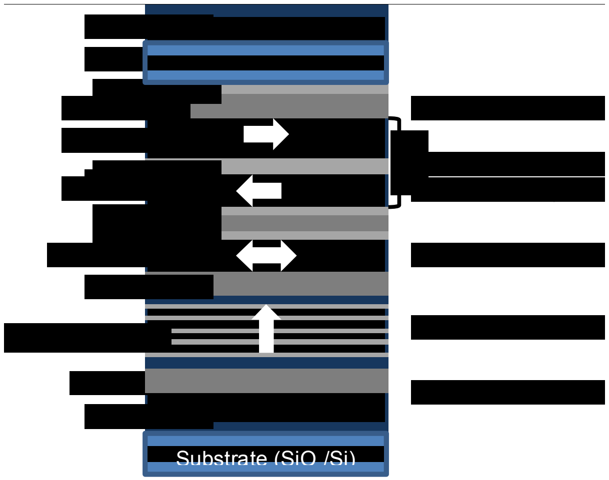
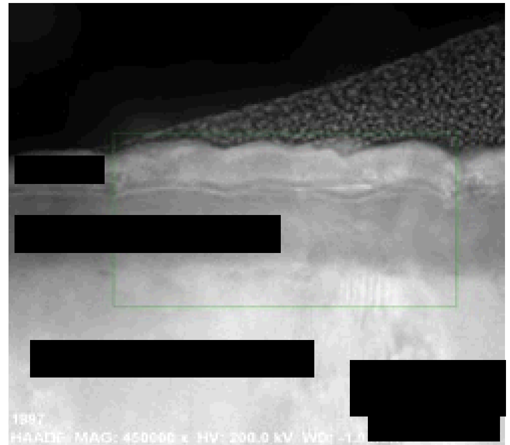
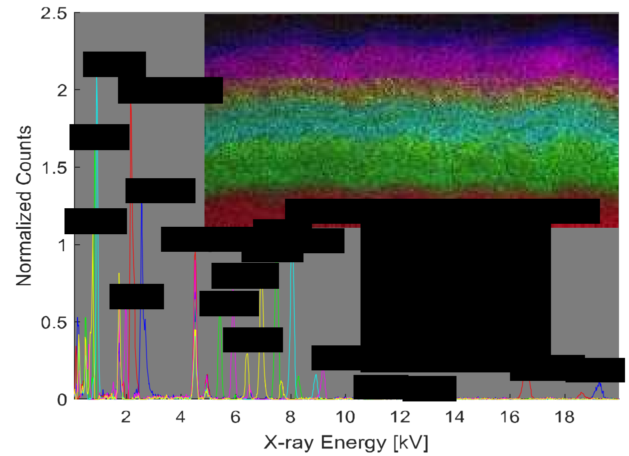


