High Resistance CNT Film for Rapid Shoe Insole Heating

NE_2010_11

Aaron Tang
Anterjot Singh Bains
Jamie Durham
Rajesh Kumar

Consultant: Dr. Aiping Yu

Introduction

A couple of questions for those in the audience:

- Have you ever felt that your feet were cold during the winter?
- Have you ever gotten your socks and feet wet from snow, rain, or a combination of both?
- Have you had trouble drying your shoes?
- Have you ever wondered if something could be done about these problems?

In that case…

- We think we might have the answer:

Customer Requirements

Our critical considerations for the design:

- **Risk of burning**
- **Heating Performance**
- **Weight**
- **Removable setup**
- **Aesthetics**

Customer Requirements

Other considerations:

- **Cost**
- **Control**

How does it work?

- Design concept driven by a version of Ohm's Law:

$$P = I^2 R$$

- Conventional design would employ a copper coil.
- Our design employs a carbon nanotube film
  - This provides high conductivity and high power dissipation.
  - Allows greater current than a copper wire loop.
  - Better conformal coverage to the contours of a shoe.

How does it work?

- By combining the equations for power dissipation and the heat flow equation, we obtain the theoretical performance:

$$\Delta T = \frac{V^2}{l^2 \times \rho \times C_{sp} \times density} \times time$$

  - ρ = Resistivity
  - *l = length*
  - V = voltage
  - C_{sp} = specific heat capacity of carbon

- It can be seen that the heating performance depends on the applied voltage, resistivity, cross-section area, density, specific heat capacity, and time.

Film-Making Procedure

Procedure Overview:

1. CNT Treatment with Nitric Acid
2. CNT Filtration – to wash away Nitric Acid
3. Sonication of CNTs in DI water
4. Film Making Filtration
5. Post Processing – electrical connections
6. Implementation – shoe assembly

Film-Making Procedure

- **1. Treatment**

- Boil MWCNT in Nitric Acid (3 hours)
- Raises purity of carbon nanotubes to usable level
- Reduces length and straightens MWCNT
- Functionalizes MWCNT with OH, C=O, and COOH end groups to enhance mechanical properties of film

- **2. Filtration**

- Wash MWNTs with DI H_2O until they have pH 6 to 6.5
- Removal of nitric acid used in purification
- Removal physical residues created by purification

Film-Making Procedure

- **3. Sonication for Film Making**

- Distribute 2.55g of wet MWCNT in 4L of DI water (for a 80 mm diameter film)
- Disperses agglomerated MWCNT.
- Enhances film uniformity

- **4. Film Making**

- Apply dispersed and purified MWCNT to vacuum enhanced filtration setup (see picture).
- Filter cake with uniform thickness becomes the carbon nanotube film.

