Nanoparticle Inks for Printed Electronics

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Technology Revolutions in Electronics
for the Past 100 Years

- Vacuum Tube Transistors: 1906 by Lee De Forest
- Solid State Transistors: 1947 by John Bardeen and Walter Brattain (Bell Telephone Laboratories)
- Integrated Circuits: 1958 by Jack Kilby (Texas Instruments)
What Next?

- The industry has followed the prediction of Moore’s Law for the last 40 years without major technology revolution.

- **Moore’s Law**: The number of transistors per unit area is doubling every 1.5 years. --Gordon Moore (founder of Intel Corporation).

- Moore’s Law is reaching its physical limit in next 5 to 10 years.

- What will be the next technology revolution in the electronics industry?

Look beyond the Silicon
Low-Cost ICs on Arbitrary Substrates

- Pentacene organic circuits on polymeric or cloth substrates
- a-Si:H strain bridge array
- Plastic solar cell
- a-Si:H active matrix Gamma ray detector on polyimide substrate
- Polymeric substrate AMLCD
Large Area & Flexible Displays

Flexible active matrix e-paper SVGA display (Plastic Logic)

World's thinnest flexible active-matrix display (Philips)

The plastic TFT-LCD display (Samsung)

World's first 3mm thick flexible digital watch (Citizen)
Low-cost RFIDs and Disposable Electronics

Current cost: 7-10 cents per tag
Target cost: 1-2 cents per tag
Printed Electronics Manufacturing

The Holy Grail: Reel-to-Reel Fab

- No lithography
- No vacuum processing (CVD, PVD, Etch)
- Reduced abatement costs
- Cheap substrate handling
- Reduced packaging costs
Tremendous Market Growth Potential for Printed Electronics in Next 20 Years

Recent report by IDTechEx predicts the PE market will reach $300B in 2027.
Printed Conductors

Highly conductive and high resolution patterns fabricated using low-cost and roll-to-roll processes (such as inkjet and gravure printing) are one of the most critical technology components in making printed electronics and displays.

NanoMas Solutions: Make conducting patterns using metal nanoparticle inks!

Market of Applications:
- Flat panel display backplanes (TFT electrodes and bus-bars)
- EMI Shielding: plasma display, LCD, etc
- RFID tags
- Electroluminescent lighting
- Printed circuit boards (PCBs)
- Touch screens
Small particle size (in nanometers) significantly reduces the melting temperature of NPs from the bulk melting point, allowing for very low processing temperatures (based on surface melting) for sintering NPs into conducting films.

Nanoparticle Inks for Printed Electronics

- Nanoparticles can be stabilized in ink solutions by organic ligand shells, which can be removed after printing.
- Nanoparticles can be further cured or sintered to highly conductive films at low temperatures.

Deposited Ag nanoparticles

Conductive Ag film on PET cured from printed nanoparticle inks
**NanoMas Proprietary Technology: Producing High Quality Nanoparticles with Large-Scale and Low-Cost Processes**

NanoMas silver nanoparticles with 5-6 nm in size (SEM)

A 50L pilot production reactor at NanoMas

NanoMas Ag nanoparticle powders and inks
NanoMas Proprietary Printable Metal
Nanoparticle Conductive Inks Technology

- Unique all solution based nanoparticle synthesis technology (patent pending), widely compatible with the low cost production processes in the chemical industry
- Low cost and fully scalable to large scale mass production
  - Scaled up to pilot production with a 50 litter reactor
- Ultra-small nanoparticle size (2 to 10 nm) with specially designed surface chemistry allows low annealing temperature, short process time, and high conductivity
- Variety of surface chemistry for different solvent dispersion and applications
- Low resistivity (as low as ~2.3 $\mu\Omega$-cm, 1.5x of pure Ag)
- Low process temperature (as low as ~90°C) compatible with most plastic substrates
- Also curable by laser or UV light at room temperature
UV-vis Characterization of NanoMAs
Gold and Silver Nanoparticles

Nano-Au (4 nm) nanoparticle solution in cyclohexane
Nano-Ag (5 nm) nanoparticle solution in cyclohexane

UV-Vis Absorption Spectra of Au and Ag Nanoparticle Solutions
NanoMas Au Nanoparticles (<5 nm)

- **DSC**: exothermic sintering between 180°C and 210°C
- **TGA**: ~10-15% weight loss between 180°C and 250°C due to loss of surface capping agent
- **Resistivity**: ~8 μΩ-cm (annealed at 200°C, 3x of bulk Au)
NanoMas Ag Nanoparticles

- **DSC**: exothermic sintering between 110°C and 160°C
- **TGA**: ~10% weight loss between 100°C and 200°C due to loss of surface capping agent
- **Resistivity**: 2.4 μΩ-cm (annealed at 150°C, 1.5x of bulk Ag)

**Metric**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mean ECD [nm]</td>
<td>5.72</td>
</tr>
<tr>
<td>Std Dev ECD [nm]</td>
<td>1.79</td>
</tr>
<tr>
<td>Count</td>
<td>726</td>
</tr>
<tr>
<td>GMD ECD [nm]</td>
<td>5.43</td>
</tr>
<tr>
<td>GSD</td>
<td>1.41</td>
</tr>
<tr>
<td>Fit GMD [nm]</td>
<td>5.98</td>
</tr>
<tr>
<td>Fit GSD [nm]</td>
<td>1.24</td>
</tr>
</tbody>
</table>

**Particle size**: 6 ±1 nm
Small Angle Neutron Scattering (SANS) Characterization of NanoMas Nano-Ag

SANS of Packed Nano-Ag (Solid)

SANS on Nano-Ag Solutions (10 wt% in d-Toluene)

SANS spectra confirmed that the Nano-Ag has an Ag core diameter of 4.6 ±1.1 nm and a 0.6 ±0.1 nm thick shell in solvent or a 0.3 nm shell in packed (solid) state.

