Ultra-Conducting Copper (UCC)

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Oak Ridge National Laboratory

2018 U.S. DOE Vehicle Technologies Office
Annual Merit Review

June 19, 2018 Project ID: ELT071

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Overview

Timeline

- Start – FY17
- End – FY19
- 50% complete

Barriers

- Meeting power density & cost targets of DOE ELT 2025
- Increasing both the electrical and thermal conductivity of windings to increase efficiency of electric motors (EMs)

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY17: $300K
- Funding for FY18: $300K

Partners

- Southwire, Magnekon, Magna, and Chasm
- NREL
- ORNL team members: Tolga Aytug, Burak Ozpineci, Ilia Ivanov, Mina Yoon, Michael McGuire, Andrew Lupini, Tsarafidy Raminosoa, Chengyun Hua, and Elena Camacena

Any proposed future work is subject to change based on funding levels

Project Objective and Relevance

- **Overall Objective:**
  - Develop a new class of high performance copper (Cu) wires using carbon nanotubes (CNT) that are higher in electrical & thermal conductivity to increase the power density of electric motors while improving the overall efficiency

- **FY18 Objectives:**
  - Identify/develop/implement scalable approaches & material technologies for the prototyping of carbon nanomaterial enabled UCC conductors
  - Utilize theoretical modelling to understand metal-nanocarbon interface properties for optimized electronic/thermal transport characteristics
  - Understand performance & power density improvements contributed by UCCs in electric motors

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Milestones

Date	Milestones and Go/No-Go Decisions	Status
Dec. 2017	Milestone: Establish necessary set-up & identify processing routes to enable scalable assembly of Cu-CNT tapes	✓
March 2018	Milestone: Prototype UCC composite conductors (> 5 cm length) using controllable techniques	✓
June 2018	Milestone: Down-select at least one promising processing approach that provides reproducible CNT alignment & performance	On track
Sept. 2018	Go/No-Go Decision: Determine if the prototype UCC composites show improved electrical conductivity compared to reference Cu, then optimize processing protocols	On track

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Approach/Strategy

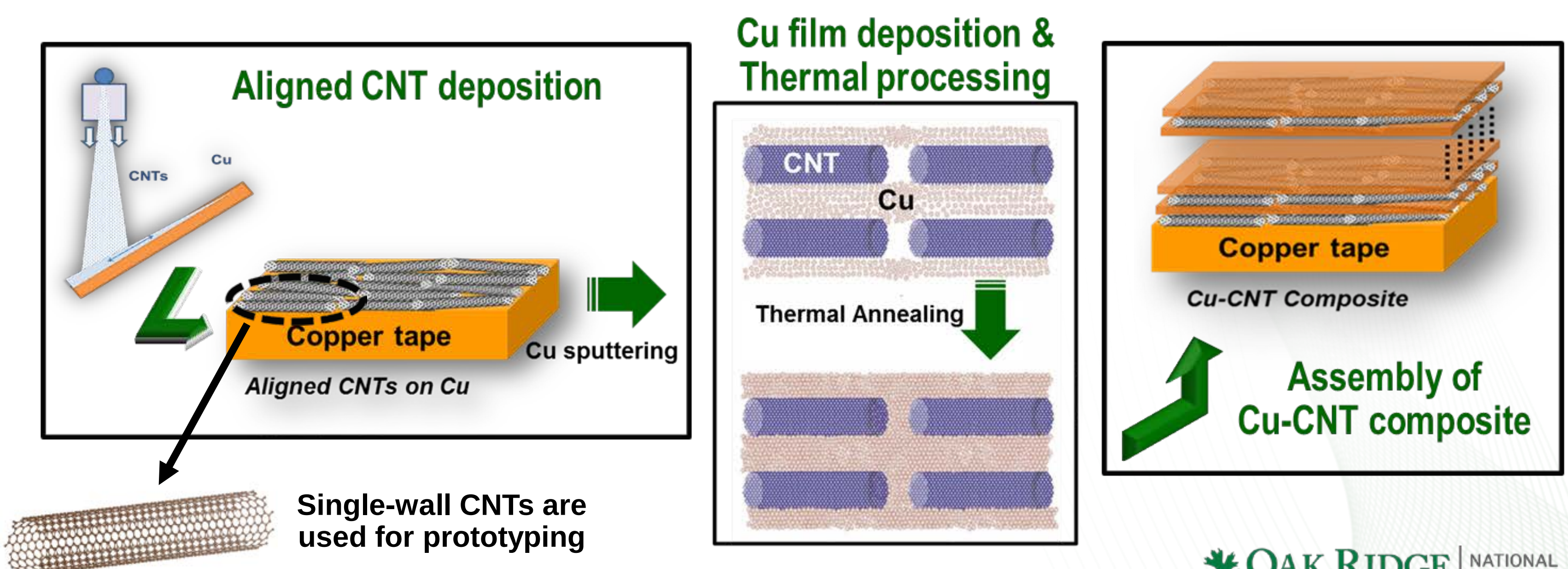
Design an advanced composite material consisting of carbon nanotubes embedded in Cu matrix – Ultra Conductive Copper (UCC)

A better conductor with reduced electrical loss enables:

- Volume/weight reductions ➡ improved power density and specific power
- Higher efficiency (i.e., lower conduction losses)

Process-flow for ORNL-UCCs:

1) CNT deposition; 2) Cu-film deposition/annealing; 3) Cu-CNT multilayer assembly



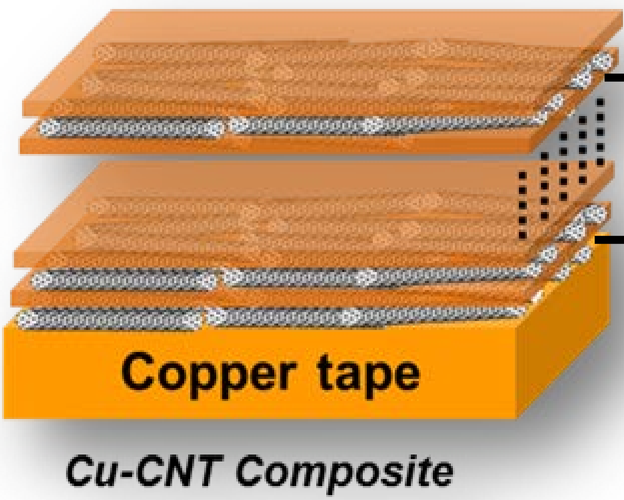
Approach/Strategy

CNTs provide extraordinary electrical, thermal, & mechanical properties compared to Cu

- ×1.7 higher electrical conductivity (along the tube axis)
- ×10 higher thermal conductivity (along the tube axis)
- ×100 current density

	Cu	CNT
Electrical Conductivity	59.6 MS/m	100 MS/m
Thermal Conductivity	400 W/m-K	4000 W/m-K
Current Density	10^6 A/cm^2	10^8 A/cm^2

ORNL UCC Multilayer Architecture



Process challenges:

Cu-film (orange layers):

Any voids/porosity from the Cu/CNT matrix needs to be eliminated

CNT-layer:

- CNTs need to be aligned along the tape length (i.e, direction of current)
- Organic processing chemicals (solvent & surfactants) used during processing must be removed from the CNT matrix

