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Walker Department
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Cu

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Advanced Electrical Conductors

An Overview and Prospects

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Overview

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REVIEW ARTICLE

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Advanced Electrical Conductors: An Overview and Prospects of Metal Nanocomposite and Nanocarbon Based Conductors

Mehran Tehrani

Advanced electrical conductors that outperform copper and aluminum can revolutionize our lives by enabling billions of dollars in energy savings and facilitating a transition to an electric mobility future. Nanocarbons (carbon nanotubes and graphene) present a unique opportunity for developing advanced conductors for electrical power, communications, electronics, and electric machines for the defense, energy, and automotive industries. Herein, the major research progress in the field of advanced nanocarbon-based and metal–nanocarbon conductors is compiled. The benefits and drawbacks of advanced conductors are also elucidated with respect to conventional ones and their materials science, mechanical and physical properties, and characterization are discussed. Finally, several areas of future research for advanced electrical conductors are proposed.

cost and inferior mechanical performance have limited its applications. Gold is less conductive than Cu but is used in highly corrosive environments because of its exceptional corrosion resistance. In certain applications, electrical conductivity may be compromised for strength, corrosion resistance, thermal expansion, etc. Over the last two decades, the need for power-dense and high-efficiency electrical systems has resulted in the emergence of advanced electrical conductors with unique sets of properties.

Room-temperature advanced conductors can be categorized into nanocarbon-based conductors and metal–nanocarbon conduc-

Cu

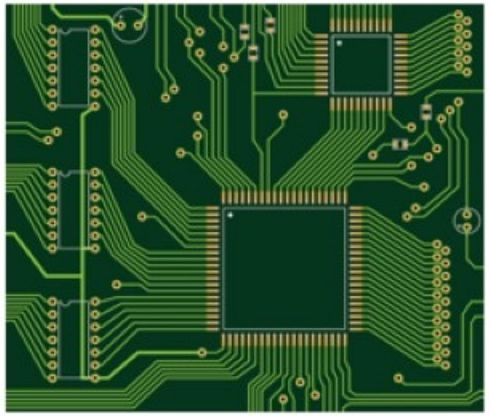
Throughout this presentation, References in [ ] refer to the ones in the above article.

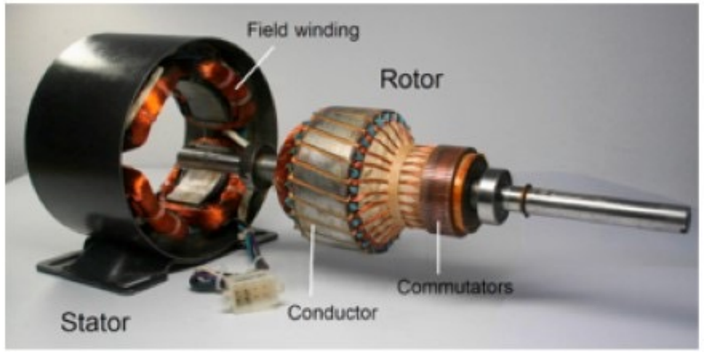
Electrical Conductors

HVDC Submarine Cable

Solar Cable

Offshore Wind Cable

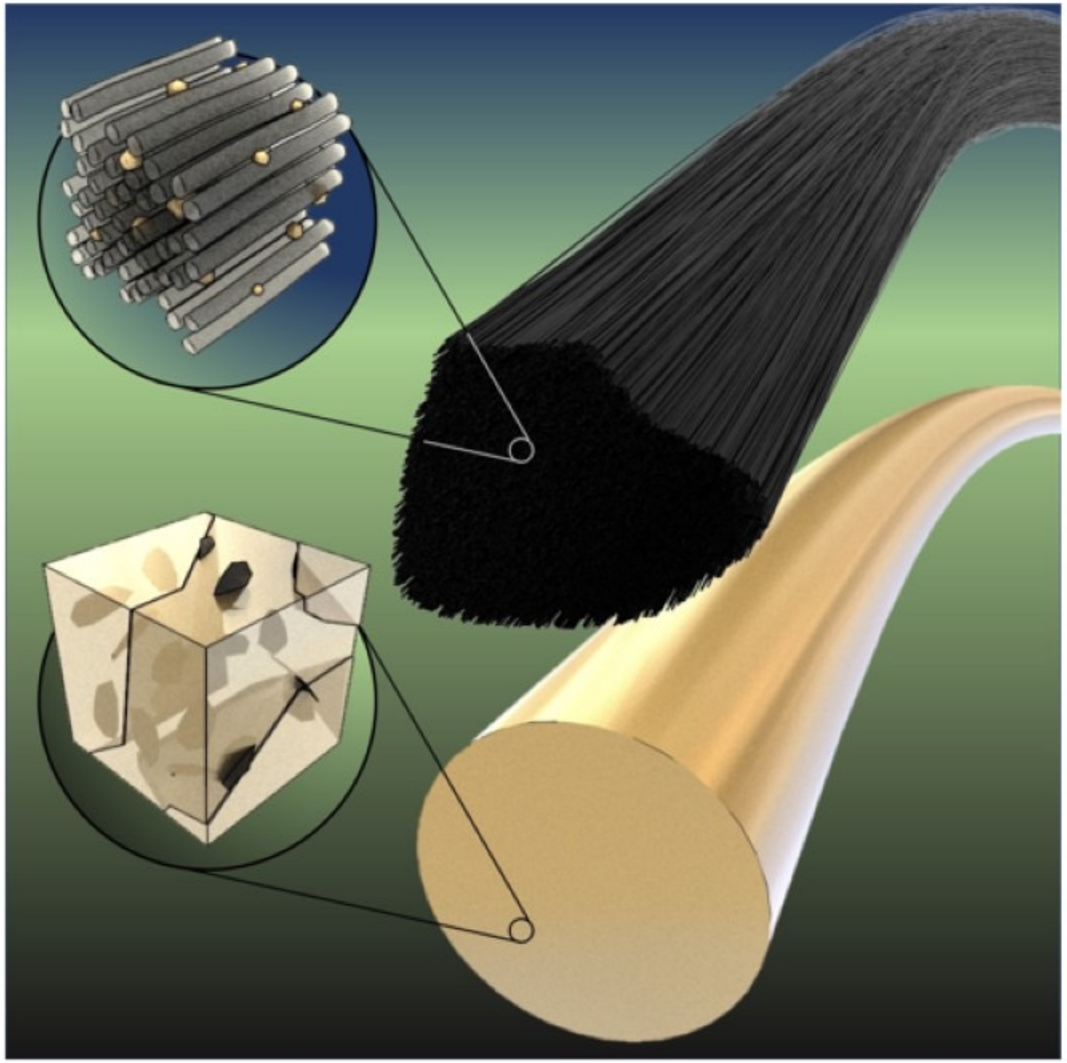




Images are taken from various interest resources.

Advanced Electrical Conductors

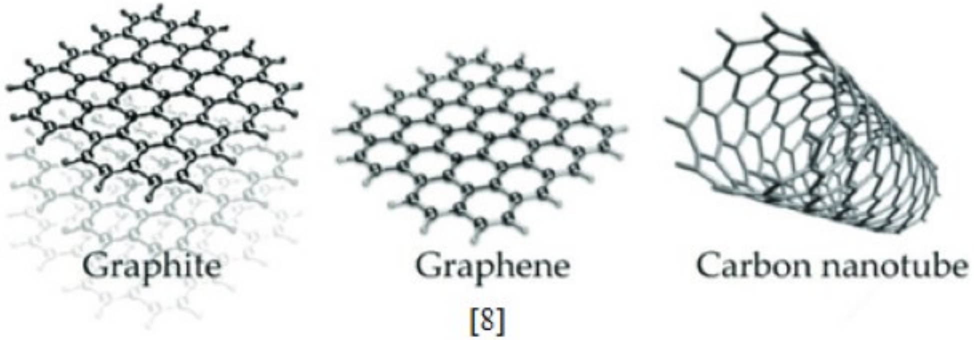
NANOCARBON-BASED:
nanocarbon matrix enhanced with dopants or intercalants



METAL-NANOCARBON:
metal matrix enhanced with nanocarbons

Room-Temperature Electrical Conductors

International Annealed Copper Standard (IACS), which has an electrical conductivity of 58.1 MS/m at 20ºC



[8]

	IACS [%]	Thermal conductivity [W mK^{-1}]	Strength [GPa]	Density [g cm^{-3}]	
Individual CNT or graphene[41,92]	33–172	>3000	20–100	1.4	$$$$$
Doped CNT fiber[7]	15	625	3	1.5	$$$$$
Doped graphene fiber[17]	2[a)]	1575	2	–	$$$
Doped carbon fiber[93]	24	>1000	1	2.5	$$$
Cu–CNT nanocomposite[50]	47[b)] ?	—	—	5.2	
Ultraconductive copper[47]	117 ?	—	—	8.9	
Copper	101	390	0.3	8.9	$
Aluminum	62	200	0.1	2.7	$
Silver	105	400	0.1	10.5	$$

[a)]An electrical conductivity of 38% IACS has been reported for a potassium-doped (measured in inert atmospheres) graphene fiber;[18] [b)]Exhibits a better electrical conductivity than copper above 80 °C.[50]

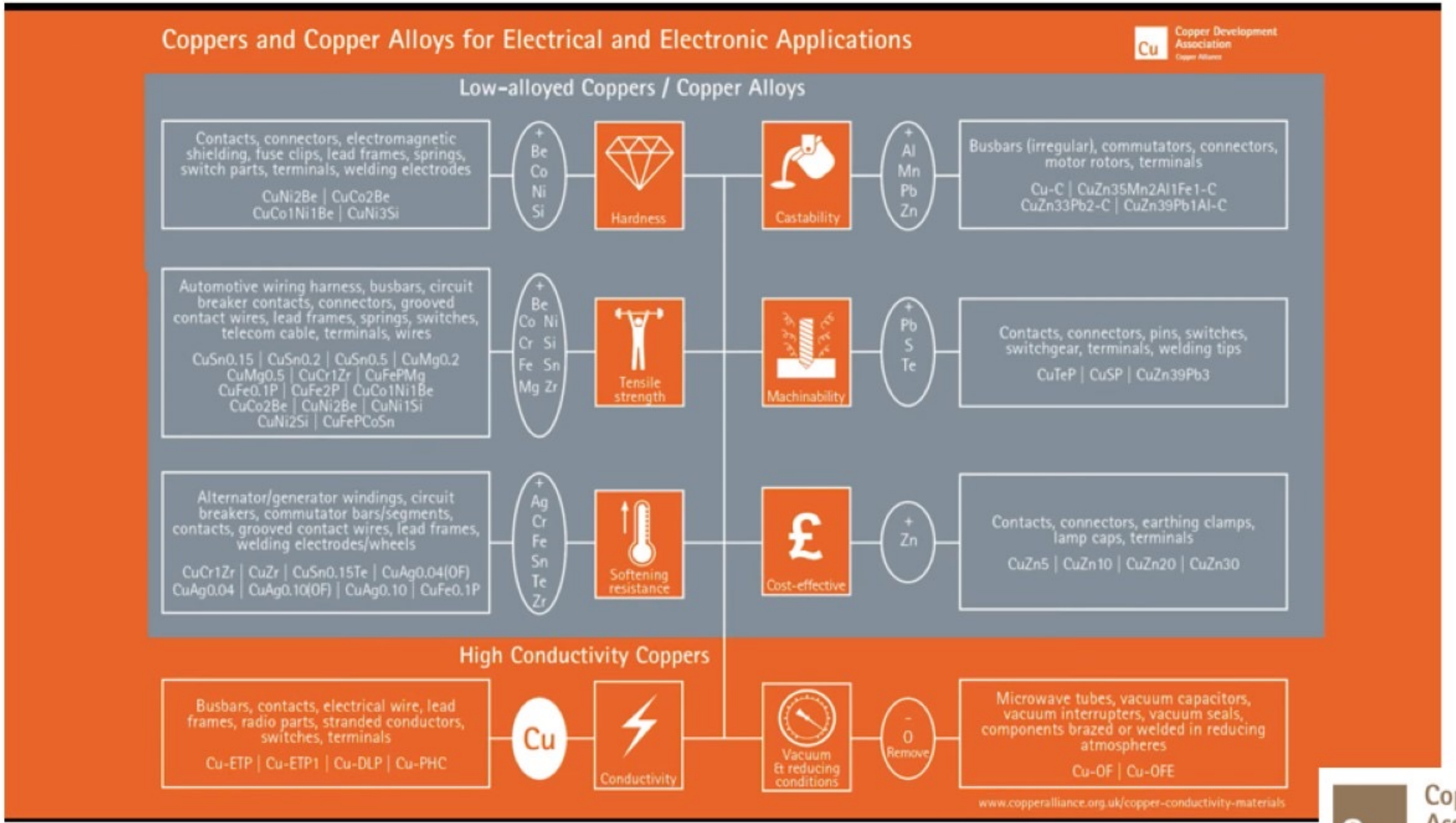
Copper vs. Aluminium

- Strength, strength per weight
- Conductivity (σ), σ per weight, σ per volume, σ per cost, elevated temperature σ
- Workability and handling (bendability)
- Corrosion resistance
- Creep
- Thermal expansion
- Ampacity (current carrying capacity)
- Cost
- Major applications

