Heterogeneous System Component Integration with Nanopackaging

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Heterogeneous Integration with Nanopackaging

- Nanopackaging for Power:
  - Capacitors, Inductors, 3D integration
- Nanopackaging for RF:
  - Passives, FSS, Tunable Elements
  - Antennas
  - Integrated heat-spreaders
  - EMI shields
- Nanopackaging for Wearable:
  - Additively-deposited Nanowire-nanoparticle interconnects
  - Wireless power + capacitive storage
- Nanopackaging for Neuro:
  - Electrodes, hermetic coatings, power sources, wireless power

FIU
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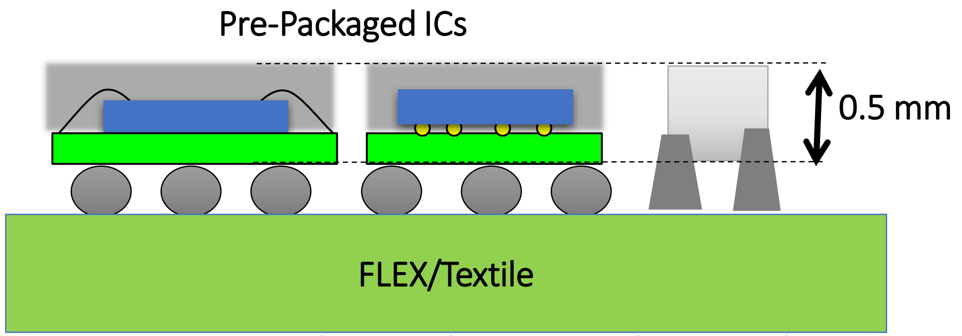
Vision: Convert 2D PCBs to 3D chip-scale Modules

Power Electronics
- **GaN and SiC – Low-cost Fan-Out Packaging**
- **Power conversion and regulation with PMIC, inductors and capacitors**

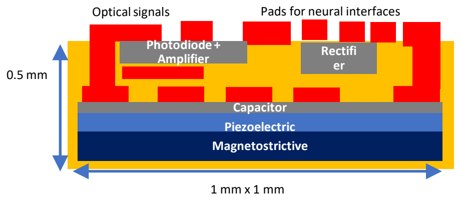
RF and mm wave Packaging:
- **Reconfigurable RF packages**
- **3D antenna-in-packages**