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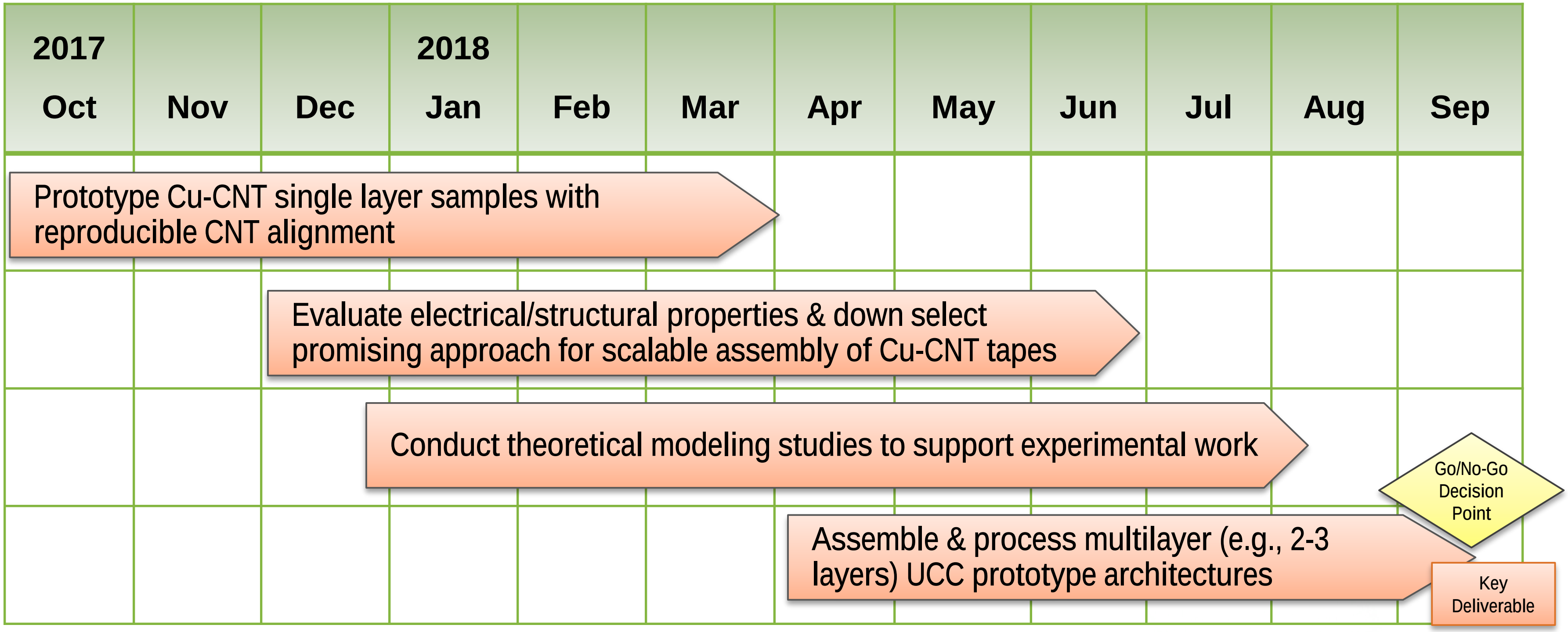
Approach FY18 Timeline



Go/No-Go Decision Point: Determine if the prototype UCC composites show improved electrical conductivity compared to reference Cu, then optimize processing protocols

Key Deliverable: Sufficient number of Cu-CNT single-/multi- layer specimens for performance evaluation

Any proposed future work is subject to change based on funding levels

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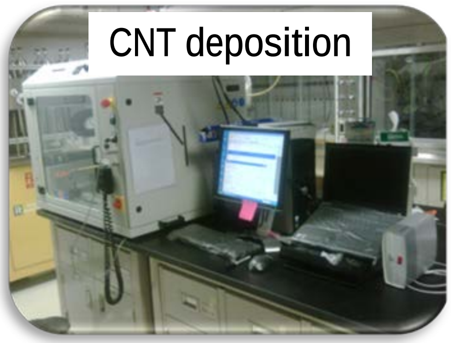
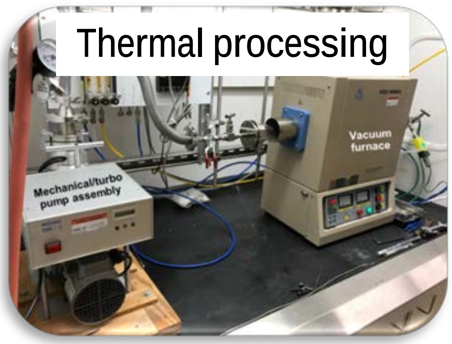
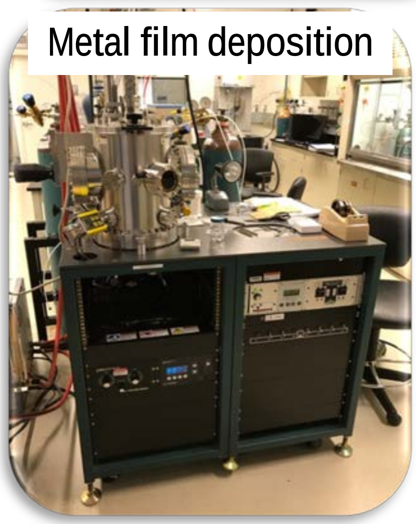
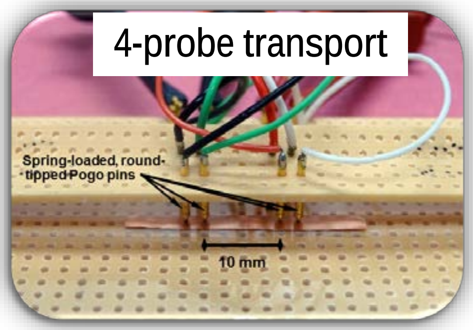
Technical Accomplishments – FY17

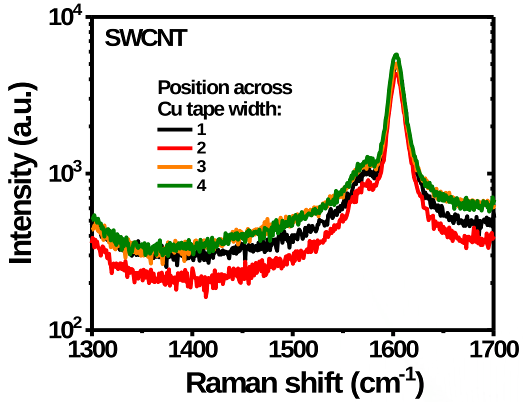
- **Established necessary processing set-up & characterization tools**
- **Investigated the viability of various solvents & surfactants for effective CNT dispersions & deposition**
- **Showed that improvement in electrical conductivity is possible at elevated temperatures using Ag/CNT/Cu composite architecture**



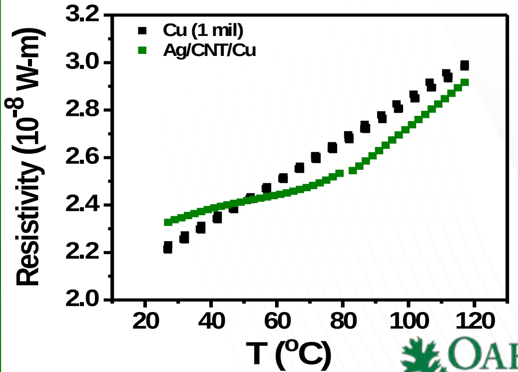








Verified uniformity of CNT coatings



Verified decrease in resistivity at elevated temperatures

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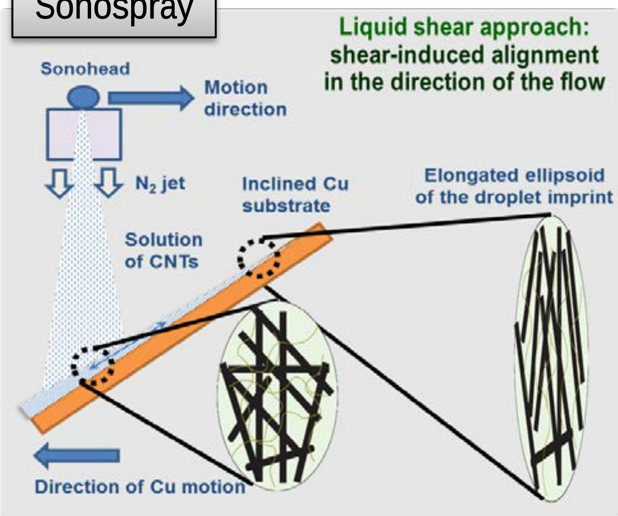
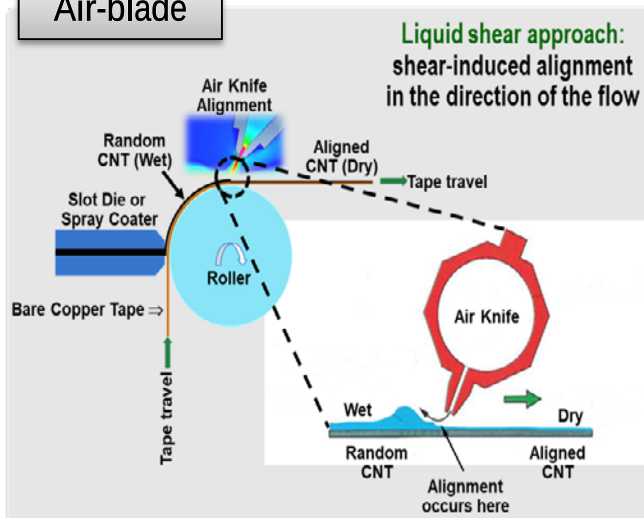
Technical Accomplishments – FY18

