Nanotechnology in Electronics Packaging, Interconnect, & Assembly: Becoming a Reality?

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Presentation Outline

• Introduction
• Application Opportunities
  – Packaging
  – Interconnect
  – Assembly
• Commercialization Strategies
  – Evolutionary
  – Revolutionary
• Reality or Hype?
Nanotechnology Fundamentals

Section 1

Nanotechnology?

- Study of matter on the scale of atoms & molecules
- 1 to 100 nm in at least one dimension

1D – Films           2D – Tubes       3D – Particles
How Small Nano?

<table>
<thead>
<tr>
<th>Water</th>
<th>Glucose</th>
<th>Antibody</th>
<th>Virus</th>
<th>Bacterium</th>
<th>Cancer cell</th>
<th>A period</th>
<th>Tennis ball</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>1</td>
<td>$10^2$</td>
<td>$10^3$</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Nanometers

- Nanodevices
- Nanopores
- Dendrimers
- Nanotubes
- Quantum dots
- Nanoshells

Human Hair ~100,000,000nm Wide
Nanotechnology Today

- Smaller
- Lighter
- Faster
- Stronger
- More Durable

Sound Familiar?

Convergence of Disciplines
Next Great Innovation?

Buckminsterfullerene Discovered (1985)

- 1996 Noble Prize in Chemistry awarded to Kroto, Smalley, & Curl
Atoms Manipulated by STM (1989)

- 2010 Kavli Prize in Nanoscience awarded to Don Eigler (IBM)

Carbon NanoTubes Discovered (1991)

- 2008 Kavli Prize in Nanoscience awarded to Sumio Iijima
What Makes Nano Interesting?

• Physical processes do not scale uniformly
  – Gravity
  – Friction
  – Combustion
  – Electrostatic
  – Van der Waals
  – Brownian
  – Quantum

What Makes Nano Interesting?

• Affects all materials
  – Metals
  – Ceramics
  – Polymers
  – Biomaterials
What Makes Nano Interesting?

- Nanotech materials exhibit remarkable new properties based on
  - Small dimensions
  - Large surface area
  - Novel structures
  - Unique combinations

Application Opportunities

Section 2
Carbon NanoTubes?

Figure 1. Dense Bundles of CNTs Grown in Contact Holes on Silicon Wafers

Source: IMEC

Nanotech Application Opportunities

- **Packaging**
  - Die Attach/TIMs
  - Flip Chip Bonding
- **Interconnect**
  - Additive Circuit Formation
  - Adhesives
- **Assembly**
  - Stencil Printing
Die Attach Materials

Table 3-1. Die Attach Materials by Package Technology

<table>
<thead>
<tr>
<th>Package Technology</th>
<th>Die Attach Material</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressed Alumina Ceramic (CERDIP)</td>
<td>Silver-Filled Glass</td>
<td>Inorganic Adhesive</td>
</tr>
<tr>
<td>Laminated Alumina Ceramic (PGA, CPFP, Side-Braze)</td>
<td>Gold-Silicon Eutectic Silver-Filled Cyanate Ester</td>
<td>Hard Solder Organic Adhesive</td>
</tr>
<tr>
<td>Molded Plastic</td>
<td>Silver-Filled Epoxy</td>
<td>Organic Adhesive</td>
</tr>
</tbody>
</table>

• Functions:
  – Mechanical
  – Electrical
  – Thermal

Conventional Die Attach Limitations

• High T Devices
  – Wide band gap power devices (SiC)
  – Hi-Bright LEDs
  – Higher melting point & thermo-mechanical properties

• Temperature Sensitive Devices
  – III-V photodetectors
  – Lower process temperatures
Nano-Based Alternatives

- Low Temp Sinter nano-Ag Paste
  - Sinters once surfactant volatilized
  - Highly reactive nano-Ag forms strong bonds
  - Several (pre)commercial sources

Source: NBE Tech

Nano-Based Alternatives

- screen printing of Ag paste on carrier sheet
- drying and expelling of solvents
- printing on chip using transfer method
- picking-up by stamp and placing onto substrate
- sintering (temperature, pressure, time)
Nano-Based Alternatives

