Material Requirements For 3D IC and Packaging

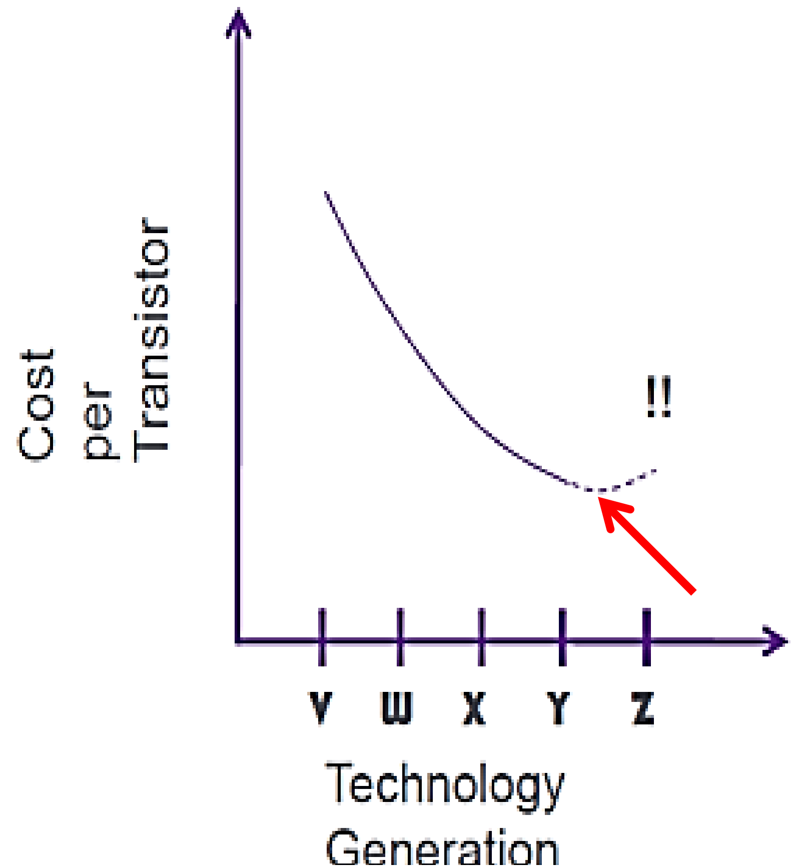
Presented by: W. R. Bottoms

Frontiers of Characterization and Metrology for Nanoelectronics
Hilton Dresden April 14-16, 2015

Industry Needs Are Changing

- ✓ Moore's Law is reaching limits of the physics
  - – Scaling can no longer support the pace of progress
  - – Power requirement and performance no longer scale with feature size
- ✓ Electronics Industry Drivers have changed
  - – Mobile wireless devices, IoT and the Cloud are driving future demand
- ✓ Electronics are entering every aspect of our lives
  - – Each area has unique requirements

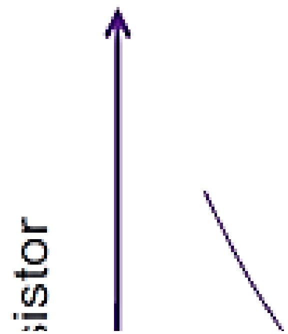
Moore's Law Scaling Is Nearing Its End



Global Foundries

You know it's really "the End" When scaling to the next node increases cost

Moore's Law Scaling Is Nearing Its End



Scaling Can help but it cannot be a major component of the solution to these challenges

Technology
Generation
Global Foundries

You know it's really "the End" When scaling to the next node increases cost

New Technology Drivers Are Emerging

Emerging Technology Drivers

There are 2 market driven trends forcing more fundamental change on the industry as they move into position as the new technology Drivers.

- ✓ **Rise of the Internet of Things**
- ✓ **Data, logic and applications moving to the Cloud**

Over the next 15 years almost everything will change including the global network architecture and all the components incorporated in it or attached to it.

The Internet of Everything
Driven by Human Communication and Machines

Smart Homes

Smart Cities

Everything connected

Sensors Everywhere

Smart transportation

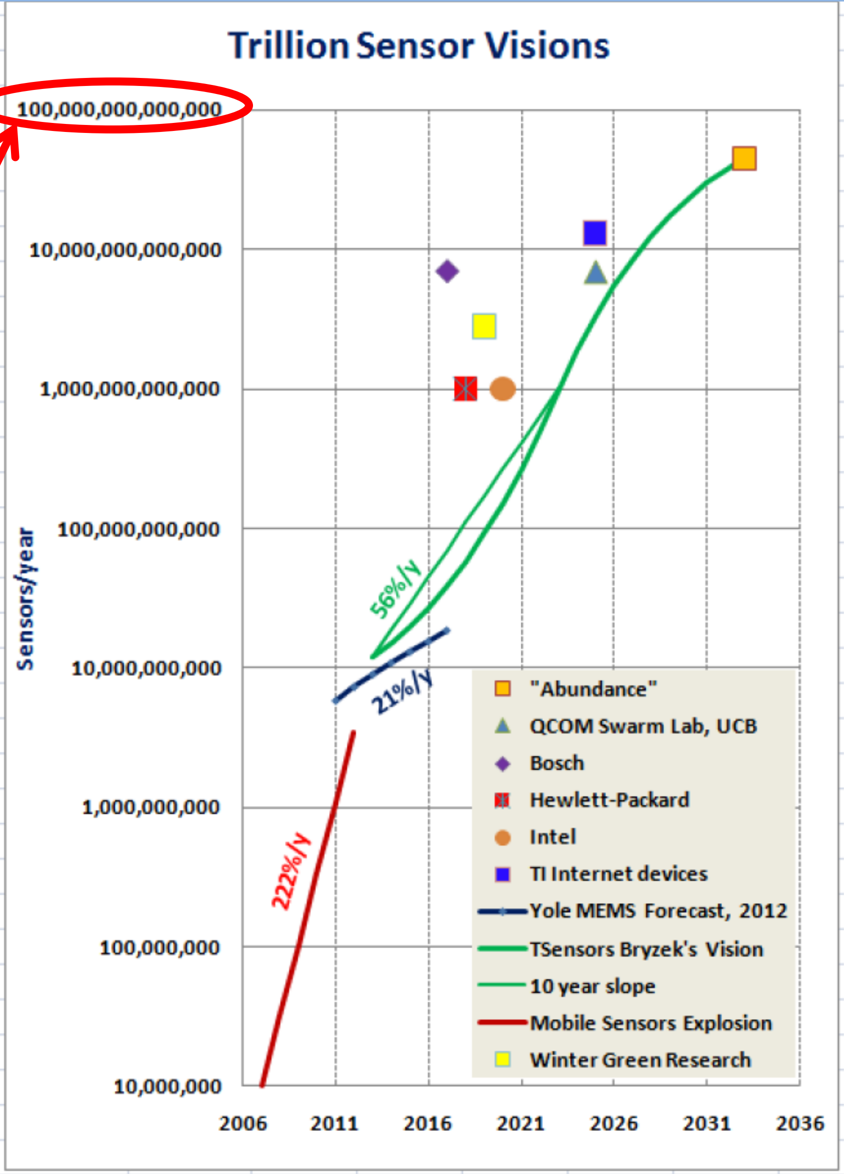
The past 25 years of internet growth was fueled by human communications. The next 25 years will be fueled by machines- much of it by IoT

IoT With Trillions Internet Connected Sensors

The projected growth is likely to be driven by applications yet to be imagined:

- ✓ Medical
- ✓ Industrial
- ✓ Agricultural
- ✓ ????