Film-Making Procedure

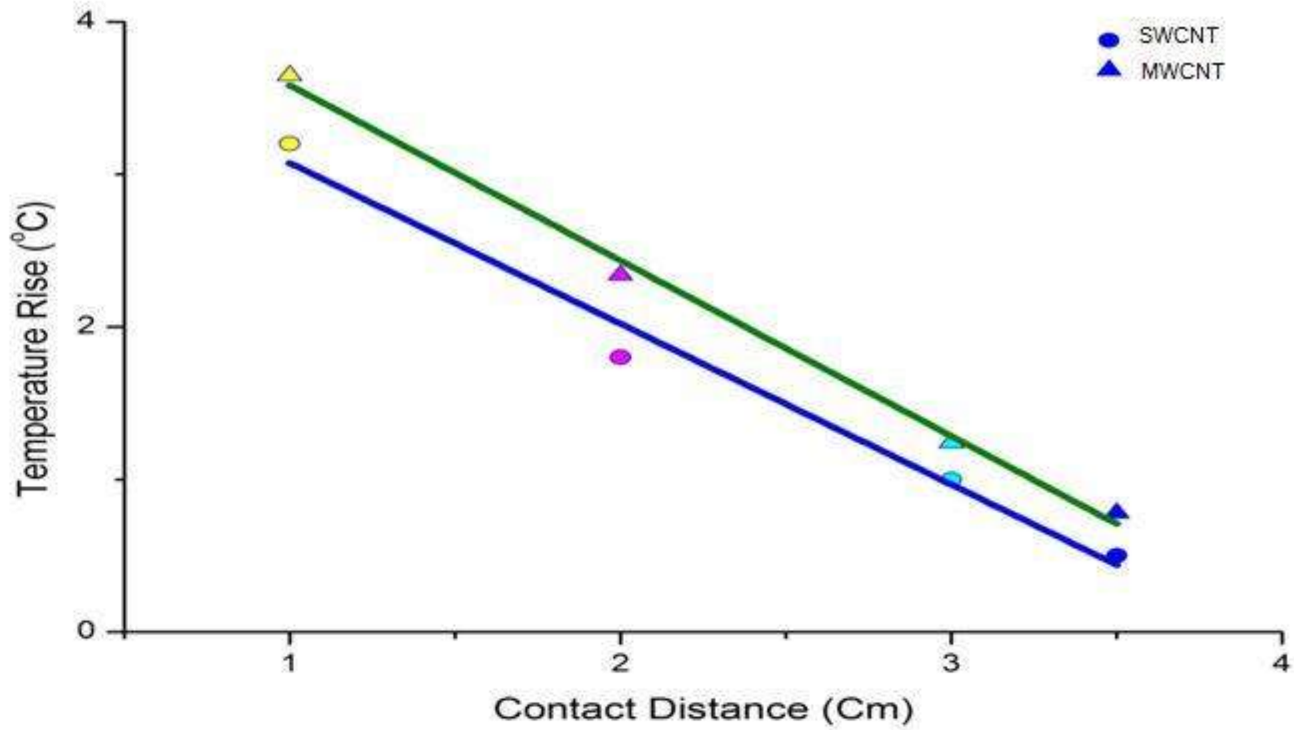
- **5. Post Processing**
  - Contacts formed with gold plasma sputtering
  - Wiring of film to complete functionality. Leads attached with silver epoxy.
- **6. Implementation**
  - Trim MWCNT film into shape of target insole.
  - Fitting of the film into the shoe.

Results

- MWNT versus SWNT
  - Flexibility / malleability:
    - MWNTs work better: film is flexible / malleable
    - SWNT films are much more brittle
  - Temperature Rise
    - MWNTs gave a higher temperature rise than SWNTs

Results

- Room Temperature Measurements:



- Both CNTs have linear relationship
- MWCNTs have better performance than SWCNTs for this application

Results Summary

- Room Temperature Measurements:

Type of Nanotube	Film Resistance (Ω)	Thickness (mm)	Temperature Change ΔT (°C)	Max. Attained Temp. (°C)
MWCNT	15	0.19	3.0	25.1
SWCNT	26	0.04	2.2	24.2

MWCNTs are therefore superior to SWCNTs for this application.

Live Testing

- MWNT Film testing outdoors (at -13°C):
  - Maximum ΔT: 5.6°C
  - Time to Max. Temperature: 2 minutes
  - Superior temperature change observed under colder temperatures than warmer.

