Opportunity and Progress of Carbon Nanotube Conductors for Space Power

Dr. Brian J. Landi
Professor of Chemical Engineering

RIT | Rochester Institute of Technology

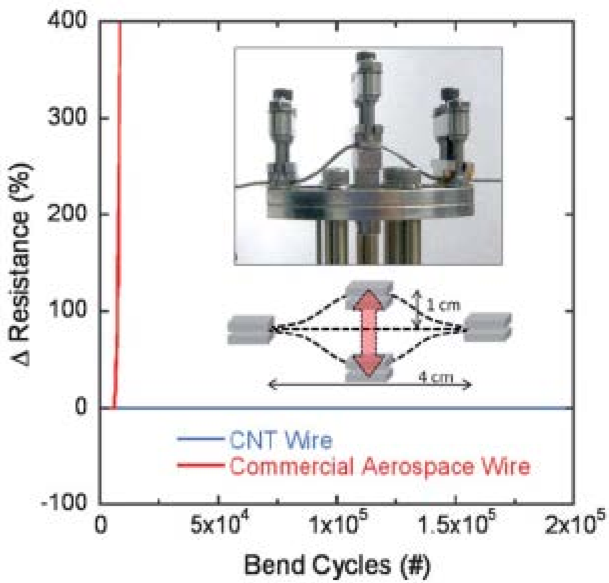
Space Power Workshop

Torrance Marriott Redondo Beach, Torrance, CA

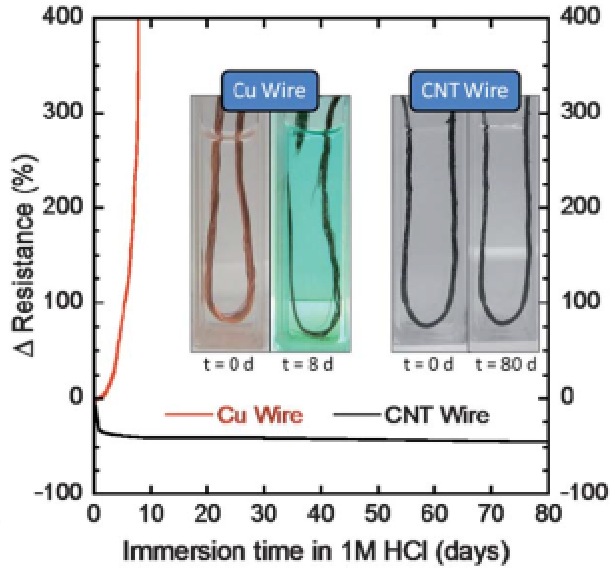
April 1–4, 2019

Advantages of Carbon Based Conductors

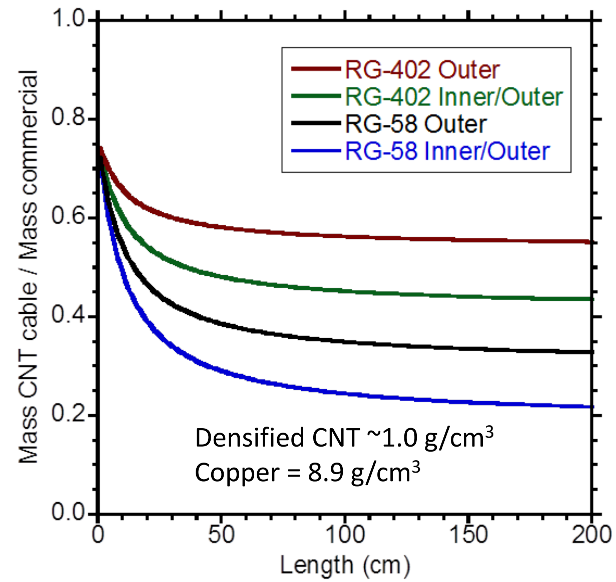
Flexure Tolerance

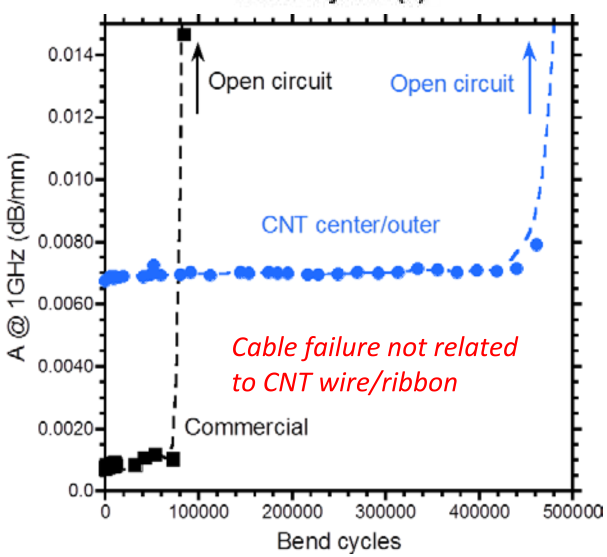


Corrosion Resistance



Mass Savings





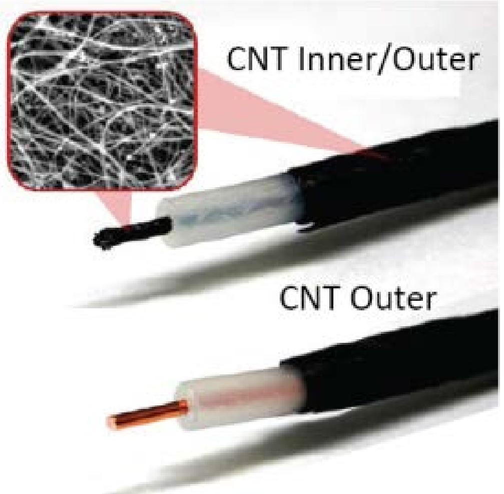
Carbon based conductors lead to benefit from increased flexibility, corrosion stability, and reduced density.

P. Jarosz, *et al. Nanoscale*, **2011,** vol. 3, pp. 4542-4553.

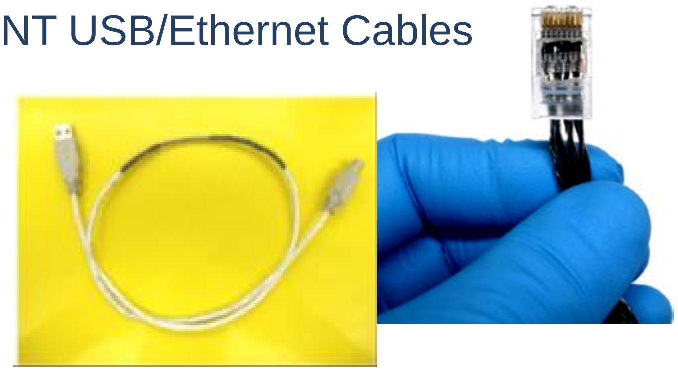
Applications for High Conductivity Carbon Conductors

Data Cable Prototypes

CNT Coaxial Cables within Specification

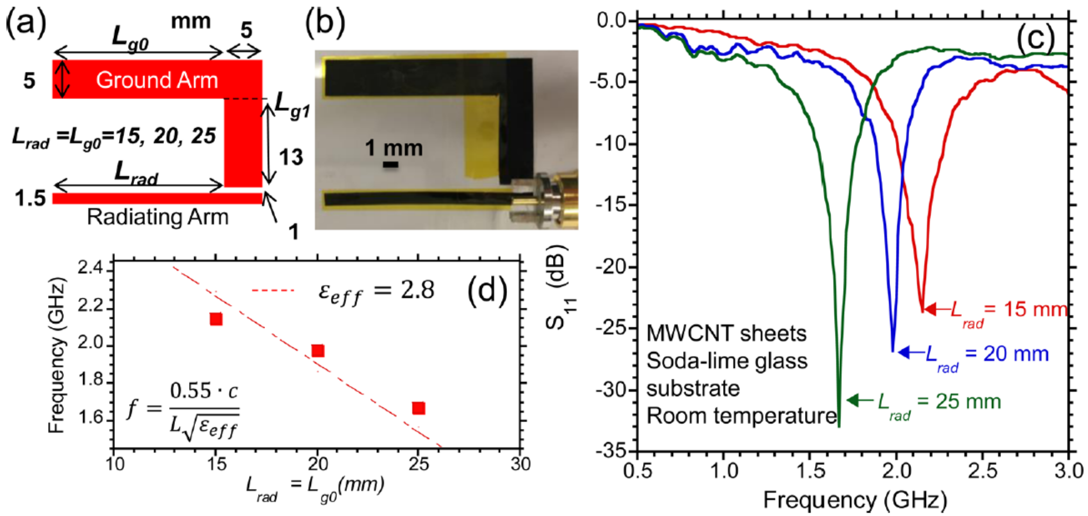


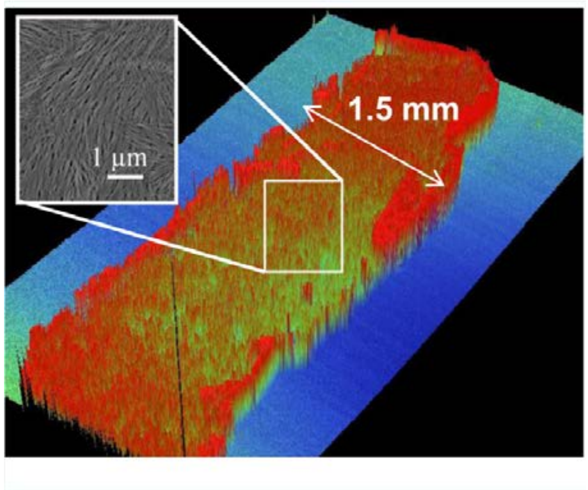
CNT USB/Ethernet Cables



Jarosz, et al. *ACS Appl. Mater. Interfaces* **2012**, *4*, 1103–1109.

