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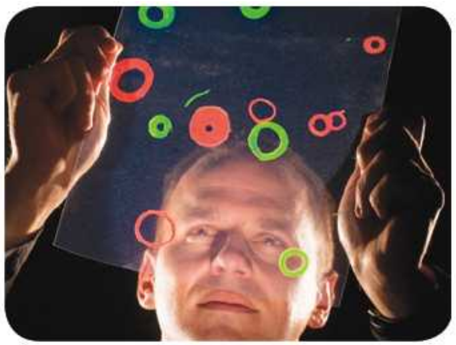

Failure Analysis and Process Improvement for Superconducting Electronics

N. Missert, M. Jenkins, P. Tangyunyong, P. Kotula, J. Michael

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Sandia's strengths in semiconductor microelectronics can be applied to yield management of superconducting electronics

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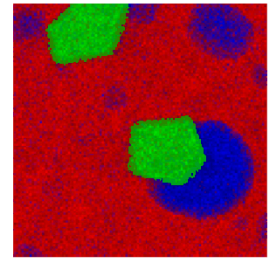
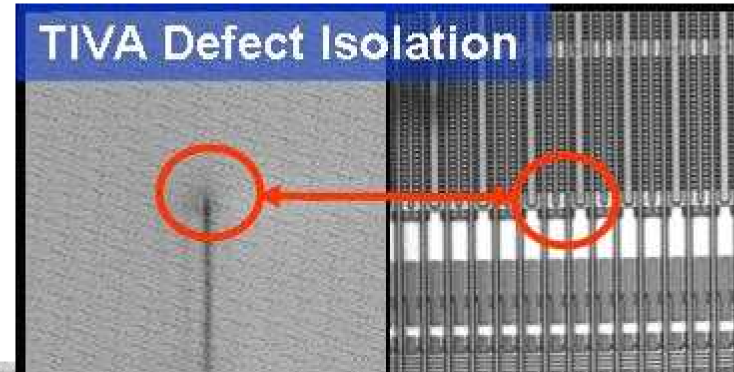
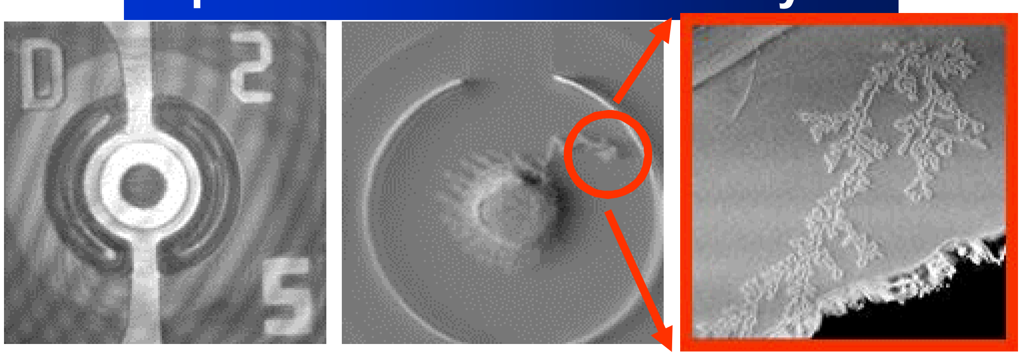
- Expertise in Si CMOS, III-V, MEMS, and Optoelectronics
- Support throughout the product life cycle
- Extensive reliability & FA capabilities, equipment, tools & techniques
- Sandia developed techniques now industry standards
  (LIVA, TIVA, SDL, etc.)
- Staff recognized world experts

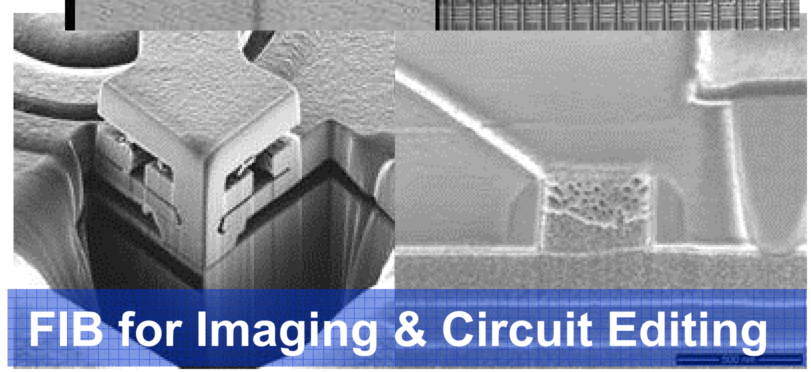


STEM/EDS/AXSIA for analyzing defects



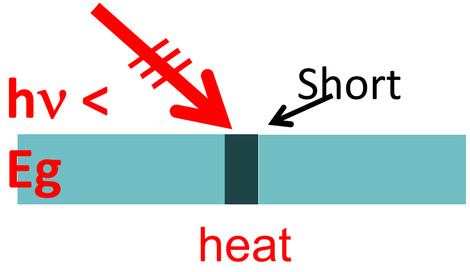
TIVA and STEM for Optoelectronic Failure Analysis

