2025 DOE
Vehicles Technology Office
Annual Merit Review

Project ID# MAT294
Bulk-Scale Ultra-Conductors
via Low-C Manufacturing Pathways

April 15, 2025

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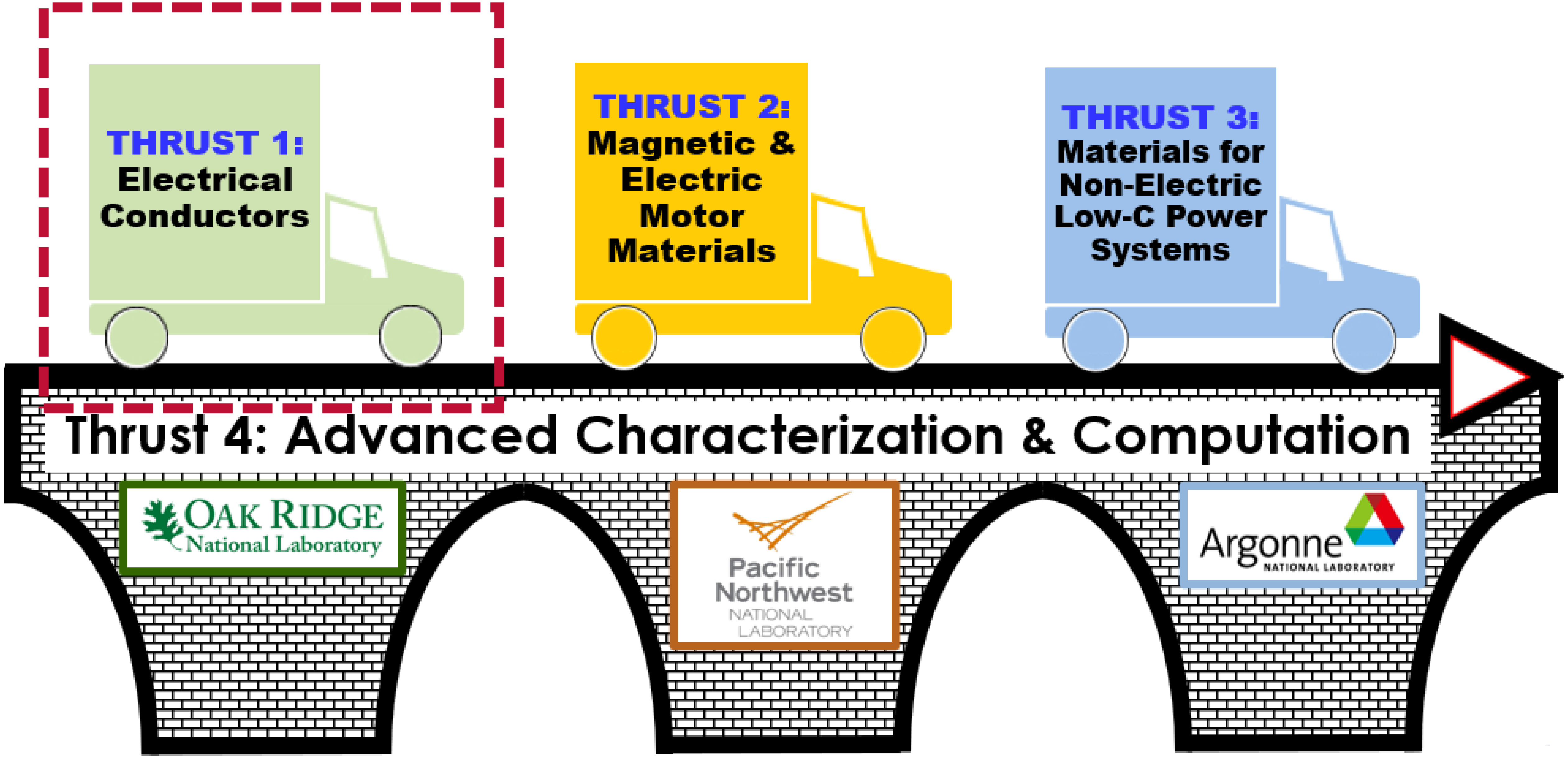
VTO Powertrain Materials Core Program 2.0

FY24-26: Accelerating Development of Advanced Materials for Propulsion



Overview

Timeline/Budget

- Task start: January 2024
- Task end: September 2026
- Percent complete: ZZ%
- **1A-25 Budget**
  - **FY25: $320k**

Barriers

- "Reduction in the volume of the components is necessary to enable electric traction drive systems to fit within the increasingly smaller spaces available on the vehicle. Motor volume reduction is limited by the flux density capacities of materials used in current electric steels and electrical conductivity limitations of copper windings"[1]
- Need for materials with enhanced electrical performance at operating temperatures

FY25 Thrust 1: Electrical Conductors	Total Budget =$1520k	Labs
Task 1A-25: Fundamentals of LW Conductor Alloy Design	320	ORNL
Task 1B-25: Printable Creep-Resistant LW Conductors	310	ORNL
Task 1C-25: Fundamentals of LW Conductor Mechanical & Physical Properties	220	ORNL
Task 1D-25: Ultra-Conducting Copper Composites (UCCs)	340	ORNL
Task 1E-25: Bulk-scale Ultra-Conductors via Low-C Manufacturing Pathways	330	PNNL

Partners

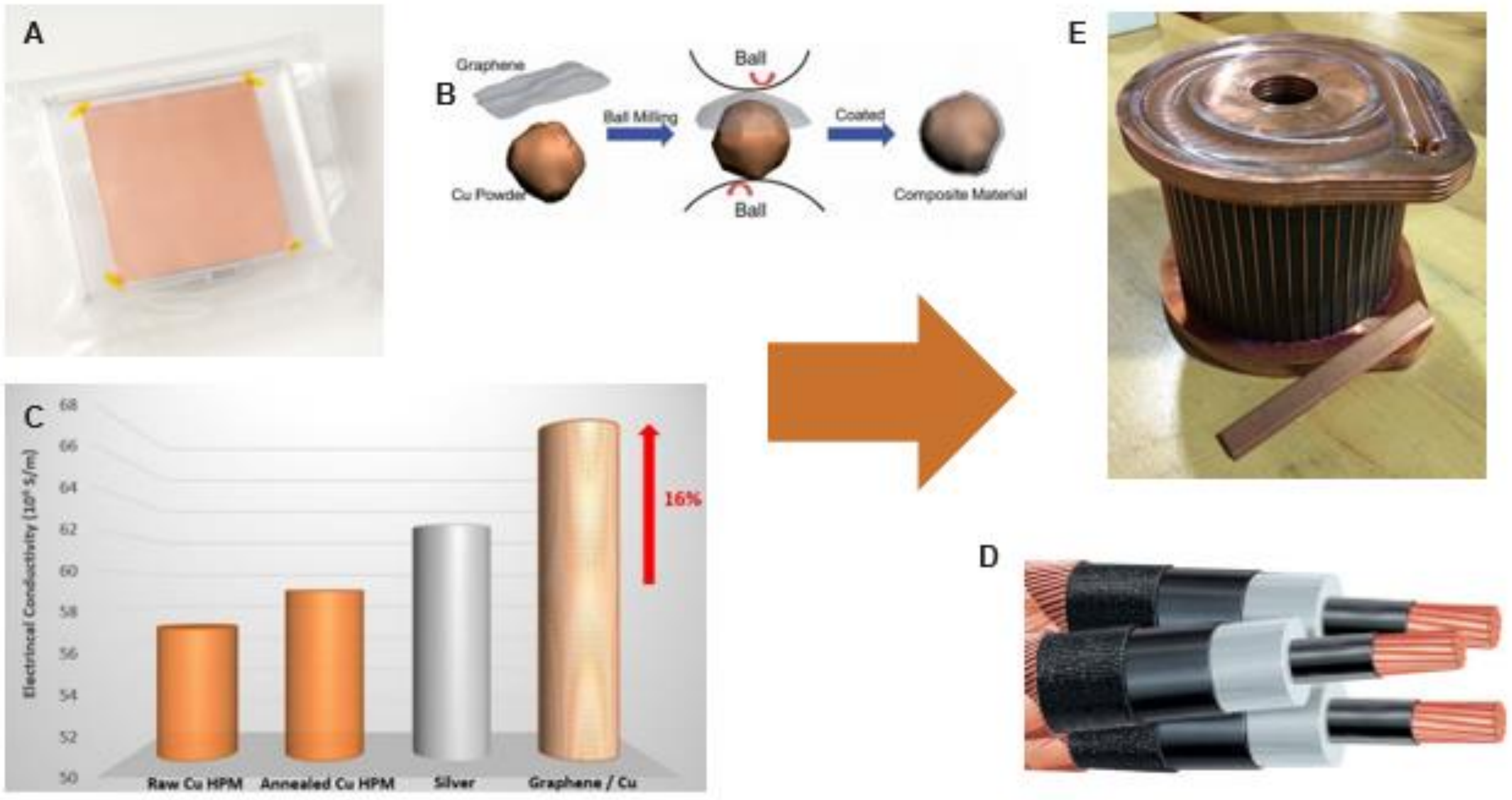
- Program Partner Labs
  - Argonne National Lab (ANL)
  - Oak Ridge National Lab (ORNL)
- Industrial partners
  - Eaton, Bosch, Schneider Electric, Southwire, EPRI, Prysmian-General Cable

[1]U.S. DRIVE Electrical and Electronics Technical Team Roadmap October 2017
https://www.energy.gov/eere/vehicles/us-drive-partnership-plan-roadmaps-and-accomplishments

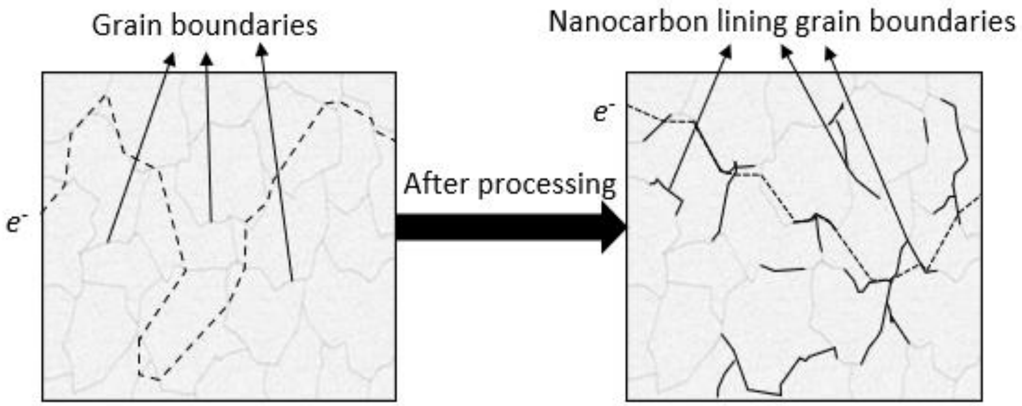
Relevance

Development of Bulk Aluminum and Copper Ultra-conductors for EV Applications

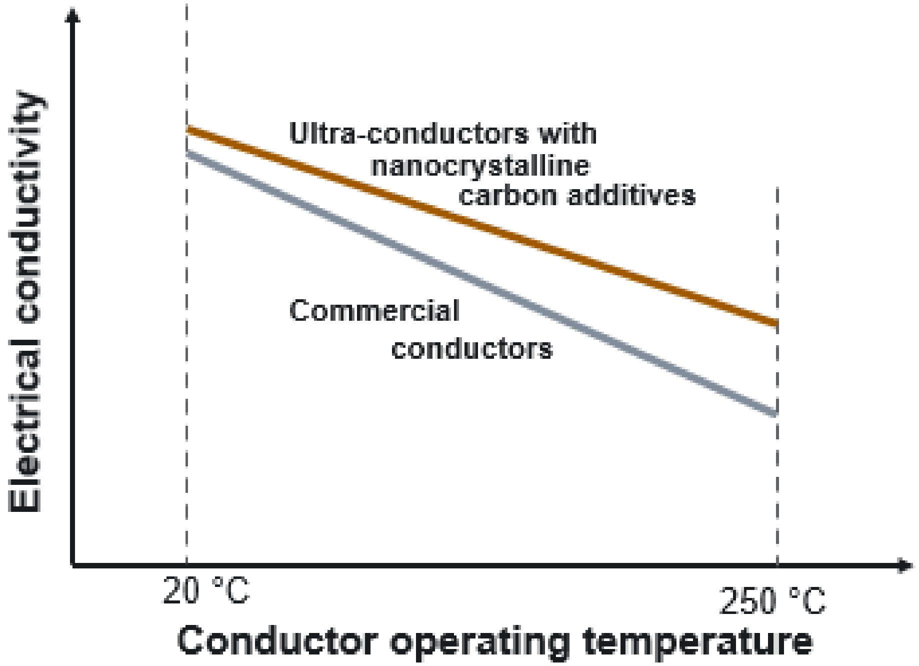
- Ultra-conductors - Materials with conductive additives (silver, carbon nanotubes, graphene, graphite) introduced to increase carrier velocities during transmission.
- Demonstrate enhanced electrical conductivity and lower temperature coefficient of resistance (TCR) at T > 20°C, *unlike superconductors*.



Ultra-conductors in the form of (A) foils and (B) powders with (C) 9 – 16% higher electrical conductivity over copper; targeted final forms of use for ultra-conductors such as (D) power cables, and (E) motor components.



Schematic showing the high velocity carrier pathways developed in metals through the addition of nanocrystalline carbon additives.

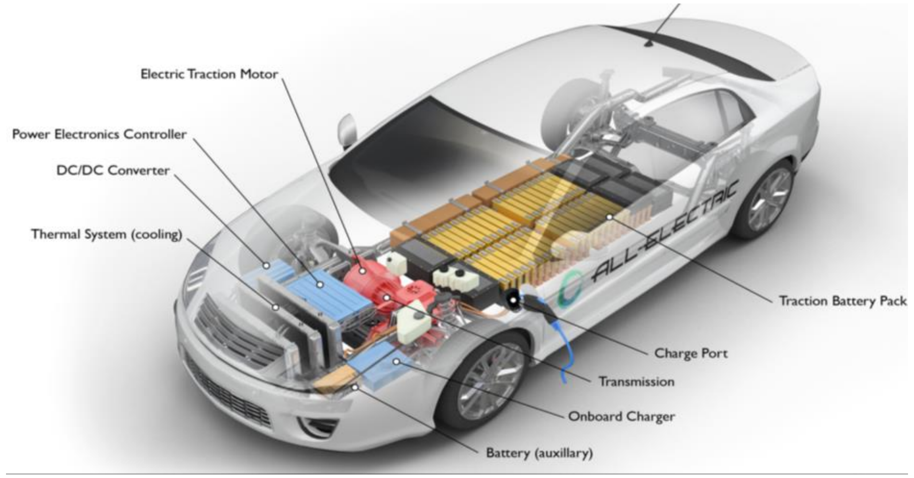


Representative schematic of bulk-scale ultra-conductor and commercial conductor conductivity as a function of temperature owing to TCR differences.

Impact of Ultra-Conductors to EVs

10% ↑ in conductivity (project target) = >2% ↑ in motor efficiency

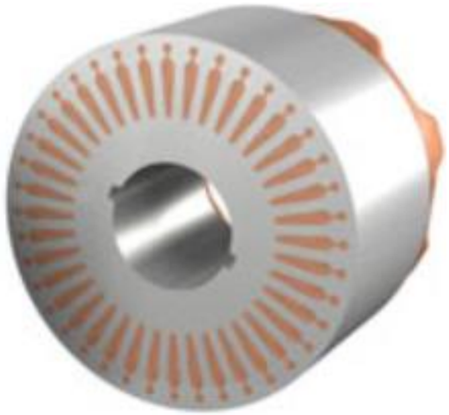
40% ↑ in conductivity (long term target) = ~15% ↓ in motor volume



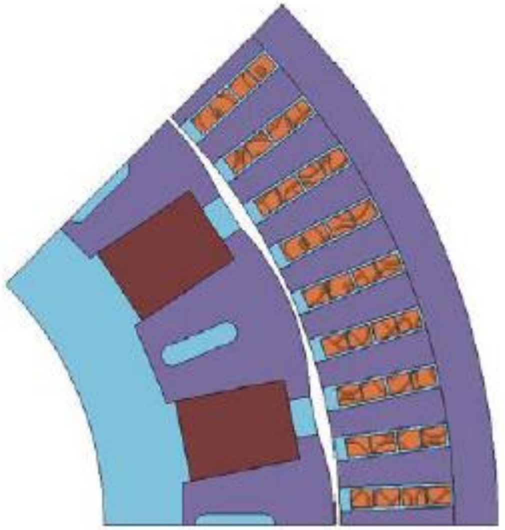
Electrical components made with aluminum and copper typically seen in EVs

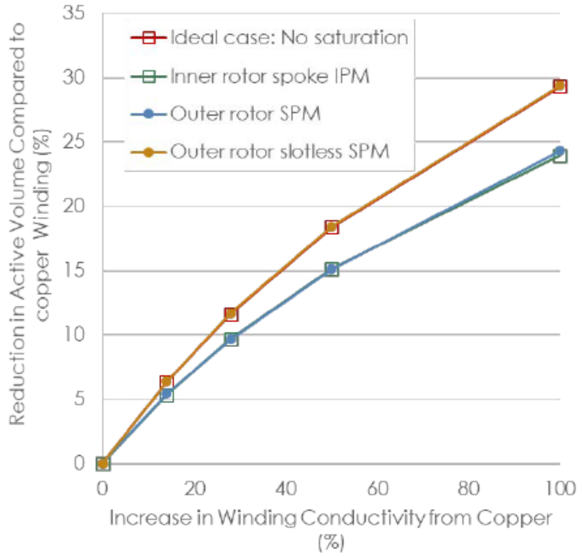
Higher conductivity at operating temperatures → Enhanced current density of conductors → Smaller conductive components or improved life → Volume or weight savings; increased energy efficiency

Efficiency of a representative EV motor as a function of shorting bar and end cap conductivity at 20°C and TCR, modeled using ANSYS[4]



Conductivity at 20°C (%IACS)	TCR [%/°C]	Efficiency [%]	Δ [%]
100.7	0.0037	76.3	--
104.8	0.0040	76.8	0.66
104.8	0.0036	77.3	1.3
110	**0.0037**	**78.1**	**2.4**
150	0.0033	82.7	8.4