RF Device Prototypes

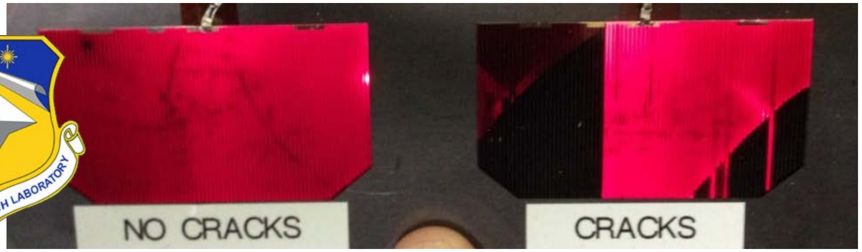




Puchades, I. et al. ACS Appl. Mater. Interfaces, **2016**, 8, 20986–20992

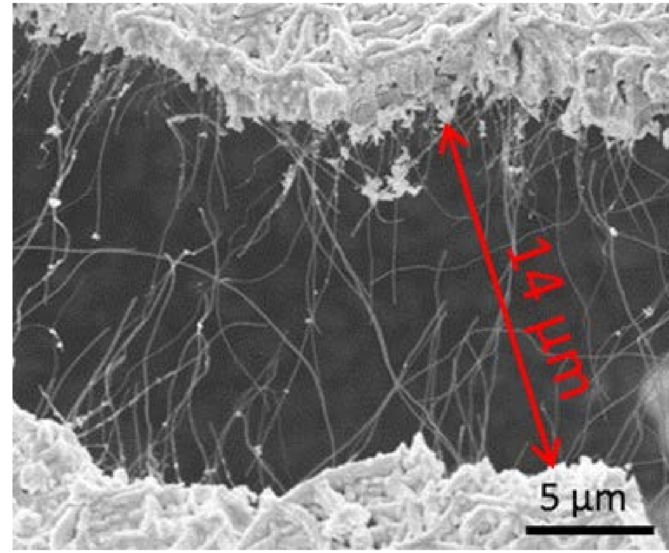
RIT

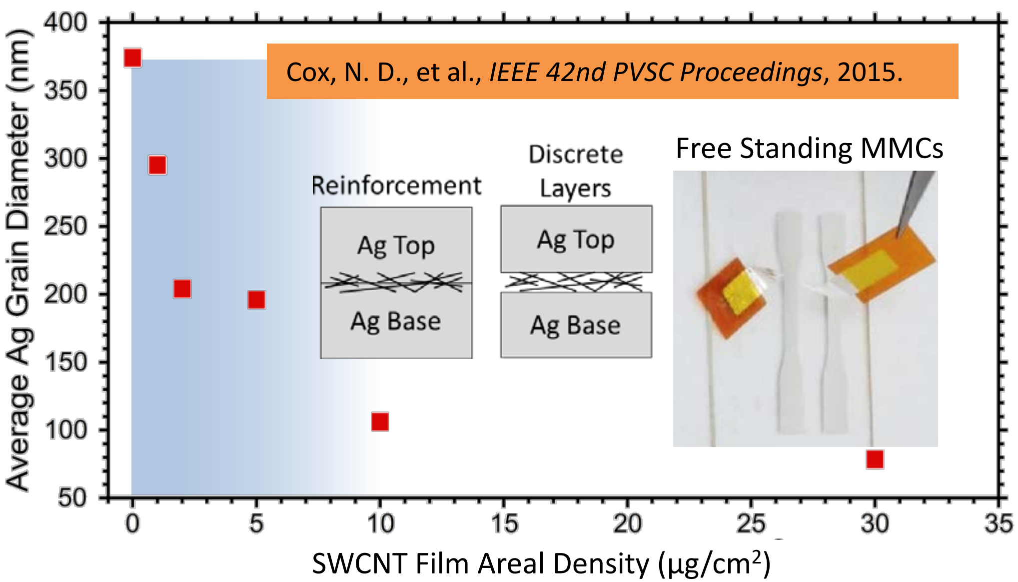
CNT-MMCs for Solar Cell Electrodes

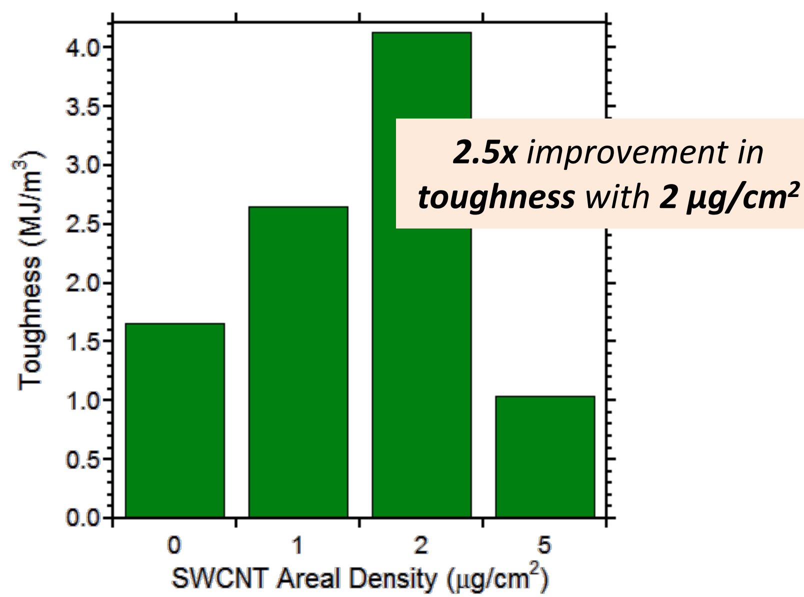


FA9453-14-1-0232

__Technology Goal:__ Overcome **loss of active area** in advanced thin film and IMM solar cells contacts due to mechanical vibration and thermal shock which “crack” grid fingers.





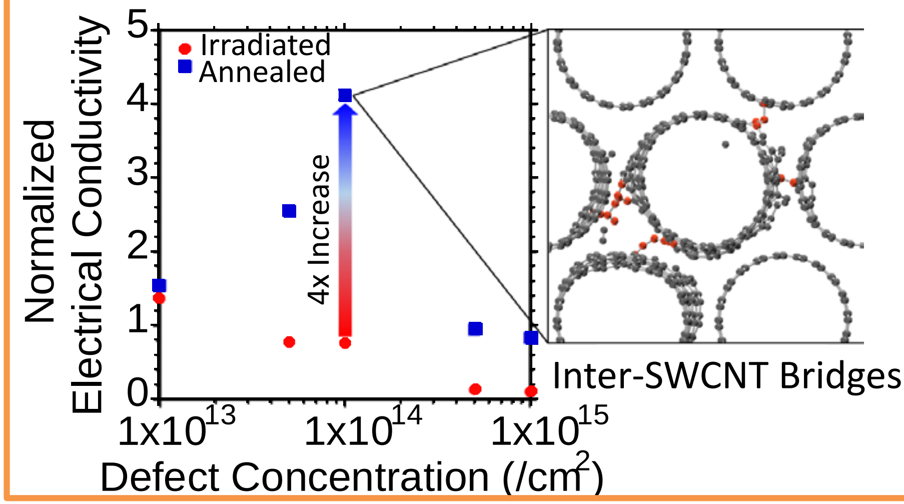


Cox, N. et al. J Mater Sci, ***2016****, 51, 10935-10942.*

Radiation Effects in CNTs

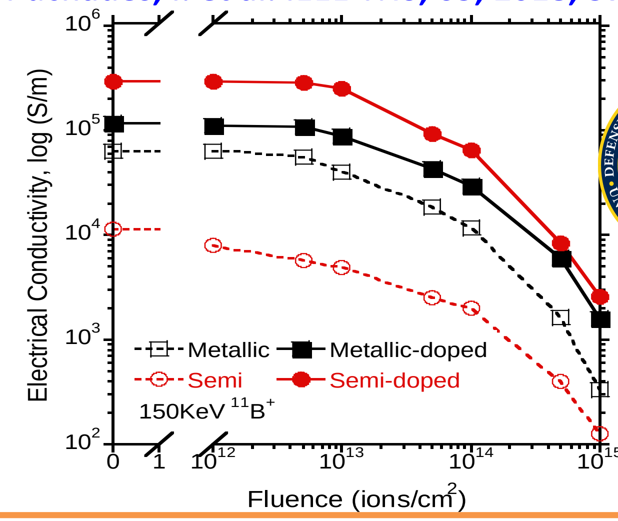
Cross-linking from Radiation + Annealing

Rossi, J. et al. J. Phys. Chem. C 2016, 120, 15488–15495



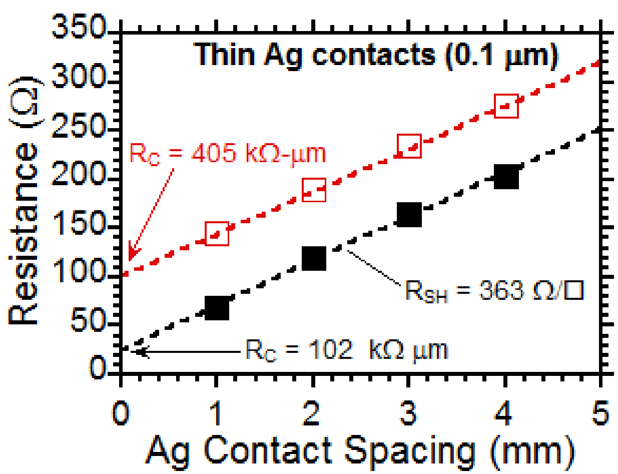
Effects of Doped Separated SWCNTs

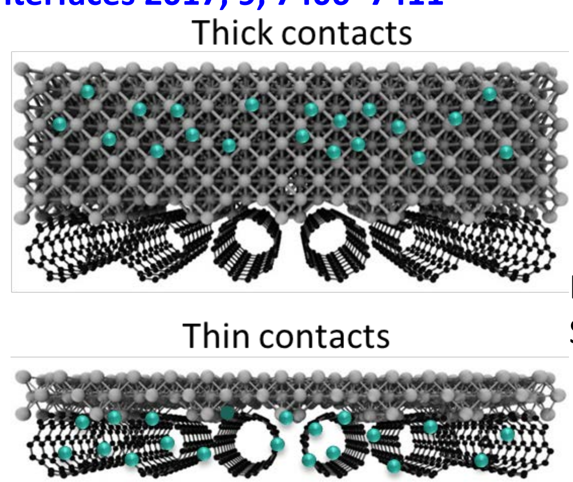
Puchades, I. et al. IEEE TNS, 65, 2018, 573.