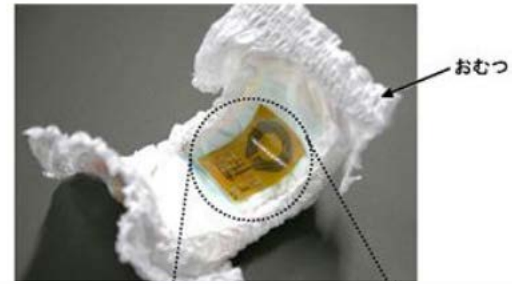
100 Trillion

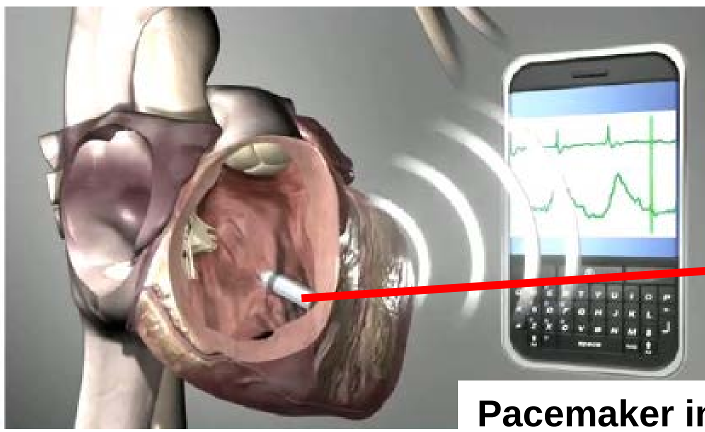


New Connected Products Are Coming

Even diapers will be connected

– 40M/day in the US alone

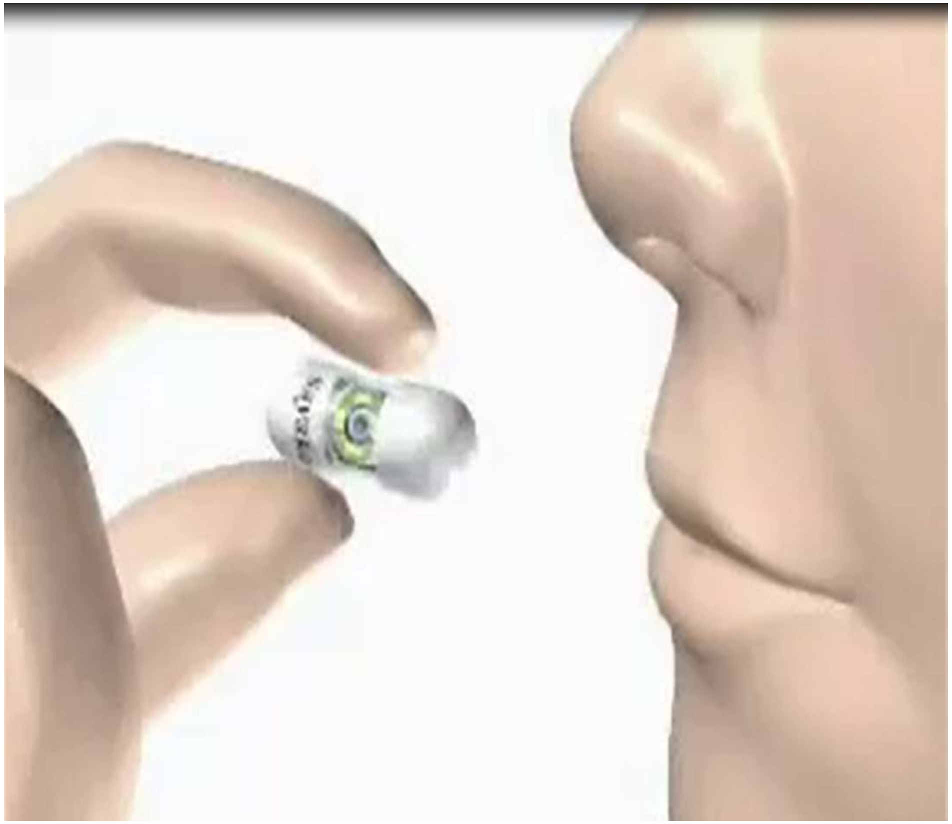




Pacemaker ir
heart
With smart pl

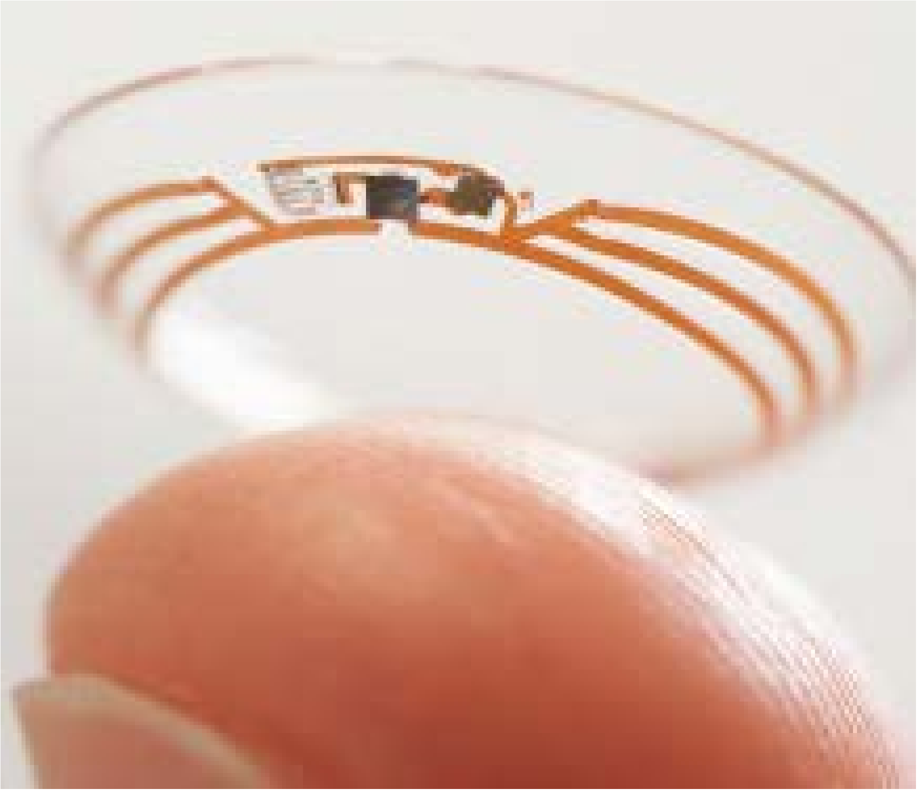
Many connected prc
and through Smart p

IoT Medical Devices



Next Generation Endoscope

Contact Lens with intelligence and control



What will we have in 15 years?

Source: https://sites.google.com/site/ism6021fall2011/telepresence-is-finally-coming-of-age

Migration to the Cloud
Data, logic and Applications

Driving Change in The Global Network

Data Traffic Drives Network Requirements

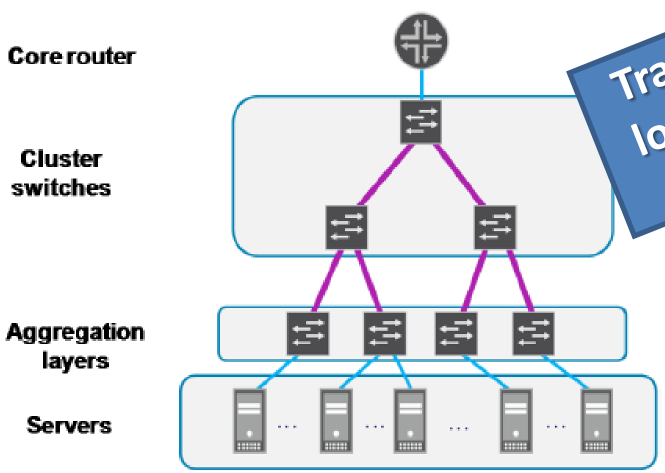
Changes driving data traffic:

- ✓ Global IP traffic will pass 1.4 Zettabytes (10^{21}) by 2017
- ✓ Wireless traffic will surpass wired traffic by 2016
- ✓ The number of mobile-connected devices first exceeded the number of people on earth this year
- ✓ IoT growth will drive demand for bandwidth
- ✓ Data, Logic and Applications are migrating to the Cloud

Today packaging is a limiting factor in cost, performance and size.

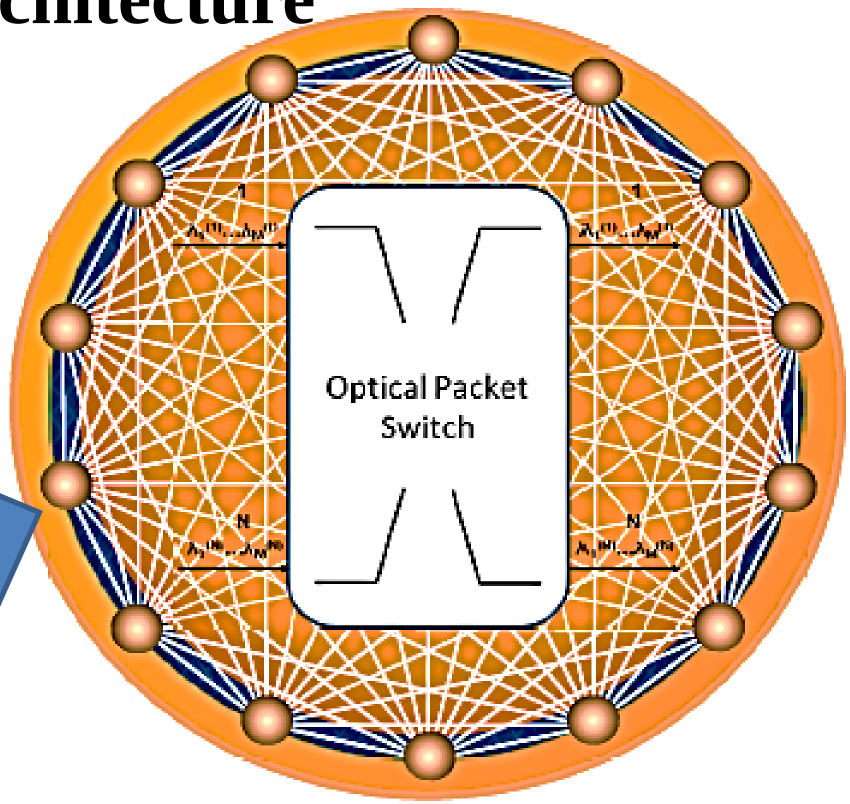
The Network Architecture Must Change Globally and Locally

