Nano-Packaging : Hype, Hope or Happening?

Are We Truly Solving Today's Big Packaging Problems with Nano-Technology*?

Ravi Mahajan, Chris Matayabas, Nachiket Raravikar

ECTC, May 26, 2015

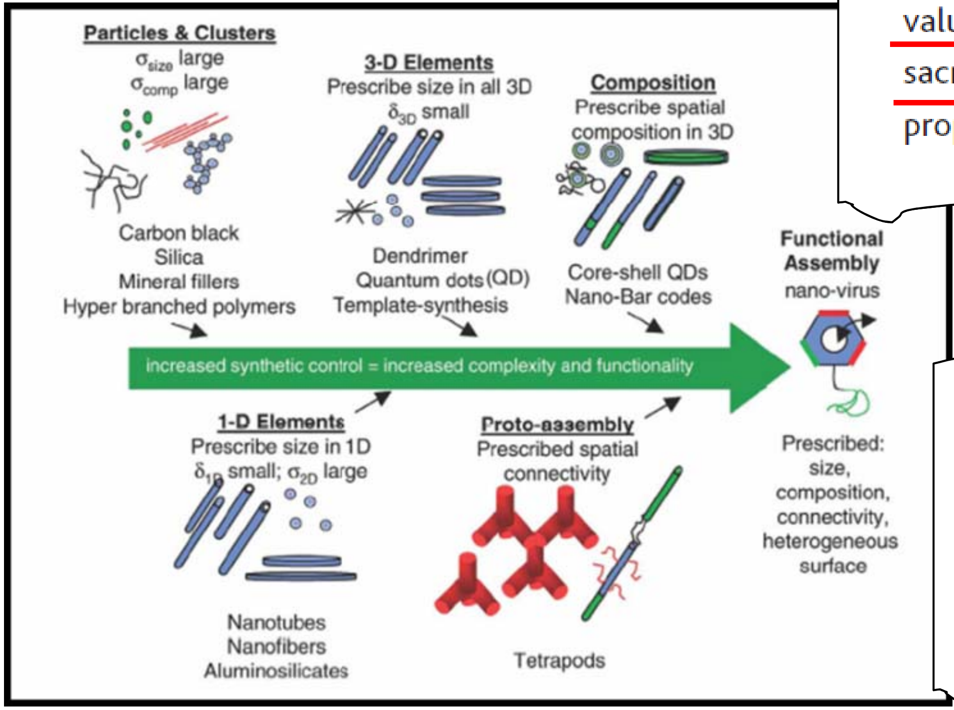
* Focus mainly on Nano Composites where 1 or more relevant dimension is ≤100 nm and where structure-properties of materials differ significantly from their bulk counterparts

More than a decade ago…….
Nano Technologies Showed Promise of New Ways of Solving Chronic Problems in Packaging……

Polymer Nano Composites : A New Class of Organic Materials

PNCs (Polymer Nano Composites)

technology. Rather, its importance comes from providing value-added properties not present in the neat resin, without sacrificing the resin's inherent processibility and mechanical properties, or by adding excessive weight. Traditionally, blend