aluminium-busbar.com

shanpowercable.com

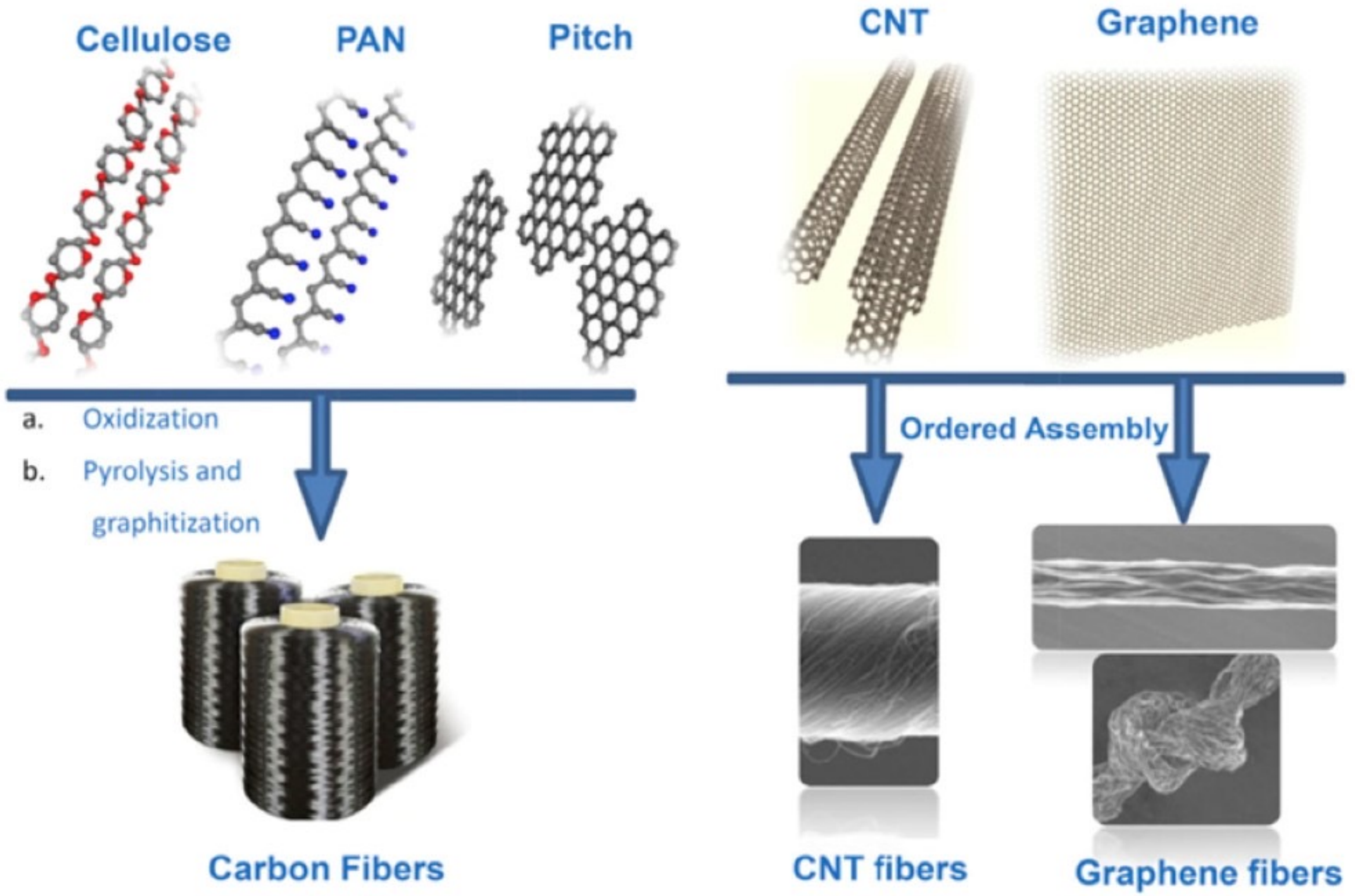
Copper Alloys



Copper Development Association
Copper Alliance

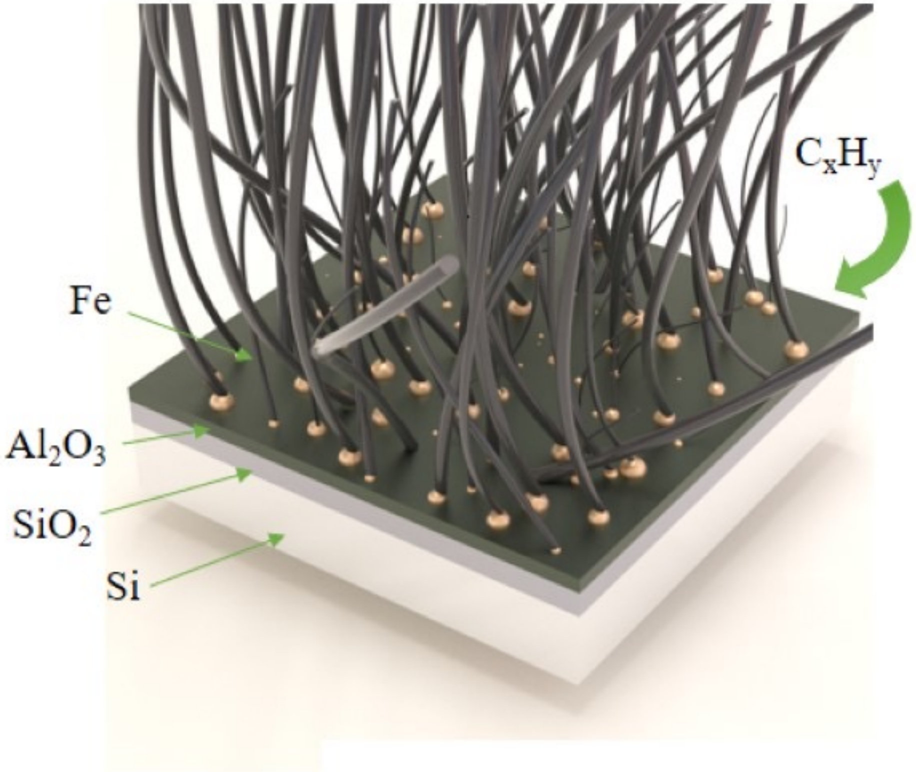
Carbonaceous Conductors

- **CNT**
  - SW-CNT
    - m-CNT
    - s-CNT
  - DW-CNT
  - FW-CNT
- **Graphene**
  - CVD-Gr
  - rGO
- **Carbon Fiber**
  - Pan-based
  - Pitch-based

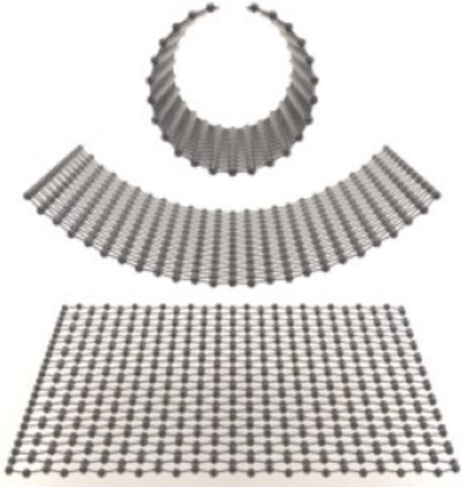


[39]

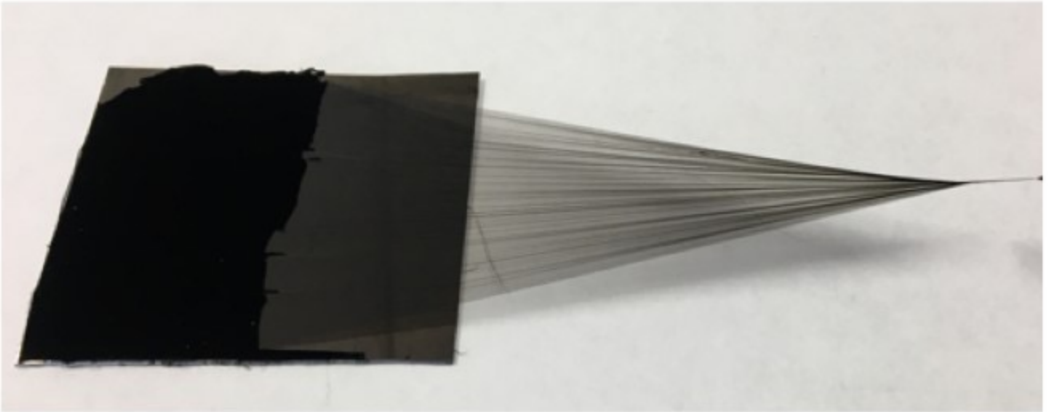
Carbon Nanotubes (CNT)



