LEGAL STATEMENT

The purpose of the information in this presentation is to guide ICA programs and provide members with information to make independent business decisions.

ANTITRUST GUIDELINES

Antitrust Guidelines for Copper Industry Trade Association Meetings

The following guidelines with respect to compliance with antitrust laws of the United States, Japan and European Community[1] are intended to govern the conduct of participants in copper industry trade association meetings, both at the meeting itself and in informal discussions before or after the formal meeting.

Price: Competitors should not discuss future prices (including terms of sale) of their products. There is no blanket prohibition against the mention of or reference to current or past prices but limits must be observed. Such references or mentions should occur only when necessary in connection with the development of association programs. For example, reference to a particular price level in comparing the cost of a copper product to a competing product is permitted. Whenever possible, such references should be discussed in advance with legal counsel.

Competitive Information: Competitors should not discuss the market share of a particular copper producer or copper fabricator's products. Furthermore, nothing should be said at a meeting which could be interpreted as suggesting prearranged market shares for such products or producer production levels. The overall market share of copper products may be discussed with regard to competition with non-copper products and general market acceptance.

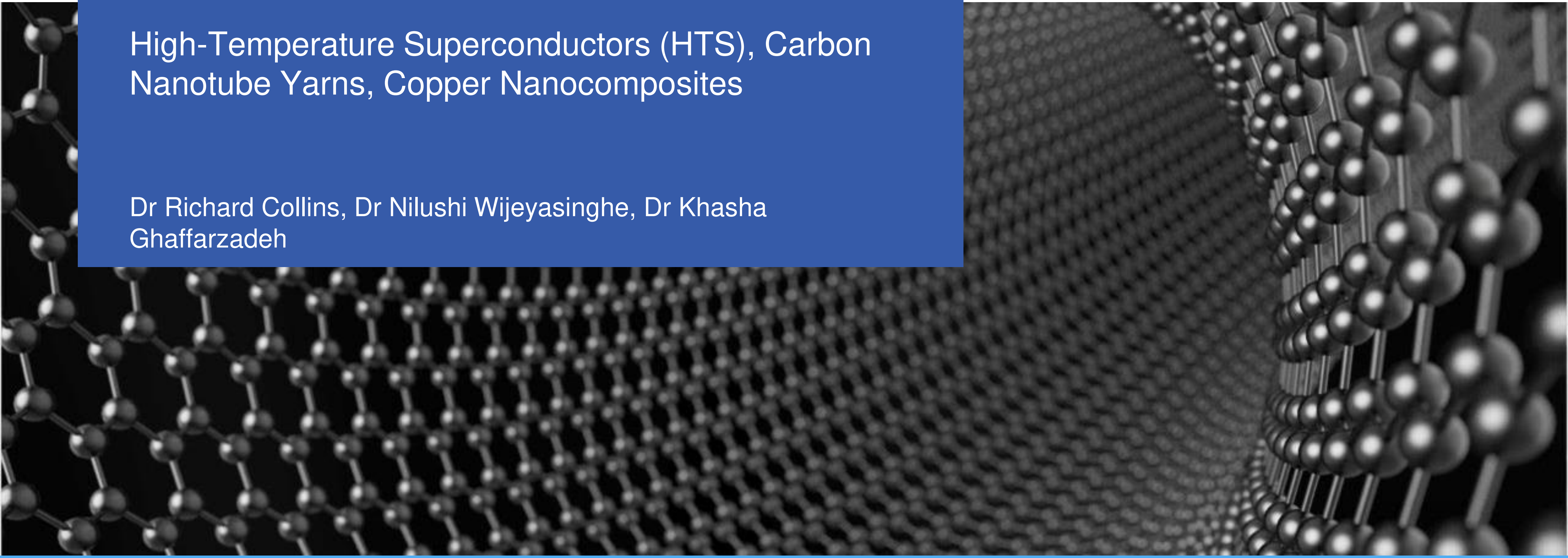
New Products: Competitors should not encourage or discourage the introduction of a new product by another competitor or reveal a particular copper company's plans to change the production rate of an existing product or to introduce a new product. No company should disclose to another company whether it is in a position to make or market a new product. New products may be discussed in a technical manner or from the standpoints of competition with non-copper products and general market acceptance. In addition, proposed methods for and results of field and laboratory testing can be considered.

The Role of Legal Counsel: Legal counsel attends association meetings to advise association staff and other meeting attendees regarding the antitrust laws and to see that none of the matters discussed or materials distributed raise even the appearance of antitrust improprieties. During the course of a meeting, if counsel believes that the discussion is turning to a sensitive or inappropriate subject, counsel will express that belief and request that the attendees return the discussion to a less sensitive area.

A paper entitled 'Copper Industry Trade Associations and Antritrust Laws' is available upon request.

10/92, 5/93, 10/10

[1] Other foreign competition laws apply to International Copper Association, Ltd. (ICA)'s activities worldwide.



Competing High Technology Conductors

High-Temperature Superconductors (HTS), Carbon Nanotube Yarns, Copper Nanocomposites

Dr Richard Collins, Dr Nilushi Wijeyasinghe, Dr Khasha Ghaffarzadeh

Threats to Copper

Copper is the standard for conductive material in bulk applications.

However, copper is not immune to changing threats and markets.

IDTechEx have been asked to investigate the status and technology readiness level of emerging conductive materials. Many are at the stage of university research only. These include:

- Pure Nanocarbon material
- Copper nanocomposites
- High-Temperature Superconductors (HTS)

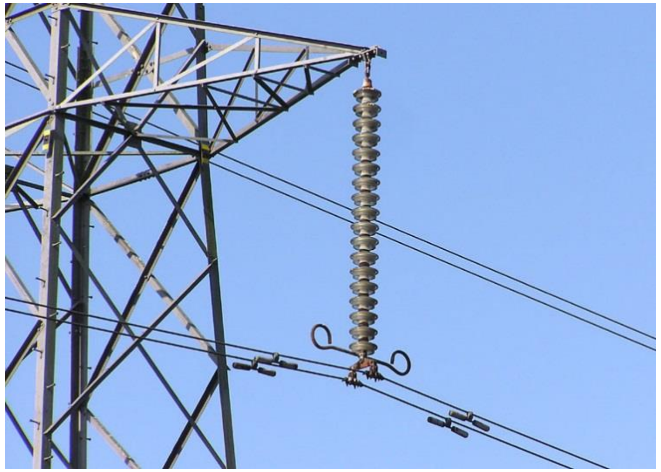

COPPER PRICE TO ALUMINUM PRICE RATIO

Copper has become relatively more expensive vs. aluminum

Source: Bloomberg Professional

wallstreetdaily.com

	Cu	Al
Conductivity (MS/m)	58.5	36.9
Density (g/cm^3)	8.9	2.7
Specific Conductivity	6.6	13.6



Carbon Nanotubes

Introduction to Carbon Nanotubes (CNT)

Since their inception in the early 1990s CNTs have had a large amount of promise.

	CNT	Copper
Density (g/cm^3)	0.1-1	8.9
Tensile Strength (GPa)	<100	0.2
Thermal Conductivity (W/mK)	<3500	400
Electrical Resistivity (μΩ•cm)	>1	1.7
Charge Carrying Capacity (A/cm^2)	10^8-10^9	10^6

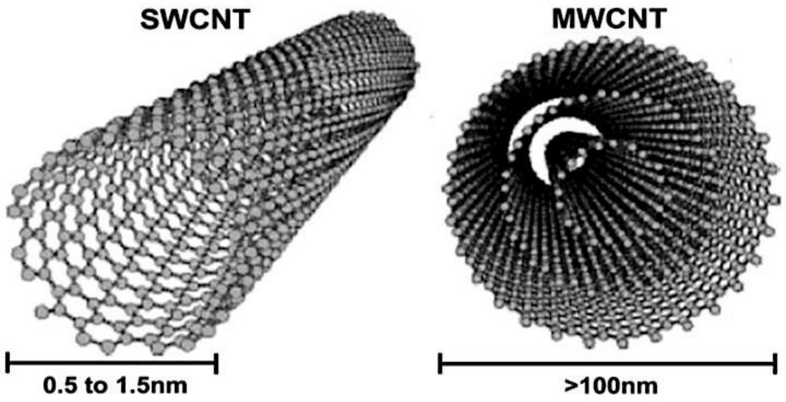
These are some of the best reported values for a variety of individual CNTs

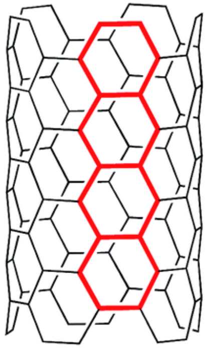
Other benefits:

- Higher flexural strength, lower temperature coefficient of resistance (TCR), lower coefficient thermal expansion (CTE), improved corrosion resistance, and cost stability (at very high volumes)