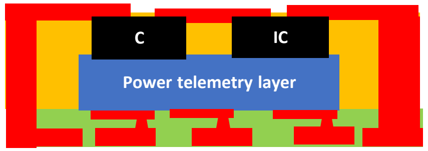
2D PCB Modules with pre-packaged chips

3D Chiplet-Scale Modules

Wireless neural link/Photosensor

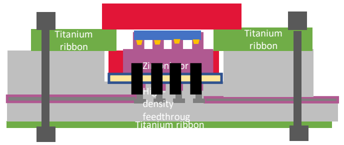


Wireless power



Fan-out GaN packages in leadframe

Hermetic chiplet package – remateable to flex

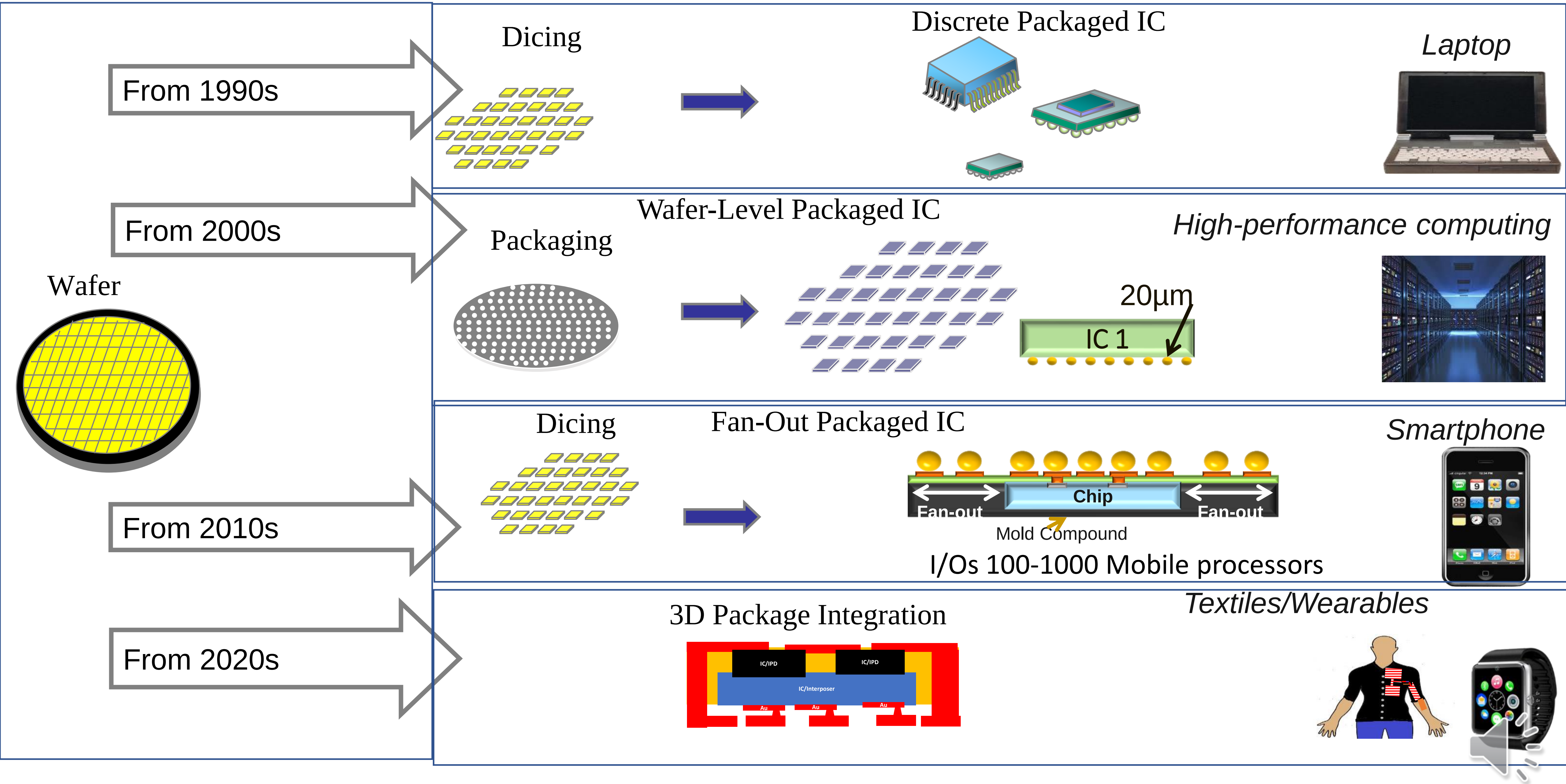


Wireless neural recording:
- **Antenna, mixer or Diode with matching networks**
- **Multiferroic Power/data telemetry;**
- **Chiplets with telemetry, rectifier and storage elements**

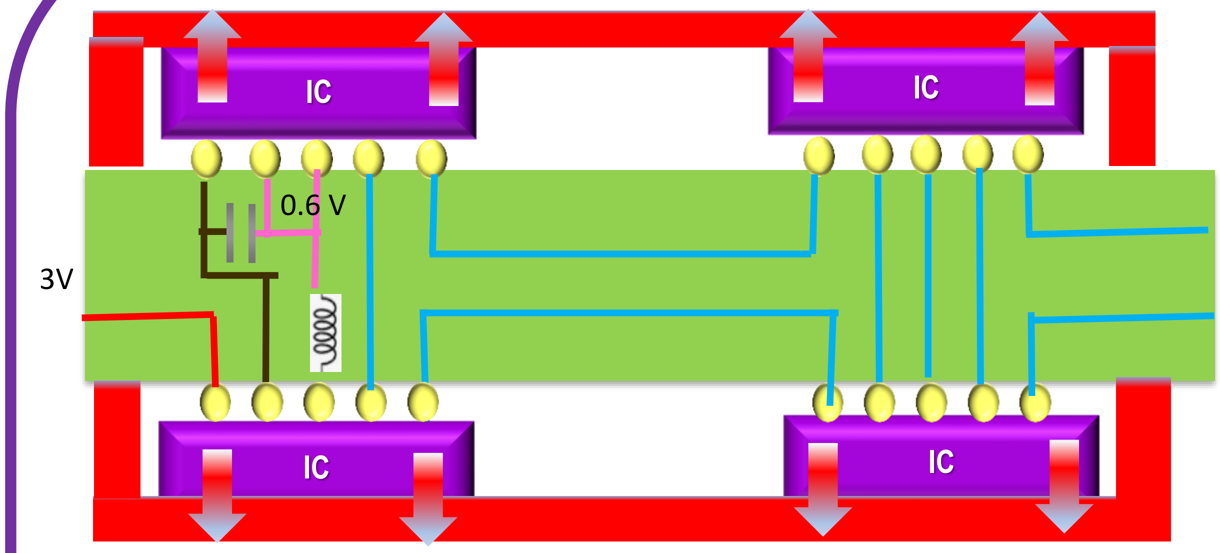
Wireless photonic sensors:
- **LED, Diodes, Amplifiers Drivers, power sources with 3D interconnections**

