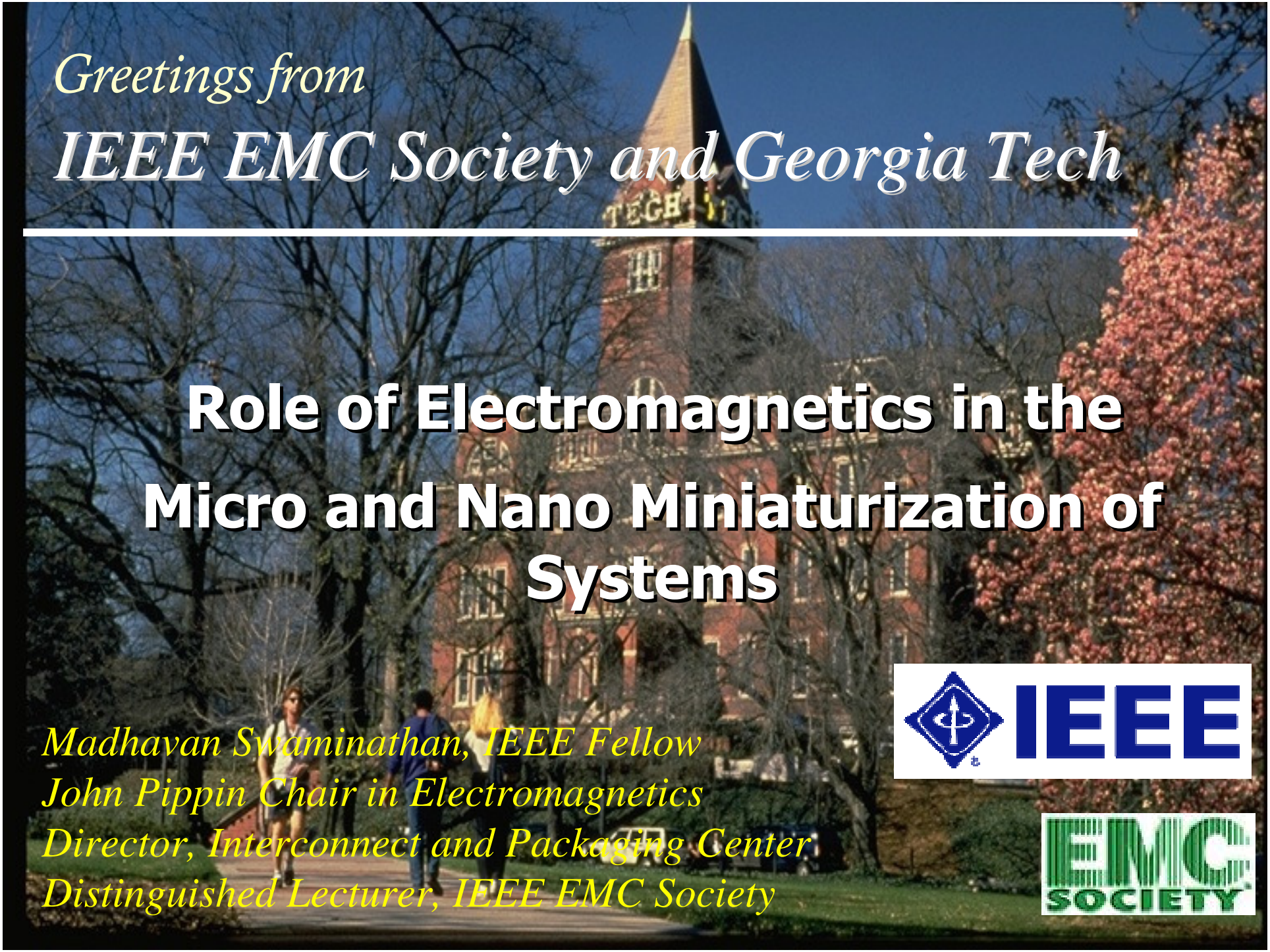


Greetings from

IEEE EMC Society and Georgia Tech

Role of Electromagnetics in the Micro and Nano Miniaturization of Systems

Madhavan Swaminathan, IEEE Fellow
John Pippin Chair in Electromagnetics
Director, Interconnect and Packaging Center
Distinguished Lecturer, IEEE EMC Society

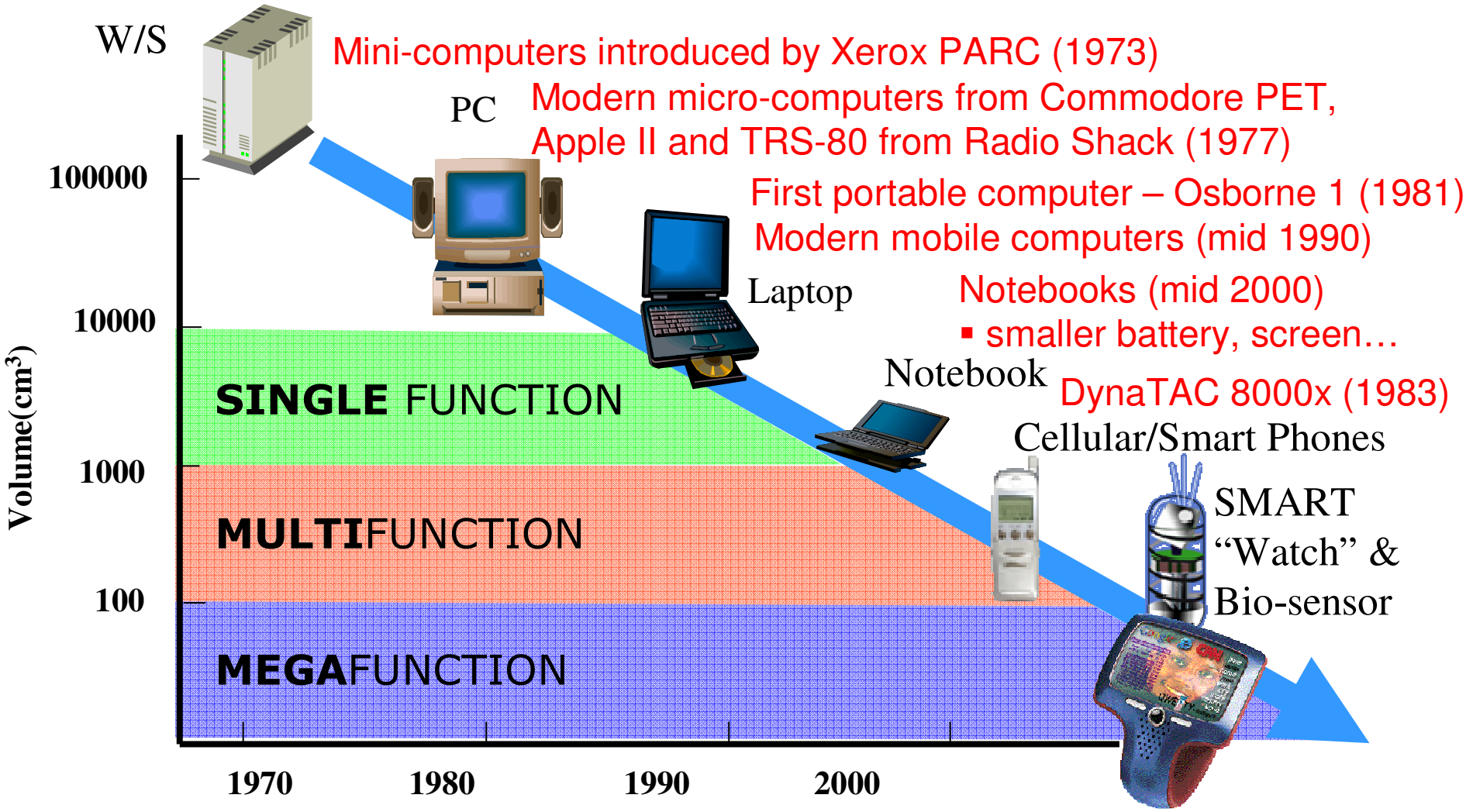
IEEE

EMC SOCIETY

Outline

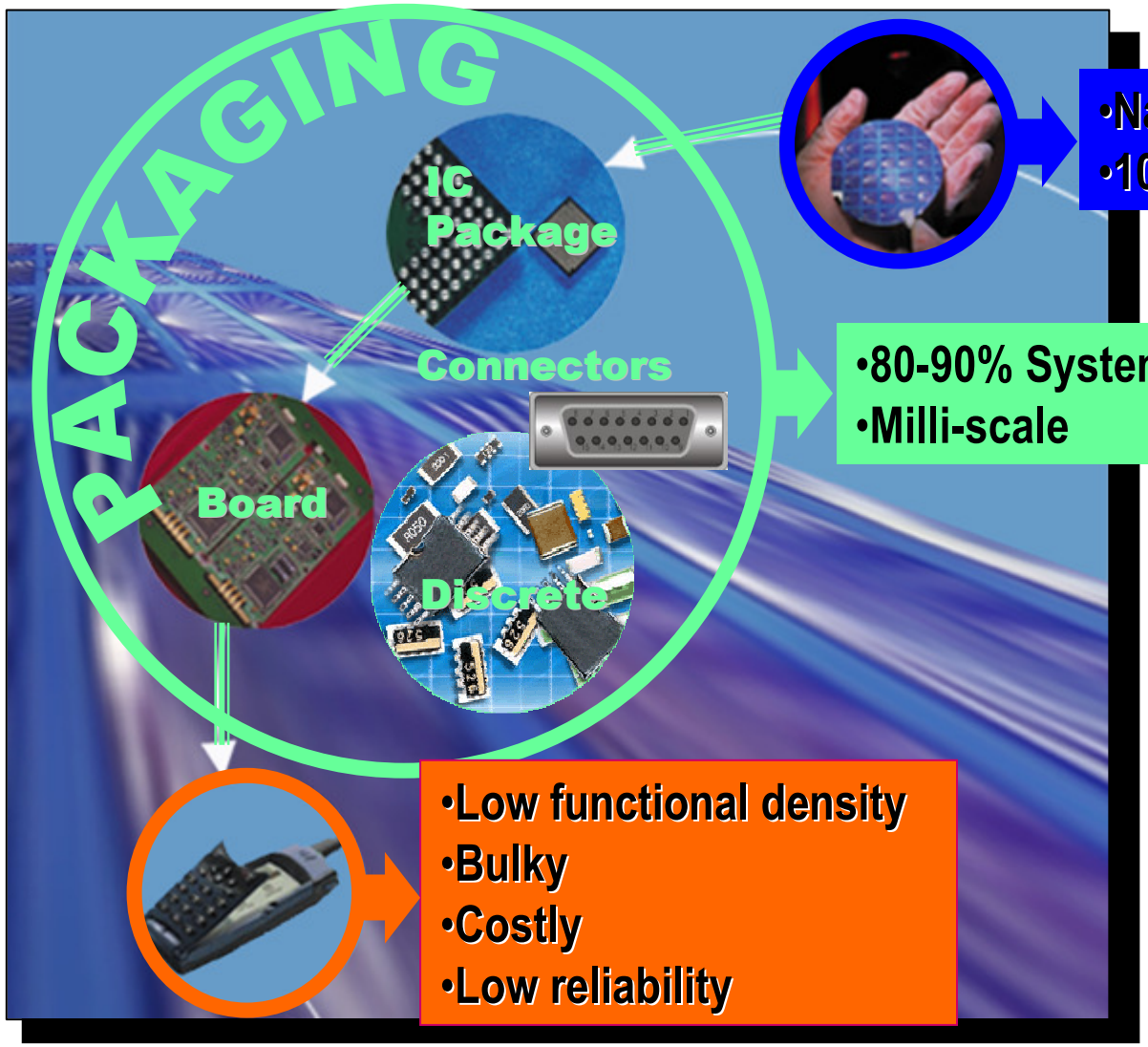
- Trends
  - What is System on Package (SoP) ?
  - Why SoP ?
- Miniaturization of Systems (Status, Challenges and Opportunities)
  - Micro-miniaturization for RF/Microwave Integration & Computing
  - Nano-miniaturization for Sensing and Computing
- Summary

What does it take to miniaturize Multi-functional Systems ?



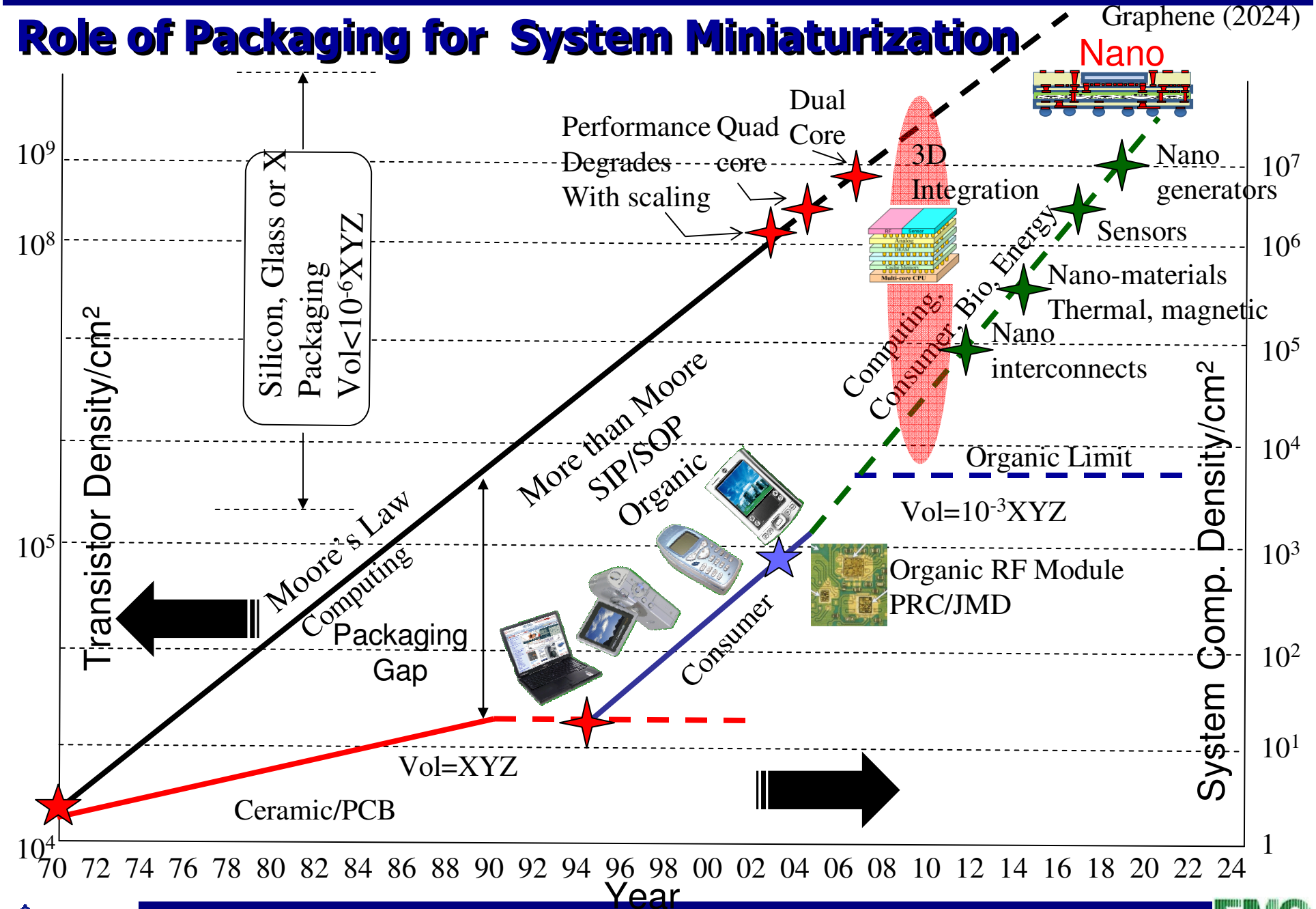
Courtesy: Packaging Research Center, Georgia Tech

Barriers to System Miniaturization



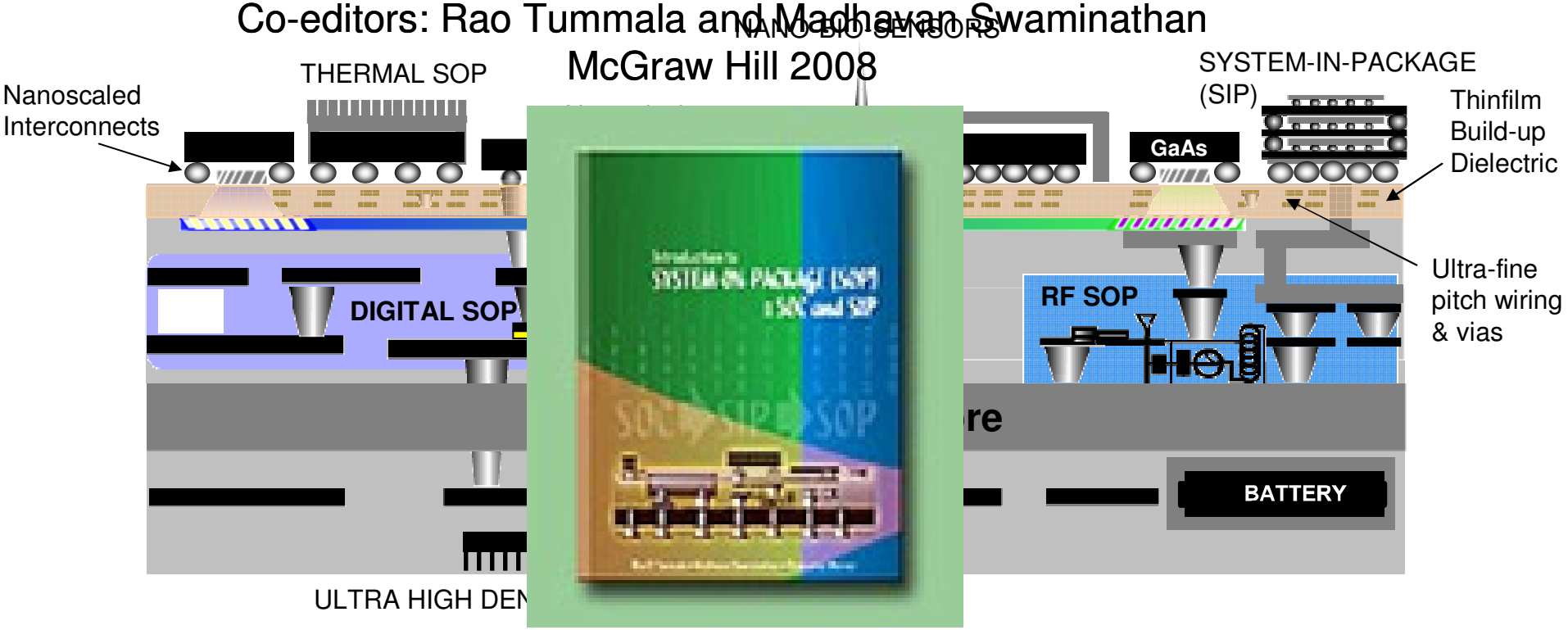
Courtesy: Packaging Research Center

Role of Packaging for System Miniaturization



System on Package – A New Paradigm for System Integration

Introduction to System on Package
Co-editors: Rao Tummala and Madhavan Swaminathan
McGraw Hill 2008



- Functional layers in the package
- Enable High System Level Component Density
- Georgia Tech – Originator of the SoP concept in 1994

Courtesy: Prof. Rao Tummala, Packaging Research Center

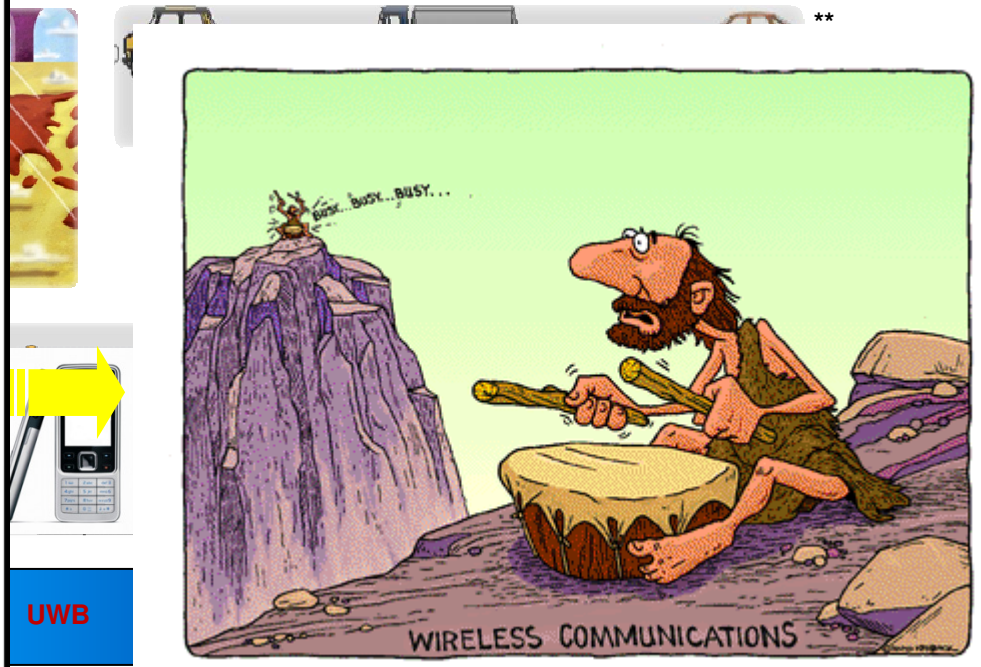
More than Moore Era – circa 1995 - Present
Engineering of Micro-systems

Wireless Communication (Circa 1995 ….)