- ✓ Higher connectivity Flat Architecture
- ✓ Higher bandwidth per port
- ✓ Lower end-to-end latency
- ✓ Lower power
- ✓ Lower cost



Traditional Hierarchical Tree Topology

Transition to lower Power & latency



Flat Network Topology

The Network Architecture Must Change Globally and Locally

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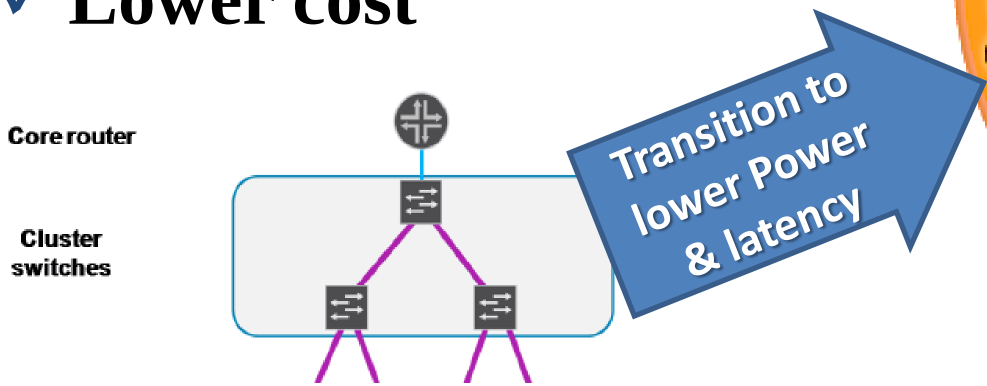
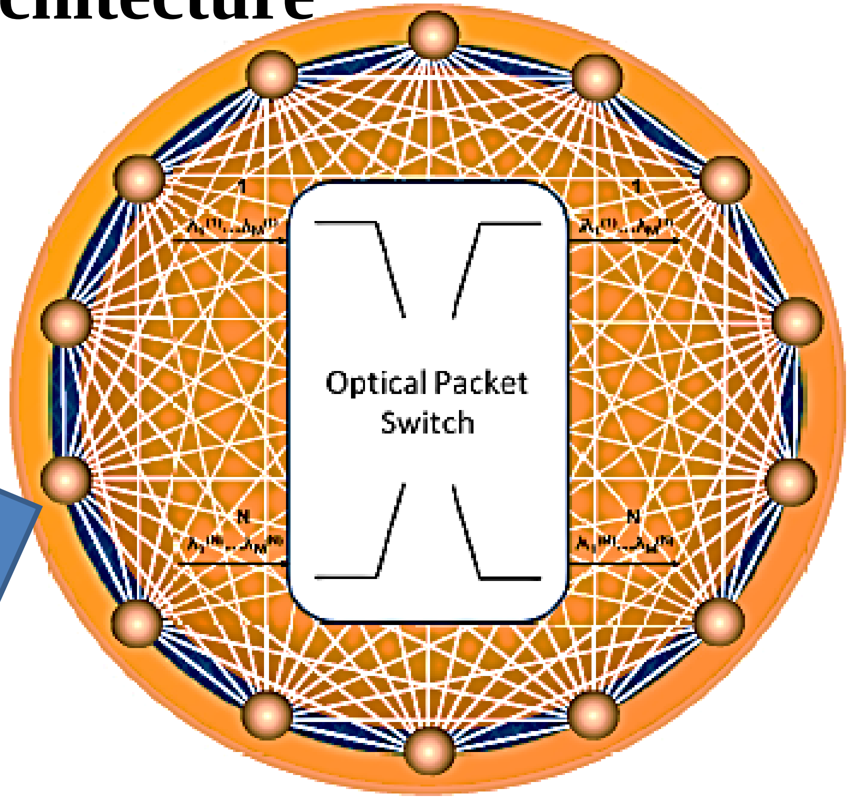




Photonics to the Board, package and even chip level may be required.

The Network Architecture Must Change Globally and Locally

All this is needed at *no increase in total cost and total Network power*.

Power and cost/function need *>10⁴* improvement over the next 15 years.

The Major Challenges to Achieve this vision include:

- ✓ **Power**
  - Delivery in complex 3D packages
  - Integrity at low operating voltage
- ✓ **Latency**
  - In the package, on the Board, in the global network and everything in between
- ✓ **Thermal management**
  - At die, package and board level
- ✓ **Bandwidth density**
  - At the die, in the package and on the board
- ✓ **Cost**
  - Initial cost, cost of power and cost of reliability in a world where transistors wear out

The Major Challenges to Achieve this vision include:

- ✓ **Power**
  - Delivery in complex 3D packages
  - Integrity at low operating voltage
- ✓ **Latency**

We must move photons closer to the ICs and all other things closer together

  - At the die, in the package and on the board
- ✓ **Cost**
  - Initial cost, cost of power and cost of reliability in a world where transistors wear out

Only a Revolution in Packaging can satisfy these diverse Needs

At the leading edge everything will change.
This requires:

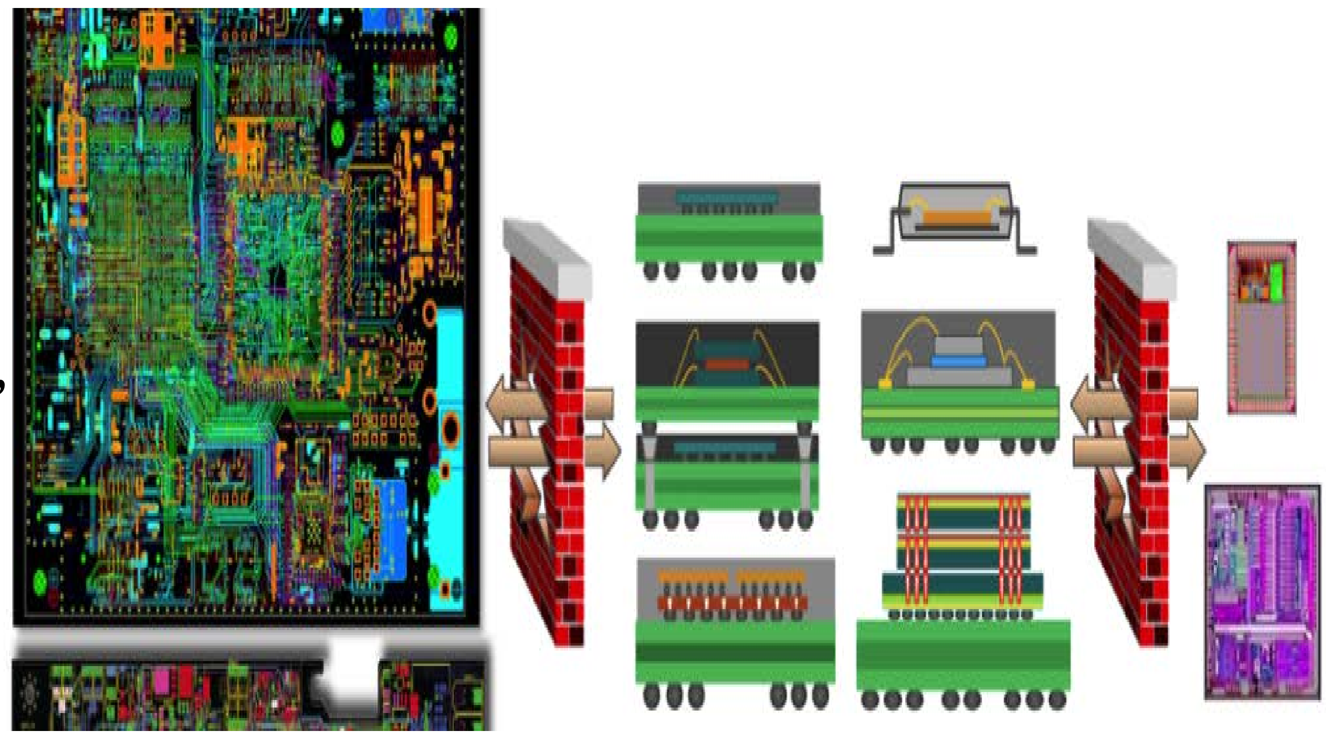
- ✓ New co-design and simulation tools
- ✓ Use of the 3rd dimension
- ✓ Heterogeneous Integration
- ✓ New materials
- ✓ New device designs and architectures
- ✓ New package architectures
- ✓ New network architectures
- ✓ New manufacturing processes