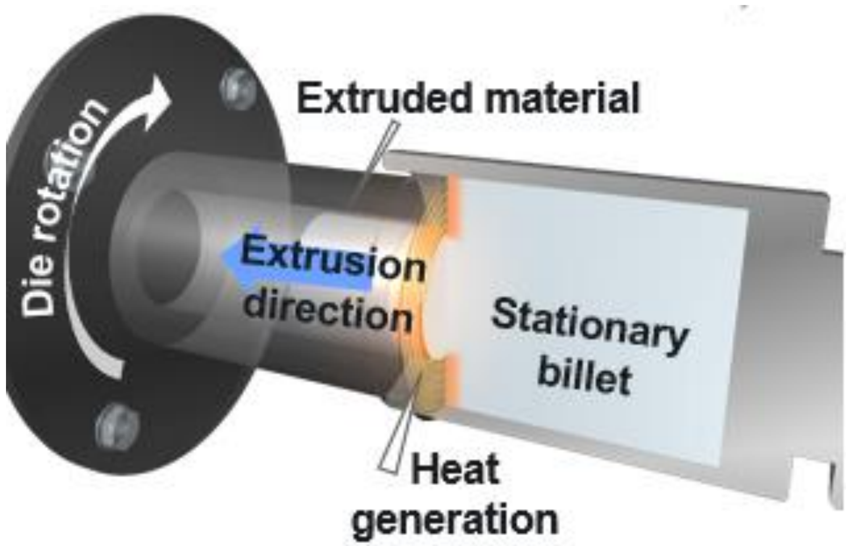


Reduction in active volume of heavy rare-earth-free permanent magnet motors (left) as a function of winding conductivity at 20 °C (right)

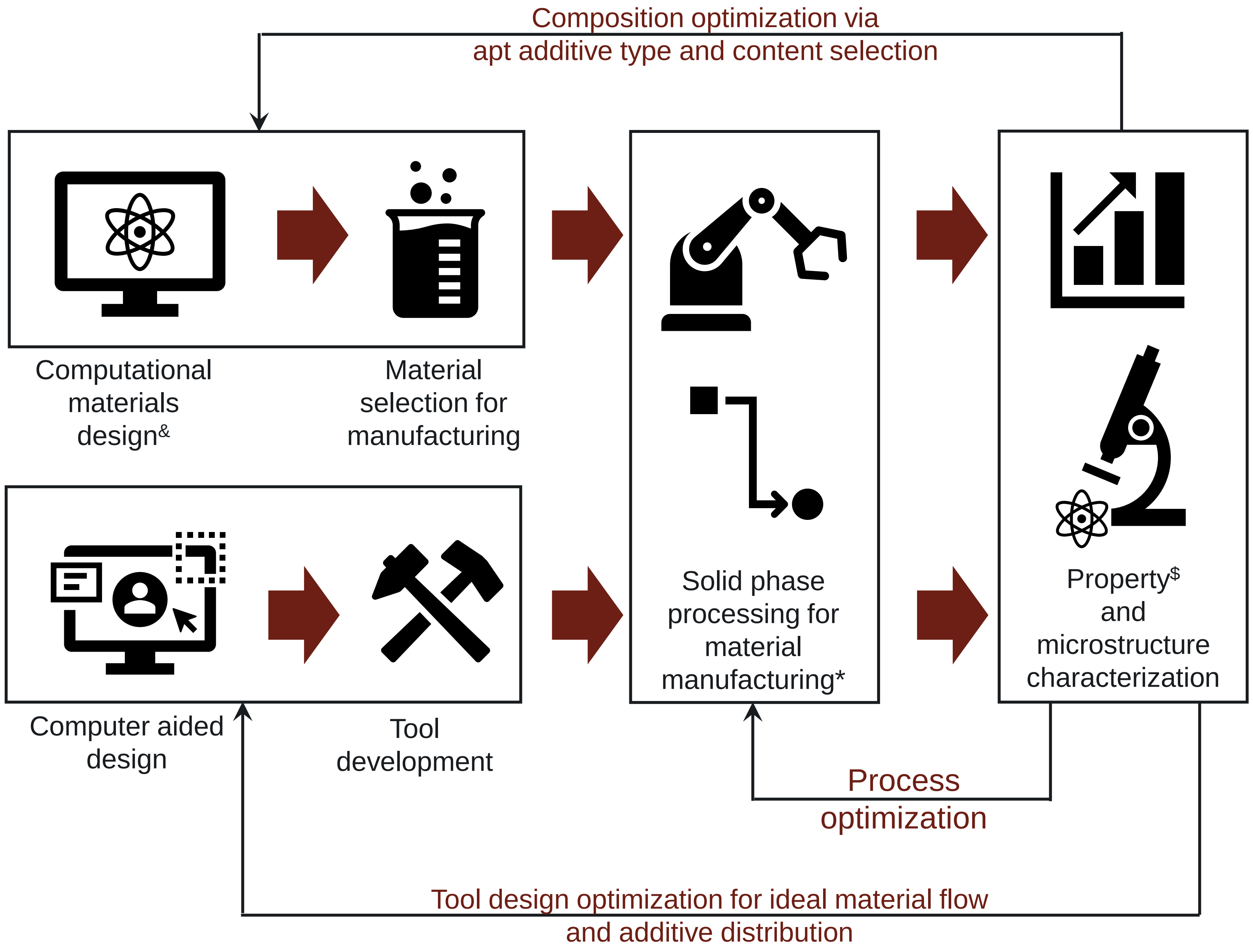
Approach

Bulk 3D Ultra-conductor Forms (Wires, Rods) Manufactured via Solid Phase Processing

Shear Assisted Processing and Extrusion (ShAPE) apparatus at PNNL



Schematic showing the ShAPE tooling and material extrusion process

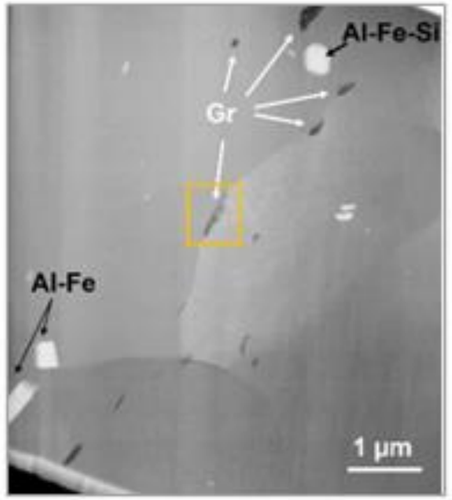


Approach

Bulk 3D Ultra-conductor Forms (Wires, Rods) Manufactured via Solid Phase Processing

EXPECTED OUTCOMES

Tooling designs and process envelopes



Microstructural features of metals and additives

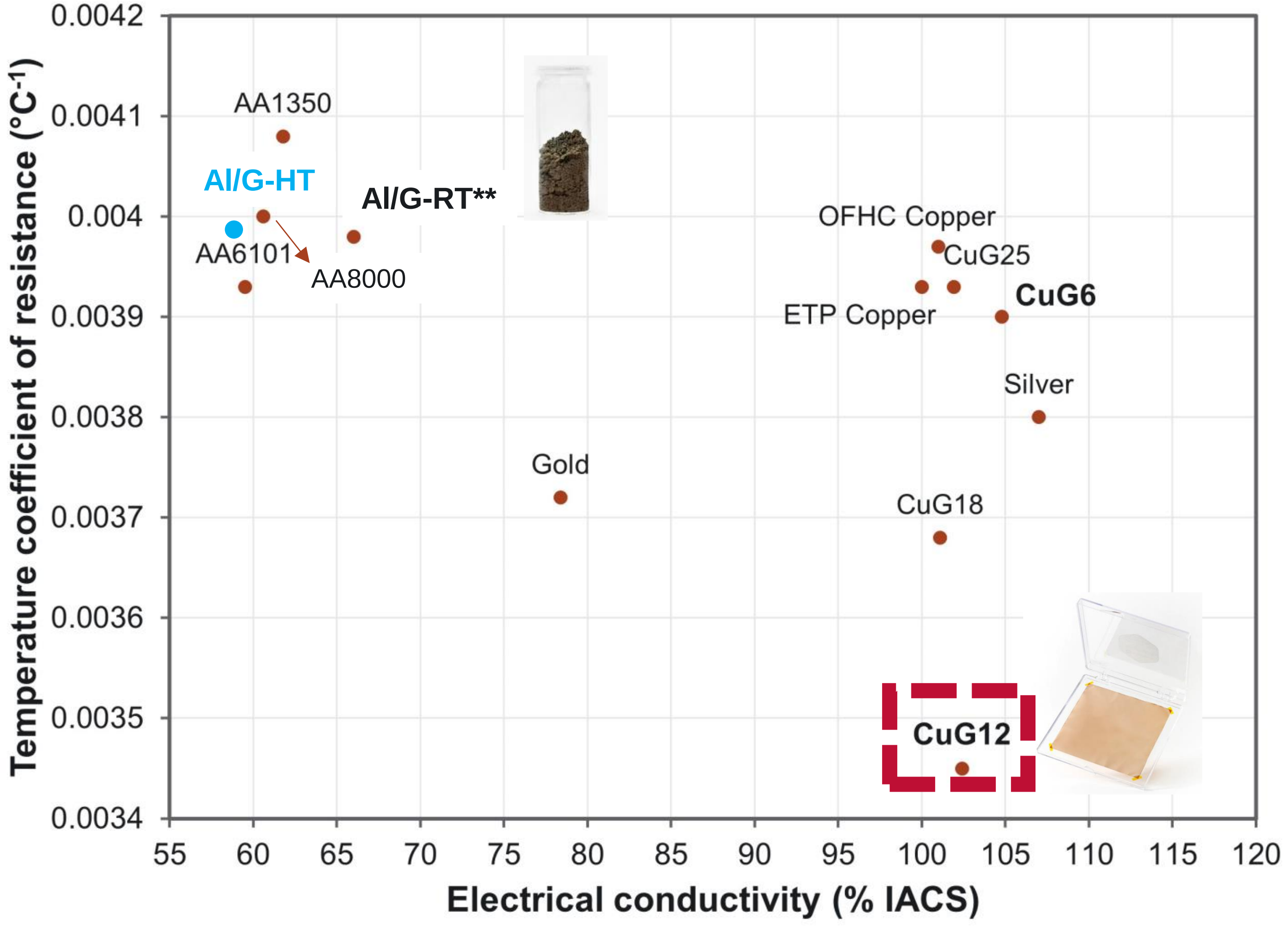
Wire spools (for component development – stretch goal)

Desired form factor for commercial use

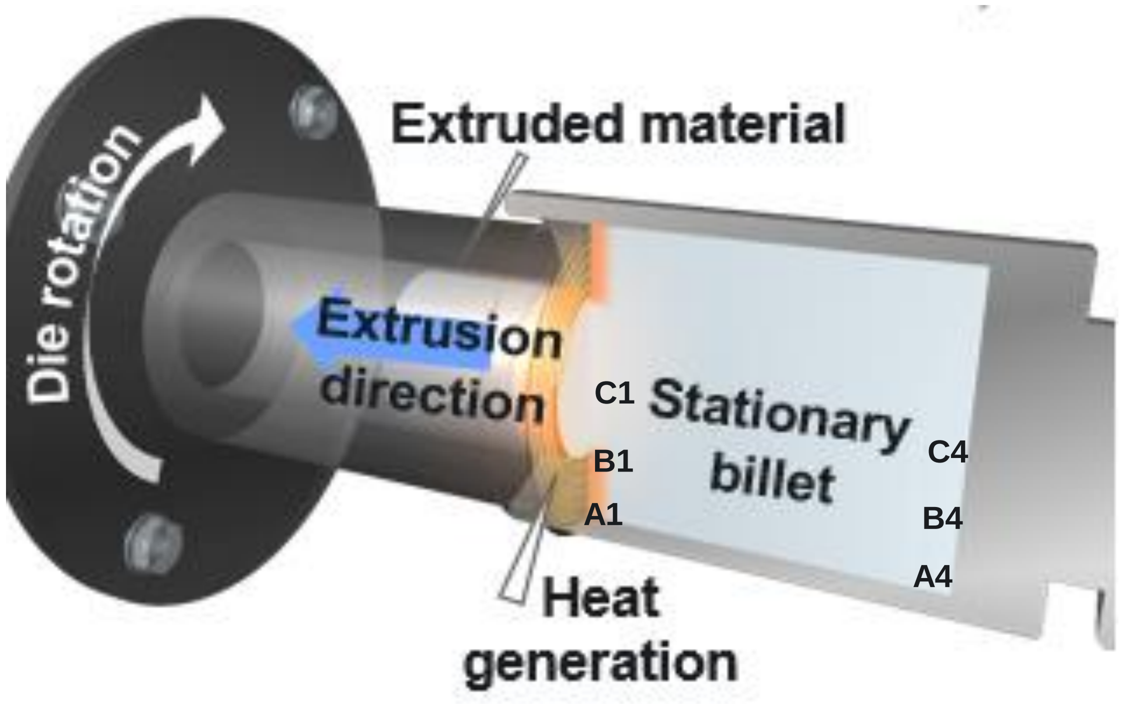
Project success measure	Description	Due date	Status
Milestone 1	Requisite quantities of semiconductor additives used for manufacturing ultra-conductors procured	12/31/24	Completed
Milestone 2	Wires manufactured with different additives (at varying compositions) via ShAPE approach and two concentrations down selected	03/31/25	Completed
Milestone 3	Wires manufactured down-selected additive concentrations via ShAPE approach at varying temperature and pressure	06/30/25	On track
Milestone 4	Property plots completed as a function of process parameters, material chemistry describing electrical and mechanical performance of ShAPE wires with semiconductor additives	09/30/25	On track
Go/No-go point	**At least 10% lower TCR ShAPE wires with novel additives resulting in higher electrical conductivity at 25 – 200 °C**	**09/30/25**	**On track**

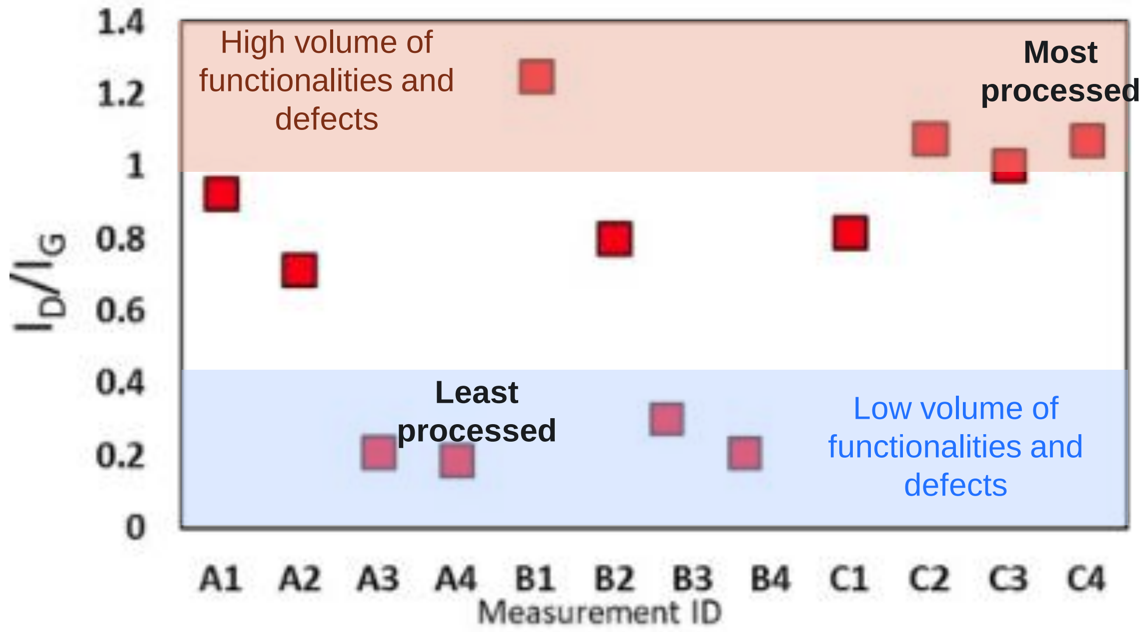
Background

Ultra-conductors with ↑Electrical Conductivity at Relevant Operating Temperatures



TCR vs. electrical resistivity at 20 °C of copper-graphene and aluminum-graphene composites with varying graphene content. Properties of relevant conductors such as AA1350, OFHC copper and silver are presented for comparison.