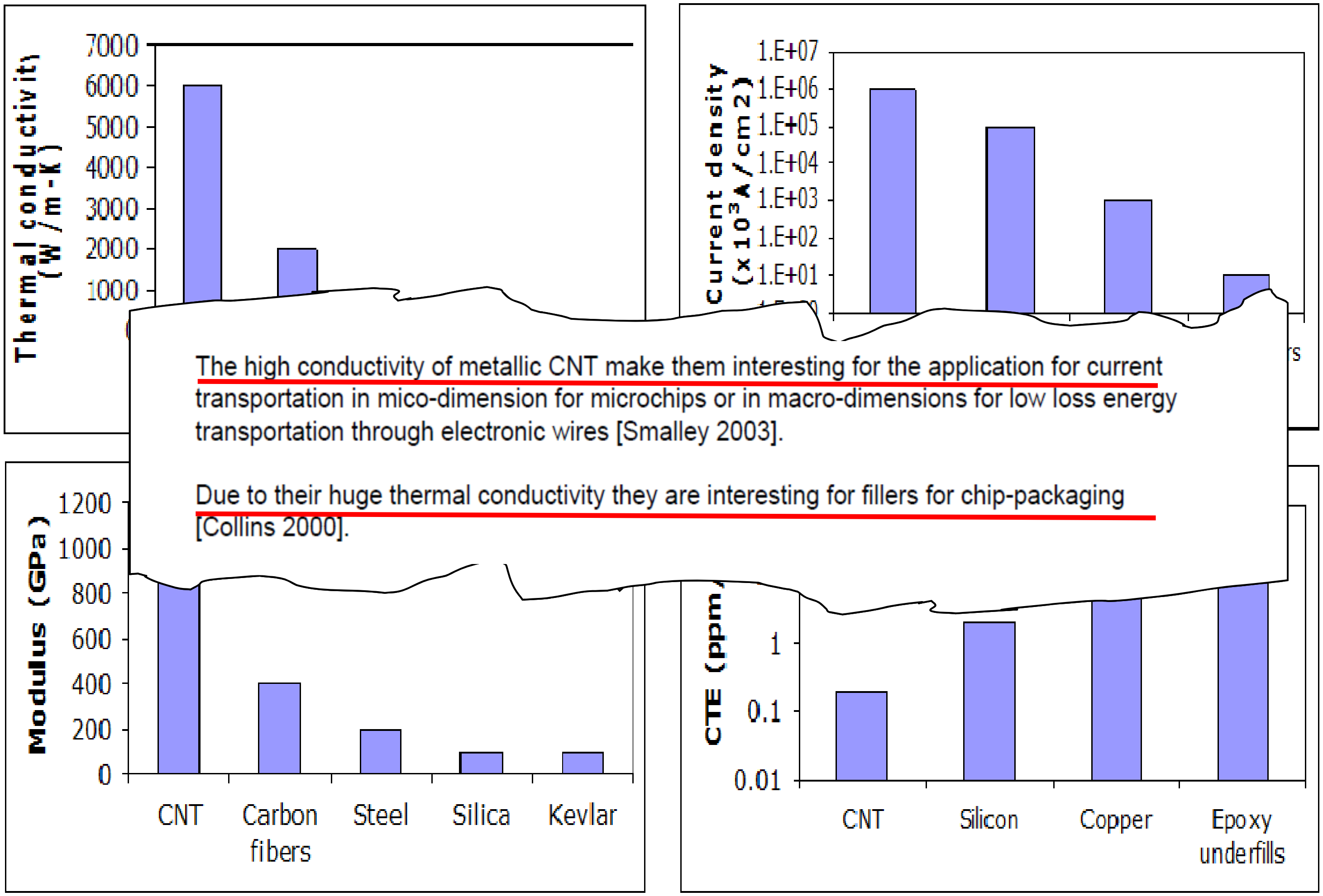


Source: R. A. Vaia & D. Wagner, Materials Today, 32-37 (Nov. 2004).

Considering the plurality of potential nanoparticles, polymeric resins, and applications, the field of PNCs is immense. For example, Fig. 1 presents a hierarchy of nanoparticles based on increasing functionality and thus, the potential to increase the functionality of the polymer matrix.

Packaging Opportunity: New, Tougher UF & Mold Materials without loss of processability, New Dielectrics with tailored properties……….

Fillers



The high conductivity of metallic CNT make them interesting for the application for current transportation in mico-dimension for microchips or in macro-dimensions for low loss energy transportation through electronic wires [Smalley 2003].

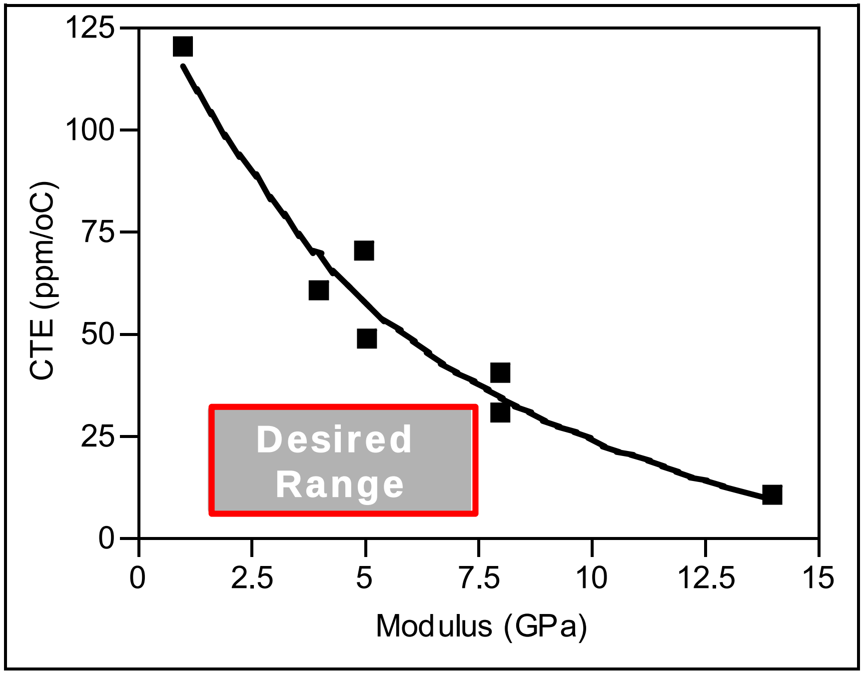
Due to their huge thermal conductivity they are interesting for fillers for chip-packaging [Collins 2000].

Packaging Opportunity : CNTs - Perfect fillers for better electron/ phonon transport and improved organic composite toughness

Can Nano-Technology Improve Mechanical Properties of Epoxies Used in Today's Packages?