• Modules for electrical power train of hybrid cars, fuel cell cars, ...
  • increasing power density / device temperature range
  • at high mechanical stress
  • no lifetime loss

• LTJT for
  • silver ribbon wires
  • diode and IGBT die-attach

Indium Corporation NanoFoil®
• Reactive multi-layer foil providing instantaneous heat
• Vapor deposited alternating nano-layers of Aluminum (Al) & Nickel (Ni)
• Activated by pulsed local energy (electrical, optical or thermal)
• Foil reacts exothermically precisely delivering localized heat up to temperatures of 1500°C in thousandths of a second
Nano-Based Alternatives

NanoFoil®
– Join components
– Melt adjoining solder layers
  • Without reflow temperatures
  • In air & at room temperature
  • No flux requirement
  • Fraction of a second
  • No reflow equipment

Nano-Based Alternatives

NanoFoil® Ignition
Nano-Based Alternatives

ORMET – Transient Liquid Phase Sintering

- Copper and alloy particles in a liquid organic formulation
- Sintered metal network

Source: Ormet

Nano-Based Alternatives

T reduction through nano-particle enhancement

Source: Ormet
Thermal Interface Materials (TIMs)

Flexible and conformity of carbon nanotube structures under an applied pressure minimizes air gap in the thermal interface and thus create higher thermal conductivity.

(a) One-sided Interfaces
(b) Two-sided and CNT/foil Interfaces

NTherma product: Lowest thermal resistance with CNTs are on both sides of the strip.

NStrip
Thermal Interface Materials (TIMs)

Flip Chip

- Reduced footprint
- Reduced profile
- Reduced inductance
- Underfill compensates for CTE mismatch
Conventional FC Limitations

- Fine pitch FC results in low stand-off solder bumps
  - Cu Pillars increase stand-off
- Alternative: Eliminate reflow
  - Sinterable nano-materials
  - Anisotropic conductive adhesives

Nano-Based Alternatives

- Focal Plane Array Assembly
  - Replace Indium (In) bumps
Nano-Based Alternatives

Focal Plane Array Assembly
- Nano-Ag low temp sinterable paste + Au pillars
- 32 μm pitch, 6 μm pads
- 15 μm pitch (next gen)
Nano-Based Alternatives

• Fraunhofer - Nano-Sponge
  – Highly compressible porous Au
  – Bonding at low T & low pressure
  – Electroplating silver-gold alloy + silver etching
  – Nano-Sponge bumps used for TC-Flip Chip bonding
Nano-Based Alternatives

Fine pitch Flip Chip with Nano-ACF

- 30um pitch silicon
- Copper pillar
- Nano-anisotropic conductive film
- Resistance comparable to solder for assembled & HAST tested assemblies

Conventional FC Limitations

- Underfill bottleneck
  - Slow capillary flow
  - Post-reflow batch cure

- No-flow variants
  - Require lower filler loading
  - Results in higher CTE
Nano-Based Alternatives

- Nanocomposite no-flow underfill
  - Self-fluxing no-flow polymer
  - 120 nm silica particles at 50% mass loading
  - No/minimal solder-pad bonding interference

Additive Circuits

- Applications include
  - Solar cells & batteries
  - RFID tags
  - Flexible displays & lighting
  - Novelties: talking and scrolling packages
Printed Conductor Limitations

Conductive Inks (Particle fillers)
- Ink curing generally requires temperatures over 400ºC
- Exceeds capability of low cost substrates
  - PET degrades rapidly above 100ºC

Nano-Based Alternatives

- Novacentrix - nano copper oxide ink
  - Print copper oxide ink
  - Reduce to Cu with an optical flash process
  - Inks formulated for Inkjet & Screen print
Nano-Based Alternatives

- IIMAK Graphene Ink
  - Electrically conductive carbon - graphene ink
  - Printed electronics applications
    - Membrane switches
    - Flexible circuits
    - Displays
    - Electroluminescent lighting
  - Screen print & dry to remove solvents, no cure

Tin Whiskers

- Conductive, crystalline “growths” from tin finishes
- System failure via short circuit
- No single accepted mechanism established
Conventional Mitigation Strategies

