Carbon Nanotube Solutions for Packaging and Wireless Sensors

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Outline

• Why Carbon Nanotubes (CNTs)?
• Carbon Electronics Center
• Materials Development Goals
• Electronics-Grade CNT Solutions
• Highly Conductive CNT Platform for Easy Application
• High-Solids CNT Platform for Screen-Printing Applications
• Use in Sensor Device Technology
• Summary and Future Directions
So Why Carbon Nanotubes?

- Semiconducting or metallic with a chirality-dependent band gap
- Ballistic conductivity: $\sim 10^8$ S/m
- High current-carrying capacity: $4 \times 10^9$ A/cm$^2$; $\sim 1000x$ of Cu
- High thermal conductivity: $\sim 3000$ W/mK; $\sim 385$ W/mK Cu
- High Young’s modulus: $\sim 1$ Tpa
- Extreme maximum tensile strength: $\sim 30$ GPa
- Very high aspect ratio: $\sim 0.5$-1.2 nm diameter length, 1-20 µm typical, but as long as 1-10 mm and even > 10 cm observed
- High thermal stability in air: $\sim 700^\circ$-750$^\circ$ C
- Radiation hardened for space applications
- Highly corrosion resistant compared to metals
What Are the Obstacles to Adoption?

- One dimensional; key properties along the length
- CNT manufacturing produces large mixtures of different chirality
  - Mixtures of semiconducting and metallic CNTs
  - Difficult to separate in scalable processes
- Defects in tubes and contamination with catalyst metals
- Poor solubility makes coating and printing inks difficult
- High cost of raw materials makes development expensive

Breaking these barriers is Brewer Science’s focus at the Carbon Electronics Center
We deliver solutions to these markets

Trusted high-volume manufacturing (HVM) supplier to top-tier semiconductor manufacturers for > 30 years
Carbon Electronics Center

**Chemical**
- Carbon Nanotubes: Dispersion, Purification, Functionalization, Enrichment
- Other Materials: Organic Polymers, Dielectrics, Metals

**Applications and Deposition**
- Formulation: Application/Deposition Specific
- Deposition: Screen, Gravure, Flexo, Ink-Jet, Spray, Spin, Aerosol Jet®

**Device Design, Fabrication, and Testing**
- Conductive Layers: Transparent, Trace, and RFID Antenna
- Devices: TFTs, Inductors, Capacitors, Diodes
- Sensors: Environmental, Bio, Chemical, Mechanical

Aerosol Jet® is a registered trademark of Optomec
Materials Development Goals

- Surfactant-free aqueous and solvent systems
- Dispersions with stable solubility
- Adhesion with no binders
- Low-temperature curing to achieve performance
- Scalable manufacturing
Electronics-Grade CNT Solutions

• Market entry in 2006 as commercial supplier of microelectronics-grade CNTRENE® C100 family of materials by license from Nantero:
  – Surfactant-free aqueous system
  – Metallic ion purity < 5 ppb levels
  – Coating quality required for IC production

• Processing for NRAM™ and sensor devices
  – Applied and processed with traditional IC device equipment and processes
  – Cure temperatures below 250° C allow freedom to use in both front and back end of device layer stacks

NTRENE® is a registered trademark of Brewer Science, Inc.
NRAM™ is a trademark of Nantero
NRAM™ Device for Embedded Memory

• Key benefits of NRAM™ cell
  – Universal non-volatile structure
  – Fast 20-ns set/reset speeds
  – Rugged; operating >10 years at 300°C
  – Radiation-hardened memory structure
  – Low power consumption
  – Flexible device stack placement

• How it works
  – Resistive cell: high/OFF, low/ON state
  – Voltage used to read, set, and reset
    • Low read voltage to test OFF/ON state
    • Medium voltage attracts CNTs together through van der Waals force – ON state
    • Higher voltage induces CNT phonon excitation overcoming the van der Waals force separating CNTs – OFF state
Soluble, Highly Conductive Functionalized CNT Platform

- Surfactant free
  - Aqueous and water/solvent dispersions with concentrations of 0.5-2.0 g/L
  - Low viscosity, typically < 10 cP at 1.5 g/L
  - Broad formulation range; many deposition types:
    - Optomec Aerosol Jet® Technology
    - FujiFilm Dimatix® Ink-Jet Material Printer
    - Drawdown Bar/Mayer Rod Application
    - Spray Coating
    - Screen Printing

- Dispersions stable for > 3 months at 21°C
- Good adhesion by repeated bend testing
- Low-temperature curing at 110° - 150°C
- Scaled from lab to liter scale

FujiFilm Dimatix® is a registered trademark of FujiFilm.
Soluble, Highly Conductive Functionalized CNT Platform