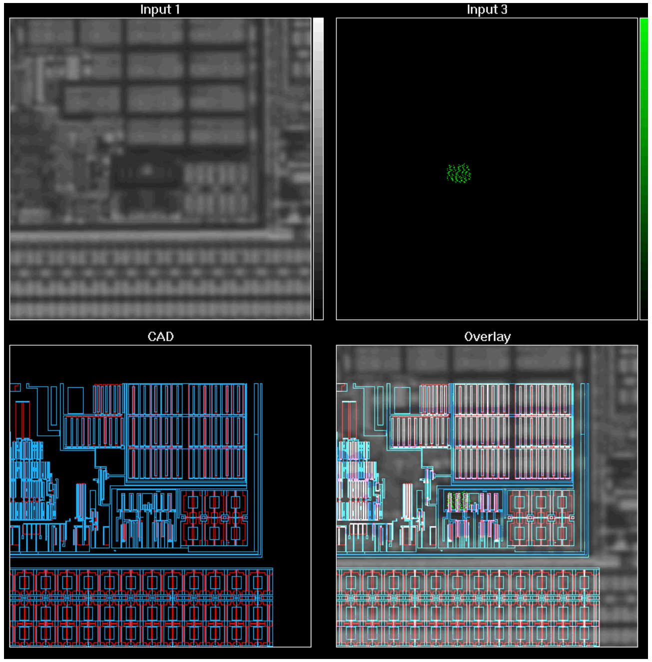




Thermally induced voltage alteration (TIVA) localizes shorts between layers on CMOS wafers

Checkpoint InfraScan 300TDE





Overlay of reflected, TIVA and CAD images

Scan laser to induce heat, activate defect, generates EMF
Pulsed stimulus, lock-in detection eliminates spreading, 0.5 µm resolution

TIVA allows defects that can't be seen by optical microscopy to be localized in multilayer IC devices

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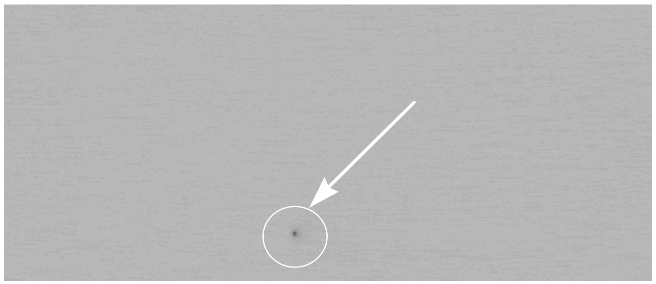
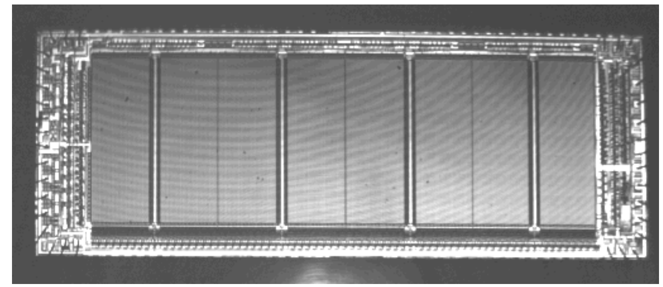
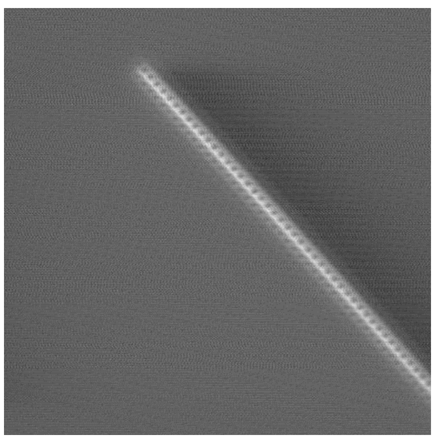