Established controllable processing techniques for CNT deposition on Cu tapes: Three scalable approaches were identified & explored

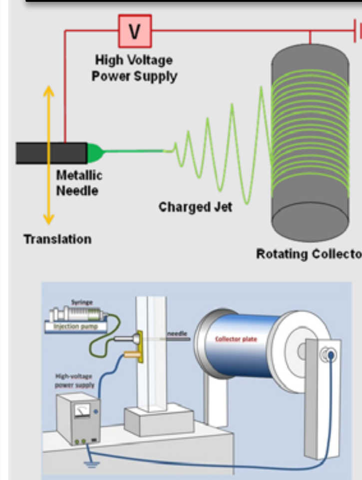
Sonospray



Air-blade



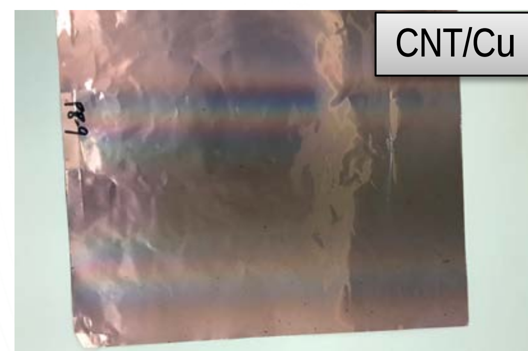
Electrospin/Electrospray



CNT suspension is extruded from the needle tip at a constant rate under high voltage

High voltage applied between the syringe & collector induce droplet elongation along deposition direction

Rotation of collector induces additional shear for CNT alignment



Liquid shear approach: shear alignment of CNTs in the direction of the flow-field induced between the droplets & the Cu substrate

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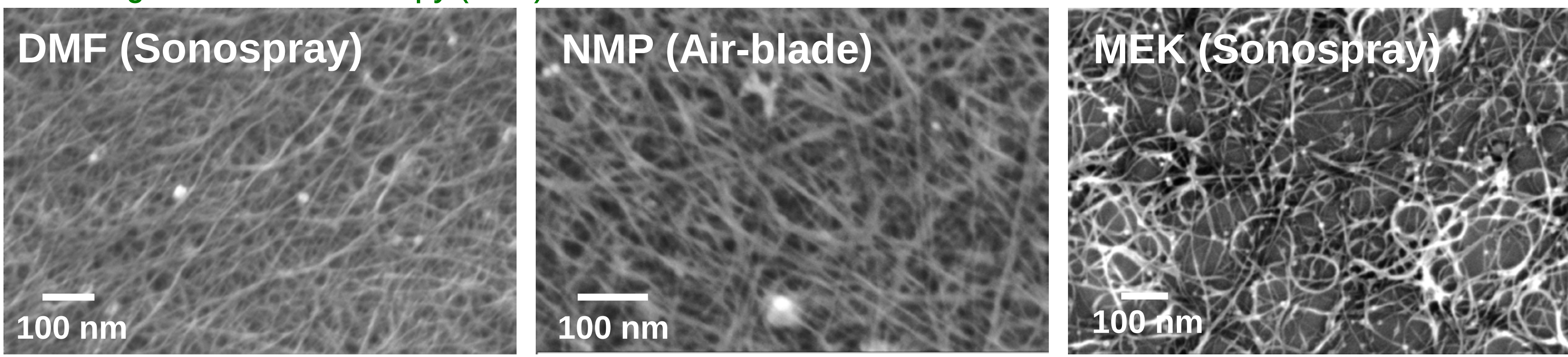
Technical Accomplishments – FY18

Created stable CNT dispersions in various organic solvent/surfactant formulations: Three different organic solvents are identified

- N-Methyl-2-pyrrolidone (NMP): Boiling Point (BP): 202 °C, ~0.24 mmHg (20 °C), – Air-blade & Electrospin
- Dimethylformamide (DMF): BP: 153 °C, ~38.75 mmHg (20 °C), – Sonospray
- Methylethylketone (MEK): BP: 79.64 °C, ~78 mmHg (20 °C), – Sonospray & Air-blade

Scanning electron microscopy (SEM)