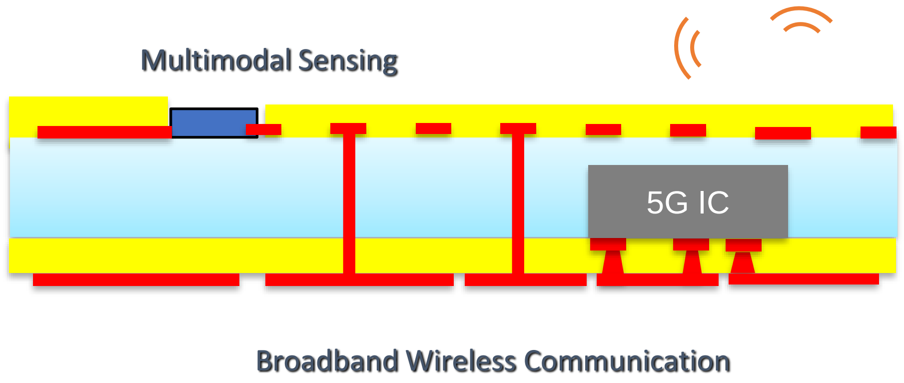
P M Raj, John Volakis and Shubhendu Bhardwaj

Wafers to Systems – Past, Present and Future



Nanopackaging Drives Future Hardware

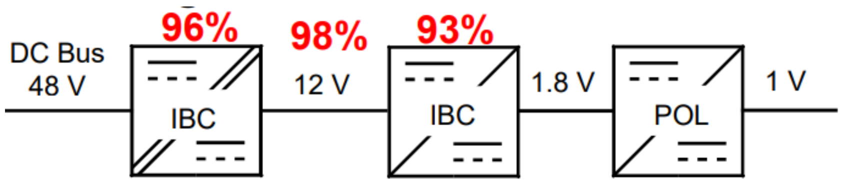




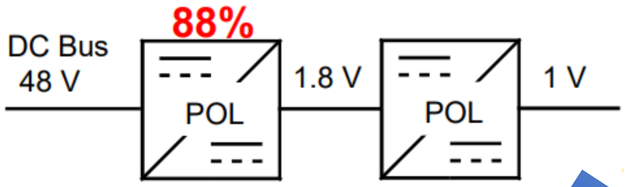
Power	**Nanocapcitors and inductors**
Thermal	**Cu-Graphene heat-spreaders**
Reliability	**ALD Inorganic films** **Humidity barriers**
RF	**Nanodielectrics and additive interconnects for 5G and wireless sensors**
Bioelectronics	**Electrodes** **Power and data telemetry** **Storage capacitors** **Remateable connectors**

