Carbon Nanotube Solutions for Packaging and Wireless Sensors

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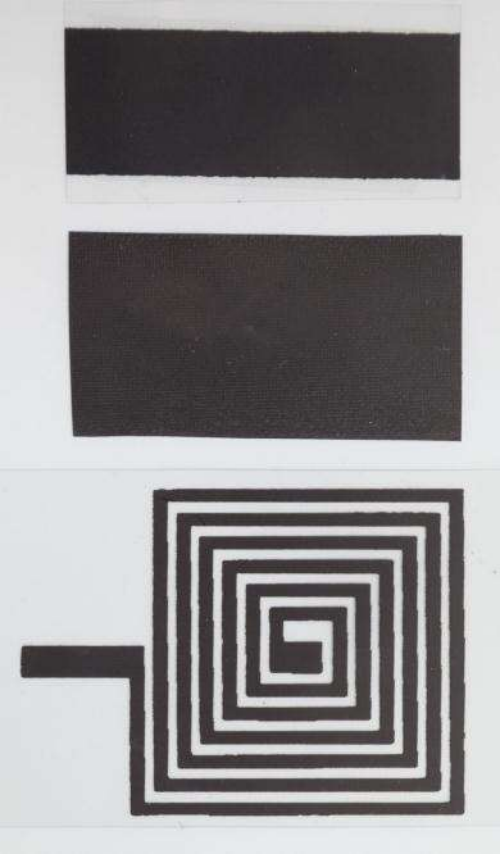
Outline

- 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: ~10^8 S/m
- High current-carrying capacity: 4×10^9 A/cm^2; ~1000x of Cu
- High thermal conductivity: ~3000 W/mK; ~385 W/mK Cu
- High Young's modulus: ~ 1 Tpa
- Extreme maximum tensile strength: ~30 GPa
- Very high aspect ratio: ~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: ~700° -750° 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

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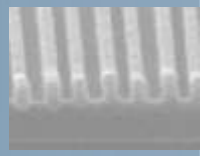
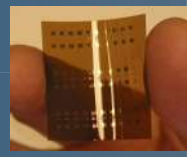
- Semiconductor Devices
- Advanced Packaging Technologies
- Carbon Electronics
- Semiconductor Equipment
- Display / Energy/ LED Devices





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

Carbon Electronics Center

Chemical

Applications and Deposition

Device Design, Fabrication, and Testing

Carbon Nanotubes: Dispersion, Purification, Functionalization, Enrichment

Other Materials: Organic Polymers, Dielectrics, Metals

Formulation: Application/ Deposition Specific

Deposition: Screen, Gravure, Flexo, Ink-Jet, Spray, Spin, Aerosol Jet®

Conductive Layers: Transparent, Trace, and RFID Antenna

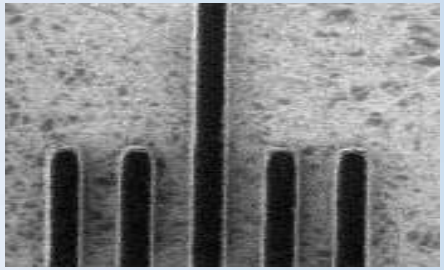
Devices: TFTs, Inductors, Capacitors, Diodes