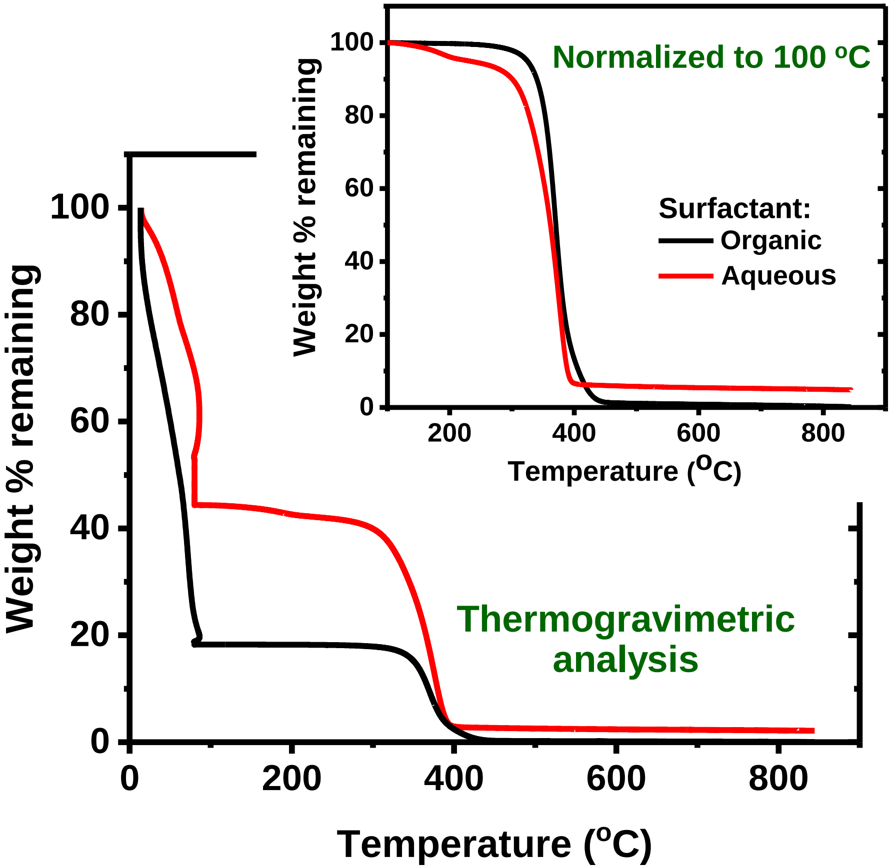


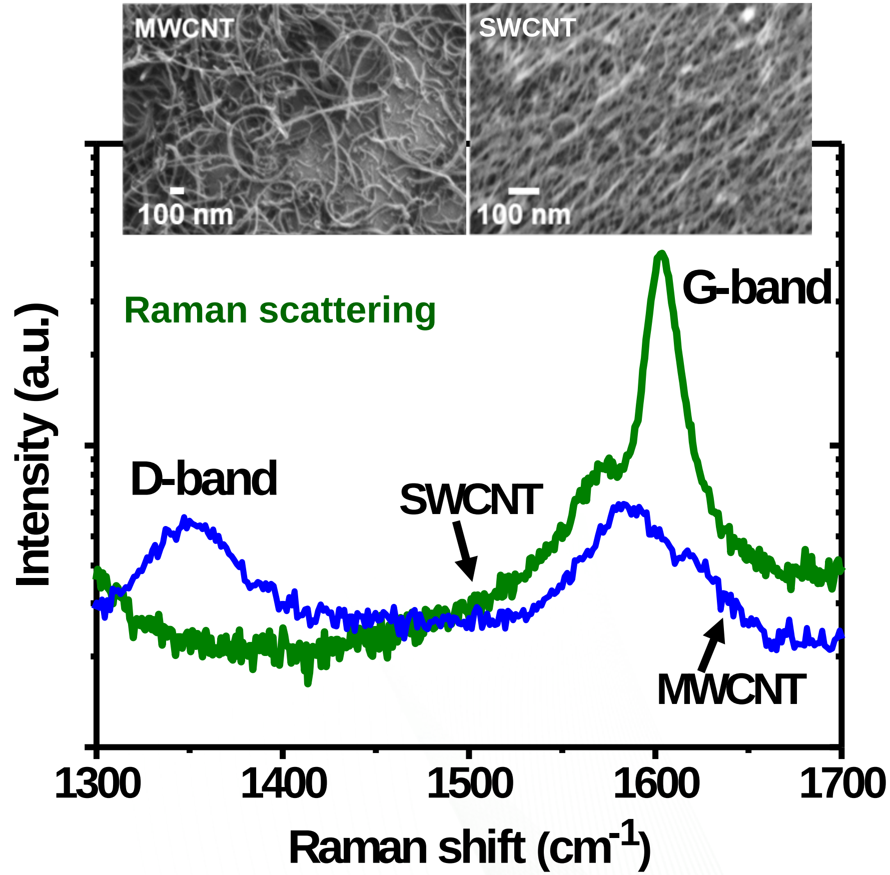
- MEK: Low BP & high vapor pressure results in non-uniform coverage & no particular CNT alignment
  ➡ quick solvent drying minimizes shear against the Cu substrate ✗
- DMF: Uniform coverage, CNT alignment – lower vapor pressure ✓
- NMP: Uniform coverage, CNT alignment – lower vapor pressure ✓
- Dispersion of CNTs in aqueous formulations are being explored

Technical Accomplishments – FY18

Identified surfactant & CNT-type to create stable CNT dispersion formulations:

Solvent: NMP & DMF; Surfactant: Commercial formulation; CNT-type: Single-wall CNTs (SWCNT)





- Thermogravimetric analysis is used to identify heat treatment temperatures for the removal of organic solvent & surfactant [e.g., @ $T \geq 400$ °C near complete removal (99.7 wt%) is achieved]
- Raman scattering is used to analyze quality of the CNTs. SWCNT is selected because a larger intensity ratio of D-band/G-band indicates higher defects for multi-wall CNTs (MWCNT)

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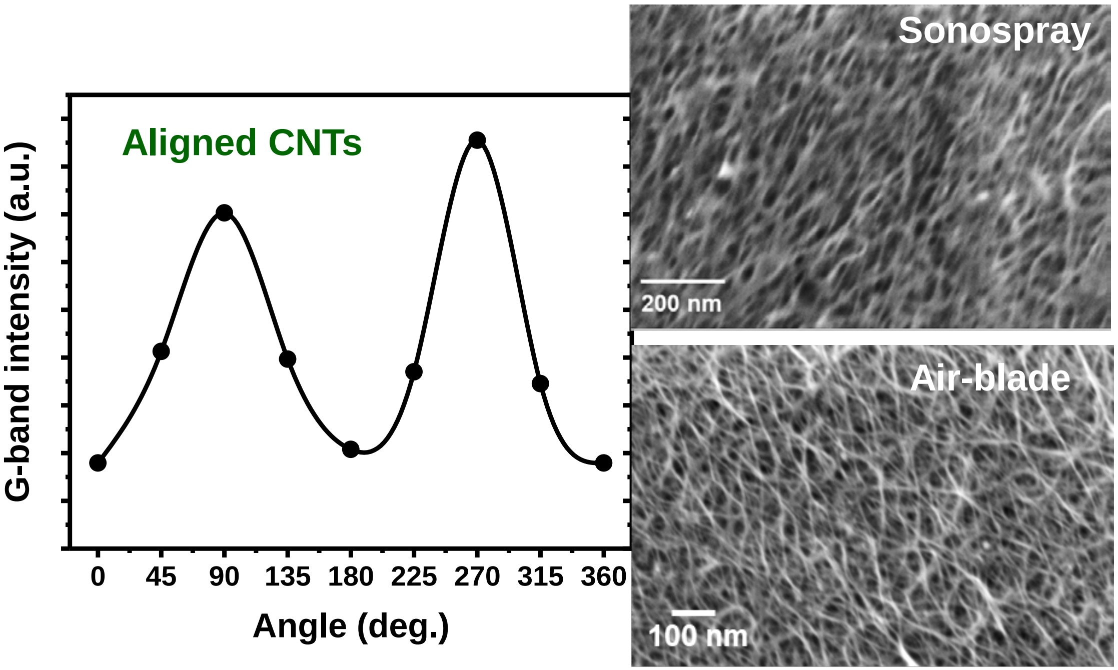
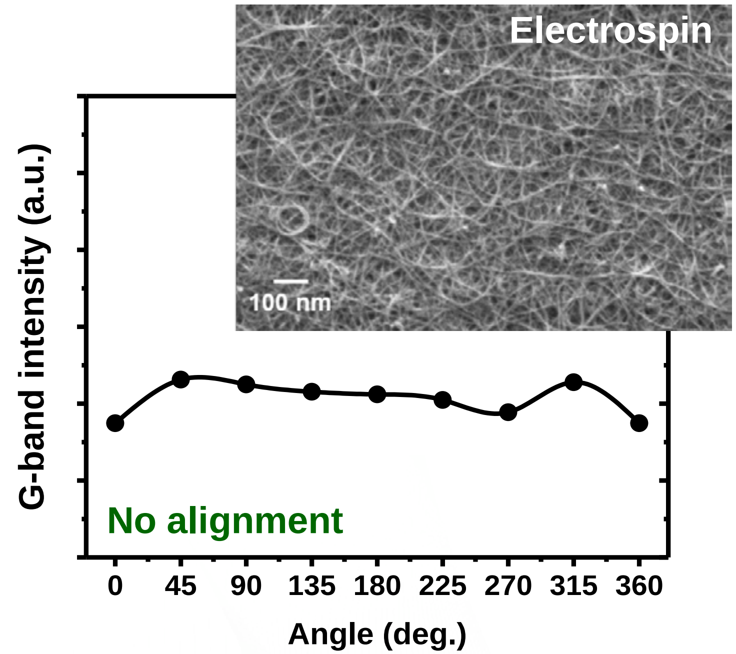
Technical Accomplishments – FY18

Confirmed shear induced alignment of CNTs deposited by sonospray & air-blade using polarized Raman spectroscopy & scanning electron microscopy





- Demonstrated preferential CNT alignment along the tape length with sonospray & air-blade approaches (faster process than sonospray); but mixed performance is observed for electrospinning
- All three techniques are still being improved

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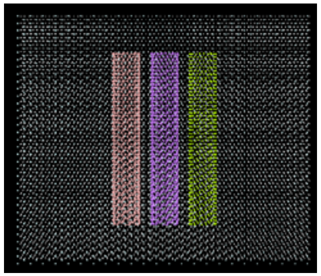
Technical Accomplishments – FY18

