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# Developing Lightweight High Electrical Performance Carbon Nanotube-Cu Wire Composites as Alternatives to Cu

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**Abstract**

**We report ultralong structurally uniform conducting carbon nanotube(CNT)-Cu composite wires 2/3rd as light as Cu with promising electrical performances, easy integrability to real circuits, and fabrication scalability prospects. Our results demonstrate CNT-Cu as potential lightweight alternative wiring materials to Cu. We made the composite wires using commercial CNT wire prepregs and industry-compatible Cu electrodeposition protocols. To encourage Cu/CNT mixing in the wires, we promoted Cu deposition within CNT wires by optimizing various electrochemical parameters, such as current density, electrolyte concentration, etc. Further, in the first systematic CNT-Cu wire structure-property relationship study, we clarify the effect of Cu spatial distribution on composite wire comprehensive electrical performance. Our findings confirm that CNT-Cu wire structural uniformity i.e., homogeneous CNT/Cu distribution and a continuous Cu matrix, is vital to maximizing overall electrical performances. Our structurally uniform composite wires exhibit low resistivities that are more stable to temperature than Cu (CNT-Cu wire resistivity ~ 1/100$^{th}$ of starting CNT wire and CNT-Cu wire temperature coefficient of resistivity: TCR ~ ½ Cu-TCR). The composite wires are also more stable to current than Cu with 28% higher current carrying capacity.**

## 1. Introduction

Light robust conducting wires substituting Cu in motor windings and electrical cables in automobiles/aircrafts are in high demand for fuel savings and $CO_2$ emission cuts. One strategy to cater to this demand is developing high-performance Cu-matrix composites with weight-reducing nanocarbon fillers of remarkable properties, such as CNTs (CNT-Cu). To become realistic lightweight alternatives to Cu, CNT-Cu with densities < Cu needs to be manufacturable as macro*wires* with electrical performances competitive to Cu. Previous CNT-Cu composites have demonstrated electrical [1-3], thermal [3], and mechanical properties [4] rivalling that of Cu. Specifically, CNT-Cu sheets and micropatterns with aligned nanotubes uniformly embedded in a solid Cu matrix have shown electrical conductivities similar to and exceeding Cu at room and high temperatures, respectively and higher stability to current-failure than Cu [1-3]. However, high electrical performance CNT-Cu as macrowires with fabrication scalability potential are yet to be reported. Further, the effect of CNT-Cu Cu spatial distribution (i.e., Cu content at surface and bulk) on overall electrical performance (conductivity and stability to current) - a fundamental structure-property correlation - is unknown. Previous works focused only on electrical conductivity vs. total Cu content, which is not representative of the Cu spatial distribution.

## 2. Summary

*Objectives*

In this paper, we (i) report the preparation of ultralong structurally uniform lightweight CNT-Cu wires and (ii) elucidate the effect of Cu spatial distribution on essential electrical properties, including room temperature resistivity ($\rho_{RT}$), its temperature dependence (TCR), and current stability (CCC, which is the maximum current the wire can carry per unit cross sectional area without failure).

*Method*

For CNT-Cu wire fabrication, we used Cu electrodeposition of CNT wire prepregs, a benign method allowing for control over composite composition. Conventional aqueous Cu electrolytes do not infiltrate hydrophobic CNT wires; therefore, we applied a novel 2-step electrodeposition [1] where Cu is first seeded from an organic electrolyte (copper acetate/acetonitrile) capable of infiltrating CNT wires. The Cu seeds were then grown using conventional acidified aqueous $CuSO_4$ electrodeposition. To demonstrate CNT-Cu wire fabrication scalability potential, we used industrial multiwall CNT wire prepregs (Muratec, Murata Machinery Ltd., Japan). We explored various parameters (electrolyte concentration, current density, and deposition time) at both stages to identify optimal conditions inducing Cu electrodeposition within CNT wires to achieve a continuous Cu matrix and uniform CNT distribution.

To study the effect of Cu spatial distribution on CNT-Cu wire overall electrical performance, wires with various internal Cu filling levels were fabricated. The dimensions, total Cu content and internal Cu filling (wt%), Cu spatial distribution, Cu grain sizes in the bulk, Cu outercoating thickness, etc. of the various wire samples were characterized by optical microscopy, gravimetry, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), etc. Then, we measured the $\rho_{RT}$ and TCR (by 4-probe measurements) along with CCC (by 2-point current-ramp method) of the various CNT-Cu wires. Corresponding properties of the starting CNT wires and pure Cu wires were measured for comparison.

*Results*

We successfully fabricated ultralong (~10 cm long) conducting lightweight CNT-Cu composite wires with nanotubes (~ 2 wt%) uniformly distributed in a continuous Cu matrix (Fig. 1A-B) all along the wire length (Fig. 1C). With a high CNT vol% (40-45%), the CNT-Cu wire density was 2/3rd that of Cu (~5.2 g/cc). We identified that electrodeposition parameters allowing slow (~ 4 µg/h per cm of the wire) and moderate (~ 145 µg/h per cm of the wire) Cu deposition rates during seeding and seed growth stages, respectively enable homogeneous CNT/Cu mixing throughout.