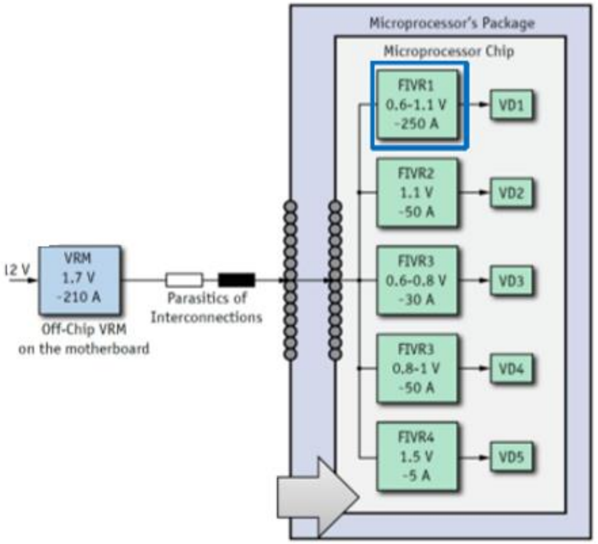
https://ieeenano.org/nanopackaging-tc

Power Delivery



Utilize Advances in:
GaN
CMOS integration
Topologies
Passive components





Minimize the stages of power conversion;

Perform power conversion right near the load;

Figures from EPC (Alex Lidow) and IBM Zurich (Arvind Sridhar)

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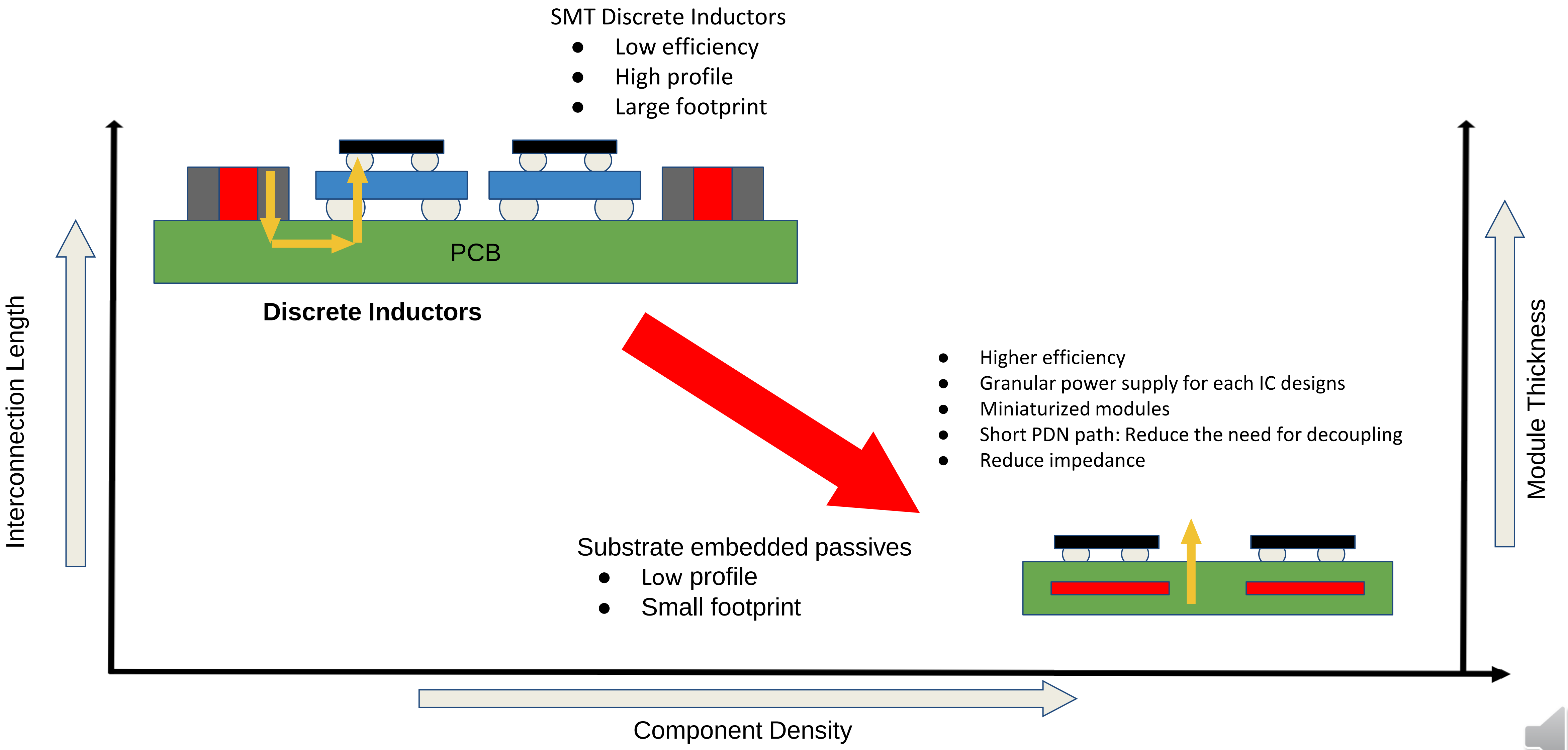
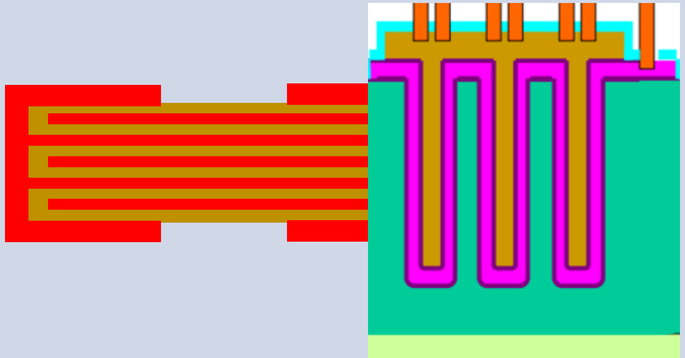
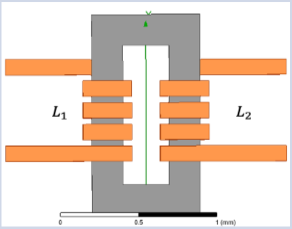
Need for Embedded Power Passives