TIVA image of short in 1MB SRAM

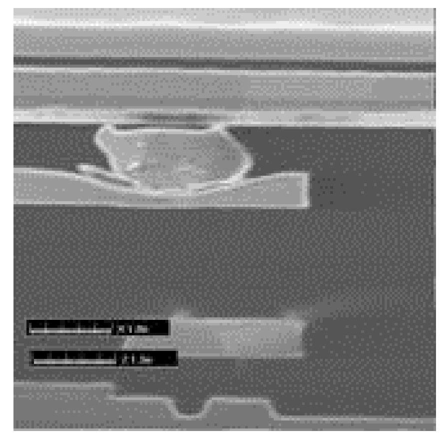


Reflected light image for registration



TIVA image of short in ROIC

Once short is localized, FIB/SEM identifies defect



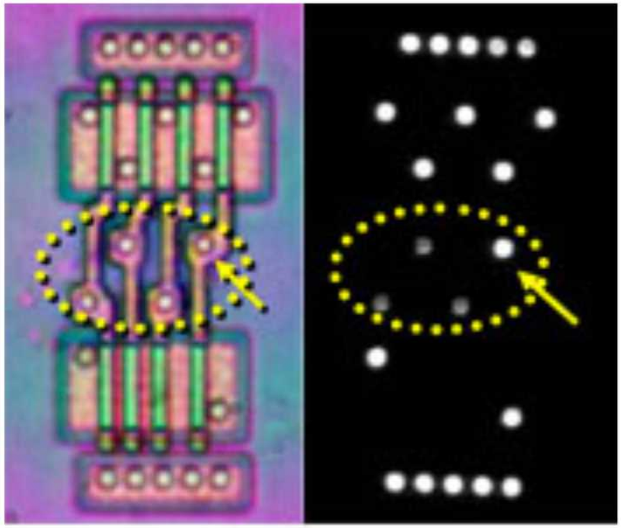
1 micron particle shorting 2 metal layers

TIVA has been used to find shorts due to particles, design flaws, and resistive connections

Floating substrate passive voltage contrast (FS:PVC) shows clear contrast between shorts and floating conductors

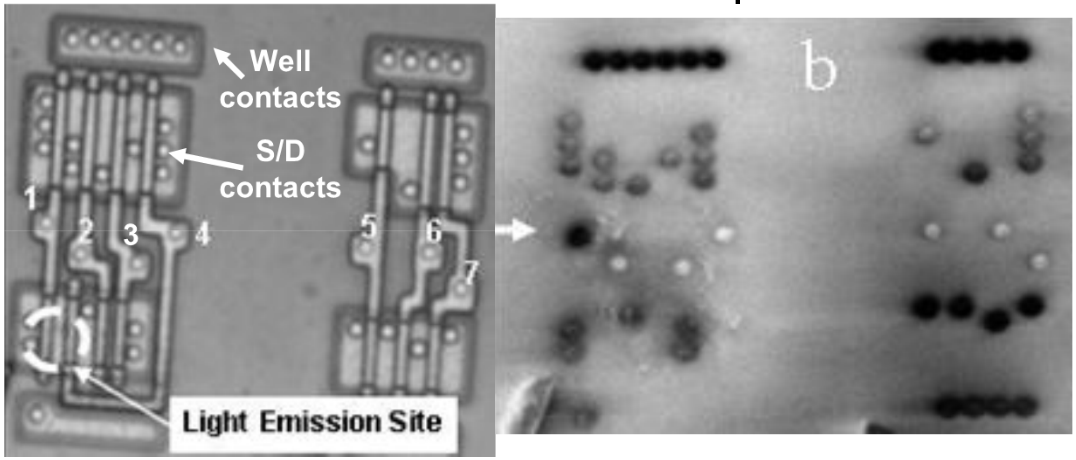
- E-beam (SEM) based technique
- Scanning electron beam charges metal and surrounding insulator by emission of secondary electrons from the surface
- Floating conductors have relatively higher positive charge than grounded or shorted conductors
- Locates shorted gates in integrated circuits

Fast acquisition rate



Optical image PVC image

Slow acquisition rate



Contrast of shorted gates relative to floating gates depends on e-beam voltage, current, and scan rate