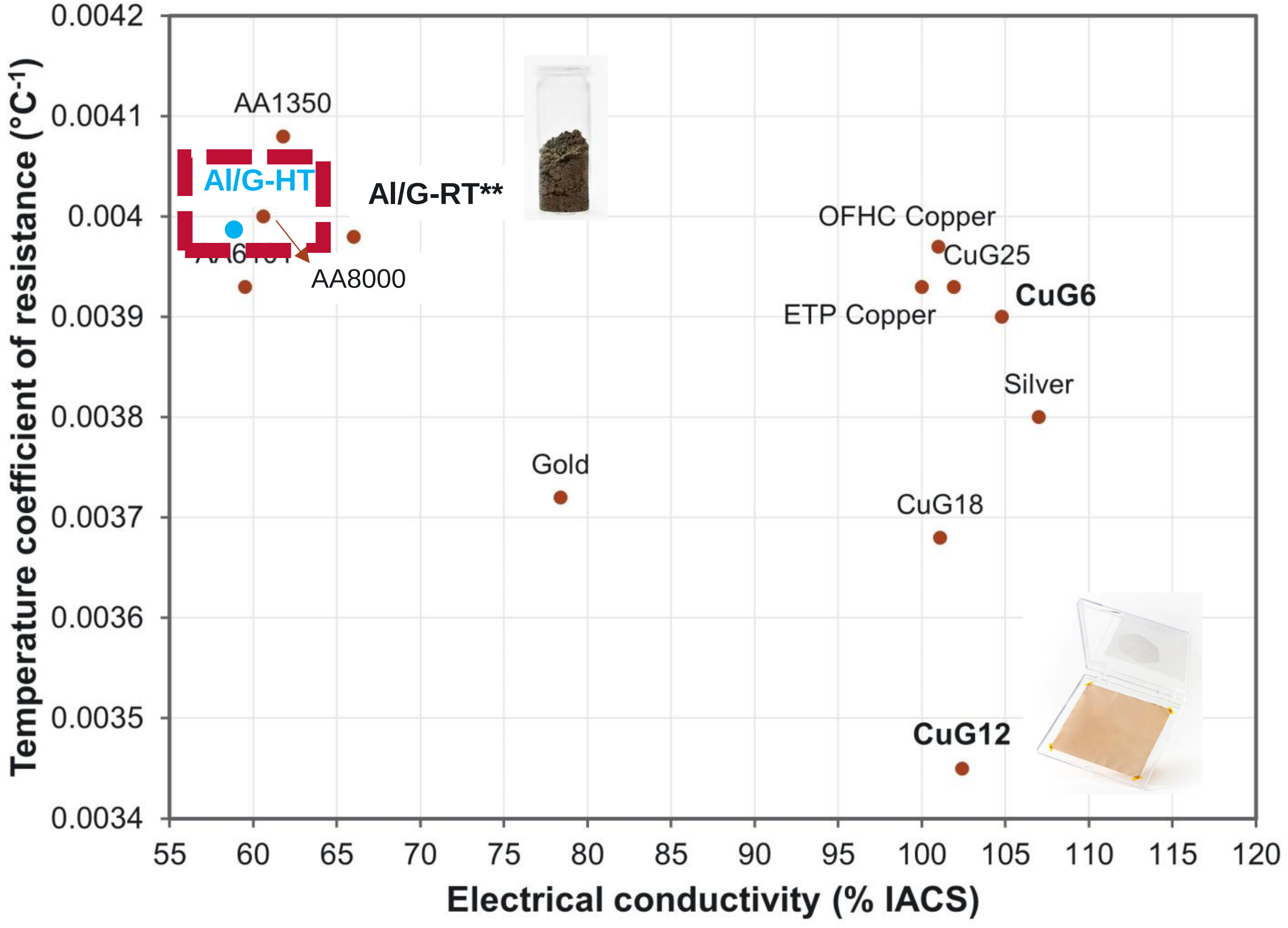




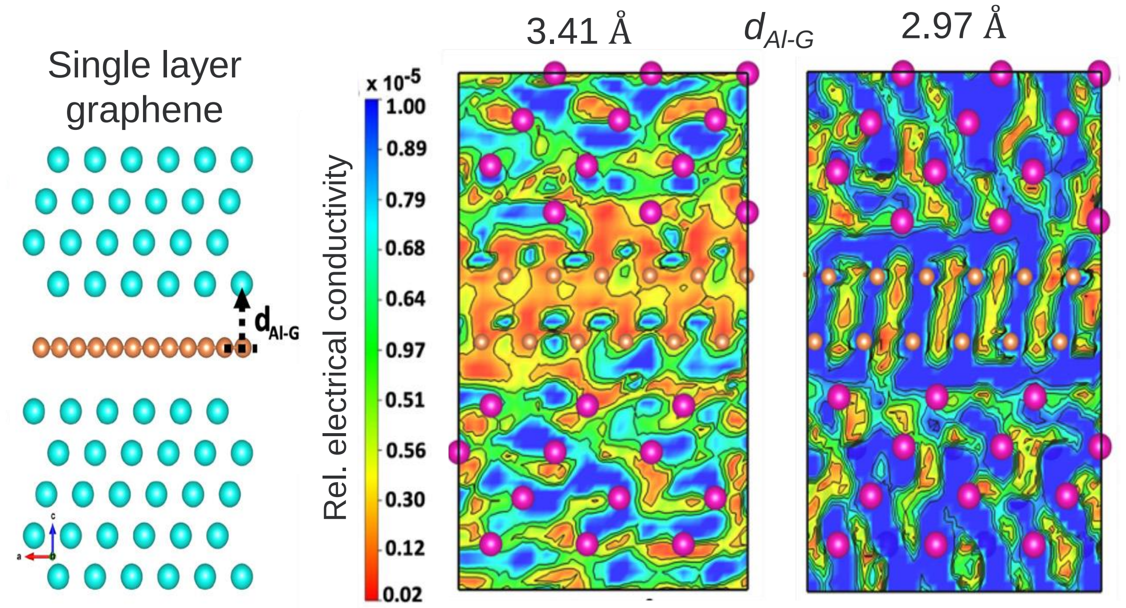
Defect density in graphene additives in different portions of the ShAPE billet experiencing varying levels of processing showing transition from semi-metallic (low I_D/I_G) to semi-conductor (high I_D/I_G) nature.

Background

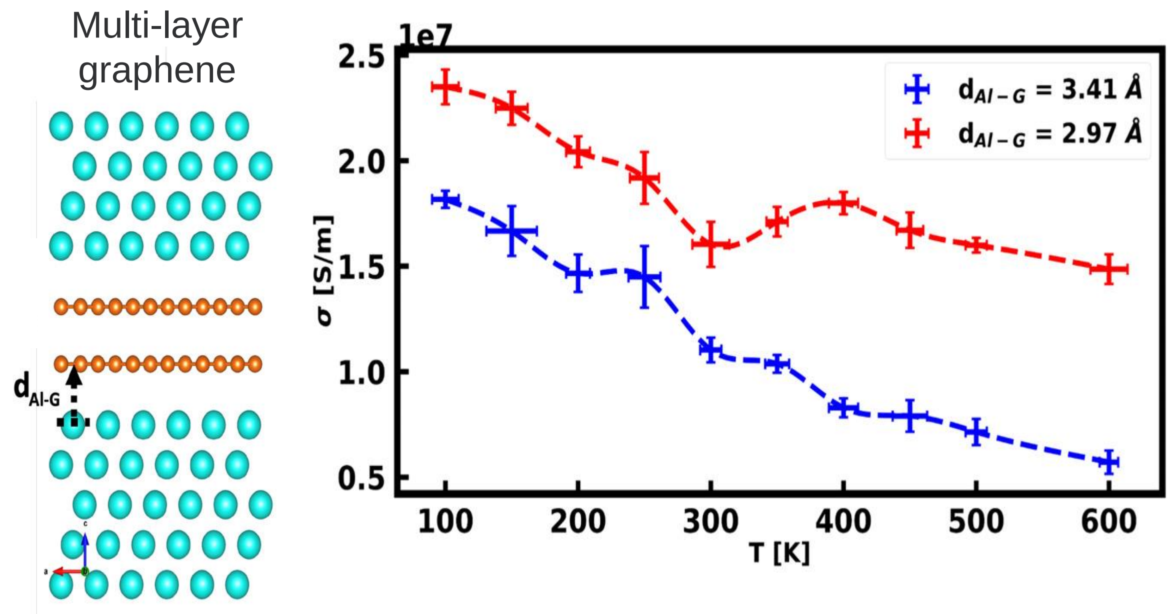
Ultra-conductors with ↑Electrical Conductivity at Relevant Operating Temperatures



TCR vs. electrical resistivity at 20 °C of copper-graphene and aluminum-graphene composites with varying graphene content. Properties of relevant conductors such as AA1350, OFHC copper and silver are presented for comparison.



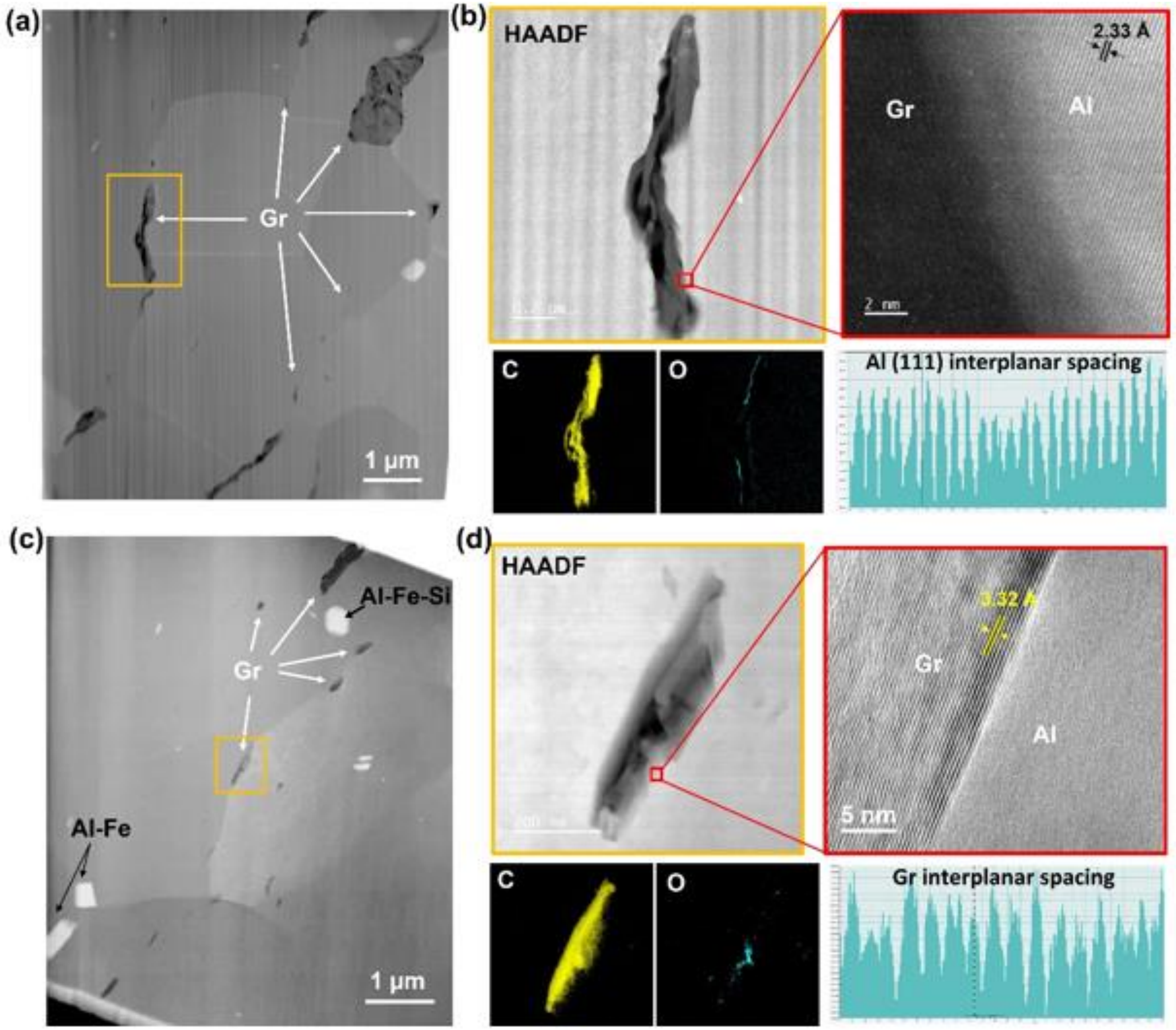
Decreasing metal-graphene spacing due to external pressure, **increasing** interaction for conduction.

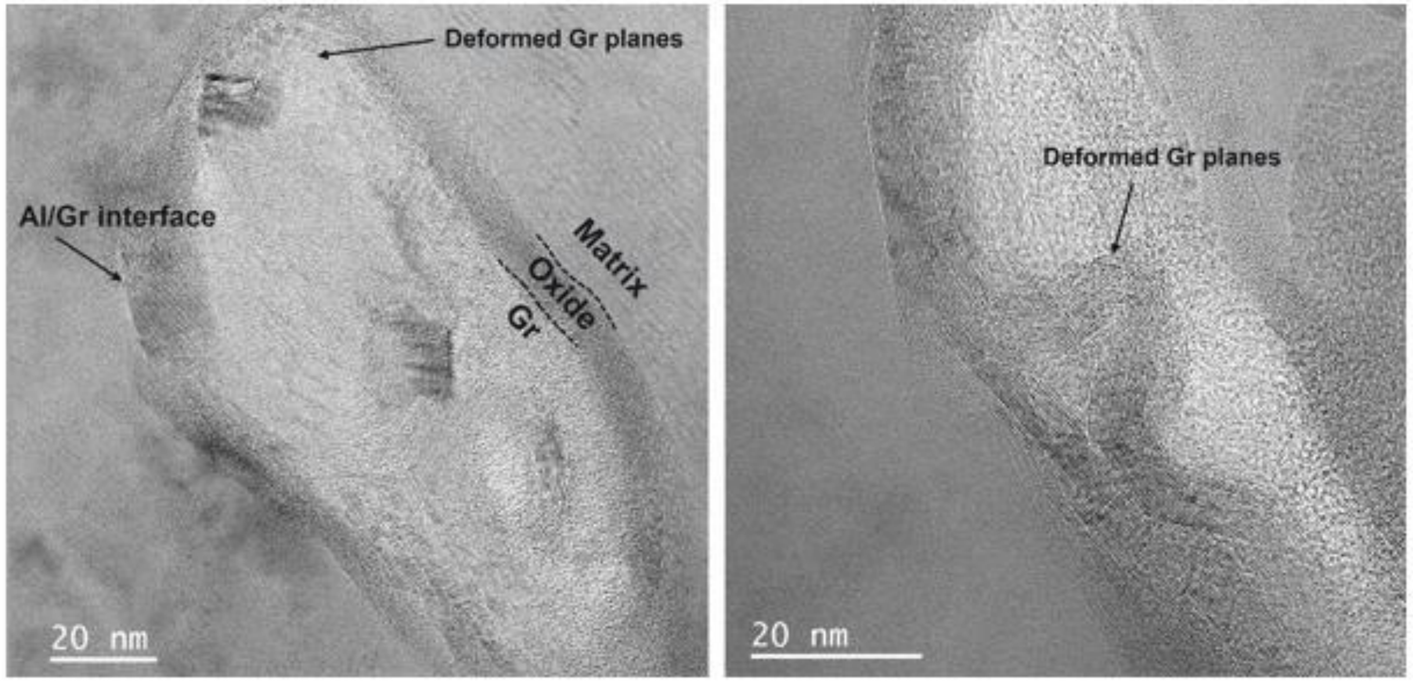


Multi-layer graphene shows curious **increase in conductivity** with increasing temperature

Technical Accomplishments and Progress

Discovered Crucial Features of High Temperature Ultra-conductor Microstructures





- Graphitic additives (suspected to be semiconductor in nature), present at grain boundaries and grain interiors.
- Minimal porosity observed in the microstructures.
- Oxygen present at the interface in some locations, often as Al-O species (confirmed by atom probe tomography*).
- AlFe and AlFeSi precipitates identified (common to AA1100).

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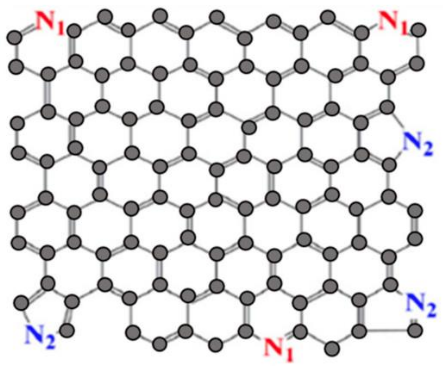
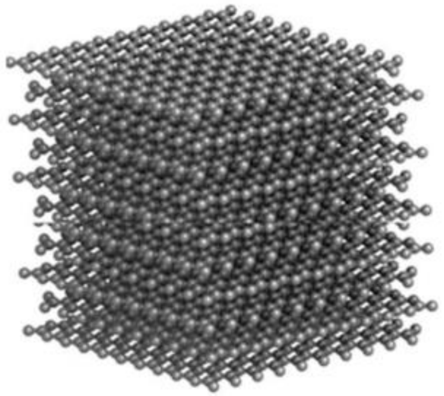
Technical Accomplishments and Progress

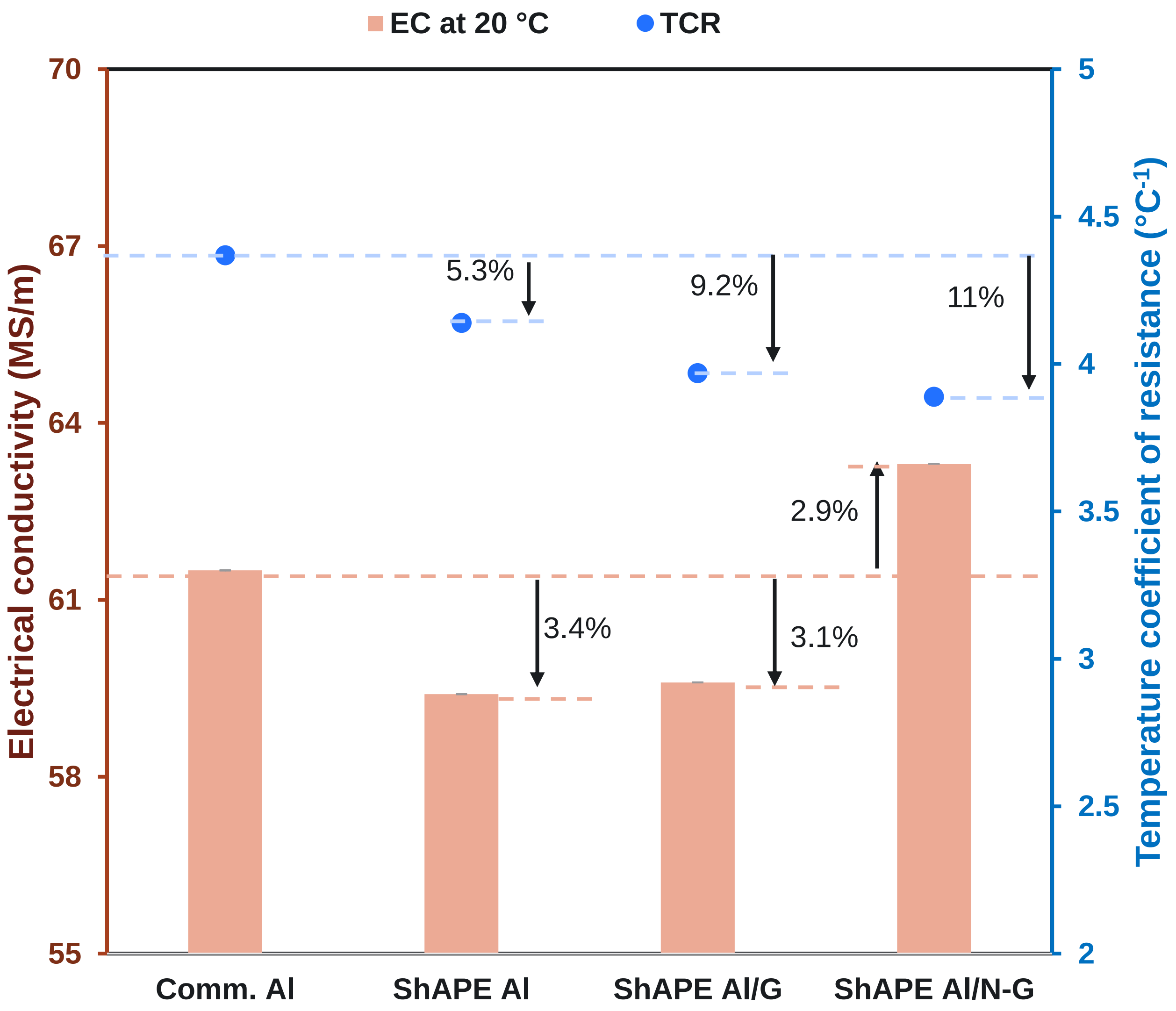
Developed New Ultra-conductors with Even Higher Performance Improvements





Nitrogen doped graphene (Graphitene) used as additive for enhancing conductivity of AA1100.