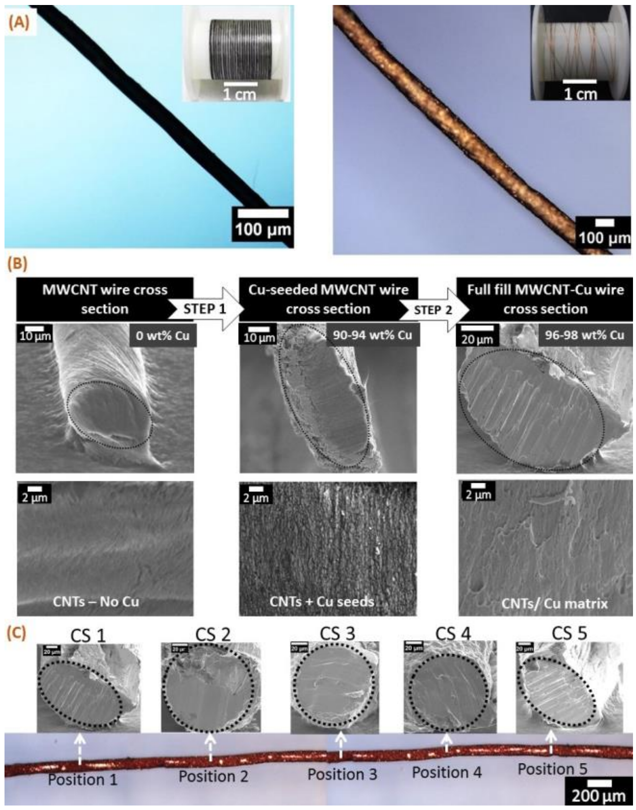


Fig. 1 (A) Initial CNT wire and CNT-Cu wire (inset: spools). (B) Low (top) and high (bottom) resolution cross section (CS) SEM images of the initial CNT wire and CNT-Cu wire after each stage of the 2-step Cu electrodeposition. (C) CS SEM images along the CNT-Cu wire length.

We confirm that a continuous Cu matrix containing evenly distributed CNTs, i.e., maximum internal Cu filling, is critical to achieving high overall electrical performances. Wires with maximum internal Cu filling exhibited (i) low $\rho_{RT}$, 1/100th of the starting CNT wires (Fig. 2A), (ii) suppressed resistance-rise with temperature and TCR ½ that of Cu (Fig. 2B-C), and (iii) 28% higher CCC than Cu (Fig. 2D). Further, the wires showed real-world applicability and were easily soldered into practical circuits (Fig. 2E). Hence, our CNT-Cu wires are promising lightweight alternatives to Cu wiring for weight-reducing applications. For example: replacing ~2 Tons of Cu wiring in a commercial aircraft with CNT-Cu wires translates to 25,000 Tons of fuel-savings and 78,000 Tons of $CO_2$ emission-cuts per year [5]. Further, the low TCR is specifically advantageous for stable high-temperature operation, e.g., in motor windings.

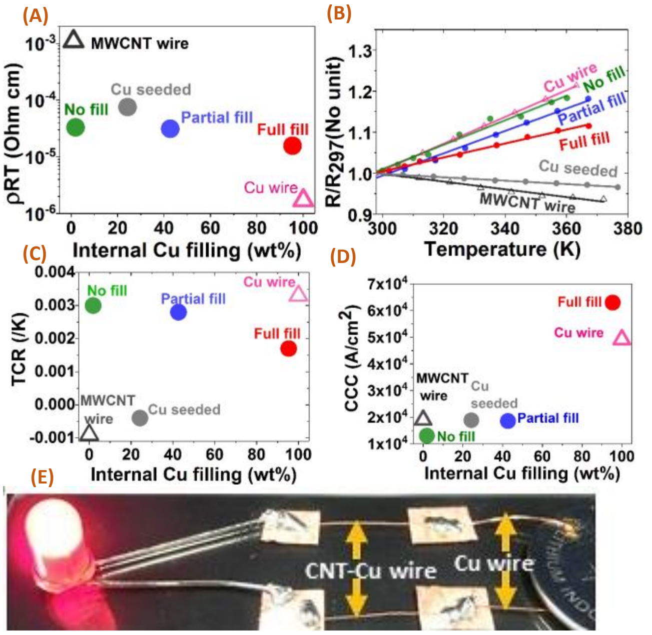


Fig. 2 (A) $\rho_{RT}$, (B) resistance vs. temperature, (C) TCR, and (D) CCC vs. internal Cu filling in CNT-Cu wires. (E) CNT-Cu wires in a practical circuit.

## 3. Conclusions

We report conducting CNT-Cu wires 2/3rd as light as Cu with homogeneous CNT/Cu mixing prepared by 2-step electrodeposition into CNT wires. Parameters encouraging internal Cu electrodeposition at both stages led to structurally uniform composite wires. We demonstrate that a continuous Cu matrix with CNTs evenly distributed throughout is critical for maximum overall electrical performance. The best CNT-Cu wires show low and temperature-stable resistivities (TCR = ½ Cu) combined with higher current stability (CCC) than Cu. With easy integrability in regular circuits, CNT-Cu show potential as lightweight alternative wiring materials to Cu.

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