Dawn of the Consumer Driven Mobile Communication Era

Integration of radio technologies in handheld devices created a huge push towards integration and miniaturization.

Not yet wireless



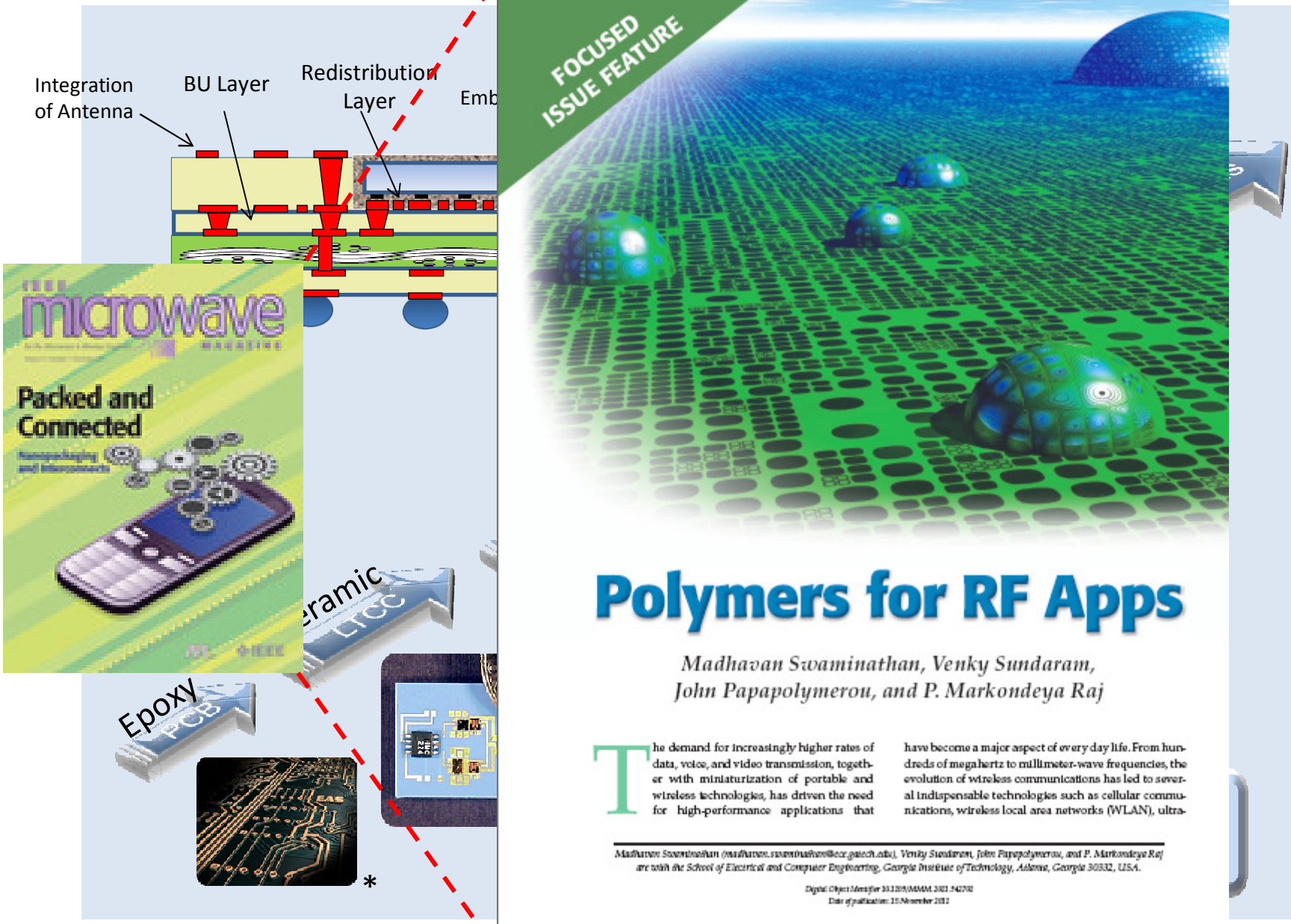
-10 GHz

57-64 GHz

trum of popular wireless technologies

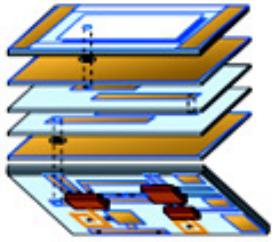
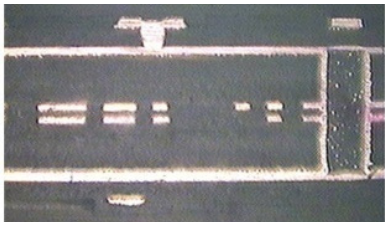
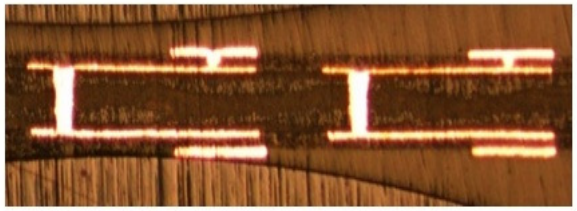
** Courtesy of www.corbisimages.com*

***www.ansoft.com, Presentation Slides by Dong-young Kim, ETRI, "60GHz SoP Tech Using HFSS and AD"*

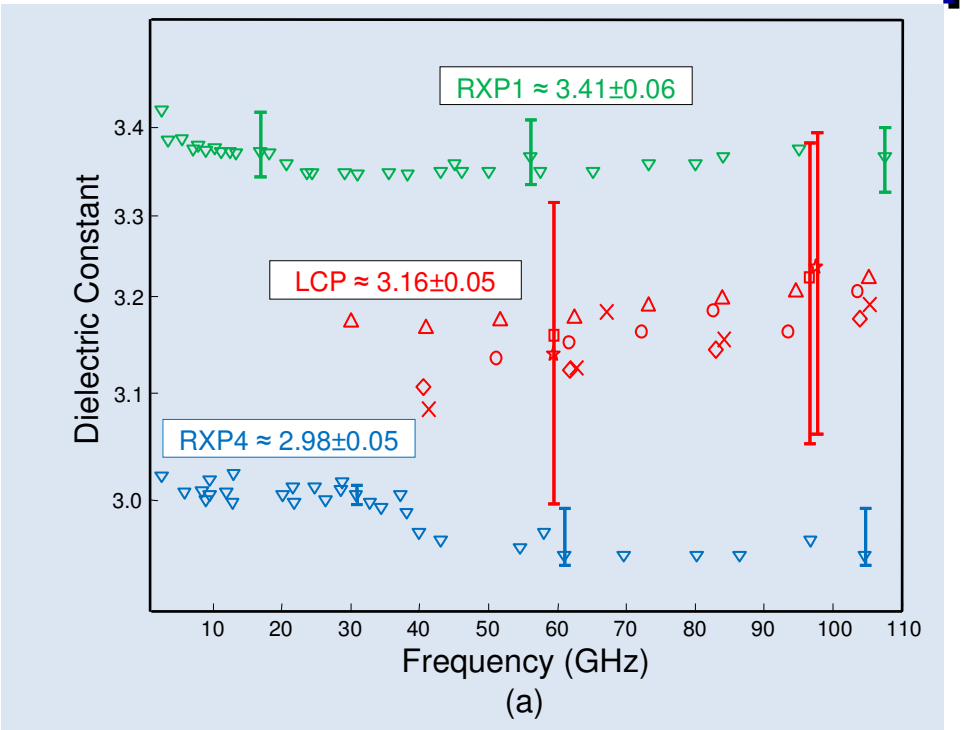


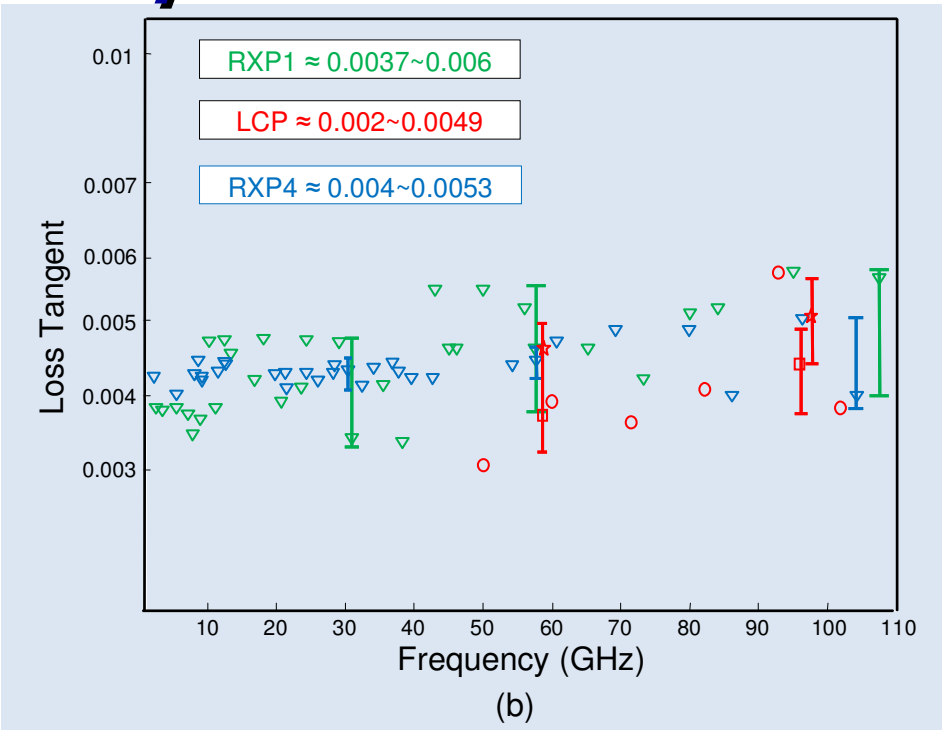
M. Swaminathan, V.Sundaram, J. Papapolymerou and R. Pulugurtha, "Polymers for RF Apps", IEEE Microwave Magazine, Dec 2011

Platforms for System Integration

LTCC	LCP	RXP
		
☑ Hermetic ☑ Multilayer ☑ Integrated-LC ☑ High-Q passive ☑ Low tanδ	☑ Hermetic ☑ Multilayer ☑ Integrated-LC ☑ High-Q passive ☑ Low tanδ ☑ Flexible ☑ PCB process compatible	☑ Hermetic ☑ Multilayer ☑ Integrated-LC ☑ High-Q passive ☑ Low tanδ ☑ Flexible ☑ PCB process compatible
☒ High processing temp (900°C) ☒ Thick (800 μm) ☒ Incompatible with PCB process	☒ High processing temp (290°C) ☒ Bondply misalignment	☑ Low cost (220°C) ☑ Ultra-thin (20 μm) ☑ Advanced fabrication
<2000	2000 - 2009	2007 - Present

Good Electrical Properties
Dielectric Constant and Loss Tangent Variation with Frequency





Dielectric Constant

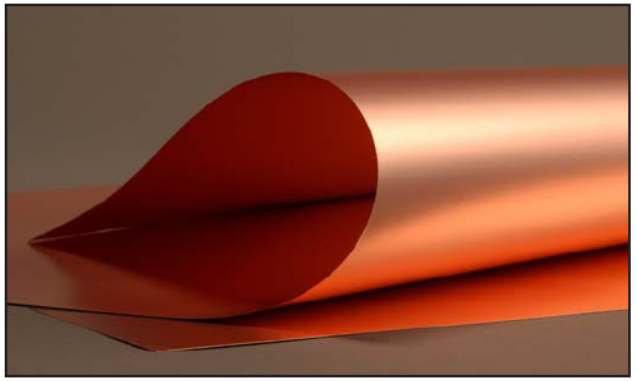
Loss Tangent

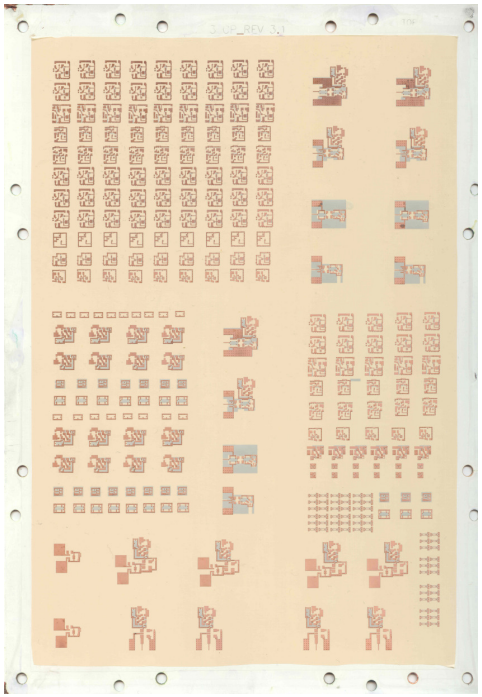
M. Swaminathan, V.Sundaram, J. Papapolymerou and R. Pulugurtha, "Polymers for RF Apps", IEEE Microwave Magazine, Dec 2011

Characterization Details: Seunghyun Hwang, Sunghwan Min, Venkatesan Venkatakrishnan, Madhavan Swaminathan, Hunter Chan, Fuhan Liu, Venky Sundaram, Scott Kennedy, Dirk Baars, Benjamin Lacroix, Yuan Li and John Papapolymerou, "Characterization of Next Generation Thin Low-K and Low-Loss Organic Dielectrics from 1 to 110 GHz", IEEE Transactions on Advanced Packaging, Vol. 33, Issue: 1, pp: 180 - 188, 2010.

LCP – High Frequency Material for RF Integration (Circa 2000 – 2009)

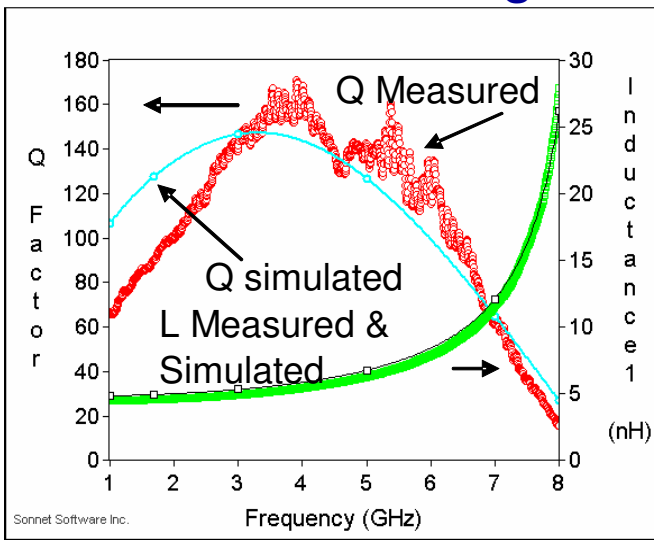
- Laminate type packaging substrate
- Thermoplastic
- Low loss (< 0.002) stable with freq. (~100 GHz)
- Moderate dielectric const. (~ 2.95)
- Large processing area (18″x12″)
- Low temperature process (~ 200° C)
- Low moisture absorption (0.04 %)
- Can be the final PWB





How Do Polymers Help ?

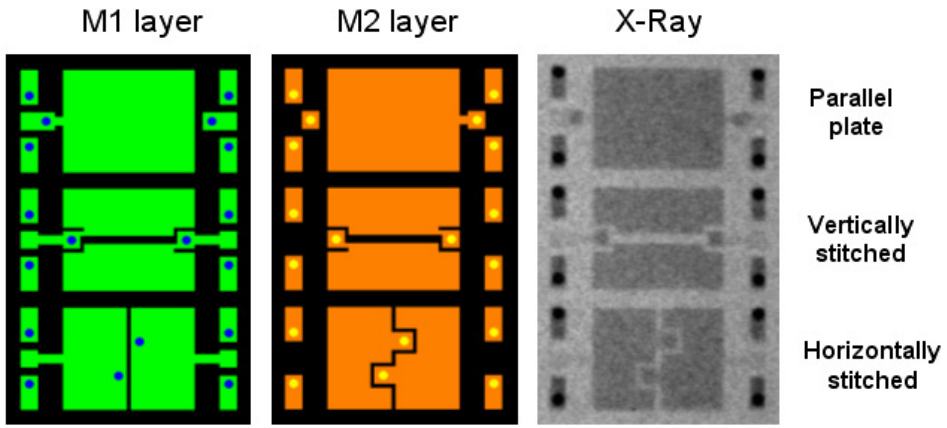
High Q Inductors (Highest reported in Organics*)



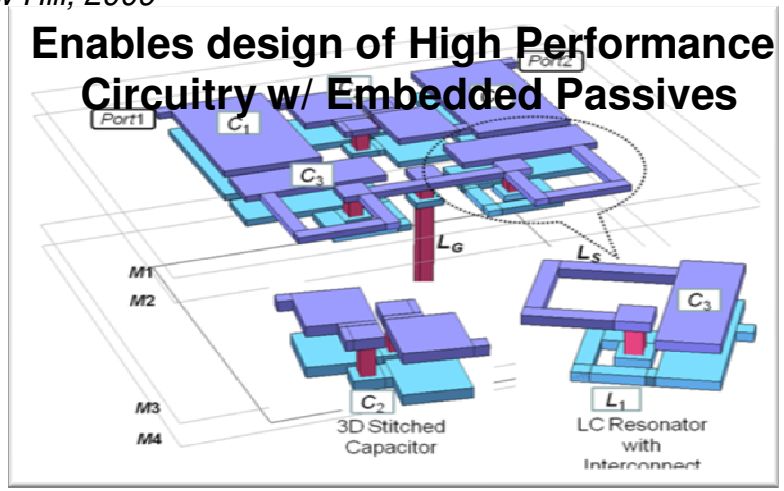
Substrate	Quality Factor	Inductance	Frequency
Silicon -Low Resistivity -High Resistivity -Micromachined	52.8 [5] 30 [6] 150 [7]	1.38nH 4nH 1nH	13.6GHz 1-2 GHz 8 – 23 GHz
Wafer Scale Packaging	38 [8]	1nH	4.7GHz
LTCC	93 [9]	9.6nH	1.15GHz
Organic Laminate* (Highest Reported)	180 [10]	4.8nH	2.2GHz

Reference in: R. Tummala and M. Swaminathan, "Introduction to System on Package", McGraw Hill, 2009

High Q Capacitors (Limit~1/tand)



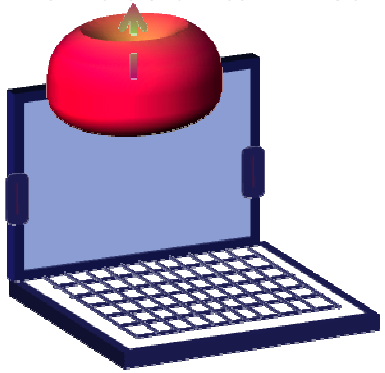
Enables design of High Performance Circuitry w/ Embedded Passives

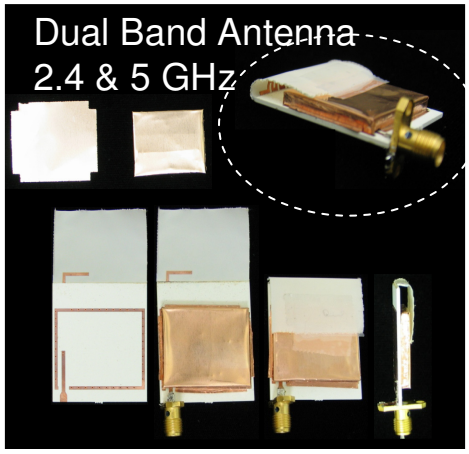


First Paper: S. Dalmia, W. Kim, S. Hwan-Min, M. Swaminathan, V. Sundaram, F. Liu, G. White and R. Tummala, "Design and Analysis of High Q-Inductors for MCM-L Technology", Proceedings of the International Microwave Symposium, Phoenix, Arizona, May 2001.

