ENERGETIC CONDENSATION GROWTH OF THINFILMS FOR FUTURE SRF ACCELERATORS

Presented by

Mahadevan Krishnan

Alameda Applied Sciences Corporation (AASC), San Leandro, California 94577

at

Nuclear Physics SBIR/STTR Exchange meeting

October 24-25, 2011
E. Valderrama, C. James  
Alameda Applied Sciences Corporation (AASC), San Leandro, California

Thomas Jefferson National Accelerator Facility (Jefferson Lab), Newport News, Virginia

K. Seo  
Norfolk State University (NSU), Norfolk, Virginia 23504

Z.H. Sung and P. Lee,  
Applied Superconductivity Center, Florida State University (FSU), Tallahassee, Florida

F. A. Stevie, P. Maheshwari,  
Analytical Instrumentation Facility, North Carolina State University, Raleigh, NC

N. Haberkorn, T. Tajima  
Los Alamos National Laboratory, Los Alamos, NM

Research is supported at AASC by DOE via SBIR Grant DE-FG02-08ER85162 and ARRA Grant DE-SC0004994

The JLab effort was provided by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177, including supplemental funding provided by the American Recovery and Reinvestment Act
Outline

- Alameda Applied Sciences Corporation: an Introduction
- Phase II Project Goals
- Relevance to NP Programs
- Current Status of Project
- Future Plans
Alameda Applied Sciences Corporation

Superconducting Thin Films

- Founded in 1994, privately held CA Corporation
- 8 employees, ~$1.5 million 2010 revenue
- Develop/license IP via contract R&D
- Three Pre-commercial areas:
  - Cathodic arc coatings CED™
  - Fast pulsed neutron sources for WMD and HE detection
  - Fast Supersonic Gas Valves

Pulsed Neutron Source

- RRR ~300, $T_c$ = 9.27K
- 2.5 and 14 MeV neutrons

Fast Gas Valve

- DPF-2
- 100Bar / 50μs opening / <500μs closing

Diamond Radiation Detectors

- UV and soft x-ray ≤ 15 keV

Cathodic Arc Coatings (CED™)

- CED™ coating of Cu cavities for SRF
- Anti-coking coating on furnace tube
- Benefit: extended interval between de-cokings

Uncoated

Coated

10 cm
Phase II Tasks and Schedule

- Coat pure Nb films on a-sapphire and Cu substrates using the CED™ coater (year I)
  - Measure the thin films (AASC and JLab and NSU)

- Coat pure Nb films on a-sapphire and Cu in the CAD chamber (year I)
  - (the CAD chamber was used in Ph-I to produce the Nb₃Sn films)
  - Measure the thin films (JLab and NSU)

- Coat Nb₃Sn on a-plane sapphire in CAD chamber (year II)
  - Measure the thin films (AASC and JLab and NSU)

- Coat the thin films using pulsed biased CAD (AASC) (year II)
  - Measure the thin films (AASC and JLab and NSU)

- Coat Nb₃Sn on Nb and/or Cu in CAD chamber (year II)
  - Measure the RF properties in the SIC facility (JLab)
Motivation

- More than 10000 particle accelerators worldwide; most use normal cavities
- Facility for Rare Isotope Beams (FRIB), ILC and other large facilities:
  - NSAC report states that as a result of technical advances, a world-class rare isotope facility can be built at ≈ half the cost of the originally planned Rare Isotope Accelerator (RIA), employing a superconducting linac.
- SRF at 2K is good, but operating at ~10K would further reduce costs as the cryogenic cooling moves towards off the shelf cryo-coolers.
- Replacing bulk Nb with Nb coated Cu cavities would also reduce costs.
- The ultimate payoff would be from Niobium and cast Al SRF cavities coated with higher temperature superconductors (e.g., Mo$_3$Re, Nb$_3$Sn, MgB$_2$, oxypnictides).

SRF with cheaper cavity materials and high-T$_c$ thinfilms would be better still.

AASC’s thin film superconductor development is aimed at these goals.
Ideal Nb Bulk Cavities

$Q_0$ at 2.07K, 1.497 GHz, fine-grain bulk niobium
Acid etch + 38 μm electropolish + 24 hr 120 C bake

(Q is BCS-limited)

29 watts

3 Nov 2010
CERN results: Nb films sputtered onto copper cavities

CERN magnetron sputtering
Coaxial Energetic Deposition (CED) Coater at AASC

- CED coater uses “welding torch” technology
- Arc source is scalable to high throughputs for large scale cavity coatings
  - Present version deposits ≈1 monolayer/pulse in ≈1ms
- Russo’s and Langner’s emphasis on UHV and clean walls is important
Cathodic Arc Deposition (CAD)
Challenges for thin film SRF: path to success

- Cu and/or Al cavity substrates might be of two different forms
  - Polycrystalline
  - Amorphous

- How do we grow low-defect Nb films on such substrates?
- Study adhesion, thickness, smoothness, RRR, stability
- Understand these issues at the coupon level
- Proceed to RF cavity level and measure Q at high fields
- Install multi-cell Nb coated Cu modules in SRF accelerator and validate the thin film solution
  - Spur acceptance of thin film Nb by accelerator community
- Continue R&D towards higher $T_c$ films and Al cavities


8. T. Tajima et al, “Bulk-like Nb Films might be Possible with Coaxial Energetic Deposition for Superconducting RF Cavities”, AVS Meeting, **October, 2011**.