Schematic of magnetic multilayer

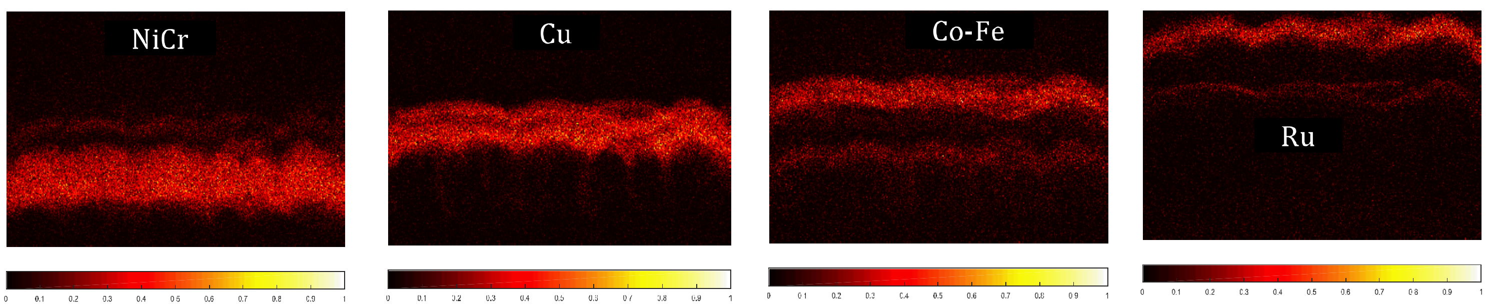


STEM image showing layer roughness



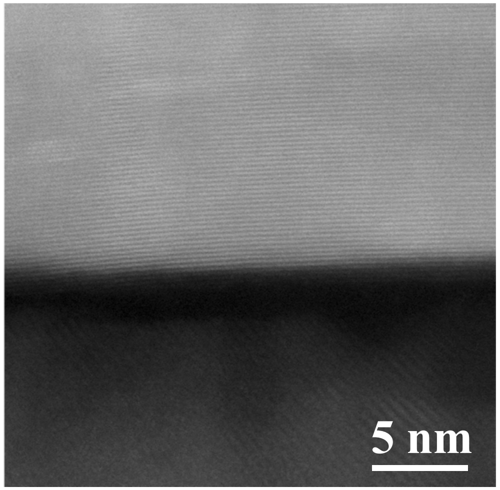
EDS phase map of same area

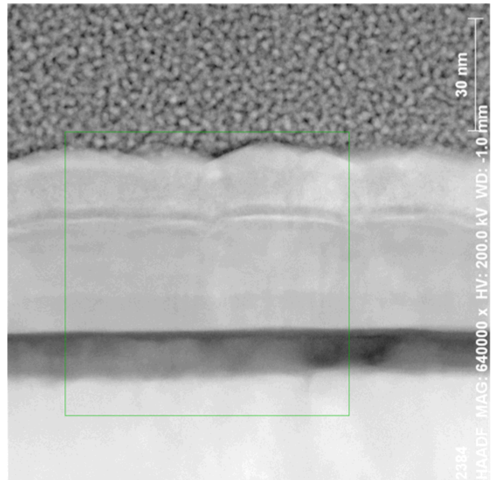
Individual component intensities

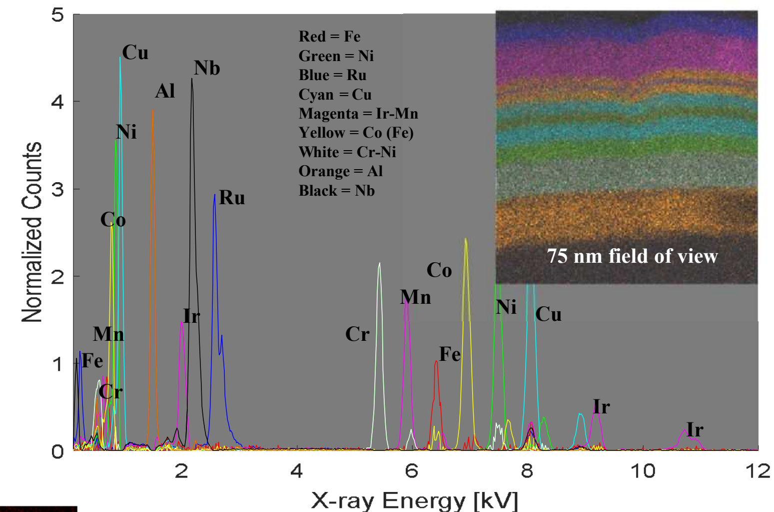


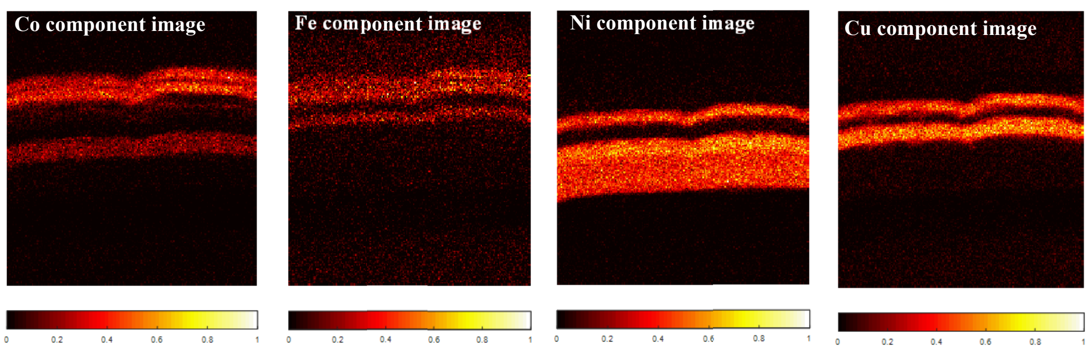
- Roughness of the underlying Nb base electrode (1-3.5nm) propagates up through the stack
- Co/Ni polarizer and NiFeCu free layer are not clearly resolved likely due to roughness
- Cu diffusion along underlying grain boundaries is observed