Sensors: Environmental, Bio, Chemical, Mechanical

Aerosol Jet® is a registered trademark of Optomec

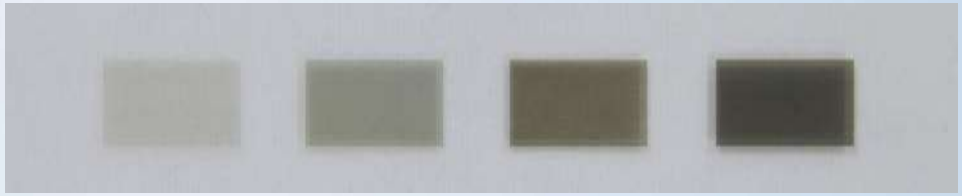
Materials Development Goals

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



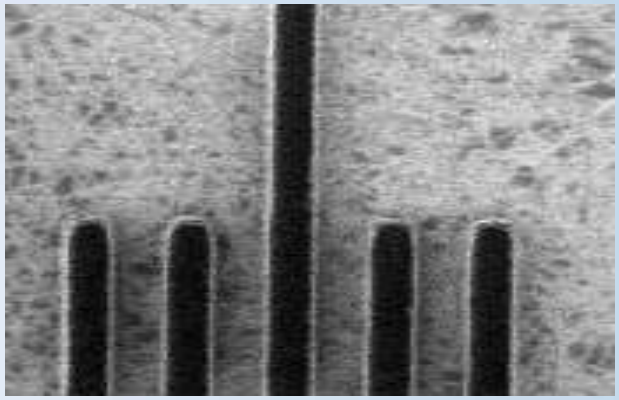
CNT mat with patterned photoresist

CNT structures printed using Optomec Aerosol Jet® technology



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

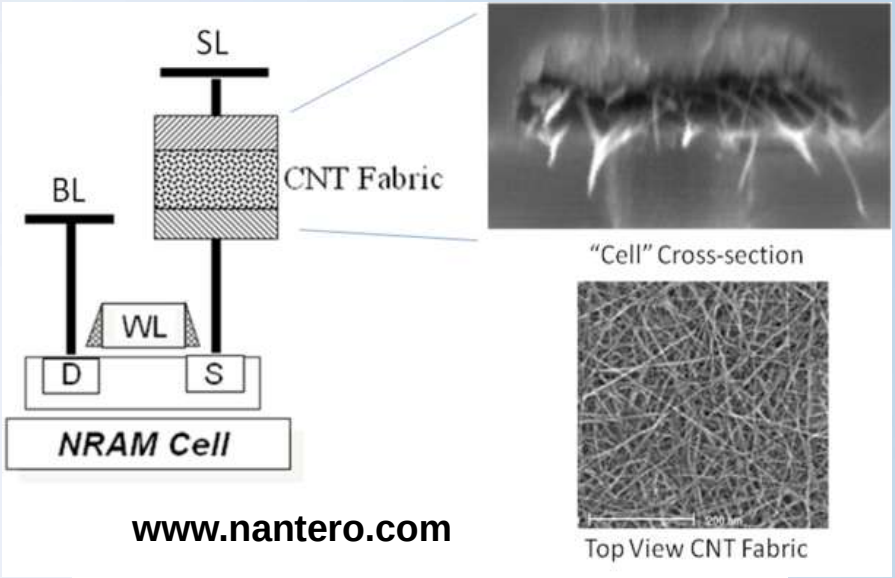


NRAM ™ is a trademark of Nantero

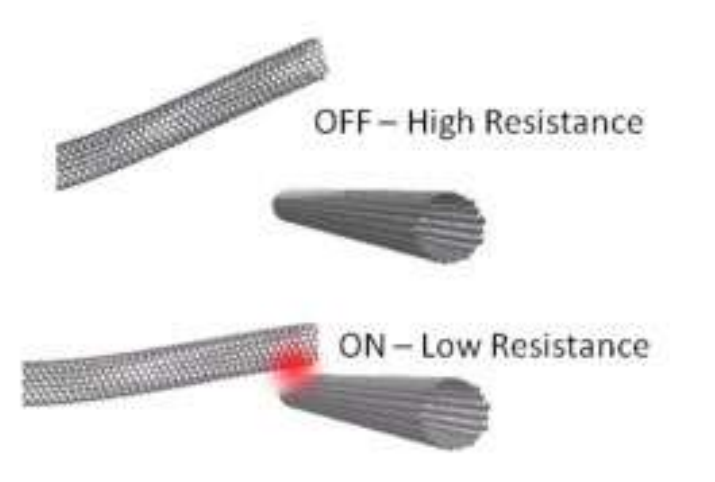
CNTRENE® is a registered trademark of Brewer Science, Inc.

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

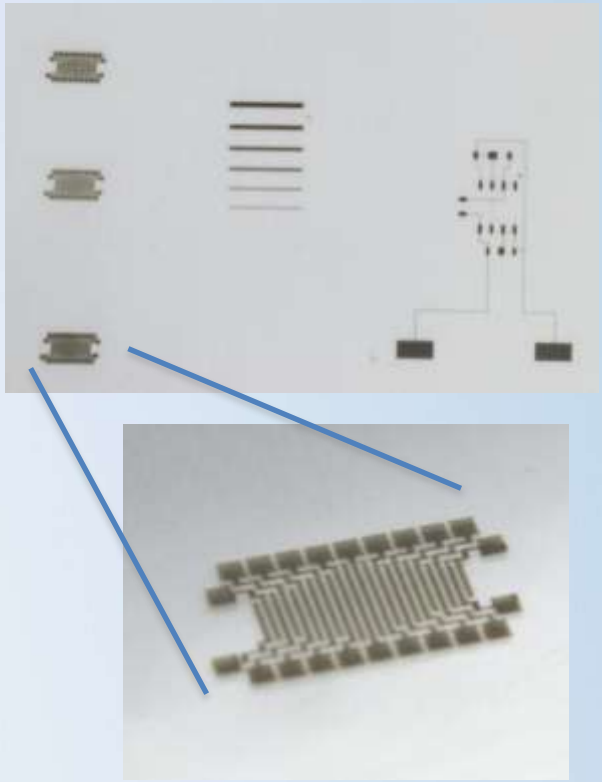


www.nantero.com



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



CNT printing using Optomec Aerosol Jet® technology

FujiFilm Dimatix® is a registered trademark of FujiFilm.