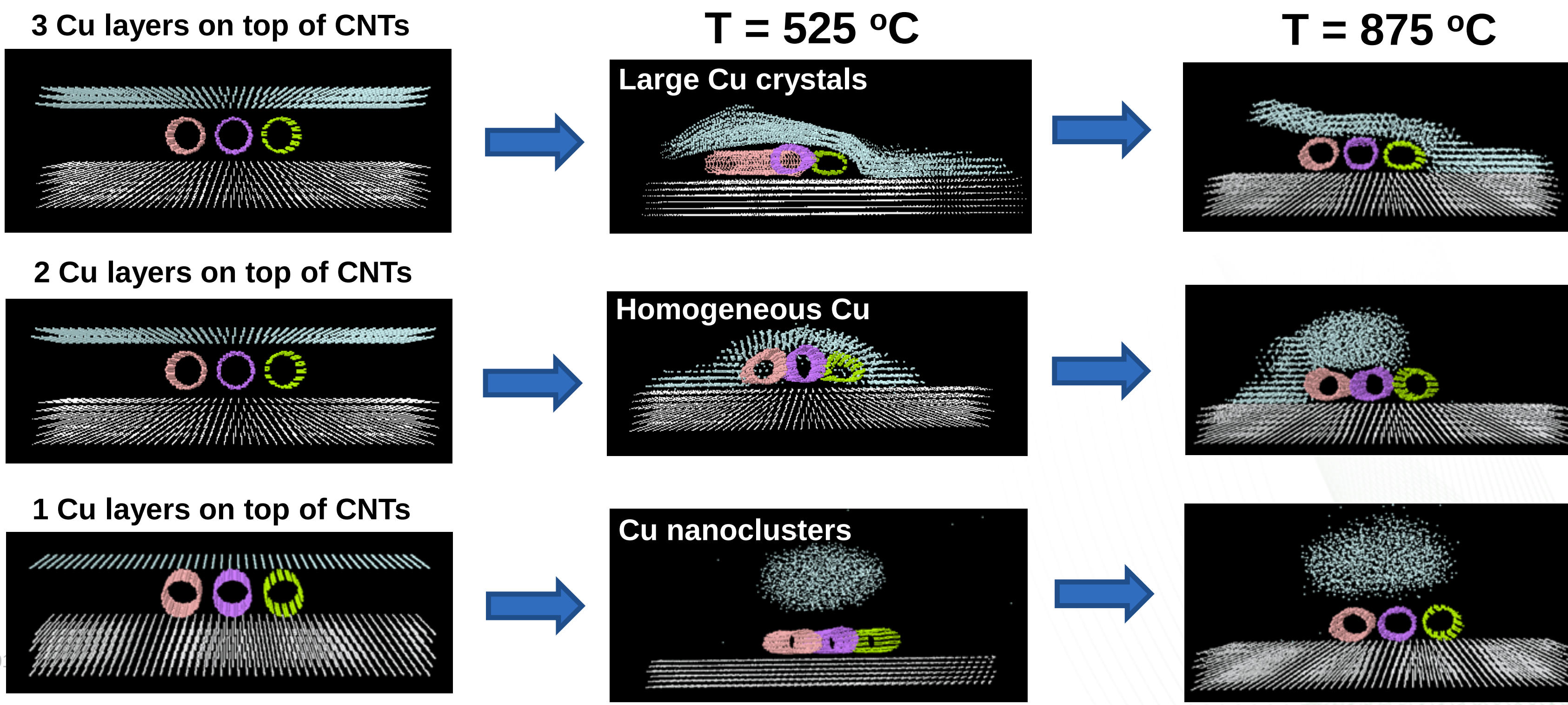
Used theoretical modeling & simulations to optimize materials & process parameters

Initial configuration (top view)



Classical molecular dynamics simulations performed to understand the energetics & kinetics of Cu coating on CNTs for experimental temperatures:

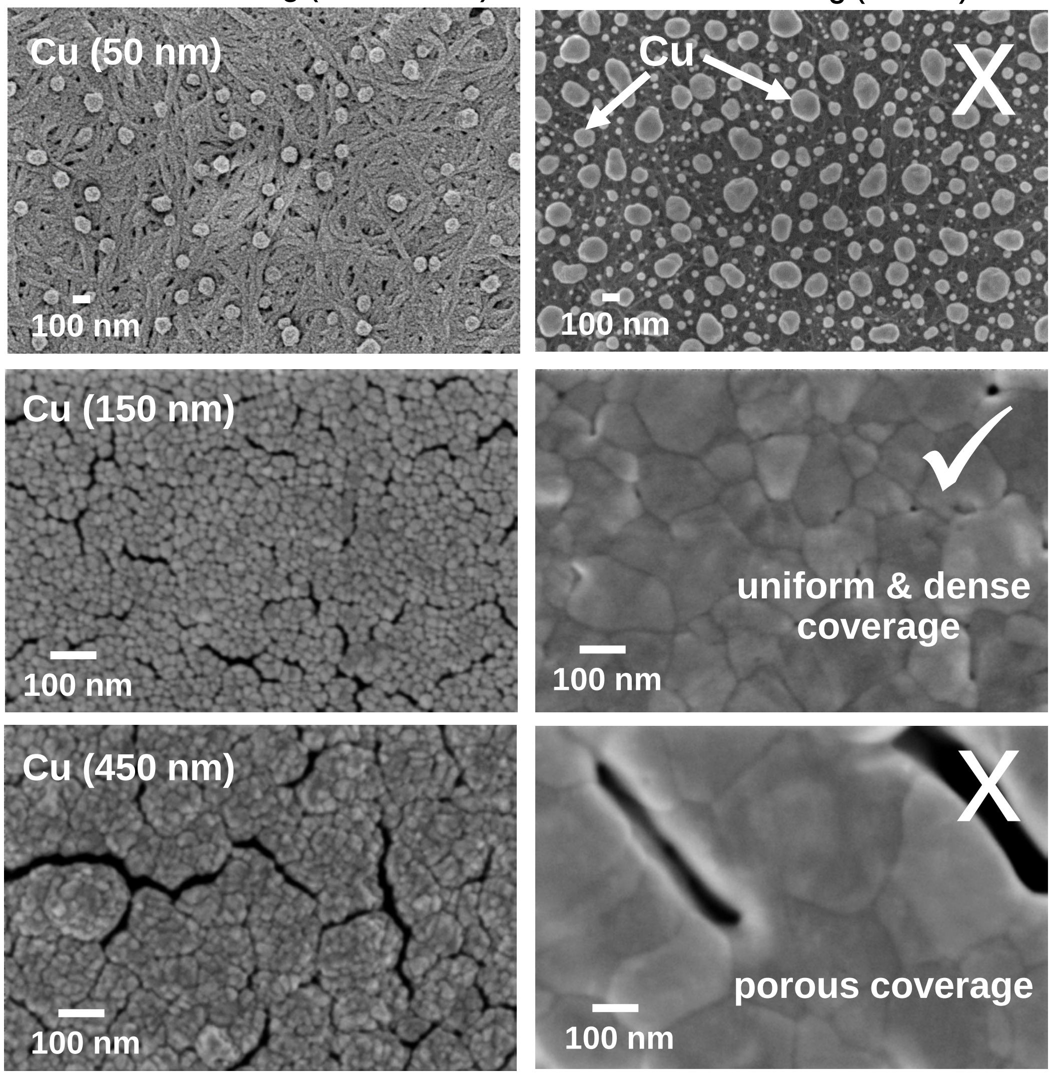
- The coating thickness (controlled by the experimental deposition rate & flux) is one of the key parameters to achieve a homogenous coating
- Identified the range of critical temperature (525 <T_C< 875 °C) above which Cu clustering is favorable independent of thickness; the optimum temperature should be fine-tuned with respect to the experimental deposition condition



Technical Accomplishments – FY18

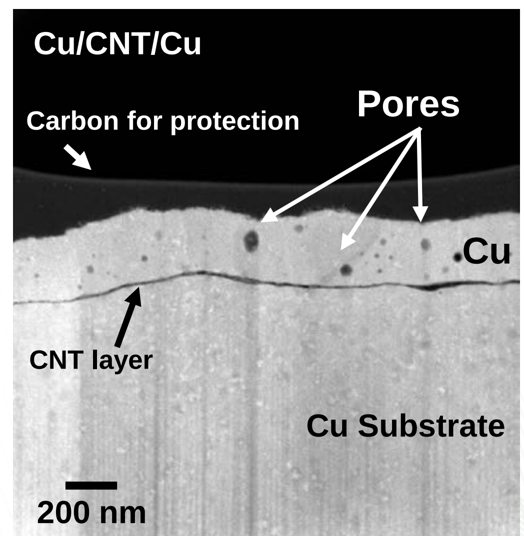
Achieved a uniform & dense Cu matrix on CNT layers

Before Annealing (Cu/CNT/Cu) | After Annealing (400 ^{o}C)



- Thickness of the Cu film & post-annealing temperature require optimization
  - Thin Cu film ➡ non-uniform, discontinuous surface coverage ✗
  - Thicker Cu film ➡ uniform & homogeneous coverage ✓
- Any current rendering defects (e.g., voids & pores) throughout the Cu/CNT matrix needs to be eliminated ➡ detrimental to current carrying capacity