Epoxy Mechanical Property Control

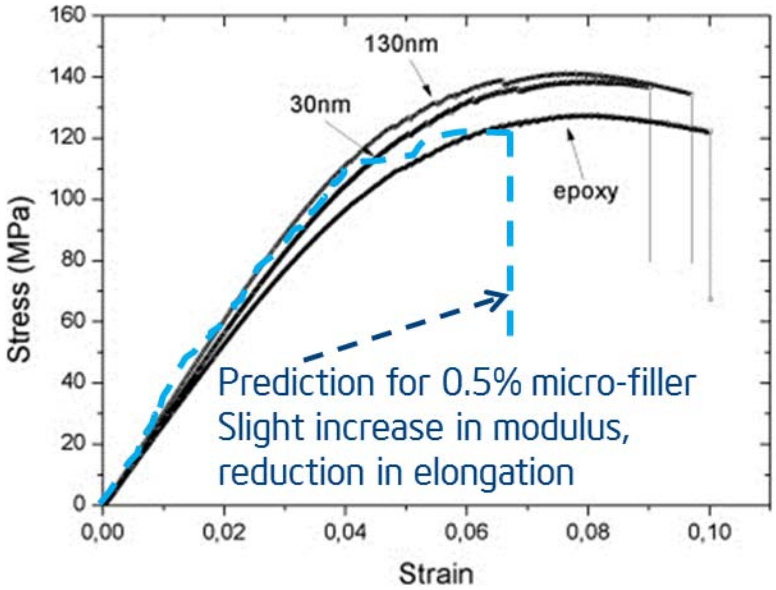
- Today, epoxy properties are controlled by addition of micron-sized fillers.
  - Modulus and CTE are strongly coupled in current polymer composites
  - New technologies are needed to achieve epoxy materials with low CTE and low modulus.
- Can PNCs be used to decouple CTE and modulus, and increase flexibility in materials ?



Modulus vs CTE for a variety of epoxy formulations with micro-fillers

Surface treated Nano-silica Epoxy Composites

- Conradi et al, *Materials Chemistry and Physics*, 137(3), 910 [2013]
- Blue dotted line Intel addition
- Surface treatment: Diglicydyl ether of bisphenol A



Prediction for 0.5% micro-filler
Slight increase in modulus,
reduction in elongation

Configuration	E [GPa]	UTS [MPa]	Elongation at break [%]	K_{IC} [MPa $m^{1/2}$]	Impact energy [J]	Impact resistance [kJ m^{-2}]
Epoxy	**2.6**	**127**	**10.0**	**0.66 ± 0.05**	**0.19 ± 0.02**	**6.4 ± 0.7**
Epoxy + 0.5 vol% 130 nm SiO_2	**3.0**	**141**	**9.6**	**0.91 ± 0.06**	**0.26 ± 0.02**	**8.9 ± 0.6**
Epoxy + 0.5 vol% 30 nm SiO_2	**2.8**	**138**	**9.0**	**0.93 ± 0.06**	**0.33 ± 0.03**	**10.8 ± 0.7**

PNCs Show Promise @ low filler loadings. Can Increased Filler Loading Get us the properties we want?