Variety of Scanning and Localized Probes for Electronic Measurements

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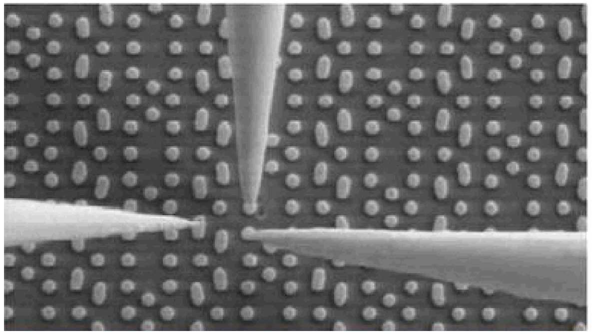
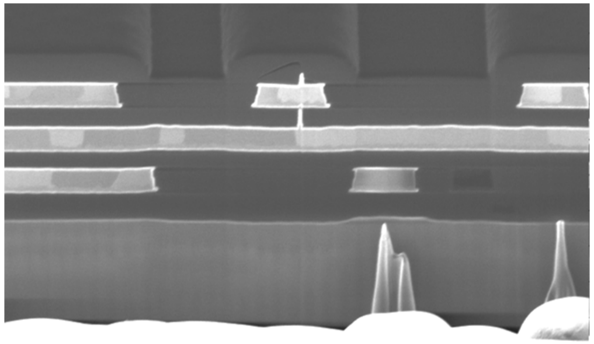
- SEM with nano-probe
- Conducting Atomic Force Microscopy
- Scanning Capacitance Microscopy
- Scanning Kelvin Probe
- Auto-probe I-V measurements on custom diagnostic chips to discover defect “signatures”