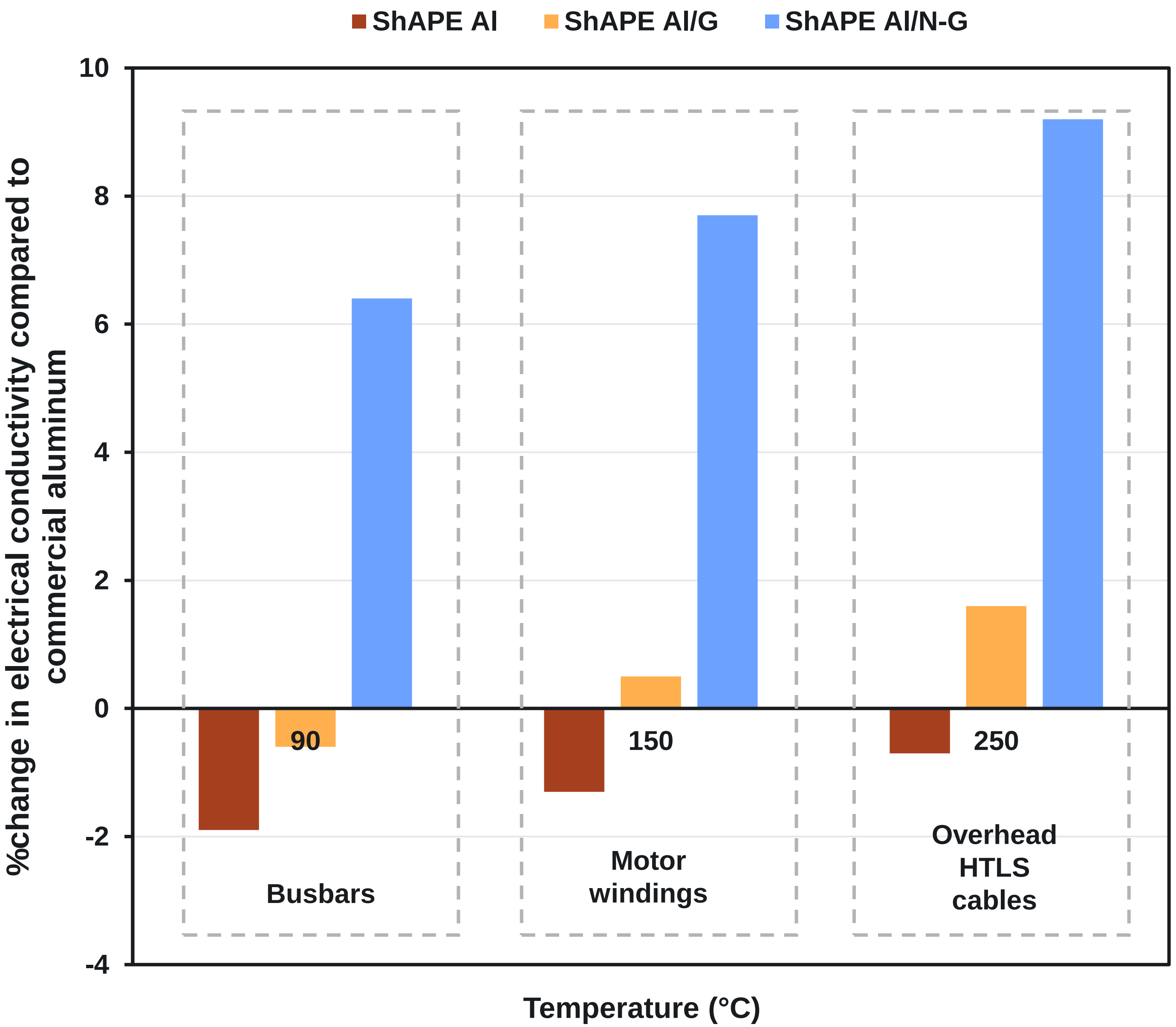
Feedstock preparation steps including sonication and foil coating for incorporating N-GNPs into AA1100 billet prior to friction extrusion via ShAPE to make 2.5-mm-diameter (10 AWG) wires.



Electrical conductivity and temperature coefficient of resistance of commercial AA1100 and various ShAPE aluminum/graphene composite wires.

Technical Accomplishments and Progress

Developed New Ultra-conductors with Even Higher Performance Improvements



Change in electrical conductivity of ShAPE wires compared to commercial AA1100-O properties at 90 – 250 °C operating temperatures.

Third-party performance evaluation on-going

Southwire, Prysmian Group, EPRI Electric Power Research Institute, Schneider Electric, EATON Powering Business Worldwide

POTENTIAL IMPACT

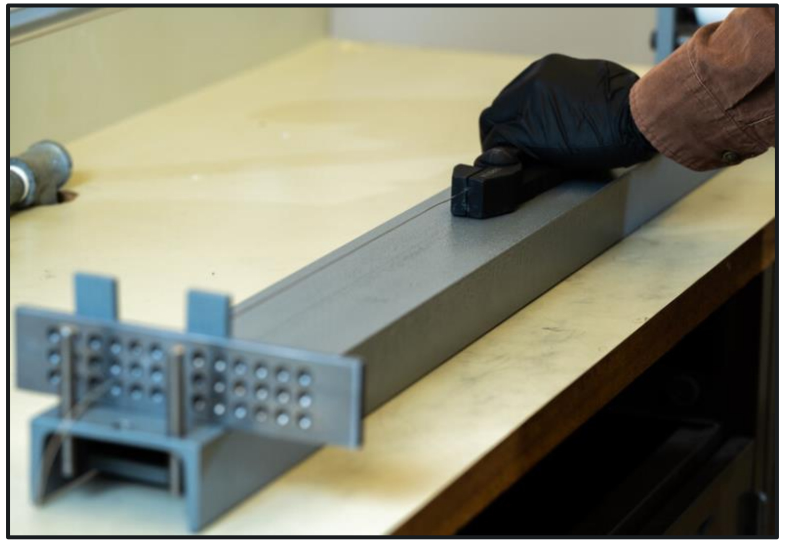
- **Lightweighting**
  - >10% lightweighting when wire harnesses are made with ShAPE composites wires compared to all-aluminum harnesses; >47% lightweighting when used in place of copper (~40% lightweighting with aluminum-only).
- **Thermal management**
  - 5-10% lower heat dissipation in ShAPE composite wires compared to aluminum wires of same size.
- **Supply chain insertion**
  - ShAPE wires can be inserted into supply chains easily owing to scalability of manufacturing and post-processibility.

Technical Accomplishments and Progress

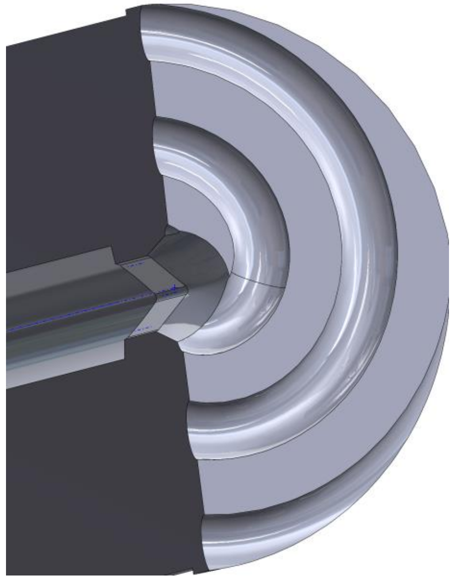
Identified Robust Manufacturing Pathways for Square Ultra-conductor Motor Wires

Design ShAPE tooling for manufacturing square magnet wires → **Identify process envelopes for manufacturing defect-free extrusions** →

Manufacture circular composite rods via ShAPE → **Draw and anneal sequentially to attain desired square cross-section** →



Drawing apparatus used to manufacture square magnet wires from circular ShAPE composite rods.



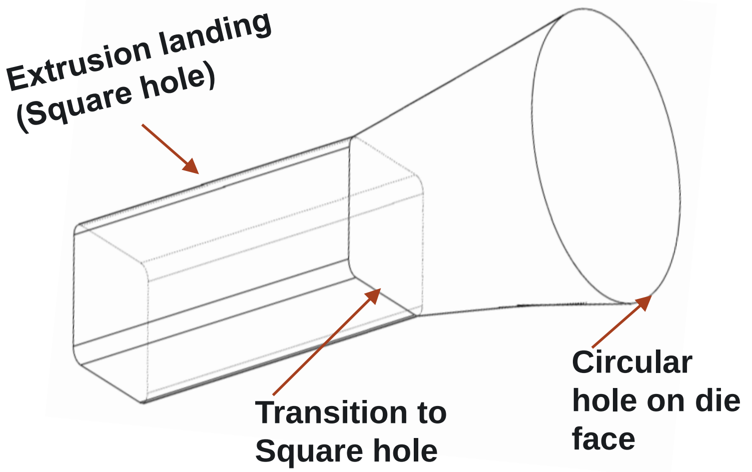
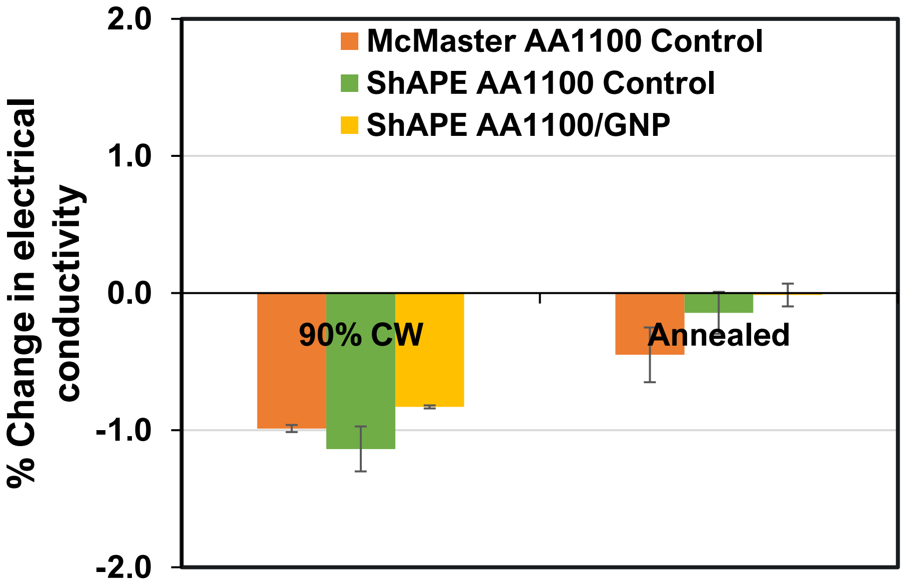


Image (left) and schematics of square wire extrusion tooling designed for ShAPE of composite magnet wires



Change in conductivity due to cold work and annealing at 400 °C for ShAPE wires.

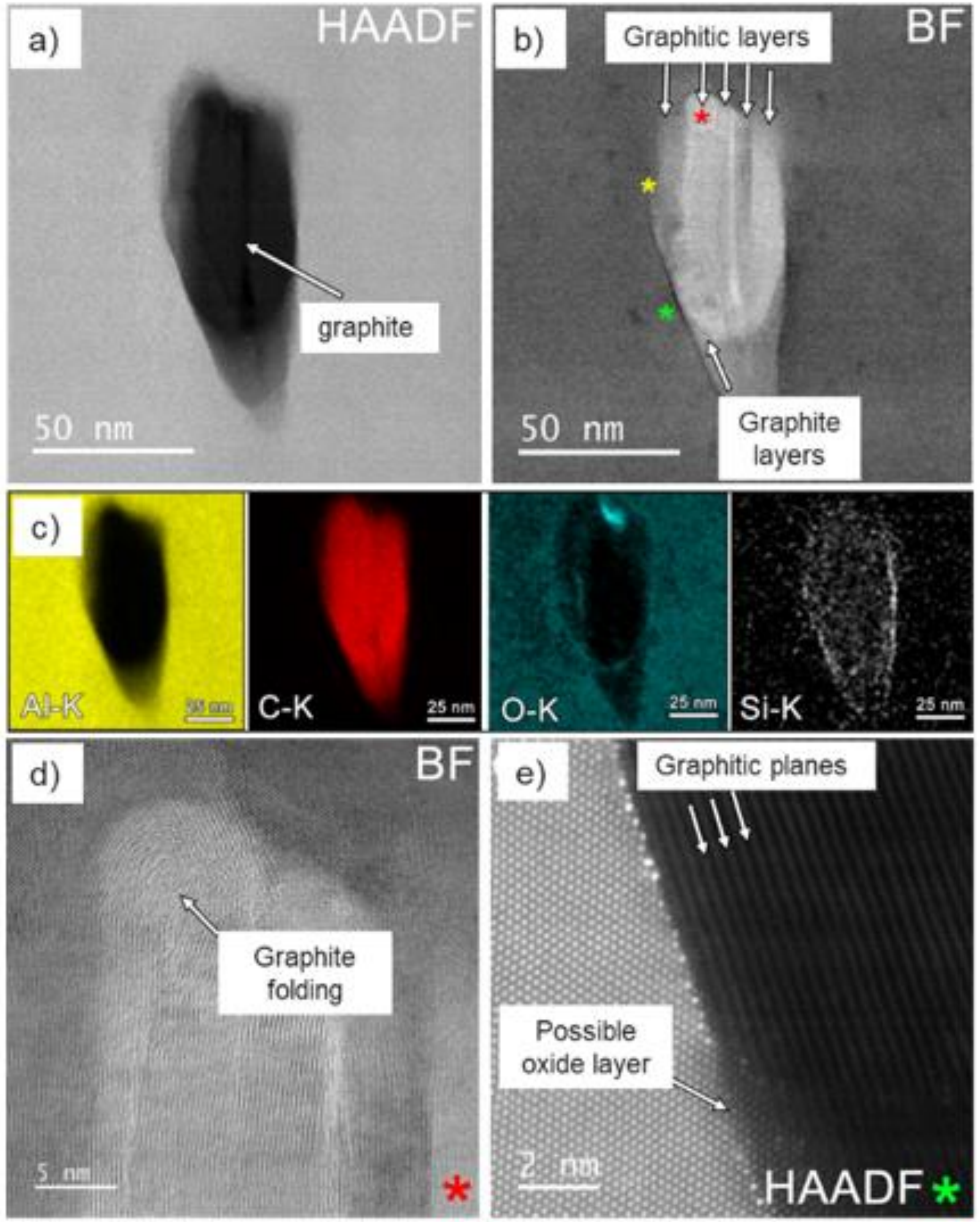
Response to Previous Year's Comments

- Project was not reviewed last year. Updates were presented in a poster.

Remaining Challenges and Barriers

- Development of square windings with nitrogen-doped graphene additives
  - Using previously developed approaches to manufacture and measure the performance of extruded + post-processed square wires

- Exploring other doped additive effects on electrical performance
  - Nitrogen-doped carbon nanotubes, effect of oxygen species in electronic performance



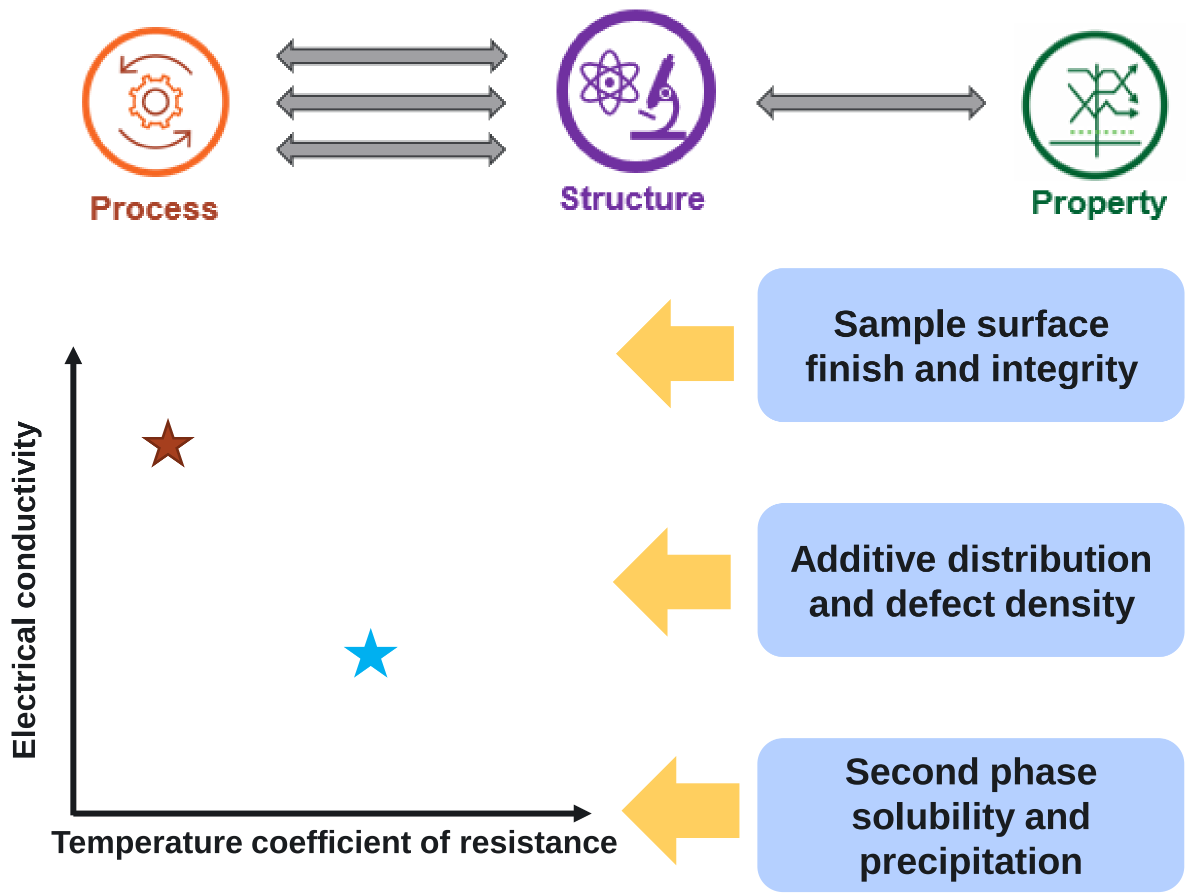
Transmission electron microscopy images of aluminum/reduced graphene oxide composite wires showing 7% higher electrical conductivity at 20 °C, developed in PMCP Phase 1 (FY 22-23), showing oxygen presence at the interface between aluminum and carbon species.