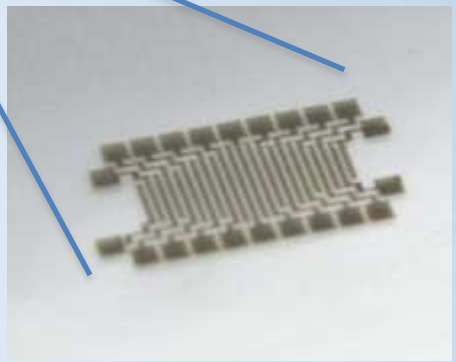
Soluble, Highly Conductive Functionalized CNT Platform

Film optical properties at 550 nm and film electrical performance

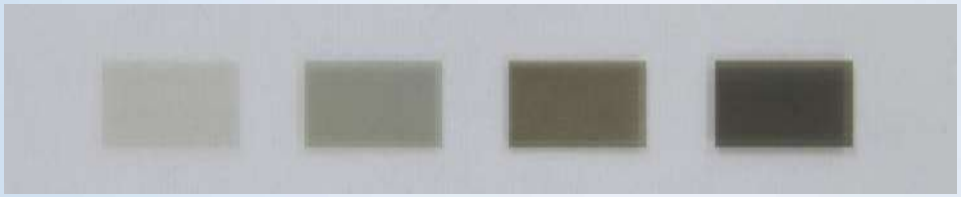
Optomec Aerosol Jet® Technology		FujiFilm Dimatix® Material Printer		Spray Coating		Drawdown Bar Coating		Screen Printing	
%T	Sheet R (Ω/Sq)	%T	Sheet R (Ω/Sq)	%T	Sheet R (Ω/Sq)	%T	Sheet R (Ω/Sq)	%T	Sheet R (Ω/Sq)
		93	3,810	93	1,340			91	4,020
90	650	90	980	90	685	90	1,800	90	2,780
		87	830	86	323			86	830
85	450	85	530	85	300	85	870	85	685
78	178	83	400	80	203	82	621	84	540
49	53			70	109	70	396		

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



CNT printed on PET

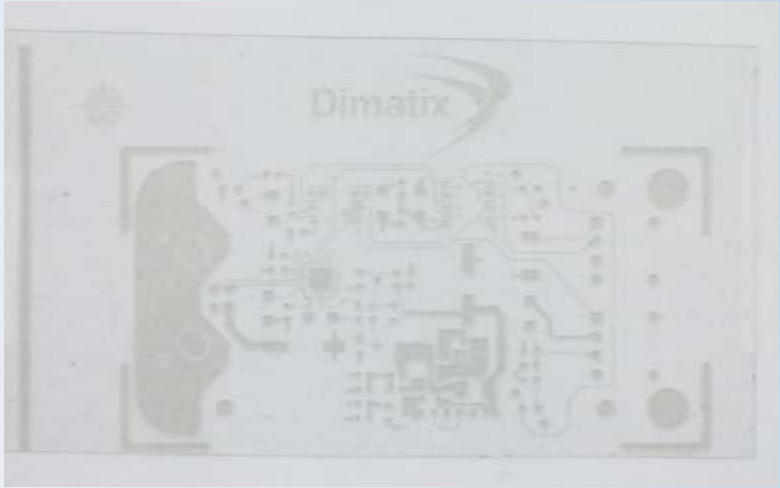


85.3% at 550 nm 470 Ω/sq	78.2%T at 550 nm 178 Ω/sq	61.6%T at 550 nm 77 Ω/sq	49.3%T at 550 nm 53 Ω/sq