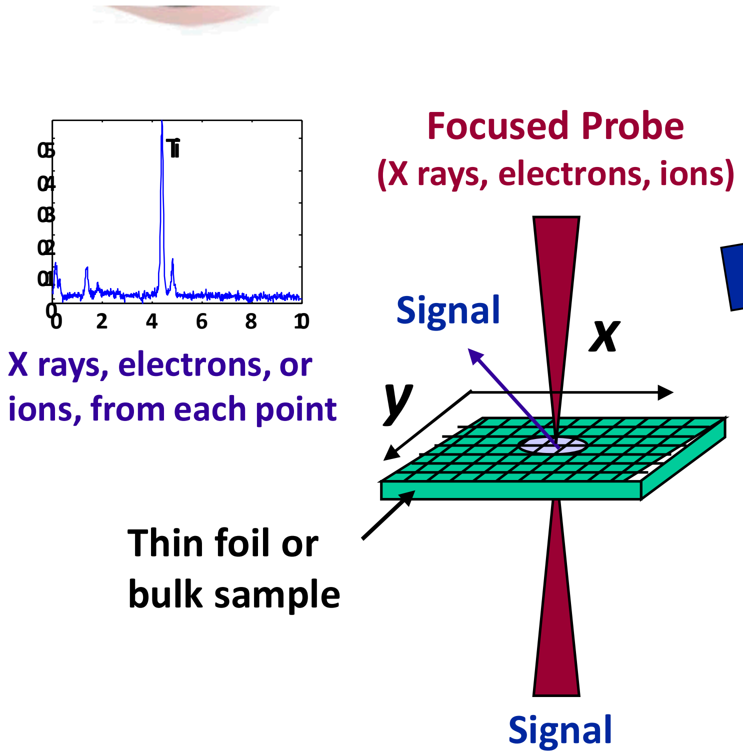
Nano-probe/SEM

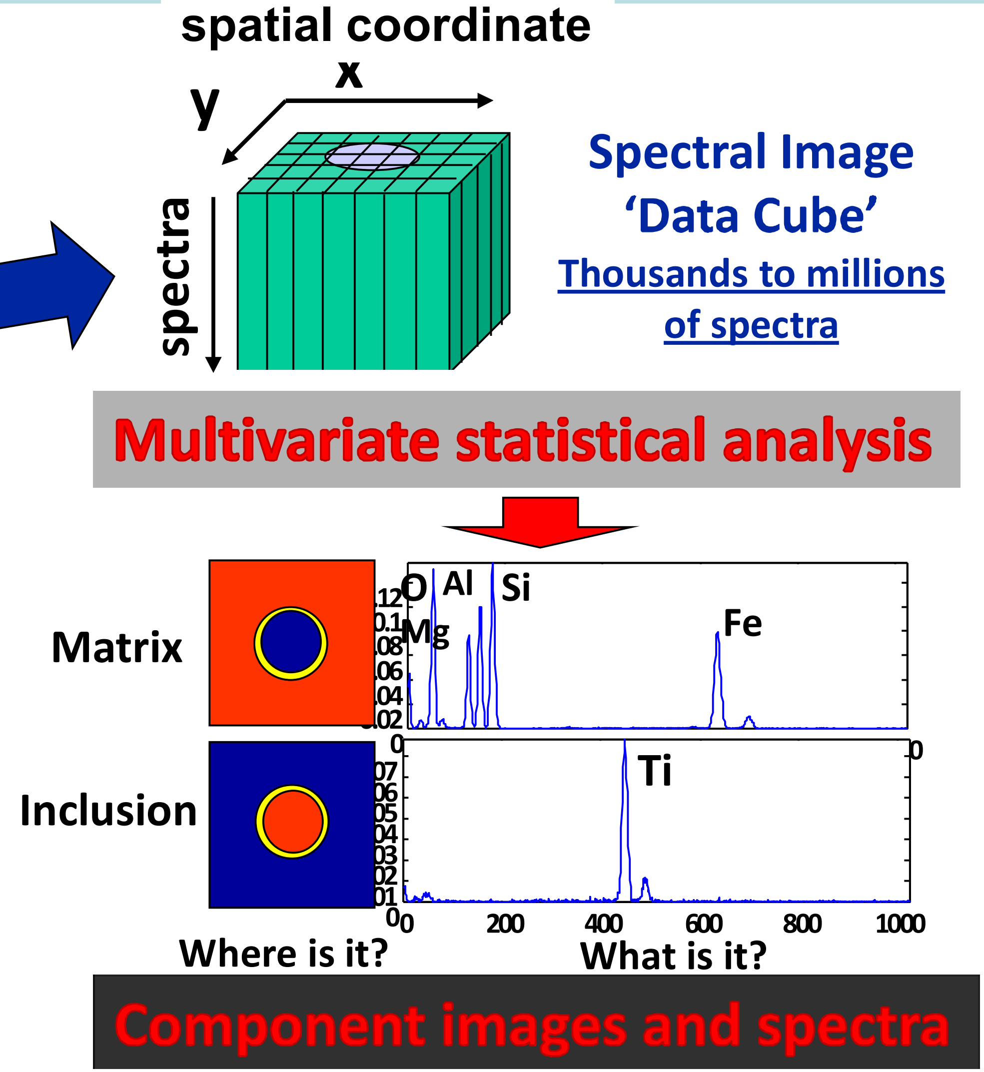
Once defects are localized, advanced characterization can guide changes in processing needed to mitigate



FIB/SEM

Multivariate statistical analysis of spectra allows sensitive mapping of material components





Correlate ***spectra*** from each pixel to obtain ultra-high sensitivity to materials components

Advanced Materials Characterization: high-resolution probes and spectral analysis

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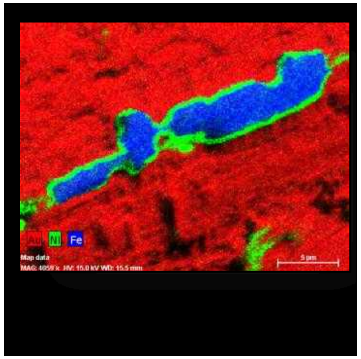
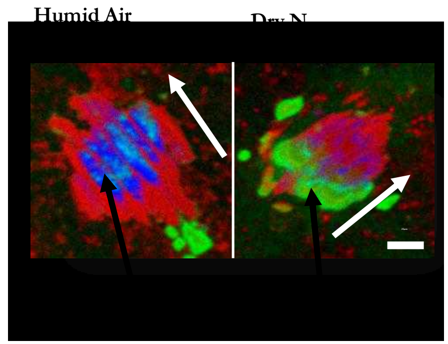
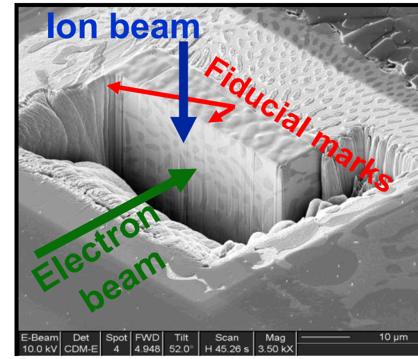
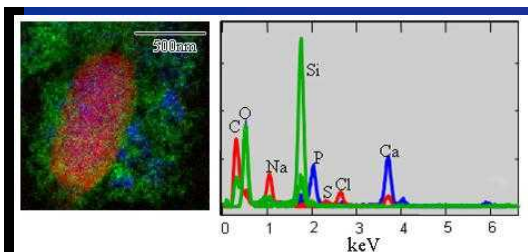