Effects of irradiated thin contacts on specific contact resistance

Cox, N. et al. ACS Appl. Mater. Interfaces 2017, 9, 7406–7411





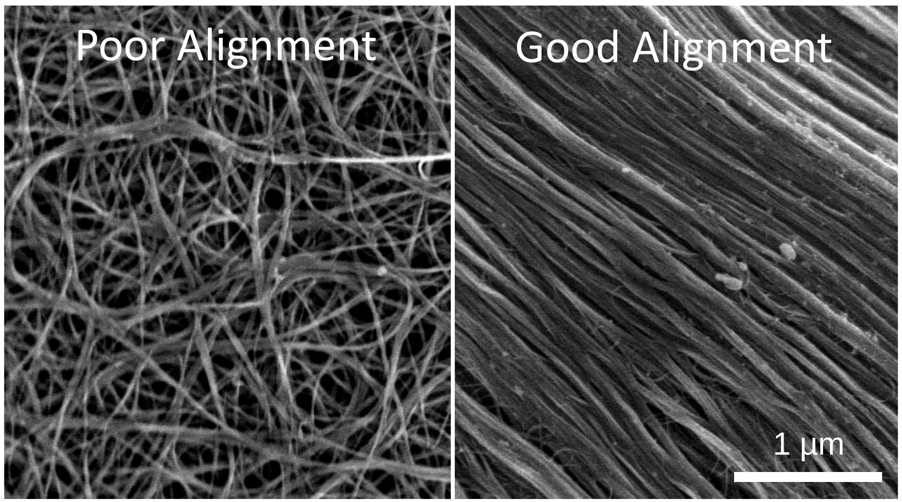
Enhanced Ag/ SWCNT interface

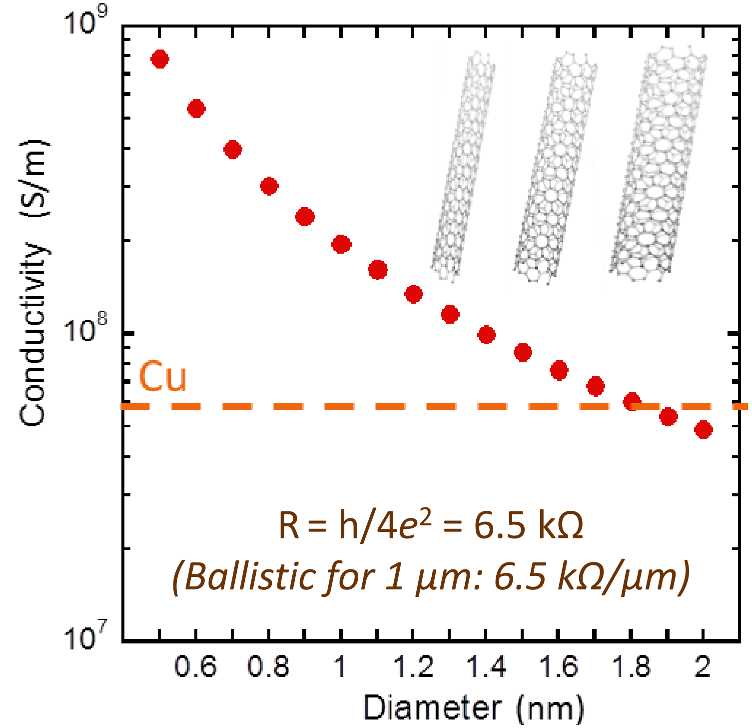
RIT

Factors Inflencing Bulk CNT Conductivity

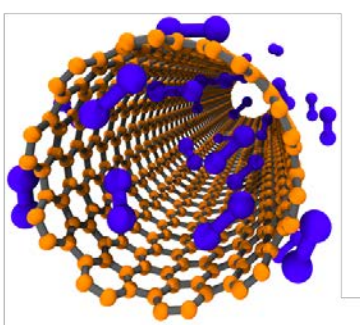
1. Alignment (Network Properties)

- Electrical transport is ballistic along the length of CNTs, thus, axially aligned CNTs have better conduction in that direction.





2. Intra-CNT Transport (Intrinsic CNT Properties)



- Diameter Dependent
- Improved by Purity and Chemical Doping

CNT chemical doping is due to non-covalent surface adsorption of electron donating or withdrawing species.

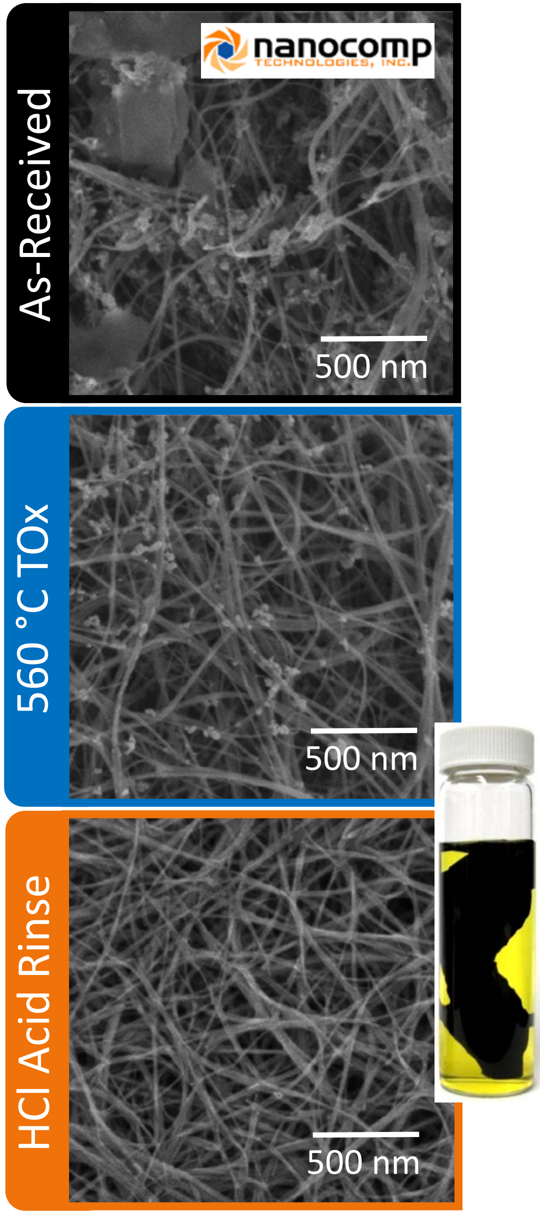
3. Inter-CNT Transport (Network Properties)

- Doping reduces tunneling barrier.
- Organization of CNTs [bundles] affects density and cross-sectional area.

Conductivity	Specific Conductivity
$\sigma = \frac{L}{RA}$	$\sigma_s = \frac{\sigma}{\rho} = \frac{\frac{L}{RA}}{\frac{M}{LA}} = \frac{L^2}{RM}$