Design of Flexible Antennas

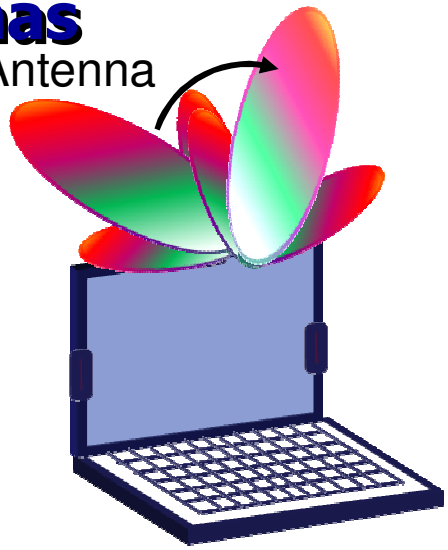
Omni-directional Antenna



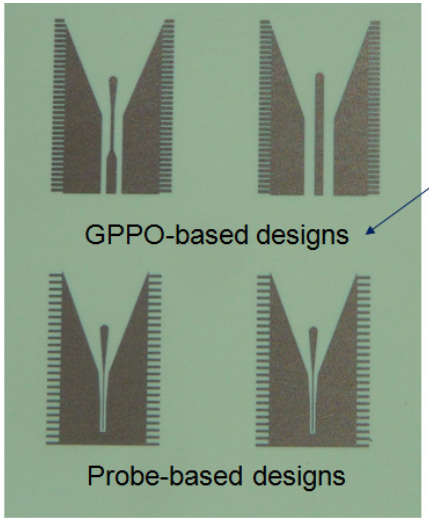


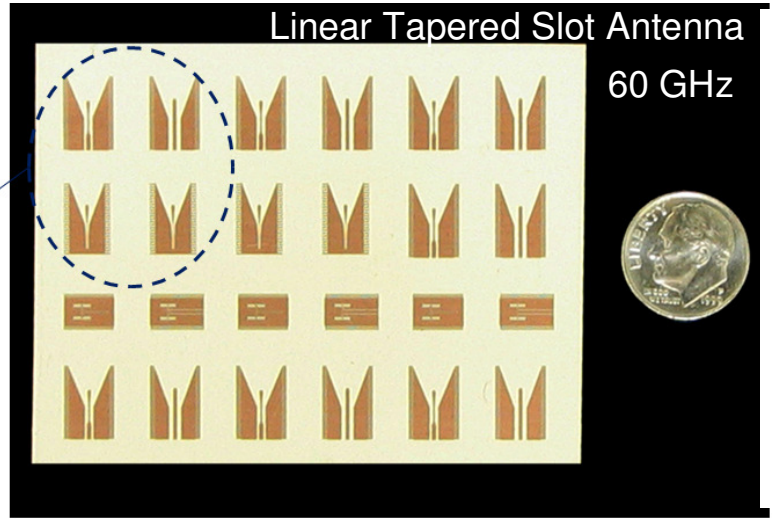
Antenna Integrated w/ RF Module

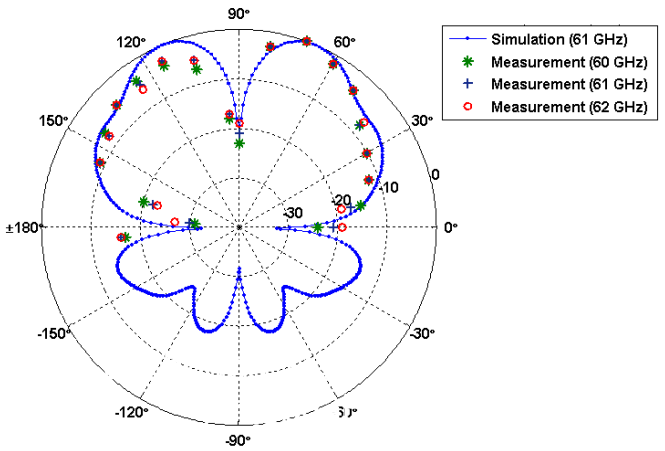
Directional Antenna



N. Altunyurt, R. Rieske, M. Swaminathan, and V. Sundaram, "Conformal Antennas on Liquid Crystalline Polymer Based Rigid-Flex Substrates Integrated With the Front-End Module", IEEE Transactions on Advanced Packaging, Volume 32, Issue 4, pp: 797 – 808, Nov. 2009.

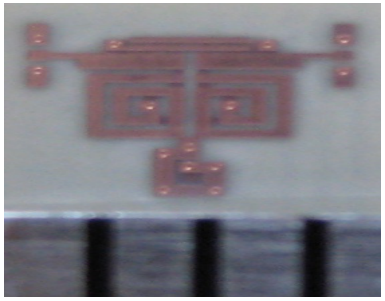




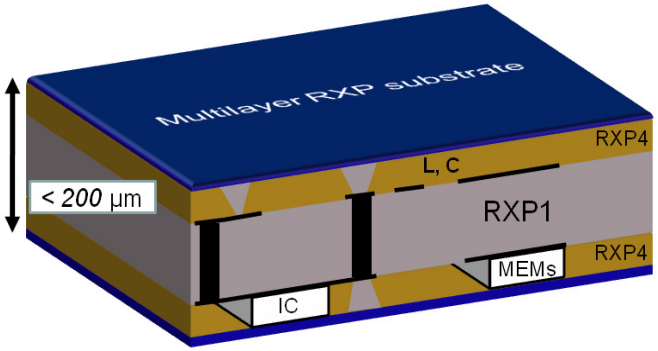


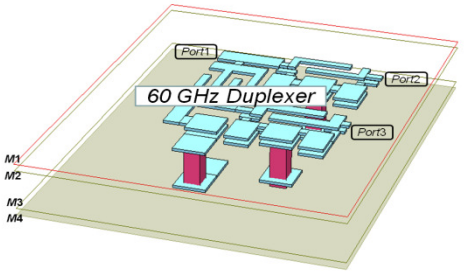
Nevin Altunyurt, "Electromagnetic Modeling of Interconnections in Three-Dimensional Integration", PhD Dissertation, Georgia Tech, 2010

RXP Replaces LCP (Circa: 2007 – Present)
High Order, High Q Filters

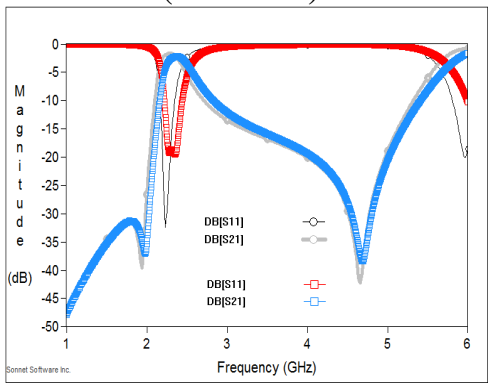


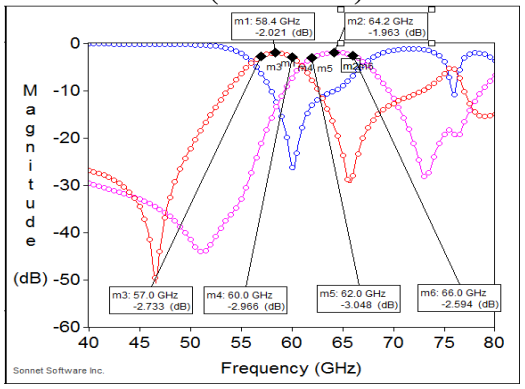
2.2mm x 3.0mm x 0.2mm
(1.2mm^3*)





1.05mm x 1.38mm x 0.2mm
(0.29mm^3)





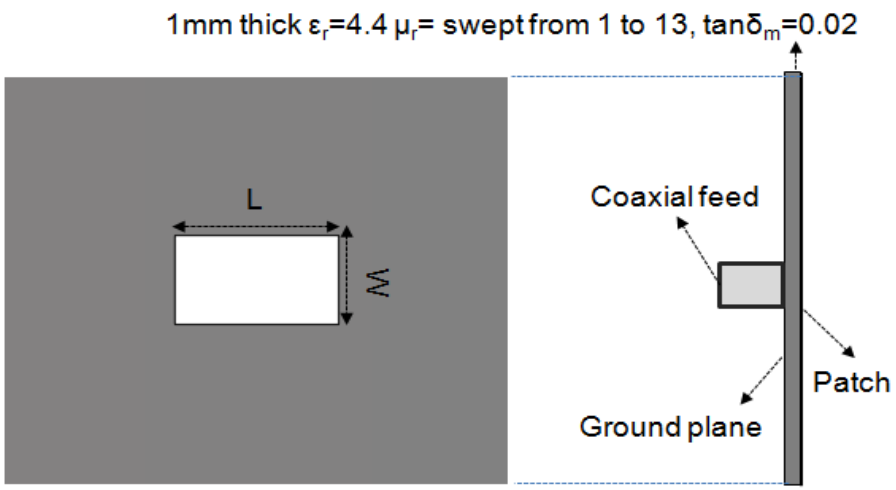
Bandwidth: 200 MHz
Insertion @2.38GHz: 2.2dB
Rejection @2.05GHz: 25.1dB
Rejection @4.71GHz: 39.1dB
-30 dB @ 200 MHz out of passband

Passband1: 57~60 GHz
Passband2: 62~66 GHz
Insertion @ 58.5 GHz: 2.0dB
Insertion @ 64 GHz: 1.9dB

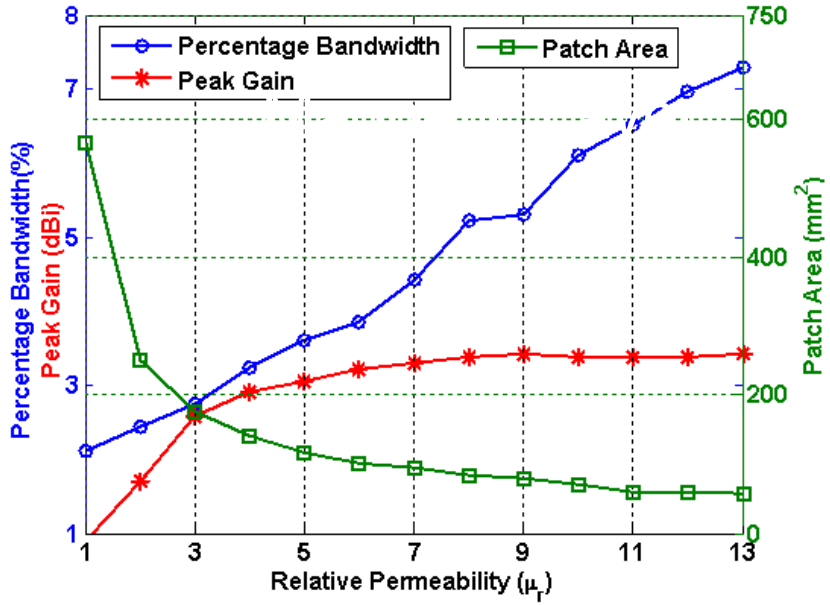
[*] World's smallest high-rejection bandpass filter

RXP: Roger's Experimental Polymer Thermosetting Polymer

Magneto-dielectrics for Antenna Design



Thin Substrate



$$BW = \frac{2\Delta f}{f_0} = \frac{1}{\sqrt{2}Q}(SWR \le 2) \qquad BW \propto \frac{1}{\varepsilon_r}$$

$$\eta = \frac{P_r}{P_r + P_{sw}}(Radiation \quad Efficiency)$$

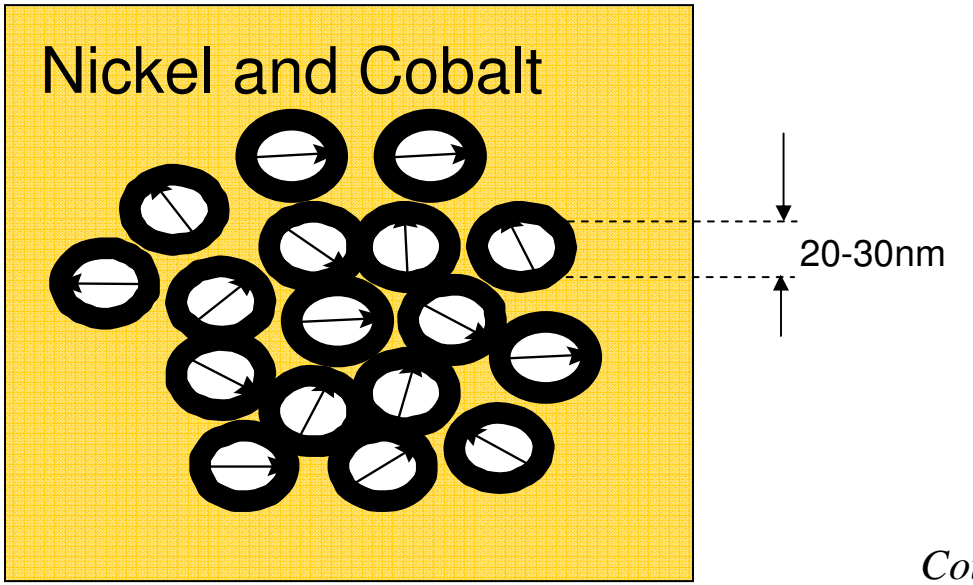
P_{sw}: Surface Wave Problematic

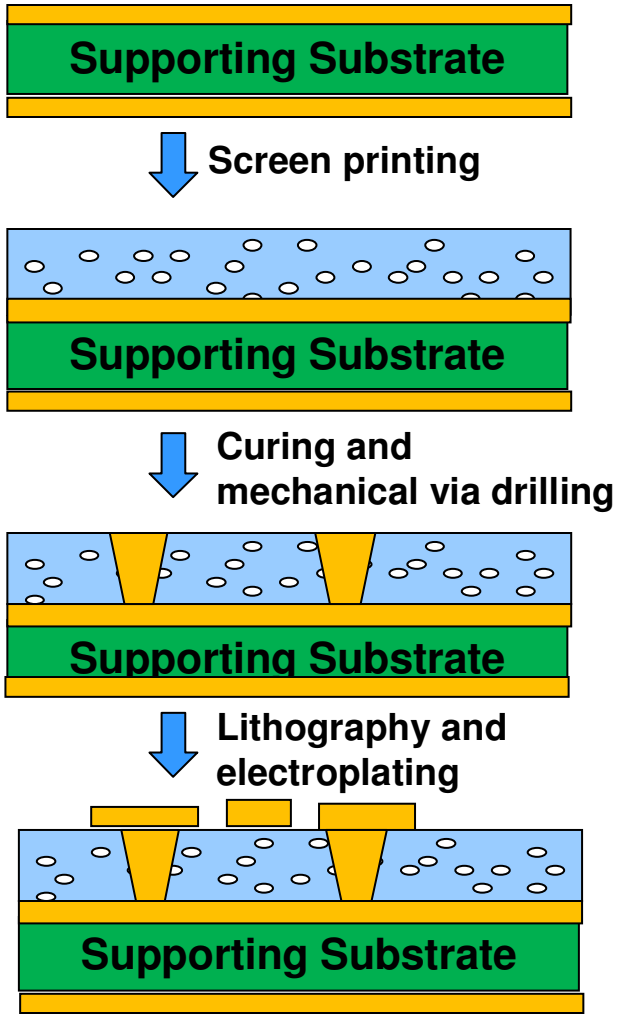
Nevin Altunyurt, "Integration and Miniaturization of Antennas for System on Package Applications", PhD Dissertation, Georgia Tech, 2010

Polymer-based Magneto-dielectric Films

- Magneto-dielectrics not available in nature – need to synthesize with right properties
- Sol-gel process

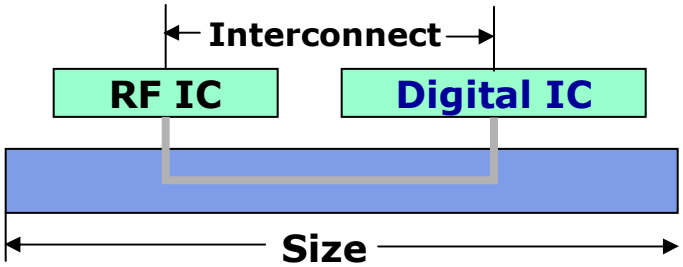
  Gel with the silica coated nano-particles
- Milled with polymer composite to create magneto-dielectric paste
- Screen printing for device fabrication