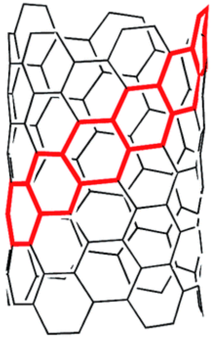
But the problems are:

- Translating to the macroscale
- Different forms (SWCNTs – MWCNTs)
- Chirality optimisation

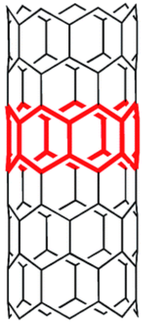




[5,5] CNT
Armchair
Metallic



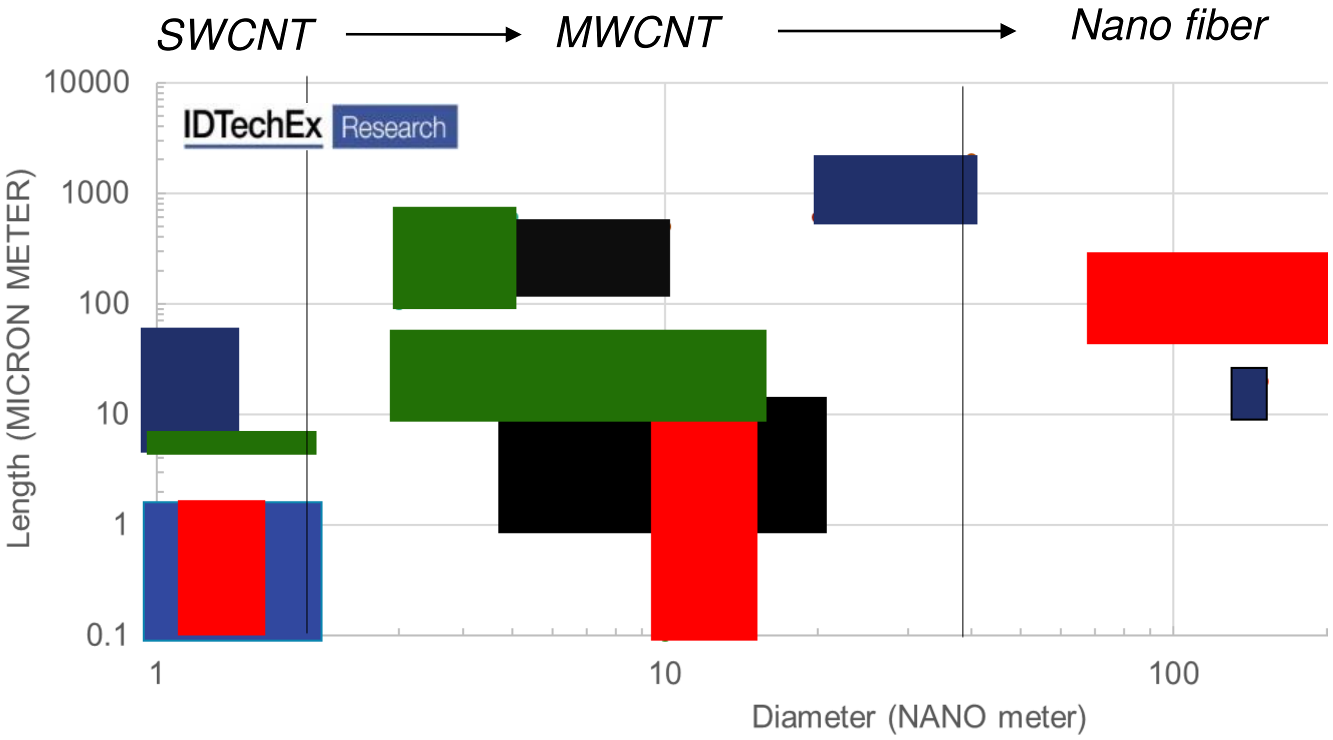
[7,5] CNT
Chiral
Semiconducting



[7,0] CNT
Zigzag
Semiconducting

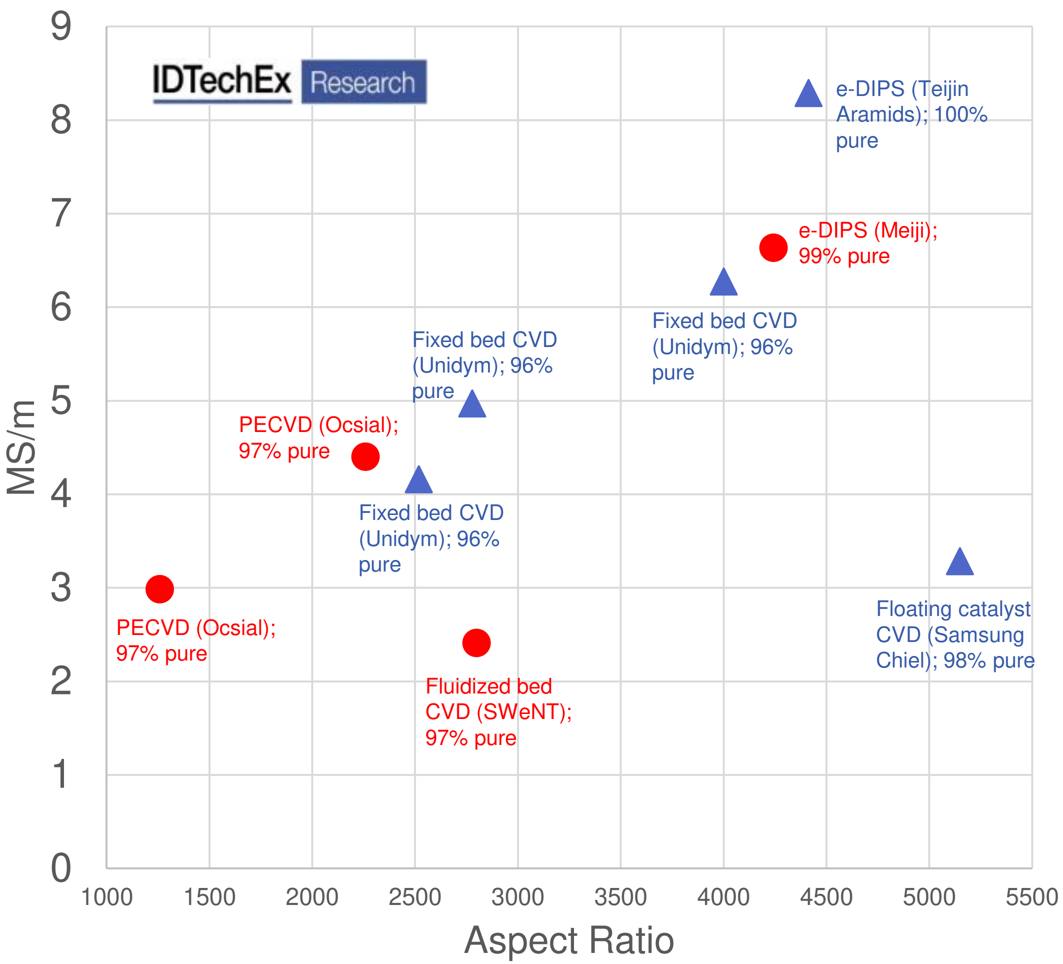
Source: Sao Paulo University and University of Oregon

Not all CNTs are equal



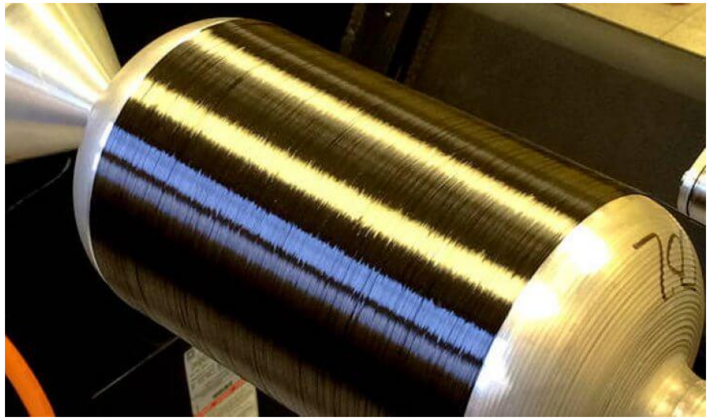
Each box corresponds to the size range of CNTs supplied by a different company

- There was a rapid rise in capacity expansion between 2006 and 2011, this was then followed by a correctional period. Across this time frame utilisation rate went up.