- Avoid pure Tin or Zinc
- Reduce stress in plated finishes
  - Hot solder dip
  - High temp anneal
  - Diffusion barrier (reduce intermetallics)
- Physical barriers (insulation)
  - Conformal coating
  - Increase spacing

Nano-Based Alternatives

- Tin Oxide Nano Particle Coating
  - Surface oxides removed from tin-plated copper
  - Tin oxide nano particles water solution sprayed
  - Annealed to regrow oxide
  - Hillocks formed instead of whiskers
  - Theory: Tin Oxide nano-particles relaxed stress
Nano-Based Alternatives

- **Rockwell-Collins - Nanocrystalline Coatings**
  - Alkali silicate glass containing nano ceramic particles $\text{Al}_2\text{O}_3 \text{ ZnO} 10-40\text{nm}$
  - Reduced whisker formation
- **Theory**: Nano-particles fill cracks in Tin that produce whiskers

Nano-Based Alternatives

**Lockheed-Martin - Lead Free Solder**
- Printable Nano-Copper paste fuses at 200°C
- Cu surface eliminates danger of whiskers
- Commercialization research at NTU (Singapore) in JV with LM
Nano-Based Alternatives

- Johns Hopkins – Nano-Texturization
  - Grain refining additives during electroplating
  - Tin over Polycrystalline Cu – whiskers
  - Tin over Nano-Cu – no whiskers
- Theory: Additives regulated tin stresses

Conductive Adhesives

- Solder replacement
- Metal-filled composite
- Usually thermoset
- Used commercially for SMT & Flip Chip
Conventional Adhesive Limitations

- **Cost**
  - Precious metal loading

- **Conductivity**
  - Filler packing

Conventional Adhesive Limitations

- Open circuits
- Short circuits

Source: Kaist
Nano-Based Alternatives

Nanoparticle impact
- Addition of nanoparticles forms additional bridges between conventional filler flakes
- Increases density of the conductive net
- Bimodal filler maintains good conductivity even at lower total filler loading
- Nano-particle reaction increases current capacity as well as conductivity

Nano-Based Alternatives

• KAIST – Nanofiber anisotropic ACF

1. Fundamentally prevent conductive particles flow
2. Insulate particles one by one
Nano-Based Alternatives

- KAIST – Nanofiber anisotropic ACF

Uniform PAN nanofibers coupled with conductive particles were made by an electro-spinning process.
- Fiber diameter: 457 ± 48 nm.

Stencil Printing

1) Alignment, gasketing of apertures to Pads
2) Squeegee motion thins paste so it flows into apertures
3) Paste recovers; stiffens up
4) Stencil separates from PWB, paste deposits release from stencil onto pads
Conventional Stencil Limitations

Nano-Based Alternatives

Nano-coated Stencils
- Nano-coatings on stencil bottom & aperture walls
- Nano-coating treatment follows etching/laser-cutting of stencil apertures
- Enhanced paste release from stencil apertures
Nano-Based Alternatives

Stencil bottom side, after 5 prints without cleaning (QFP 500µm)

Passive Components

- Essential to all electronic systems
- System miniaturization
  - Need smaller footprint & profile passives
- Speed & frequency increase
  - Need higher value capacitors
- Translates to demand for ultra-high dielectric constant materials
Nano-Based Alternatives

- Nano-Composite Dielectrics
  - Matrix (often polymer) with nano-sized filler
  - Example Barium titanate (ceramic dielectric)
    - High dielectric constant
    - Poor resistance to breakdown
    - Complex, high temperature processes
  - Nanoparticles of BaTiO$_3$ dispersed in polymer
    - Encapsulated prevents aggregates

Source: Georgia Tech

Nano-Based Alternatives

- Apricot VNE™ Technology
  - Metal coated ceramic particles shrink & coalesce during MLCC firing
  - Metal coatings coalesce
    - Increase apparent surface area
    - Reduce apparent dielectric thickness
    - Significant capacitance increase
  - Fully compatible with MLCC production