Cross-sectional Z-contrast TEM



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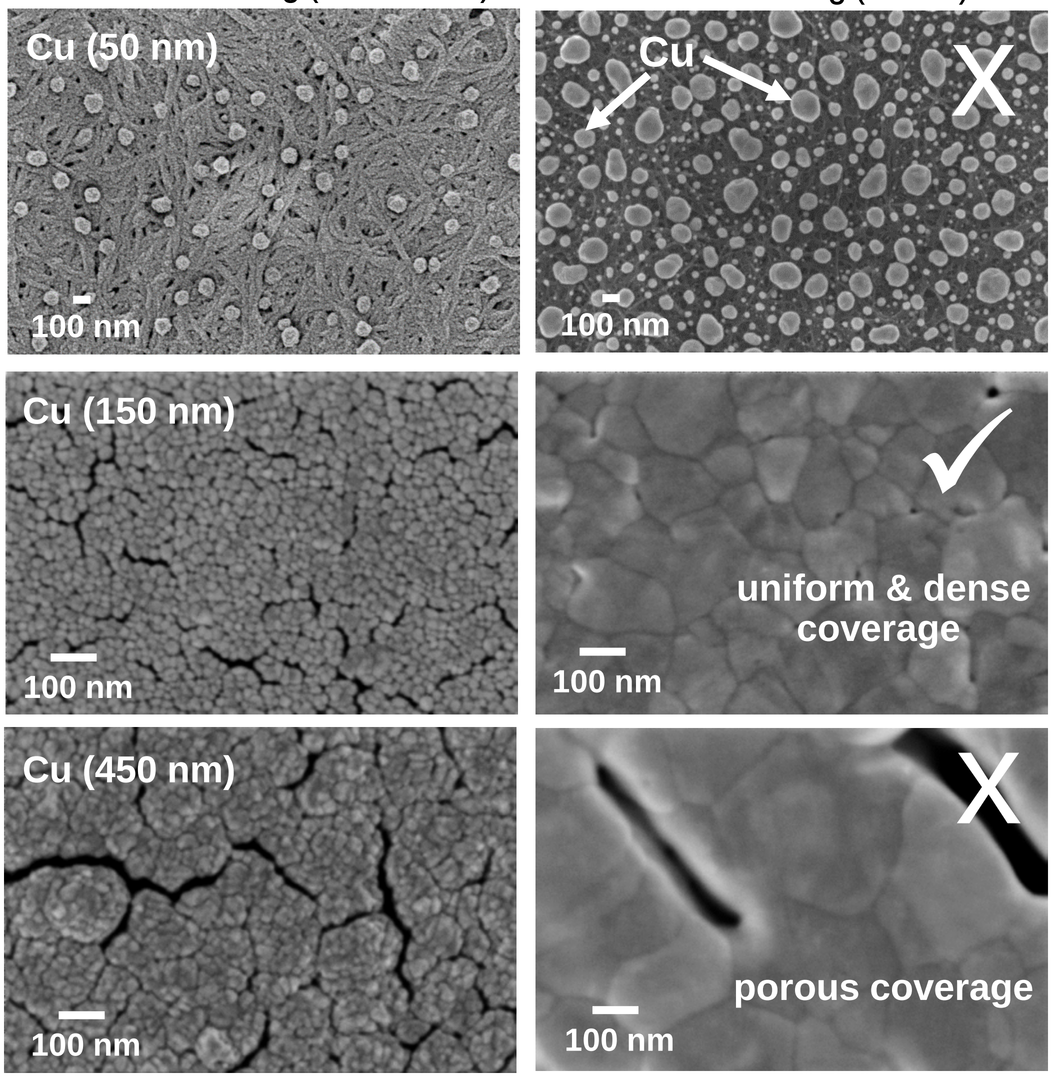
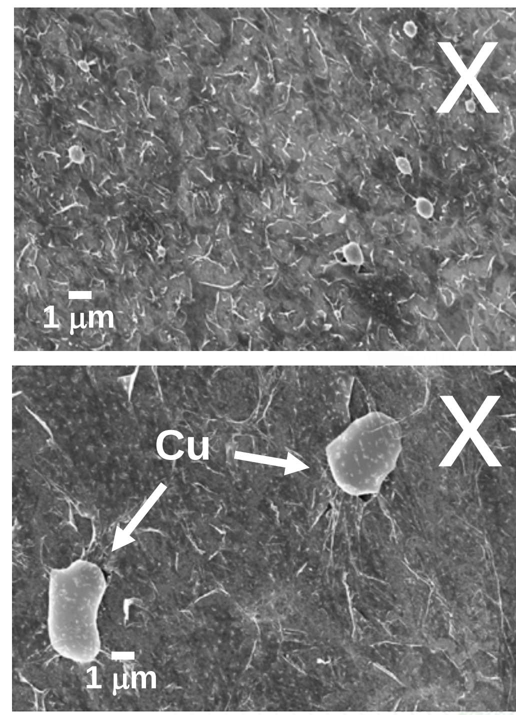


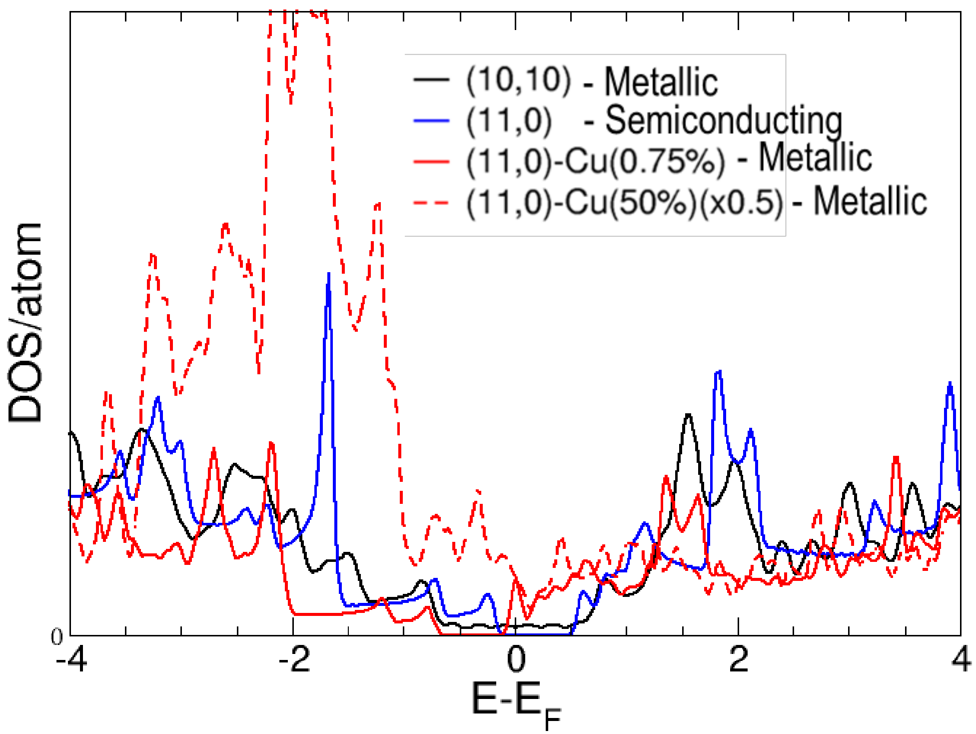
- Thickness of the Cu film & post-annealing temperature require optimization
  - ➥ Thin Cu film ➡ non-uniform, discontinuous surface coverage ✗
  - ➥ Thicker Cu film ➡ uniform & homogeneous coverage ✓
- **Annealing temperature ≥ 800** °C ➡ evaporation of Cu

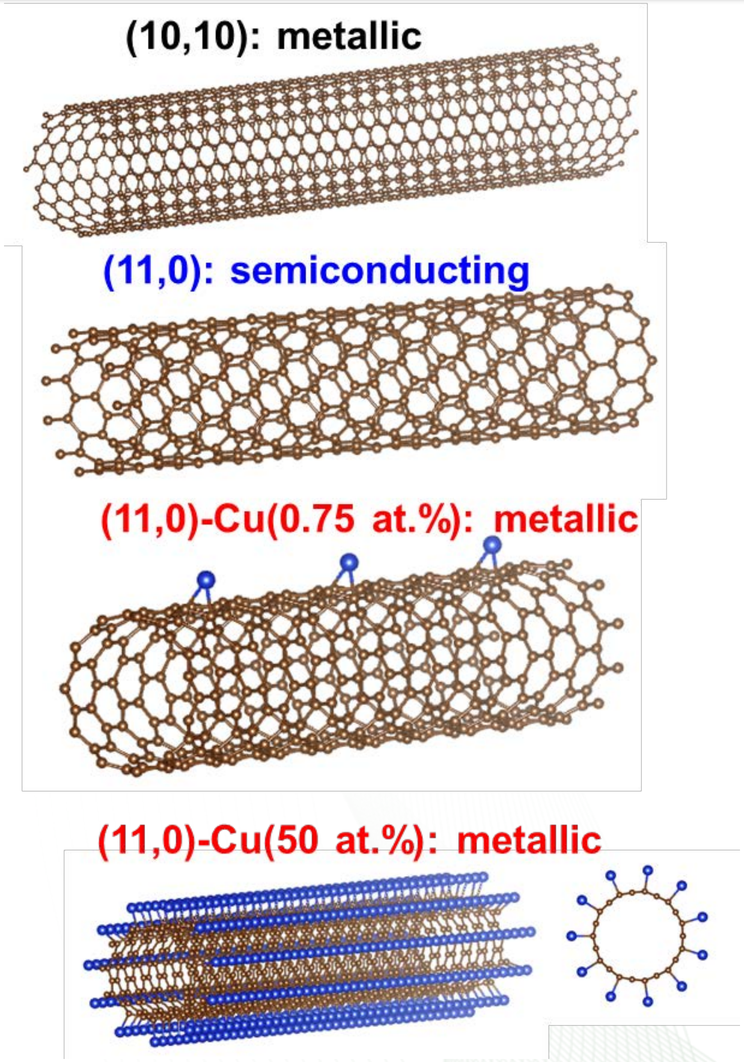
After Annealing (900 °C)