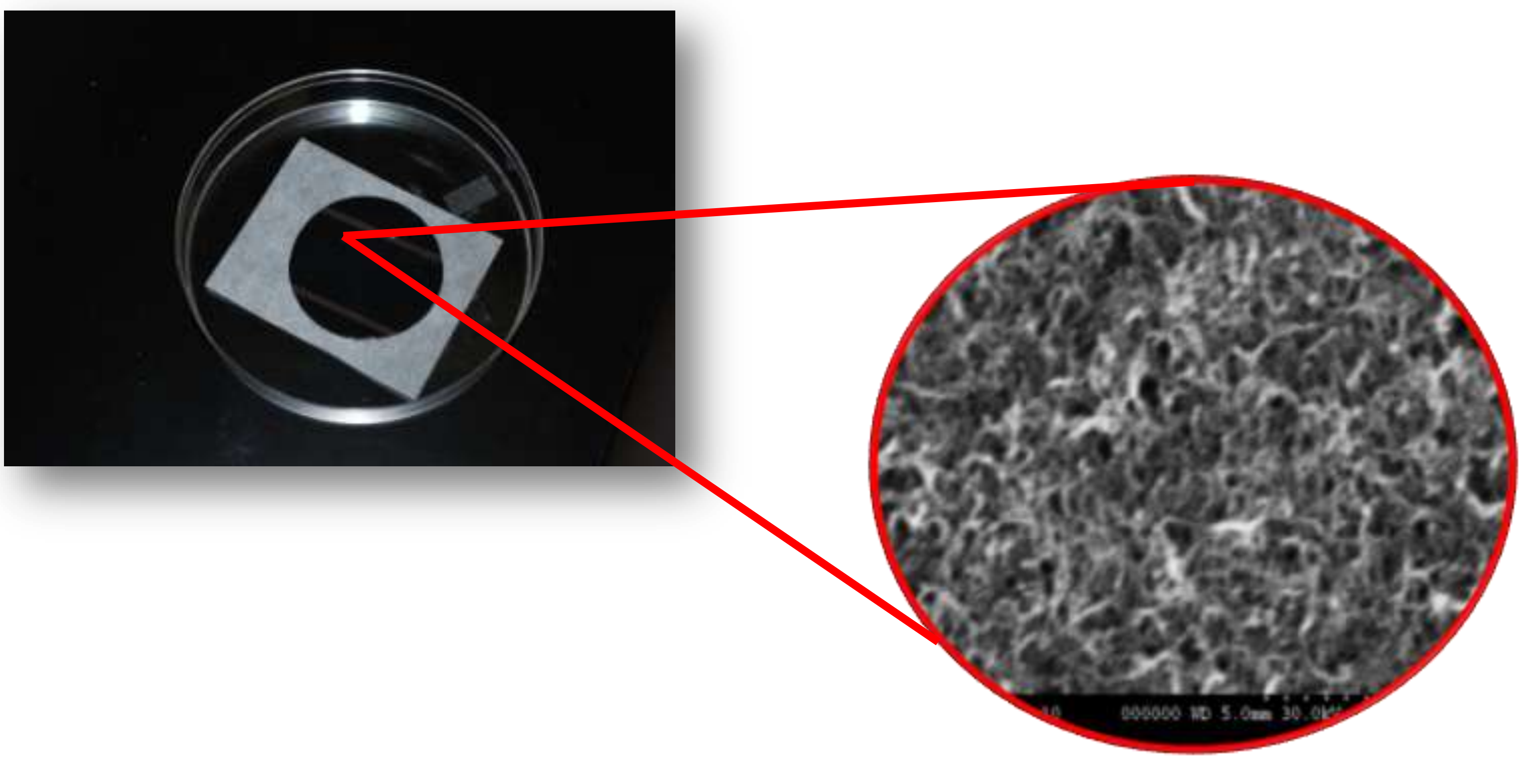
Film Resistance Data

	Resistance with Gold Contact (Ω)	Resistance without Gold Contact (Ω)
MWCNT	15	18
SWCNT	26	32

- SWCNT film has a greater resistance than the MWCNT film
- Adding gold contacts with plasma sputtering significantly reduces contact resistance.

SEM Micrograph of Film

- Shows uniform dispersion and uniform density of MWNTs in film



Concluding Remarks

Specifications for 2010 -11 Sole Warmer	Requirements	Results
Heating Cutoff	40 °C	Not an issue
Minimum Temperature Change (ΔT_{min})	3 °C	3°C (Room) / 5.4°C (Live)
Time to achieve ΔT_{min} (Ambient T > 10°C)	20 minutes	2 minutes
Time to achieve ΔT_{min} (Ambient T < 10°C)	30 minutes	Less than 2 minutes
Maximum Additional Shoe Weight	500 grams	234.8grams
Battery Type	9V	9V
CNT Mass	200 grams	36 grams

Recommended Improvements

- Add on/off switch
  - Viable option because insole heating occurs quickly
  - Extends battery life
- Design a containment case for the film
  - Completely eliminates chances of exposure to MWNTs
  - Extends film performance by slowing degradation over time
  - Protection from moisture
  - Improve film integrity

Questions?

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