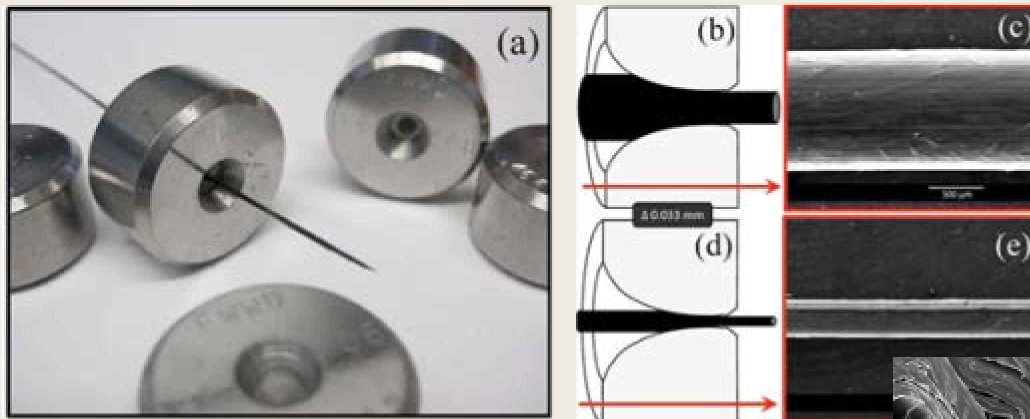
RIT

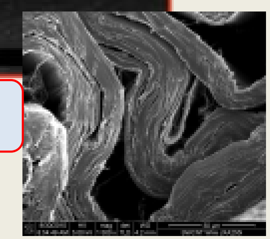
CNT Purification and Wire Fabrication



Wire fabrication Approaches – Top Down vs. Bottom Up

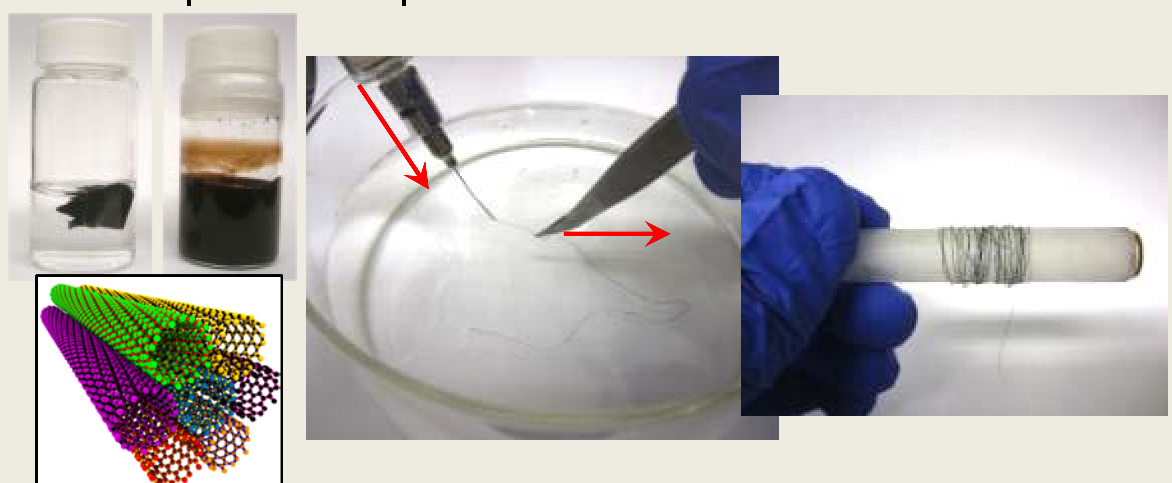
Radial Densification





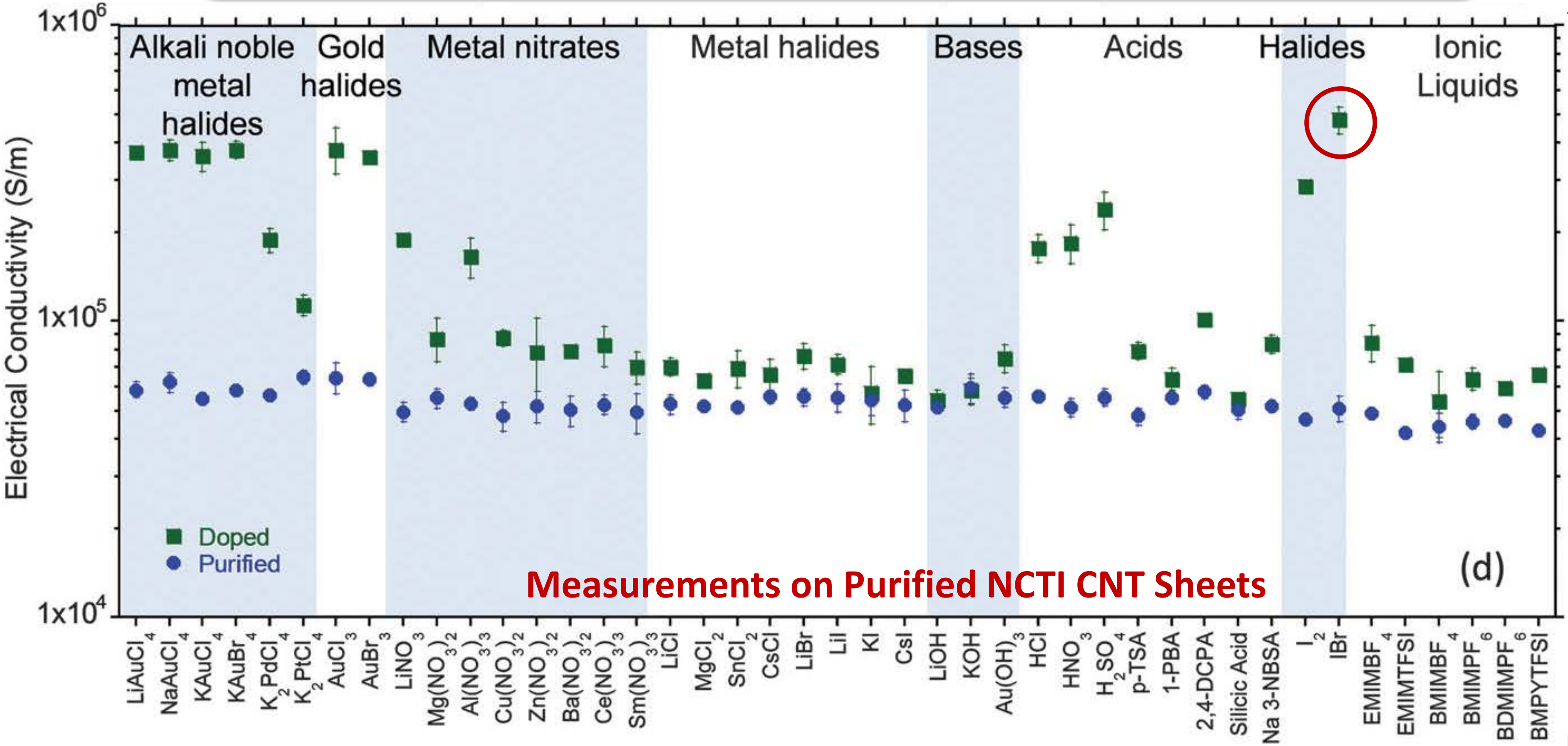
Alvarenga, J.; et al., *Applied Physics Letters,* **2010,** 97, 182106

Superacid Dispersion and Extrusion



RIT

Chemical Dopant Influence on CNT Conductivity

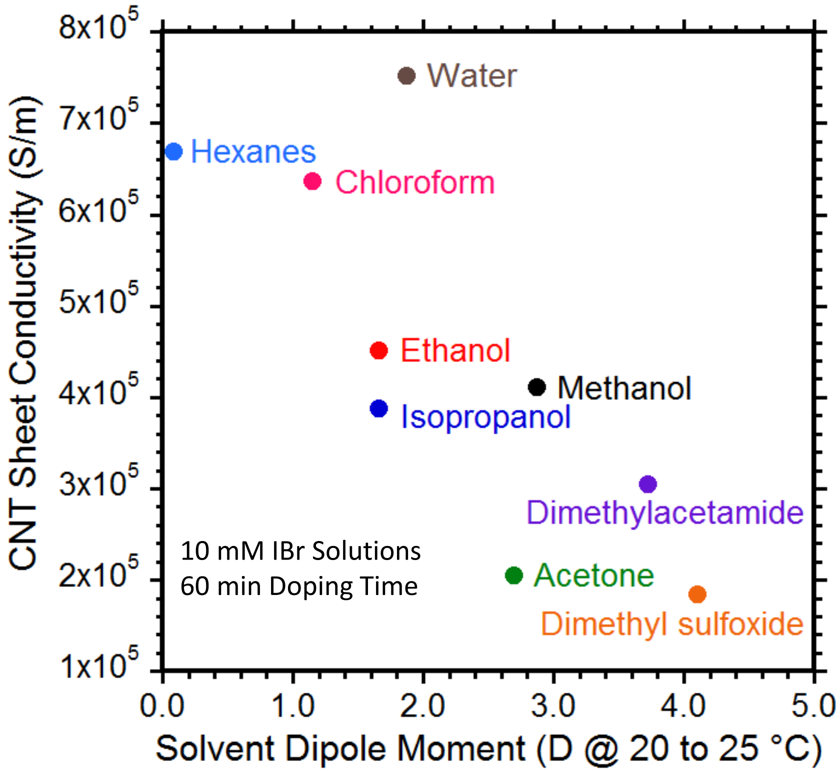


- The noble metal halides and halides represent the best improvement in conductivity, even over strong acids. The lack of conductivity improvement in all high-electrochemical potential species may due to low dopant adsorption or competing solvent effects.
- CNT chemical doping is due to non-covalent surface adsorption or charge-transfer complexes of electron donating or withdrawing species (i.e. n- or p-type doping).

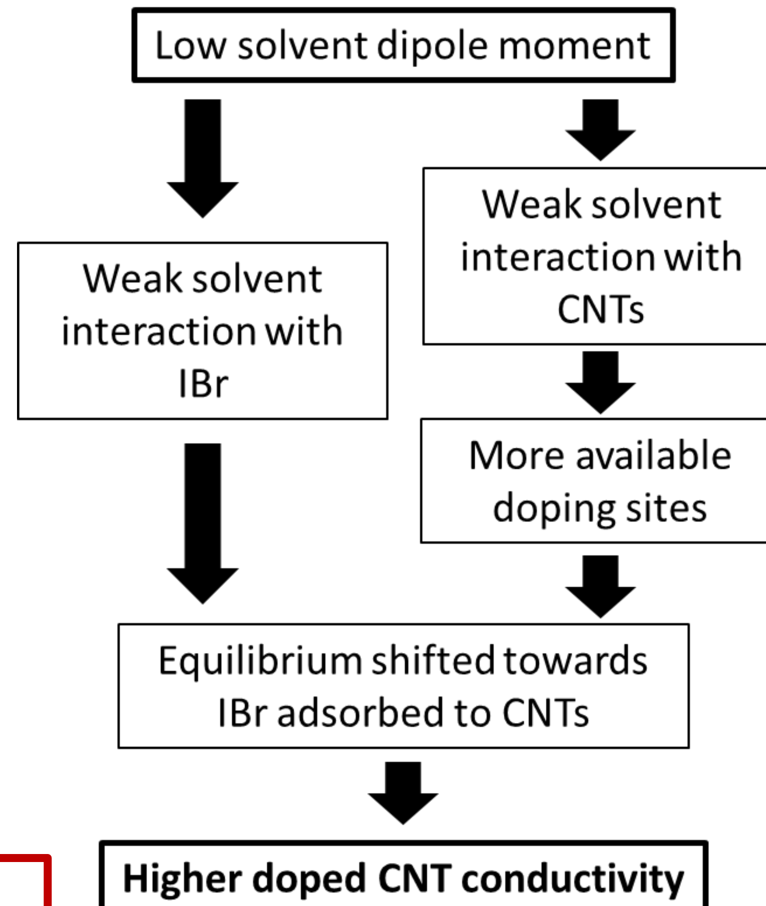
Puchades, I. et al. *J. Mat. Chem. C.* 2015, 3, 10256

Dopant Delivery in CNT Sheets: Solvent Matters

Measurements on Purified NCTI CNT Sheets



Proposed Mechanism:



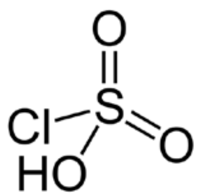
IBr:Solvent interactions show prominent solvatochromic behavior with varying solubility and doping effectiveness.