Source: Apricot Materials, Alan Rae
Nano-Based Alternatives

- Resin-coated copper capacitive (RC3) nanocomposite
  - Ferroelectric-epoxy nanocomposites
  - Bulk decoupling capacitance
- Reported by Endicott Interconnect Technologies

3D Printing

- No longer exclusive to hobbyists & hackers
- Commercial applications include
  - Rapid prototyping
  - Rapid manufacturing
  - Mass customization
- R&D applications include
  - Chemistry – creating novel compounds
  - Medicine – artificial organs & prosthetics
3D Printing Limitations

• Original 3D printers used thermoplastics
  – Applied in successive 2D layers
  – Fully additive process
• Plastic lacks rigidity & strength
• Plastic unsatisfactory “scaffold” for biologics
• Plastic nonconductive

Nano-Based Alternatives

• Electro-chemically active inks
  – 3D print micro batteries
  – lithium metal oxide compound nanoparticles
  – Inks for anode & cathode
Nano-Based Alternatives

Direct printed additive packaging

- Direct print
  - CNT composite substrate (1)
  - Interconnect (3)
- Pick & Place conventional components
- Direct print
  - Conductive adhesive (4)
  - Encapsulant (2)

Ke Sun, Teng-Sing Wei, Bok Yeop Ahn, Jung Yoon Seo, Shen J. Dillon and Jennifer A. Lewis
Lewis Research Group, Harvard University

Note: 3D interdigitated microbattery architecture (3D-IMA) is fabricated by printing concentrated lithium-ion inks
Nano-Based Alternatives

Completed test circuit built with direct print additive packaging

Commercialization Strategies

Section 3
Evolutionary

Section 3a

Evolutionary = Minimum Risk

• Incremental improvements to an established technology
Evolutionary = Minimum Risk

- “Drop in” solutions
  - e.g. nano coated stencils
- Understood by current customers
- Compatible with infrastructure
  - Supply chain
  - Equipment & processes
  - Specs & standards
- Favored by established vendors

Evolutionary ≠ Zero Risk

- Value capture difficult
  - Customers challenge price increases
  - Efficiency good for user but not vendor
- Improvement may not be “good enough”
  - Incumbents advance as well
- Startups & new entrants at substantial disadvantage
Revolutionary

Section 3b

Revolutionary = Disruptive

New technology that unexpectedly displaces an established technology
  - Lacks refinement
  - Often introduces performance problems
  - Appeals to a limited audience
  - May not yet apply to a proven practical application
Incumbents Often Dismiss Disruptive Innovation

Winning Disruptive Innovations

- Telephone vs telegraph
- Steam locomotive vs diesel electric
- Solid state electronics vs vacuum tubes
- Mini-mills vs integrated steel producers
- Digital cameras vs film
- Amazon vs brick & mortar bookstores
- Streaming Media vs iTunes vs compact disks vs records
Value Recognition Critical

- Unrecognized value
  - Threat
  - Lack of a response is a response
- Recognized value
  - Opportunity
  - Rapidly reconfigure value chain
  - Integrate innovation into manufacturing

Disruptive Innovation Challenges

- Extensive qualification necessary
- Standards & specs don’t exist
  - Standards bodies require critical mass
- Inertia: Resistance to change
  - Fault finding vs credit taking
Disruptive Innovation Opportunities

- Redefine value chain
  - Capture more value
- Advantage - Startups & New Entrants
- Customer pull vs market push

Nanotechnology: Reality or Hype?
Section 4
Reality or Hype?

Exaggerated & Over-promised
- Widespread misinformation
- Scientists exaggerate anticipated benefits to justify funding
- Alarmists peddle doom-&-gloom prophecies advancing their own agendas

► Hype
Reality or Hype?

Provides vital performance enhancements
- Electronics packaging, interconnect, & assembly
- Evolutionary & revolutionary advances
- Commercially available today
- Exciting & promising R&D in progress

► Reality

Reality or Hype?

► Both

• Challenges
  – Separate the light from the heat
    • Identify
    • Communicate
  – Capitalize on low-risk evolutionary paths
    • Low hanging fruit
  – Exploit disruptive innovation carefully
    • Recognize opportunity & value
Reality or Hype?

Hype Cycle Indicators

Thank You!!

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