Co-design and Simulation Tools for Packaging are Critical Needs

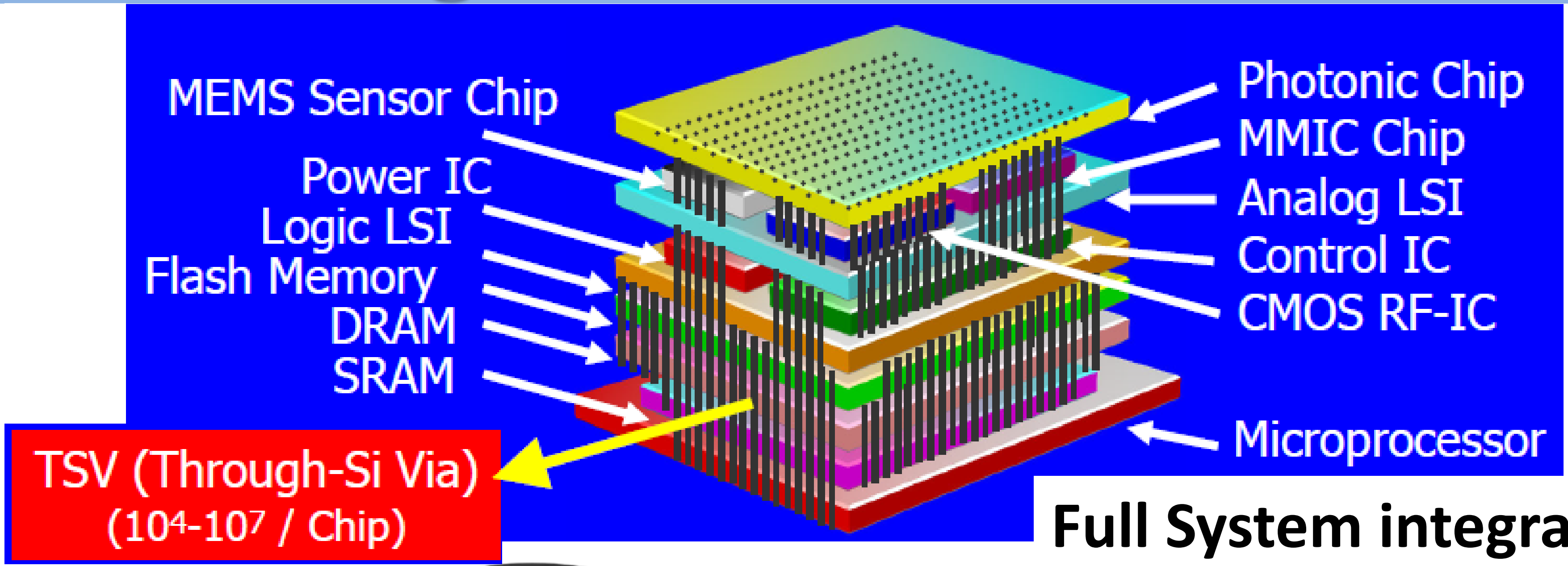
Tools that integrate across the boundaries of device, package, printed circuit board and product will speed the process of migration to higher density (SoC, SiP, 2.5D, 3D, etc.).

This enables:

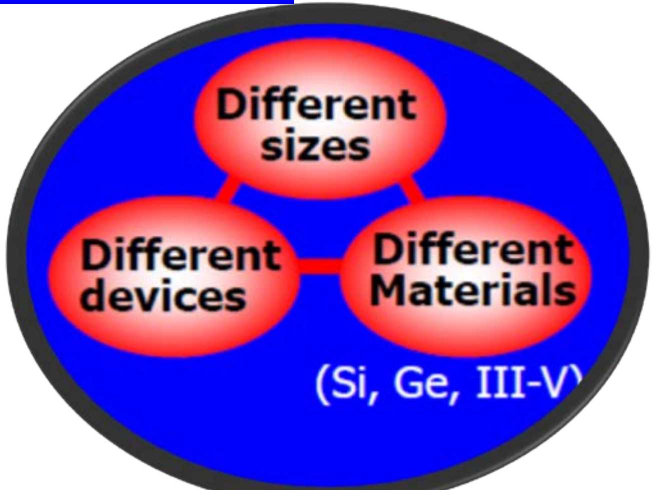
- ✓ Increased performance and bandwidth
- ✓ Decreasing latency, power, size, cost
- ✓ Reduced time to market



3D Packaging And Heterogeneous Integration Will Be Essential



Full System integration in a 3D Package



Heterogeneous integration presents new packaging Challenges

Source: Tohoku University

Heterogeneous Integration by Circuit Fabric Type

- ✓ Logic

Hots spot locations not predictable, high thermal density, high frequency, unpredictable work load, limited by data bandwidth

- ✓ Memory

Thermal density depends on memory type and thermal density differences drive changes in package architecture and materials

- ✓ RF

Noise isolation is critical, may require compound semiconductors with different mechanical properties

- ✓ MEMS

There is a virtually unlimited set of requirements; hermetic, non-hermetic, variable functional density, plumbing, stress control, etc.

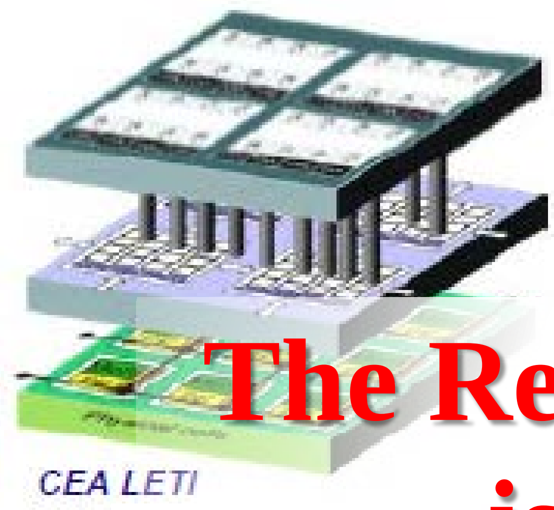
- ✓ Photonics

Extreme sensitivity to thermal changes, O to E and E to O, Optical signal connections, new materials

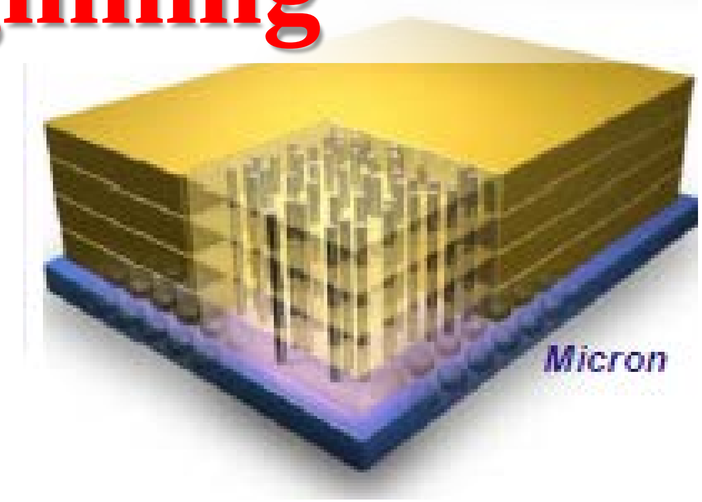
- ✓ Plasmonics

Requirements are yet to be determined but they will be different from other circuit types

Other 3D Package Examples of Heterogeneous Integration



The Revolution in Packaging is just beginning



New Materials Will Be Required

Many are in use today

- ✓ Cu interconnect
- ✓ Ultra Low k dielectrics
- ✓ High k dielectrics
- ✓ Organic semiconductors
- ✓ Green Materials
  - Pb free
  - Halogen free

But improvements are needed

Many are in development

- ➢ **Nanotubes**
- ➢ **Nano Wires**
- ➢ **2D Replacement for Si**
- ➢ **Macromolecules**
- ➢ **Nano Particles**
- ➢ **Composite materials**

100% of the packaging materials changed during the last decade

More than 50% will change again during this decade

New Materials

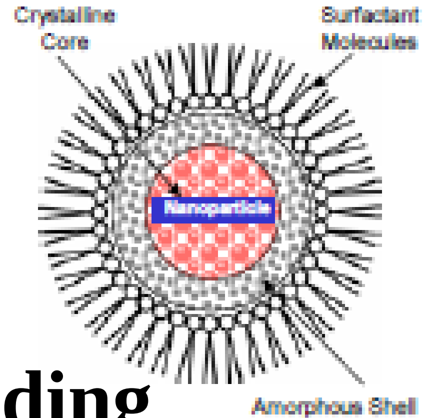
- ✓ Conductors
- ✓ Semiconductors
- ✓ Dielectrics
- ✓ Composites

Carbon Conductors Look Better Than Cu

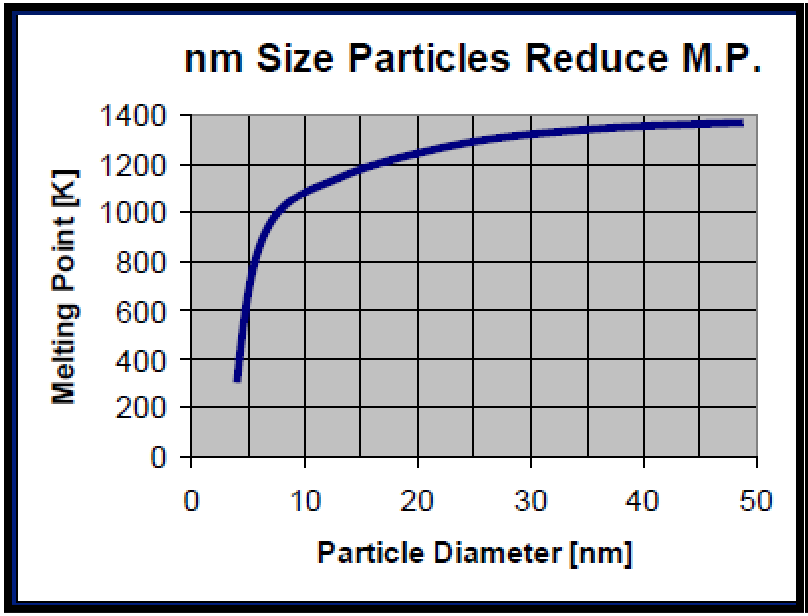
	Cu	CNT	GNR	
Max current density (A/cm²)	**~10^6**	**> $1x10^8$**	**> $1x10^8$**	**x10^2**
Temp. Coefficient of Resistance (10^{-3} /K)	**4**	**< 1.1** *Kane, et al. Europhys. Lett.,1998*	**-1.47** *Shao et al. Appl Phys. Lett., 2008*	
Mean Free Path @ room-T (nm)	**40**	**> 1000** *McEuen, et al. Trans. Nano., 2002*	**~ 1000** *Bolotin, et al. Phys. Rev. Let. 2008*	**x25**