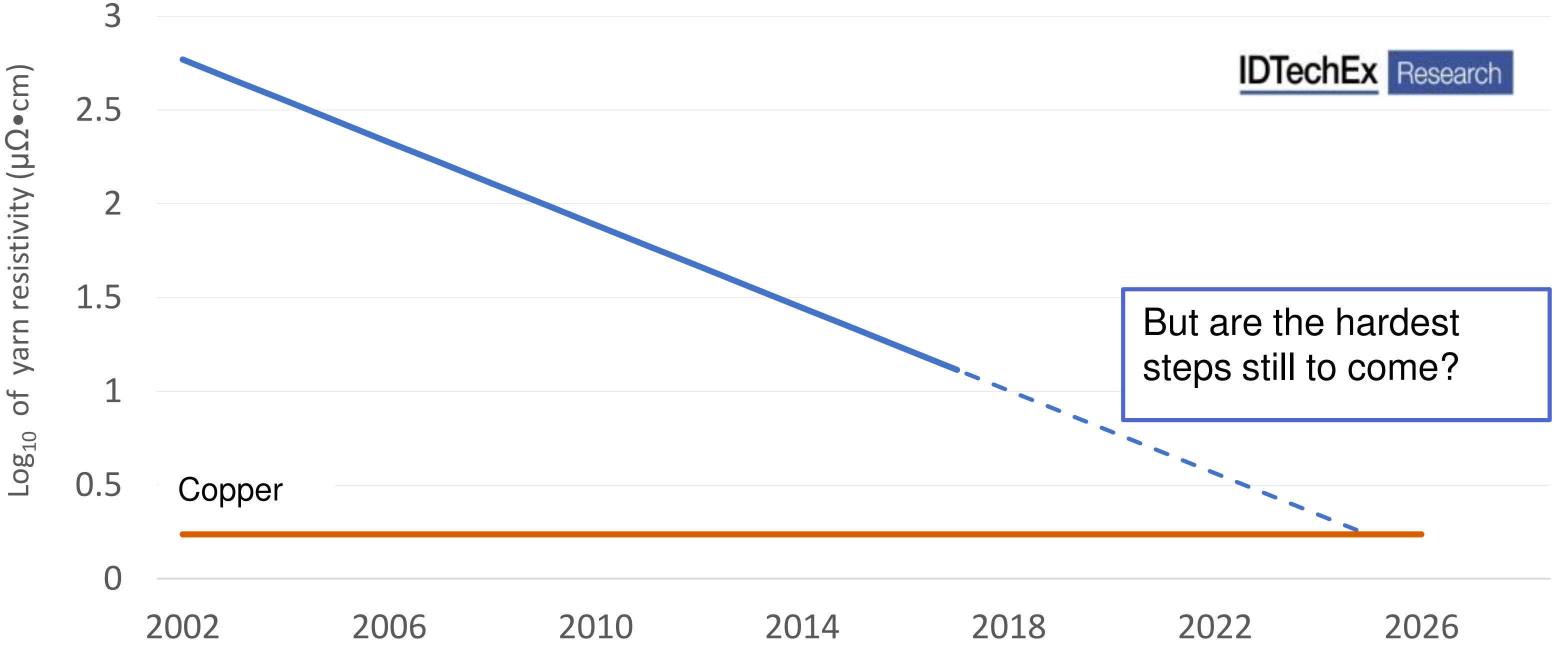


Progression of CNT fibres

- The progression to macroscale CNT wires/yarns/tapes has been challenging, but there have been significant advancements over the past 10-years.



Progression of best resistivity results for CNT yarns



But are the hardest steps still to come?

This line represents the historic advancements in this field and the progression if this continues. The blue line represents CNT yarn and orange line copper. Note that this does not take into account the emerging improvements to copper conductivity

Source: Nanocomp Technologies

Formation of CNT fibres

Tunability vs Scalability are the main challenges for this industry

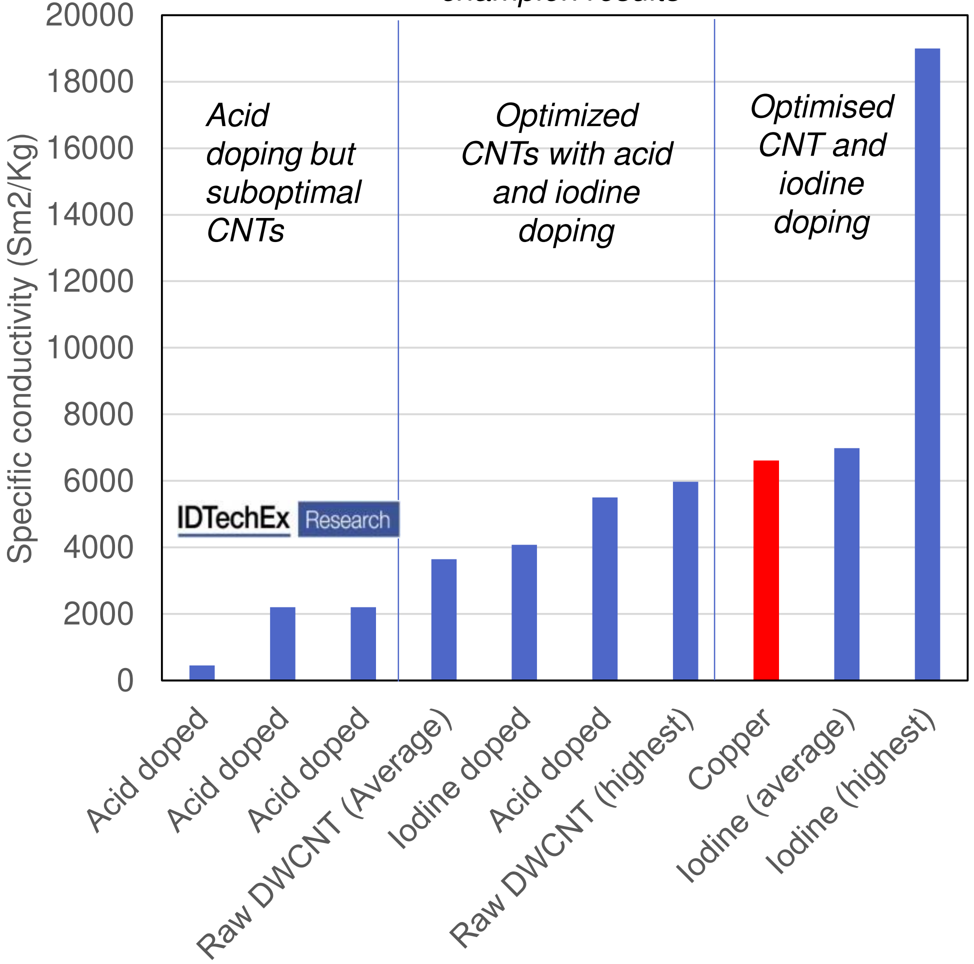
	Advantages	Disadvantages	Resistivity (μΩ•cm)	Density (g/cm^3)	Tensile Strength (GPa)	TRL Level (1-5)	Main player(s)
1-step CVD	1-step, scalable process, long length yarns, proven process.	Impurities, low conversion, cannot refine CNT feedstock.	50-500	0.5-1.0	1-3	2-4	Nanocomp Technologies, Q-Flo, Shanghai Jiao Tong U, Cambridge U.
Wet Spinning	Tuneable CNT usage, good alignment	Superacid used and capacity limited by chamber size.	15-100*	1.5-2.0	1-3	3	RICE University (Dexmat), RIT
Dry Spinning	Tuneable CNT, facile drawing process.	Poor resistivity through worse interconnects and alignments	1500-2000	0.5-1.0	1-3	3	Hamamatsu Carbonics and Murata Machinery
Electrospinning	Targets interconnects, electrospinning facile	High energy source for interconnects, not scaled.	~200	0.5-1.0	N/A	1	Surrey U.

*Note that due to the process used these fibers made *via* this route can have some acid dopants as a residuum from the CSA used.

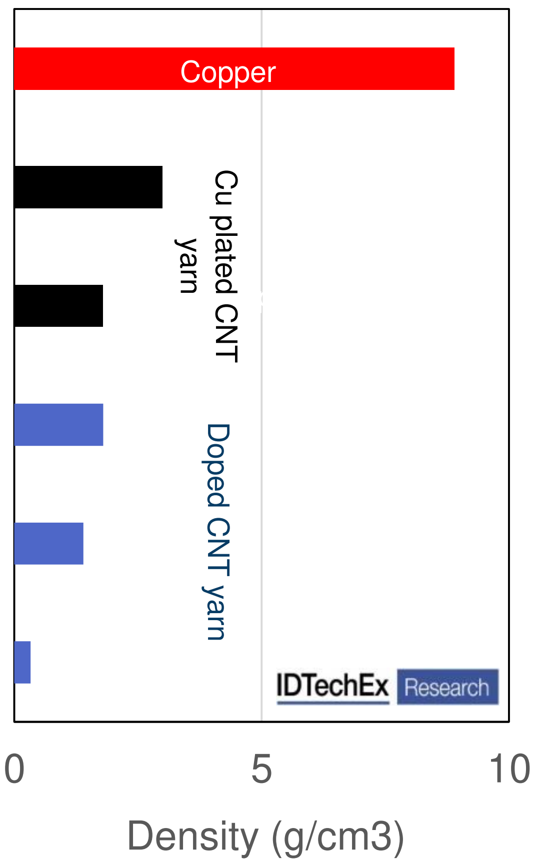
Dopants and specific conductivity

- Proof-of-concept stage, but many dopants struggle with stability.
- The industry still requires an innovative leap to compete with copper.
- The undoped yarn can outperform Cu for specific ampacity.
- Does the yarn have to reach copper in order to displace it?