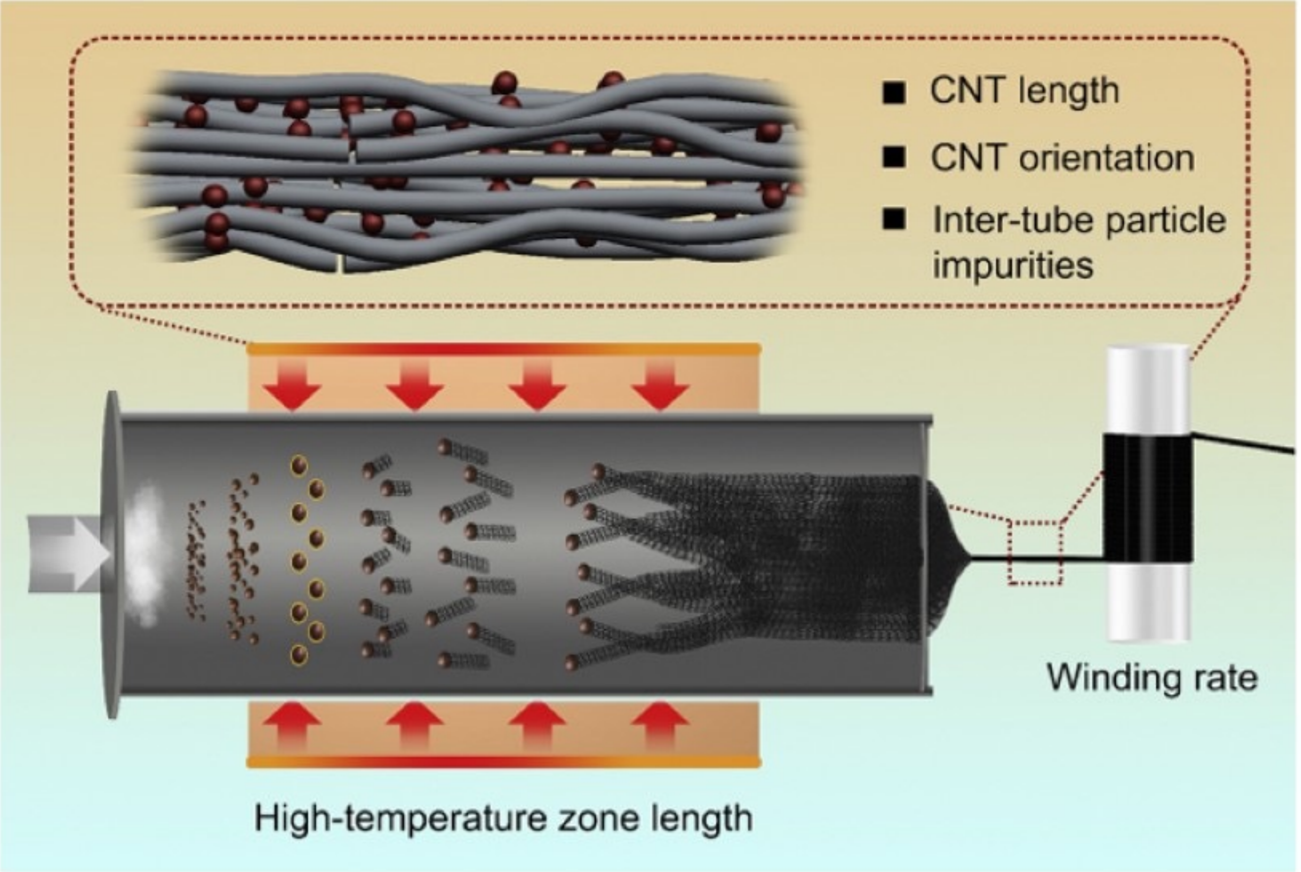
CNT nucleation and growth



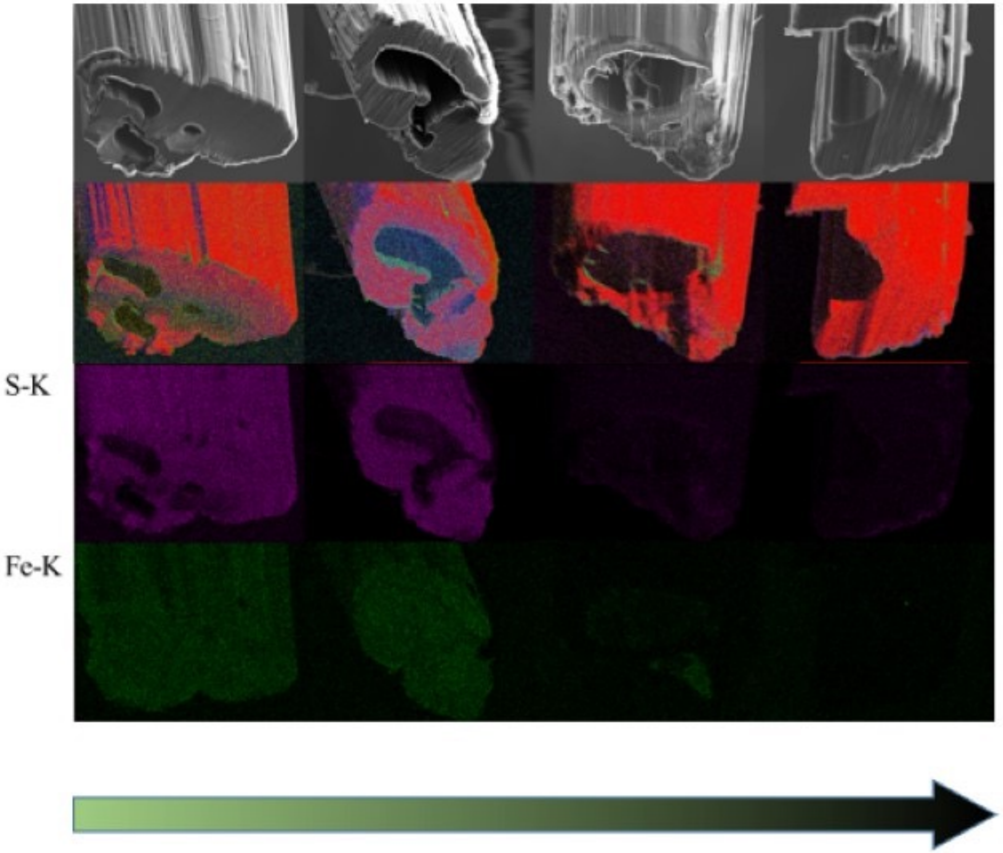
Multi-walled
Carbon Nanotube



CNT: Synthesis and Purification

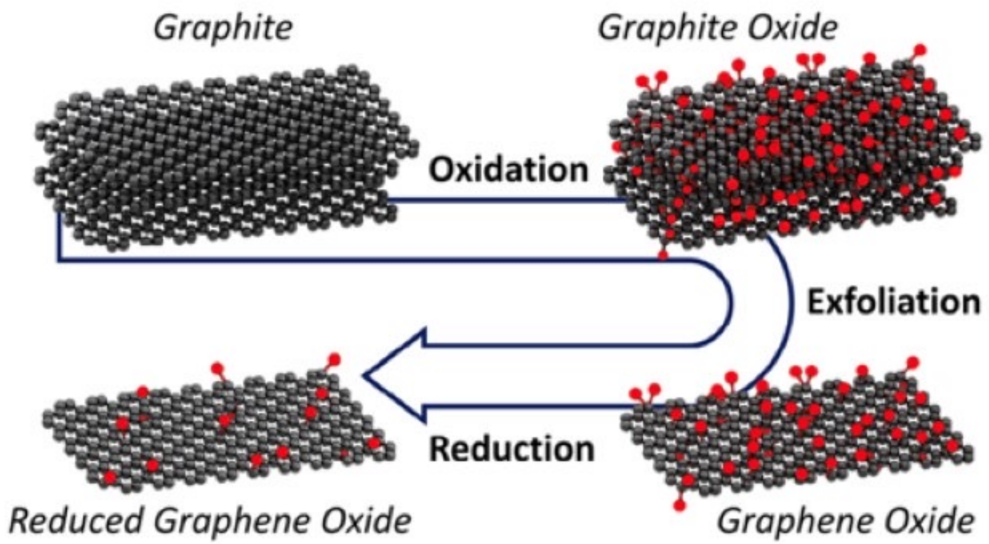


Materials & Design 203 (2021): 109557.

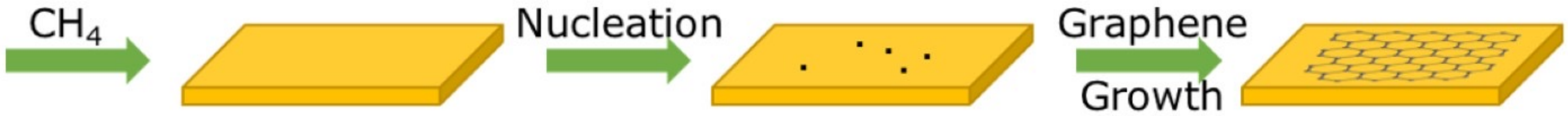


Khanbolouki and Tehrani, Carbon 168, 2020, 710-718.

Graphene: Quality vs. Quantity and Price



$$CH_4 \longrightarrow C\ (\text{Graphene}) + 2H_2$$



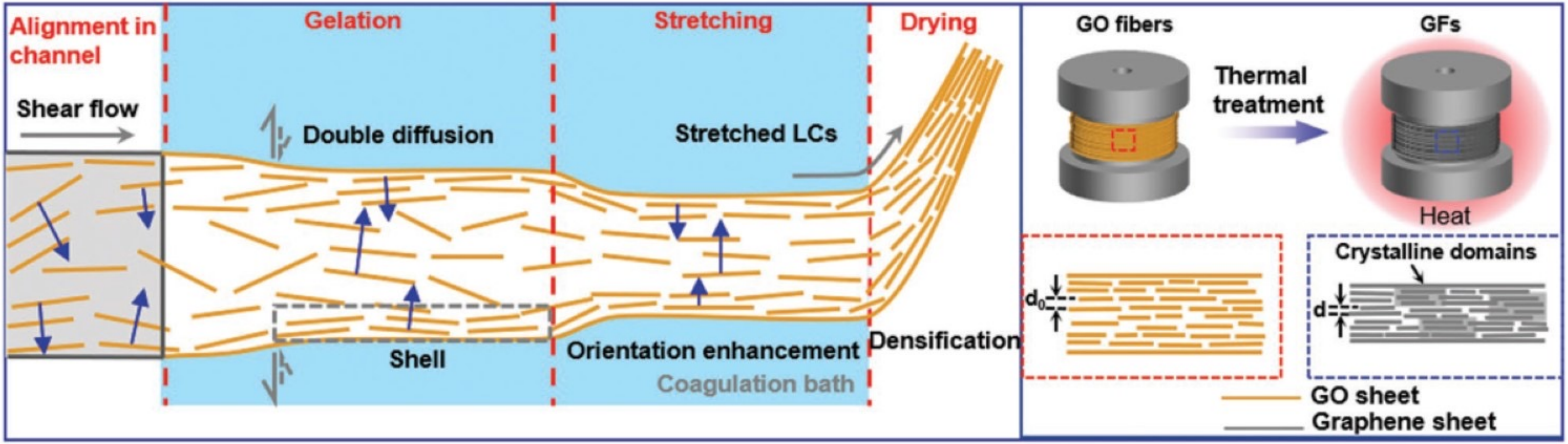
https://www.acsmaterial.com/blog-detail/cvd-graphene.html

Commercial CNT Yarns

	Dominant CNT type	CNT length [μm]	Raman I_G/I_D (quality)
Lintec: dry spun from a CNT forest[4]	MWCNT	<500	1
Huntsman: dry spun from FC-CVD[94]	FWCNT	<2000	2–5
DexMat: wet spun from a CNT–acid solution[95]	DWCNT	<20	>50

	Tensile strength [GPa]	Electrical conductivity [MS m^{-1}]	Density [g cm^{-3}]
Lintec: dry spun from a CNT forest[4]	<1	0.1	0.5
Huntsman: dry spun from FC-CVD[94]	1	0.3–2	0.5–0.9
DexMat: wet spun from a CNT–acid solution[95]	0.4–2.8	3–10	0.8–1.6

Graphene Fibers



Adv. Mater. 2020, 32, e1902664.

R&D of Graphene Fibers

2011
- First work with wet-spinning
- Strength: 140 MPa
- Modulus: 7.7 GPa
- Electrical conductivity: 250 S cm^{-1}

2013
- Giant GO sheets as building blocks
- Strength: 501.5 MPa
- Modulus: 11.2 GPa
- Ag nanowires doping
- Electrical conductivity: 900 S cm^{-1}

2015
- Blending small and large GO sheets
- Strength: 1080 MPa
- Modulus: 135 GPa
- Electrical conductivity: 2210 S cm^{-1}
- Thermal conductivity: 1290 W m^{-1} K^{-1}

2016
- Defect engineering management
- Strength: 2200 MPa
- Modulus: 400 GPa
- Chemical doping
- Electrical conductivity: 220000 S cm^{-1}

2017
- Calcium doping
- Superconductors

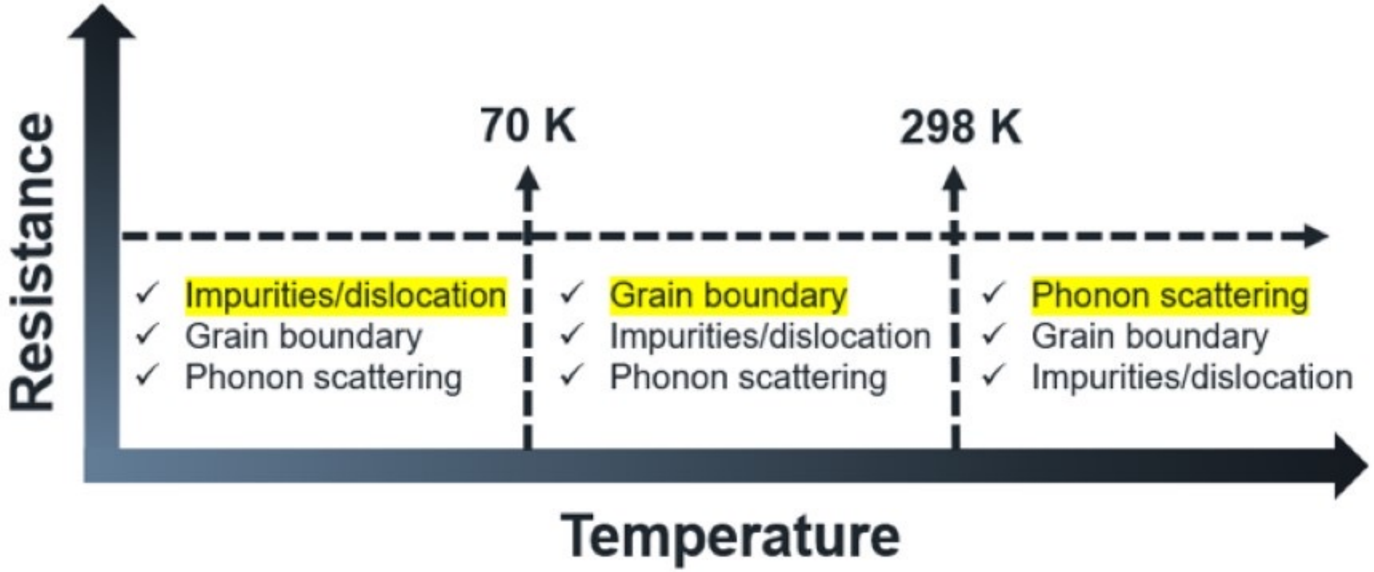
2019
- Microfluidic design
- Strength: 1900 MPa
- Modulus: 309 GPa
- Electrical conductivity: 10400 S cm^{-1}
- Thermal conductivity: 1575 W m^{-1} K^{-1}

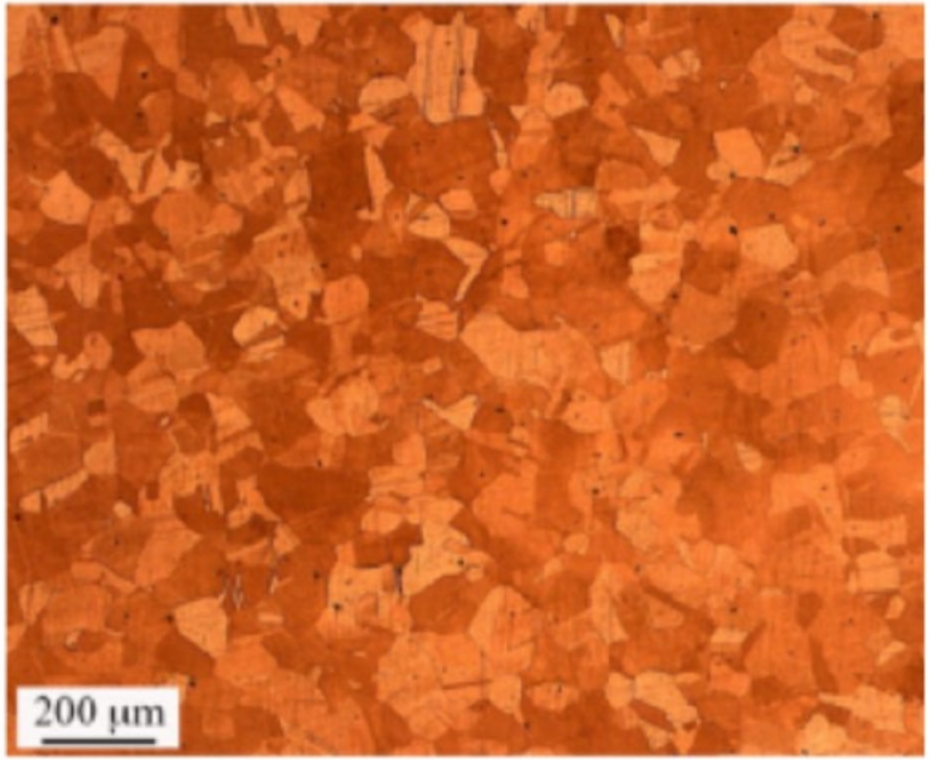
Adv. Mater. 2020, 32, e1902664.