Epoxy PNC Properties with increasing Filling %

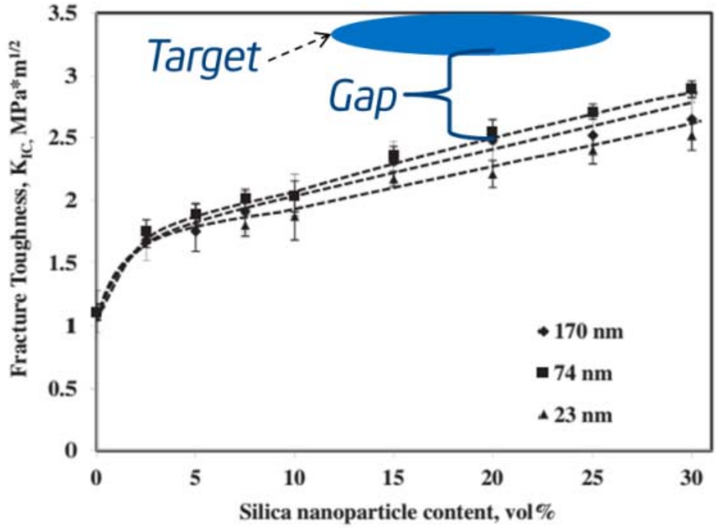
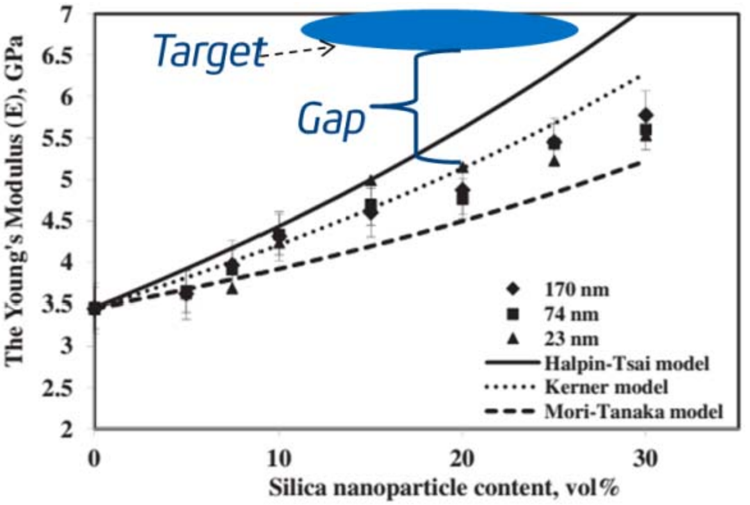
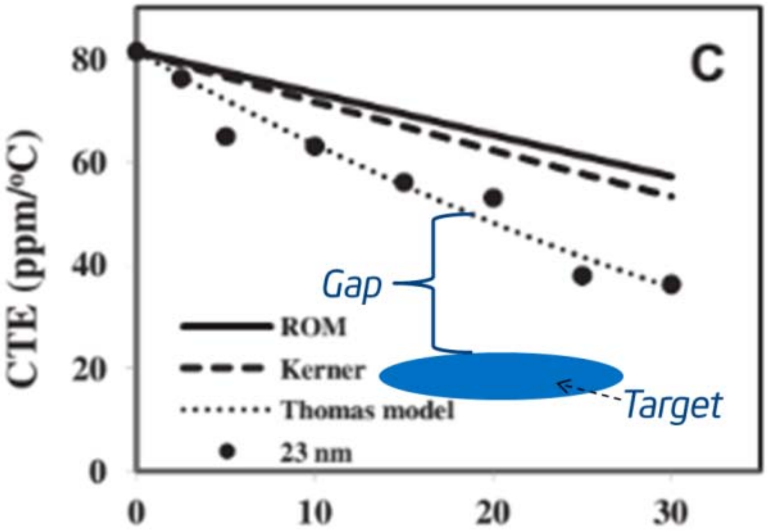


Fig. 4. The fracture toughness (K_{IC}) of r
content compared for different sizes of s



redictions and experimental data for the
as a function of filler content compared at

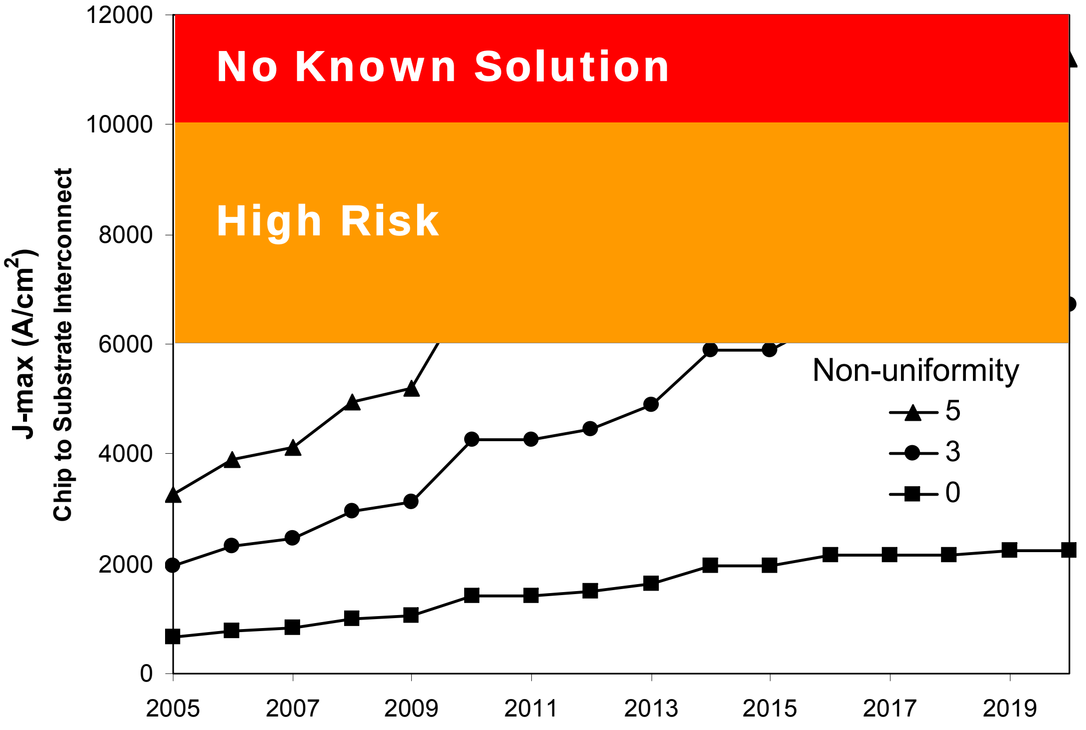


Dittanet et al, Polymer, 53, 1890 [2012]

Is Even Higher Nano-filler loading the path to achieving E & K_{IC} Targets ?
Will increased filler loading compromise cost and processability?