A.R. Bucossi, et al., *ACS Appl. Nano Mater.* ***2018****, 1, 5, 2088-2094*

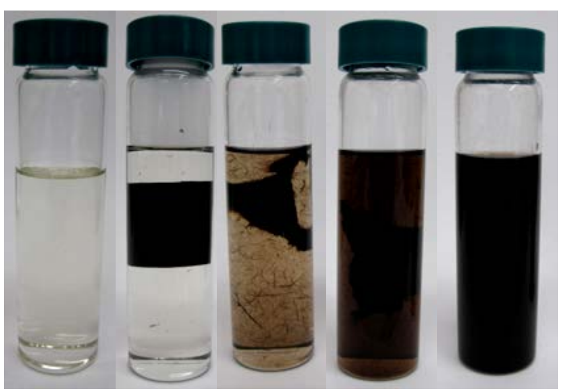
RIT

Dispersion in CSA and Coagulation

<u>Superacid</u> –an acid with an acidity greater than that of 100% pure sulfuric acid



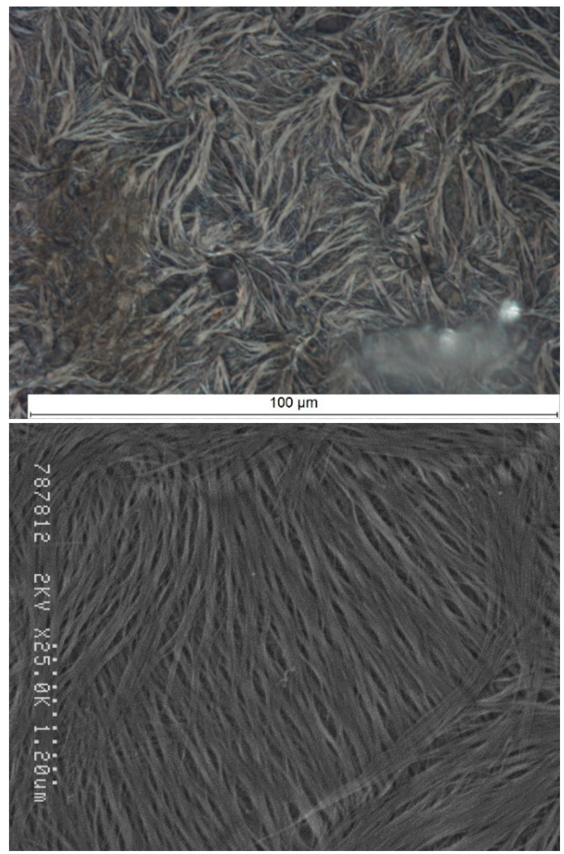
Chlorosulfonic acid (CSA) is used in several studies to disperse CNTs

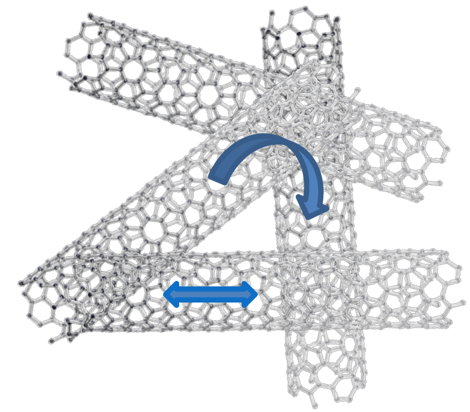


<u>Protonation</u> of CNTs leads to **<u>Dispersion.</u>**

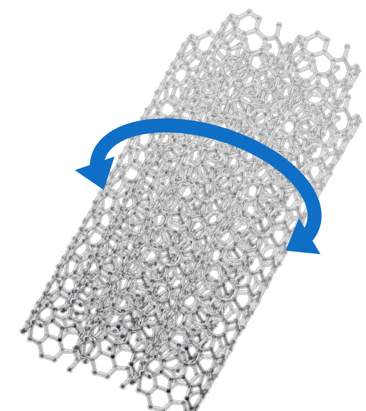
[Davis et al. *Nat. Nano.* 2009, 4, 830]

Filtered CSA Films show crystallinity using microscopy, but no preferential alignment



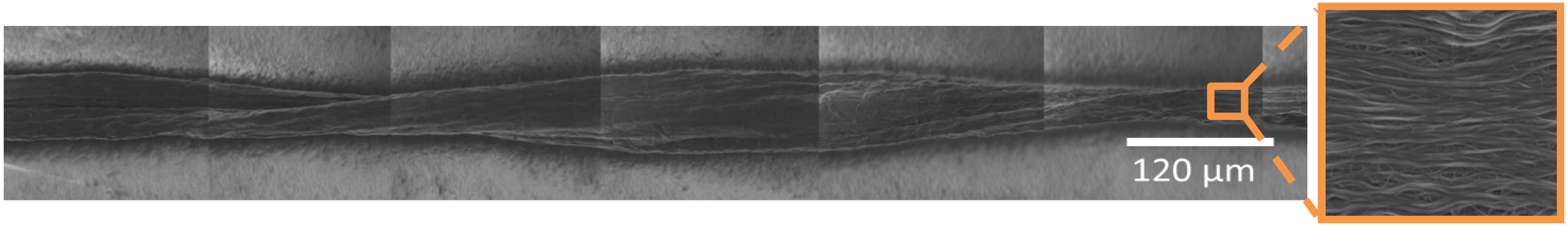


CNTs in well-aligned aggregates provide maximum conductivity

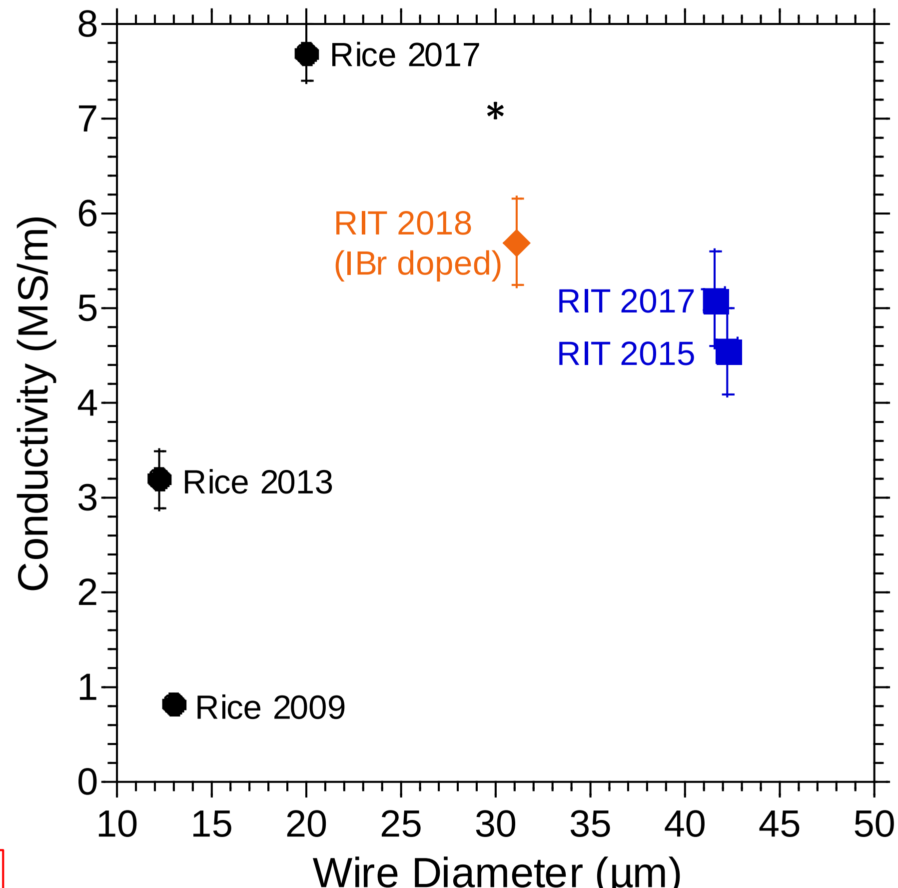


Shear forces on coagulating dispersion induce alignment which is exploited using a syringe needle in extruded wires.