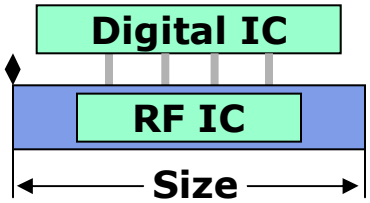


Courtesy: Packaging Research Center

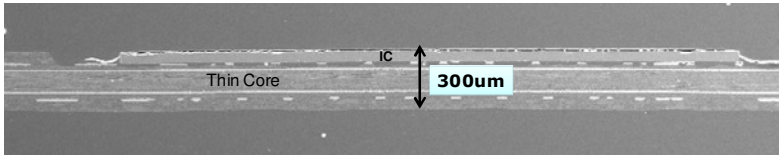
Ultra-thin RF Modules



Conventional Packaging

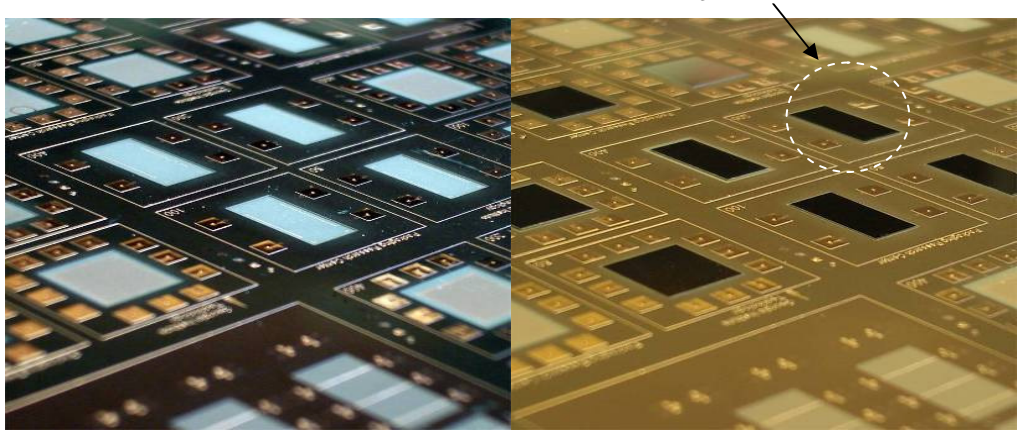


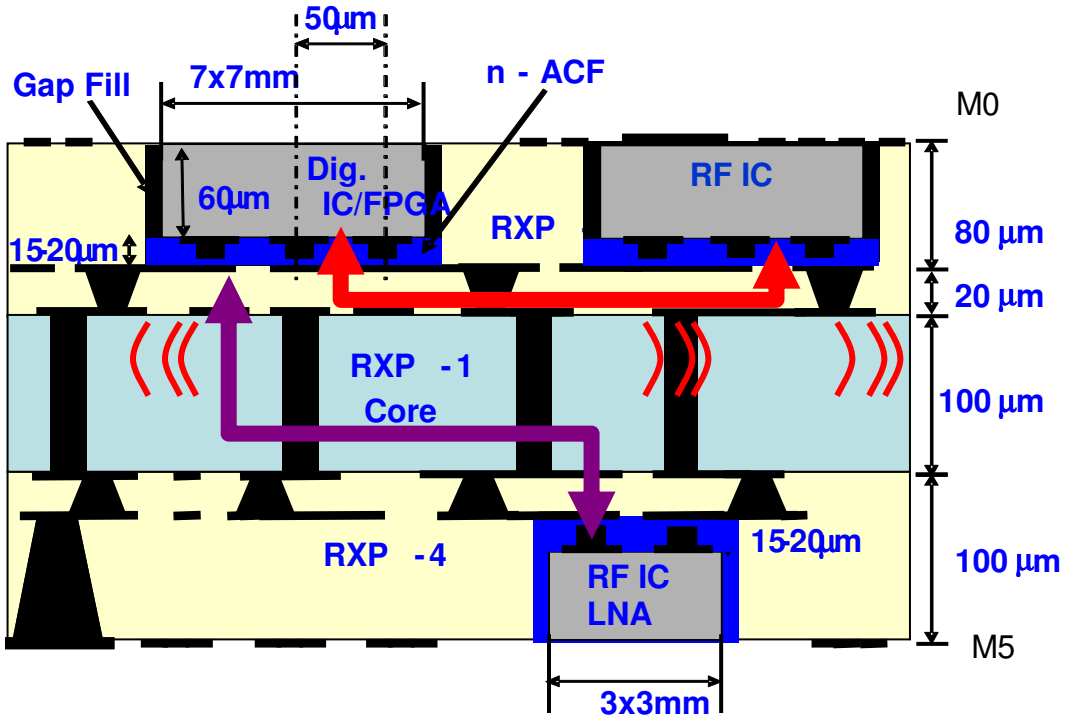
With Embedded ICs



Total Thickness = 300um

Easy to remove heat

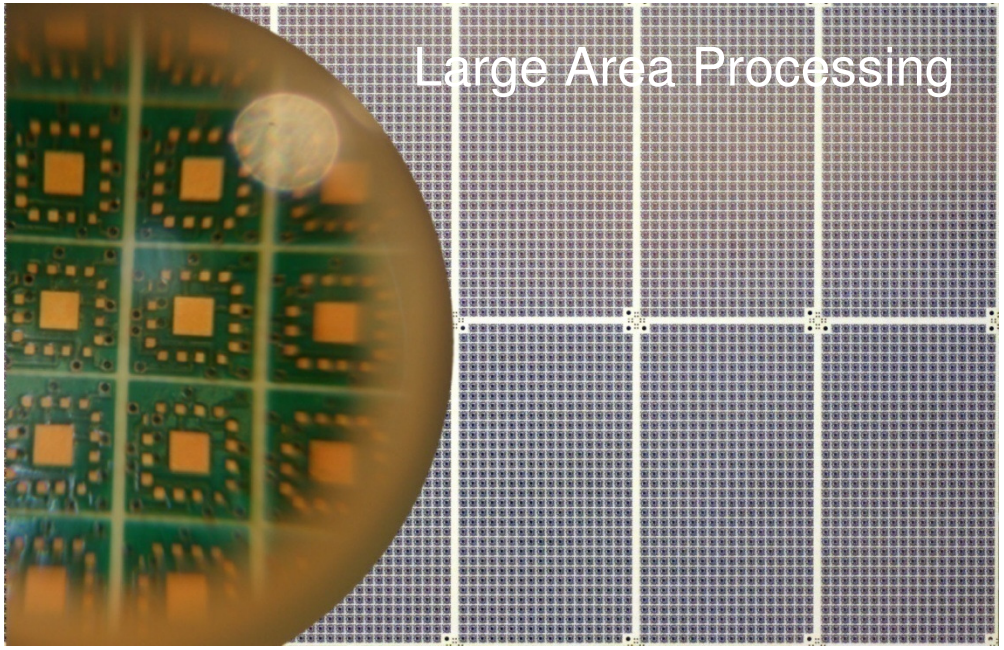


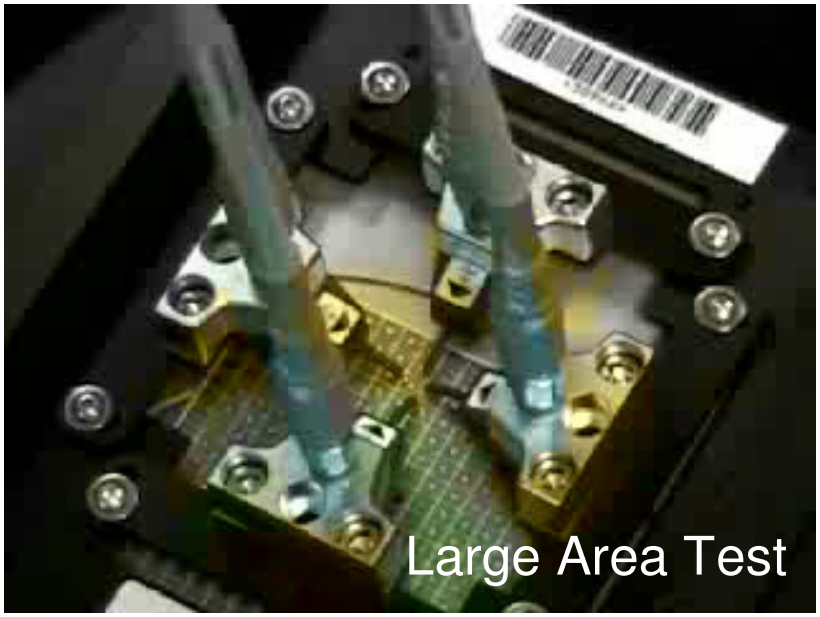


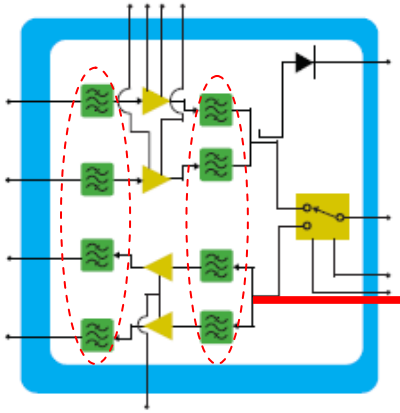
Courtesy: Packaging Research Center

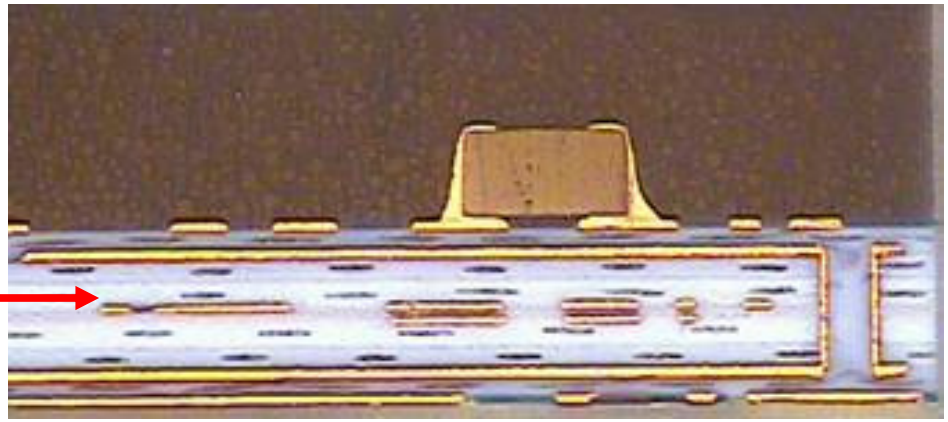
M. Swaminathan, V.Sundaram, J. Papapolymerou and R. Pulugurtha, "Polymers for RF Apps", IEEE Microwave Magazine, Dec 2011

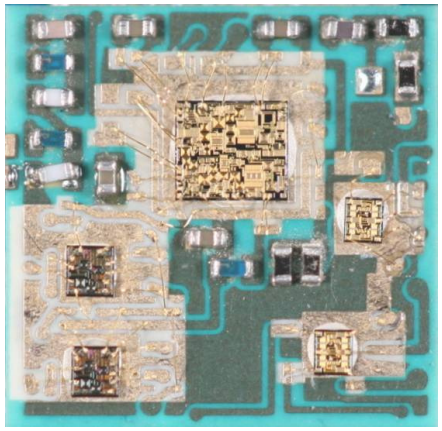
Large Area Manufacturing





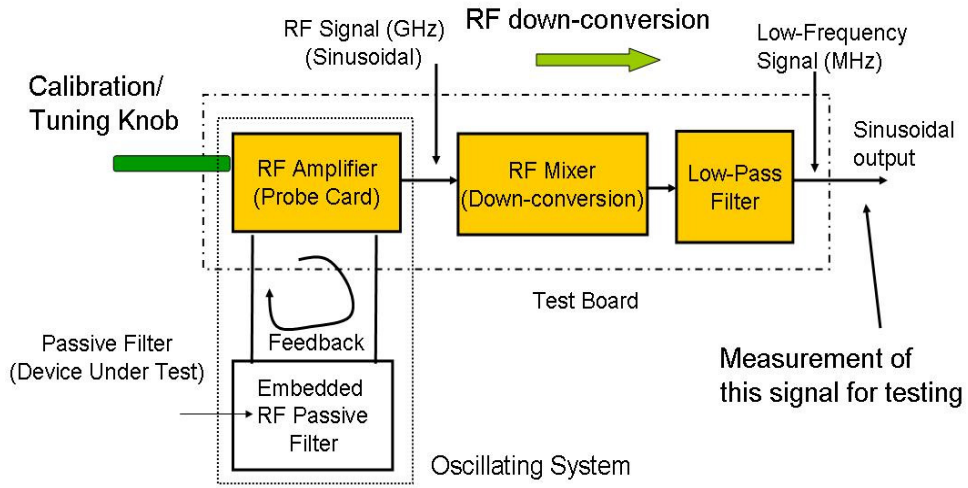


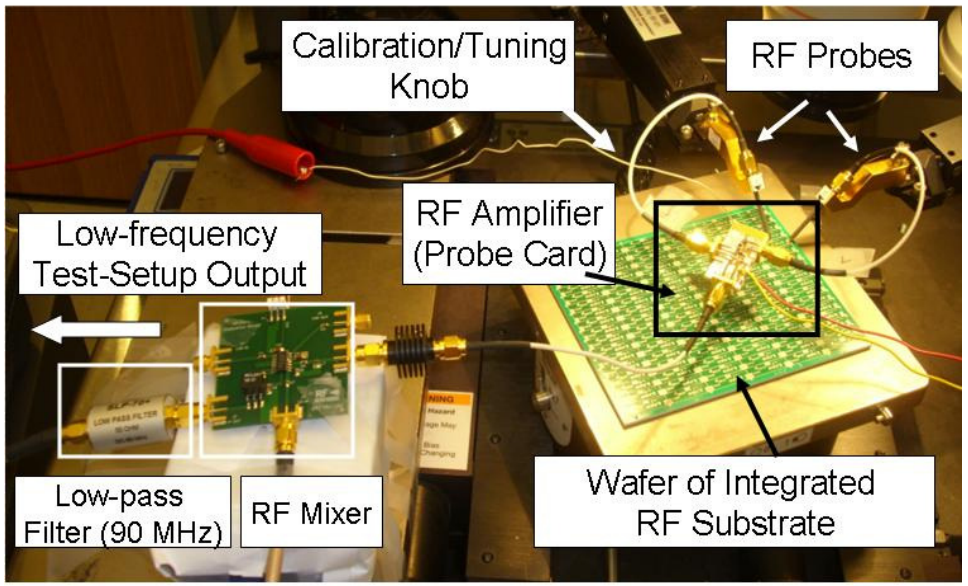


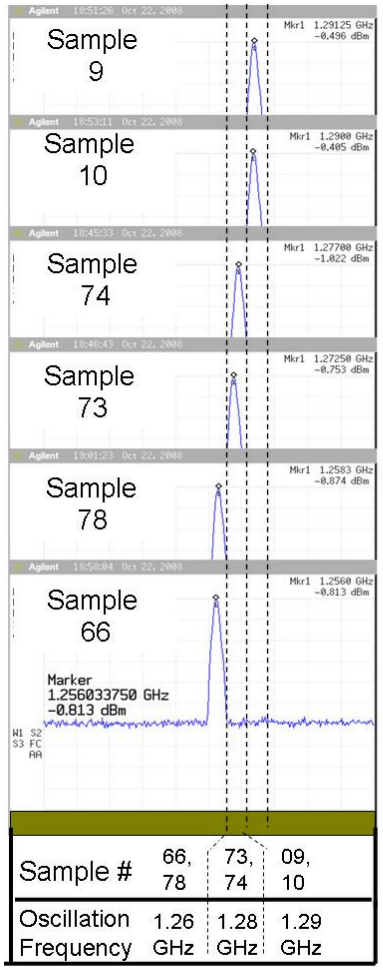


World's smallest organic RF Module, Courtesy: Jacket Micro Devices (JMD), Founded in 2004, Acquired by AVX Corp. in 2009

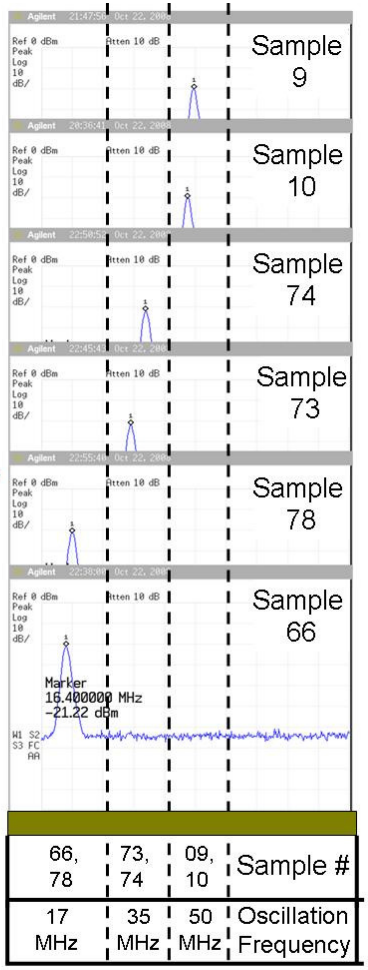
RF Test Method (High Frequency Testing @ Low Frequency)







A. High-Frequency Signal
(RF Amplifier Output)



B. Low-Frequency Signal
(Proposed Test-Setup Output)

A.Goyal, M. Swaminathan, A. Chatterjee, "Low-Frequency and Low-Cost Test Methodology for Integrated RF Substrates", IEEE Transaction on Advanced Packaging, Volume 33, Issue 3, 2010, pp(s) 669-680

What Comes Next ?

Continuous drive towards New Technologies …

At Reduced Cost …..

Even More Integration to Come
Dawn of the Even M(o)ore Era

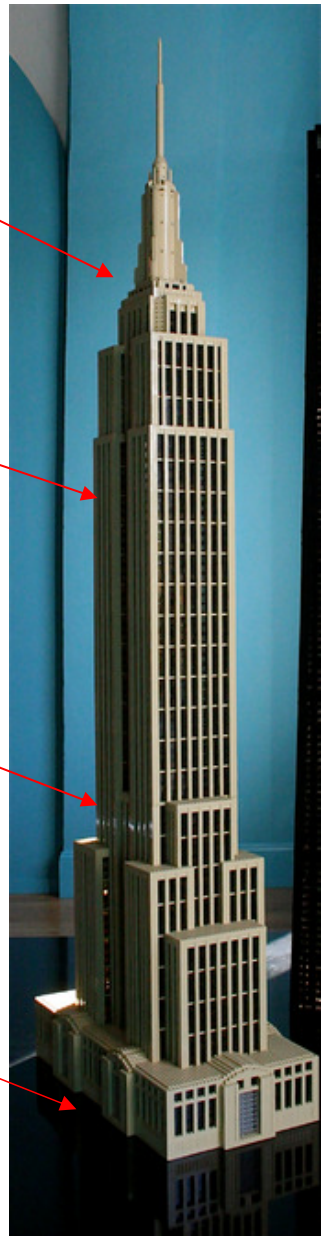
Going Vertical

Good cooling System to remove heat

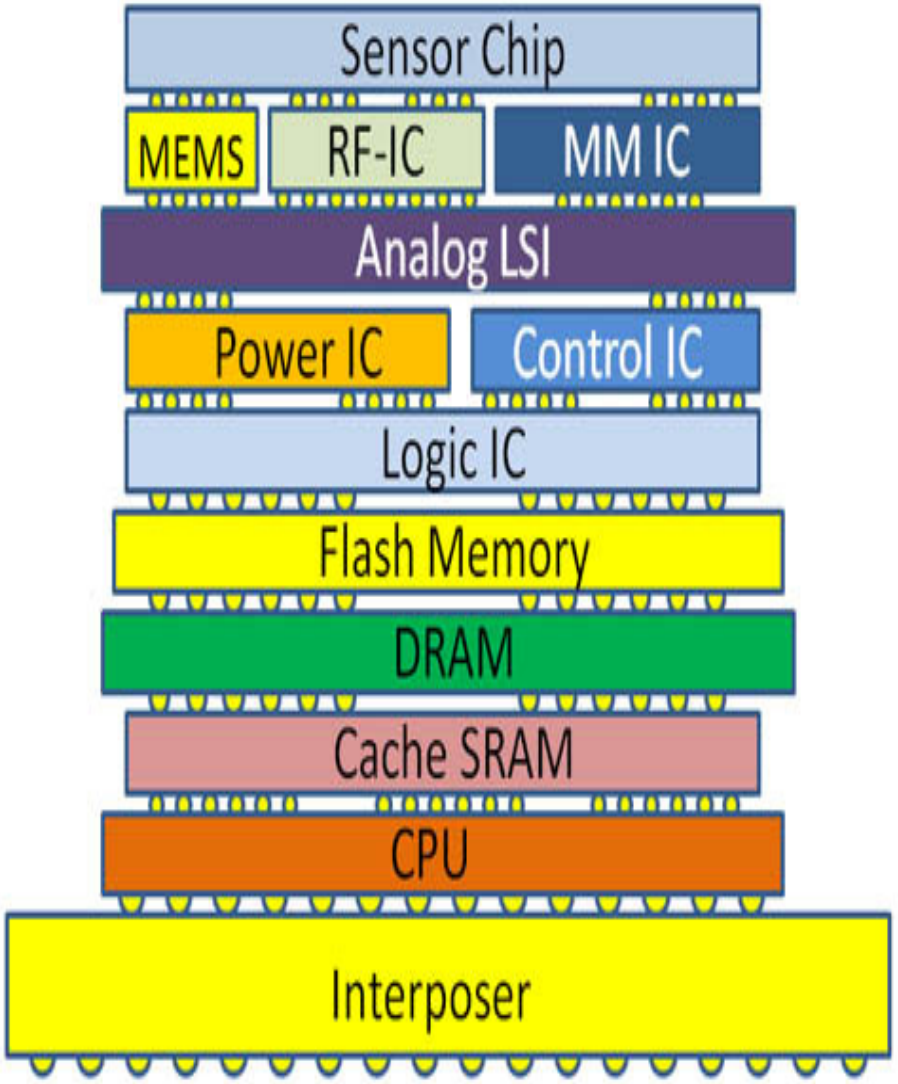
Mechanical Integrity to Protect against Hurricane