Collaboration and Co-ordination

- Argonne National Laboratory – Quarterly meetings
  - Supporting APS and XANES work on Al/graphene and Cu/graphene composites to characterize microstructure
- Industrial Advisory Panel – Monthly/Quarterly meetings with individual stakeholders
  - Southwire, EPRI and Prysmian-General Cable: cable manufacturing for transportation applications
  - Eaton, Schneider: automotive component applications
- Academic Partners – Monthly meetings
  - Ohio University: DFT modeling
  - North Carolina State University: PPMS measurements, microstructural characterization

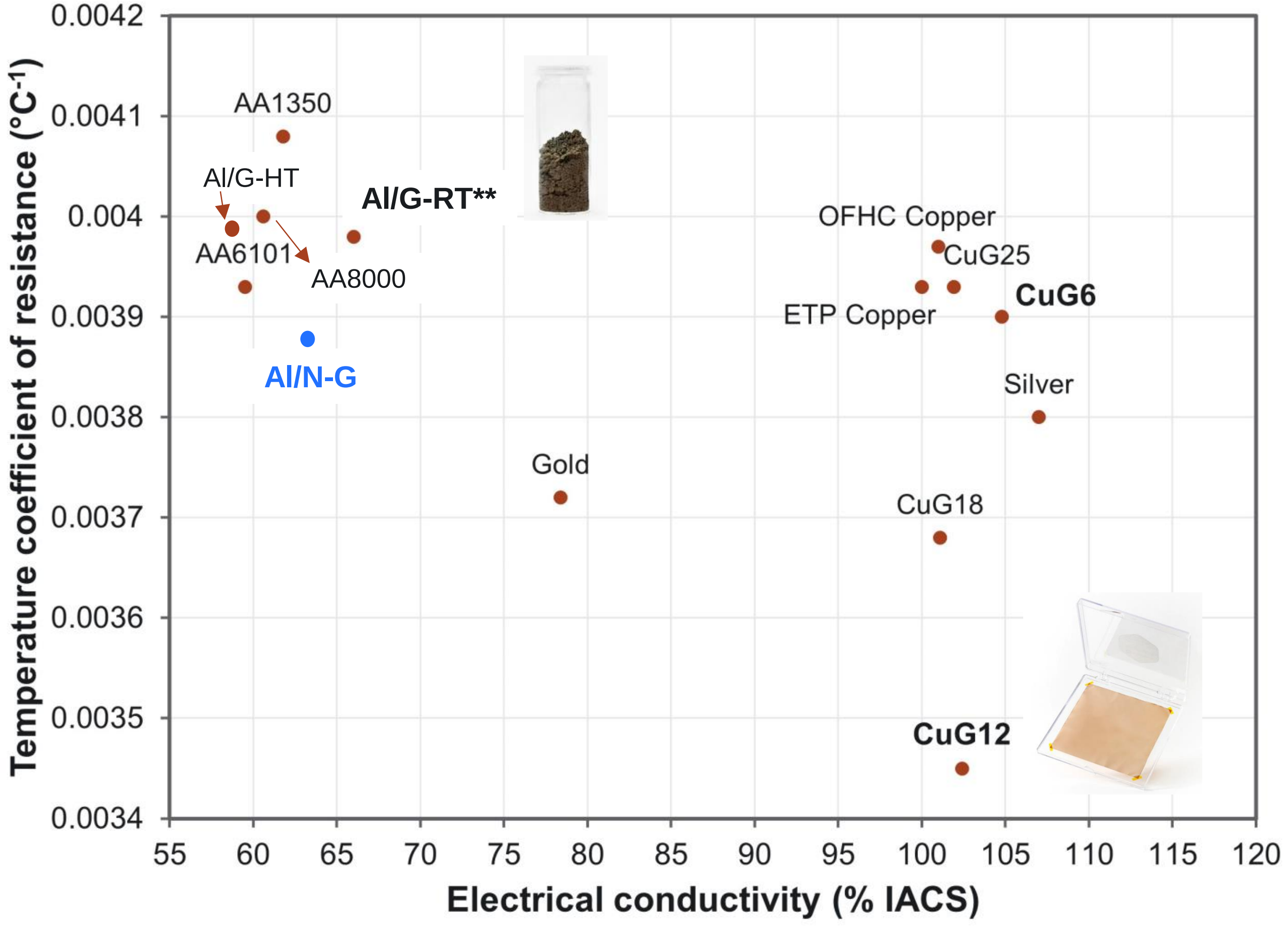
Proposed Future Work

- Understanding evolution of conductivity improvement
  - Atom force microscopy and physical property measurement system analysis for electronic property characterization across scales
- Determining effect of processing conditions
  - Evaluating electrical properties as a function of synthesis temperatures and forces/pressures
- Identifying role of nitrogen and other dopants
  - Advanced multi-modal material characterization for nitrogen location in composite developed at different manufacturing envelopes

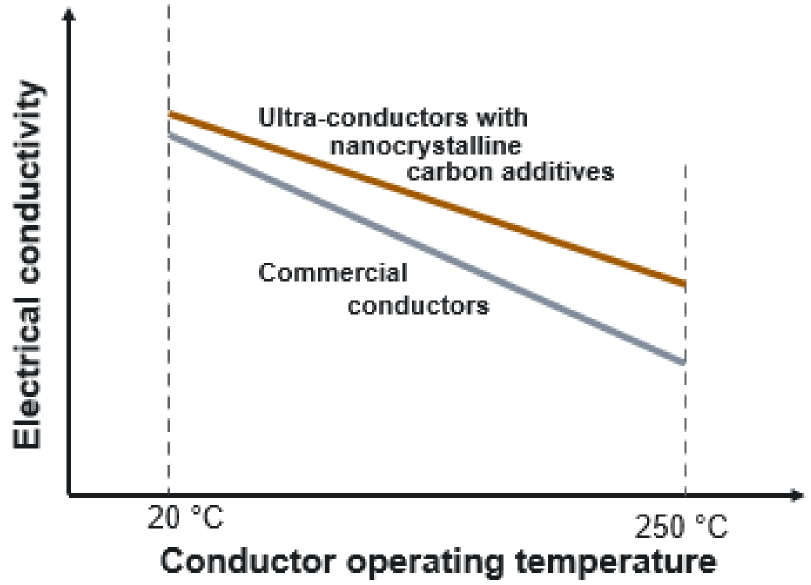


Summary

Development of Bulk Aluminum and Copper Ultra-conductors for EV Applications



TCR vs. electrical resistivity at 20 °C of copper-graphene and aluminum-graphene composites with varying graphene content. Properties of relevant conductors such as AA1350, OFHC copper and silver are presented for comparison.



- Developed new bulk-scale ShAPE ultra-conductors with nitrogen-doped graphene additives showing >7-9% higher conductivity at 150 – 250 °C over commercial aluminum.
- Identified material features of interest in ultra-conductor microstructures resulting in enhanced conductivity.
- Developing direct-extrusion and drawing/annealing pathways for manufacturing square magnet wires with enhanced electrical performance.

Significant Products

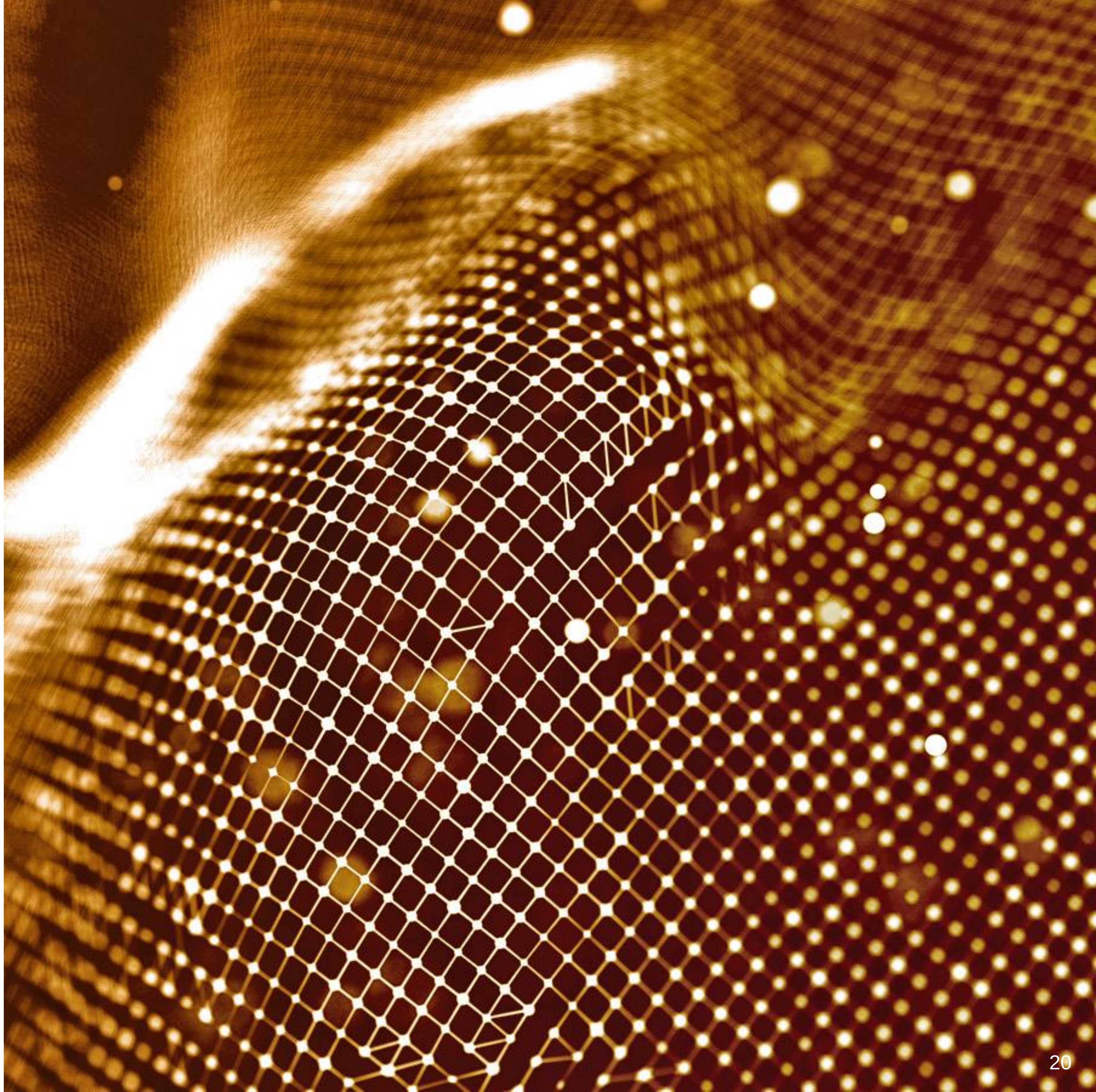
Publications

1. William Frazier, Keerti S. Kappagantula, A computational study of the effects of graphene additions on electrical properties of polycrystalline copper, Composites Communications, Volume 52, December 2024, 102124.
2. Aditya Nittala, Lloyd Furuta, Joshua Silverstein, Alex Poznak, Frank F Kraft, Keerti Kappagantula, Electrical property enhancement of non-heat-treatable wrought aluminum alloys using graphene additives, Journal of Alloys and Compounds, Volume 1003, October 2024, 175434.
3. Kishor Nepal, Chinonso Ugwumadu, Kashi Subedi, Keerti Kappagantula, David Drabold, Physical origin of enhanced electrical conduction in aluminum-graphene composites, Applied Physics Letter, Volume 124, February 2024, 091902.
4. Kishor Nepal, Chinonso Ugwumadu, Kashi Subedi, Keerti Kappagantula, David Drabold, Electronic conductivity in metal-graphene composites: the role of disordered carbon structures, defects, and impurities, Journal of Physics: Materials, Volume 7 (2), February 2024, 025003.
5. Julian Escobar, Aditya Nittala, Xiao Li, Woongjo Choi, Matthew Olzsta, Sten Lambeets, Arun Devaraj, Tanvi Ajantiwalay, Keerti Kappagantula, Friction extruded bulk aluminum/graphene ultra-conductors with enhanced electrical conductivity, npj 2D materials, in preparation.
6. Aditya Nittala, Md. Reza-E-Rabby, Julian Escobar, Jijo Christudasjustus, Sten Lambeets, Arun Devaraj, Tanvi Ajantiwalay, Keerti Kappagantula, Role of graphene distribution in feedstock on enhancing electrical properties of friction extruded aluminum ultra-conductors, Journal of Manufacturing Processes, in preparation.
7. Aditya Nittala, Md. Reza-E-Rabby, Farhan Ishrak, Pedro Ottoni, Bharat Gwalani, Keerti S. Kappagantula, On post-processability of friction extruded aluminum/graphene ultra-conductors, Materials & Design, in preparation.
8. Xiao Li, Aditya Nittala, Jijo Christudasjustus, Bharat Gwalani, Shivakanth Shukla, Timothy Roosendaal, Behai Ma, Dileep Singh, Chen Zhou, James Schroth, Glenn Grant, Keerti Kappagantula, Friction Extrusion of Bulk-scale Copper/Graphene Ultra-Conductors with Enhanced Electrical Conductivity, RSC Nano-Horizons, in submission.

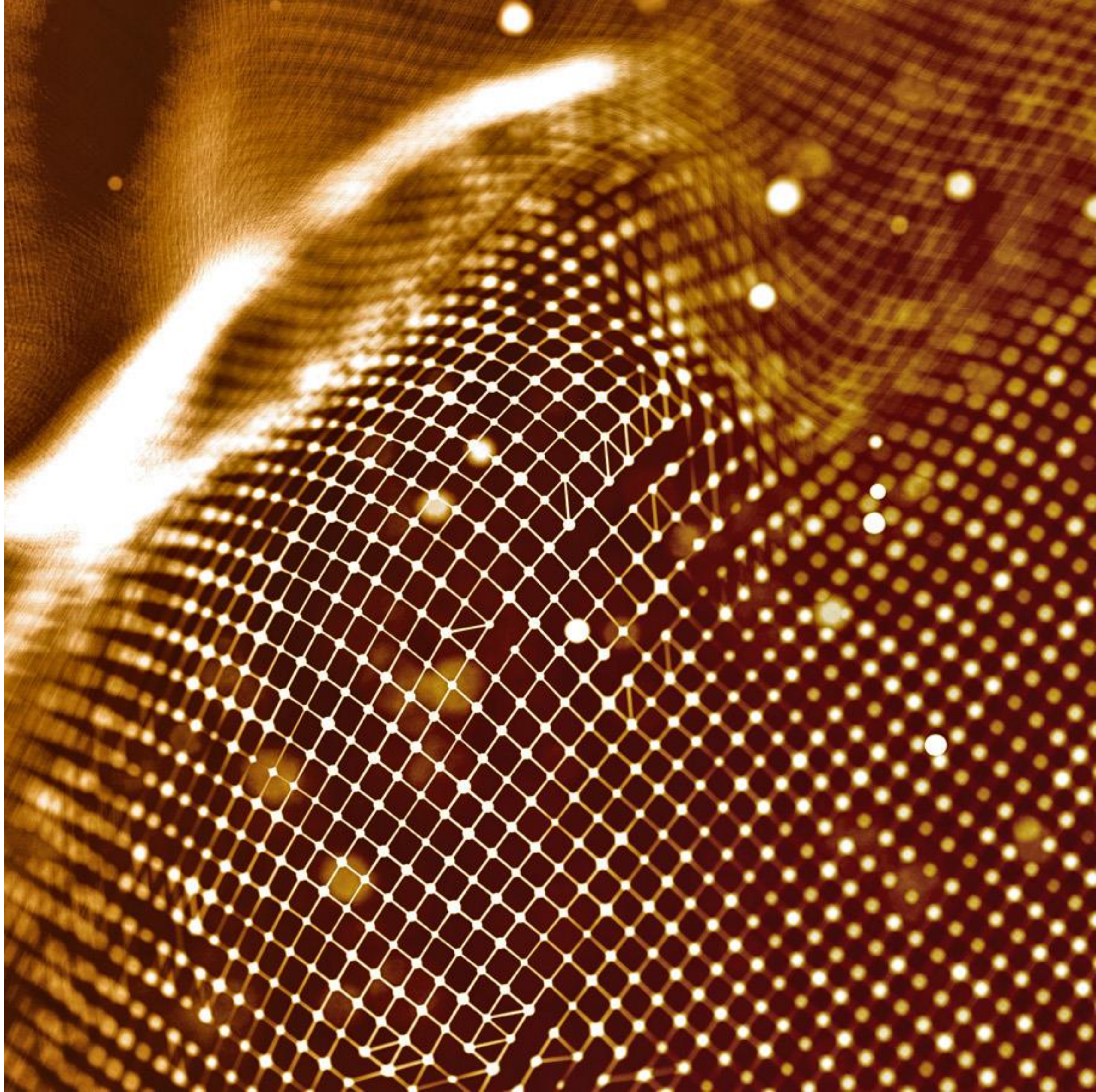
Patents, Invention Disclosures

1. US Non-provisional Patent Application: EXTRUSION PROCESSES, FEEDSTOCK MATERIALS, CONDUCTIVE MATERIALS AND/OR ASSEMBLIES, Keerti S Kappagantula, Glenn J Grant, Aditya K Nittala, Xiao Li, MD Reza-E-Rabby, WoongJo Choi, Bharat Gwalani, Joshua A Silverstein, (iEdison No. 0685901-13-0018), IPID 30343-E, Patent Master ID 10706, Appl. Date: 03/2023
2. EXTRUSION PROCESSES, FEEDSTOCK MATERIALS, CONDUCTIVE MATERIALS AND/OR ASSEMBLIES Keerti S Kappagantula, Glenn J Grant, Aditya K Nittala, Xiao Li, MD Reza-E-Rabby, WoongJo Choi, Bharat Gwalani, Joshua A Silverstein (iEdison No. 0685901-13-0018), IPID 30343-E WO9, Patent Master ID 10708, Appl. Date: 03/2023
3. PCT: ALUMINUM/CARBON COMPOSITES WITH ULTRA-HIGH CONDUCTIVITY Keerti S Kappagantula, Glenn J Grant, Aditya K Nittala, Xiao Li, MD Reza-E-Rabby, WoongJo Choi, Bharat Gwalani, Joshua A Silverstein (iEdison No. 0685901-20-0035), IPID 31815-E WO, Patent Master ID 10707, Appl. Date 03/2023
4. IDR - Magnet Wire Development via Shear Assisted Processing and Extrusion (ShAPE) Platform (iEdison No. 0685901-24-0136), Keerti S. Kappagantula, Md. Reza-E-Rabby, Aditya Nittala, Pedro Ottoni, IPID 33101-E, Filing Date: 06/2024