Technical Accomplishments – FY18

Confirmed transformation of semiconducting CNTs into metallic tubes through Cu doping using first-principles density functional theory calculations





Even with small amount of Cu-doping (e.g., 0.75 at.%) density of states (DOS) peak at the Fermi level

- Density of the conduction electrons increases with the doping level
- Conversion of semiconducting CNTs into metallic tubes is verified

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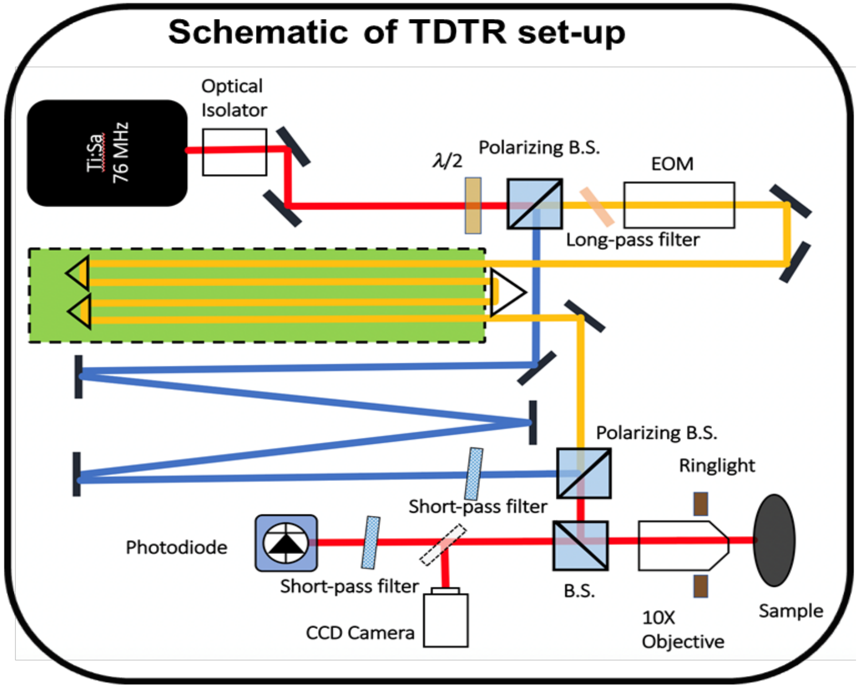
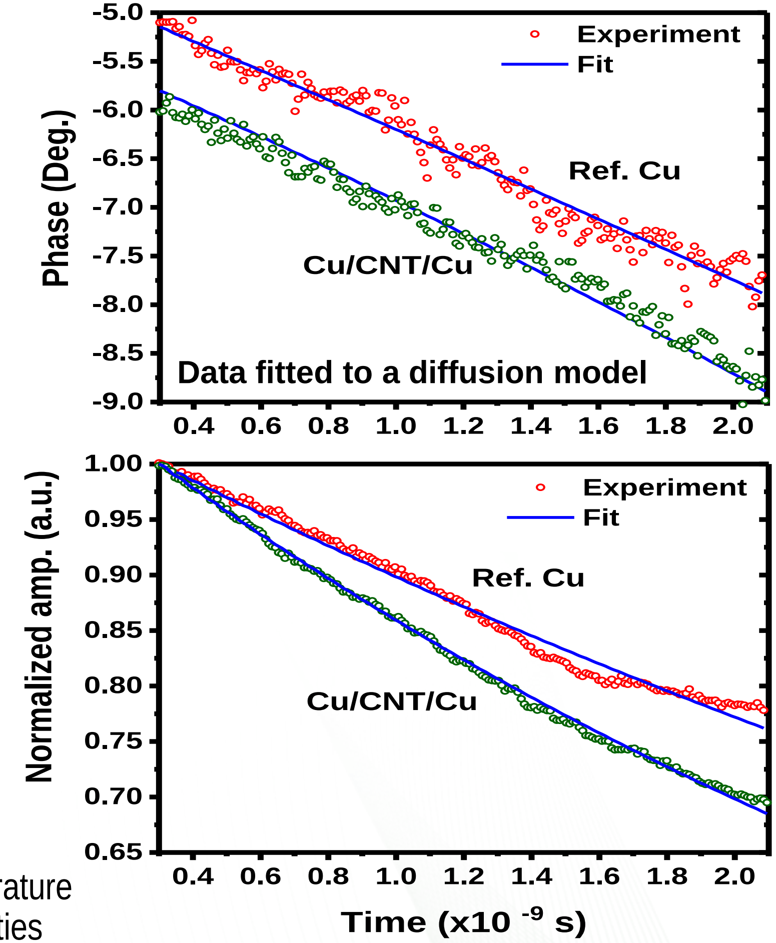
Technical Accomplishments – FY18

Confirmed influence of CNT interface on the thermal properties of UCCs using a transient ultrafast laser technique (Time-domain thermoreflectance - TDTR)

k (Ref.Cu): 412.72 W/m-K, Bulk Cu: 386 W/m-K
k (Cu/CNT/Cu): 295.03 W/m-K





- TDTR is a non-contact technique that relates optical properties to the temperature changes of the surface. Currently configured to measure cross-plane properties
- Results confirmed near bulk value for reference Cu & expected reduction in cross-plane (i.e., perpendicular to tape plane) thermal conductivity, k, for Cu-CNT [SWCNT, k: (Radial: 1.52 vs. Axial: 3500 W/m-K)]
- In-plane (i.e., along the tape) measurements requires modification of the optical configuration – in progress