- Core radius: 23 ± 1 Å
- Core radius σ: 5.5 Å
- Shell thickness: 6 ±1 Å

Q_{max} = 0.120 Å^{-1}

interparticle distance ~ 5.2 nm
Superior Performance of NanoMas NanoSilver Inks due to the Ultra-Small Nanoparticle Size

![Graph showing resistivity vs. annealing temperature for NanoMas and competitors.](image)

- NanoMas NanoAg (5 nm)
- NanoAg (~25 nm) from competitors
- Ag bulk resistivity

**Graph Details:**
- **X-axis:** Annealing Temperature (°C)
- **Y-axis:** Resistivity (µΩ cm)
- Materials compared: PET and Kapton
Printed Conductive Patterns on Plastic Substrates

13.56 MHz RFID antenna printed on PET and polyimide

Miniature RF coil printed on PET

Printed flex circuit on polyimide
**Inkjet Printed NanoSilver Contacts in Fabricating a-Si:H TFTs on Glass**

### Source
- Ag (~ 30 nm)
- Cr (~ 5 nm)
- n+ a-Si:H (~ 50 nm)
- a-Si:H (~ 200 nm)
- a-SiNx:H (~ 300 nm)
- Cr (~ 35 nm)
- Glass Substrate

### Drain

<table>
<thead>
<tr>
<th>L (µm)</th>
<th>110</th>
<th>140</th>
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<tbody>
<tr>
<td>µ (cm²/Vs)</td>
<td>~ 0.91</td>
<td>~ 0.97</td>
</tr>
<tr>
<td>V_T (V)</td>
<td>~ 1.68</td>
<td>~ 1.41</td>
</tr>
</tbody>
</table>

* Data courtesy of Dr. Yongtaek Hong of Seoul National University, Korea
Printed NanoSilver Contacts in Fabricating Organic TFTs

- Organic Semiconductor: poly(3,3-didodecyl-quaterthiophene) or PQT-12
- Source and drain printed with NanoMas NanoSilver inks and annealed at 145°C
- Device channel length of ~43 um and width of ~300 um
- No obvious contact resistance

* Data curtesy of Dr. Jurgen Daniel of PARC
Inkjet Printed TFTs with ZnO and Ag Nanoparticle Inks

- Print or coat with ZnO nanoparticle ink
- Heat step at 200°C to anneal
- Print silver nanoparticles for source/drain, and annealed at 150°C

Mobilities: 0.1-0.15 cm²/Vs
On/Off: \( \sim 10^5 \)
About Cost...

- What Printed Electronics should shoot for are high productivity, large size and volume, high flexibility, and ultimately the LOW COST.
- The nanoparticle inks should also be made by LOW COST processes.
- NanoMas makes sure all the nano-materials it makes can be mass produced with LOW COST processes.
NanoMas Technology and Product Roadmap

- NanoMas current products include NanoSilver™ and NanoGold™ conductive inks.
- Under development with its proprietary technology, NanoMas will also provide inorganic nanoparticle and polymer semiconductor inks, as well as electroluminescent (EL or LED) inks for PE applications.
- NanoMas also has the technologies to mass produce high quality carbon nanotubes and carbon nanofibers.

NanoMas Product Portfolio

Printable Electronics & Displays
- Silver nanoparticle inks
- Gold nanoparticle inks
- EL nanoparticle inks
- Semiconductor nanoparticle inks
- Polymer semiconductor inks
- Inorganic dielectric inks
- Polymer dielectric inks

Functional Nanomaterials
- Silver nanoparticles
- Gold nanoparticles
- Carbon nanotubes
- Carbon nanofibers
- Decorated carbon nanotubes
- Magnetic nanoparticles
- Novel catalysts for making carbon nanomaterials
Other Nanomaterials Developed at NanoMas Technologies, Inc.

NanoMas Nanomaterials
- Metal nanoparticles
- Compound nanoparticles
- Carbon nanotubes
- Carbon nanofibers
- Carbon nano/micro rods
- Decorated carbon nanofibers
- Zinc oxide nanowires

Potential Applications
- Functional inks
- Nanocomposites
- Biosensor
- Catalysis
- Fuel cells
- Biomedicine

Carbon Nanosprings and Nanoscrews
Multiwalled Carbon Nanotubes
Carbon Double Helical Nanofibers
Hybrid Metal/Carbon Nanostructures
Zinc Oxide Nanowires
Structured Carbon Fibers
Carbon Superstructures
Carbon Microrods
NanoMas Technologies, Inc. is an early stage start-up company, located in the Innovative Technologies Complex (ITC) on the campus of Binghamton University (SUNY) in Binghamton, New York, where is also the home of Center for Advanced Microelectronics Manufacturing (CAMM), funded by the USDC to lead the development of next generation roll-to-roll (R2R) microelectronics manufacturing.

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