Thank you



Technical Backup Slides



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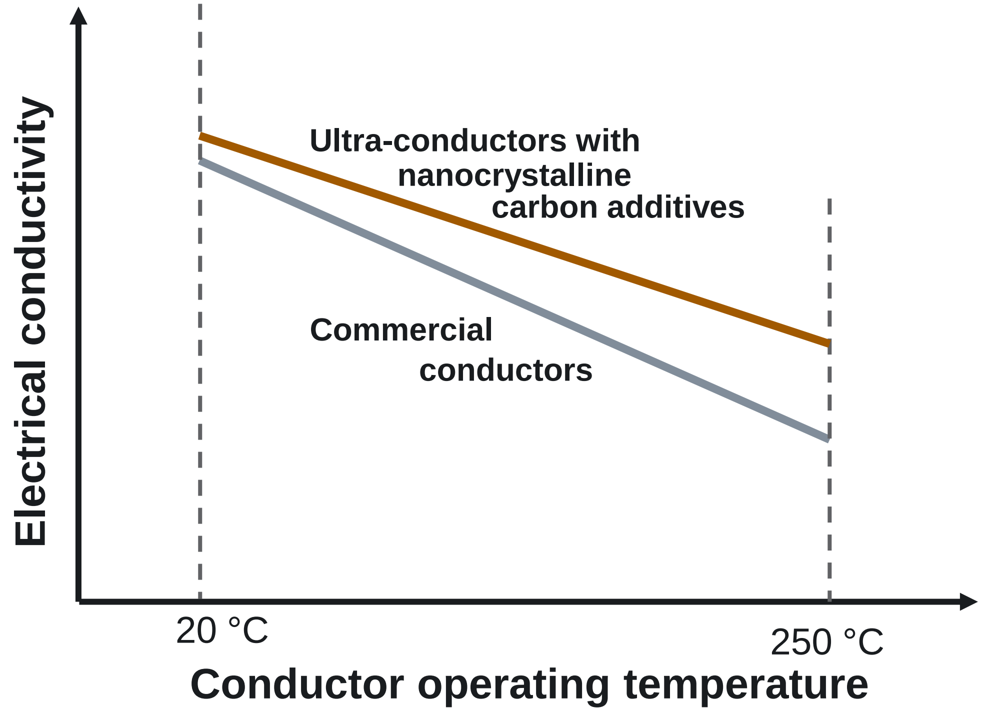
Electrical properties and measurement metrics of interest

- Properties of interest:
  - **Electrical conductivity (EC) (20 °C)**
  - **Temperature coefficient of resistance (TCR)**

- Important metric for energy efficiency – **I^2R** in a given time period ***t*** at an operating temperature ***T***
  - Lower **I^2R** implies lower energy losses
  - I is controllable, so R (resistance) is of interest



Electrical conductivity

$$R_{20} = \frac{V}{I} = \rho_{20}.\frac{l}{A_c}$$

$$\sigma_{20} = \left(\frac{I}{V}\right)\frac{l}{A_c}$$

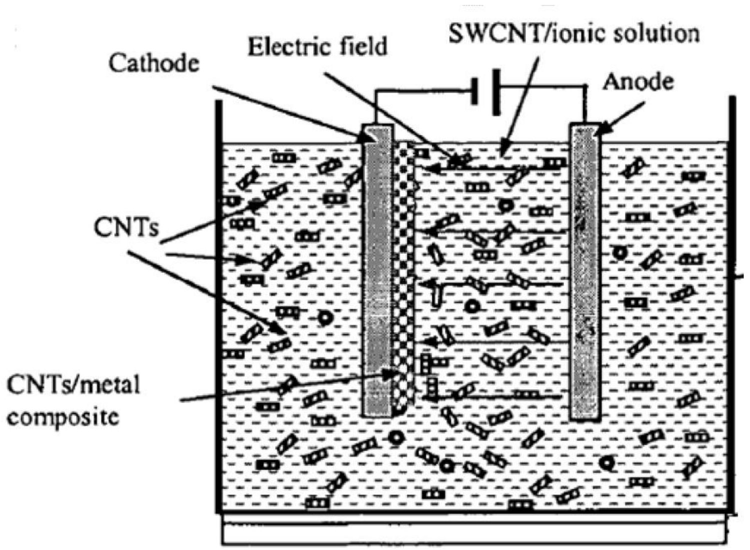
Temperature coefficient of resistance

$$\alpha = \frac{1}{R_{20}}\frac{(R_T - R_{20})}{(T - 20)}$$

ASTM B193

NIST Calibrated Properties

However, enhancing electrical performance at *industrially significant volumes* is very challenging



Copper-carbon nanotube composite manufacturing using electrolytic co-deposition method.

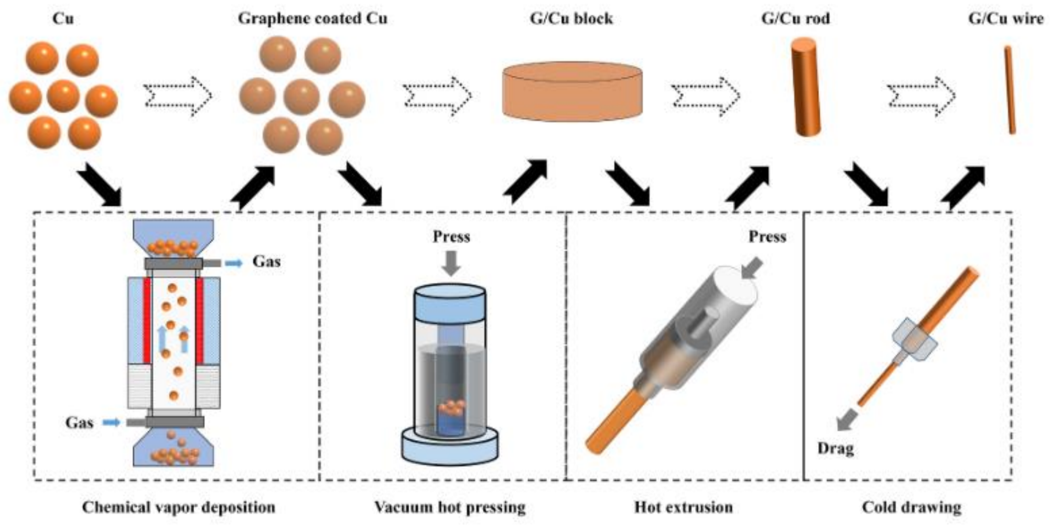
Common problems with various approaches

Porosity

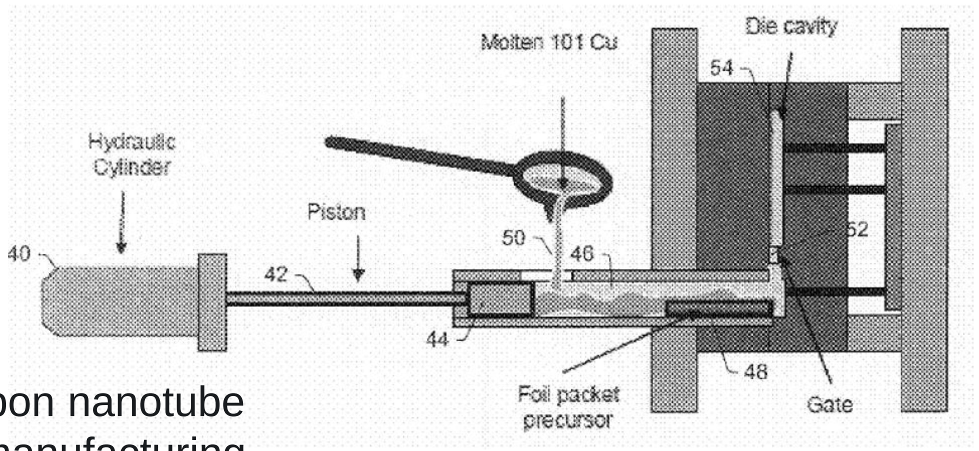
Additive agglomeration

Sub-optimal interfaces

Structural damage to additive structures



Extrusion and drawing of graphene coated powders



Copper-carbon nanotube composite manufacturing using direct die-casting.

Field assisted melt-manufacturing of covetics

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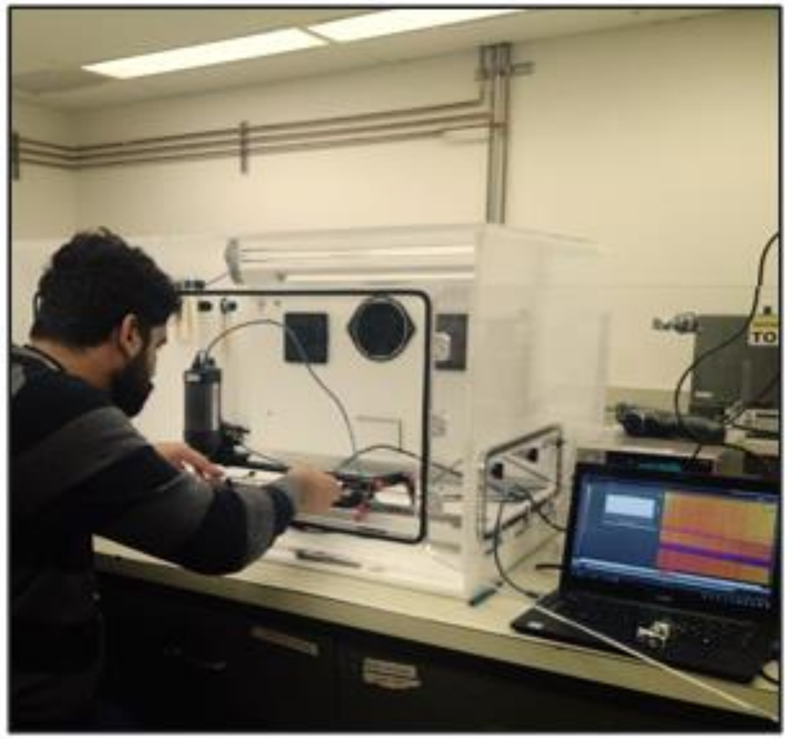
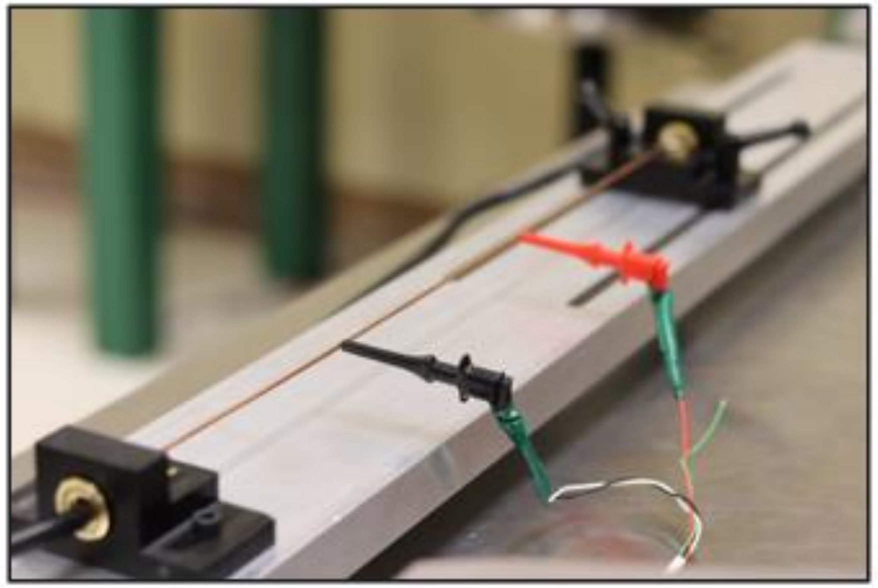
Electrical properties are characterized using ASTM B193 for bulk samples

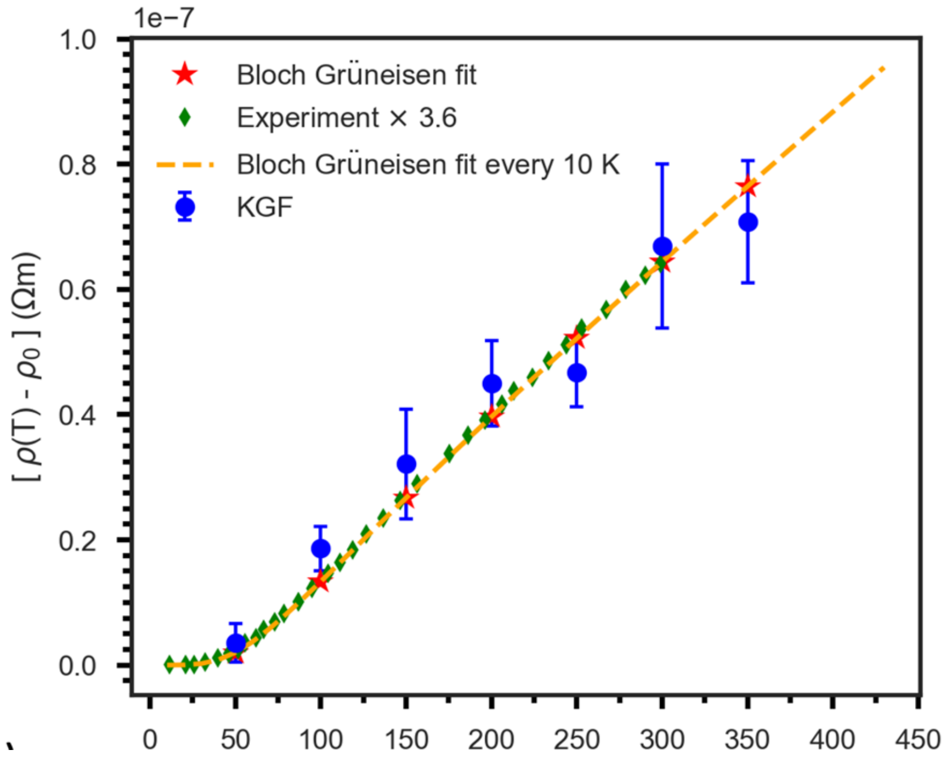


- Capable of measuring electrical conductivity, current density and temperature coefficient of resistance
- Comprises of a custom-made base across which wire samples (1 – 2 m long) are fixed
- Wire diameter measured using Keyence LS 7010 with LS 7601 controller optical micrometer (0.5 microns resolution)
- Non-contact IR camera monitoring temperature continuously during testing (0.5°C resolution)
- Standard pooled error in conductivity measurement ~0.01% IACS, current density measurement 0.5 A/mm^2
- Relative accuracy of measurements = 95%

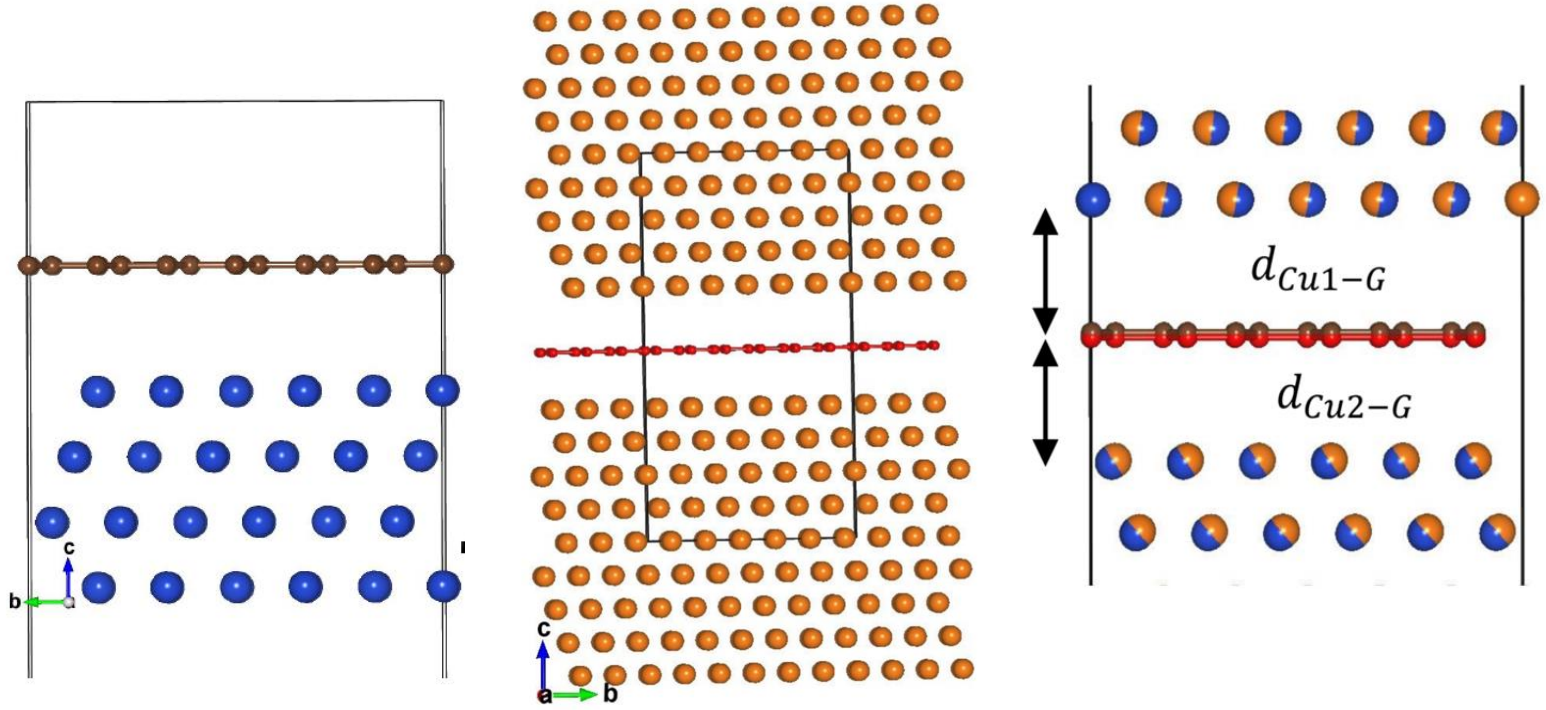


Does graphene participate in carrier conduction in ultra-conductors at the atomistic scale?