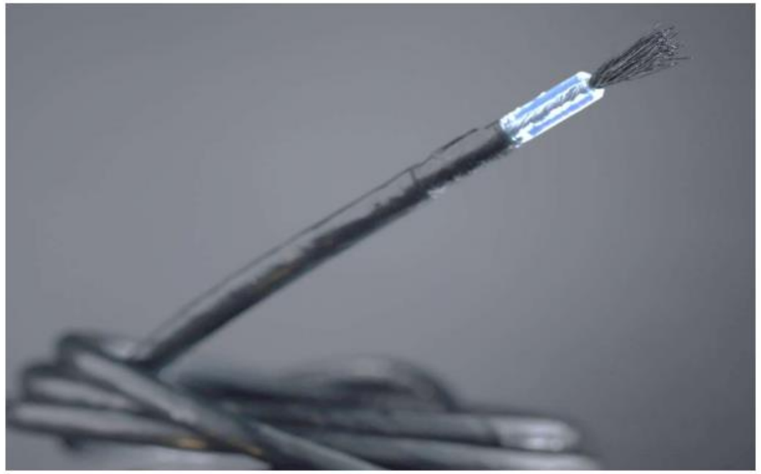
Higher performance than copper demonstrated with champion results



CNT yarns are light weight!

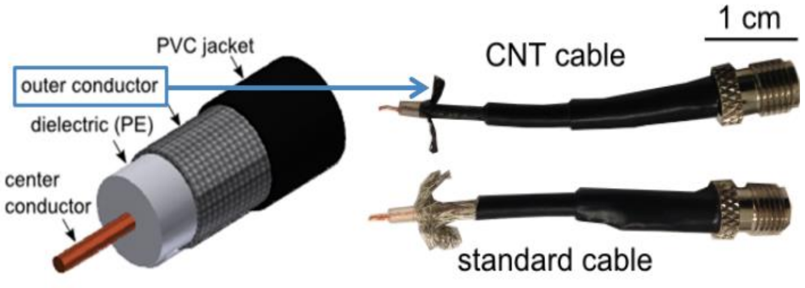


Early CNT yarn applications



- High frequency data cables, particularly in defence applications. When above 20 GHz there is a significant pay off from the skin effect.

Main Driver: Skin effect and lightweighting
Timeline: Already in use



- Roles in military jets both as EMI shielding outer conductors and power cables.

Main Driver: lightweighting
Timeline: Non-critical roles within 5-10 years.

Following applications will be electric motors (10-15 yrs) and low power electronic applications (15+ yrs)

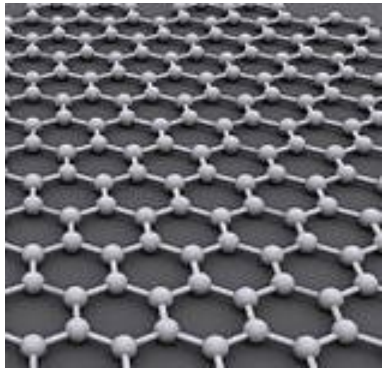
Source: Nanocomp Technologies and DexMat

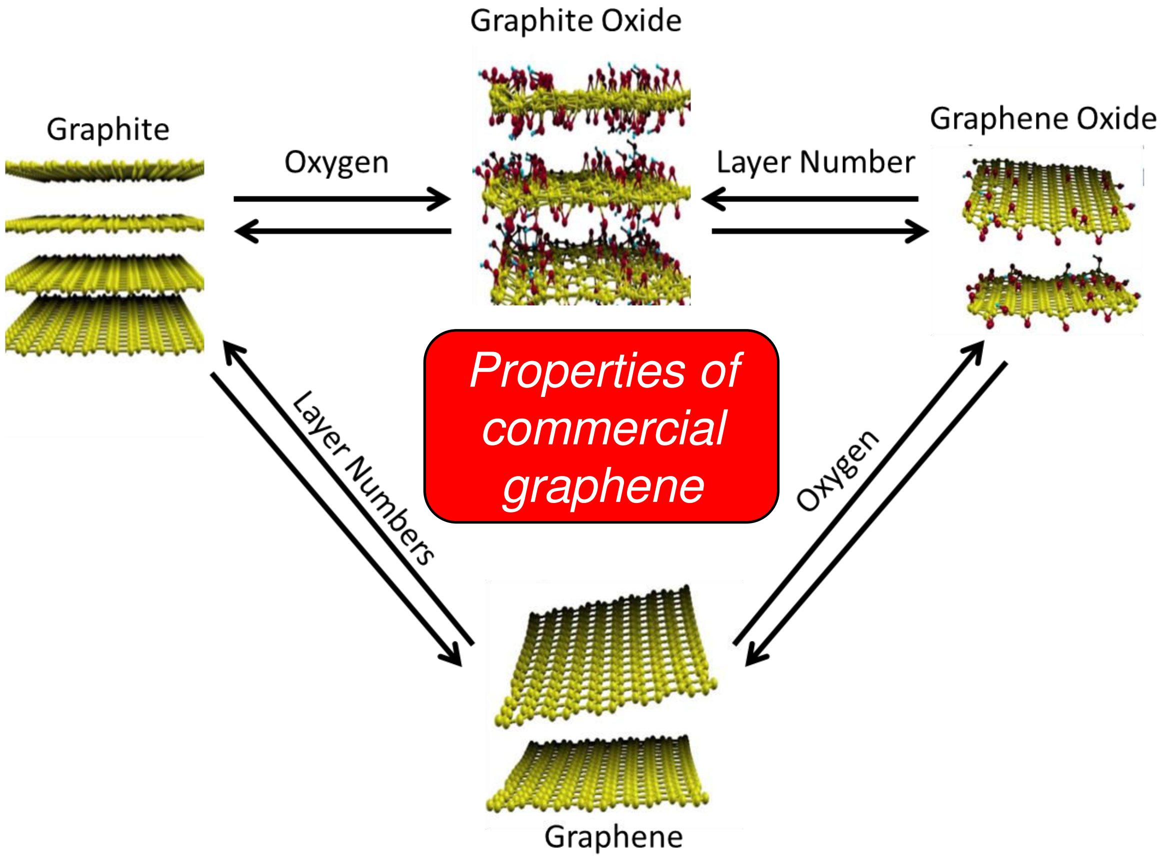
Graphene

Graphene: ideal vs reality (I)

Ideal graphene = wonder material → Commercial graphene = more down to earth

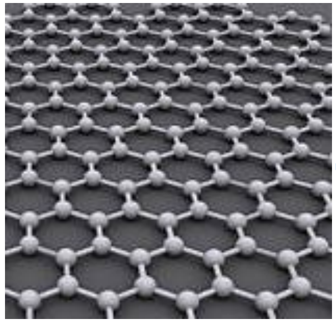
- Superlative properties:
  - 2D sheet of carbon atoms→ Thinnest imaginable material
  - Higher conductivity than silver at room T (1 uOhm.cm)
  - Record thermal conductivity (outperforming diamond)
  - Highest current density at room T (106 times of copper)
  - Highest intrinsic mobility (100 times more than in Si)
  - Largest surface area (~2,700 m2 per gram)





Graphene: ideal vs reality (II)

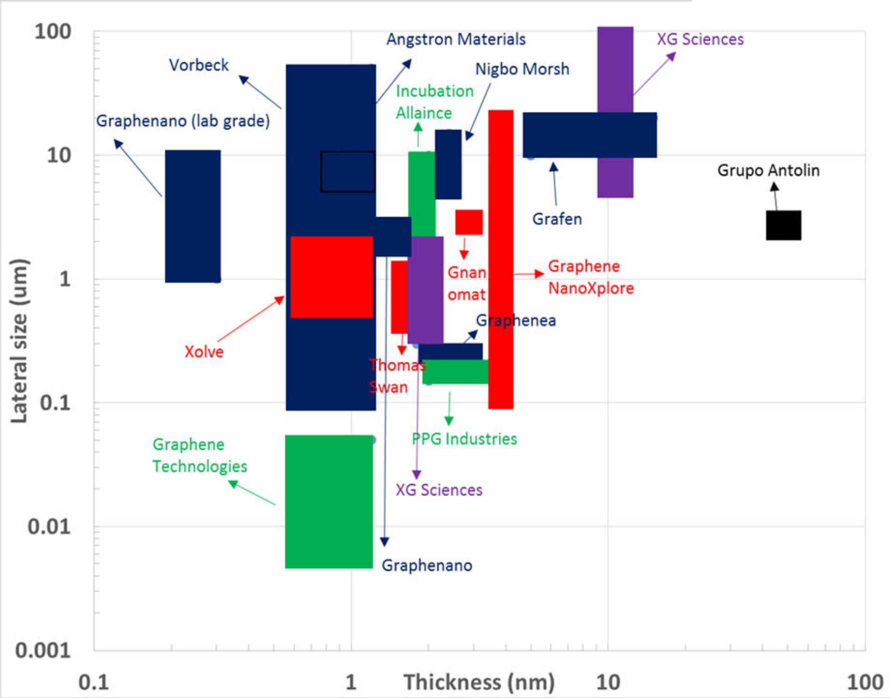
Idea graphene: 2D, pristine, large-area defect-free single-crystalline flake or film