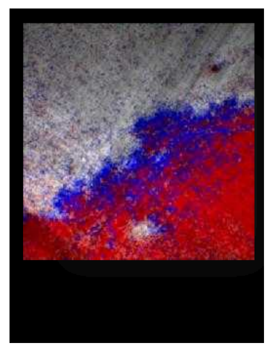


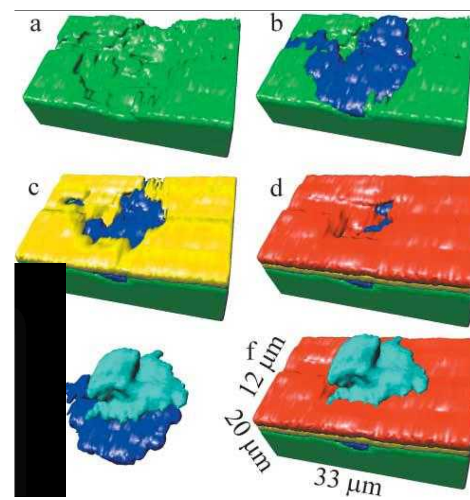
ToF-SIMS





TEM

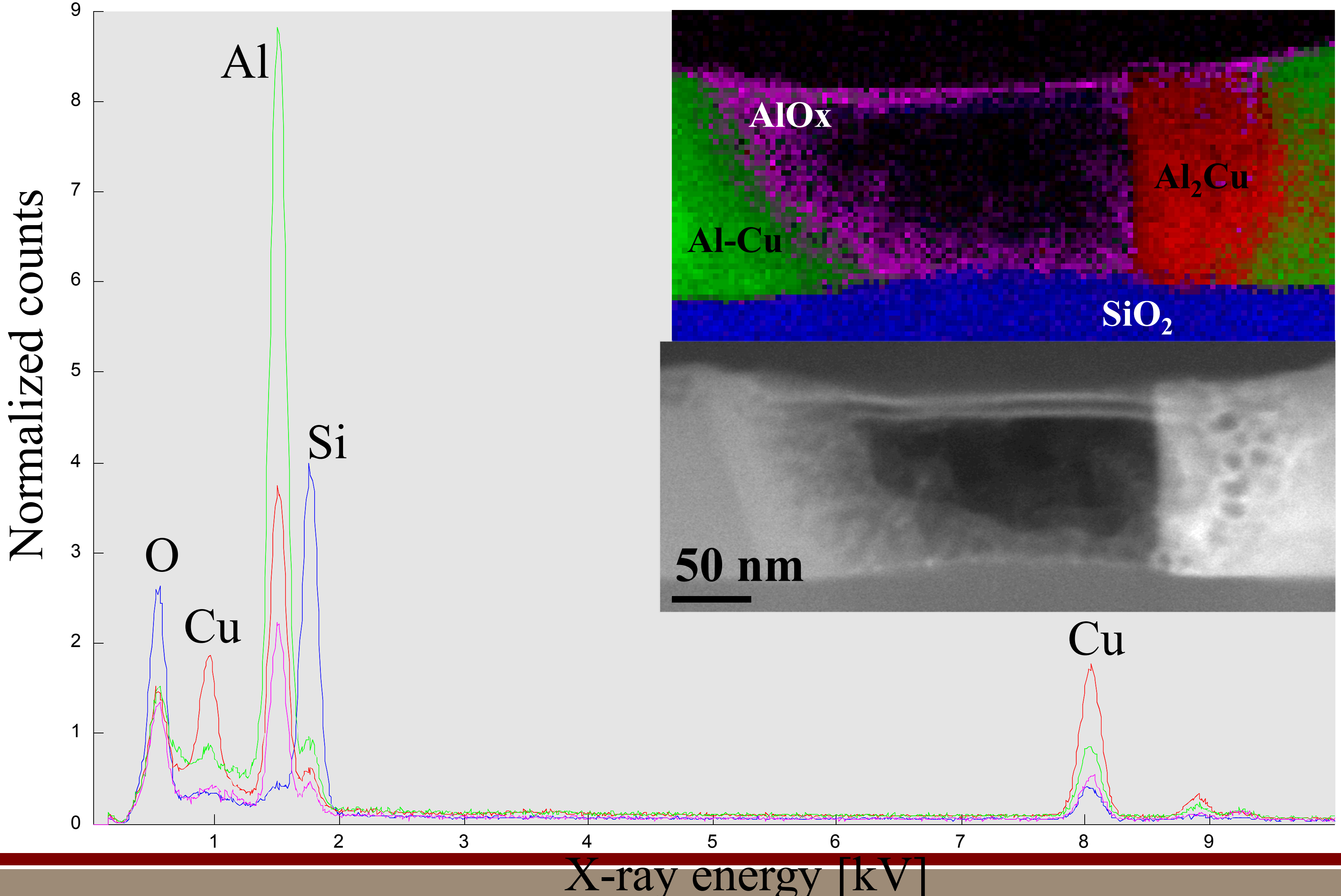




Serial FIB sectioning
EDS mapping-tomographic
spectral imaging

Multivariate spectral analysis can be combined with a suite of characterization techniques to identify materials components at interfaces: surface contamination, barrier non-uniformity, anodization irregularities, etc.