- Temperature dependence of the conductivity in copper understood with Bloch-Grüneisen model
  - includes no defects and does not explicitly take structure into account
- Kubo-Greenwood formula over extended molecular dynamics simulations at fixed temperatures



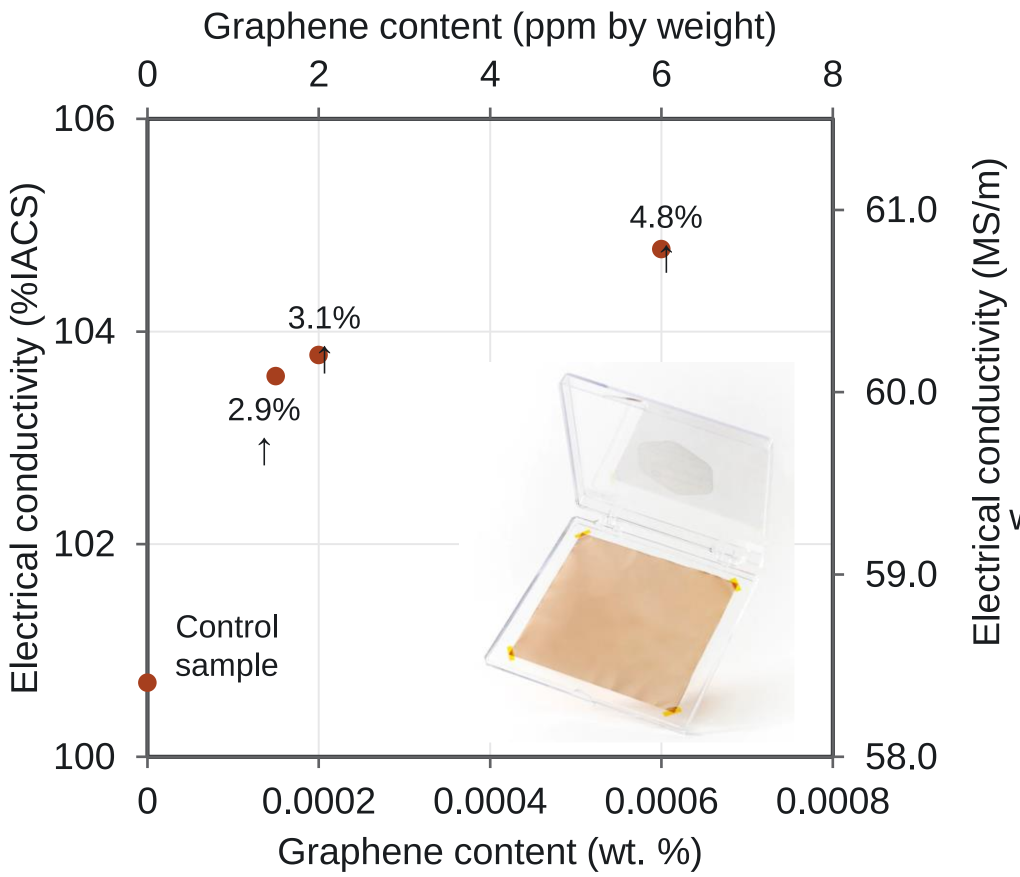
Electrical resistivity of copper from KGF/MD simulations as a function of temperature compared to experimental results



Graphene over copper (left); graphene embedded between copper atoms on both sides (center); and schematic showing distance between copper and carbon atoms

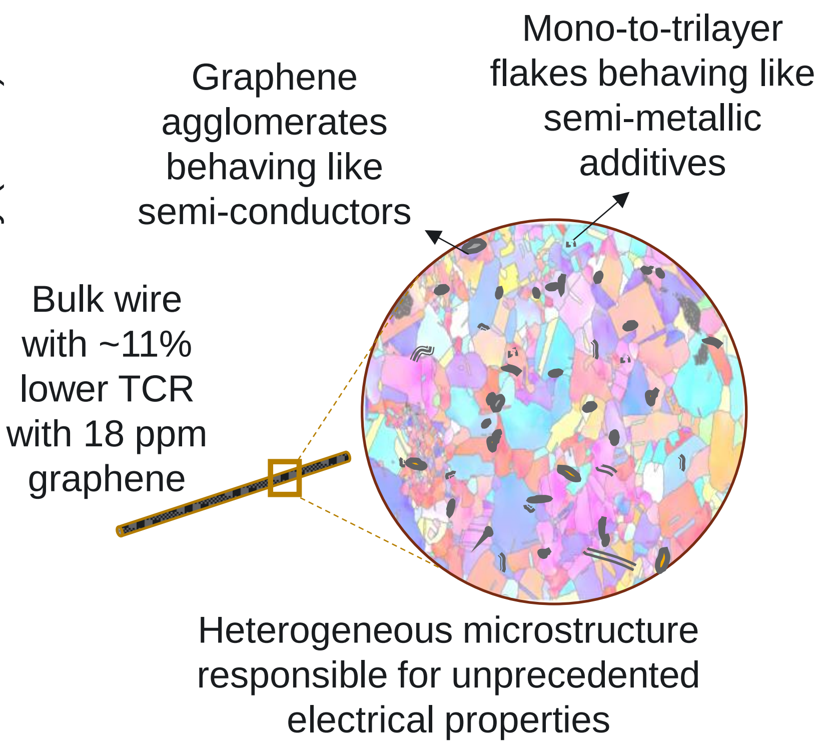
- Computationally demanding ab initio density functional methods – plane wave VASP code
- Accurately treat the electronic structure, compute the total energies, interatomic forces and atomic dynamics
- Space projected conductivity to:
  - Visualize atom-by-atom conduction activity in real space
  - Interrogate roles of defects, disorder, and thermal effects

ShAPE ultra-conductors, show high conductivity and low TCR at bulk scale



Electrical conductivity of copper + graphene composite samples as a function of graphene content at 20 °C.

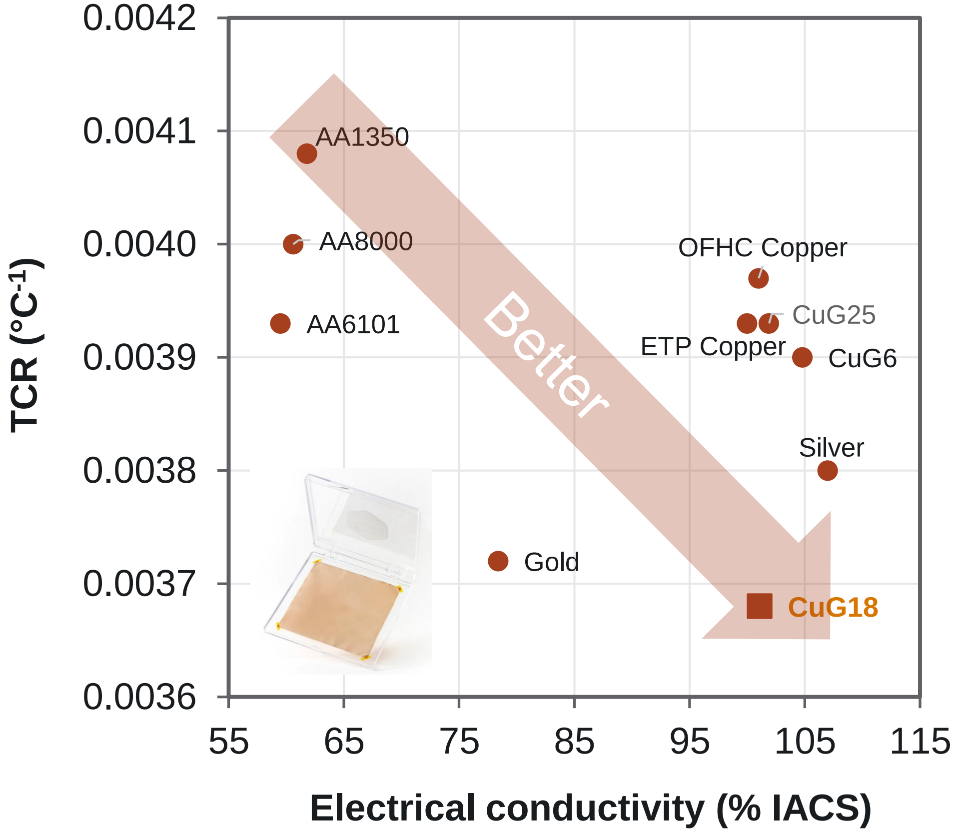
Inset: Graphene coated copper foils (procured commercially) used as feedstock for making copper ultra-conductors with enhanced electrical conductivity



High temperature conductivity improvement in copper attributed to semi-conductor like graphene additives which lead to thermal generation of carriers at elevated temperatures

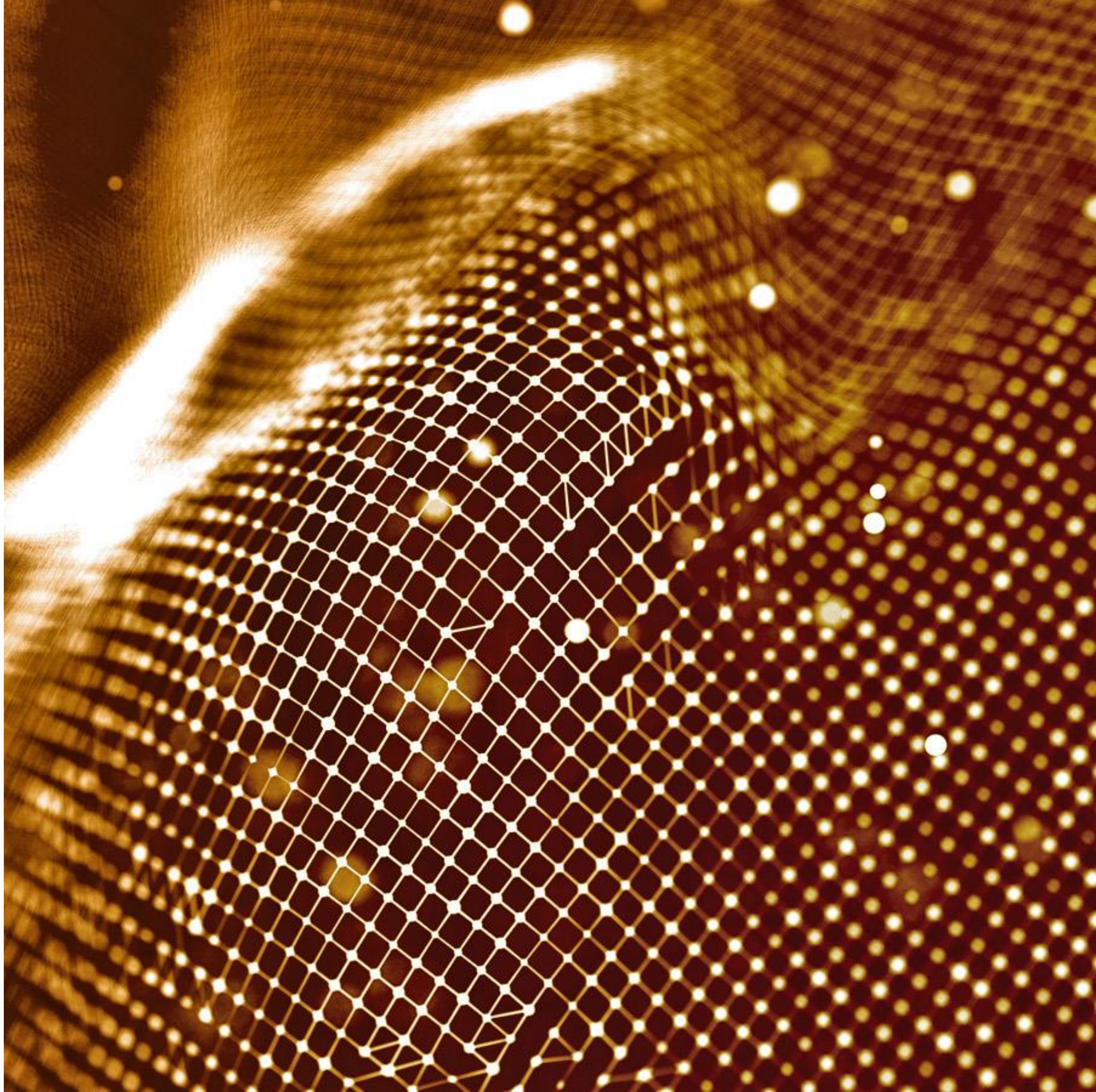
Copper-graphene composites with 18 ppm graphene (CuG18) show the **11% lower TCR** than commercial equivalents.

Gwalani et al. Mater & Des. 237:112555, 2024



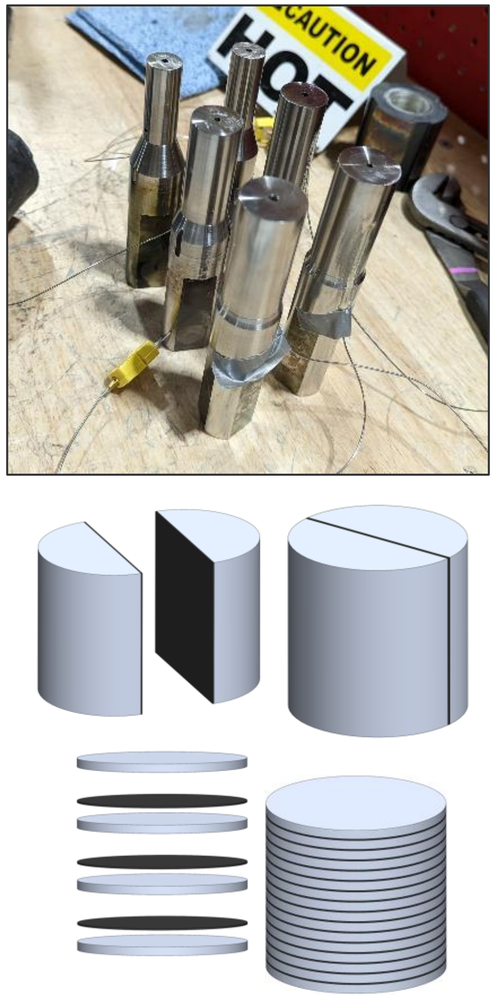
TCR vs. electrical conductivity of copper-graphene composites with varying graphene content. Properties of relevant conductors such as AA1350, OFHC copper and silver are presented for comparison.