Can Nano-Technology to Improve Transport Properties of Today's Packaging Materials?

Current Transport

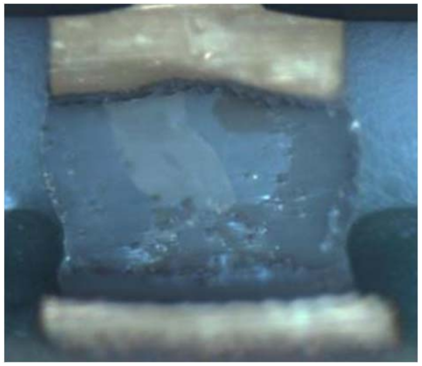


ITRS 2005 Roadmap for Cos
performance CPU's.

- No known J-max solution for solder J-max > 10^4 A/cm^2.
- Solders to enable J-max up to 10^5 A/cm^2 needed for high power, fine pitch chip-substrate interconnect

Packaging Opportunity : Nano-(Filled/Structured) Solders to Improve J-Max

Nano Solders : Needs, Current Status


SnCu interconnect with large grains

Grain refinement of alloys

- Improves both strength and toughness
- Improves J-max capability of interconnects

Current Status

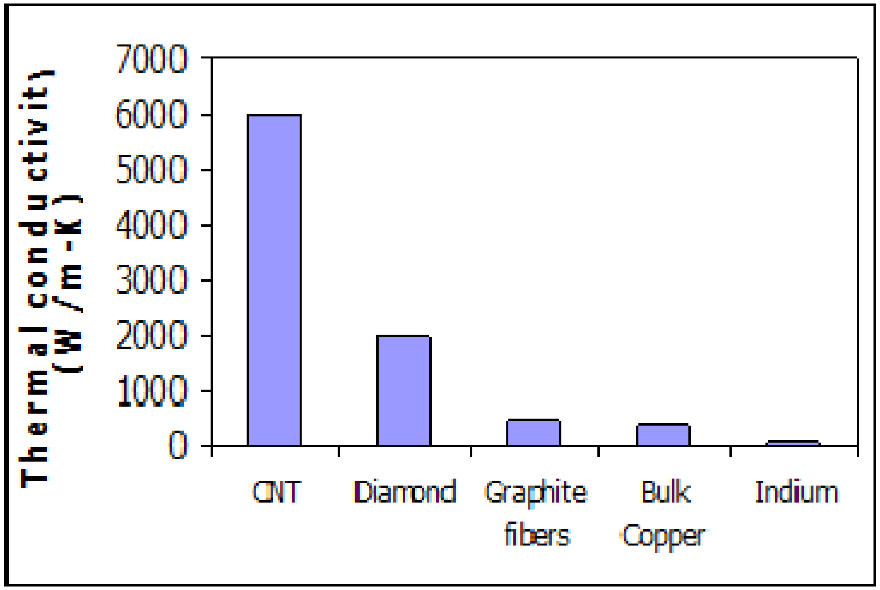
Improvements have been demonstrated but We are not there yet……..

- Demonstrated grain refinement down to 100nm by thermal mechanical processing, but has manufacturability barriers to implementation. [Guo, Zhen, and Tan, Li. Fundamentals and Applications of Nanomaterials. Norwood, MA, USA: Artech House, 2009.]
- For example, the “Roadmap Report Concerning the Use of Nanomaterials in the Aeronautics Sector” has grain refined metals as “unspecified” in their 10 year roadmap [http://www.aimme.es/archivosbd/observatorio_oportunidades/roadmap_report_nan

Multiple solder reflows during Assembly often reset the grain structure
We still need Nano-Composite Technologies that stabilize grain structure thru Multiple Reflows

Thermal Transport

- Carbon [or BN] nanotubes have highest conductivities of any known material
- Creates anticipation of new thermal and interconnect materials.
  - Promise has not been realized yet due to high interfacial resistance (nanotube to polymer/metal).



Source: R. S. Prasher, et al., *Intel Technology Journal*, Volume 9, No. 4, page 285-96 (2005).