Conduction Mechanisms

Conductivity = charge carrier density **X** charge carrier mobility

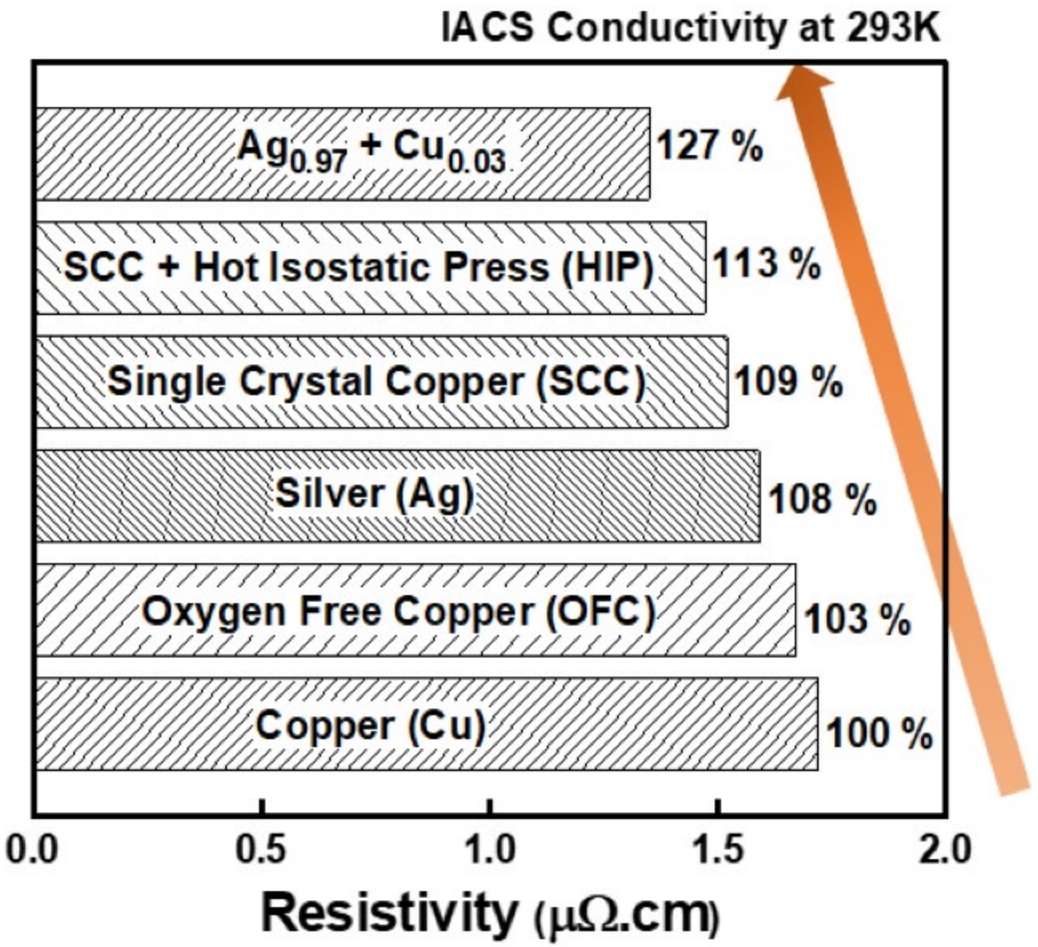
Metals ~10^{28} /m^3 30-50 cm^2/ (V·s)

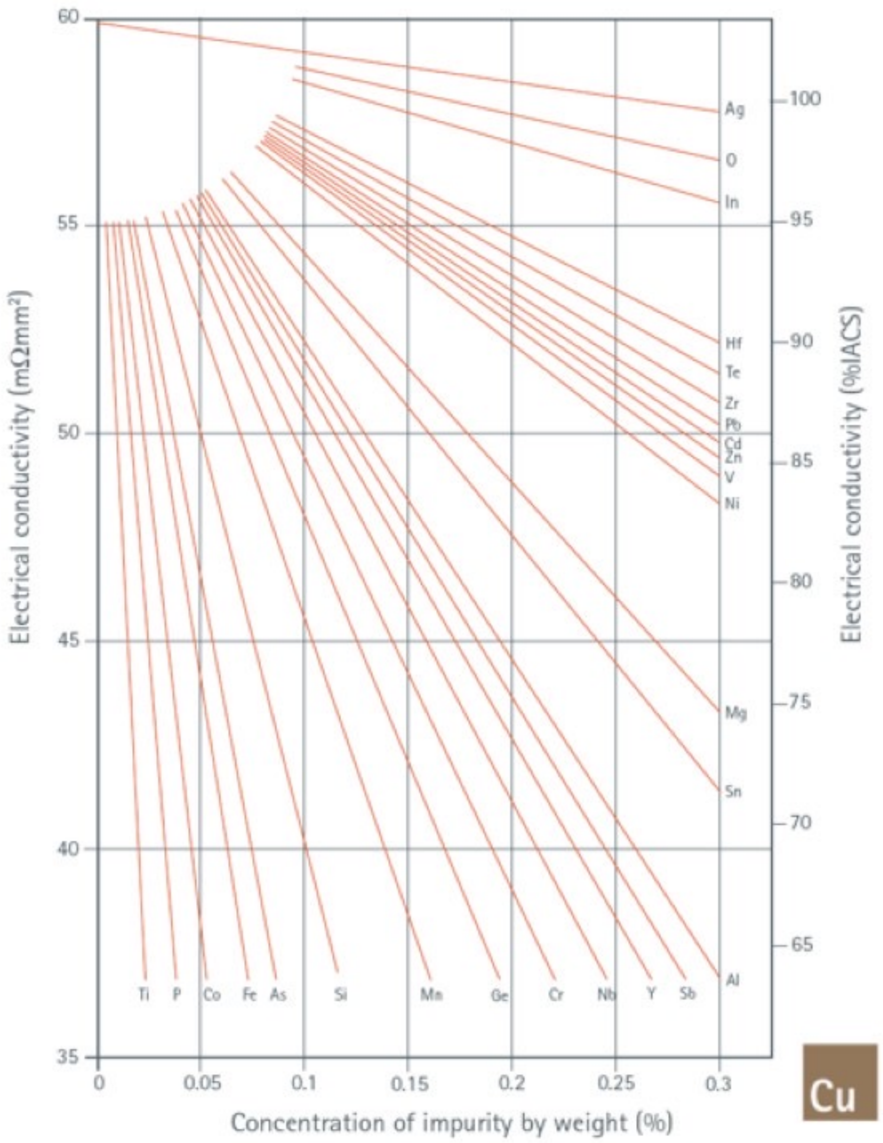




Adv. Eng. Mater. 2018, 20, 1700503

Single Crystal Conductors





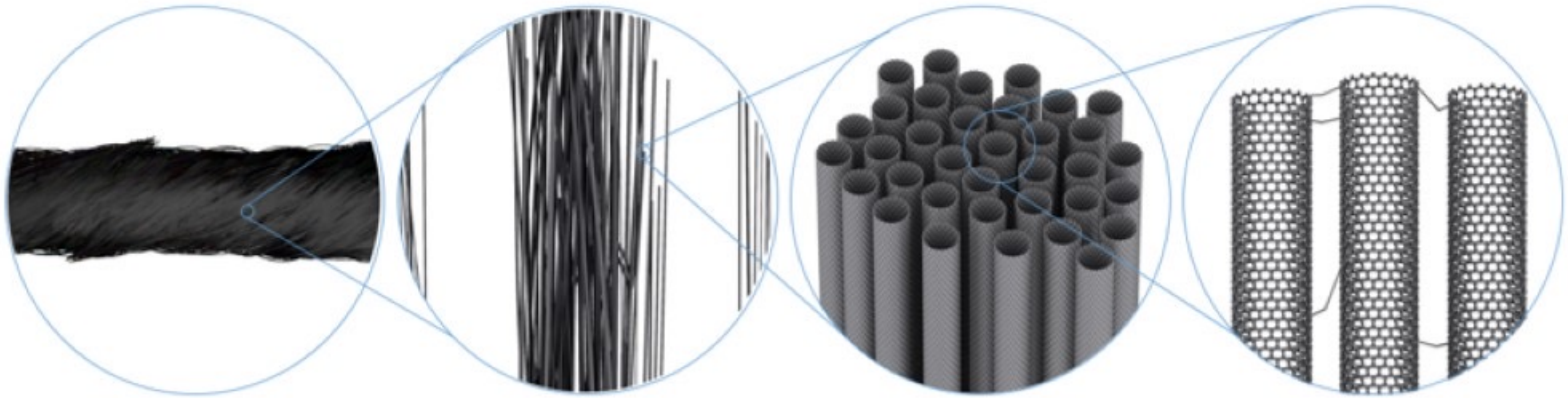
Ajmal, M., et al., CrystEngComm, 2012. **14**(4): p. 1463-1467.
Cho, Y.C., et al., Crystal growth & design, 2010. **10**(6): p. 2780-2784.
Kim, J.Y., et al., Scientific reports, 2014. **4**(1): p. 1-5.

Copper Development Association
Copper Alliance

Conduction Mechanisms

Conductivity = charge carrier density **X** charge carrier mobility

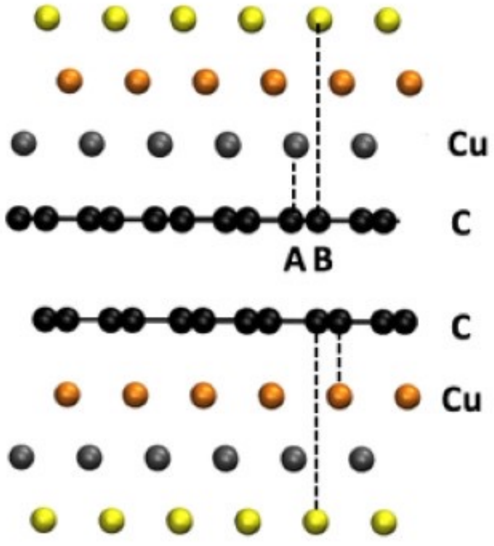
Nanocarbons ~10^{14} /m^3 100,000-200,000cm^2/ (V·s)