Film optical properties at 550 nm and film electrical performance

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<th>Optomec Aerosol Jet® Technology</th>
<th>FujiFilm Dimatix® Material Printer</th>
<th>Spray Coating</th>
<th>Drawdown Bar Coating</th>
<th>Screen Printing</th>
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Inks for Optomec Aerosol Jet® Technology Process

- Inks provided as aqueous or water/solvent formulations
- Shelf life exceeds 3 months at room temperature
- Broad substrate compatibility: PET, polyimide, glass, silicon, paper, printed circuit board, and many others
- Print fine structures (down to 25 µm) or area films
- Transparent conductive: 450 Ω/sq at 85%T and 650 Ω/sq at 90%T at 550 nm
- Conductive trace applications: < 50 Ω/sq with conductivity performance to ~73,000 siemens/m
- Cures on platen so no additional curing required
Ink for FujiFilm Dimatix® DMP-2800 Printer

- Used a tuned water-solvent mix for 10-pL drop volume cartridges for PET and paper substrates
- Shelf life exceeds 3 months at room temperature
- Print structures (down to 75 µm) or large-area films
- Transparent conductive: 530 Ω/sq at 85%T and 980 Ω/sq at 90%T at 550 nm
- Conductive trace applications: < 150 Ω/sq with conductivity performance to ~24,000 siemens/m
- Requires curing between 110°C and 150°C

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<td>85%T at 550 nm</td>
<td>530 Ω/sq</td>
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All CNTs printed on PET
CNT Ink for Spray Coating

- Aqueous solutions from 0.5 to 2.0 g/L
- Shelf life exceeds 3 months at room temperature
- Print patterns down to 50 µm with stencil; large-area films depend on platen size
- Transparent conductive: 300 Ω/sq at 85%T and 685 Ω/sq at 90%T at 550 nm
- Conductive trace applications to 0.5 Ω/sq at ~5-µm film thickness
- Cures on heated platen, no additional curing step
- Broad substrate compatibility

Spray-coated CNT on polyimide film; inductor/capacitor RC circuit for wireless temperature sensor

- 93%T at 550 nm
- 1520 Ω/sq, 1 pass

- 89%T at 550 nm
- 754 Ω/sq, 2 passes

CNTs printed on PET
Drawdown Bar/Mayer Rod Coating

- Tuned water/solvent mix for PET substrates was used
- Shelf life exceeds 3 months at room temperature
- High-speed large-area films on plastic substrates
- Transparent conductive: 870 Ω/sq at 85%T and 1800 Ω/sq at 90%T at 550 nm
- Requires curing between 110° C and 150° C

CNTs printed on PET

- 93%T at 550 nm
  - 3300 Ω/sq
  - 7-gauge wire

- 85%T at 550 nm
  - 870 Ω/sq
  - 12-gauge wire

- 83%T at 550 nm
  - 650 Ω/sq
  - 20-gauge wire
Highly Conductive Screen-Printing Paste Platform

- Independent single-walled conductive CNT platform
- Surfactant-free solvent-based system; from 0.1–8.0 grams of CNTs per kg of paste
- Shear thinning system designed for screen-printing performance
- Demonstrated on wide range of screen-printing materials and screen meshes
- Dispersions stable for > 3 months at 21°C, require only simple mixing prior to use
- Low-temperature curing at 110° -150°C
- Scaled from lab scale to 1-kg batches
- Transparent conductive: 1,000 Ω/sq at 85%T and 2,780 Ω/sq at 90%T at 550 nm
- Conductive trace applications to 6 Ω/sq with a single pass at ~ 3.2-μm film thickness

Screen-printed CNT paste on PET: a) 3 passes, 1 Ω/sq; b) 1 pass, 6 Ω/sq
All-Orgnic Temperature Sensor

Handheld transmitter/receiver

All-organic sensing element
40 mm × 40 mm
All-Orgnic Temperature Sensor Evaluation

- HP 4195 network analyzer, transmission/reflection test kit, and prototyping board with BNC connectors
- Shifting of resonant frequency by 8 MHz with $\Delta T = 25^\circ C$
Interdigitated Electrode (IDE) Humidity Sensor

- Resistance change of more than 20% was observed while monitoring a moisture increase of 15% at room temperature
Summary

• Brewer Science brings its leadership in technology development and production competency to CNT materials for printed electronics

• Brewer Science introduces two new CNT platforms for printed electronics
  – Highly conductive, stable, surfactant-free, low-temperature-cured, low-viscosity system broadly compatible with most application technology and substrates
  – Stable thick-film paste for pattern and area screen-printing applications

• Next steps are to develop these materials for flexo, gravure, and slot die coating applications

• Brewer Science demonstrated the use of the above materials in a passive, all-organic temperature sensor system

• Brewer Science’s goal is to bring the unique properties of CNTs in easy-to-use production-capable platforms
Acknowledgements

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  – Jacqueline Garrison – Screen-printing paste
  – Alex Diao – Device design, process, and test for all-organic temperature sensor

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