Reviewer Only Slides

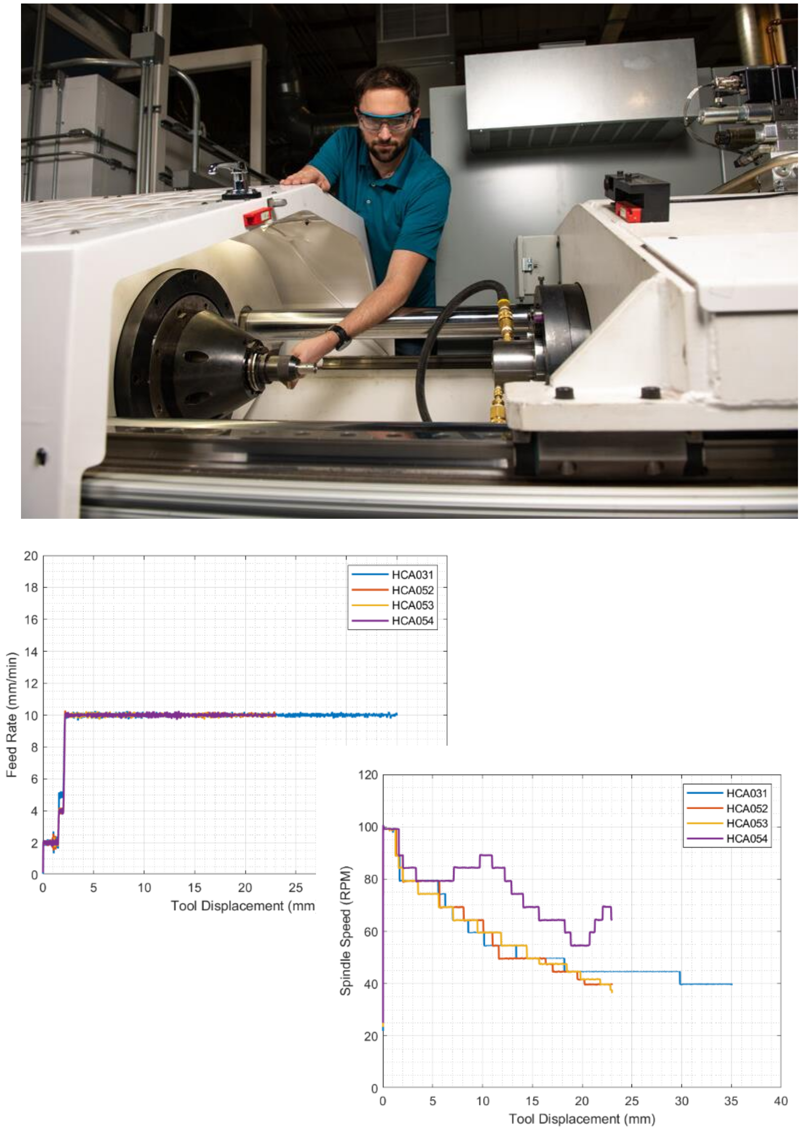


PNNL is operated by Battelle for the U.S. Department of Energy

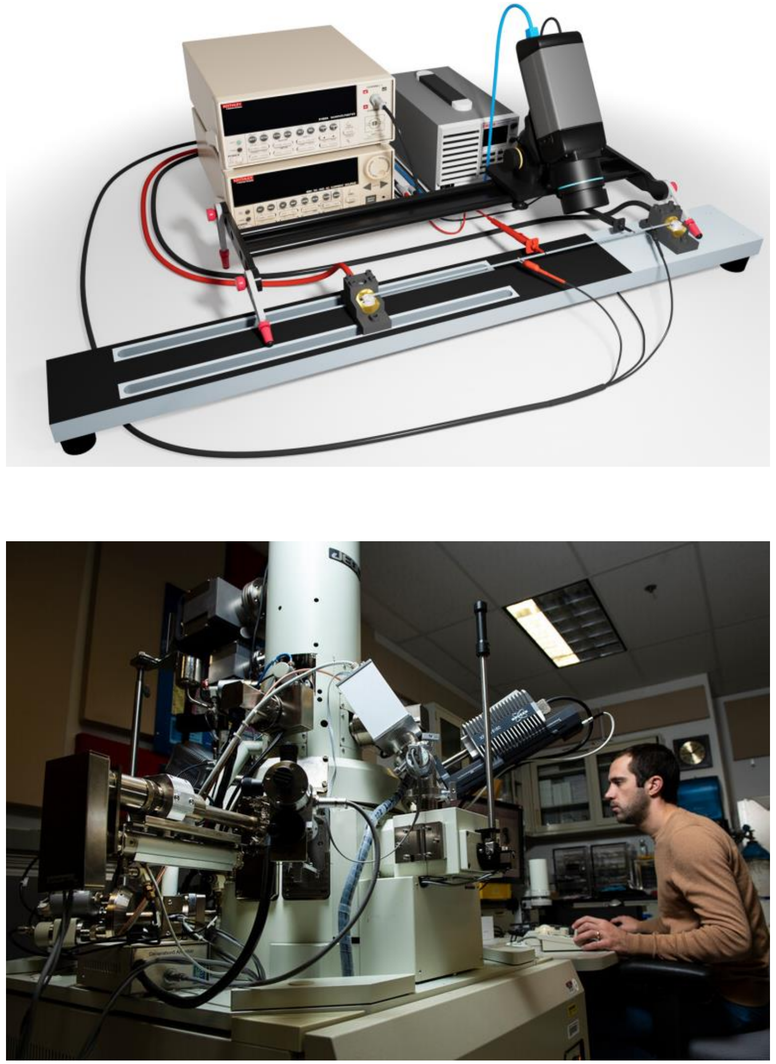
Development for ShAPE ultra-conductors comprises of composition/process/structure development



Billet and tooling design

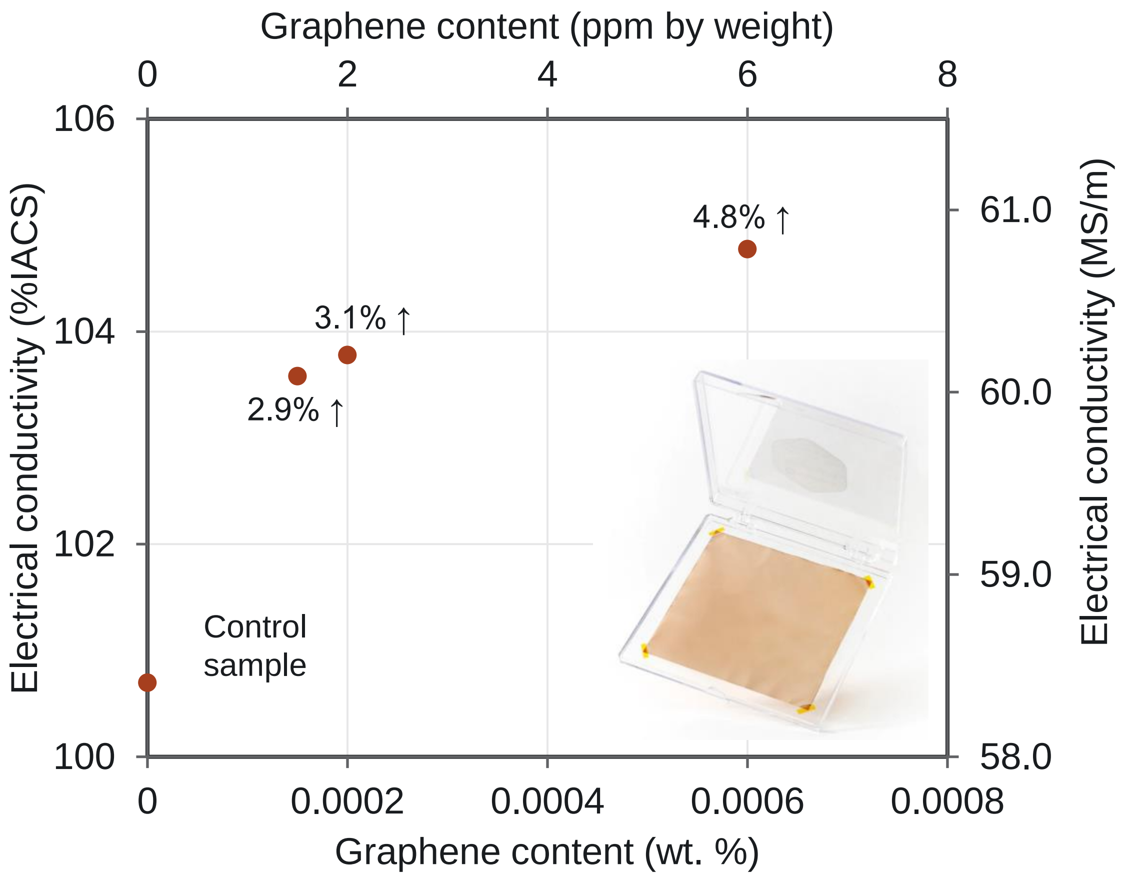


Process window and parameter design



Property and microstructure characterization

ShAPE ultra-conductors, made with CVD graphene feedstock, show high conductivity at bulk scale



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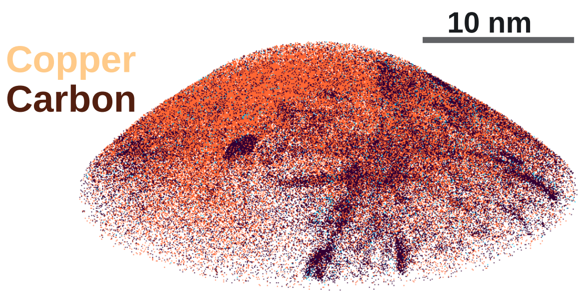
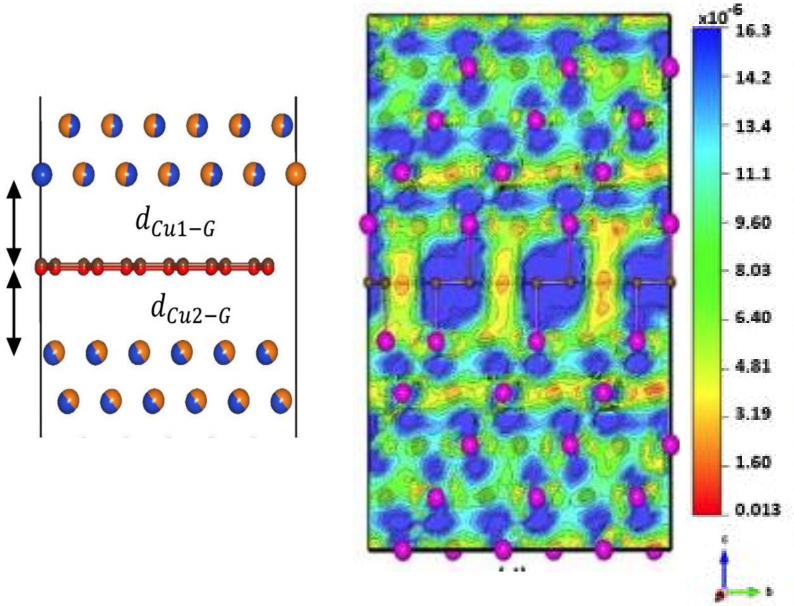


Copper and carbon atoms distributed across the APT sample lifted from a copper grain boundary in the ShAPE composite

Isoconcentration surface of carbon depicting graphene flake morphology in ShAPE composite

APT results showing the presence of graphene as flakes at copper grain boundaries

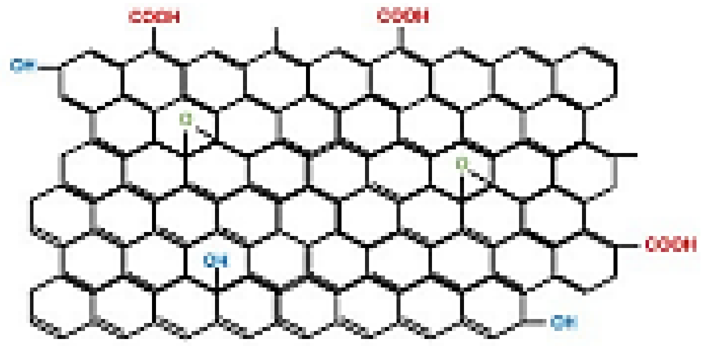


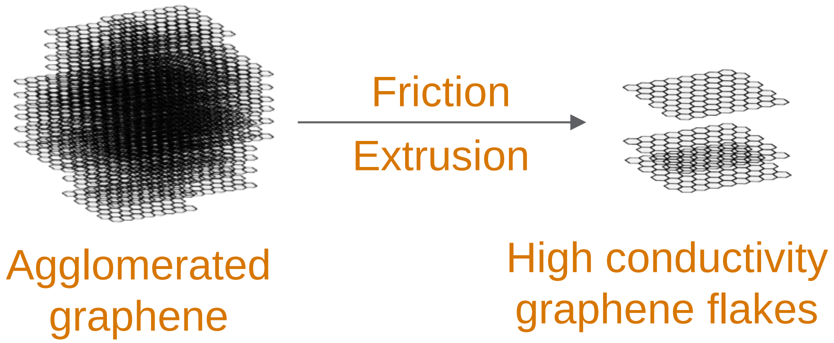
DFT model showing underlying representative mechanism of enhanced conductivity in copper/graphene composites (left) with decreasing interfacial distance resulting in carriers from copper accessing graphene (signified by blue regions in space projected conductivity representation on right)

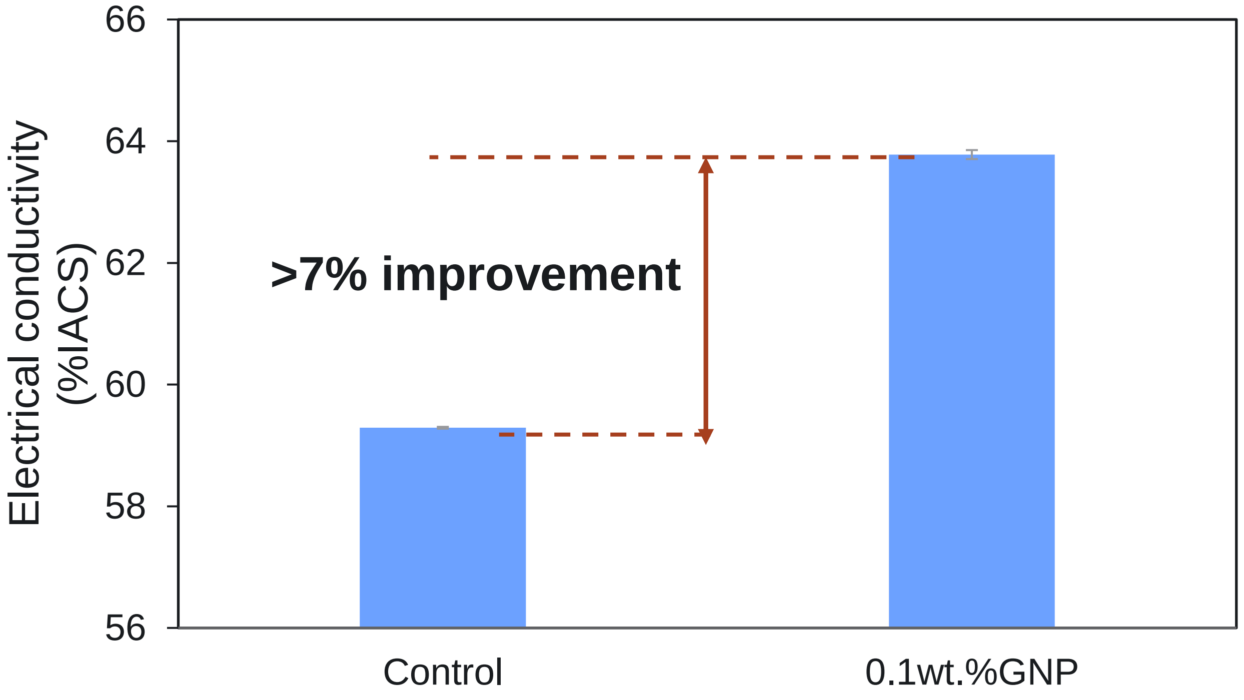
K. Subedi et al., Appl. Phys. Lett. 122:031903, 2023

Pacific Northwest NATIONAL LABORATORY

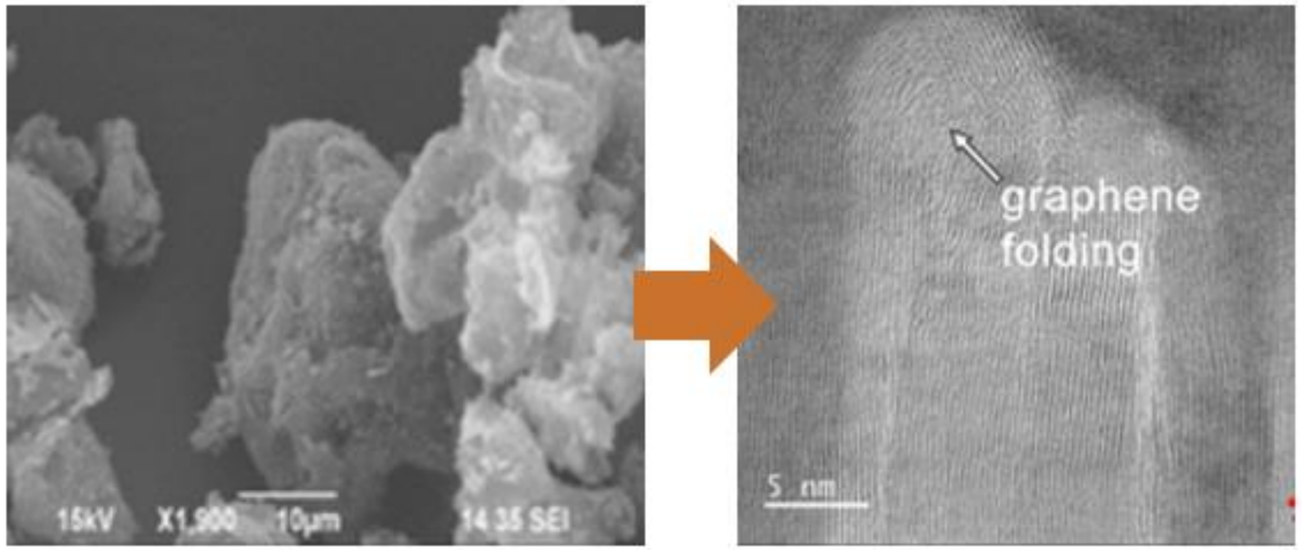
ShAPE can improve aluminum conductivity at bulk scales using low-cost additives





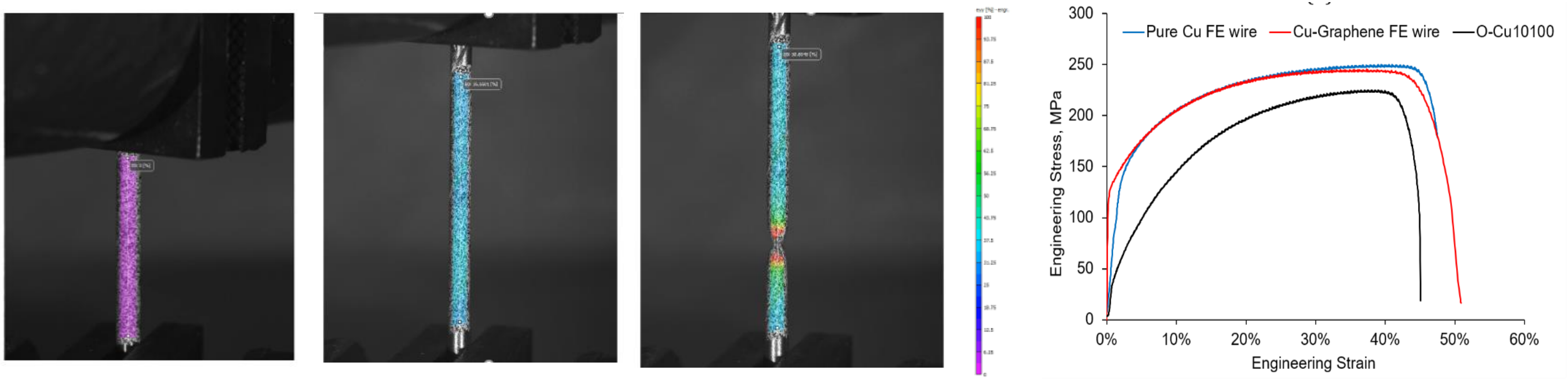


Electrical conductivity AA1100/graphite nanoparticle (GNP) composites as a function of GNP content



Low-cost GNP feedstock transforming to highly crystalline graphene-like structures in aluminum ShAPE wire

Other properties, (like mechanical), are largely unaffected or improved for ShAPE Ultra-conductors



- Mechanical testing of copper graphene composite samples (conductivity = ~105% IACS) with digital image correlation analysis
  - Wires deform similar to annealed copper samples
- Copper graphene sample has 51% elongation and 221 MPa UTS (Annealed copper UTS = 220 MPa)
- ShAPE enhanced conductivity with no loss to mechanical performance; high %elongation makes sample conducive for standard industry forming operations such as drawling or rolling