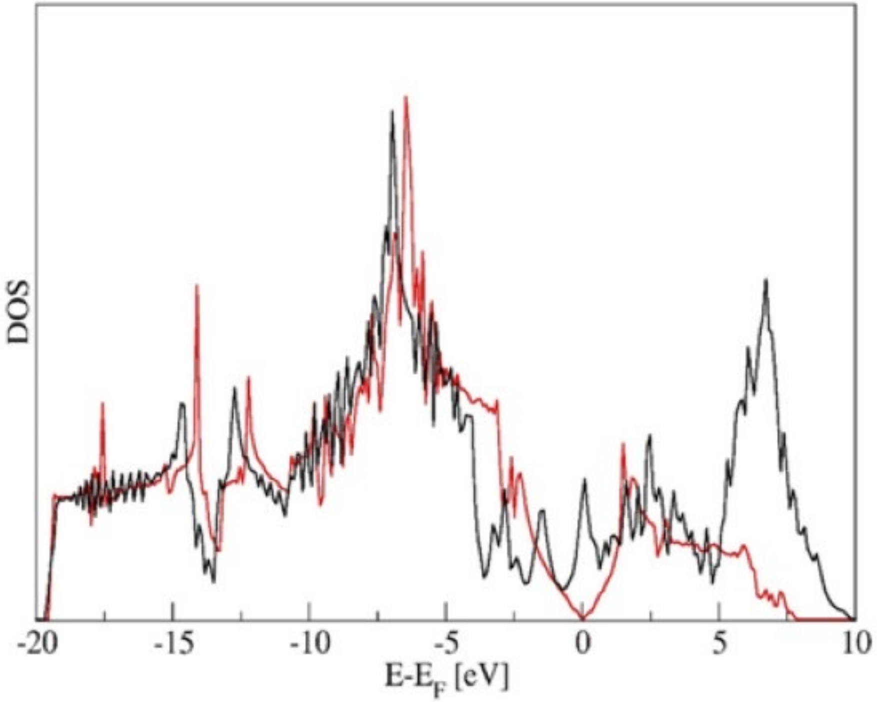


Electronically Hybrid Conductor

Conductivity = charge carrier density **X** charge carrier mobility

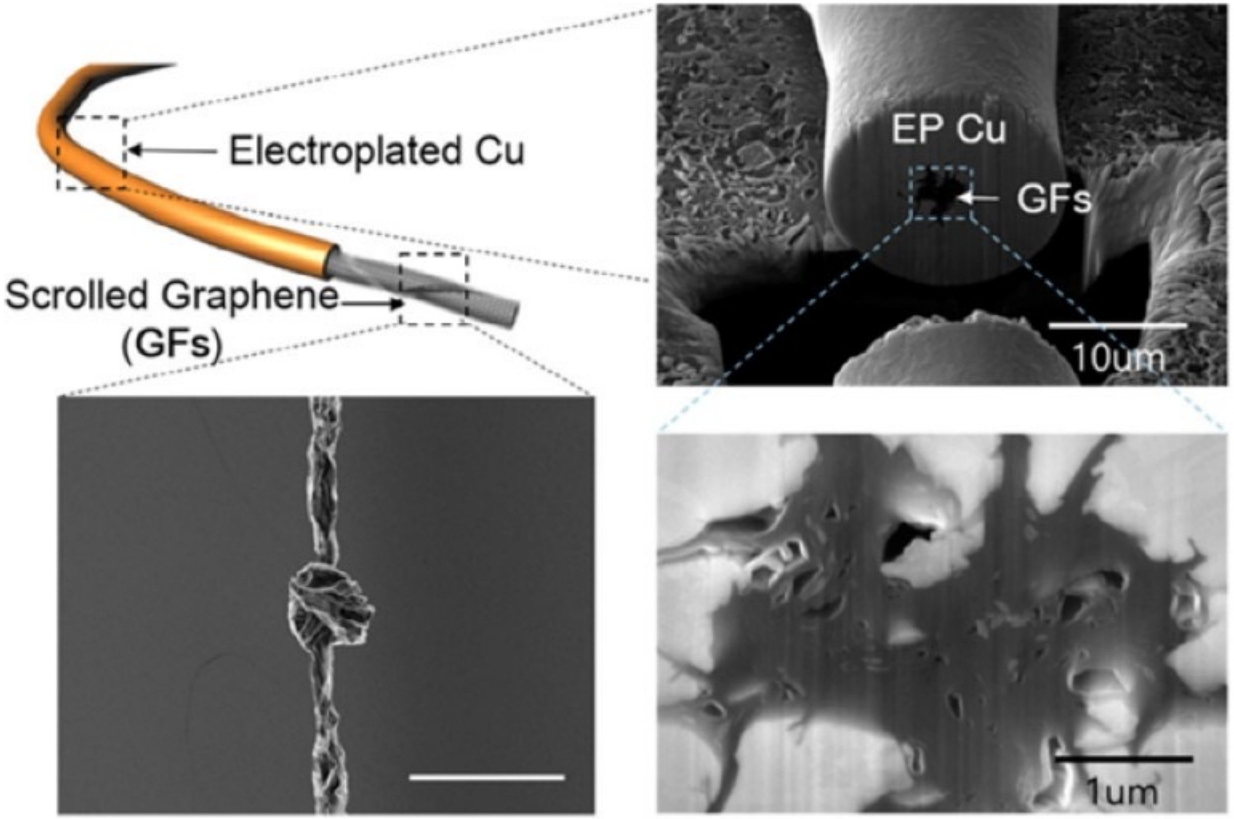
Metals	~10^{28} /m³	50-50 cm²/ (V·s)
Nanocarbons	~10^{14} /m³	100,000-200,000cm²/ (V·s)

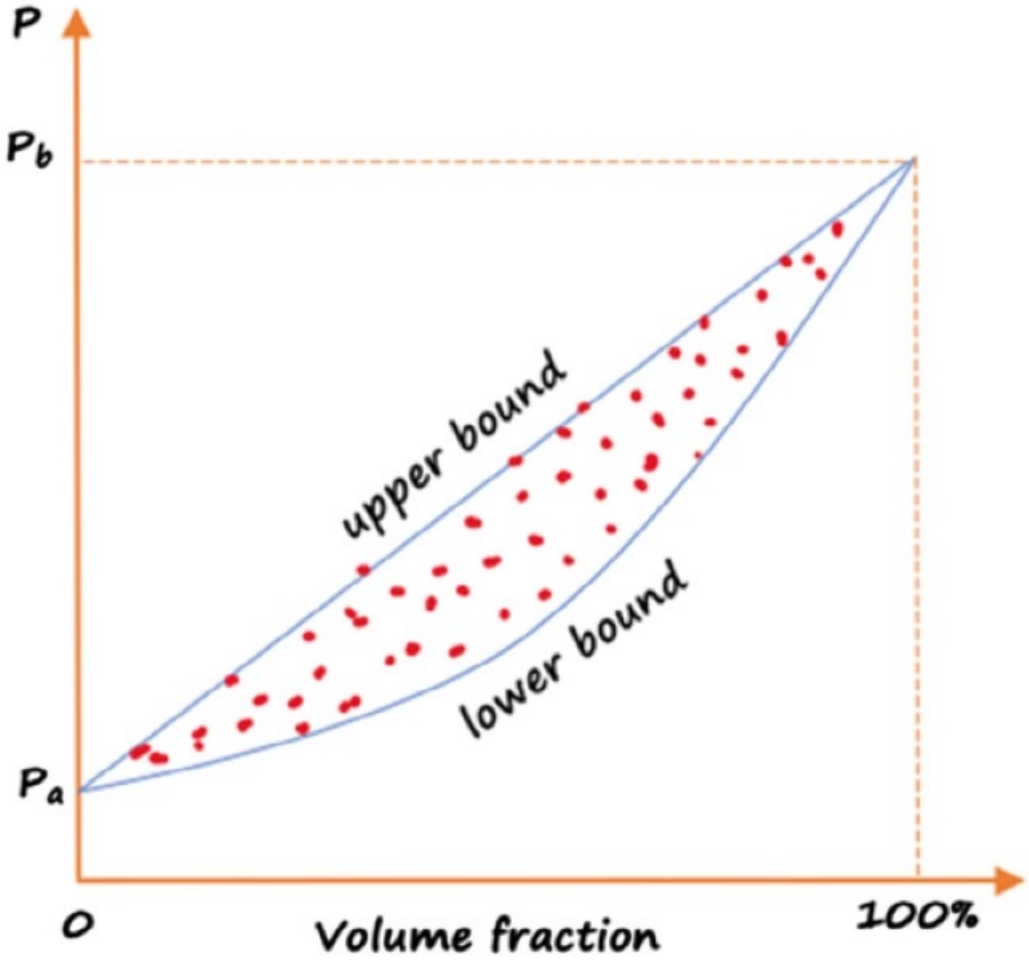




Tehrani and Gonzales, unpublished work.

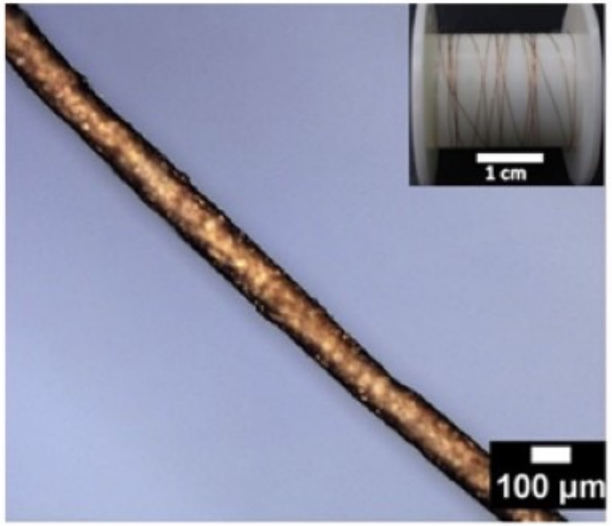
Composite Properties

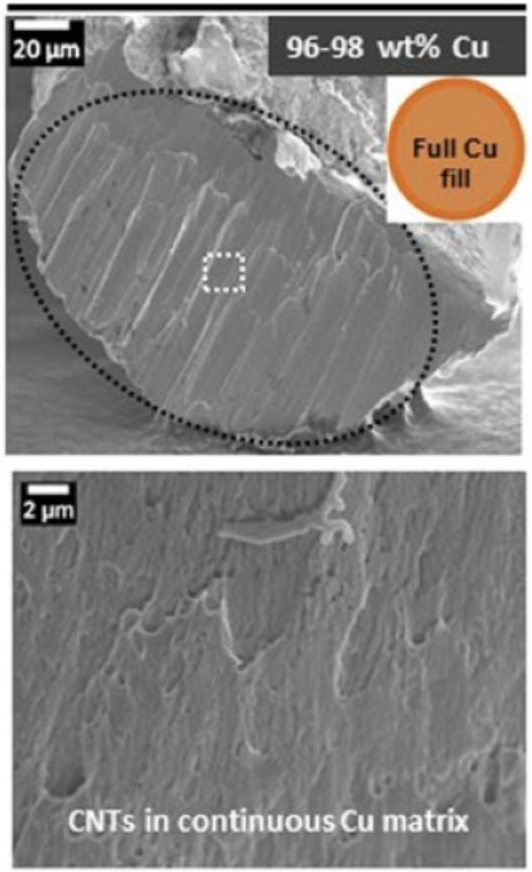


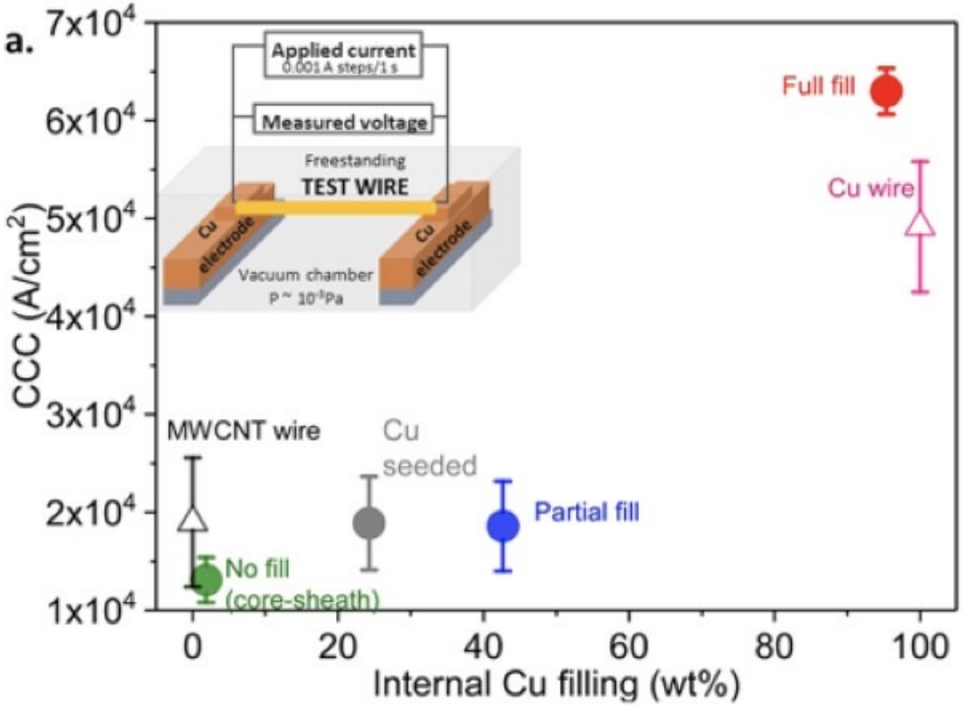


[91]