Residual Al-AlOx on Nb base electrode provides a smooth template for magnetic multilayer growth: NYU-COST_H8



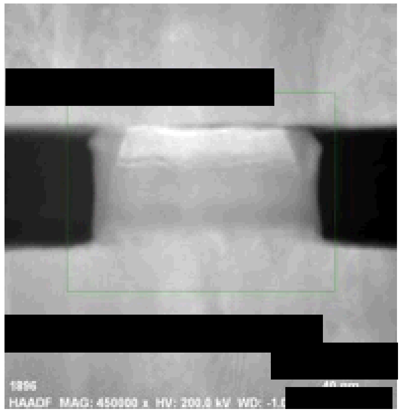




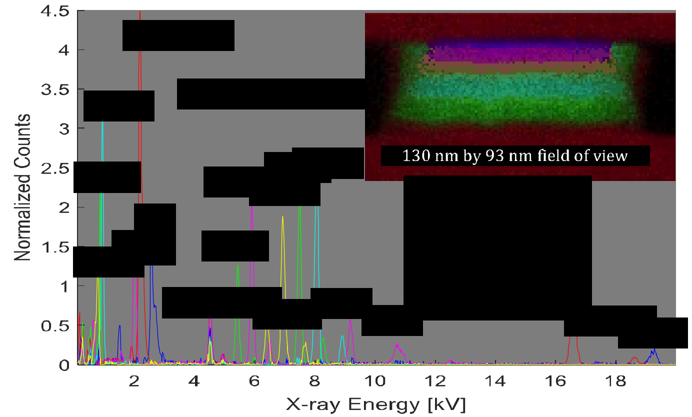


- Grains with epitaxial growth of individual layers observed on Al-AlOx template
- Sub-nm thick individual layers in Co/Ni polarizer are resolved
- NiFeCu free layer is smooth and continuous
- Strain imposed by crystalline Nb template may influence subsequent layer growth

First COST nanopillars on Nb base electrode show desired geometry but also etch residue

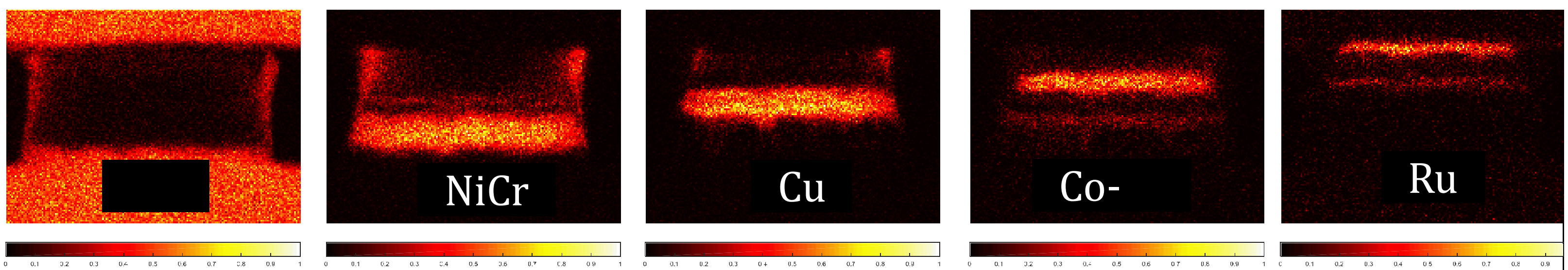


High magnification STEM image of nanopillar



EDS phase map of nanopillar showing sidewalls are not cleanly etched

Individual component intensities



- Nanopillar has vertical sidewalls, 103 nm in diameter and 50 nm high
- Nanopillar etch extends a few nm into the Nb bottom electrode without trenching
- Lower roughness than full stack, but significant Nb, NiCr and Cu along sidewalls-etch residue

Summary

- FIB/STEM/EDS analysis of morphology, structure, chemical constituents can provide insight into variation in properties among specific devices and guide changes in fabrication and processing
- No significant difference in Nb base electrode morphology observed between JJs with target I_c/R_n relative to outlier JJs
- Observed F in active area of 7 JJs with low R_n and/or high I_c, while control JJs have F confined to anodized JJ sidewalls
- Magnetic multilayers for cryogenic memory grown directly on Nb base electrode have roughness that degrades magnetic properties – Al-AlOx layer at surface of base electrode results in smooth and continuous individual layers
- Feedback from these studies led to further optimization of the Ar ion beam etch, eliminating re-deposition on COST nanopillar sidewalls