Towards commercial type

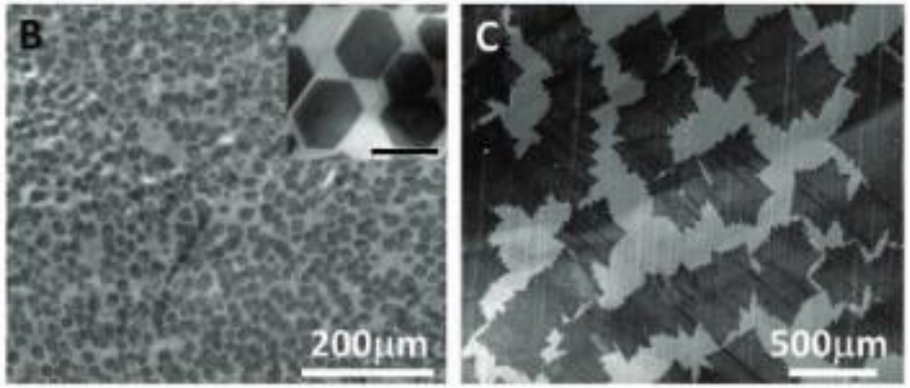
Platelet or powder type

- Variety of graphene powders covering a large range in later size and thickness (see opposite)
- Not all are equal: property and thus application depending on specific properties changes
- Numerous production processes for powder type

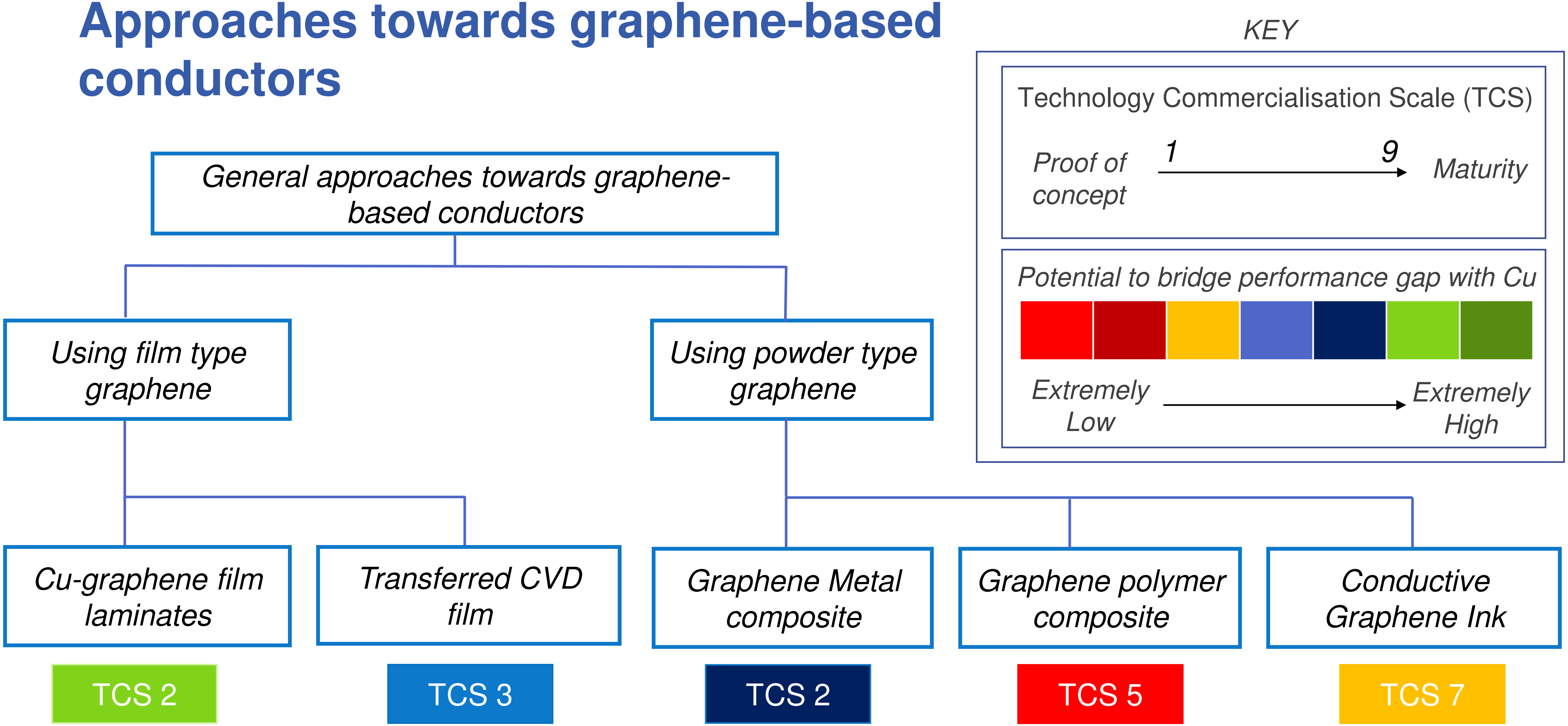


Film type

- Simple R2R CVD growth on Cu foil possible but challenge is how to transfer without damaging material & reducing yield?
- Polycrystalline structure thus not as good as ideal single-crystalline 2D graphene



Approaches towards graphene-based conductors



KEY

Technology Commercialisation Scale (TCS)

Proof of concept 1 → 9 *Maturity*

Potential to bridge performance gap with Cu

🟥 🟥 🟨 🟦 🟦 🟩 🟩

Extremely Low → *Extremely High*

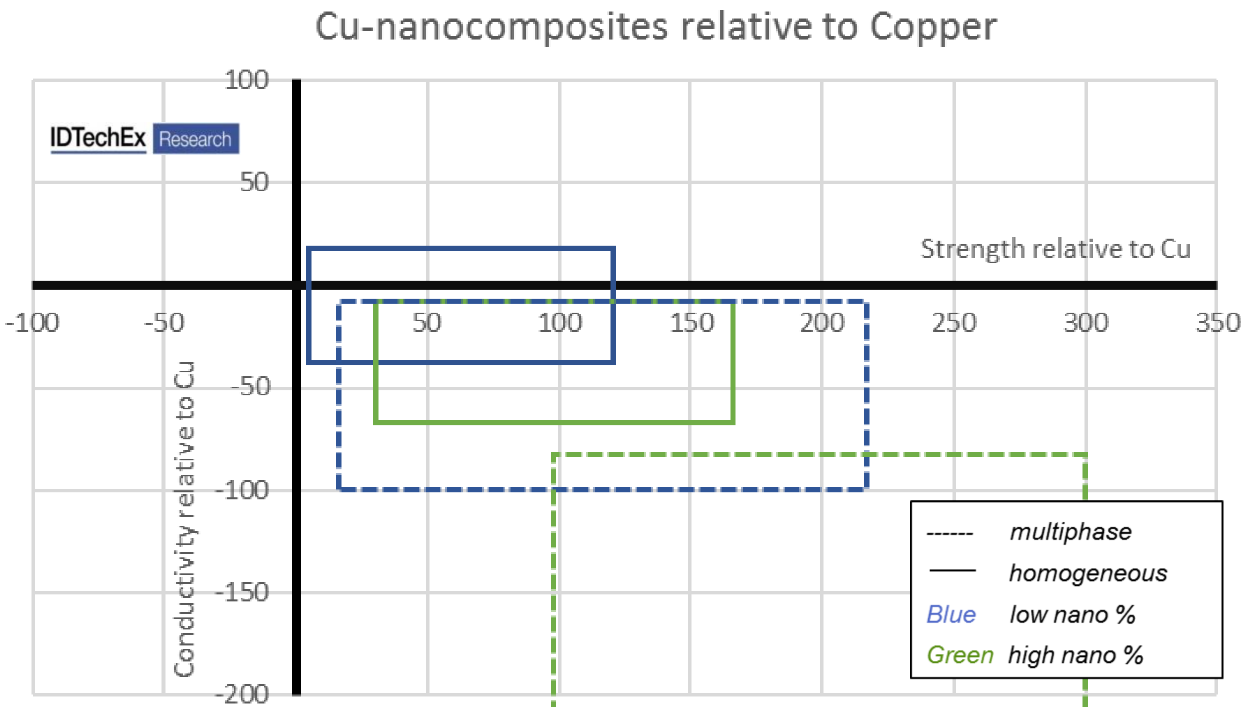
General approaches towards graphene-based conductors