Nanocomposites: Synergistic Properties

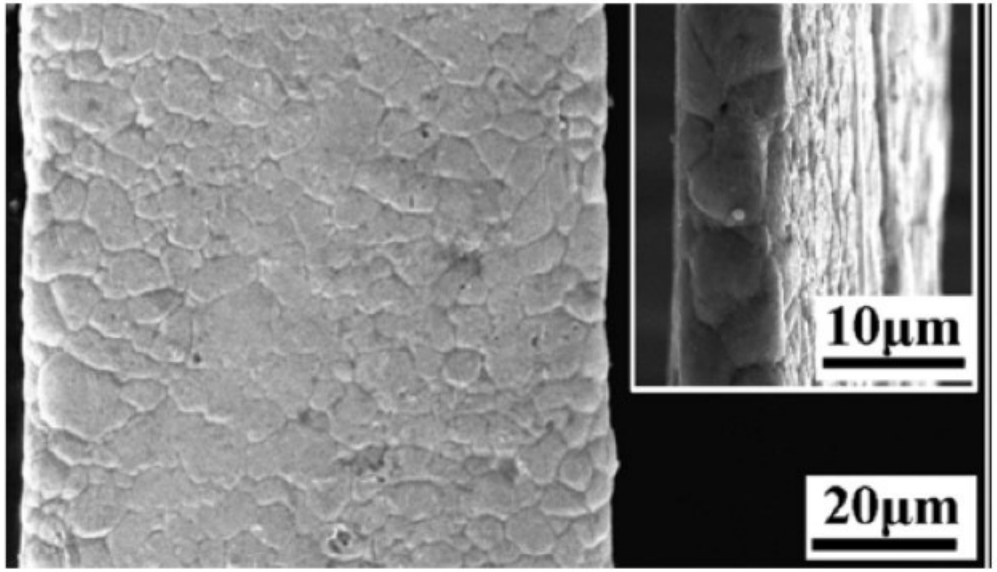


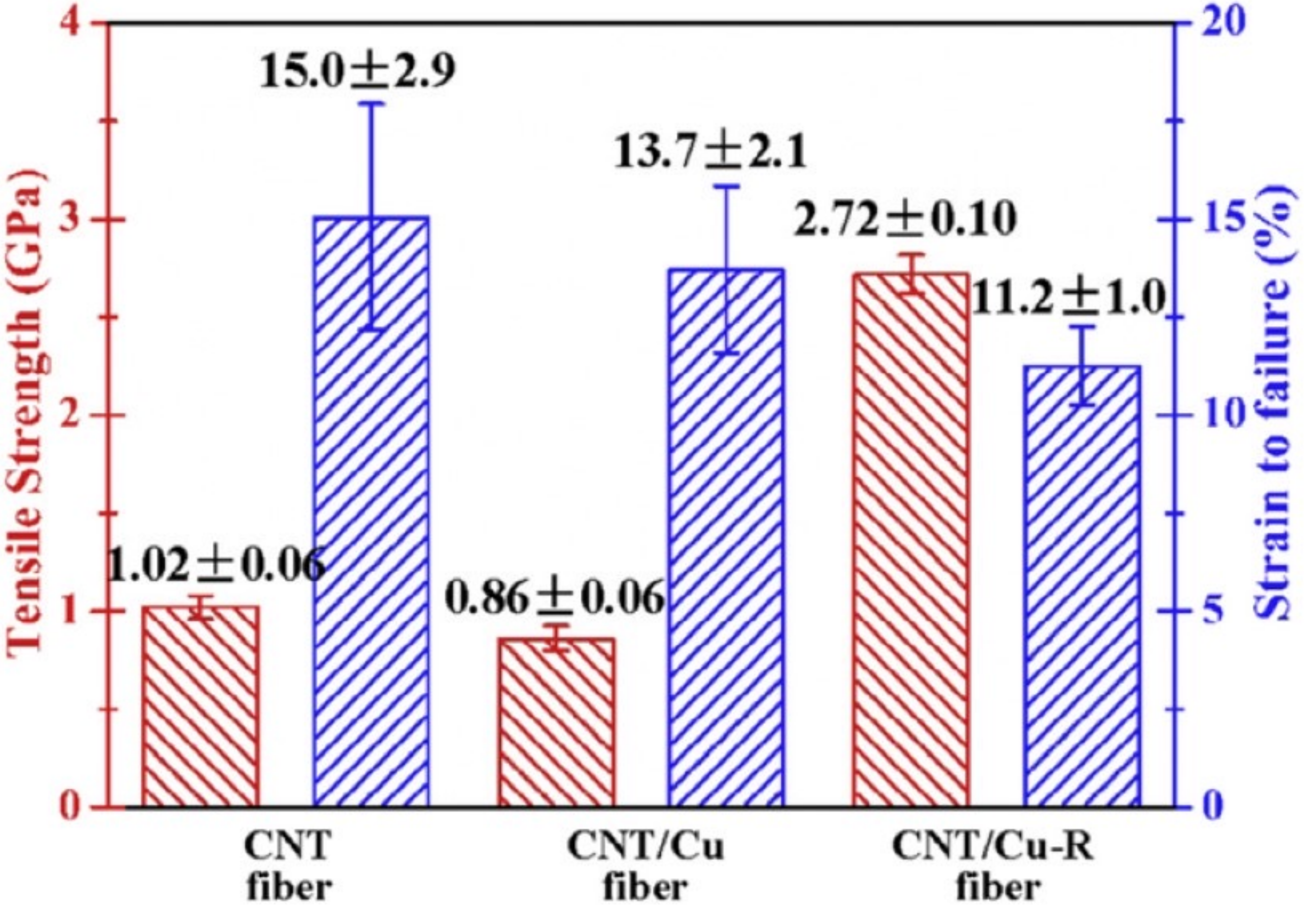




Scientific Reports, 2017 7: 9267

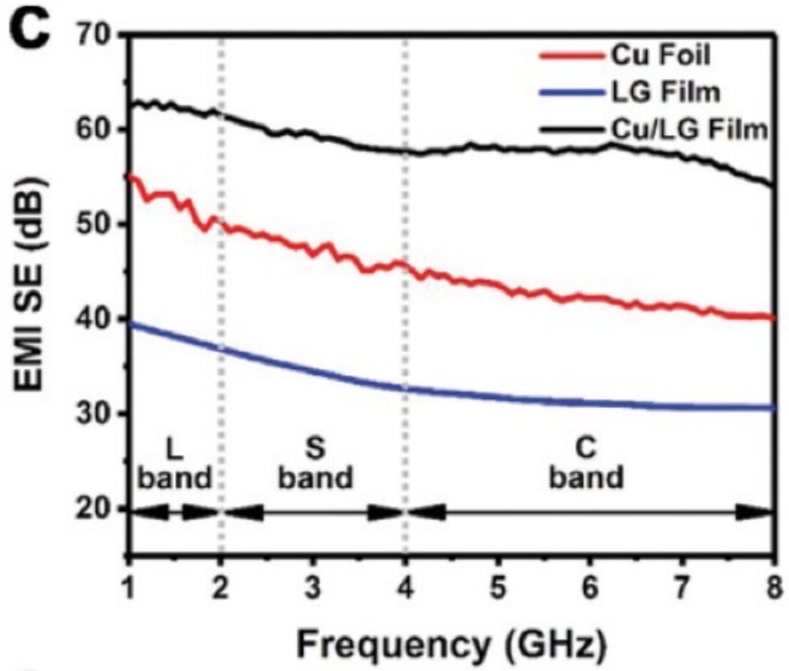
Nanocomposites: Synergistic Properties

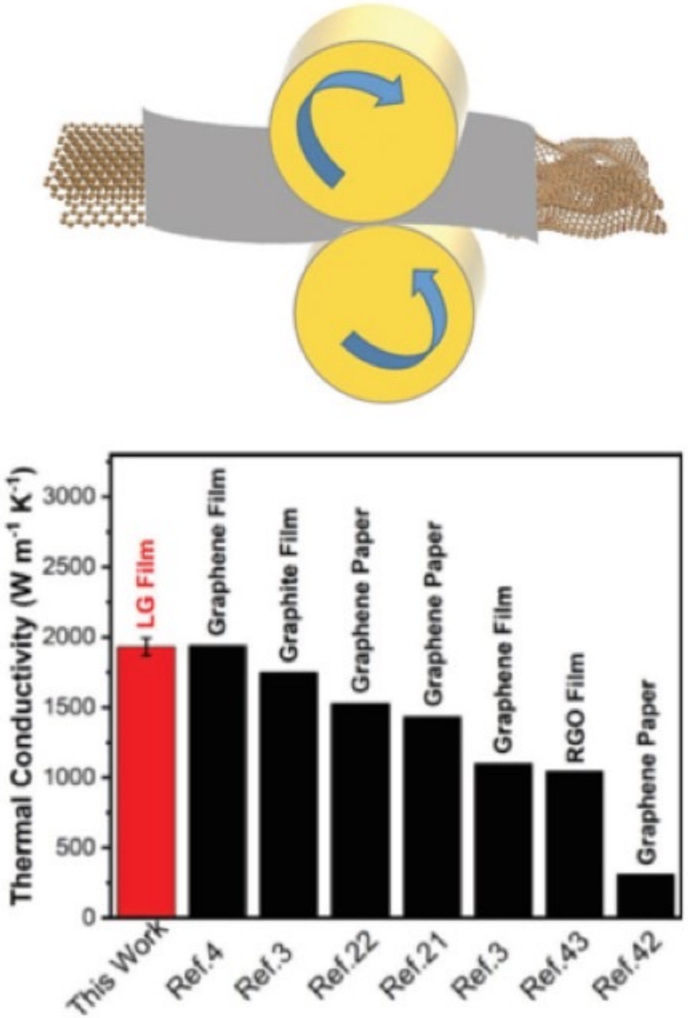


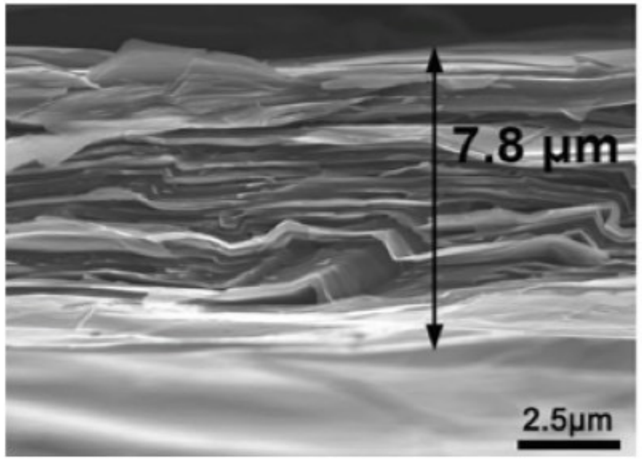


Applied Surface Science Volume 441, 31 May 2018, Pages 984-992

Electromagnetic Interference (EMI) Shielding



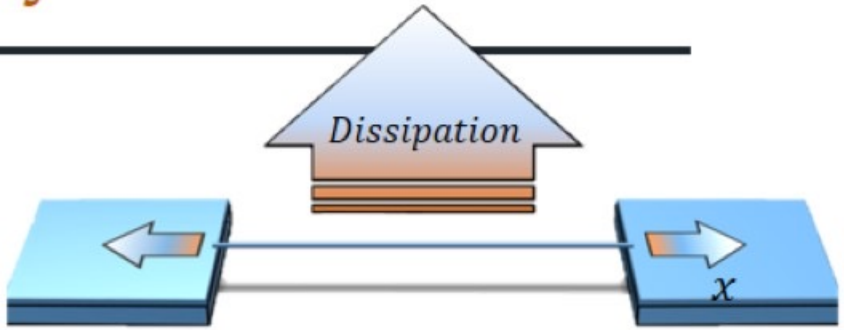




Small 2018, 14, 1704332

Modeling Ampacity

- $Heat\ storage + Heat\ dissipation = Heat\ generation$
- All these terms are temperature dependent



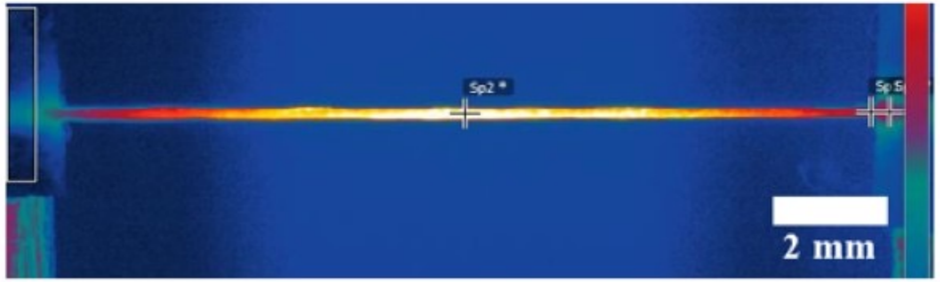
$$\frac{\partial}{\partial x}\left(\kappa_{x_0}(T(x)) \cdot A \cdot \frac{\partial T(x)}{\partial x}\right)$$ *Conduction*

$$-h(T) \cdot P \cdot (T(x) - T_0)$$ *Convection*

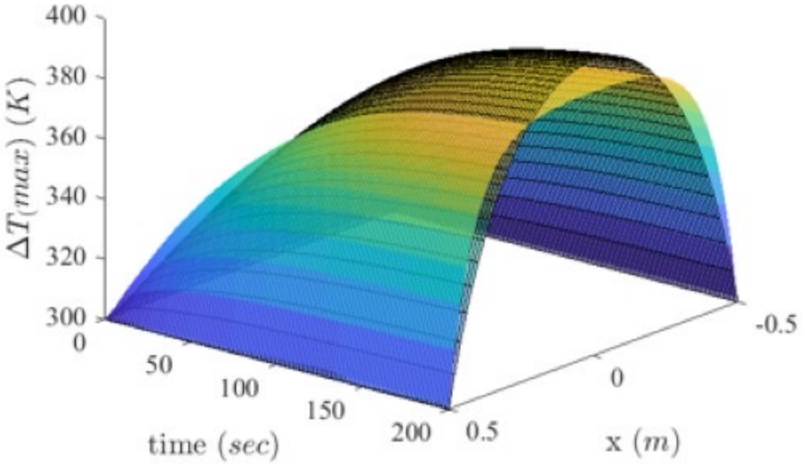
$$-\epsilon \cdot \sigma \cdot P \cdot (T(x)^4 - T_0^4)$$ *Radiation*