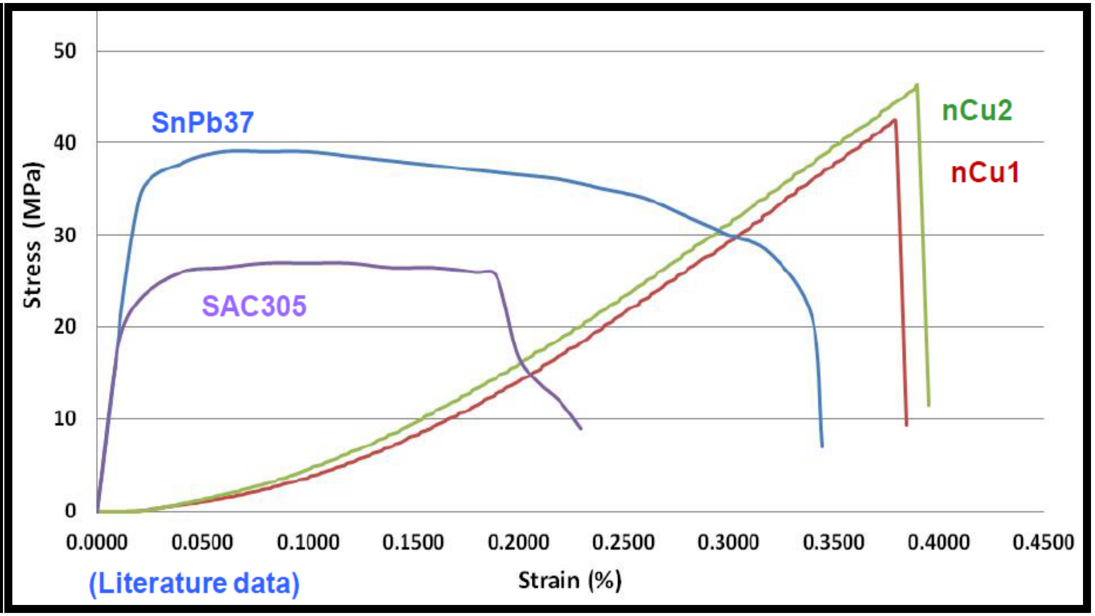
Many questions still to be answered before graphene or CNT can be considered as a practical interconnect materials. The results so far are very promising.

Low temp Cu Nano-solder



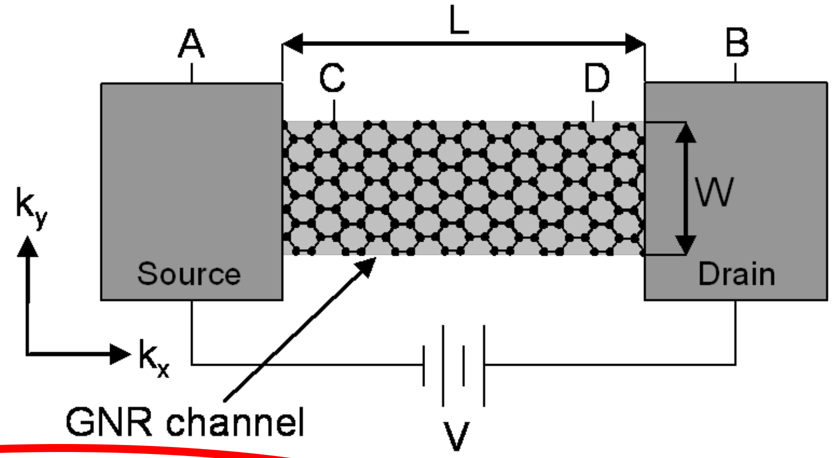
- ✓ Package assembly at low temp (100C)
- ✓ Reflow solder to PCB <200C
- ✓ Consistent with Direct Interconnect Bonding



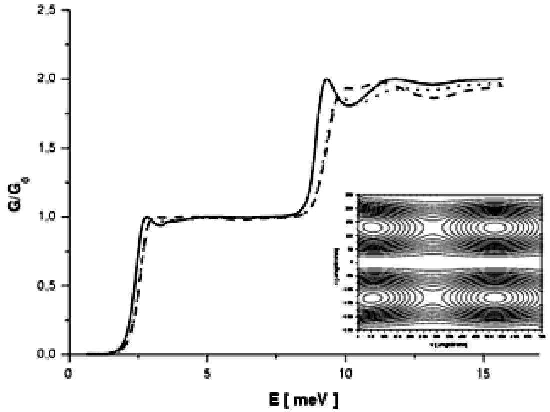


New Semiconductors
2D Replacements for Si

2D Replacements for Si



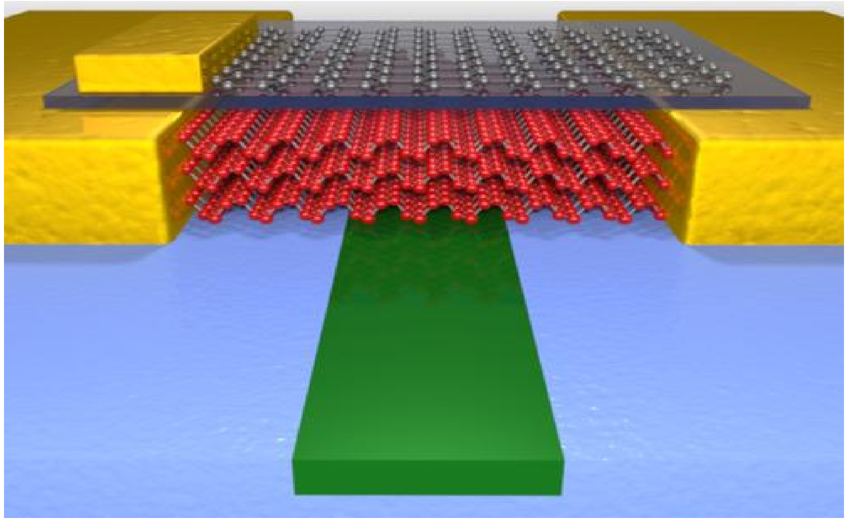
Graphene nanoribbon field-effect transistor



Conductance is function of initial electron energy and on/off ratio is poor. Contacts A and B are at two different Fermi levels.

Source: Brazilian Journal of Physics

2D Replacements for Si

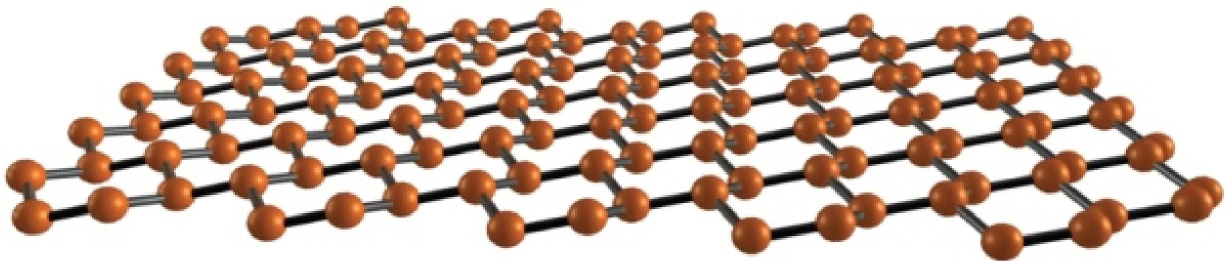


2D Black phosphorous

- ✓ Has a band gap for high on/off ratio
- ✓ Compatible with Si making it a good candidate for silicon photonics
- ✓ The bandgap is tunable by varying # of layers on silicon substrate
- ✓ It is a direct-band semiconductor

Source: EE Times

2D Replacement for Si

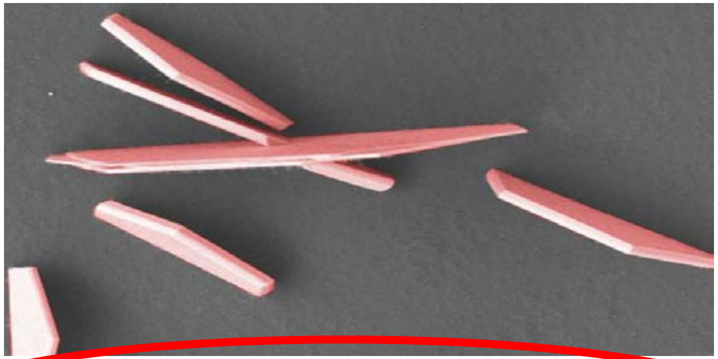


Silicene

Its carbon-based cousin graphene gets more attention, but silicene is catching up. Unlike graphene, silicene has a band gap and may be a fast follower.