SWCNT Wire Fabrication



- High-purity SWCNT wires extruded from CSA resulted in highest reported conductivity for acid-doped wires.
- Thermal imaging determined thermal conductivity of 300 W/mK.
- Coagulant composition (acetone) and low temperature directly affect wire uniformity through kinetic passivation vs. reaction with acid and decomposition – exceeding **5 MS/m.**
- **Doping the best performing wire with IBr lead to an RIT record of 5.7 ± 0.5 MS/m.**

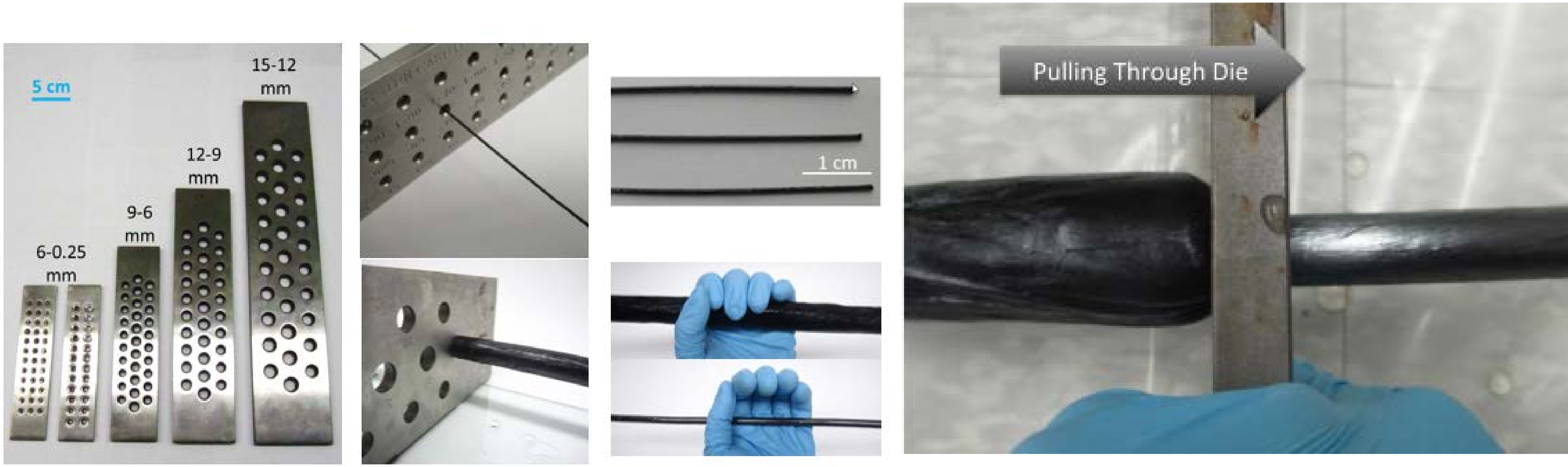


Bucossi, A. et al. *ACS Appl. Mater. Interfaces*, **2015**, 7, 27299.

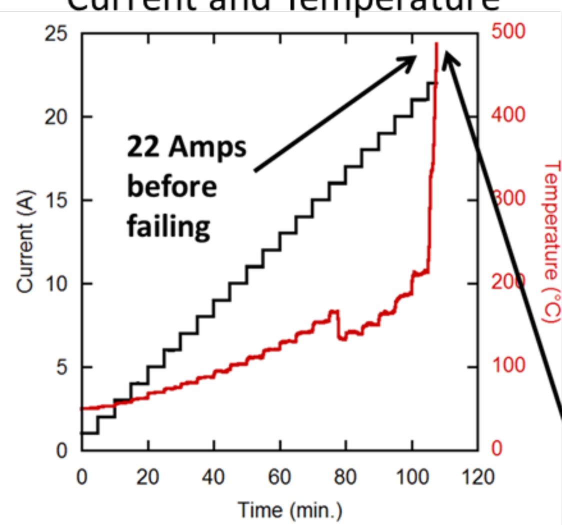
*Tsentalovich, Dmitri E., et al. *ACS applied materials & interfaces* 9.41 (2017): 36189-36198.

RIT

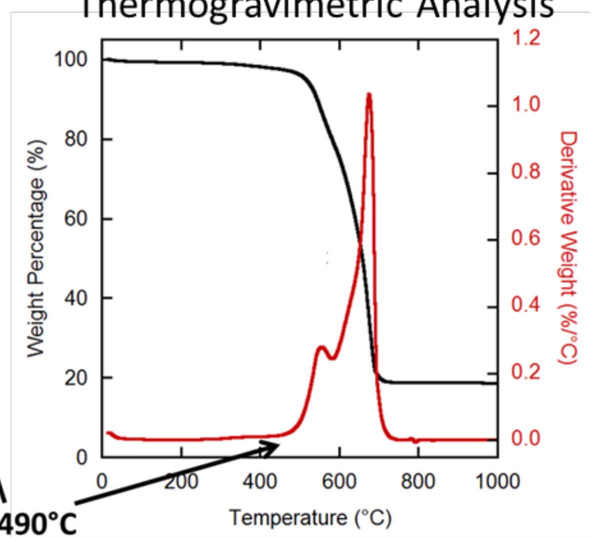
Wires from NCTI Sheets and Failure Current Testing



Current and Temperature



Thermogravimetric Analysis



~490°C

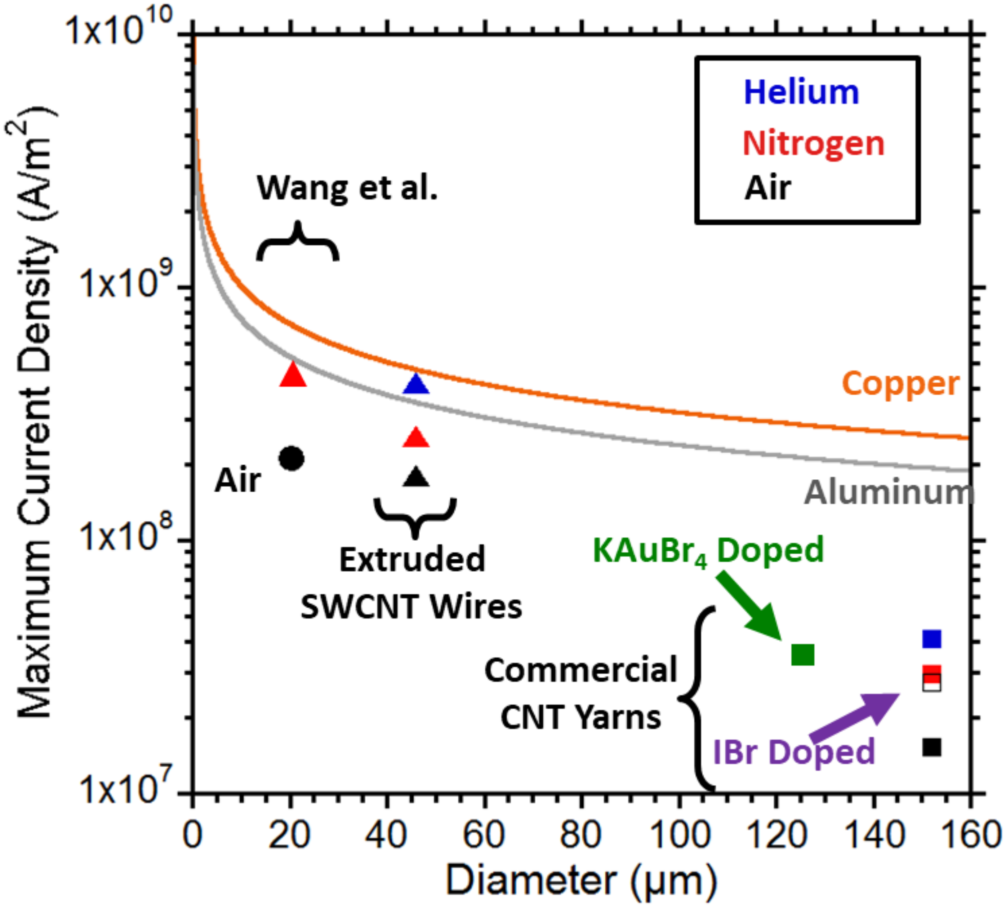
- 5 mm diameter CNT wire.
- Failure due to oxidation of CNTs in air, unlike metals which typically fail due to melting.

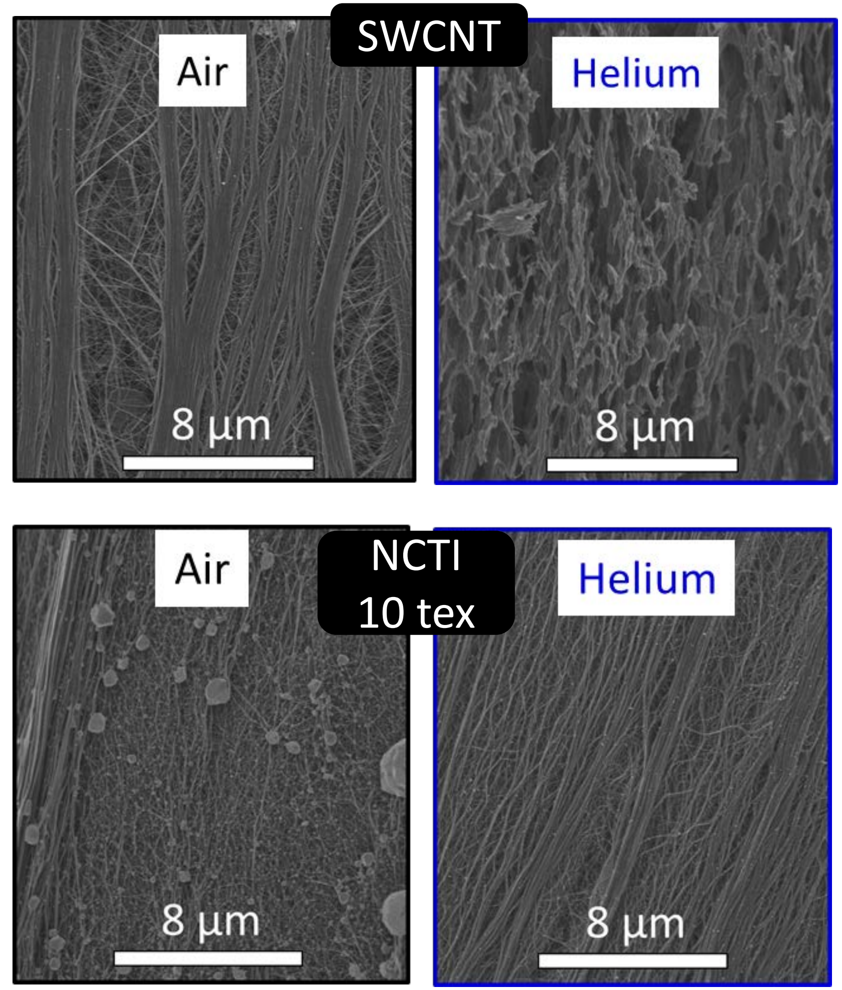
Cress, C.; et al., *Journal of Applied Physics*, **2017**, 122, 025101