R&D Needs

Capacitors 	Density	High K dielectrics; Enhance electrode surface area; New dielectrics and deposition processes
	Frequency stability	Electrodes and connectivity with lower parasitics
	Integration	Thinner form-factors; Substrate or wafer or fan-out embedding

Inductors  	Density	Higher permeability with saturation field and high resistivity
	Efficiency	Low coil DC losses ; Low core losses with low coercivity and eddy currents
	Integration	Substrate- or wafer-compatible process
	Current-handling	Design innovations; Scalability in thickness to handle higher current

Magnetic Material Options Today

	Thickness Microns	Coercivity A/m	Resistivity µ Ohm cm	Saturation Flux (Tesla)	Permeability
Mn,Zn ferrites	>100	3-5	10,000	0.6	5000
Nanocrystalline and amorphous flakes	>15	3	110	1.2	15000

0.1 – 5 MHz

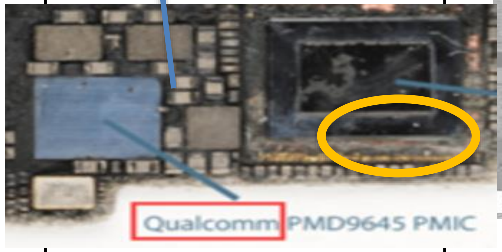
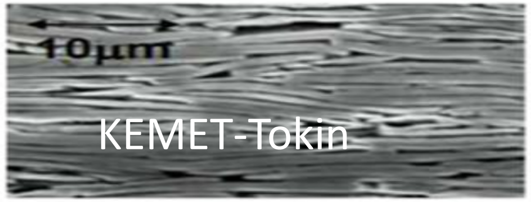
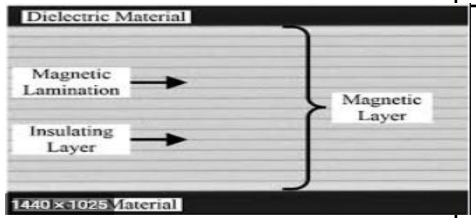
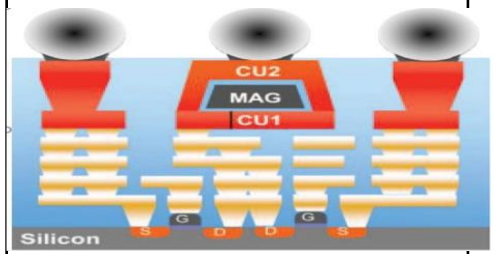
Electroless thinfilms	3-5	10-20	100	1	<<1000
Plated thin films	2-100	20-80	35	1.3	~1000
Flake composites	25-500	100-200	10,000	0.8	100-150