- ✓ 2D crystals of silicon were identified theoretically in 1994
- ✓ The name ‘silicene’ is coined in 2007.
- ✓ Fabrication of silicene nanoribbons in 2009
- ✓ First reports of silicene sheets formed on silver in 2012
- ✓ First demonstration of silicene transistor in 2015

2D Replacements for Si



Silicon Telluride

One of a class of 2D chalcogenide semiconductors that have band gaps. Elements can be substituted (Mo, W, S, Se, etc.) to tailor properties.

Silicon Telluride is a 2D chalcogenide semiconductor:

- ✓ It is transparent but brilliant red
- ✓ It is a native p-type semiconductor.
- ✓ Can be grown as nanoribbons, flat nanoplates or standing nanoplates
- ✓ Can be used as light detectors and light emitters
- ✓ High on/off ratios

Composite Materials

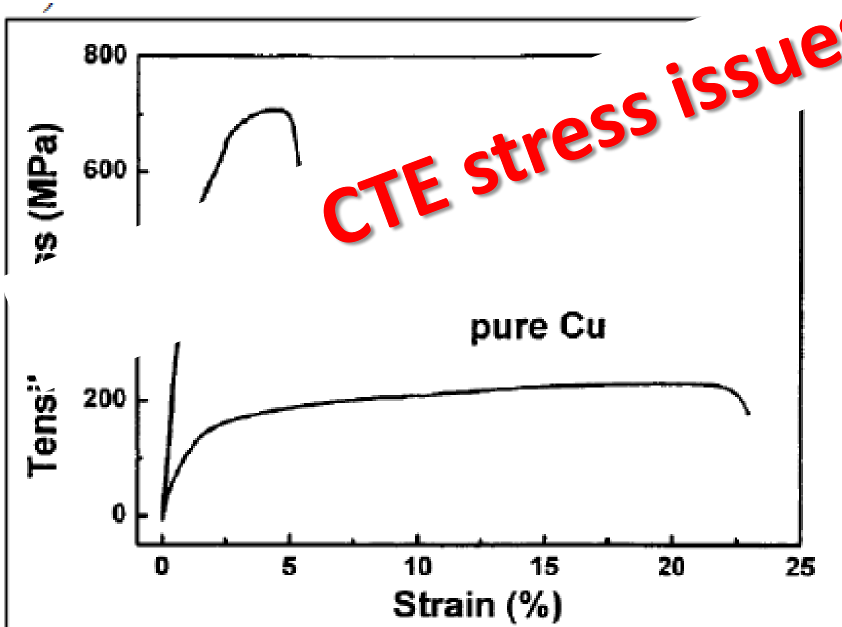
Properties not available in Nature

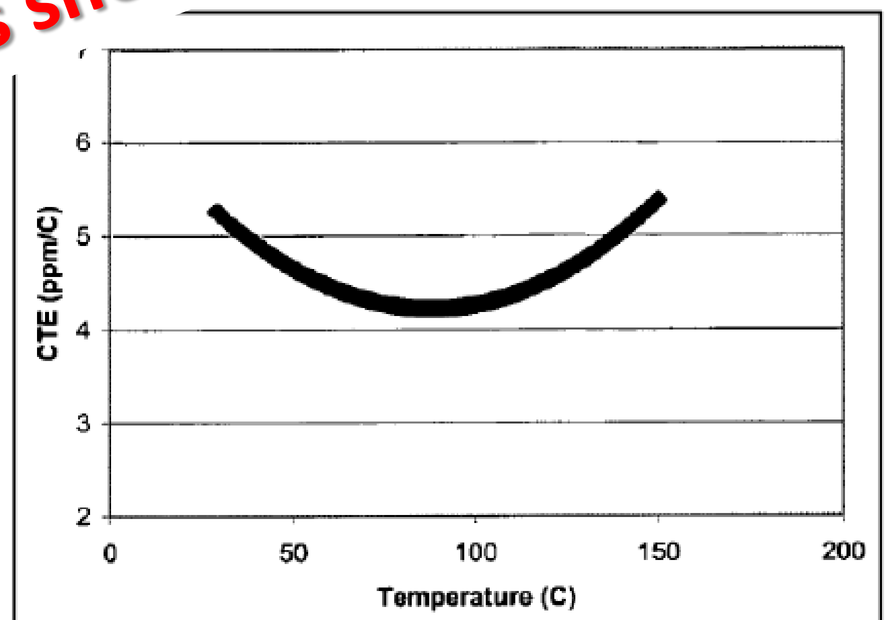
Composite Cu Properties

Measured Properties show:

- ✓ The strength of the Cu-SWCNT composite is more than twice that of pure copper
- ✓ Ductility is significantly lower.
- ✓ Coefficient of thermal expansion r... ween 4 to 5.5x10-6/°C vs 17x10-6/°C ... u.

CTE stress issues should be solved!





Conductors Are Changing

Composite Copper is in evaluation.

Current status:

Measurement	Conventional Copper	TeraCopper®
Resistivity (Ohm·cm)	**1.66×10^{-6}**	**1.26×10^{-6}**
Conductivity (S/m)	**6.02×10^{7}**	**7.94×10^{7}**
Increase in Conductivity	N/A	32%
Avg. Current Capacity(Amps/cm²)	**3.88×10^{4}**	**5.57×10^{4}**
Increase in Current Capacity	N/A	44%

The first electrical performance improvement in copper since 1913 makes composite copper the most electrically conducting material known at room temperature.

Targets for improvement compared to conventional copper are:

- ✓ **100 % increase in electrical conductivity**
- ✓ **100% increase in thermal conductivity**
- ✓ **300% increase in tensile strength**

Source: NanoRidge

Polymer CNT Composites

Until recently results were disappointing:

- ✓ Less impact on thermal, mechanical and electrical properties than expected.
- ✓ Now that is changing rapidly due to:
  - Higher purity
  - Fewer defects
  - Chirality control
  - Reduction in production cost

Polymer CNT Composites

Until recently results were disapp

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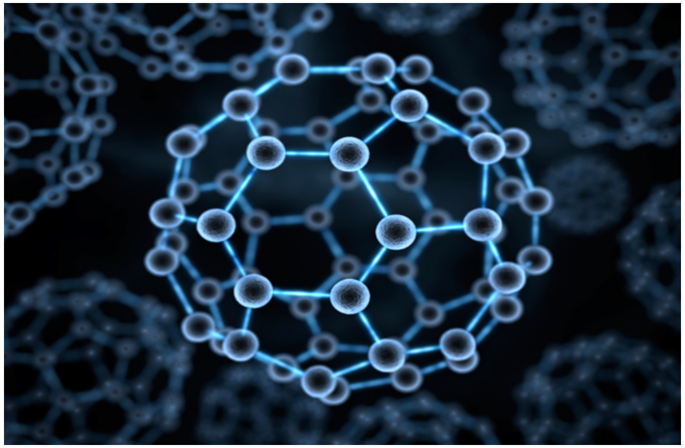
Half the CNT yields 10 to 100X improvement in electrical conductivity

Other key parameters: strength, thermal conductivity, CTE yet to be reported

Composite Nanomaterials



Nano-composites improve high voltage capacity for polymer insulators in high voltages cables.

- ✓ The addition of carbon nanoballs (Buckyballs) to polymer insulated high voltage lines increases voltage capacity by 26%
- ✓ Theoretically it should be even better with optimization
  - – Dispersion of Buckyballs in the polymer
  - – Optimal nano-particle loading of polymer
  - – Understanding the mechanism

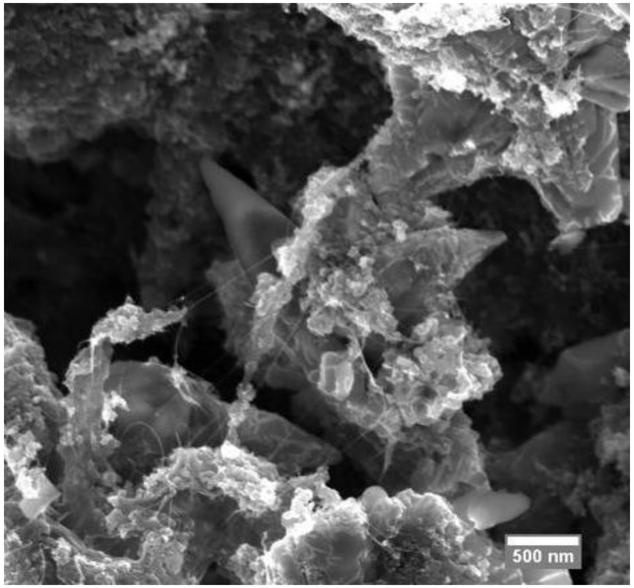
Source: Chalmers University of Technology

Nanomaterials are changing Energy Storage

Superior ultracapacitors with an inexpensive composite of graphene flakes mixed with single-wall carbon nanotubes.