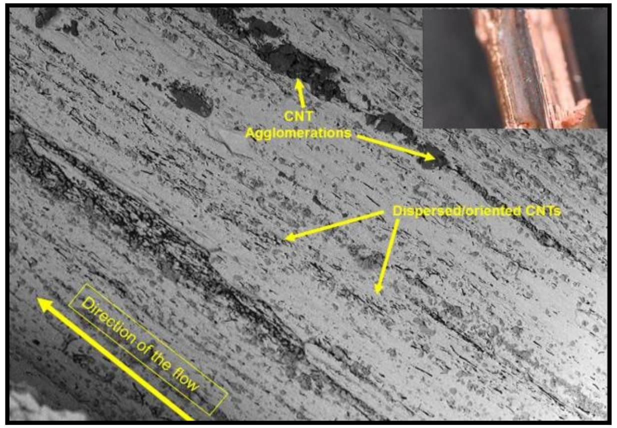
- *Using film type graphene*
  - *Cu-graphene film laminates* — TCS 2
  - *Transferred CVD film* — TCS 3
- *Using powder type graphene*
  - *Graphene Metal composite* — TCS 2
  - *Graphene polymer composite* — TCS 5
  - *Conductive Graphene Ink* — TCS 7

Copper Nanocomposites

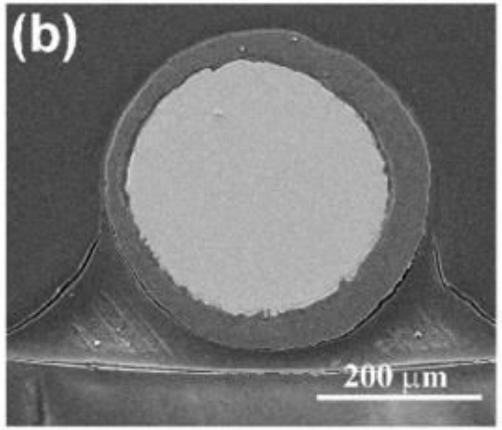
Comparison of copper nanocomposites

- Sometimes called nanocomposites, nanoalloys, or ultraconductive copper but all refer to the inclusion of conductive material into a Cu matrix.
- The additives are usually CNTs or graphene and can be included in a range of volume percentages.





Homogeneous (CSU)



Multiphase (LANL)

- The properties range are shown on the left-hand side, but is important to also consider:
  - Impact on ampacity
  - Density (important for high %)
  - Thermal conductivity
  - Temperature coefficient of resistance (TCR)
  - Usability of material

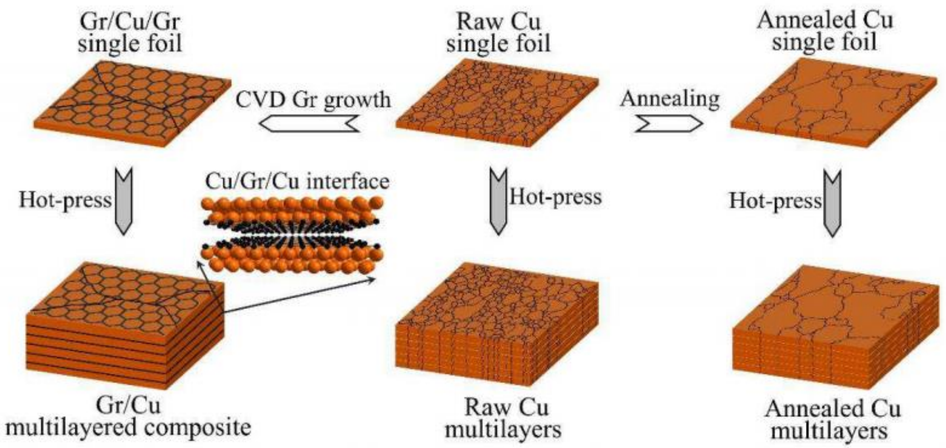
Production on copper nanocomposites

- The key is to introduce these nanoparticles without damage to their structure, without agglomeration, and a strong interaction with the metal matrix.
- Many have common challenges in reproducibility, poor metal wettability, scale, cost effectiveness, upstream supply chain and the ability to make a usable wire.

	Mechanical	Chemical	Electrical
Types of procedure	Powder metallurgy, ball milling, casting, hot extrusion	Molecular level mixing, *in situ* growth	Co-deposition, electroplating
Advantages	Easy scalable process, tuneable raw material	Good homogeneity, no dependence on raw material	Can make multi-phase, can be continuous
Disadvantages	Damage of nanoparticles, usually low vol %, not yarn	Often multi-step, small scale	Typically poor infiltration, small scale, inconsistent distribution

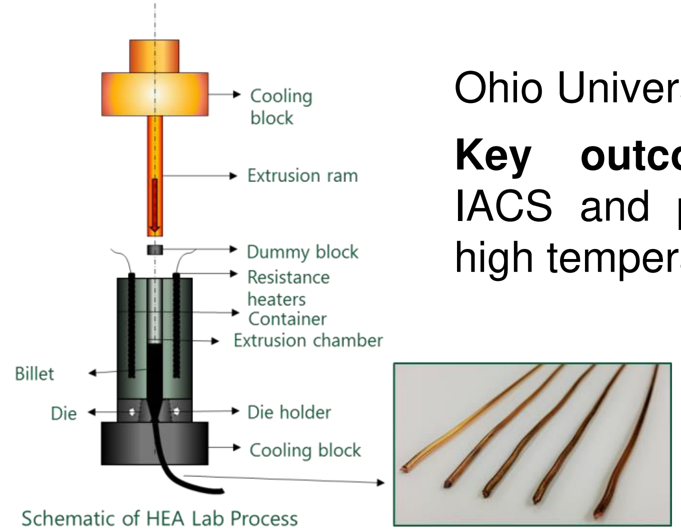
Copper nanocomposites

Highlighted here are three particularly notable processes, there are many more that have been reported to IDTechEx that provide results over 100% IACS or with specific benefits



Shanghai Jiao Tong University, China

Key outcome: 118 % IACS.



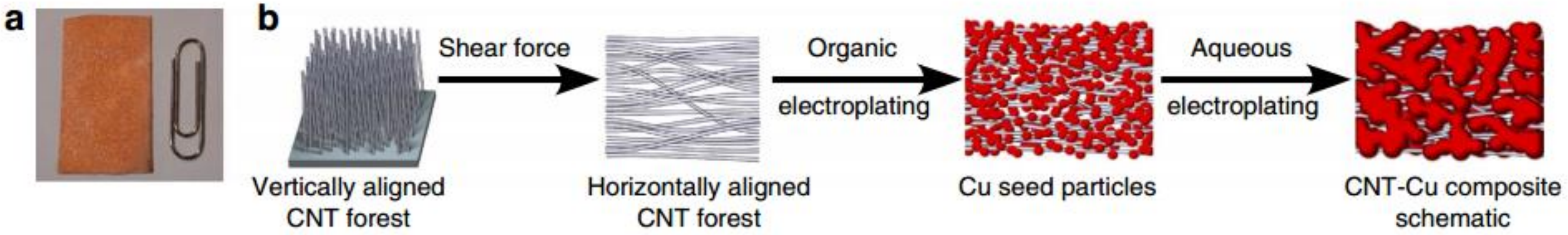
Schematic of HEA Lab Process

Ohio University, USA

Key outcome: 104 % IACS and performance at high temperature

National Institute of Advanced Industrial Science and Technology, Japan.

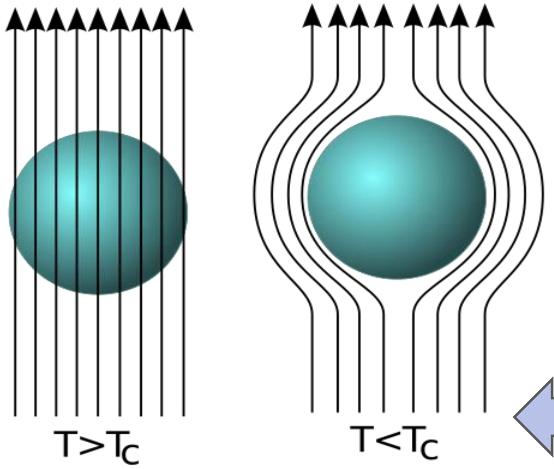
Key outcome: 100-fold increase in ampacity relative to copper



Source: AIST, Shanghai Jiao Tong University, Ohio University

High-Temperature Superconductors (HTS)

Properties of superconductors



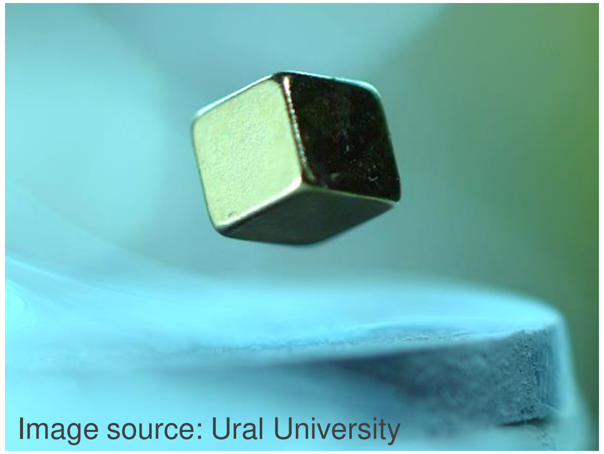


Image source: Ural University

Popular demo of the Meissner effect: magnet levitating above superconductor cooled below T_C.