$$+\frac{i^2}{A} \cdot \rho(T(x))$$ *Generation*

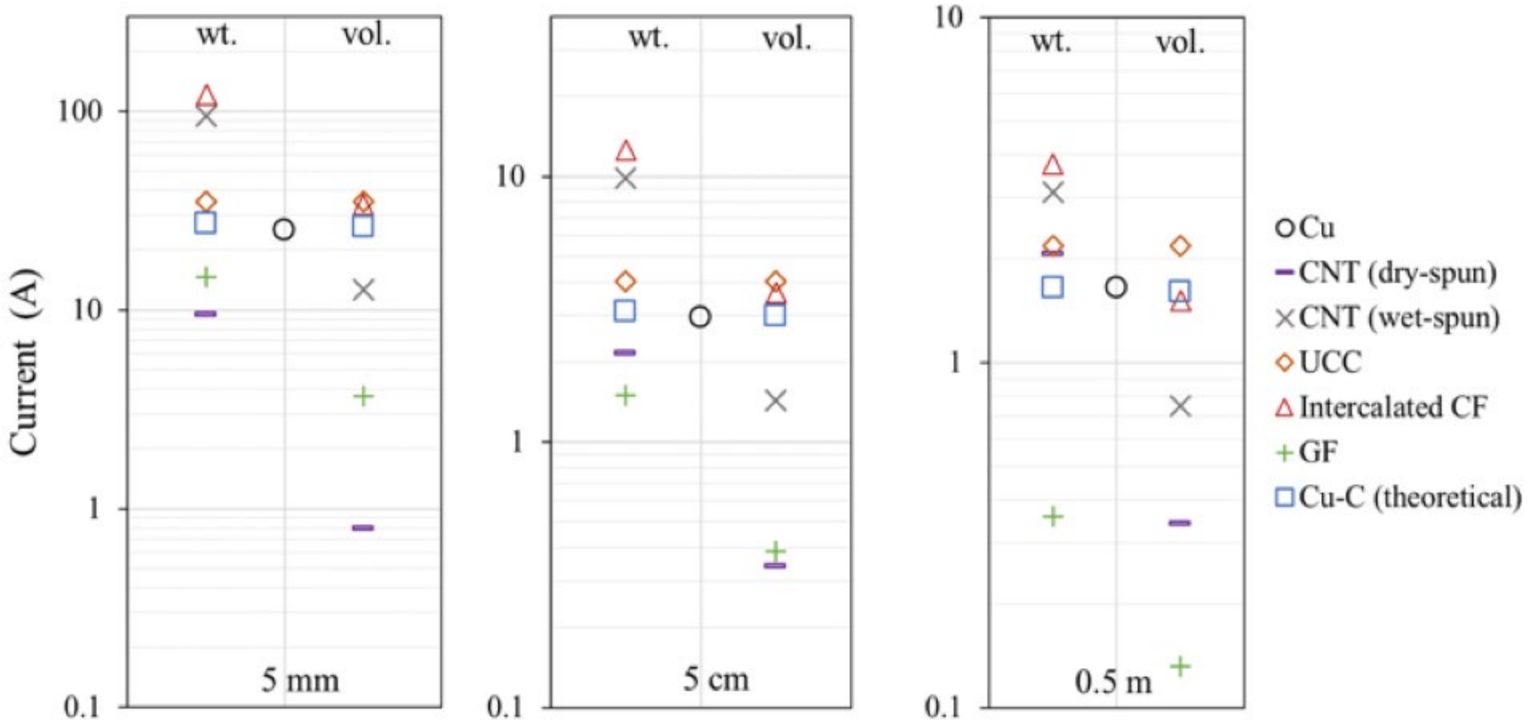
$$= 0$$



Transient solution



Numerical Simulation of Ampacity in advanced electrical conductors

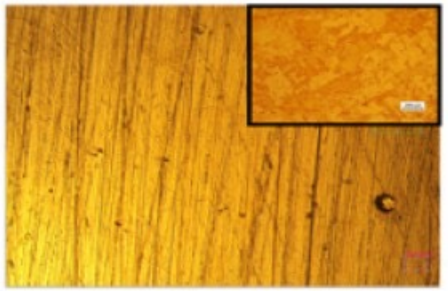


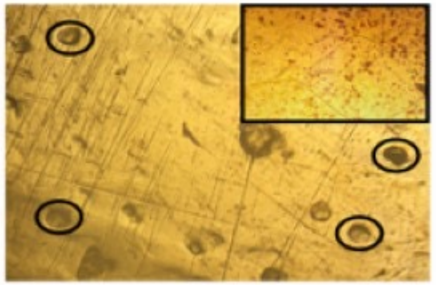
wt. – Comparison based on equivalent weight conductors
vol. – Comparison based on equivalent volume conductors

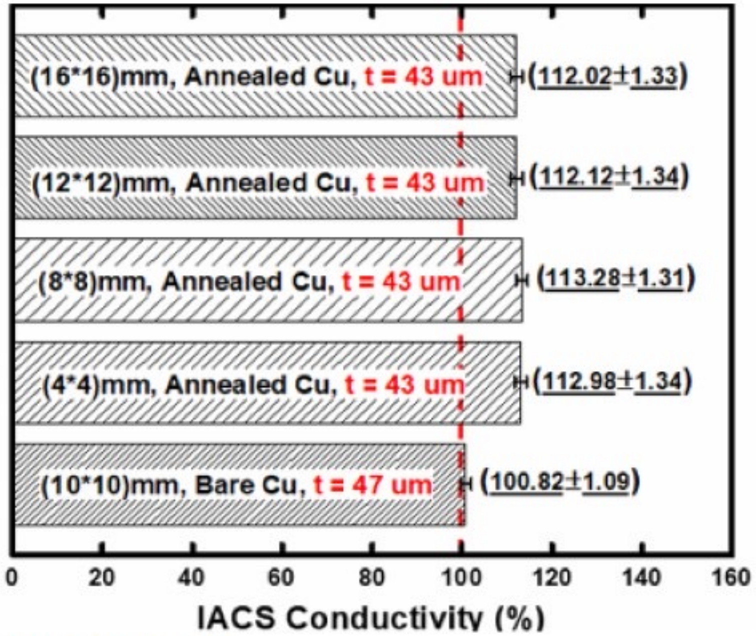
- Comparison of different conductor materials based on equivalent weight and equivalent volume
- Calculated currents (A) required to raise the temperature of the conductor (lengths of 5 mm, 5 cm and 0.5 m) to a maximum temperature of 150°C

Tehrani, Unpublished

Measurement Errors

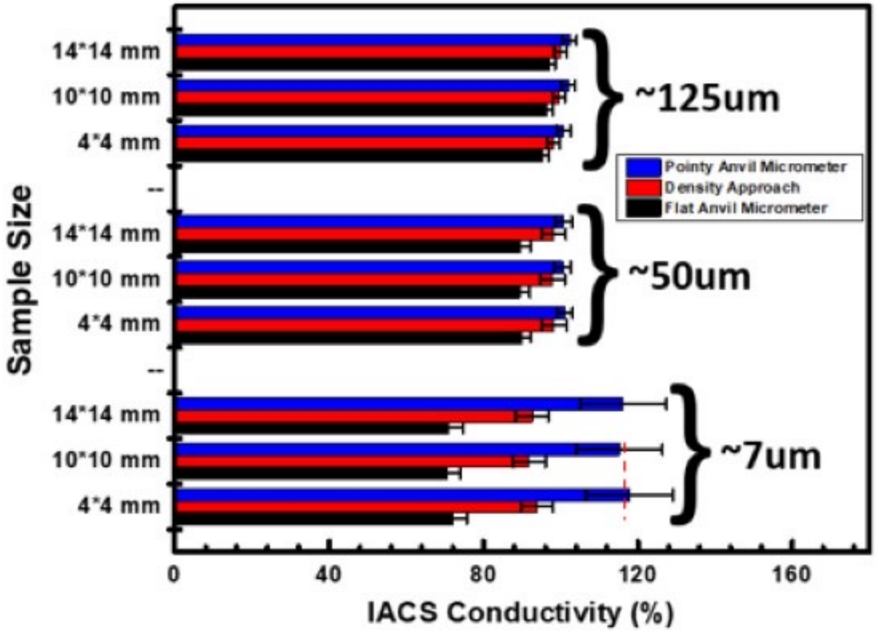






$$\rho = \frac{RA}{L} \qquad e_\rho = \sqrt{\left(\frac{\partial \rho}{\partial R}\right)^2 e_R^2 + \left(\frac{\partial \rho}{\partial A}\right)^2 e_A^2 + \left(\frac{\partial \rho}{\partial L}\right)^2 e_L^2}$$

wires/fibers: $\sigma/\rho = (L^2/RM)$



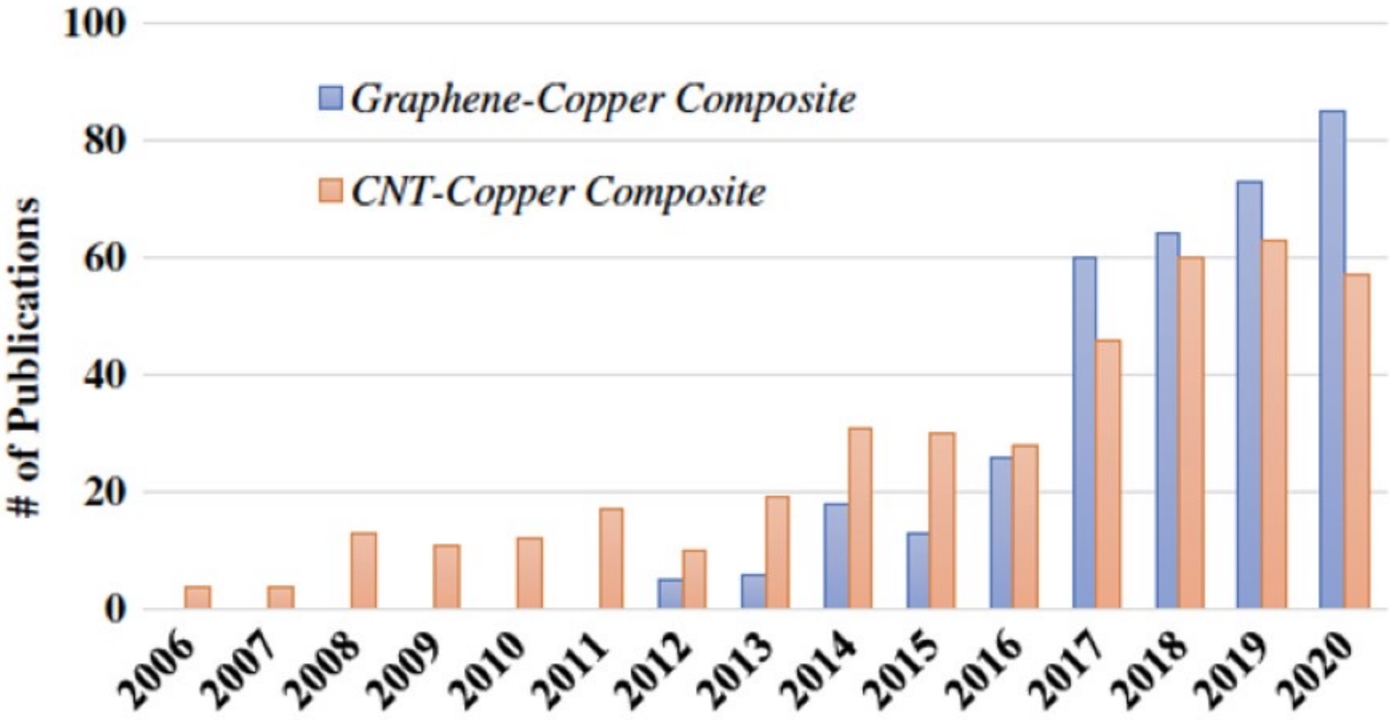
Tehrani, unpublished work.

Numbers

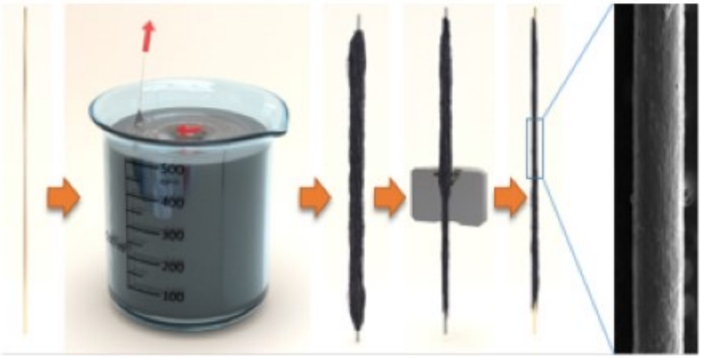
#number of patents since 2012 on nanocarbon–metal composites mentioning
electrical conductivity as a characteristic

- 30 in 2012
- 35 in 2013
- 42 in 2014
- 71 in 2015
- 83 in 2016
- 94 in 2017
- 134 in 2018
- 118 in 2019

most of these patents are from China.