The great advantage of this hybrid structures design is:

- ✓ Graphene provides good conductivity in plane of nanostructures and high surface area for the ultracapacitor.
- ✓ Single walled carbon nanotubes connect the structure into a stable, uniform network

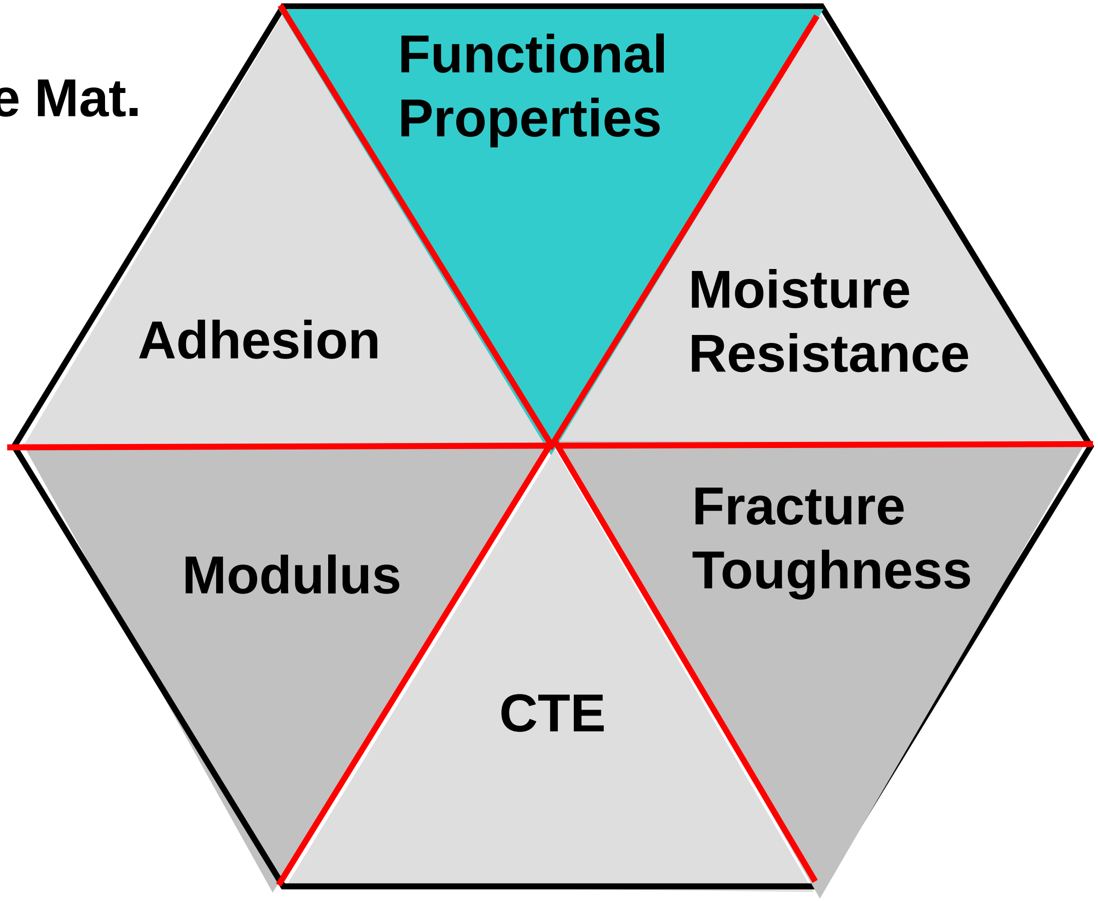


SEM image of ultracapacitor's hybrid film with graphene flakes and single-walled carbon nanotubes.

Source: George Washington University

Packaging Materials Requirements

Examples
Thermal Interface Mat.
Mold Compound
Conductors
Adhesives
Underfill



- ✓ Highly coupled Material Properties
- ✓ Novel materials needed to optimize performance for each parameter

Packaging Materials Requirements

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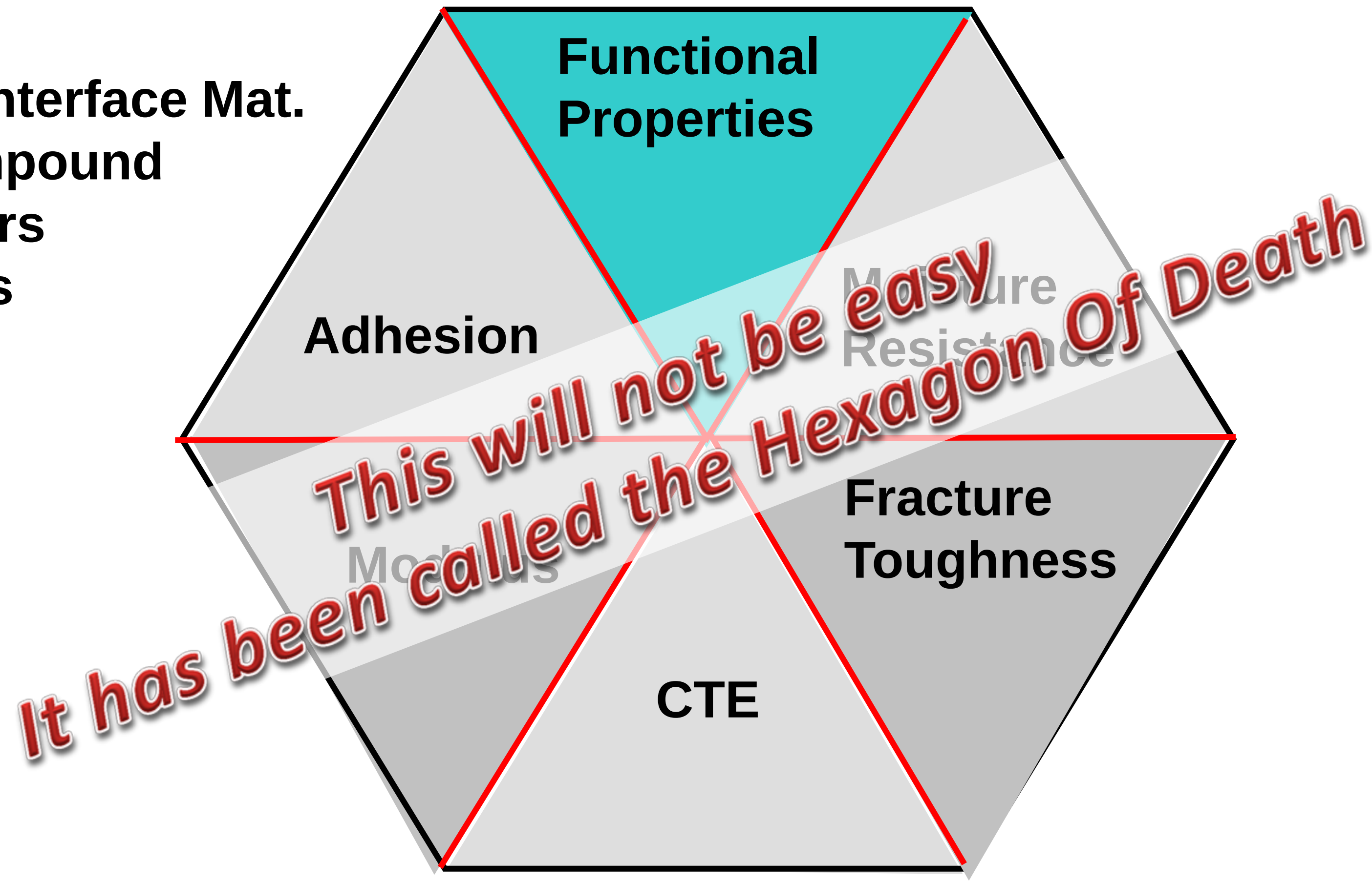