Conductor v. Superconductor

- Superconductivity at $T < T_C$
- 100x current capacity of copper. Zero resistance & zero heat loss until critical current (I_C) flow.
- External magnetic fields excluded. Applied field & angle affects I_C

1st & 2nd Generation HTS

- 1G = bismuth based, BSCCO
  Silver matrix: high raw materials cost
- 2G = rare-earth metal based, ReBCO
  Re = yttrium (Y), gadolinium (Gd)
  Most common: YBCO, T_C = 93 K
- Both 1G & 2G are copper oxides

Critical Temperature (T_C)

- Low-T superconductor (LTS):
  liquid He cooling to 4 K; metallic
- High-temperature superconductor (HTS):
  liquid N cooling to 77 K; ceramic, oxide
- Magnesium diboride (MgB_2): T_C = 39 K
  Liquid H cooling or He gas cryocooler

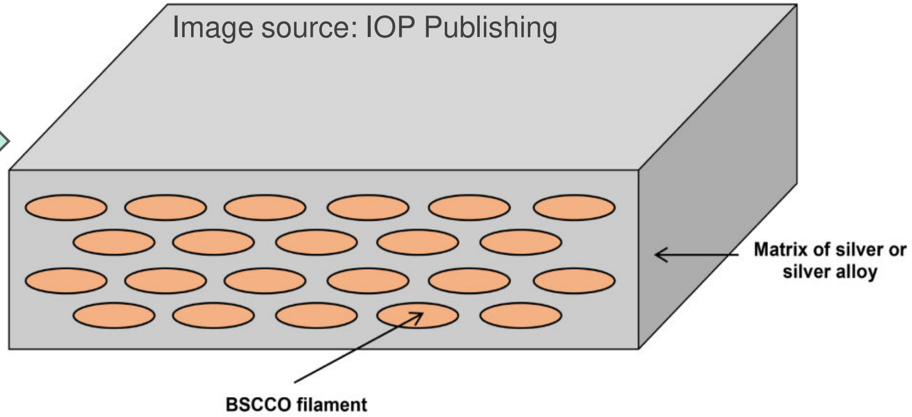
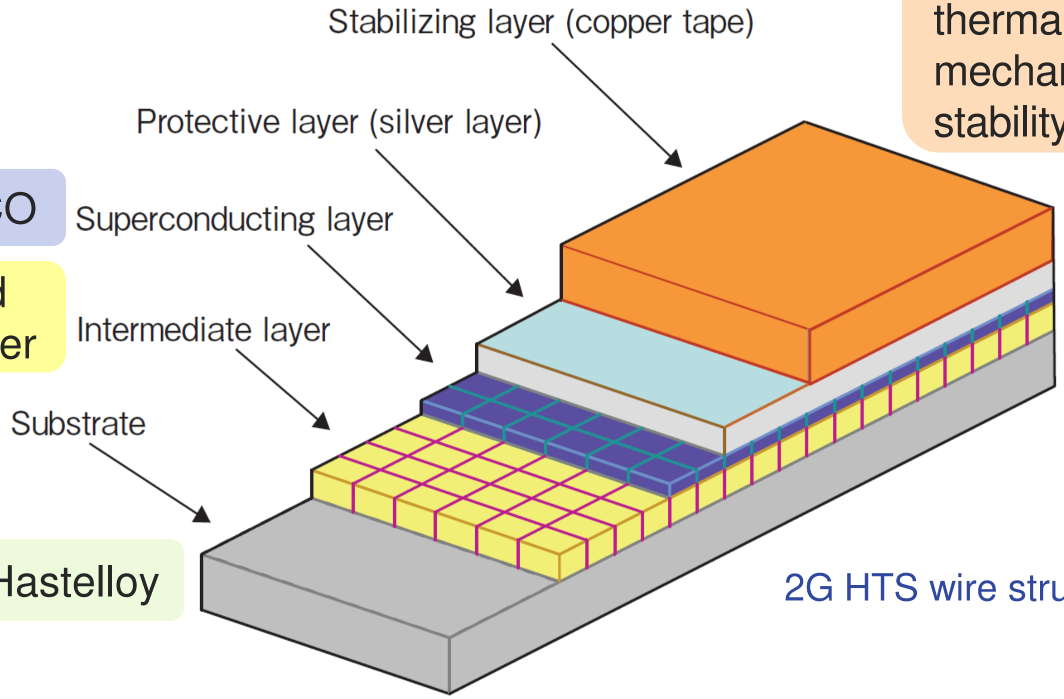


Image source: IOP Publishing

Ag matrix of 1G HTS wire stabilizes (electrically & thermally) & couples BSCCO filaments

Applications of HTS materials

- **Wire (tape)** – **commercial** (not building wiring)
- **Electric power grid** – **demos**
  - High-voltage cable: underground transmission
  - Medium-voltage cable: underground distribution
  - Superconducting fault current limiter (SFCL); transformer
- **Rotating machine (compact, high power)**
  - Generator: wind turbine (AMSC SeaTitan, 10 MW)
  - Motor: ship propulsion (Northrop Grumman and AMSC, 36.5 MW)
- **Other applications** include: Degaussing system (US Navy, AMSC), Magnetic energy storage (Boeing), Low-voltage cable: data center (AMSC), RF circuit: receiver & amplifier (HYPRES), Current lead (ITER fusion project), Tokamak: nuclear fusion reactor, Medical: MRI and NMR, MagLev vehicles



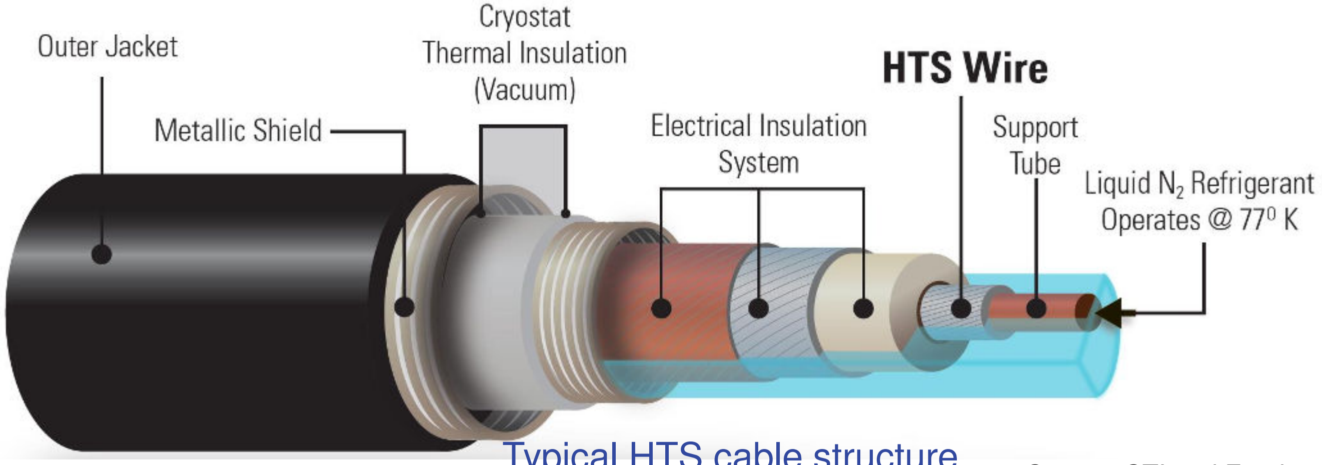
Electrical, thermal & mechanical stability