AASC’s CED coated Nb films match RRR of bulk Nb!

- Nb thin films grown on sapphire and MgO crystals have demonstrated higher levels of RRR than were reported by the pioneers, and XRD spectra reveal crucial features.

![Graphs showing RRR vs Tdep and Tpreheat for a-plane sapphire, MgO(100), and c-plane sapphire.]


**RRR-585 (±1% error)** measured on 5μm film on MgO.

**RRR-330** measured on a-sapphire.
**RRR of Nb thin films on MgO substrates**

- Pole Figures show change in crystal orientation from 110 to 200 at higher temperature

![Diagram showing pole figures and RRR values](image)

- Polycrystalline
  - 110
  - RRR=7, 150/150

- Monocystal with two orientations
  - 110 & 200
  - RRR=181, 500/500

- Monocrystal with 100 orientation
  - 200
  - RRR=316, 700/700

Observations about bulk single crystal Nb orientation


PROGRESS ON LARGE GRAIN AND SINGLE GRAIN NIOBIUM – INGOTS AND SHEET AND REVIEW OF PROGRESS ON LARGE GRAIN AND SINGLE GRAIN NIOBIUM CAVITIES, P. Kneisel, Proceedings of SRF2007, Peking Univ., Beijing, China

◆ Cavity #5 showed a different behavior than all other single crystal/large grain cavities after baking: the Q-drop did not disappear after 12 hours. The crystal orientation of the single crystals of this cavity was (110) with a tilt against the surface. For cavity #4 the crystal orientation was (100).

◆ The surface of both cavities appeared quite different after BCP: whereas cavity #4 exhibited a very smooth, shiny surface, the surface of cavity #5 was “rough” (orange peel/fish scale appearance) and less shiny.

◆ Obviously, there is a difference in the reaction of the BCP chemicals at different crystal orientations (D. Baars et al., "Crystal orientation effects during fabrication of single or multi-crystal Nb SRF cavities", SRF07, Beijing, Oct. 2007, TH102; http://www.pku.edu.cn/academic/srf2007/proceeding)

Could CED (Energetic Condensation) be used to grow (100) Nb films on existing Nb cavities to help improve performance?
SIMS analysis of CED films to study impurities

- The H count rate in CED film is 7000x lower than in bulk Nb!
- The Oxygen level in RRR=9.5 film is much higher
  - RRR=9.5 film was deposited at “room temperature”
- Role of NbO in flux pinning?
Summary and Future Plans

- Our RRR data show that our films match bulk Nb
- Our $B_{\text{pen}}$ data also match bulk Nb
- Our densely packed films have 7000x less H than bulk Nb
- Next steps are to coat SRF cavities and test for Q-slope while continuing to improve high-$T_c$ films such as Nb$_3$Sn and others
- Our CED energetic condensation process could have an impact on existing and future SRF designs
  - Nb-on-Cu bellows (APS) could be inserted into APS upgrades (G. Wu)
  - Nb-on-Nb cavities could enhance existing SRF accelerators (P. Kneisel)
  - Nb-on-Cu cavities could have an impact on low-$\beta$ SRF (FRIB et al)
  - NbN coatings could passivate Nb cells and improve reliability (G. Ciovati)
  - NbN coatings could (when integrated into multi-layer coatings a la Gurevich) boost maximum E-field in future designs
  - Nb$_3$Sn and MgB$_2$ coatings could increase $T_c$ and reduce cost
Lower Cl values between Nb matrix and MgO substrate indicate that there could be an amorphous or non-structured layer between them.
TEM/AFM of high RRR film: sharp interface with substrate

- Energetic Condensation (subplantation) physics drives an adhesive, non-porous, sharp interface between substrate and Nb film
- Nb surface is smooth (~5nm roughness)
“Mold” effect of subplanted Nb films: high RRR film

This macro landed on 2.4µm Nb film

This macro landed near MgO surface

No Columnar structure; XRD shows (100) single crystal

Contrast due to FIB milling trace

Thickness ~ 2.43µm

Thickness ~ 2.27µm
RRR-316: Cross sectional EBSD: dense, monocystal film

Conductor – Mounting material

MgO

Nb

0.15μm scan step size

MgO

ALAMEDA APPLIED SCIENCES CORPORATION

aasc10vp01-23
XRD Pole Figures for Nb thin films grown on Borosilicate

Subplantation physics of energetic condensation at work here

(110) Nb on Borosilicate at 150/150C

- (211) plane
- (110) plane
- Phi (rotation)
- [110]
- Psi (tilt)

A strong [110] Nb fiber structure perpendicular to the substrate

(110) Nb on Borosilicate at 400/400C

- [110]

At higher coating temperature, in-plane texture shows that [110] fiber texture is highly oriented to the substrate