Nanometer scale corrosion of Al beneath oxide is clearly seen using TEM/EDS with multivariate spectral analysis



Fabrication issues in MIT-LL Nb/Al, AlOx/Nb process can impact yield

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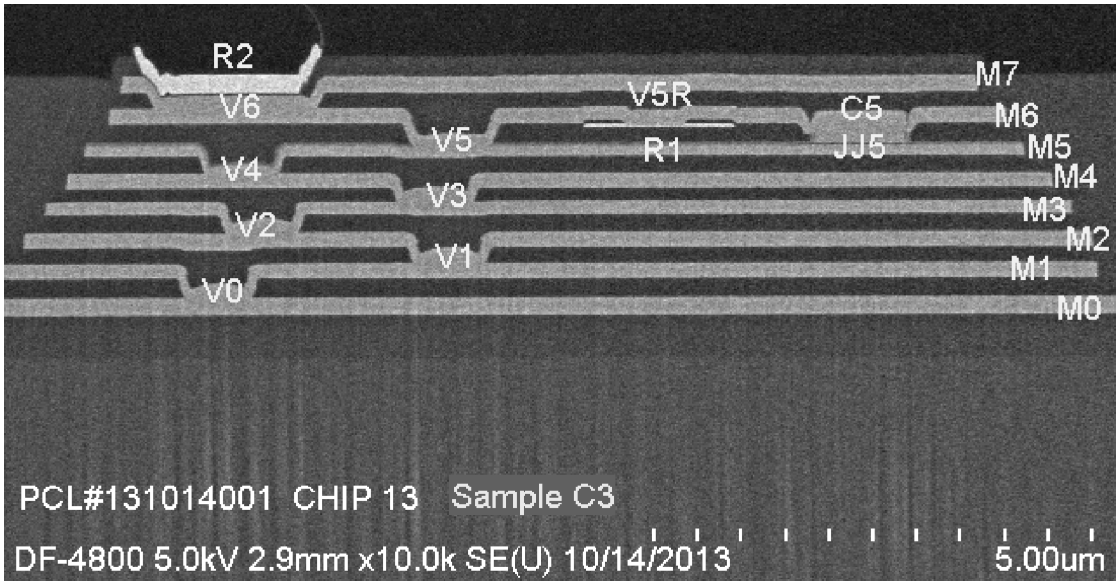
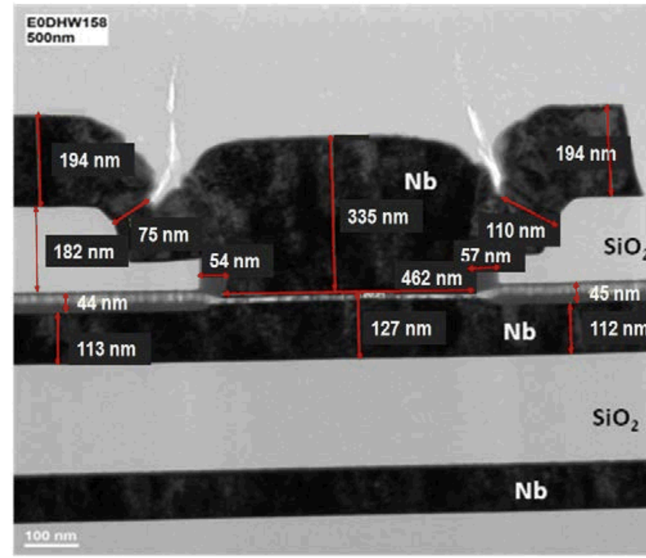
MIT-LL 8 metal layer Nb process: Nb metal, resistor, Al/AlOx junction, SiO_2





Current fabrication issues

- Nb etch (SF_6, Cl) - inactive layer at edges
- Hydrocarbon contamination
- Nb anodization uniformity
- Nb/SiO_2 interface interdiffusion

Future fabrication issues (Additions)

