

ABSTRACT

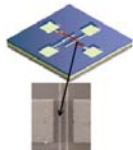
Environmental assessments of manufacturing two carbon nanotube (CNT) applications are investigated: a CNT switch and a CNT-polymer mesh (for potential applications as transistors and electromagnetic interference (EMI) shielding). Life cycle assessment (LCA) techniques including inventory analysis and impact evaluation are utilized. Results indicate significant environmental impact contribution to airborne inorganics, climate change, and fossil fuels due to materials used in cleansing processes and electricity consumption.

INTRODUCTION

- Current research at the Center for High-rate Nanomanufacturing (CHN) includes assembly and transfer of nanoelements such as carbon nanotubes (CNTs)
- CNTs have great potential in a variety of applications including structural polymers, super capacitors, batteries, sensors, and shielding due to their unique electrical, mechanical, and thermal properties (i.e. metallic/semiconducting, high tensile strength, high thermal conductivity)
- Significant uncertainty exists regarding the environmental, health, and safety (EHS) attributes of nanomanufacturing processes using CNTs
- It is prudent to assess CNT processes and products while in the developmental phase to inform and guide advancement of safe, economically competitive, environmentally responsible nanotechnologies

CNT APPLICATIONS

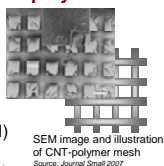
CNT switch



Schematic and SEM image (top view) of CNT switch
Source: CHN Overview 2008

- Consists of a CNT spanning a trench in a silicon wafer segment
- Upon voltage application, CNT deflects to complete the circuit and remains in that position without additional energy, meaning it is non-volatile

CNT-polymer mesh



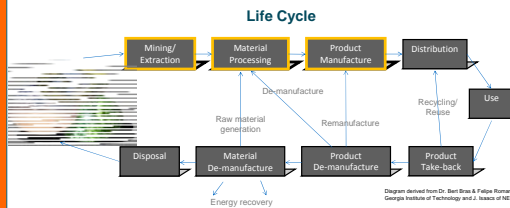
SEM image and illustration of CNT-polymer mesh
Source: Journal Small 2007

- Composed of CNT bundles arrayed perpendicular to one another on a polymer (PMMA) substrate
- Can potentially be used as electromagnetic interference (EMI) shielding, which helps prevent obstruction of local electromagnetic fields in electronic devices

METHODOLOGY

Life Cycle Assessment (LCA)

- LCA is a tool to investigate the environmental impacts associated with a product's life cycle



- Consists of 4 interconnected stages: goal definition and scope, inventory analysis, impact assessment, interpretation

Goal Definition and Scope

- "Cradle-to-gate" approach—life cycle is considered up to distribution to consumer

- Functional unit defined as one device (either one CNT switch or one CNT-polymer mesh)

Inventory Analysis

- Process parameters and inventory data collected by observation of laboratory practices at CHN

- Inventory includes inputs (raw materials, energy, equipment used) and outputs (emissions to land, water, air)

- High-pressure carbon monoxide (HiPco) SWNT production process included as feedstock to CNT product manufacture

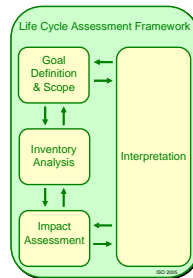
Impact Assessment

- Involves characterizing environmental impacts associated with given process and evaluating contributions to each impact category

- LCA software SimaPro™ used to determine environmental impact with Eco-Indicator 1999 (EI99) method, Hierarchist perspective → Long-term time perspective; substances included if there is consensus regarding their effect; damages avoidable by good management; fossil fuels assumed not easily substituted

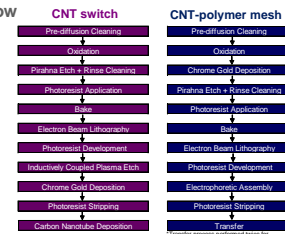
Interpretation

- Value-laden analysis based on impact categories

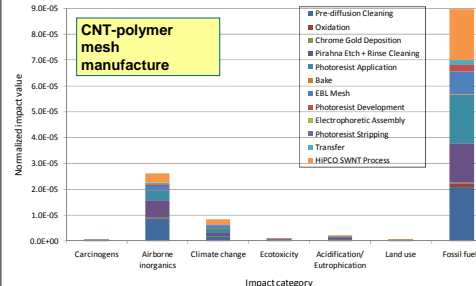
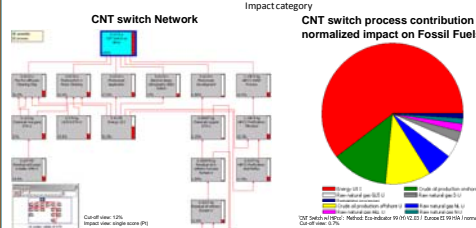
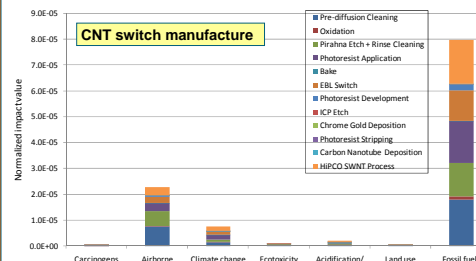


RESULTS

Process Flow Diagrams



Environmental Assessment



CNT-polymer mesh manufacture has generally higher environmental impact

EI99 HIERARCHIST CHARACTERIZATION			
Impact category	Unit	CNT Polymer Mesh	CNT Switch
Carcinogens	DALY	9.87E-09	8.43E-09
Airborne organics	DALY	4.97E-10	3.57E-10
Airborne inorganics	DALY	4.08E-07	3.51E-07
Climate change	DALY	1.32E-07	1.17E-07
Radiation	DALY	2.77E-09	2.37E-09
Ozone layer	DALY	1.84E-10	1.57E-10
Ecotoxicity	PDF-m ³ yr	6.19E-02	5.30E-02
Acidification/Eutrophication	PDF-m ³ yr	1.229E-02	1.071E-02
Land use	PDF-m ³ yr	4.440E-03	3.707E-03
Minerals	MJ surplus	1.113E-03	9.586E-04
Fossil fuels	MJ surplus	7.531E-01	6.687E-01

DALY= Disability Adjusted Life Years, PDF-m³yr= Potentially Disappeared Fraction per area
[MJ] per year, MJ surplus= Additional MJ of energy required for future extraction of the resource

SUMMARY FOR CNT APPLICATIONS

- Manufacturing with CNTs impacts fossil fuels, airborne inorganics, and climate change
- Airborne inorganics impact due to use of sulfuric acid in pre-diffusion cleaning and piranha etch & rinse cleaning
- Fossil fuels impact dominated by processes that require energy-intensive equipment (i.e. wet bench for cleaning, spinner for photoresist application, scanning electron microscope (SEM) for EBL, HiPco process)
- Slightly greater environmental burden for CNT-polymer mesh processes
- Until EHS toxicity information becomes available for CNTs, these LCAs will only provide information on energy and chemicals

CONTINUING WORK

- Extension of LCA scope to use and end-of-life phase
- Estimation of energy and economic ramifications during use when CNT applications replace existing technologies
- Identification of potential barriers or advantages to recycling CNT materials within existing infrastructure
- Economic assessment of manufacturing CNT applications
- Comparison with existing semiconductor manufacturing processes
- Employ data envelopment analysis to aid in analysis due to EHS uncertainties of CNTs

REFERENCES

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