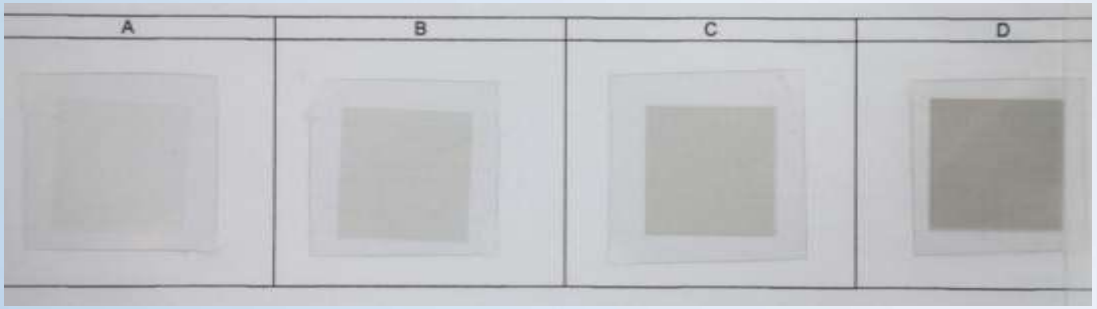
CNT printed on glass

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



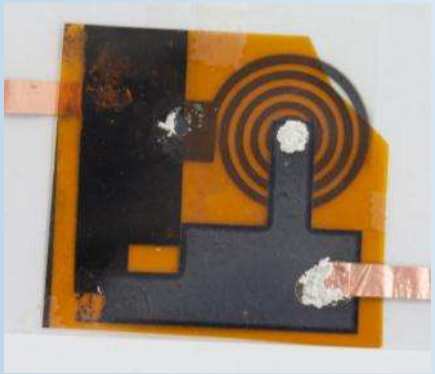
All CNTs printed on PET



98%T at 550 nm 100,000 Ω/sq	95%T at 550 nm 60,000 Ω/sq	91%T at 550 nm 2,000 Ω/sq	85%T at 550 nm 530 Ω/sq