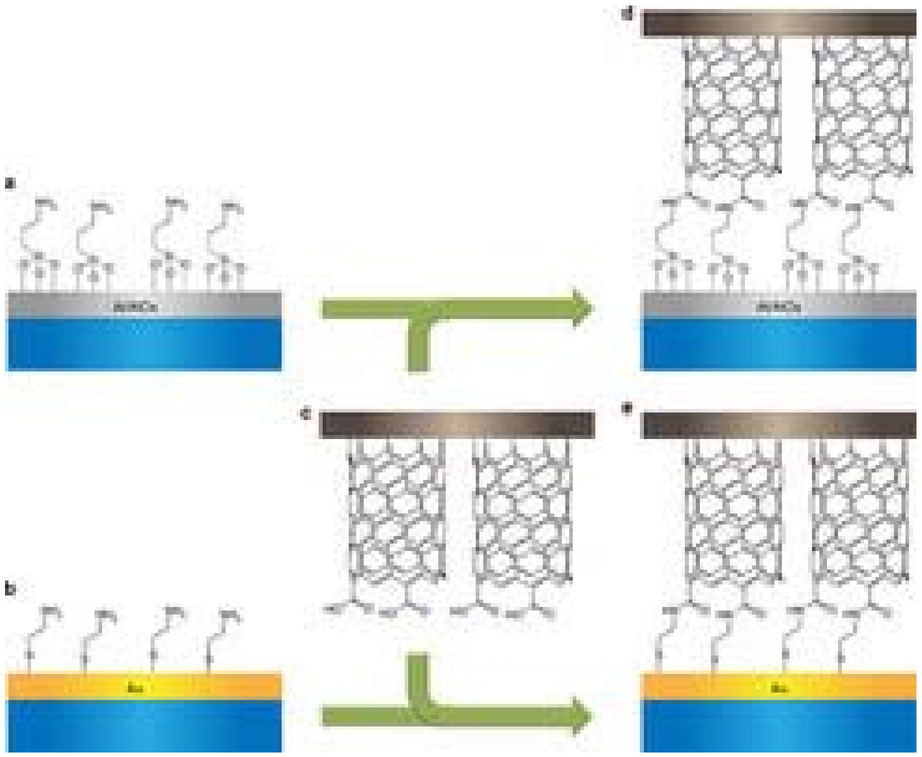
$$k_{composite} = f\left(\frac{R_{particle-to-matrix}}{d_{particle}}\right)$$

$R_{particle\text{-}to\text{-}matrix}$ must proportionally scale with $d_{particle}$ reduction for nanomaterials.

CNT $R_{particle\text{-}to\text{-}matrix}$ ~ 5E-6 m2K/W. Need $R_{particle\text{-}to\text{-}matrix} < 2E\text{-}8\ m^2\ K/W$

Thermal transport through covalent functionalization of nanotubes

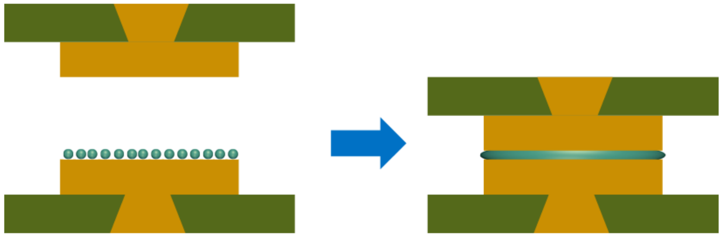
Kaur et al, Nature Communications, 5, 3082 [2014]



‘R’ of functionalized CNT-Si ~ 7E-7 m2K/W…
Much lower than the ‘dry contact’ CNT-Si ~ 3.5E-6 m2K/W!
Still almost an order of magnitude greater than the ‘target’ of < 2E-8 m2K/W!

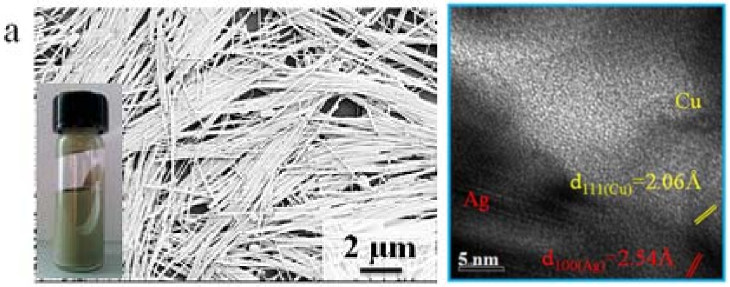
Can Nano-Technology to Enable Low Temperature Assembly?

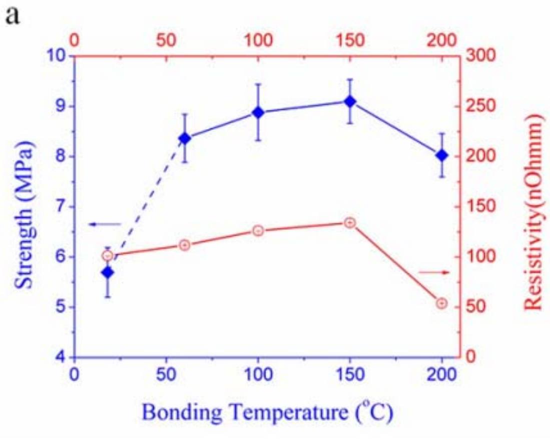
Cu to Cu Bonding : Current Status



Researchers have demonstrated low temperature Cu-Cu bonding using nanomaterials. Examples