1 – 10 MHz

Nanomagnetic films	1-10	10	200-300	1.5	200-500

10 – 150 MHz

Inductor Technologies

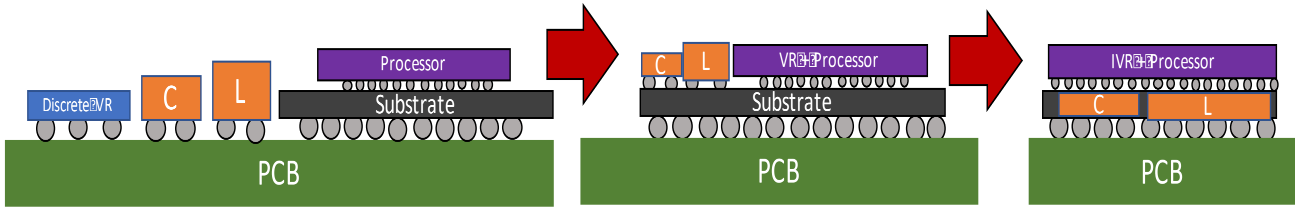
	Discrete (Ferrite or Metal powder)	Magnetic composites –substrate-embedding	Nanomagnetic films: On-chip	Need
L/Rdc nH/milliohm	15-25	5-10	0.1-0.2	>>10
Q	>20	<10	5	>20
Current-handling A/mm2 Thickness	0.01 – 0.1 200- 500 microns	0.1 – 1 50 - 200 microns	5-10 A/mm2 25 microns	5-10 A/mm2 25-50 microns core
Cost	Low	Low	High	Low
	Discrete (Ex.0.5 x 0.1 x 0.5 m 	  Substrate-embedded inductors Magnetic Core (0.5 - 0.6 mm)	  Intel and Ferric	

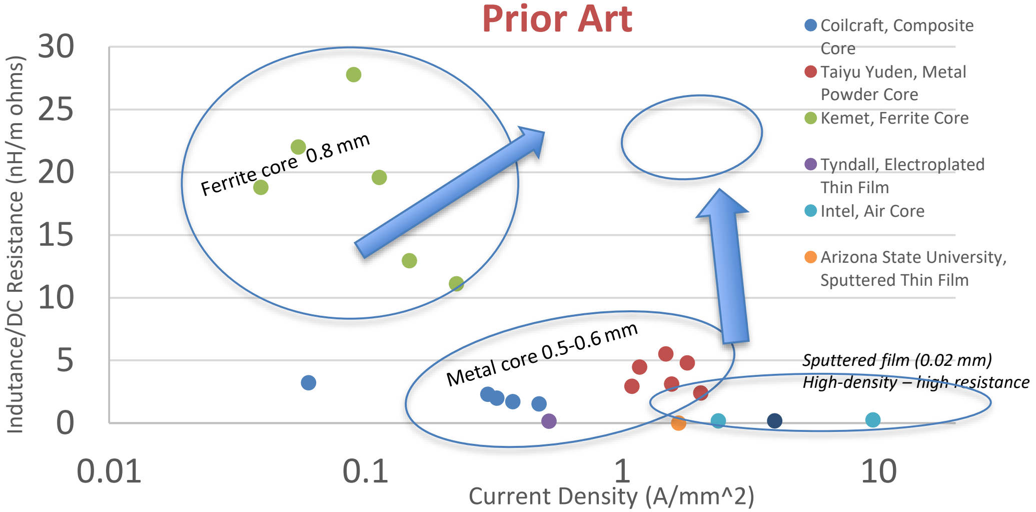
High-Density Embedded Inductors for Integrated Voltage Regulators (Carlos Riera Cercado, Huy Nguyen)

Objectives

- Embedded inductors for power converters:

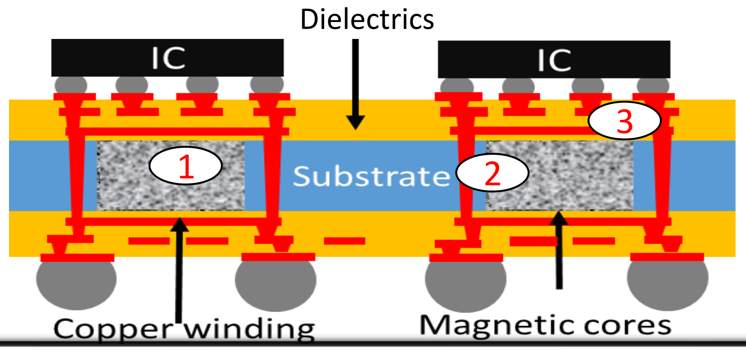
Target
20 nH/milliohm
2 A/mm2
20-50 microns