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

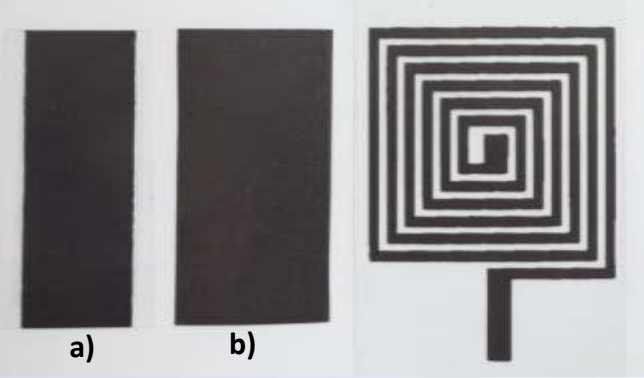
93%T at 550 nm
3300 Ω/sq
7-gauge wire

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



91%T at 550 nm
3300 Ω/sq

84%T at 550 nm
900 Ω/sq

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

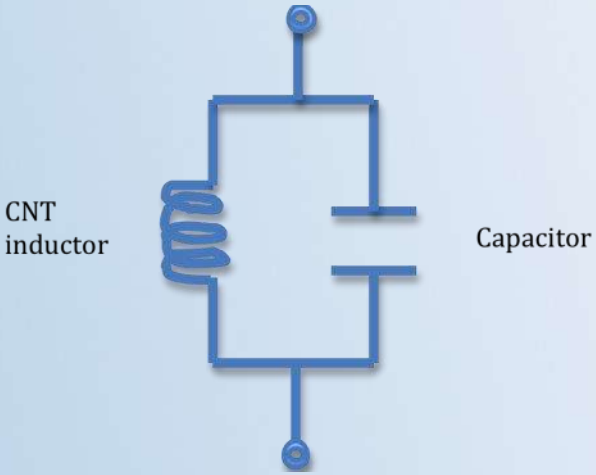
All-Organic Temperature Sensor

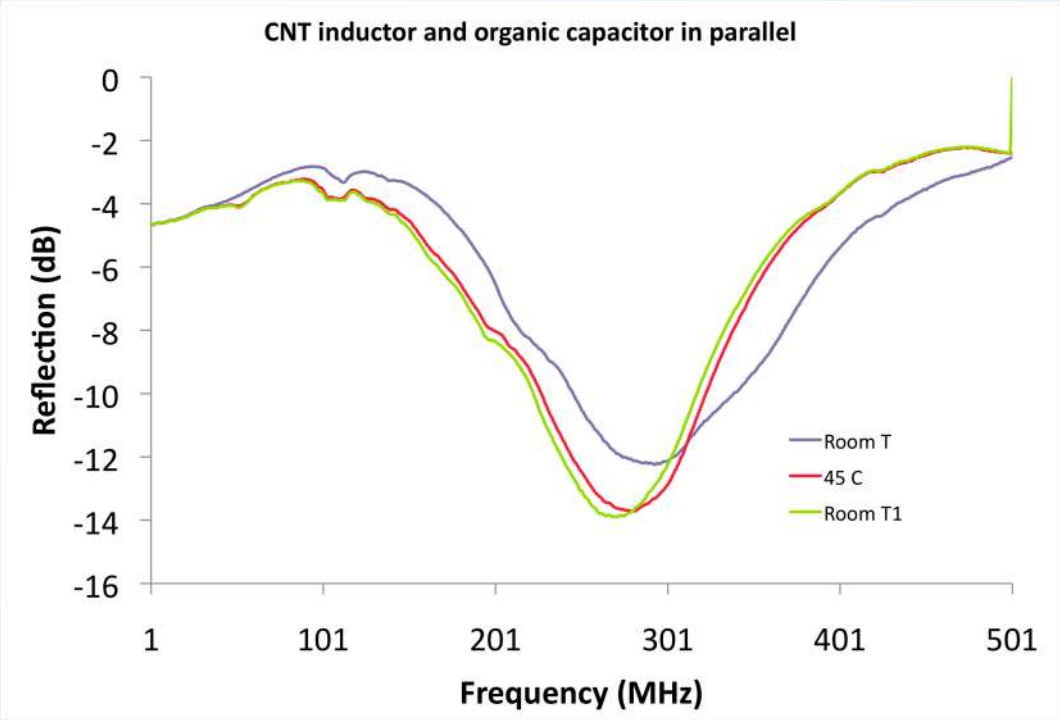
Handheld transmitter/receiver

All-organic sensing element
40 mm × 40 mm

All-Organic 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



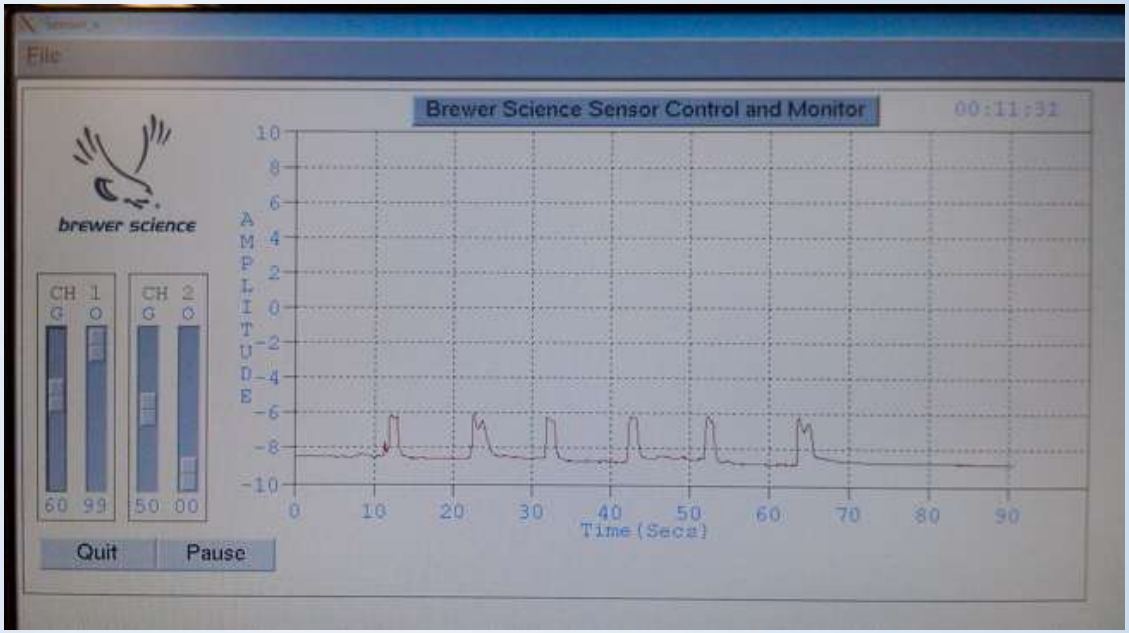


Interdigitated Electrode (IDE) Humidity Sensor

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

IDE (Ag)

Functionalized CNT film



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

- Brewer Science, Inc.
  - Chris Landorf – Functionalization of highly conductive platform, spray and drawdown bar
  - Vijaya Kayastha – Inks and process for Optomec Aerosol Jet® technology
  - John Bledsoe – Ink and process for FujiFilm Dimatix® DMP2800 DMP system
  - Jacqueline Garrison – Screen-printing paste
  - Alex Diao – Device design, process, and test for all-organic temperature sensor

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