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Anisotropic and Isotropic CNT Sheets

a subsidiary of CVD Equipment Corporation

Karlheinz Strobl, Riju Singhal, Mathieu Monville, Shihsheng Chang, Subarna Banerjee
CVD Equipment Corporation, 355 South Technology Drive, Central Islip, NY 11722, USA

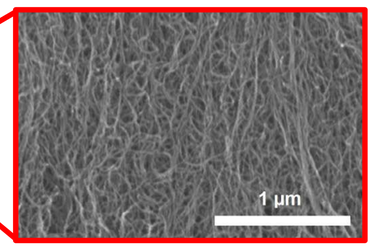
Objectives : ***- fabricating large size (>m²) carbon nanotubes (CNT) sheets***
- mastering the nanomanufacturing process to tailor the sheet properties to a given application in a flexible, scalable and economical manner.

INTRODUCTION

A CNT Sheet, popularly referred to as "Buckypaper", is a porous, paper-like sheet manufactured by assembling multi- double-, or single-walled carbon nanotubes in a flexible, nonwoven fabric style manner [1,2,3].

Such sheets could be economically manufactured with "paper manufacturing" technologies in rolls that are up to multiple meters wide.

4" x 5" CNT Sheet



CNT bundles randomly oriented in a plane observed on the top surface of a CNT Sheet (top view, SEM)

Cross section of CNT Sheet showing layered structure (tilted view, SEM)

Applications for flexible, porous CNT Sheets include:

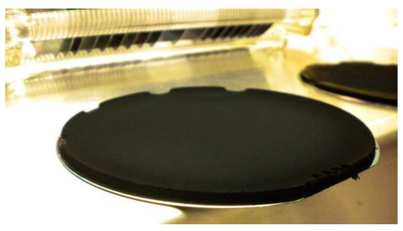
- **Energy storage** (electrodes for batteries, ultracapacitors)
- **Filtration** (membranes, filter)
- **Electromagnetic Shielding**,
- **Armors** (fire, artillery protection)
- **Composites (**for aerospace industry)
- **Thermal Interface Materials**

FABRICATION

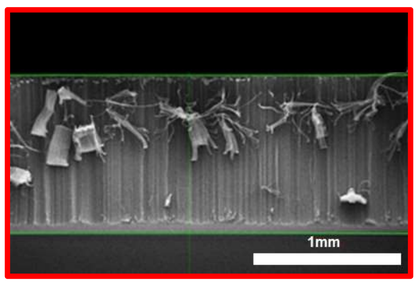
1. Synthesis of Long VACNTs

- *mm-long Vertically Aligned Carbon Nanotubes* (VACNTs) are grown on *firstnano* CVD tool, in volume batches (*several g per hour*).

EasyTube® 3000



Multiple 4" Si wafer substrates with 3 mm tall ***VAMWCNTs***



VAMWCNTs *cross section of as manufactured VACNTs (SEM)*

2. CNT Temporary Suspension

- VACNTS are removed from substrate and put into a suitable liquid to prepare a CNT suspension.
- Less hazardous chemicals are preferred to make the dispersion process industrially scalable.
- Ultrasonication can be used to disperse the CNTs into a temporary stable suspension of less than
- 100 nm thick CNT bundles,
- while preserving the mm length of the CNTs.

Vacuum Filtration *is a typical R&D method to manufacture CNT sheets*

3. CNT sheet manufacturing and optional post-processing treatments

- Suspension of CNTs is vacuum filtered.
- CNT sheet is dried and
- Optionally post-processed:
  - acid treatment,
  - directional alignment, etc.

Optional Post-processing *acid treatment*

> SCALABLE, SUSTAINABLE, MULTI-STEP NANOMANUFACTURING PROCESS <

- Vacuum filtration and/or paper making-like manufacturing processes inherently create a flexible, porous sheet-like material that is highly ***ANISOTROPIC***.
- This ***anisotropy affects*** the physical properties of the material, and can ***modify*** its **effectiveness** for a given application.
- Thus **CONTROL of the ANISOTROPY** is desired to be able to **OPTIMIZE the CNT Sheet Production Process** for a given **APPLICATION!**.