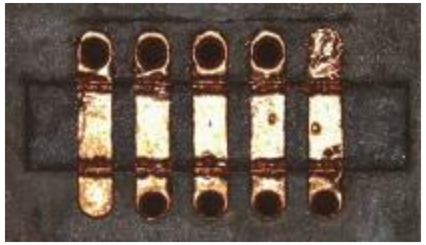
Unique Approach

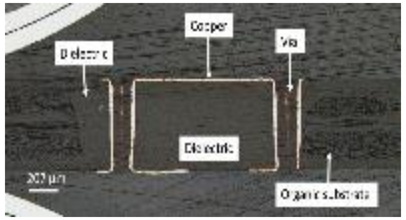
1. Substrate-compatible magnetic composites with high permeability
   - High permeability for high-inductance density
2. Embedded solenoid inductors
   - Embedding for miniaturization
   - Design for high-current density
3. Substrate design rules to fabricate thick copper
   - Low resistance

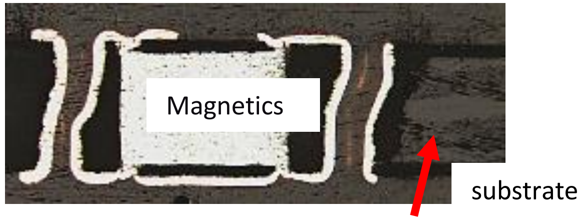


Major Accomplishments

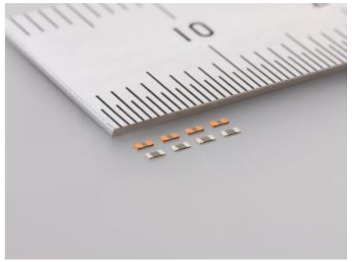
- Embedding of high current density and high-efficiency inductors embedded in organic substrates. Current status:
  - Thickness: 500 um
  - Inductance: 8nH/mm^2,
  - Current: Projected to 1 A/mm^2
  - Resistance: projected to <10 m Ω

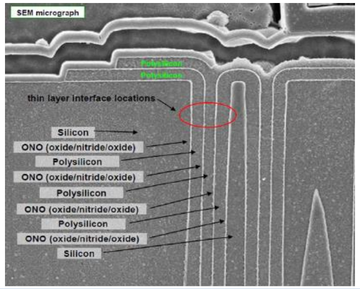






Capacitor Technologies



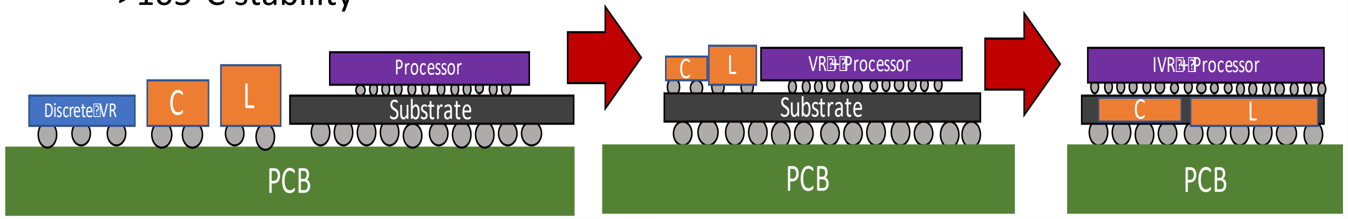


	MLCC (Murata)	Trench Caps (Murata)	Ta Chip (AVX)	Emerging Need
Volumetric Density	20 μF/mm^3	1 μF/mm^3	~10 μF/mm^3	50-100 μF/mm^3
Thickness	100 μm	100 μm	600 μm	50-100 μm
Freq. Stability	10-100 MHz	>1-10 MHz	0.2 -1 MHz	>10 MHz
ESR	~10 mΩ	50 mΩ x μF	>100 mΩ x μF	~50 mΩ x μF
% ΔC/V	-13 % to -70% (1 to 4 V)	~ 0 %	~ 0 %	~ 0 %
Max. Temp	85° C	150° C	125° C	>125° C
	PICK AND PLACE			FILM EMBEDDING WAFER OR PANEL INTERCONNECTS