- New mΩ resistor layer
- High inductance NbN layer
- Stacked JJs for inductors
- High R_{sq} shunt resistor
- Scaling magnetic memory

"Intrinsic" defects in AlOx – Hydrogen plays a significant role in critical junction parameters

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Amparo, Tolpygo, IEEE Trans. App. Supercond. 2011 – H increases the work function of Nb, decreases junction I_c, G_N, mobile H changes these parameters with time

S. K. Tolpygo, D. J. C. Amparo, R. T. Hunt, J. A. Vivalda, and D. T. Yohannes, IEEE Trans. App. Supercond. 2013, Eliminate H from vacuum system during oxidation increases I_cR_{sg} and reduces variation

Tolpygo, Amparo, Hunt, Vivalda, Yohannes, IEEE Trans. App. Supercond. 2011 – Al diffusion stop layers are effective in protecting junction from further interlayer H diffusion during processing, dramatically reducing the spread in J_c

Fundamental electronic properties of AlOx that determine I_c variation may pose the most challenging issue for yield

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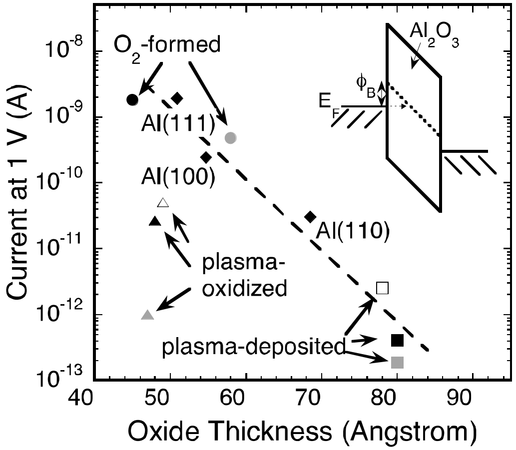
Effect of hydrogen on electronic properties of AlO_x depends on bonding site

MIM structures



Ambient T transport measurements and DFT on oxides on Al (111) show interstitial H as dominant electronic defect

ERD measures H-content

High H – high conductivity – field assisted tunneling

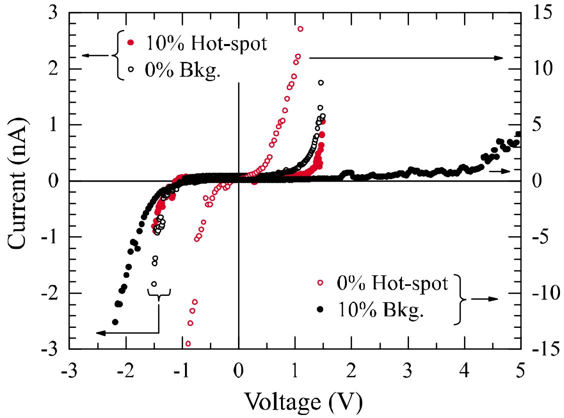
DFT: mid-gap trap for interstitial H

Jennison, Schultz, Sullivan, Phys. Rev. B **69**, 041405(R), 2004

MgO electronic defect appears to be related to oxygen content

- C-AFM measures local current hotspots
- Increased O_2 during deposition reduces density and magnitude of current hotspots
- Hypothesize O_2 vacancy defect

Kim et. al., Appl. Phys. Lett., 97, 263502, (2010).



Electronic defects in AlO_x and at interfaces can be manipulated

Mather, Perrella, Tan, Read, Buhrman, APL, **86**, 242504, 2005 – Thermal annealing, electron bombardment can fill oxygen vacancy sites and increase band gap

Holder, Osborn, Lobb, Musgrave, PRL, 111, 065901 2013 – DFT shows bulk hydrogenated Al vacancies have favorable formation energies under O_2-rich conditions

El-Batanouny, Strongin, Williams, PRL 46, 269, 1981 – Hydrogen uptake kinetics depends on interfacial electronic structure – Pd (110) on Nb (110) – no dissociation and chemisorption of H

Can the bonding sites for H in the oxide be eliminated or controlled??

Sandia's capabilities/expertise in failure analysis, characterization, and materials science will provide feedback to guide yield management

Improved fabrication yield:

- Reduced process variation
- Reduced photolithography errors
- Improved anodization uniformity
- Improved design margin

Improve barrier non-uniformity:

- Understand defects controlling oxide electronic properties – I_c variation
- passivate H-bonding sites in the oxide
- interfacial engineering
- incorporate H-getters away from junction areas

Define fabrication-compatible strategies to control wafer processing and oxide electronic properties in order to eliminate "random" defects