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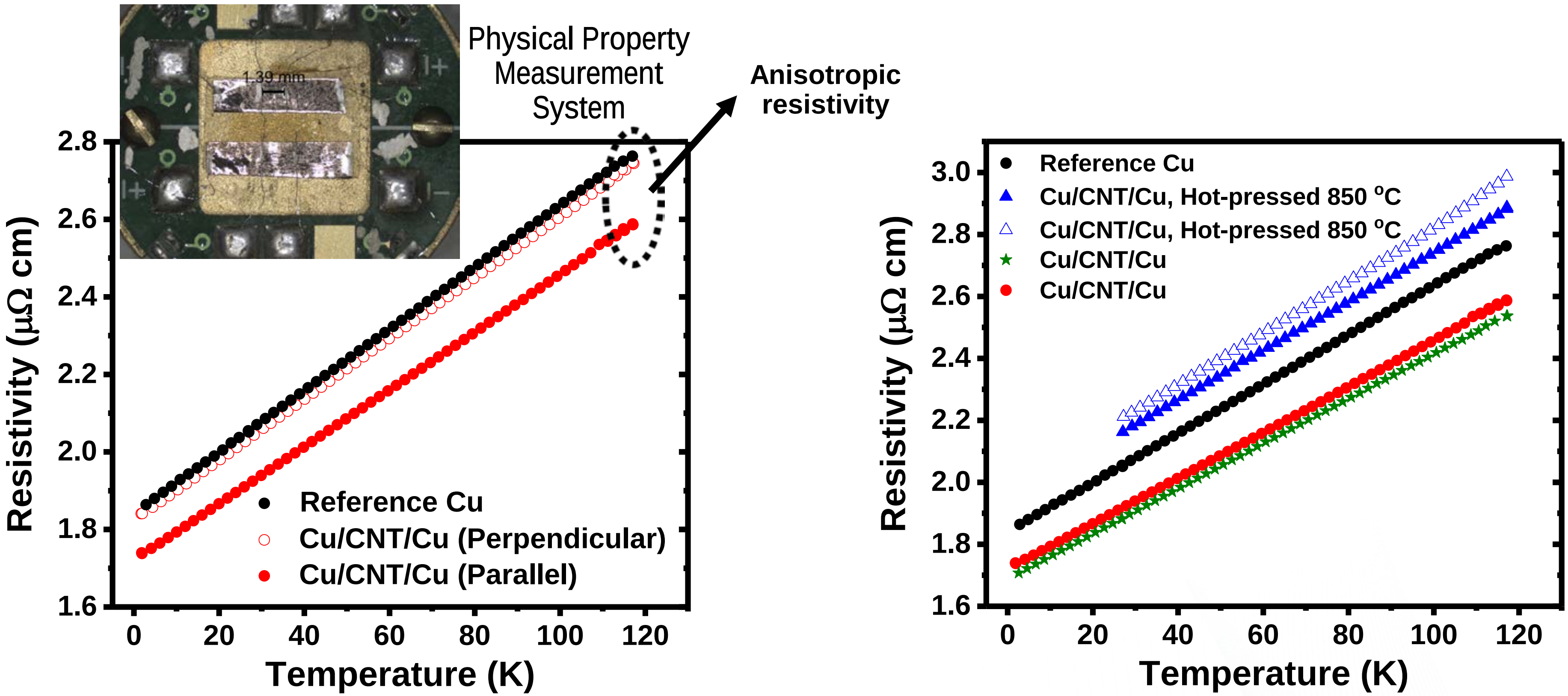
Technical Accomplishments – FY18

Demonstrated improved conductivity over reference pure Cu for prototype single CNT layer UCC composites



- Decreased resistivity ~5 - 8% for Cu/CNT/Cu prototype samples has been realized (T = 0 - 120 ^{o}C)
- Observed anisotropic resistivity wrt. direction of the CNT alignment
- Higher resistivity for hot-pressed samples ➡ either contamination or damage ensued in the CNT layer **X**
- Integration of additional CNT layers for the assembly of multilayer UCC composites is in progress

Technical Accomplishments – FY18

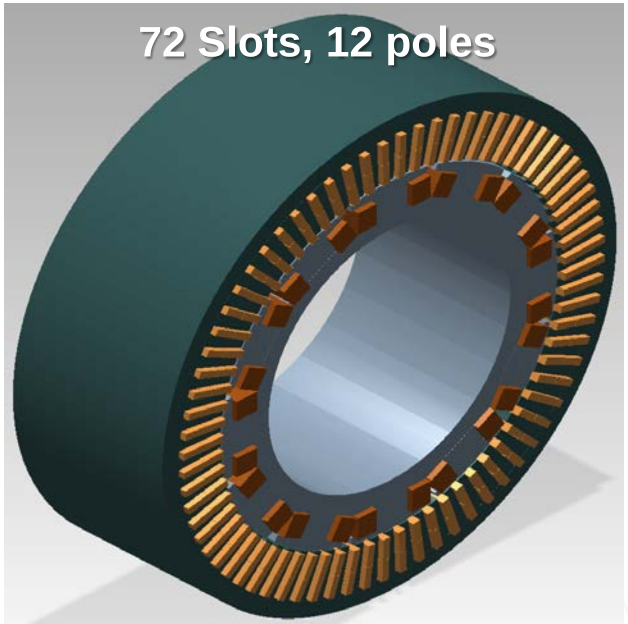
Analyzed benefits of UCC on the weight/volume reductions in electric motors

	Reference copper	CNT/Cu
Outer diameter (mm)	242.00	242.00
Stack length (mm)	85.62	79.67
Mass		
Rotor core mass (kg)	5.90	5.49
Rotor coils mass (kg)	1.96	1.87
Stator core mass (kg)	9.93	9.24
Stator winding mass (kg)	4.28	4.12
Total	**22.07**	**20.71**
Stator slot fill factor (%)	56.00	56.00
Rotor slot fill factor (%)	66.93	66.93
Performance		
Torque (N·m)	201.04	201.04
Input power (kW)	107.57	107.54
Output power (kW)	**100.00**	**100.00**
Efficiency (%)	**92.97**	**92.99**
RMS phase voltage (V)	262.94	249.22
RMS phase current (A)	229.56	243.17
RMS current density (A/mm²)	17.92	18.98
Loss - Total (kW)	7.57	7.54
Loss - Winding (kW)	4.72	4.76
Loss - Rotor coils (kW)	1.49	1.49
Iron loss (kW)	1.35	1.29

For the same power & total loss (i.e., similar efficiency), UCC composite tapes enable:

- **6% reduction in mass**
- **7% reduction in volume**

UCC-based wound rotor synchronous motor design



Calculations assumed:

- **DOE targets (2025): 100 kW continuous**
- **Rotor/stator winding temperature = 150 °C**
- **Power & loss is constant in ref. Cu & CNT/Cu designs**
- **Rectangular tape winding**

Please see poster:
Project ID: elt074
Non-Rare Earth Electric Motors
T. Raminosoa, ORNL, June 19

Responses to Previous Year Reviewers' Comments

One reviewer commented: "In addition to using results from evaluation and materials research to design, build, and test the prototype, the feasibility of using CNT and the high-Si lamination in the motor design needs to be addressed."

Response: The feasibility of UCC integration in motors is evaluated & results are provided in the technical accomplishments section

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Collaboration and Coordination with Other Institutions

Initiated discussions with Southwire, Magnekon, Magna International

Chasm Advanced Materials, Inc: Supplier of CNTs

Southwire: Manufacturing & performance characteristics & evaluation of UCCs for general wire production

Magnekon: Manufacturing, performance characteristics, & evaluation of UCCs for motor windings

Magna International: Benefits of UCCs for electric motors (size reduction & performance improvements)

Remaining Challenges and Barriers for FY18

- Production of stable CNT dispersions in aqueous formulations is needed to eliminate utilization of organic solvents
- The amount of surfactant in the suspension formulation needs to be minimized (without effecting the dispersion stability) for improved electrical performance
- The influence of CNT-type (single-wall vs. double-wall vs. multi-wall; long vs. short tubes) on the alignment & electrical properties of the samples. The most effective CNT type needs to be identified
- The influence of additional layers on the CNT alignment & electrical performance of the multilayered UCC assembly needs to be established
- Large parameter space involved in producing UCC tapes

Proposed Future Work

Remainder of FY18:

- Continue process optimization efforts for the production of UCCs
- Continue integration of additional Cu/CNT stack(s) on the first Cu/CNT/Cu architecture & investigate their influence on the electrical performance
- Identify the most promising approach for the scalable assemble of UCCs

FY19:

- Continue processing, optimization, characterization efforts & fabricate prototypes
- Incorporate detailed theoretical modelling efforts to support/speed-up experimental work
- Analyze electrical & thermal impacts of additional Cu/CNT layers

Summary

- **Relevance:** Advanced materials with higher electrical conductivity are needed to increase power density & reduce cost while improving performance & reliability of electric motors
- **Approach:** Design an advanced conductor with reduced electrical loss
- **Collaborations:** Initiated interactions w/ material suppliers & wire manufacturers
- **Technical Accomplishments:**
  - Identified three scalable processing techniques for CNT depositions as well as solvent, surfactant & CNT type to produce stable dispersions
  - Achieved CNT alignment using sonospray & air-blade techniques
  - Conducted microstructural analyses to provide key insights into process optimization
  - Demonstrated that theoretical modeling can support experimental efforts
  - Confirmed influence of CNT interface on the thermal properties of Cu/CNT
  - Developed single-layer UCC prototypes, performed electrical characterizations using custom designed set-up(s), demonstrated improved conductivity over reference pure Cu
  - Analyzed benefits of UCC on the performance of electric motors
- **Future Work:** Continue processing, optimization, characterization efforts, & fabricate prototypes; incorporate detailed theoretical modelling efforts to support/speed-up experimental work; analyze electrical & thermal impacts of additional Cu/CNT layers