Communication Between Floors With minimum interference

Strong Foundation to protect against earthquake & entry/exit to outside world



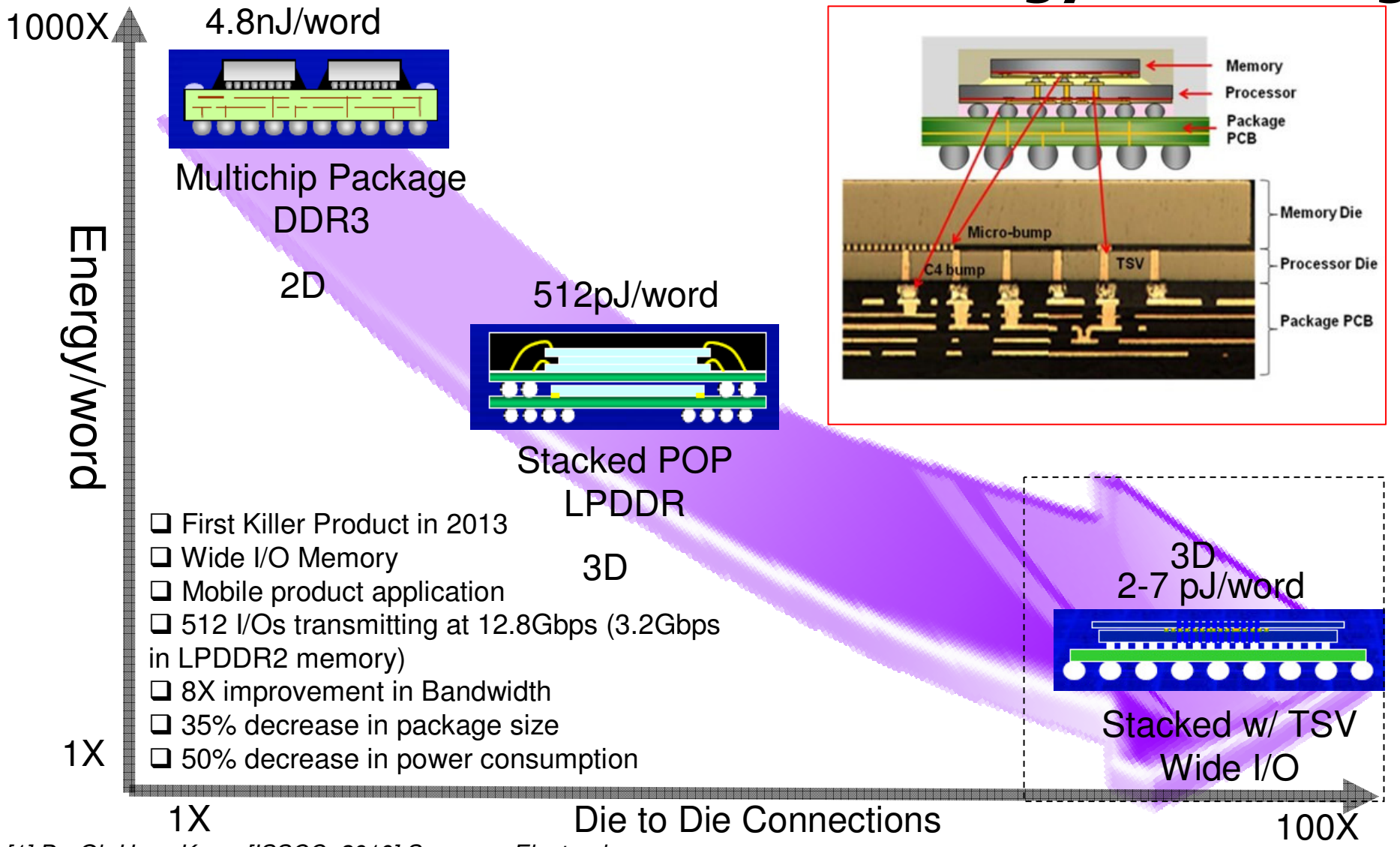
Empire State Building



Micro-system

www.ipc.gatech.edu

Next Semiconductor Revolution - 3D Integration
3D Interconnects Enable Low Energy Processing

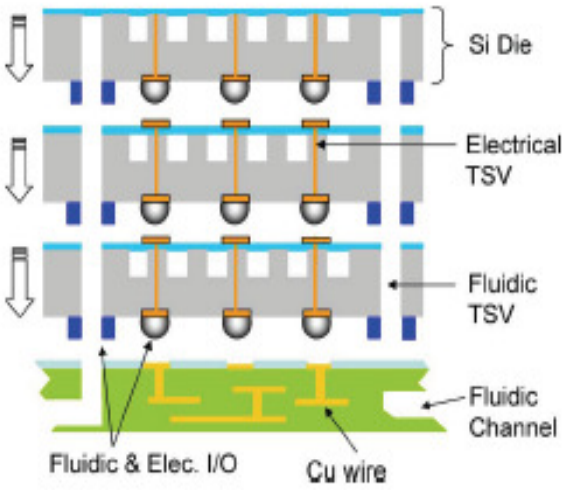


- First Killer Product in 2013
- Wide I/O Memory
- Mobile product application
- 512 I/Os transmitting at 12.8Gbps (3.2Gbps in LPDDR2 memory)
- 8X improvement in Bandwidth
- 35% decrease in package size
- 50% decrease in power consumption

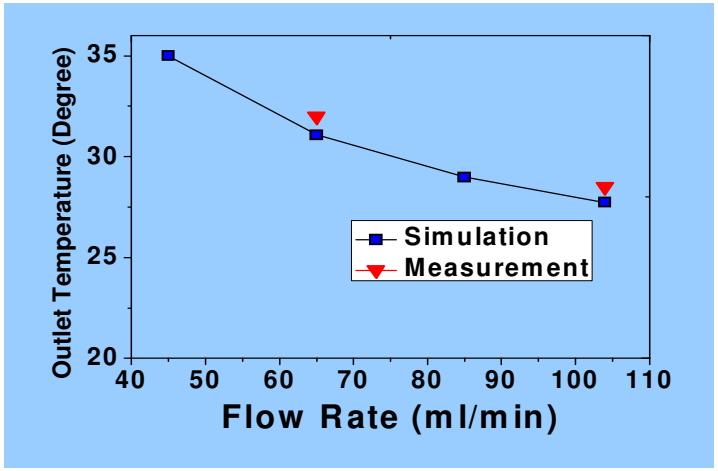
[1] Dr. Oh Hyun Kwon [ISSCC, 2010] Samsung Electronics

Courtesy: Part Greg Taylor, Intel and Paul Franzon, NC State

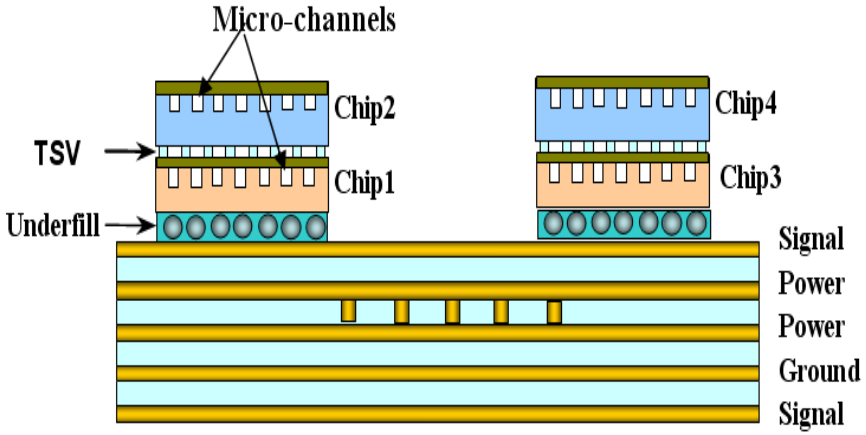
Removing Heat – A Major Challenge for 3D Integration for High Power Chips



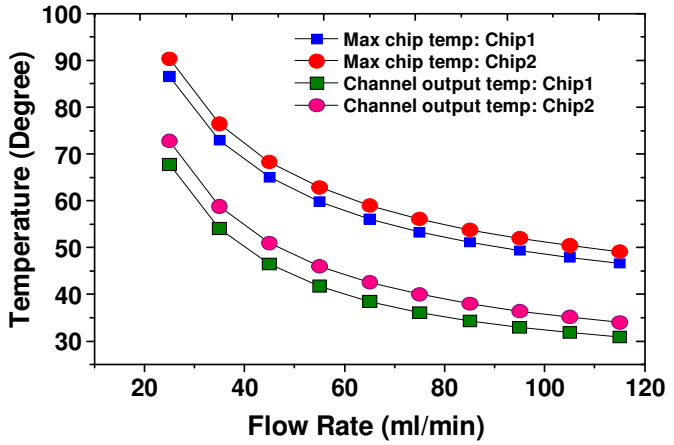
Correlation with measurement



3D System with micro-channels

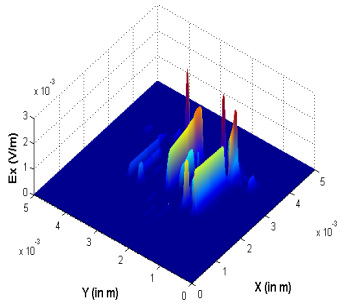


Max temperature v.s. flow velocity

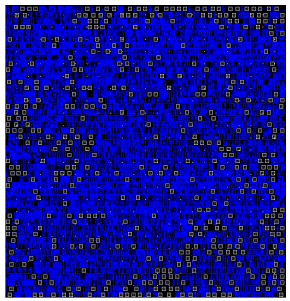


J. Xie, M. Swaminathan, "Electrical-thermal co-simulation with micro-channel water cooling in 3D integration," accepted with revision by *IEEE Trans. Advanced Packaging, 2010.*

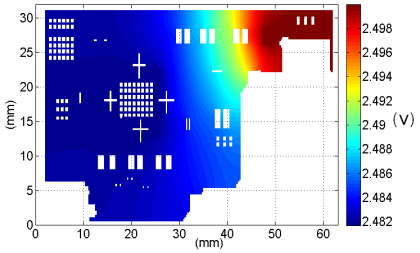
Modeling for 3D Integration



Signal Integrity

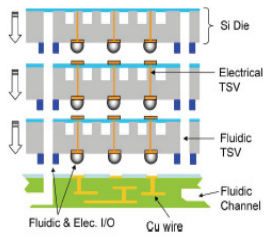


Place & Route

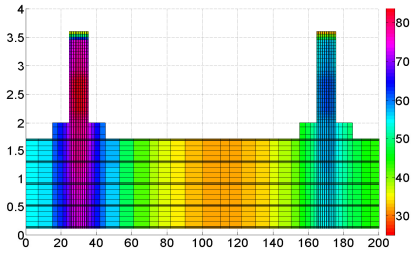


Power Delivery/DC/AC EMI

Electrical (EMC)

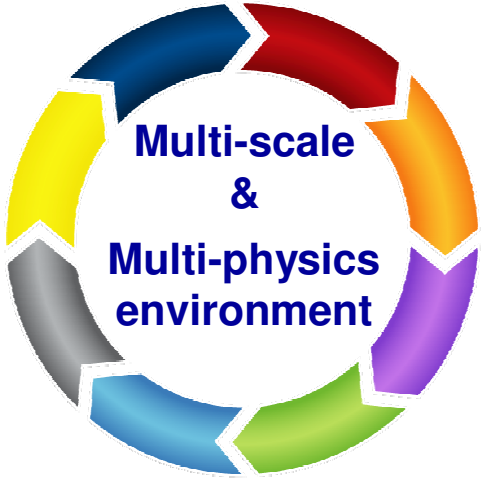


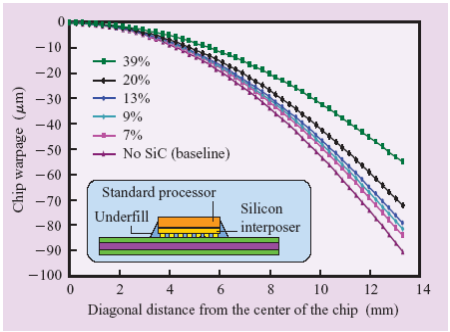
Thermal Management



Joule Heating

Thermal

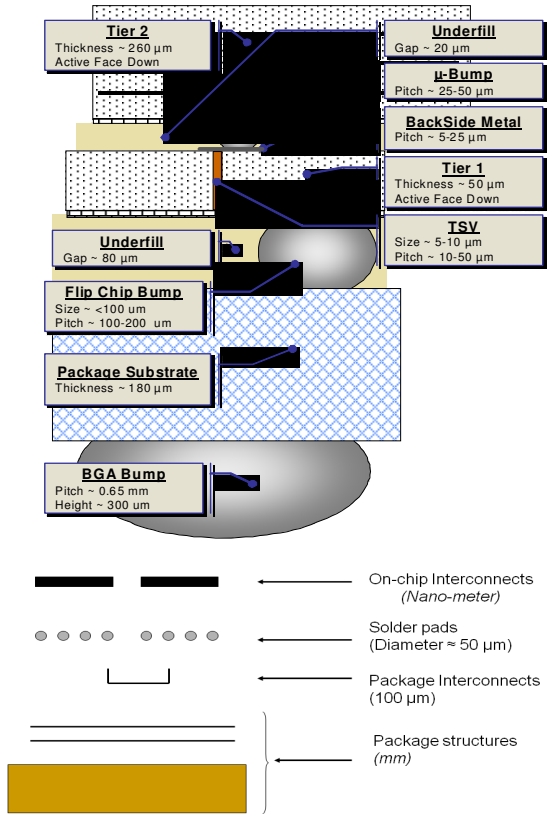




Mechanical Stresses

Mechanical

Multi-scale Geometry



Multi-physics – Interaction between Power Delivery and Heat Generation

- Steady-state Electrical Problem

$$\nabla\cdot\left(\frac{1}{\rho(x,y,z,T)}\nabla\phi(x,y,z)\right)=0$$

$\rho(x,y,z,T)$: Electrical Resistivity

$\phi(x,y,z)$: Electrical Potential

- Steady-state Thermal problem

$$\nabla\cdot\left(k(x,y,z)\nabla T(x,y,z)\right)=-P(x,y,z)$$

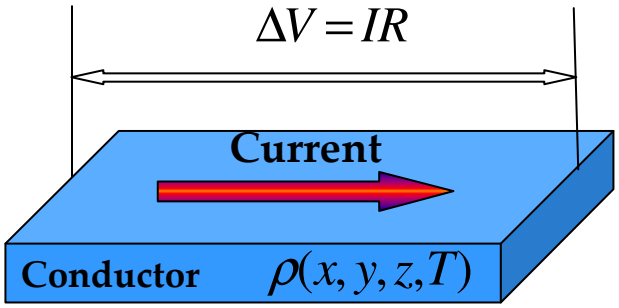
$k(x,y,z,T)$: Thermal conductivity

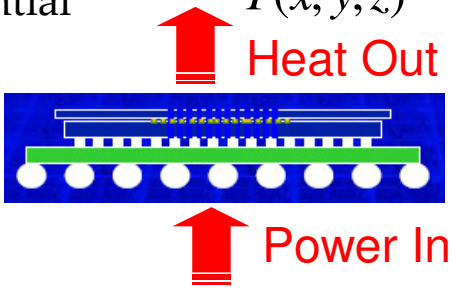
$T(x,y,z)$: Temperature

Ohmic Loss → Joule Heat:

$$\vec{P}_{Joule}(x,y,z)=\vec{J}\cdot\vec{E}(x,y,z)$$

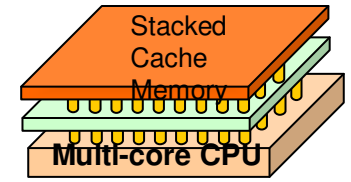
$$\Delta V=IR$$

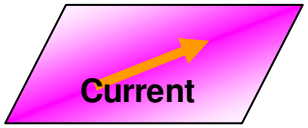




Heat sources $P(x,y,z)$

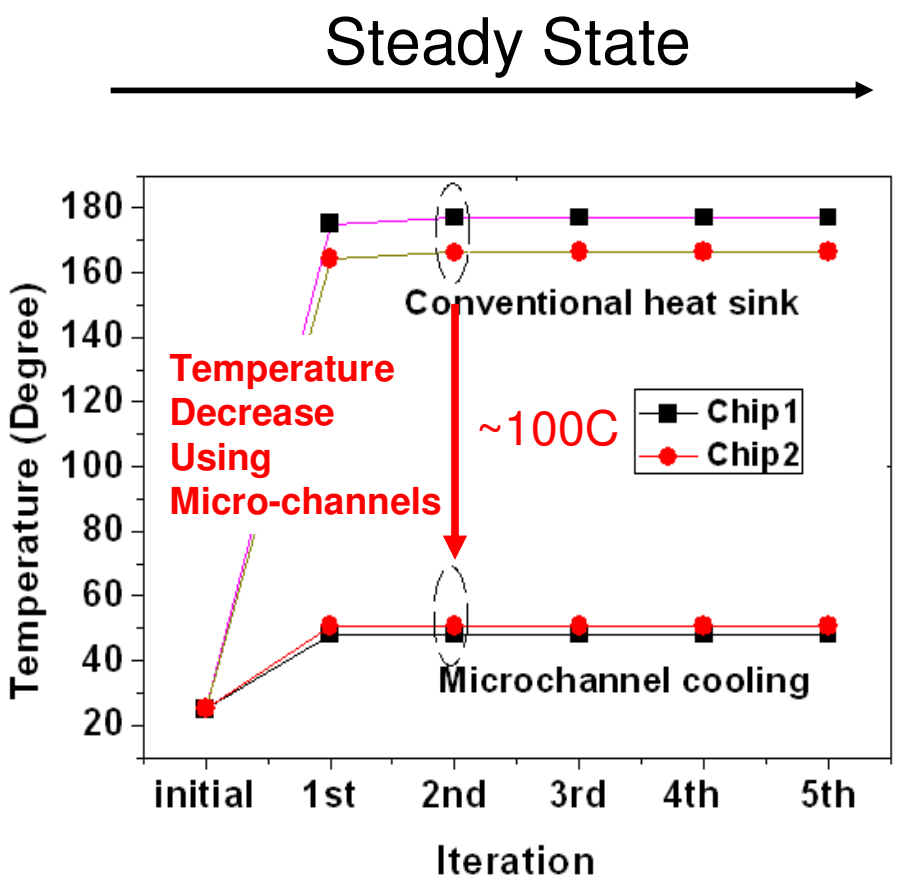
Power from Transistors

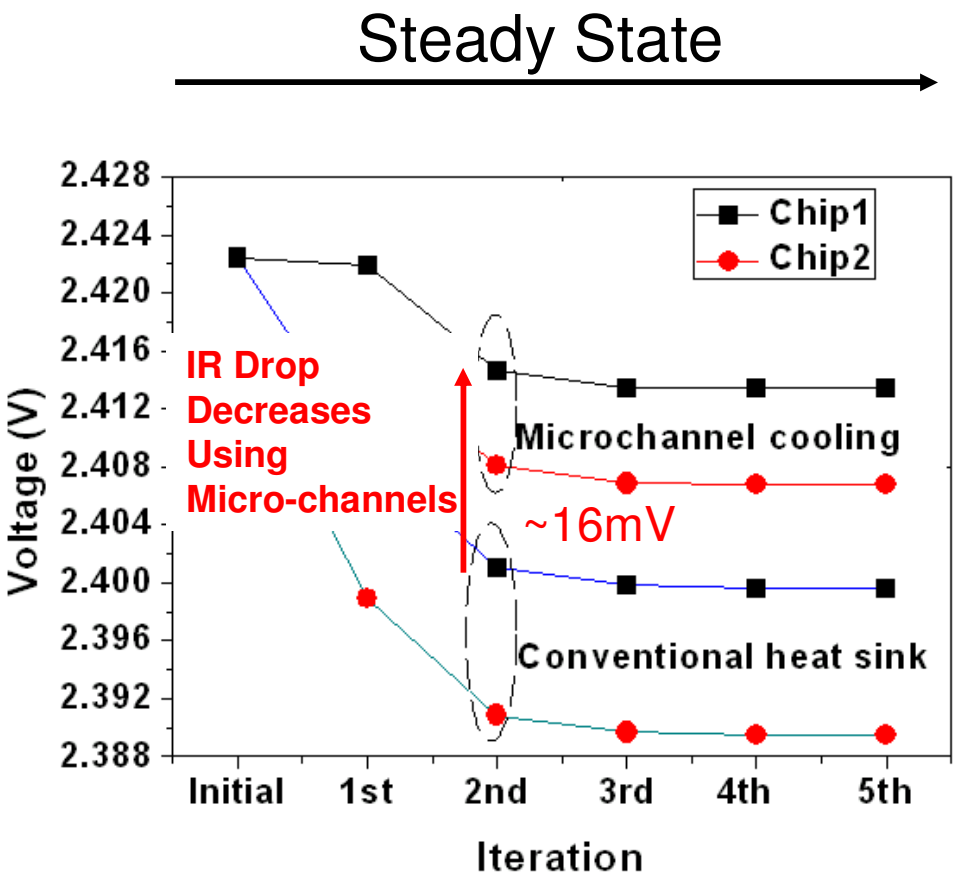




Joule heating

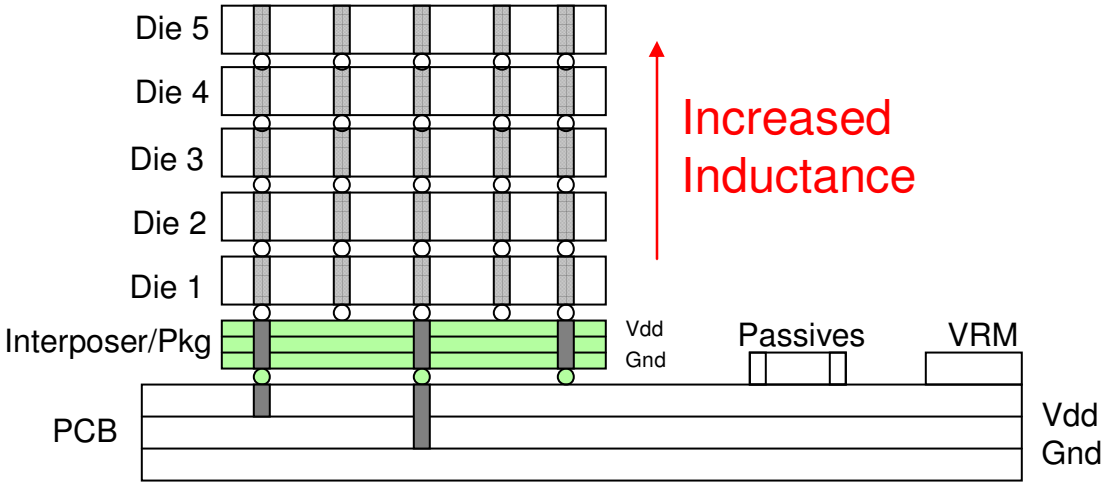
Temperature and IR drop with Micro-fluidic Cooling

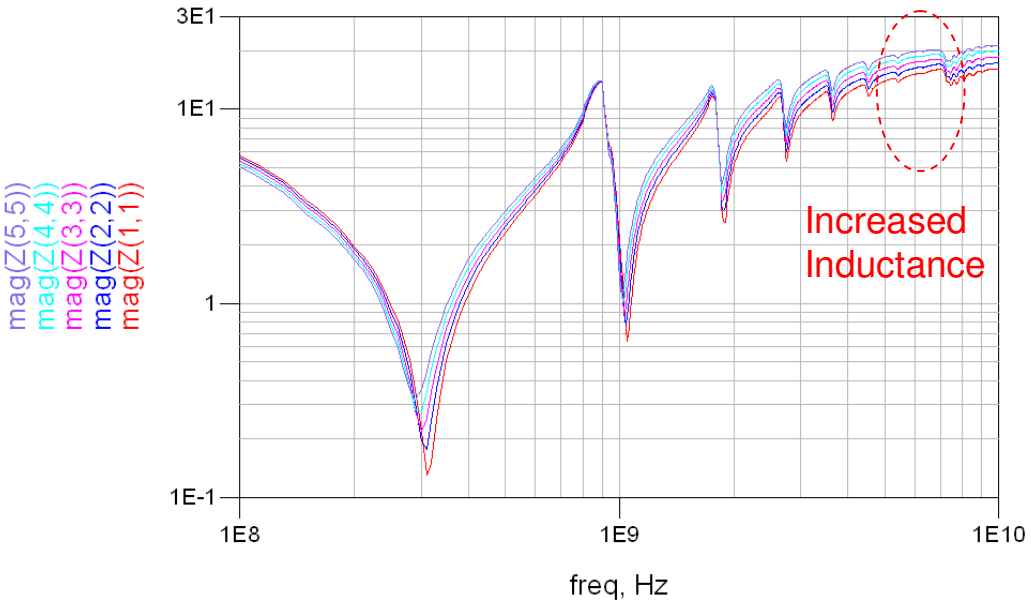




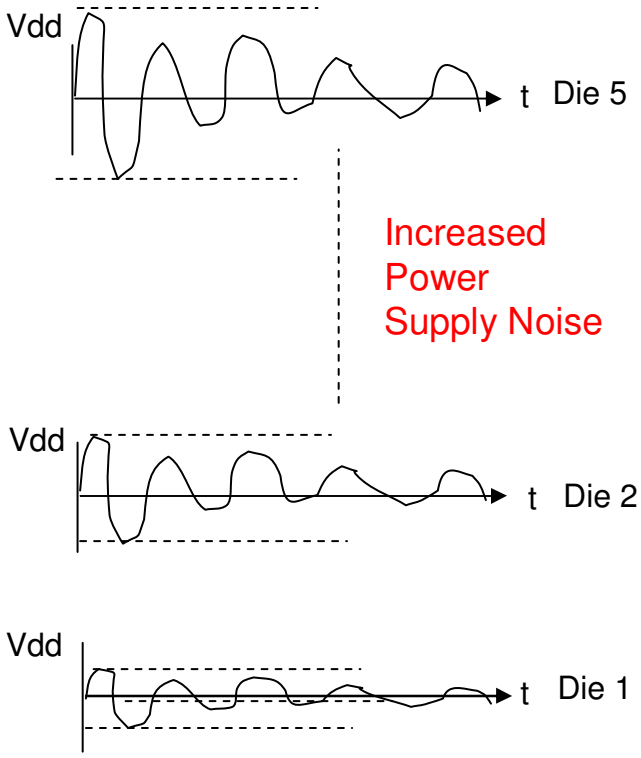
Temperature (Flow rate: 104 ml/min)

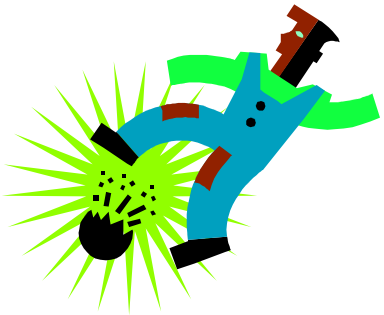
Power Distribution and Simultaneous Switching Noise
A Big Problem for 3D Integration





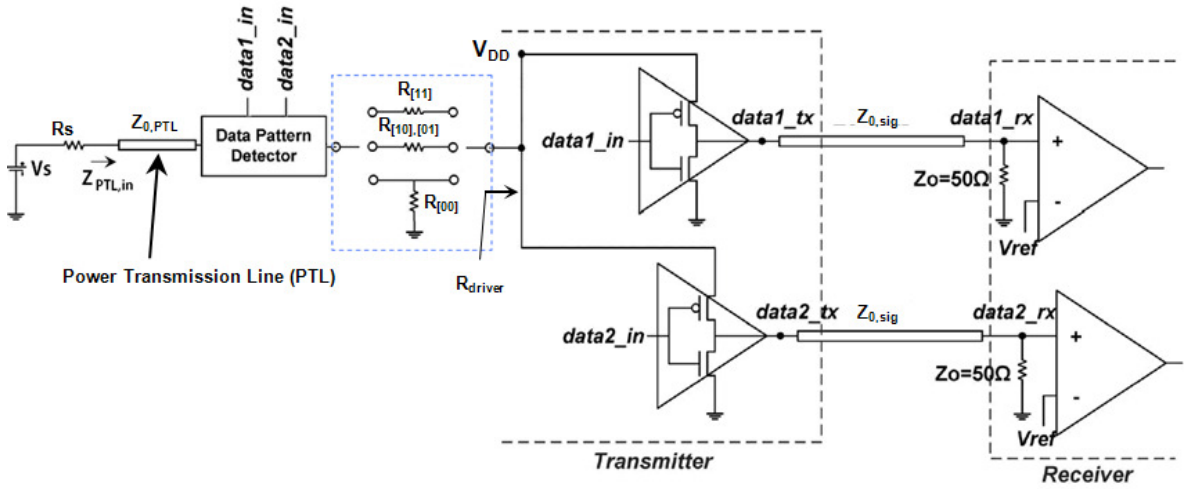
Power Supply Noise





Modified Power Distribution and Signaling Constant Voltage Power Transmission Line (CVPTL)

- Power planes replaced with Power Transmission Line (PTL)
- Depending on the input data, a data pattern detector is used to select a resistor path in the PDN to keep the impedance looking into the input of the PTL ($Z_{PTL,in}$) constant.
- Dynamic resistor path compensates for varying current to keep V_{DD} constant regardless of data.



Calculate resistor values:

$$R_{driver}[k] = \frac{R_{on} + R_L}{k}$$

$$R_{path}[k] = \frac{1}{V_{dd}}\left(V_s \cdot R_{driver}[k] - V_{dd}\left(R_{driver}[k] + R_{sw} + R_s\right)\right)$$

for k = 0,1,…,N-1

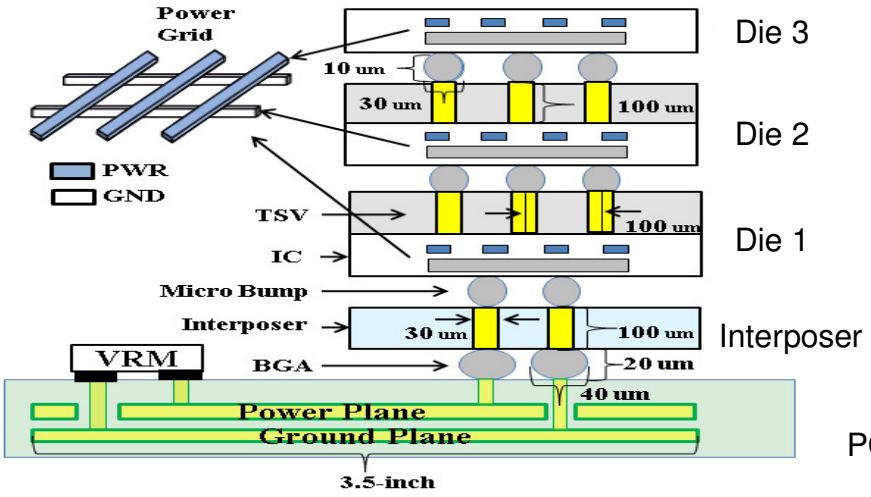
$$R_{path}[N] = \frac{1}{V_{dd} - V_s}\left(-V_{dd} \cdot \left(R_s + R_{sw}\right)\right)$$

[1] Telikepalli, S..; Swaminathan, M.; Keezer, D.; "Minimizing Simultaneous Switching Noise at Reduced Power with Constant Voltage Power Transmission Lines for High-Speed Signaling," To be presented at the International Symposium on Quality Electronic Design (ISQED), 2013

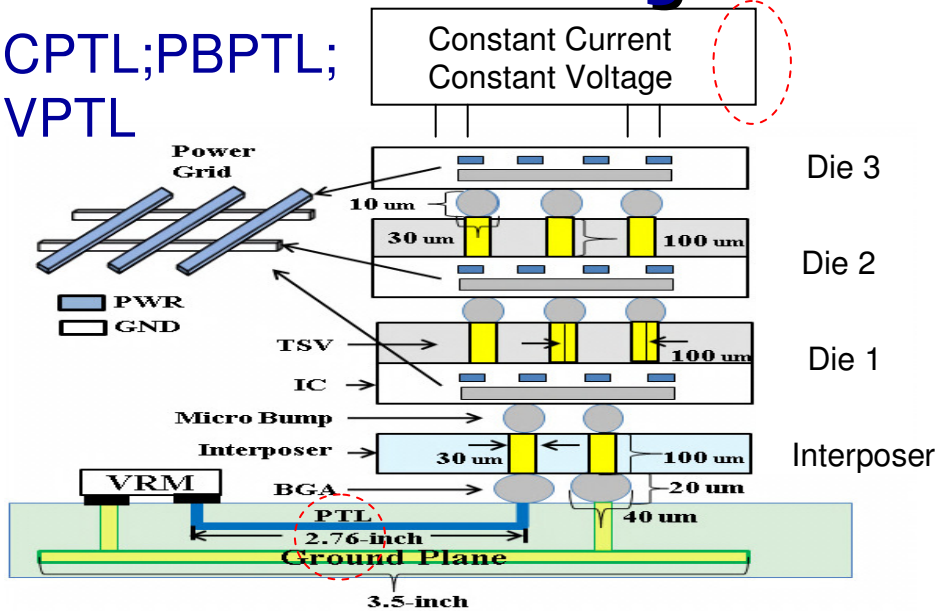
[2] Huh, S.; and Swaminathan, M. , "Are Power Planes necessary for High Speed Signaling", Designcon 2012. Best Paper Award in the RF and Design Category.

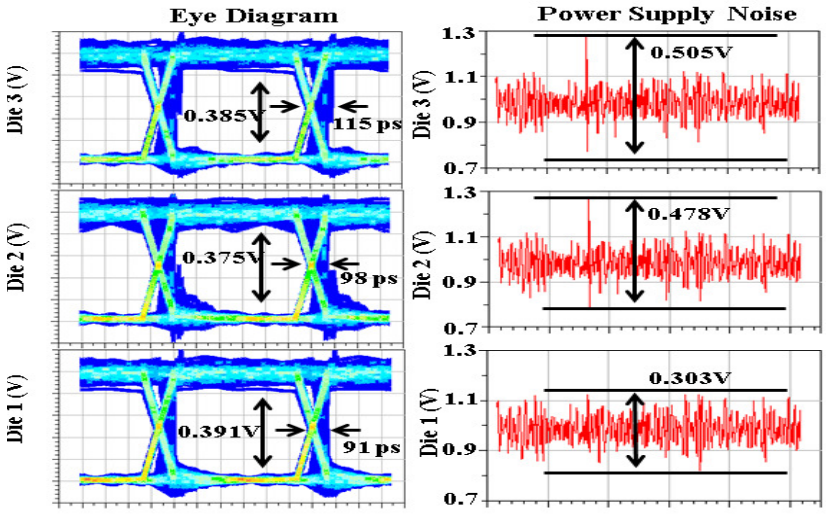
Alternate Power Distribution Scheme for 3D Integration

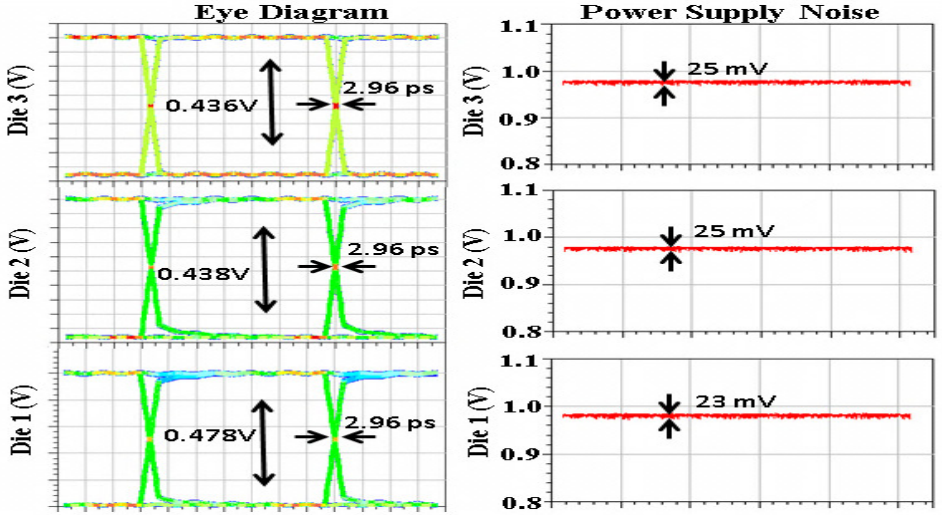
Conventional



CCPTL;PBPTL; CVPTL

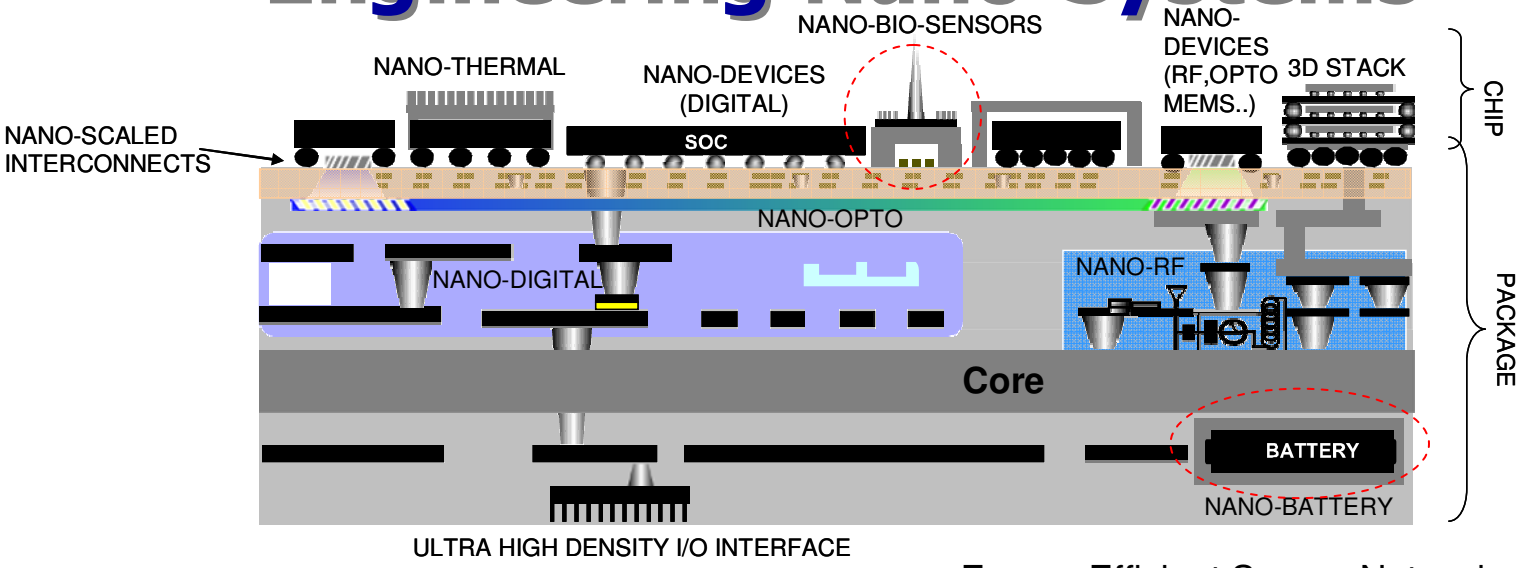




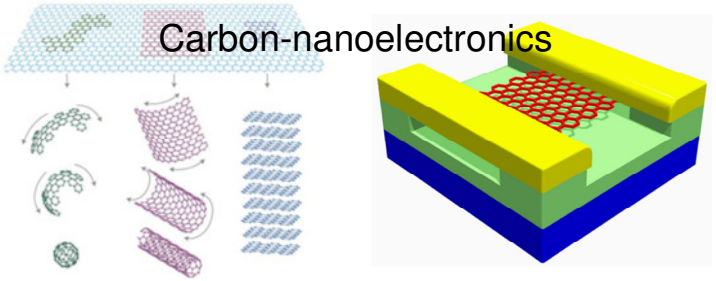


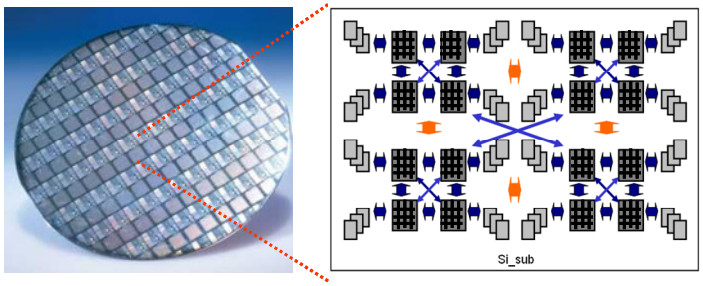
M. Swaminathan, "Design for Power Integrity – Status, Challenges and Opportunities", DL Talk, IEEE EMC Society, 2012-2013