RIT

Max Current Density for CNT Conductors

Summary of Results

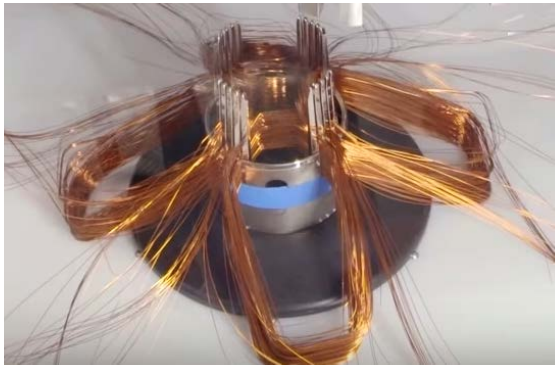




- Preventing oxidative failure of extruded SWCNT wires enables them to reach maximum current densities greater the fuse law calculations for aluminum.
- SEM analysis shows abrupt failure of NCTI yarns in inert environments where extruded SWCNT wires achieve higher max current density and damage of materials.

RIT

Considerations in Design of Hybrid Conductors

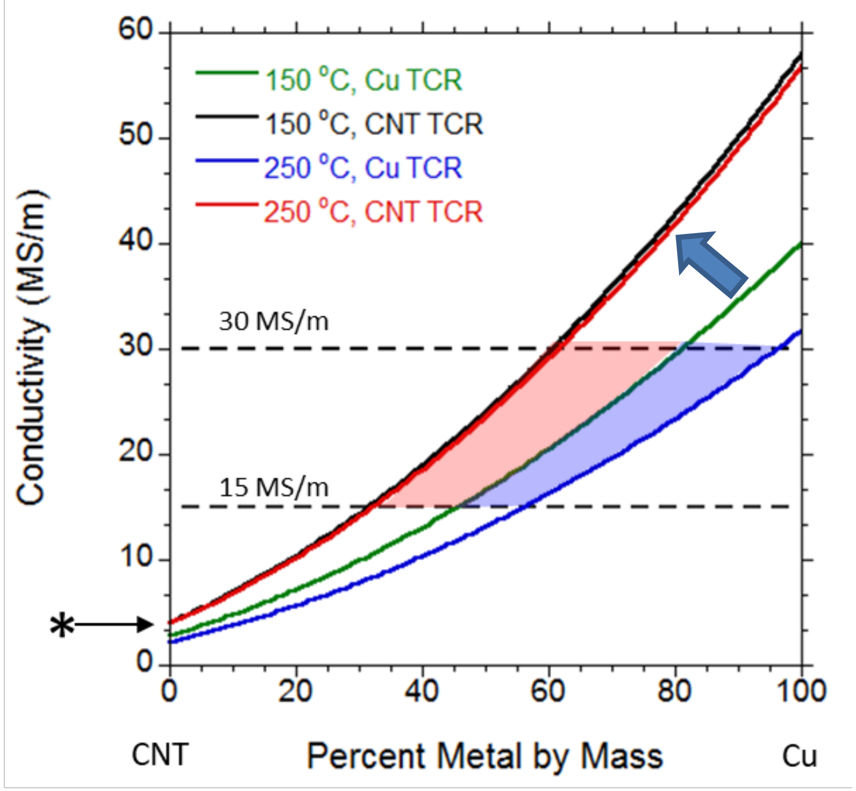


>800 m of Cu in standard electric vehicle stator

youtube.com/watch?v=nZkyfZqlptA

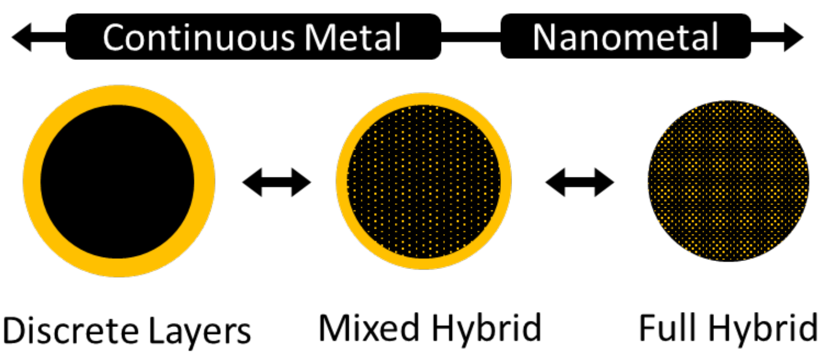
– **I^2R losses and excess mass** leads to inefficiencies in wire electrical transport (ex. Motors).

– Operation at 150-250 °C exacerbates the problem due to the **positive temperature coefficient of resistance (TCR)** of most metals used.



OPPORTUNITY

- **Carbon conductors** are ~10x lower conductivity than Cu, but **have improved TCR and density.**
- Metal integration can bridge CNT:CNT junctions dependent on deposition technique and "wettability".
- A hybrid has potential for higher conductivity and better TCR at lower copper mass.



*Bucossi, A. et al. *ACS Appl. Mater. Interfaces*, **2015**, 7, 27299–27305

Experimental CVD Approach

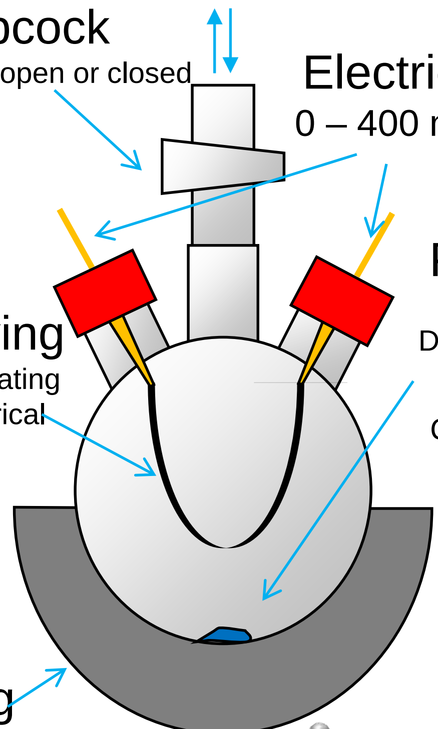
To Schlenk Line (inert)
5% H_2/95% Ar or Vacuum

Stopcock
Vacuum line open or closed

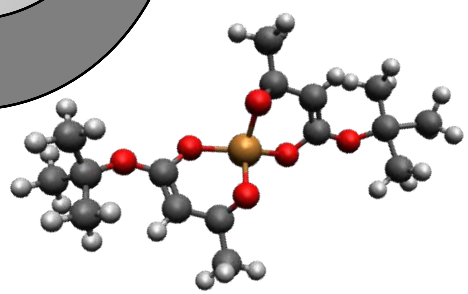
Electric Leads
0 – 400 mA current

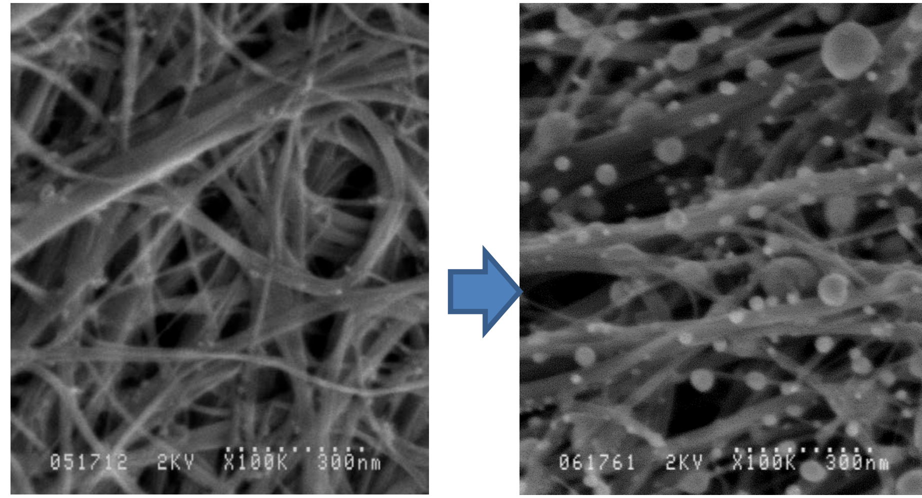
Precursor
M.P. 110°C
Deposition Temp. 225°C
Cu(II) bis(t-butyl acetoacetate)

CNT Roving
Local Joule heating through electrical current

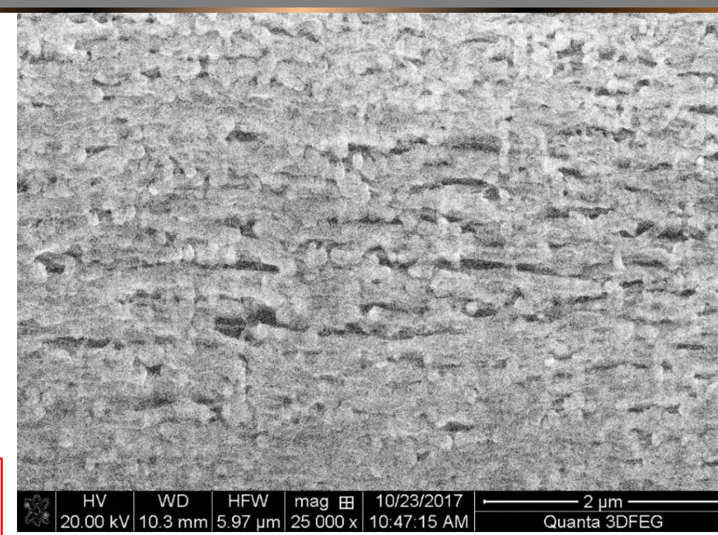


Heating Mantle
Heat for vaporization of precursor





SEM reveals metallic nanoscale particulate on roving and penetration into the CNT network based on FIB-SEM.