Prospects



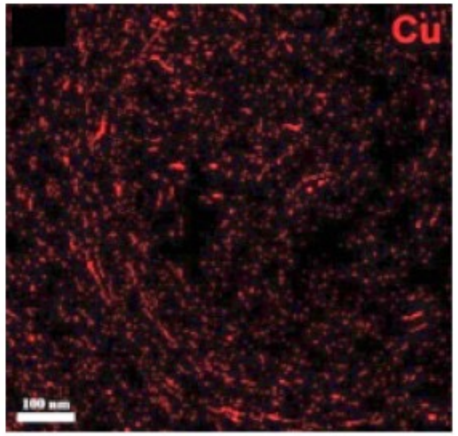
Scalable Processing

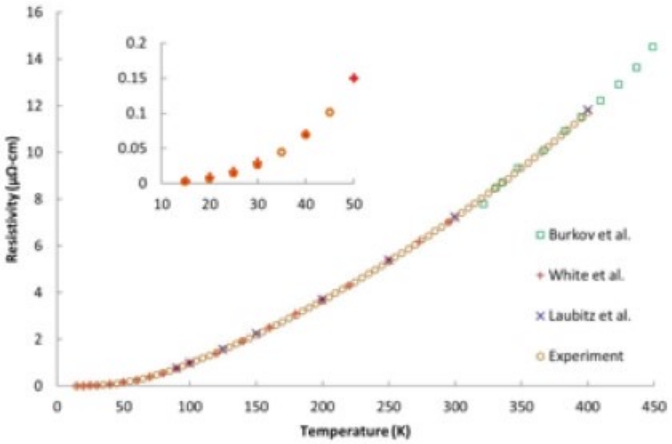
Materials Science

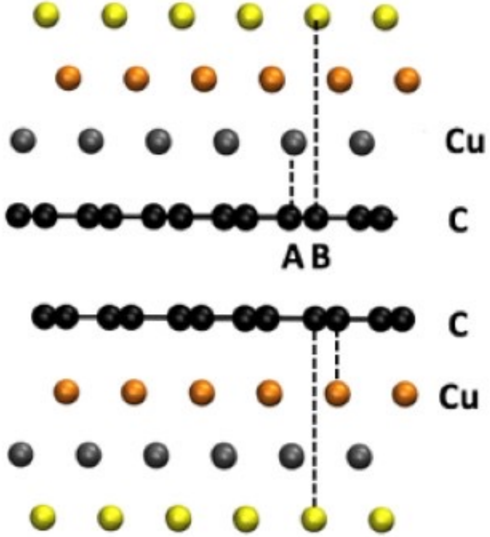
Advanced Conductors

Physics

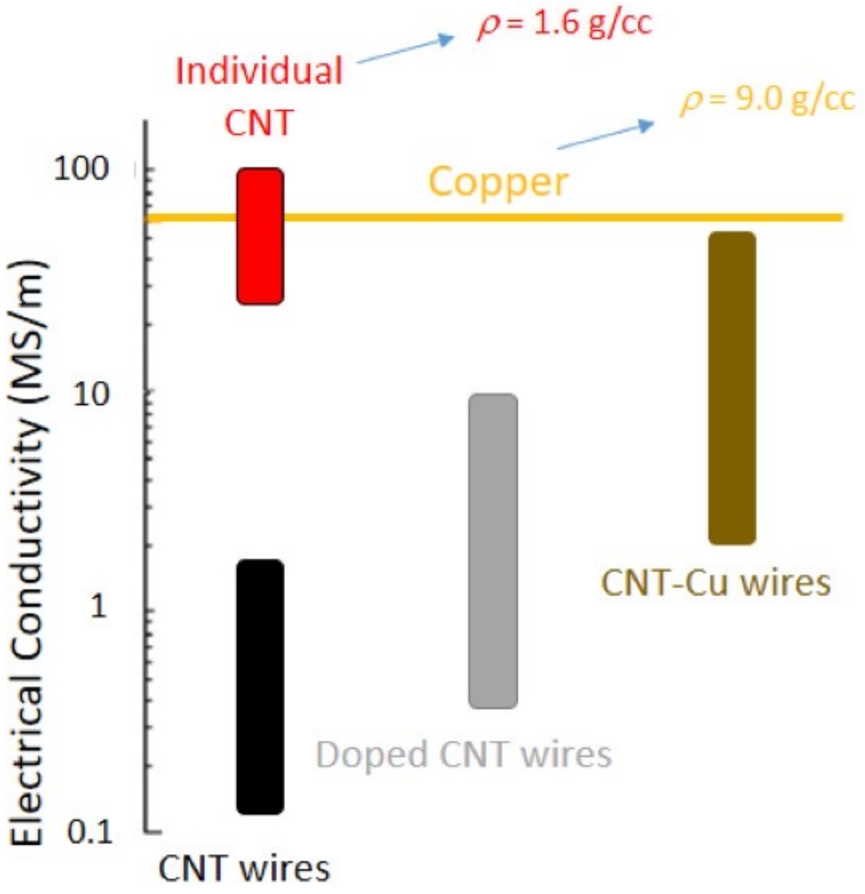
Atomistic Simulations



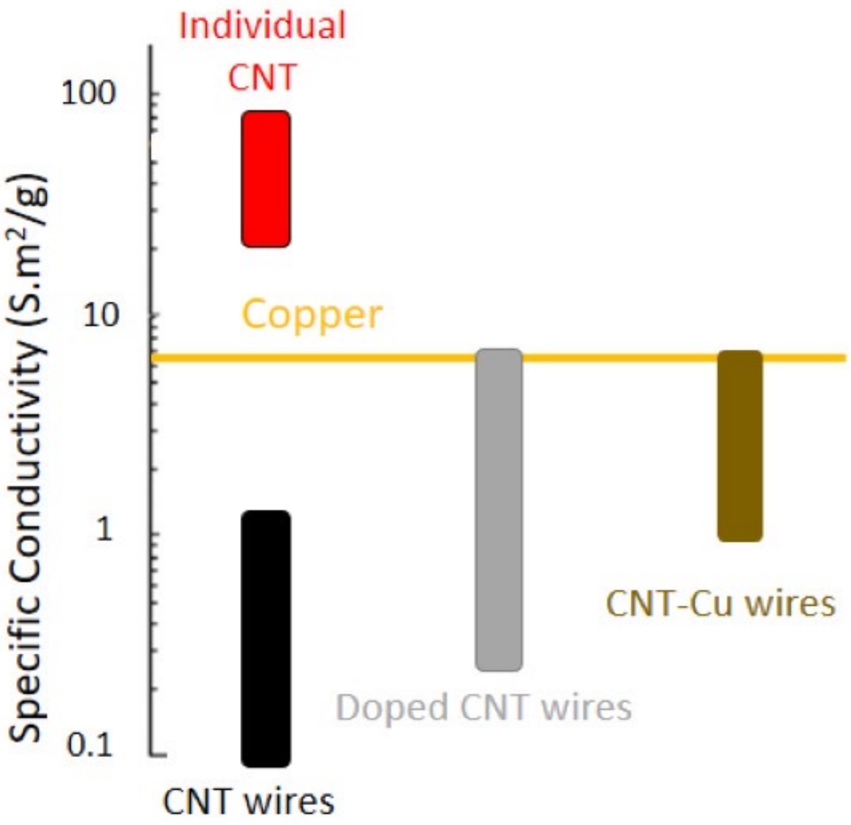




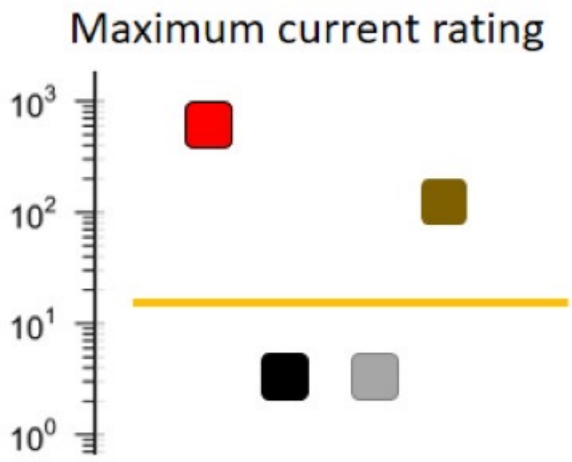
Summary



ρ = 1.6 g/cc
Individual CNT
ρ = 9.0 g/cc
Copper
100
10
1
0.1
Electrical Conductivity (MS/m)
CNT-Cu wires
Doped CNT wires
CNT wires



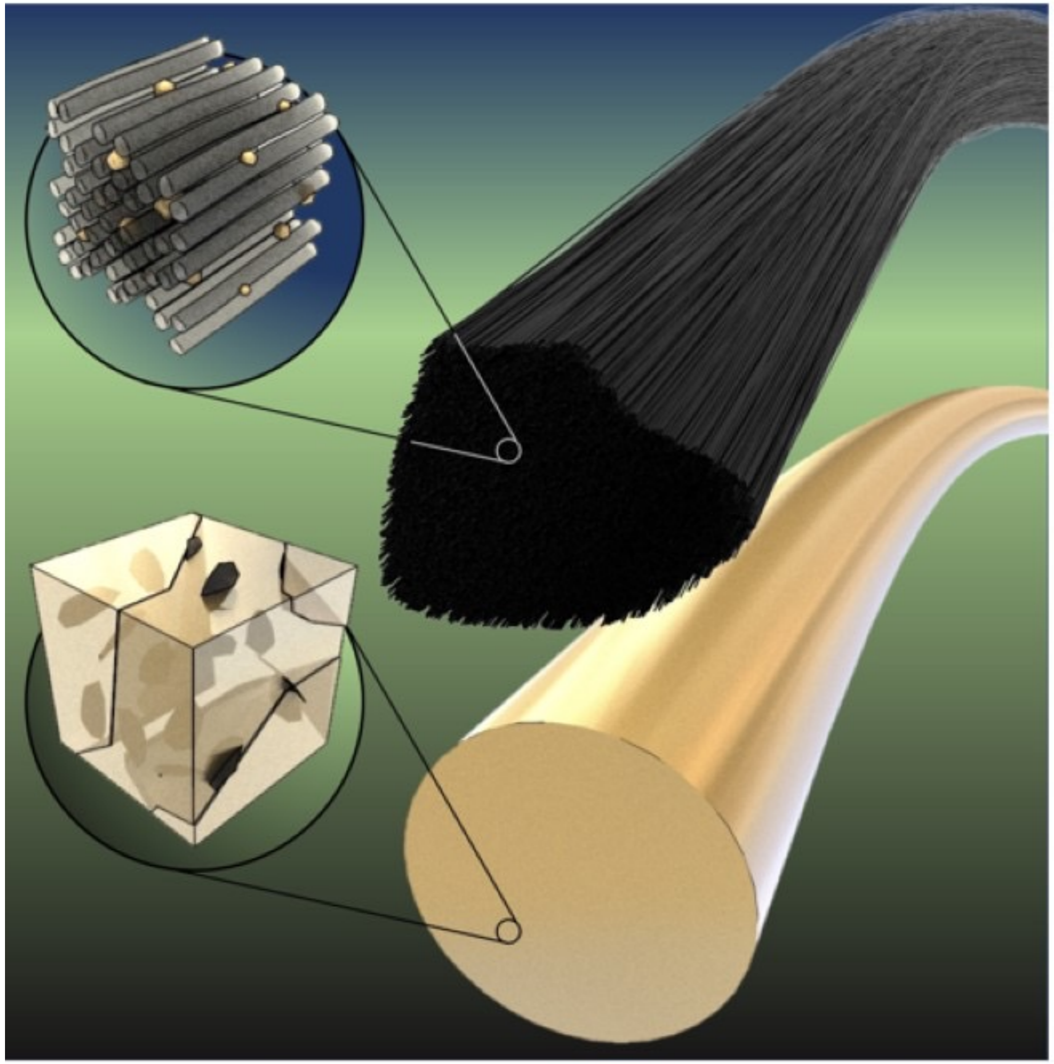
Individual CNT
100
10
1
0.1
Copper
Specific Conductivity (S.m²/g)
CNT-Cu wires
Doped CNT wires
CNT wires



Maximum current rating
10³
10²
10¹
10⁰

Summary

- Electrical Conductivity
- Mechanical properties
- Thermal conductivity
- Temperature Coefficient of Resistance (TCR)
- Thermal expansion
- Emissivity
- Ampacity
- EMI Shielding



Thank you for watching!

The University of Texas at Austin

WHAT STARTS HERE CHANGES THE WORLD

The University of Texas at Austin
Walker Department
of Mechanical Engineering
Cockrell School of Engineering