- ✓ Highly coupled Material Properties
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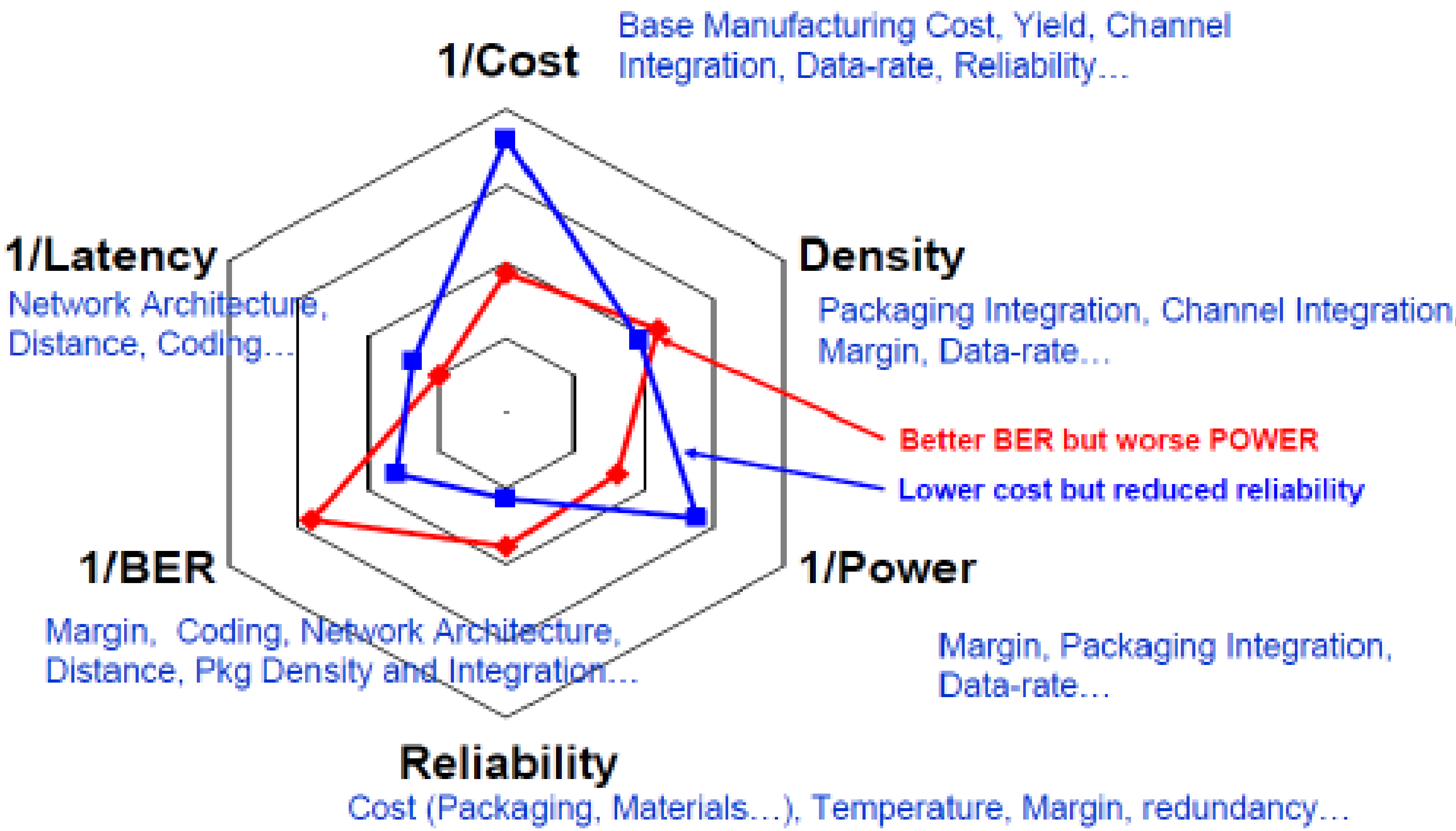
Trade-offs For Optimization



This chart is equally relevant for integrated circuits, photonics, plasmonics and new materials with slightly changed parameters

Source: IBM

Interfaces control Materials Properties

Everything is getting thinner

- ✓ All layers in a packages
- ✓ All layers in integrated circuits
- ✓ Composite structure interfaces

In many cases bulk properties no longer matter

- ✓ Metals
- ✓ Insulators
- ✓ Semiconductors
- ✓ Composites

Interfaces control Materials Properties

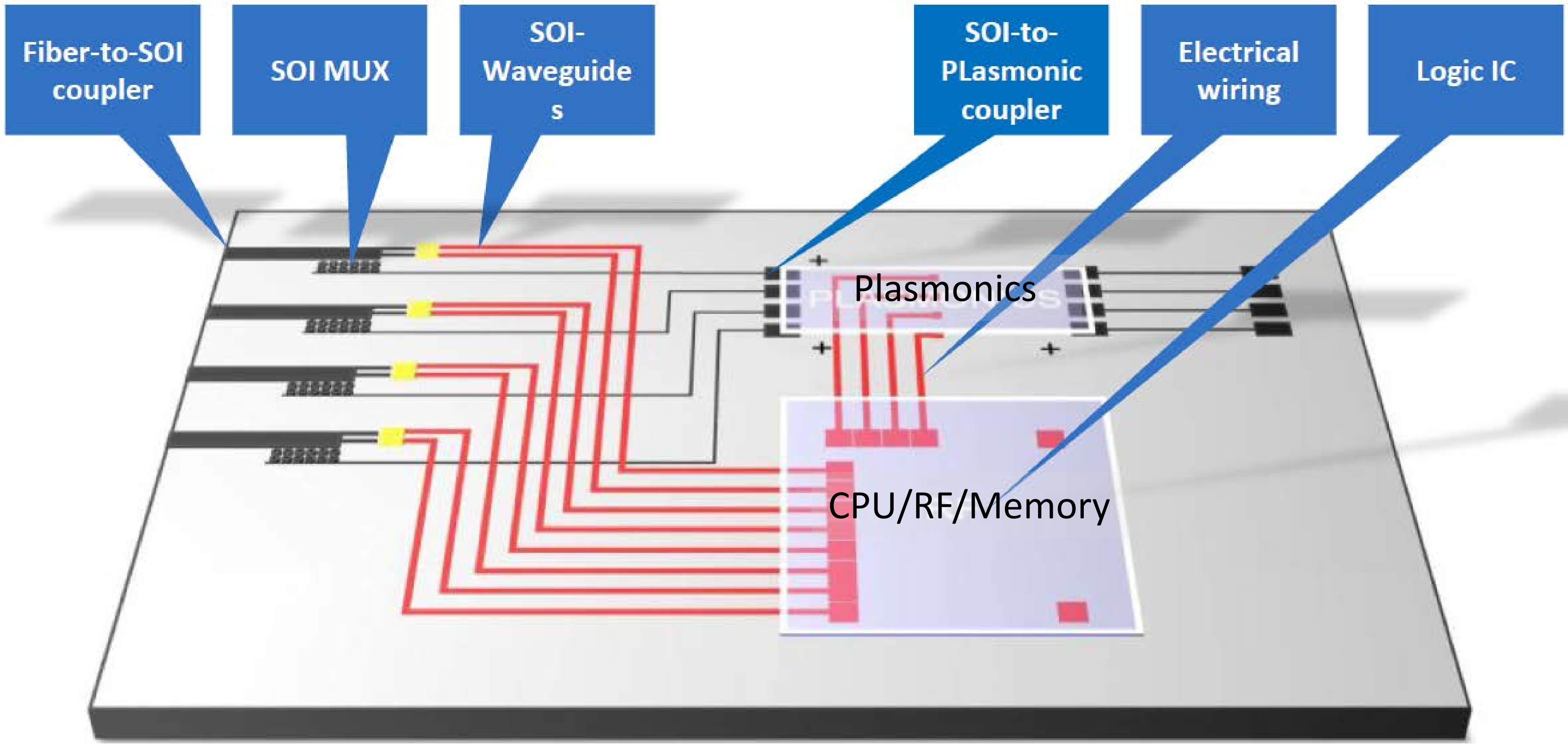
Everything is getting thinner

- ✓ All layers in a packages
- ✓ All layers in integrated circuits

We don't yet have metrology to define the interface properties which we must have to optimize a structure

- ✓ Insulators
- ✓ Semiconductors
- ✓ Composites

Co-integration Of Electronics, Photonics And Plasmonics On SOI



Source: Dr. Nikos Pleros
Aristotle University

Co-Integration of Technologies

Use each technology where it is the best:

- ✓ Electronics
  - – Active logic and memory (Processing and routing)
  - – Smallest size
- ✓ Photonics
  - – High bandwidth
  - – Energy efficient
  - – Long and intermediate distance
- ✓ Plasmonics (R. Zia et al., "Plasmonics: the next chip-scale technology", Materials Today 9(7-8), 2006)
  - – Much smaller than photonic components
  - – Potentially seamless interface between Optics and Electronics
  - – Low power active functions
  - – Sub-wavelength confinement of photon energy

Summary

Requirements for IoT/Cloud driven Global Network

- ✓ Cost and power reduced by $>10^4$
- ✓ Flatten the architecture increase ports by $>10^6$
- ✓ Reduce latency
- ✓ Support software defined networks

~~Technology identified can deliver 10^3 improvement at most.~~
A majority of improvement will come from materials & packaging.
~~Innovation is needed but is it practical to find another order of magnitude?~~

In the first 40 years of Moore's Law scaling every parameter improved by more than one million times.

Maybe 2 orders of magnitude in 15 years is too conservative

Conclusion

New devices and new materials will drive the development of new metrology tools and techniques. Some key issues are:

- ✓ Interfacial adhesion
- ✓ Nano-particle dispersion
- ✓ Interfacial stress/strain
  - Layer to layer
  - Matrix to nano-particle
- ✓ Porosity

Conclusion

New devices and new materials will drive the development of new metrology tools and techniques. Some key issues are:

These data sets will be essential to enable optimization of new, engineered materials and processes demanded by the emerging technology drivers

- Matrix to nano-particle

✓ Porosity

Thank You for Your Attention