1-4 µm ReBCO

Textured oxide buffer

Hastelloy

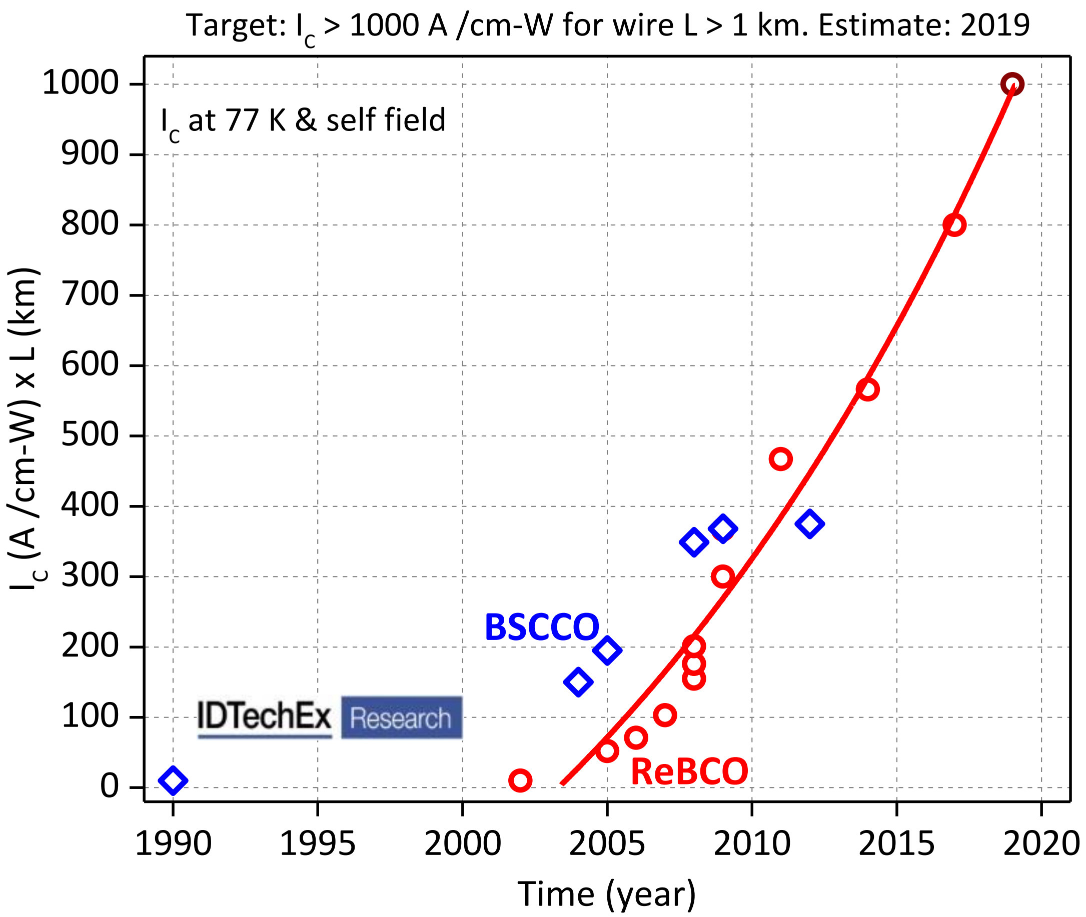
2G HTS wire structure.



Typical HTS cable structure.

Source: STI and Furukawa

HTS technology advances & adoption



Historical trends in R&D of YBCO & BSCCO. HTS discovered in 1986 by IBM researchers, Müller & Bednorz. Plot shows how I_C (77 K & self field) in long wires increased over time.

- **Advantages of HTS underground cables:**
  - HTS cable transmits 3-5x power of Cu cable with equal cross section: minimize land use in dense urban areas.
  - Transmit power at higher current & lower voltage: fewer transformers.
  - Zero resistance: minimize power loss from remote renewables (long cables) & no heating of soil.
  - Low magnetic field generation; self-shielding cable.

- **Challenges in HTS cable technology adoption:**
  - 1 km cable requires >100 km HTS wire: process yield & production capacity.
  - 2G wire production is dominated by process cost (80%), not raw materials cost (20%).
  - HTS wire cost is 20-25% of cable cost: cooling system cost dominates.
  - Target wire cost: $20-30 /kA m for large-scale adoption.
  - Many utility companies lack cooling expertise.
  - New tech = investment risk and inertia

HTS wire suppliers & system integrators

- **Main Players:**
  - ○ 30+ HTS wire suppliers & integrators
  - ○ Most use ReBCO (▲ = BSCCO)

  [MgB_2 – Columbus Superconductors HyperTech Research, Nexans, STI]

- **Cost of 2G HTS wire (without cooling):**
  - ○ Average product = \$100 /kA m
  - ○ Lowest quote = \$30-80 /kA m

  [MgB_2 ≈ \$10 /kA m]

- **2G HTS wire production capacity:**
  - ○ 300-1000 km /year (width = 4 mm)
  - ○ Limits: process, end-user demand

\$ = commercial HTS wire supplier

Europe	North America	Asia
Nexans (France)	Southwire (USA)	Sumitomo (Japan) ▲\$
BASF (Germany) acq. Deutsche Nanoschicht \$	Bruker (USA) acq. Oxford Instruments OST \$	LS Cable & System (S. Korea)
Siemens (Germany)	AMSC (USA) \$	Fujikura (Japan) \$
Innogy subs. RWE (Germany – utility)	SuperPower (USA) subs. Furukawa \$	Furukawa (Japan) acq. SuperPower \$
Bilfinger Noell (Germany)	STI: Superconductor Technologies, Inc (USA) \$	Shanghai \$ Superconductor (China)
SuperOx (Russia) \$	ComEd (USA – utility)	SuNAM (S. Korea) \$
THEVA (Germany) \$	MetOx (USA) \$	SCSC (China) \$
OXOLUTIA (Spain)	HYPRES (USA)	InnoST (China) ▲\$

R&D institutes and associations:

- ○ Center for Advanced Power Systems – Florida State University (USA)
- ○ National High Magnetic Field Laboratory – Florida State University (USA)
- ○ Texas Center for Superconductivity – University of Houston (USA)
- ○ CERN (Europe); Conectus consortium (Europe); CCAS coalition (USA)

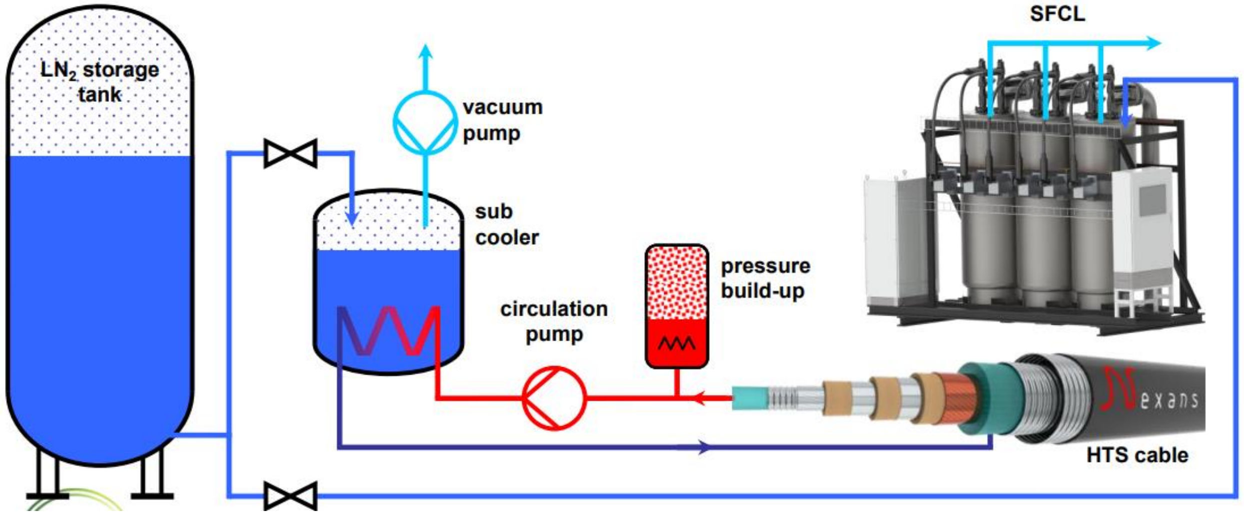
HTS projects: present status & future prospects

HTS Projects

- AmpaCity 2013-2016: Nexans & RWE/Innogy
- Resilient Electric Grid 2014 – present: AMSC & ComEd.
- Eurotapes 2012-2017: Bruker & Nexans
- Fast Grid 2017 – present: H2020 with 12 partners
- Siemens HTS R&D 2015 – present: Siemens & Australia Defence Science and Technology Group

Industry Outlook

- "No significant impact on the Cu industry within the next 10 years."
- "Displacing 1% of Cu cables is the ultimate goal." (upper limit)
- "HTS wire can be cost competitive with Cu wire if production is scaled up to 100,000 km /year." (>2030)



Source: Nexans

Outlook

Conclusions and Outlook

- Continued research has displayed a range of promising results, but is still a long way off being competitive with copper (or aluminium) in terms of properties and cost.
- High-Temperature Superconductors continue to improve with most efforts going into reducing the processing costs.
- Nanomaterials show ever more promise:
  - CNT yarns have had resistivity improvements, But they have now reached a limit that is dependant on the raw material production and improved post-yarn processes.
  - Copper composites have show mixed results with CNTs and graphene. Of late advancements with graphene have proved the most promising. This will help keep copper ahead of the curve.

Supporting your strategic business decisions on emerging technologies

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