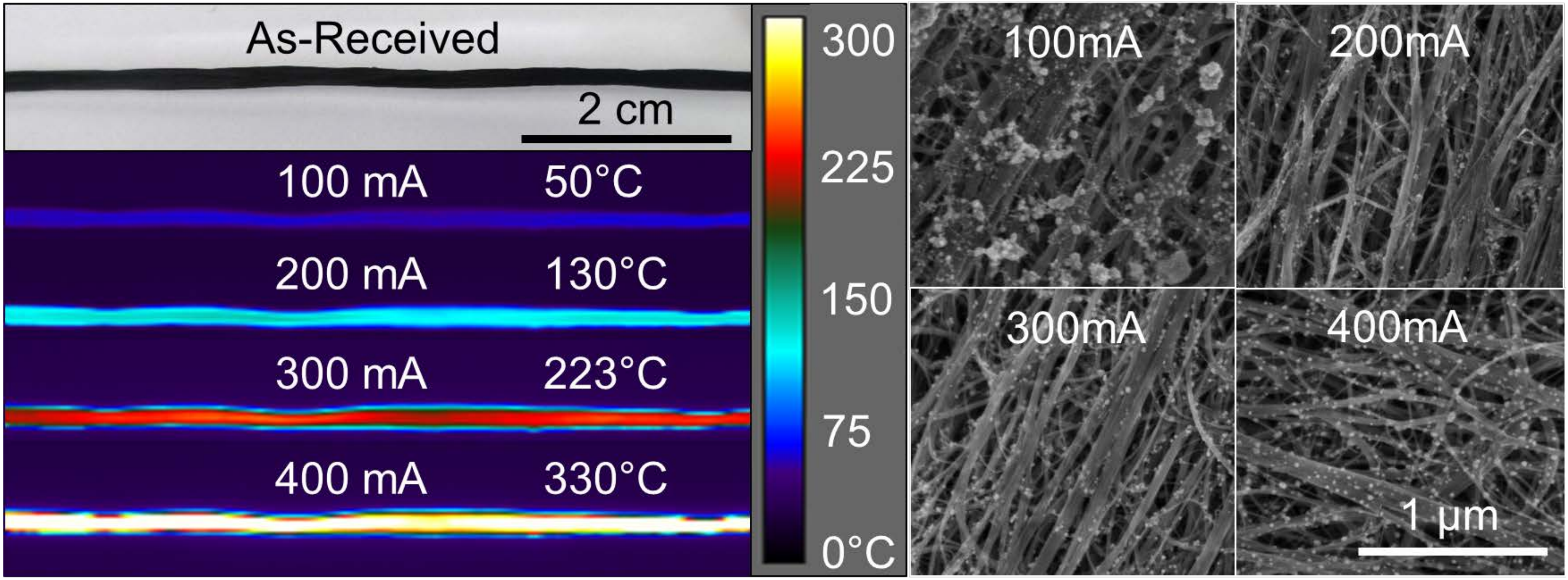


Precursor vaporized and thermally decomposes onto CNT surface during Joule heating of CNT Wire.

Landi, B.J., et al. Prov. Patent App. No. 62/698321, **2018.**
Leggiero, A.P., et al. *ACS Appl. Nano Mater*. **2019**, 2, 1, 118-126.

RIT

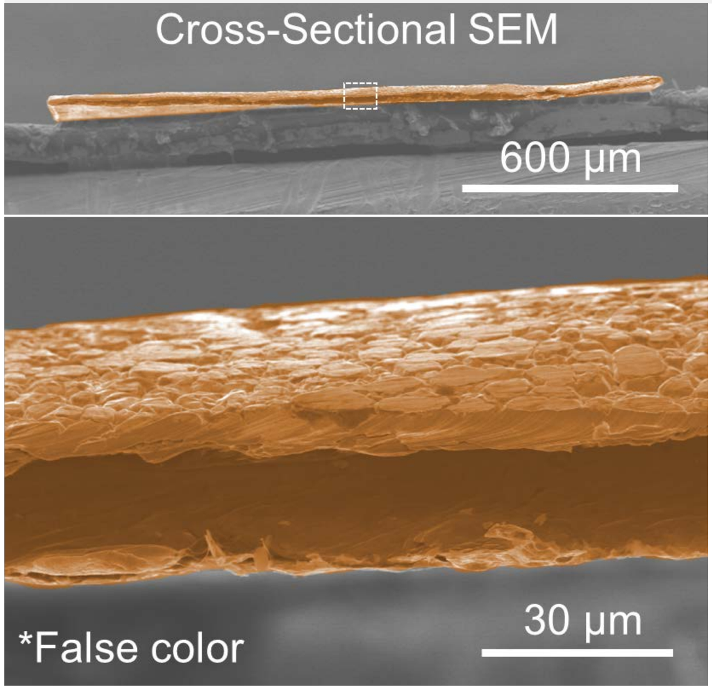
Applied Current Control of Deposition



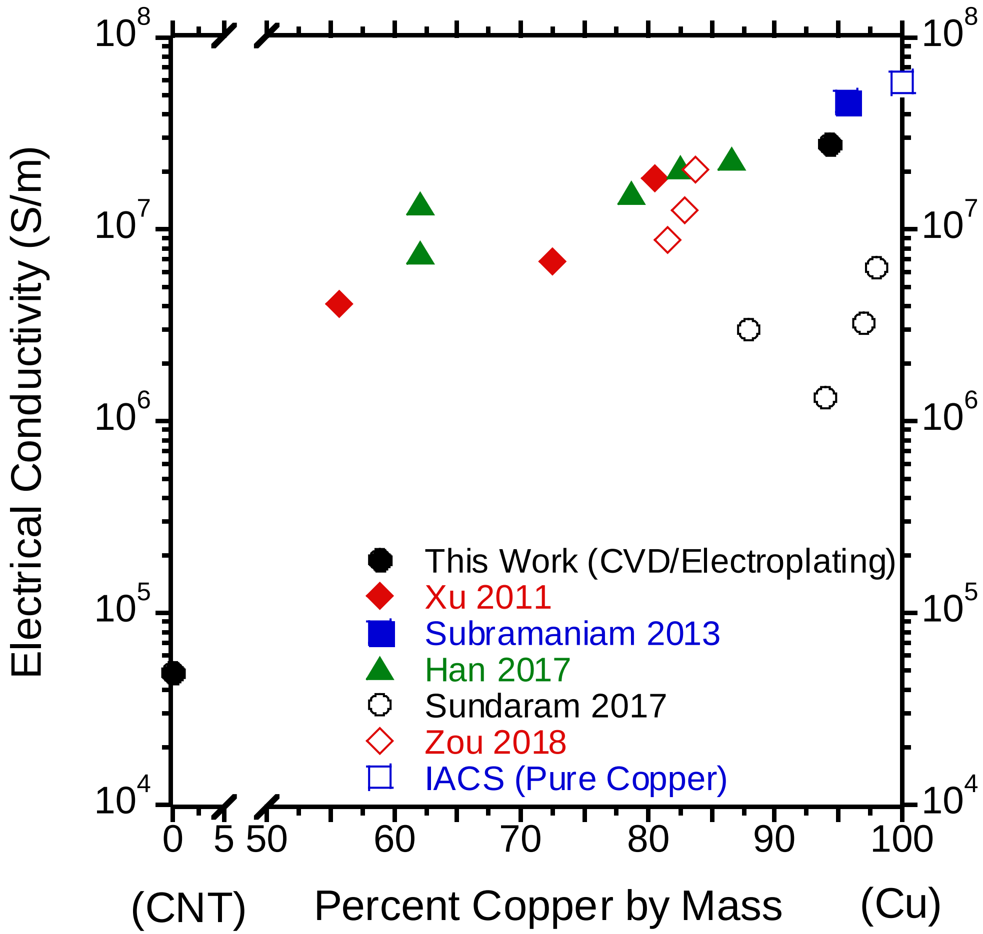
- Thermal images of roving under applied current in air show that between 200-300 mA, the temperature appears to cross over the deposition temperature of $Cu(tBAOAC)_2$ (>225°C).
- SEM analysis of samples from bias at 300 and 400 mA show uniform particle distribution.
- Samples biased at 400 mA had a slightly higher rate of failure.

Conductivity of $Cu(tBAOAC)_2$ Seeded and Electroplated Samples

Cross-sectional area was evaluated from optical and SEM images to calculate conductivity.



Sample	$Cu(tBAOAC)_2$ Seeded + Electroplated
Copper Mass %	94.2%
Cross-Sectional Area (m²)	3.13E-08
Resistance/Length (Ω/m)	1.14
Conductivity (MS/m)	28.1



Leggiero, A.P., et al. *ACS Appl. Nano Mater*. **2019**, 2, 1, 118.

The 94.2% Cu-CNT hybrid conductor achieves a high conductivity of 28.1 MS/m for its copper mass loading, 569x CNT starting conductivity.

Acknowledgements

United States Government

Office of Naval Research Science & Technology

(N00014-15-1-2720)

U.S. DEPARTMENT OF ENERGY

DE-EE0007862