- Au nanoparticle bonding [N. A. Alcantar, et al., Acta Materialia 51 (2003) 31–47]
- Ag nanoparticle bonding [Y. Akada, et al. Materials Transactions, Vol. 49, No. 7 (2008) pp. 1537]
- Ag nanowire bonding [Peng Peng, et al., Scientific Reports, 5 : 9282, March 2015]





but there are barriers to Implementation

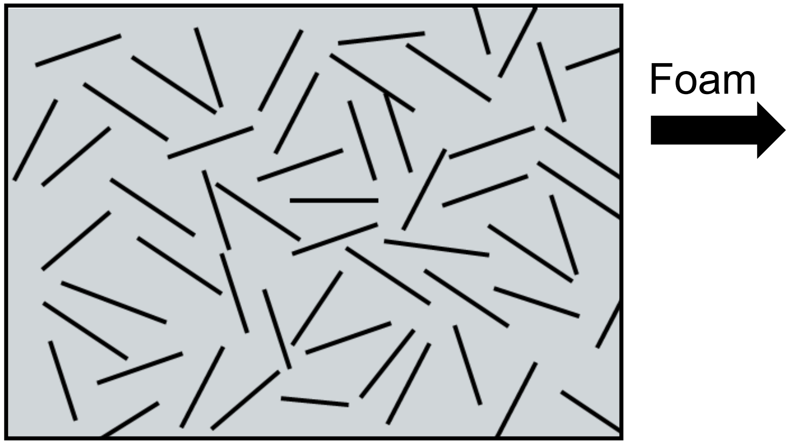
- Requires atomically smooth surfaces and high coplanarity
- Gives bond line thickness < 100 nm

Opportunities for Creating Nano Composites for Micro-Scale Problems

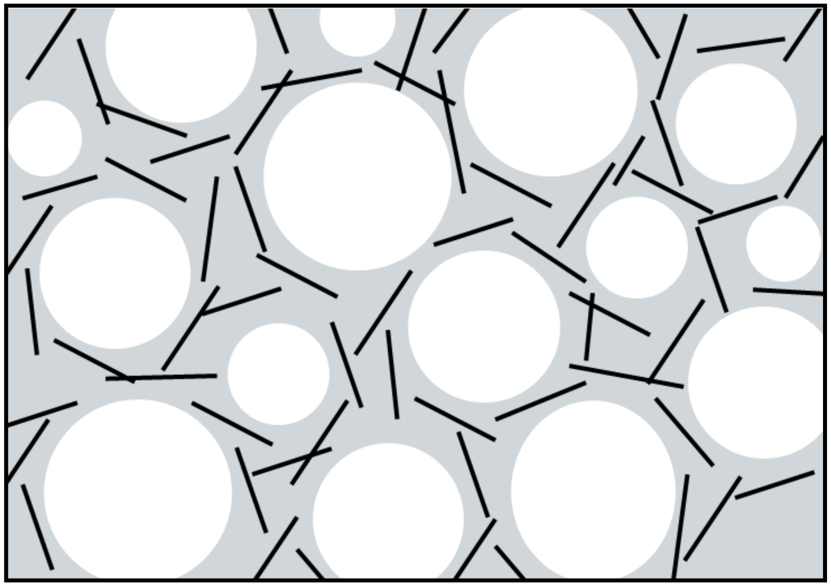
Foam Structured Nano Composites

Foaming is an example of manufacturing process to form 3D materials

- Electrical conductivity of PMMA comprising graphene nano platelets increased by 7 orders of magnitude with increasing volume expansion by CO2 foaming. [M. Antunes, et al, Journal of Nano Research Vol. 26 (2014) pp 63-74]



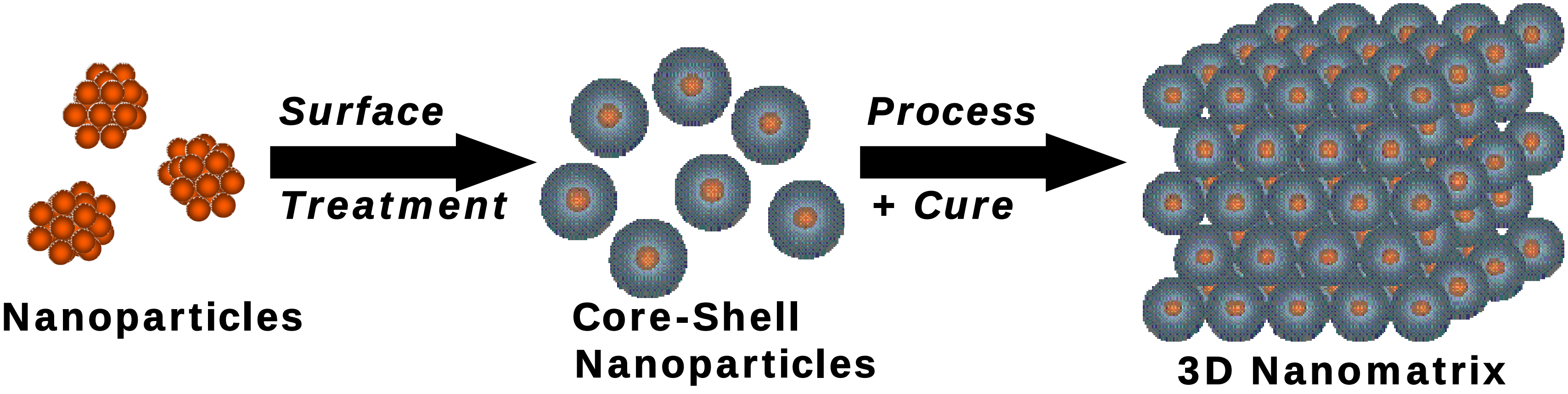
Conductivity ~10^{-14} S/cm at <0.10 vol% CNT