Engineering Nano-Systems

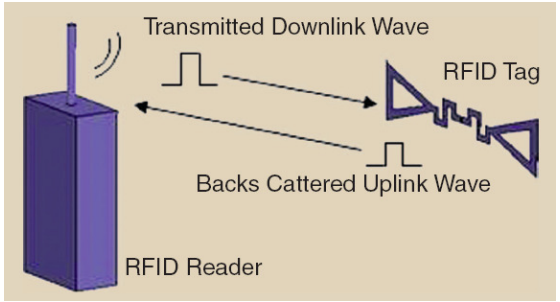


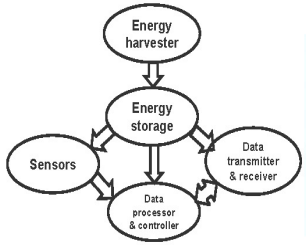
Energy Efficient Multicore Processors

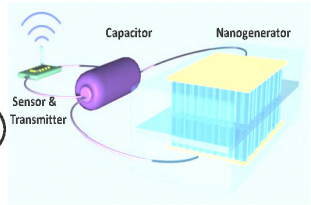




Energy Efficient Sensor Networks

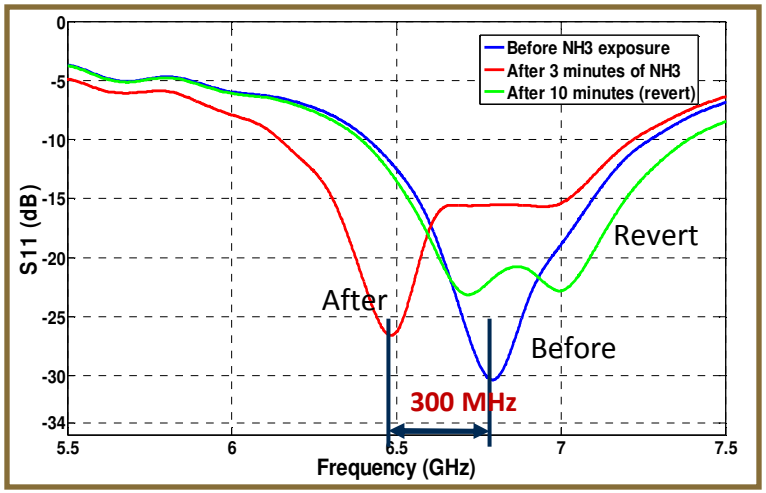


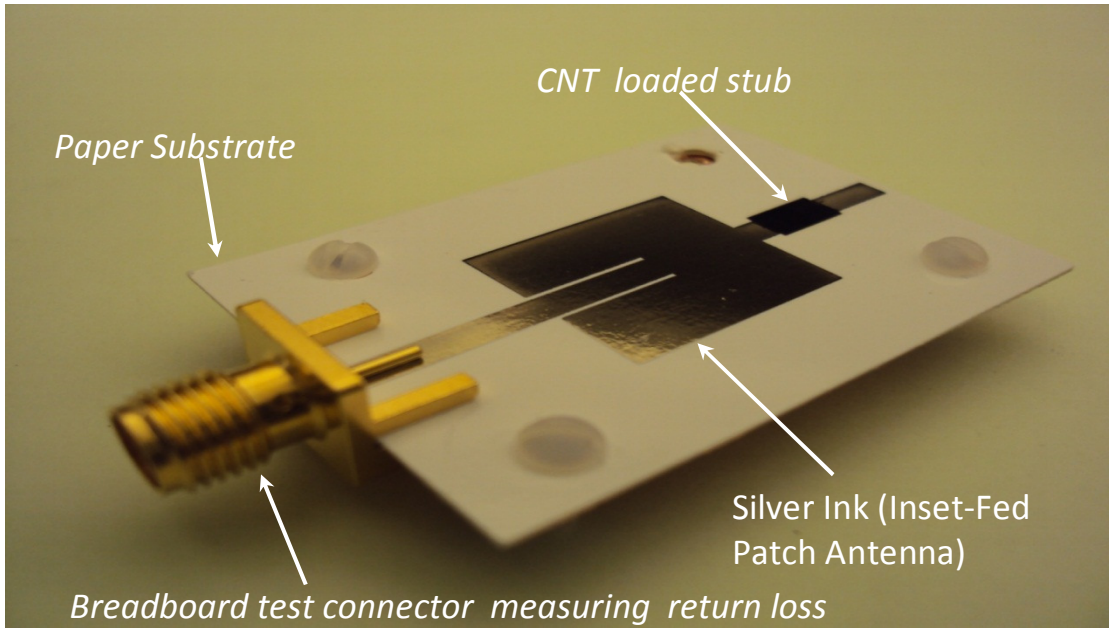




CNT Based Antenna for Sensor Applications

- **Trace ammonia OFF/ON/OFF (25 ppm)**
- **Phenomenon #1:**
  RF Resonance Frequency Shift
  (remote [standoff] RF detection)
- **Phenomenon #2:**
  Passive Backscatter Measurement
  (less sensitive to environment than #1)

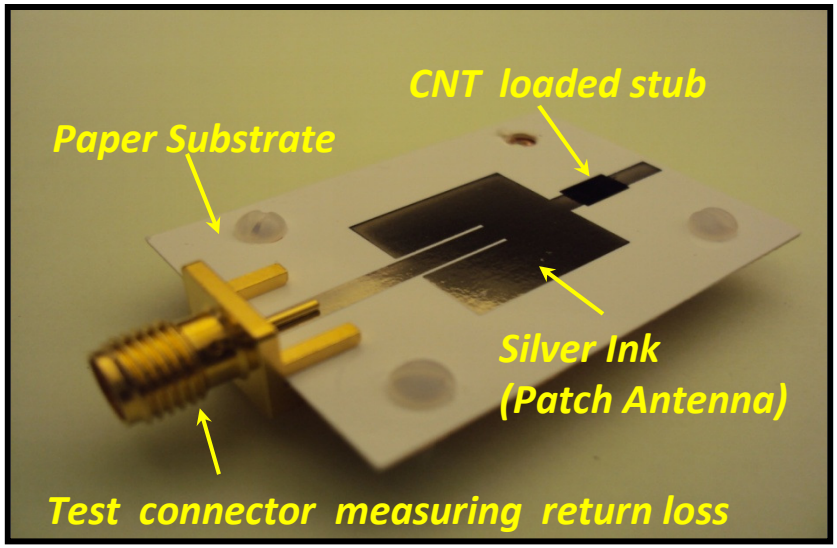




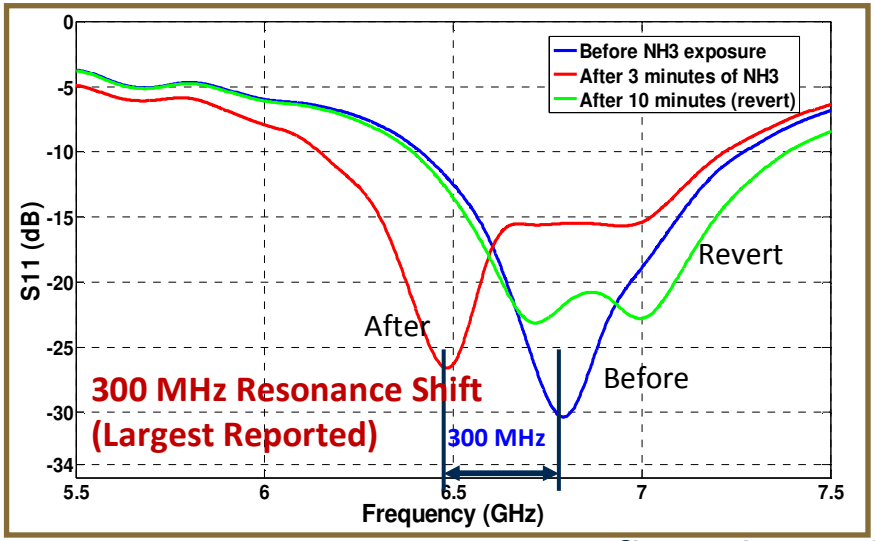
Unique Approach
Apply CNT to only a small part of the antenna to Minimize conductive losses

Courtesy: K. Naishadham, GTRI
M. Tentzeris, GT

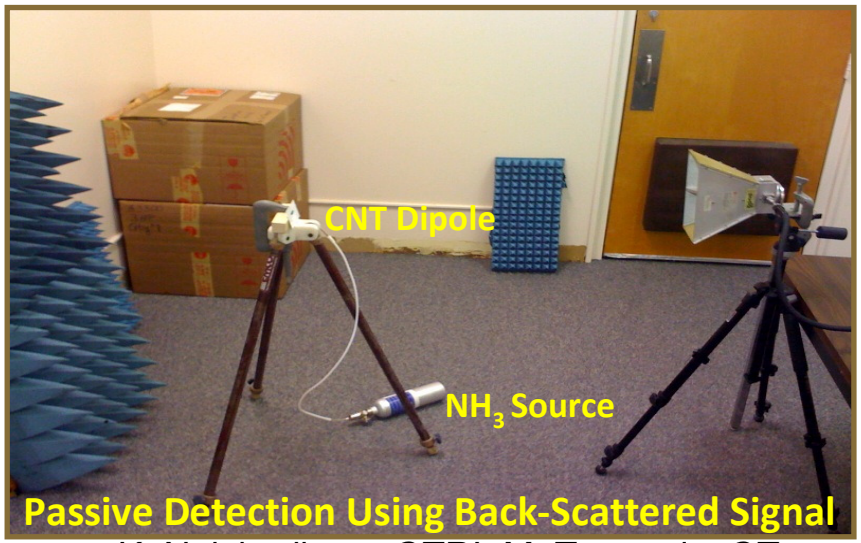
CNT based Antenna Sensor Experimental Validation



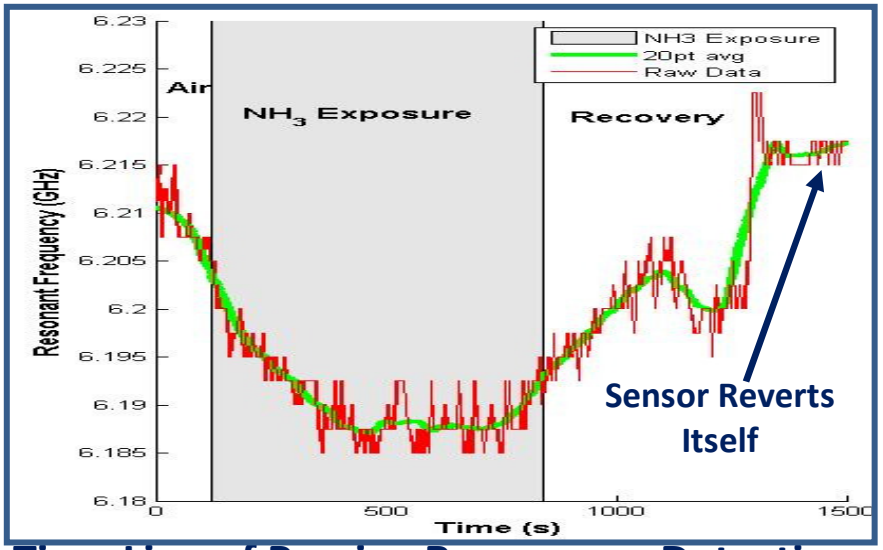
Detection of Ammonia Using Resonance Shift



Low-Power Detection Using Reflected Signal

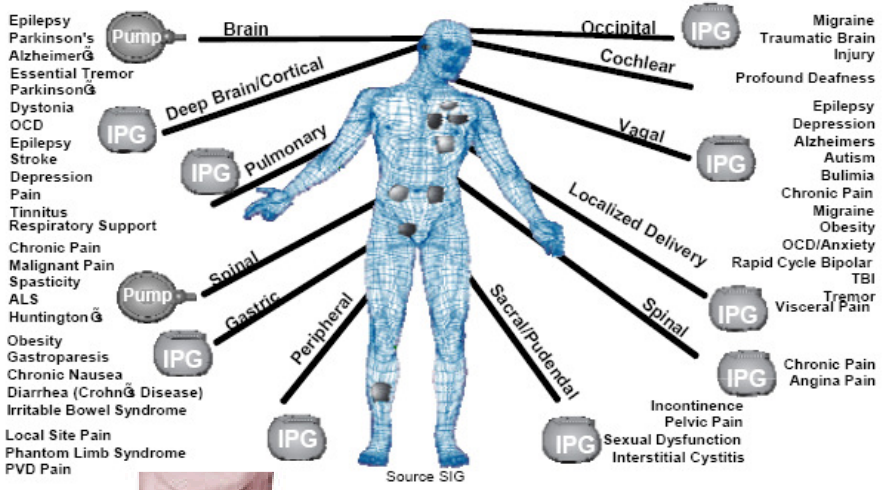


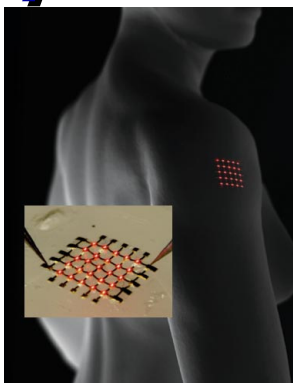
Courtesy: K. Naishadham, GTRI, M, Tentzeris, GT

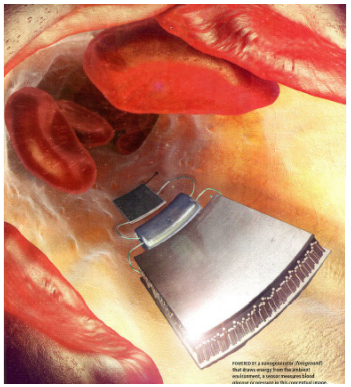


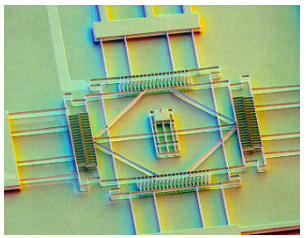
Time Line of Passive Resonance Detection

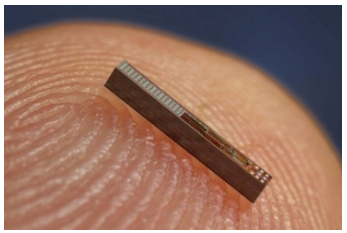
Harvesting Energy from Body Motion
The Battery Problem

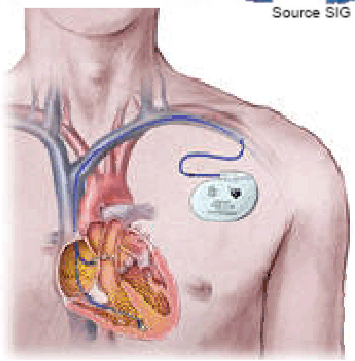












How much energy does each of us have?

Table 1. Mechanical energy from typical body motions and the expected electrical energy can be generated.

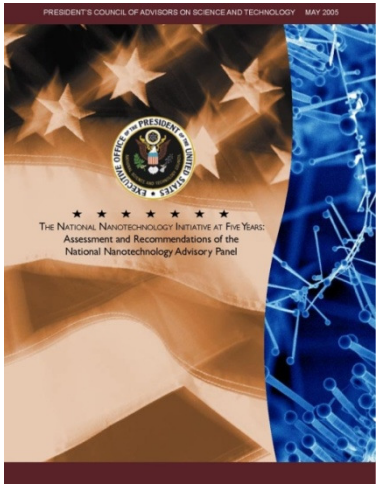
Activity	Mechanical	Electrical	Electrical energy per movement
Blood flow	0.93W	0.16W	0.16J
Exhalation	1.00W	0.17W	1.02J
Breath	0.83W	0.14W	0.84J
Upper limbs	3.00W	0.51W	2.25J
Fingers type	6.9-19mW	1.2-3.2mW	226-406μJ
Walk	67.00W	11.39W	18.9J

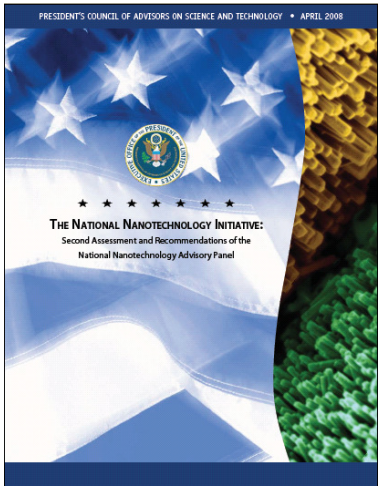
Irregular energy:
- Low frequency;
- Variable frequency;
- Variable amplitudes

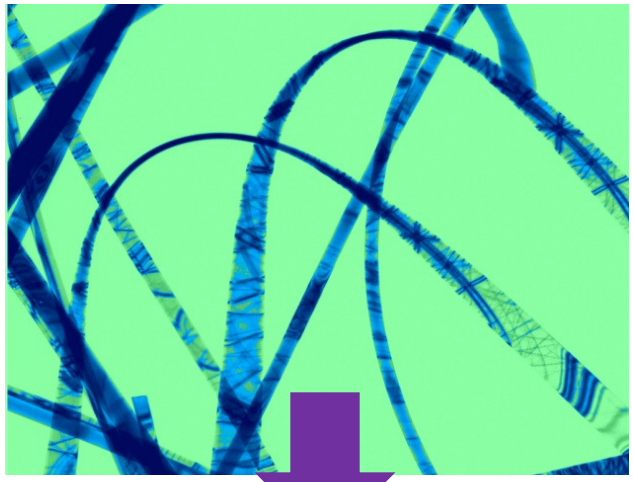
Courtesy: Z. L. Wang, Georgia Tech

Controlled Growth of ZnO Nanowires

ZnO



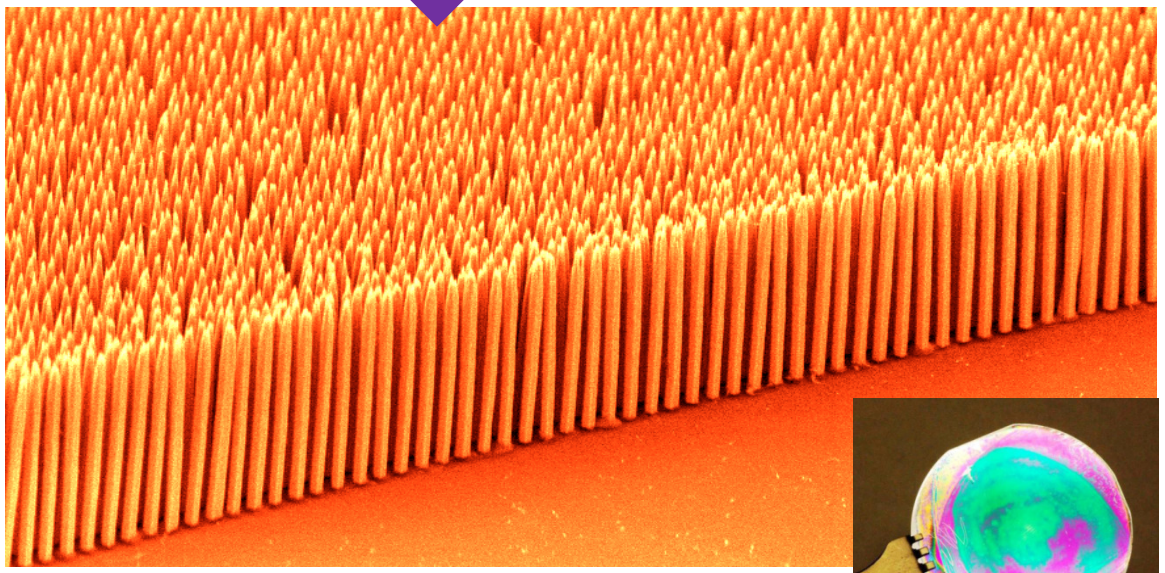




Science 291 (2001) 1947

ZnO:

- Semiconductor
- Piezoelectricity
- Optical material



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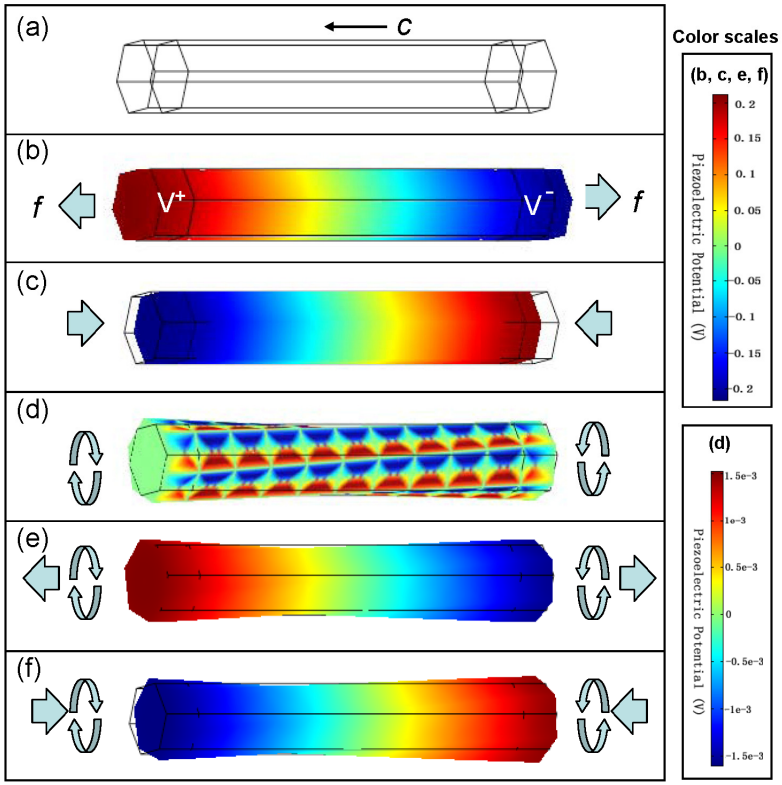
Courtesy: Z. L. Wang, Georgia Tech

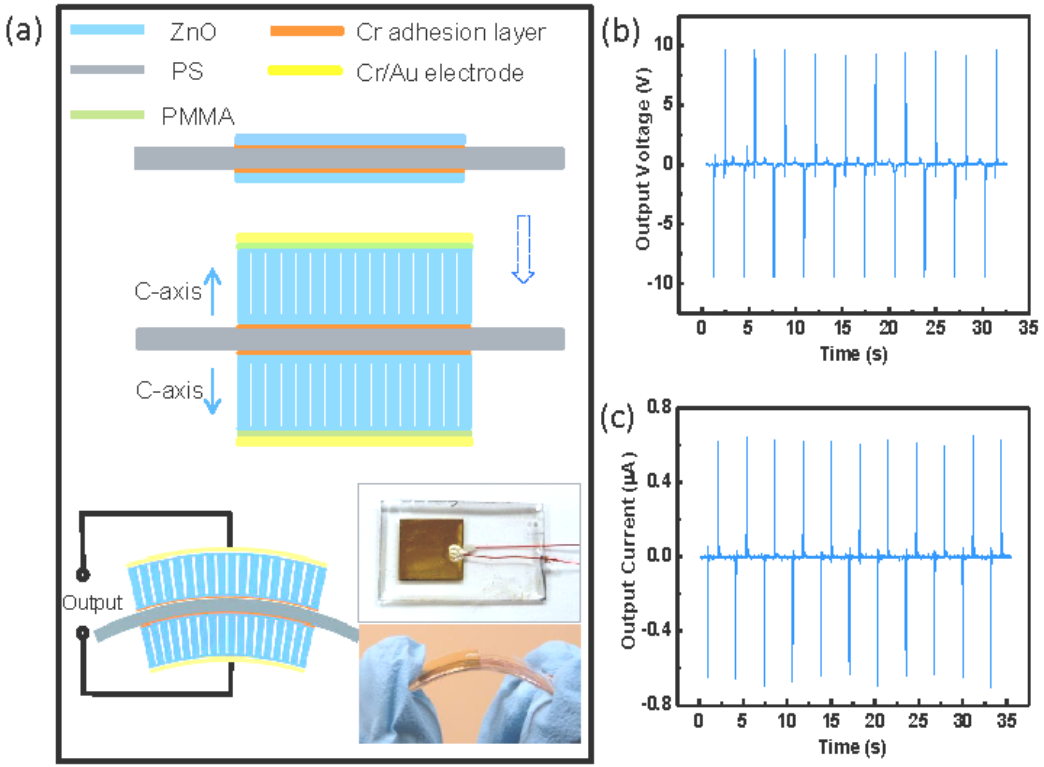
ZnO Nanowire and Nanogenerator Operating Principle

Piezoelectric potential for ZnO nanowire



60 – 85nN of force

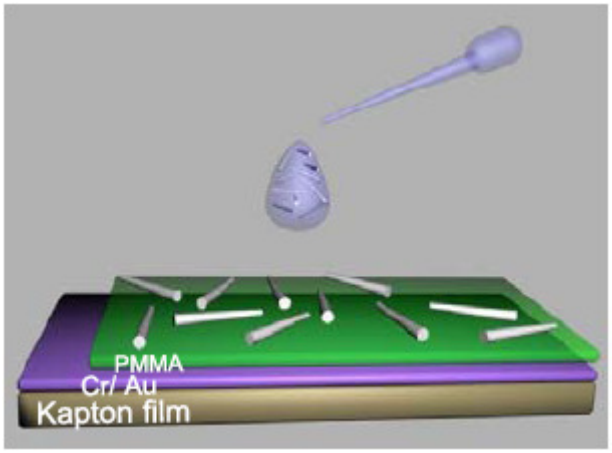
Nanogenerator and its output

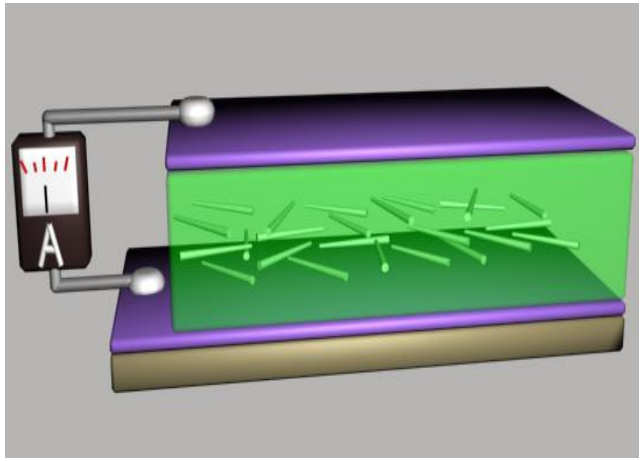


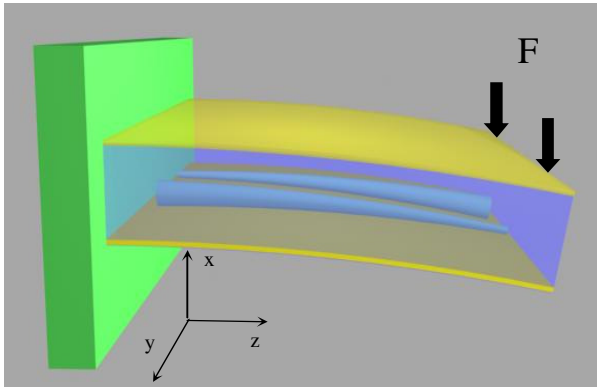
Flexible

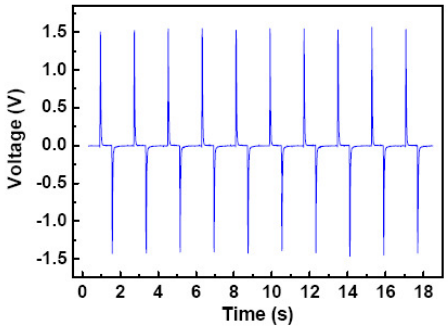
Courtesy: Z. L. Wang, Georgia Tech

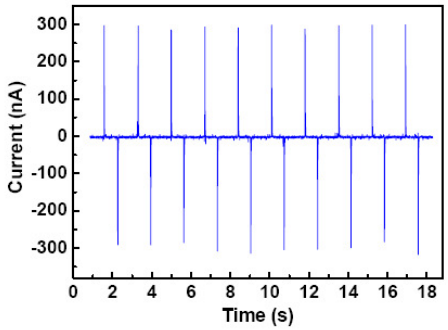
Driving LCD using Nanogenerator

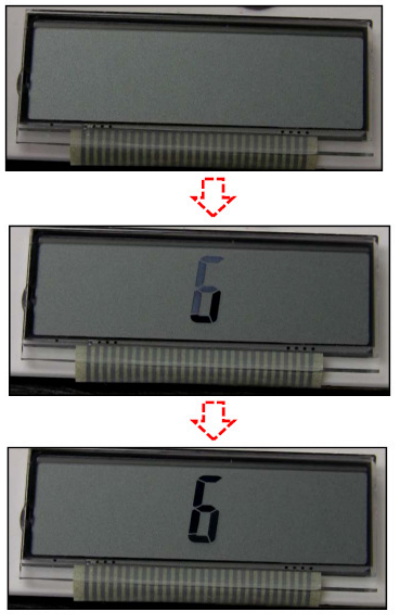


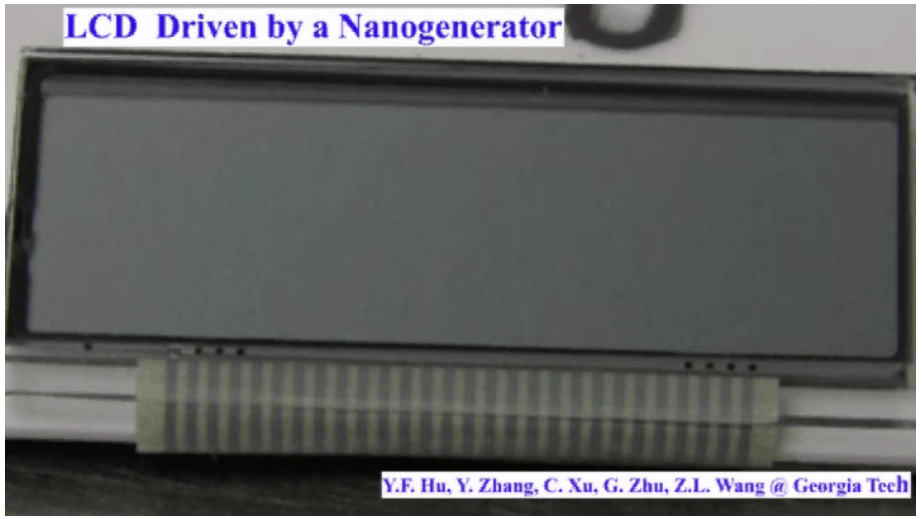












Hu, Zhang, Xu … Wang, Nano Letts.

Courtesy: Z. L. Wang, Georgia Tech

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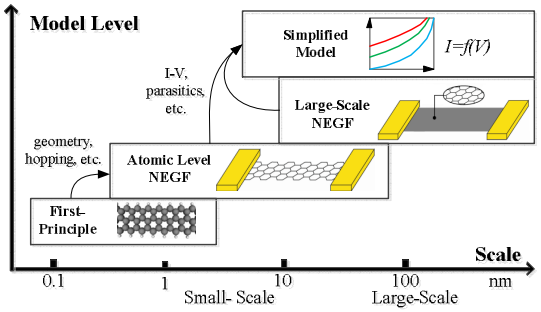
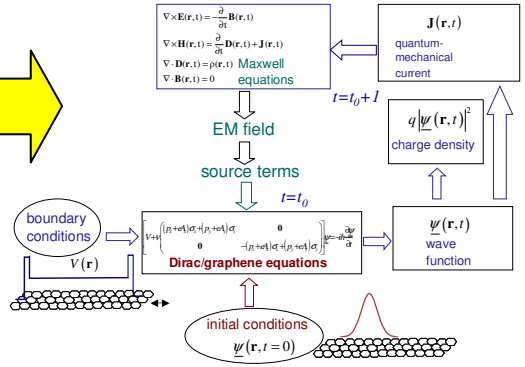
What will limit the move from Nano-Science into Nano-Engg. ?
Need for a Computational Cyber Infrastructure

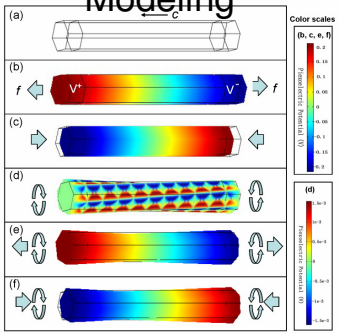
Electrical/Thermal Transport Modeling



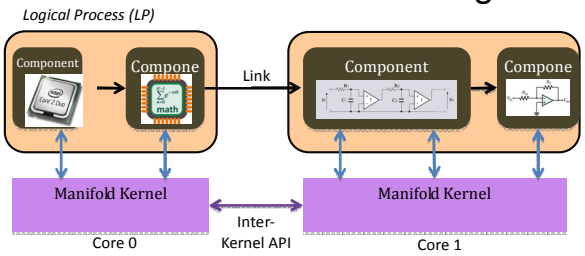
Combined EM/Device Modeling



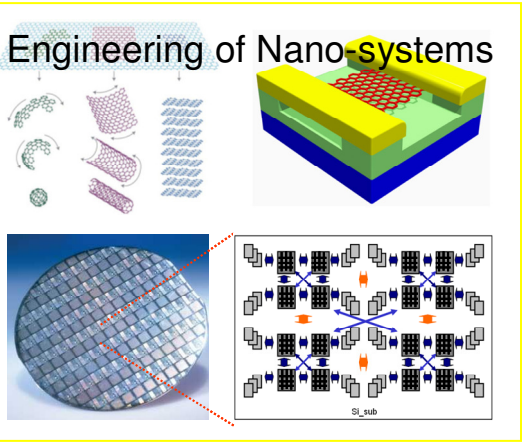
Energy Harvesting Modeling



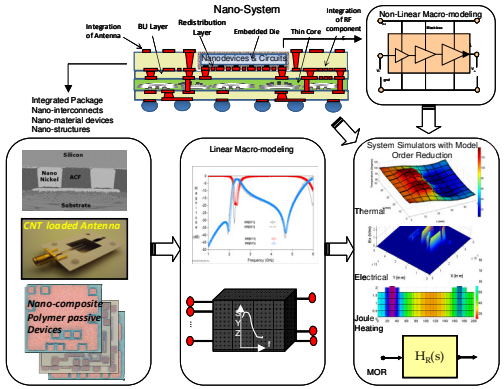
Architectural Modeling



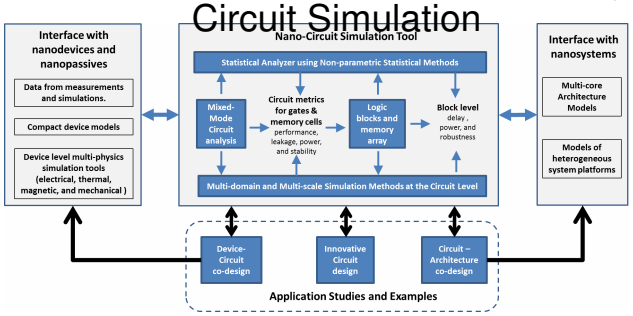
Engineering of Nano-systems



Package/System Modeling



Circuit Simulation



Summary

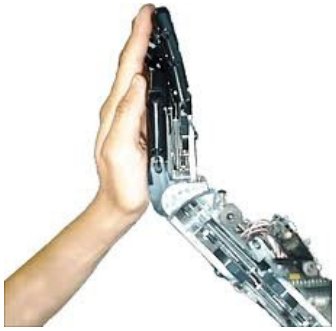
- Similar to transistor integration for ICs, System on Package (SOP) technologies provide component integration for systems
- Digital, RF and Optical convergence have been the drivers for SOP over the last two decades
- SOP has led to ~1000X reduction in the size of system level components
- Nano convergence with sensing and energy harvesting – the next big wave for SOP
- Move from the regime of Nano-science to the realm of Nano-engineering required
- Requires a further ~1000X reduction in system component dimensions to enable nano-systems

Innovations from our Engineering Community Required!

Upcoming Book on 3D Design and Modeling for 3D ICs and Interposers

- Focus on Design, Modeling and Tools for 3D
- Authors: M. Swaminathan and K. J. Han
- Chapters
  - System Integration Concepts
  - Modeling of Cylindrical Interconnections
  - Modeling of Through Silicon Vias
  - Electrical Performance & Signal Integrity
  - Power Distribution and Return Path Discontinuities
  - Thermal Effects
- Publication Date: 2013
- Published by World Scientific Publishers

Thank you



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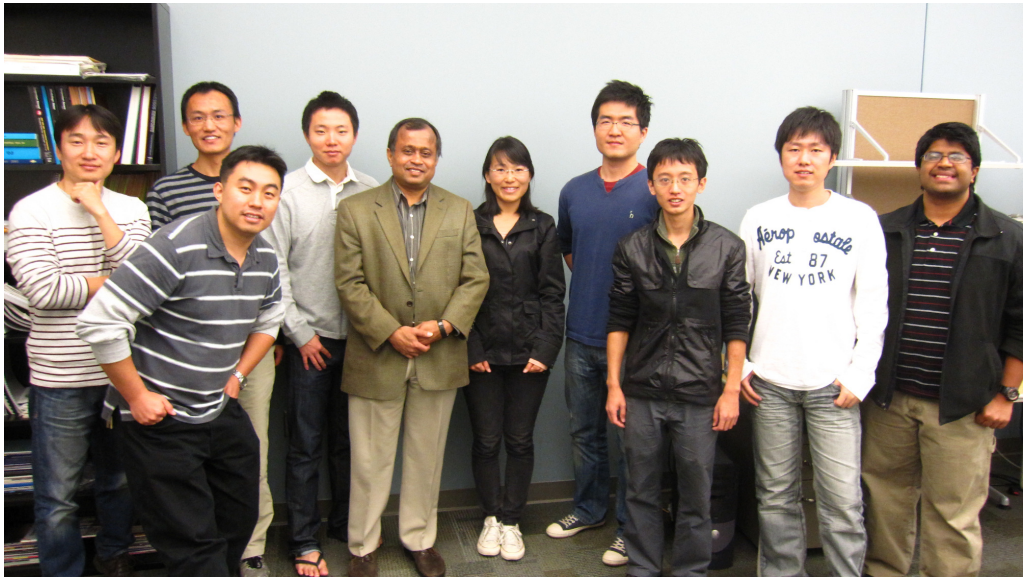

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