CHARACTERIZATION

Typical properties of our processed CNT Sheets

Areal density, ρ_S	g/m²	10 to 100
Thickness, ***d***	µm	30 to 200
In-plane conductivity, $\sigma_{//}$	S/m	15,000 to 35,000 *after acid treatment:* 50,000 to 110,000
Through-plane conductivity, σ_m	S/m	30 to 50
Anisotropy ratio in Electrical conductivity, r_σ	-	500 to 850
Tensile Strength	MPa	>25
Thermal conductivity, ***κ @ ambient***	W/(mK)	*in testing*
EMI Shielding Effectiveness ***@ 10 GHz***	dB	50 *after acid treatment:* 55

The ratio of in-plane to through-plane electrical conductivity of the standard processed (vacuum filtration) CNT Sheets confirms its highly ***ANISOTROPIC*** nature.

The as-prepared CNT Sheets can be further treated with acid and other post processing methods to modify the electrical, thermal conductivity and other physical properties (strength, etc.). Thus by tuning the manufacturing process, more optimized CNT Sheets can be manufactured for a given end-use application.

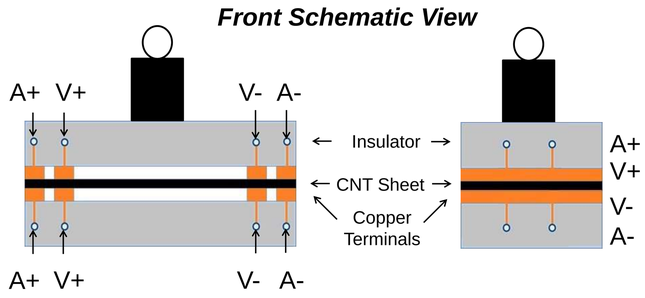
Electrical and Thermal Conductivity: In-plane and Through-plane

New setups were designed for in-plane and through-plane electrical and thermal conductivity measurements per ASTM [4] and other standards.

Electrical Test Setup

In-plane ***Through-plane***

Front Schematic View

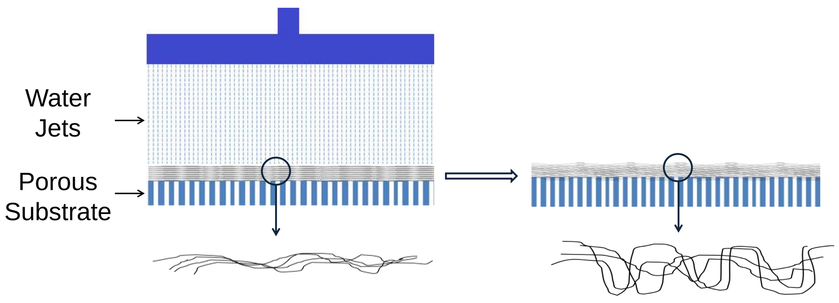


Top Schematic View of Base with CNT sample sitting on terminals

CNT SHEET ANISOTROPY MODIFICATION: PROPOSED METHOD

Hydro-entanglement

- Drag forces on individual CNTs re-orients them in the direction of fluid flow, as demonstrated by Zhang [5].
- This principle has been used to partly re-orient some CNTs also perpendicular to the plane of the CNT Sheet.
- The more the CNTs are also oriented in the direction perpendicular to plane of the CNT Sheet, the more the through-plane material properties are affected.
- This should result in a smaller difference between in-plane and through-plane material properties, thereby resulting in more isotropic CNT sheets.



JUST BEFORE TREATMENT: Bundles of nanotubes are entangled randomly mostly parallel to the substrate

AFTER TREATMENT: CNT bundles are entangled more randomly in all three directions

SUMMARY

- CNT Sheets made from mm-long Vertically Aligned Carbon Nanotubes (grown by a CVD process) can be fabricated by a cost-efficient scalable manufacturing process (similar to papermaking).
- Standard CNT Sheet manufacturing processes result in a highly flexible, porous, anisotropic sheet material.
- By adding additional secondary manufacturing process steps the CNT Sheet properties can be better tuned for a given target application.
- In addition, because of its non negligible influence on the properties of the final sheet, control of the anisotropic nature of the CNT Sheets is desired to further optimize their value proposition.
- We believe that a combination of vacuum filtration and hydro-entanglement treatment is one of the ways to achieve better control of anisotropy of the material properties of CNT sheets.
- Respective experimental verification of these assumptions are underway.

REFERENCES

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CVD Materials Corporation | 355 South Technology Drive | Central Islip, NY 11722 | Tel: 631.981.7081 | Fax: 631.981.7095 | www.cvdmaterialscorporation.com