Conductivity ~10^{-7} S/cm at <0.10 vol% CNT

Need brainstorming and further research on ways to use foaming and related manufacturing processes to increase electrical and thermal conductivity of CNT composites to values of interest

Synthesis of 3D Nanomatrix Materials



Leverage unique properties of nanomaterials in 3D assemblies

- Comprises nanoparticle core and polymer shell.
- Liquid / paste with thermal cure is preferred.

New class of materials

- Titania/PS Core/Shell Assembly: High dielectric constant materials prepared by emulsion precipitation of titania rods (19nm x 4nm), surface treatment with PS oligomer (Mw 8400), then spin coated film [A. Maliakal, et al., J. Am. Chem. Soc., 127 (42), 14655 -14662 (2005).]
- Alumina/PMMA/PU Core Shell Assembly: Material prepared by emulsion processing with in situ formation of alumina-rich core, PMMA-rich shell, then PU shell. Particles were

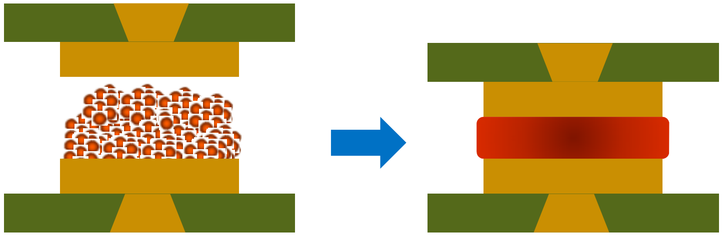
Need more research on 3D Nano-matrix materials tied to real world problems

Nanotechnology, 16, 1950-1959 (2005).]

Nano Composite Paste Bonding

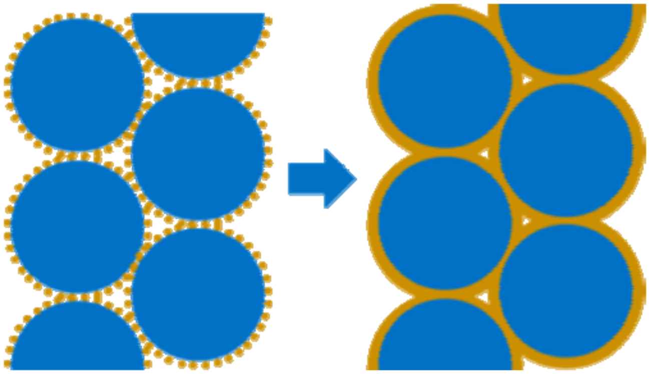
To be useful for assembly, the nanopaste concept needs to be modified

- Ability to adapt to die and substrate dynamic warpage during assembly of > 50 um, and resulting into a minimum bond line thickness > 10-20 microns
- Bonding die to substrate with as-plated roughness



One <u>possible</u> solution is a (Nano + Micro) Composite paste

- Micron size Cu particles
- Au or Ag nanoparticles
- Curable flux that controls the reaction



Bridge the scale by repeating the nano scale bonding

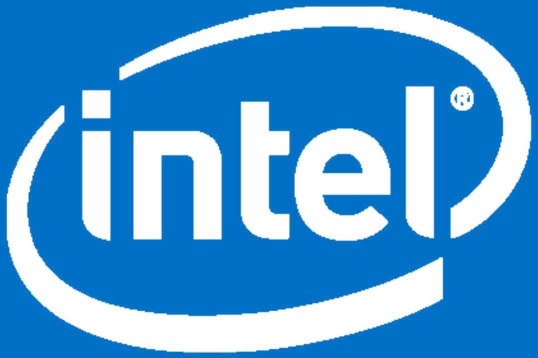
Need researchers to bridge the nano to micro scale by developing Innovative Solutions like (Nano + Micro) Composite pastes

Key Messages

- Potential of Nano-technology has not **yet** translated into meaningful solutions at the Micro-scale (where all the packaging issues really are!!!)
  - Need clever ways to bridge the length scale between nanotechnology and bulk materials
- Some part of Research in Nano Materials must focus on practical realization of the promise of Nano-technology
  - Some ideas on reducing percolation threshold and interface resistance demonstrated in literature, however, still a lot of fundamental engineering, integration challenges need to be addressed before realizing Nano Ingredient Based Composites for thermal or electrical transport applications

To get back to the question asked in this panel…..

Is Nano-Packaging	
Hype,	I am too polite to say yes
Hope or	Well…….I am hopeful ☺
Happening?	Not as Fast as I would like


intel®