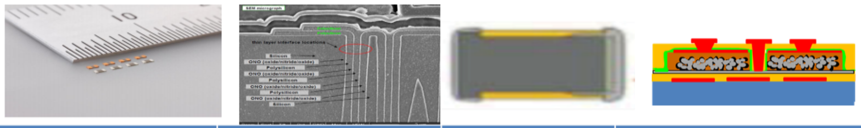
High-Density Capacitors for Integrated Voltage Regulators

Objectives

- Ultra-high density capacitors:
  - >1 µF/mm^2 at 1 MHz,3-48 V, & 50 mΩ ESR
  - 1 nA/µF leakage current
  - Simpler processing on wafer or package
  - 100 µm thickness
  - >105°C stability



Prior Art



	MLCC	Trench Caps	Ta Chip	Emerging Need
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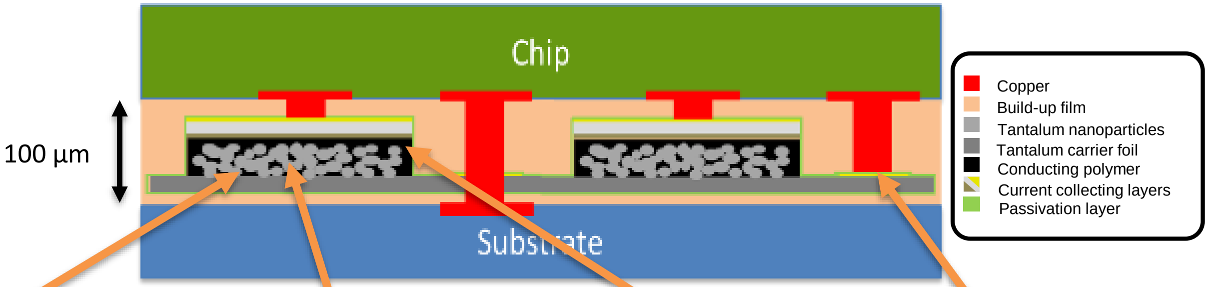
	PICK AND PLACE			FILM EMBEDDING WAFER OR PANEL INTERCONNECTS

Unique Approach



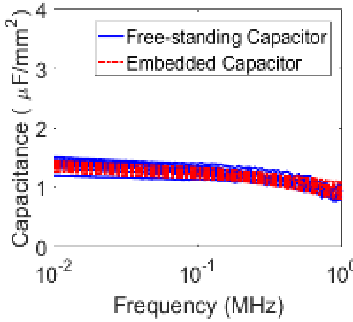
Printed Tantalum Nanoparticles Anode
- High-surface area at ultra-thin form-factor
- Scalable to any design need

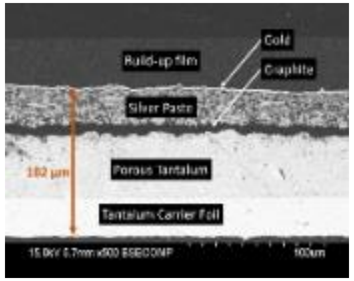
Nanoscale Ta_2O_5 Dielectric
- Paraelectric for DC bias and temperature stability
- Amorphous for low leakage current

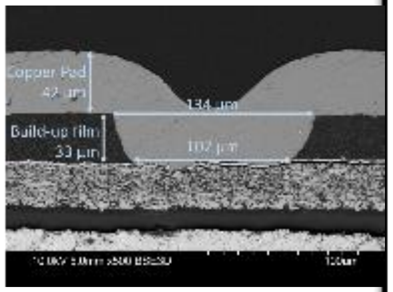
Conformal Conducting Polymer Cathode
- Low-resistivity and thick coating for low ESR
- Self-healing for low leakage current

Foil-transfer integration
- Thin-film lamination
- Ultra-short copper interconnections for reduced impedance
- Low-cost, panel-scale, 3D approach

Major Accomplishments

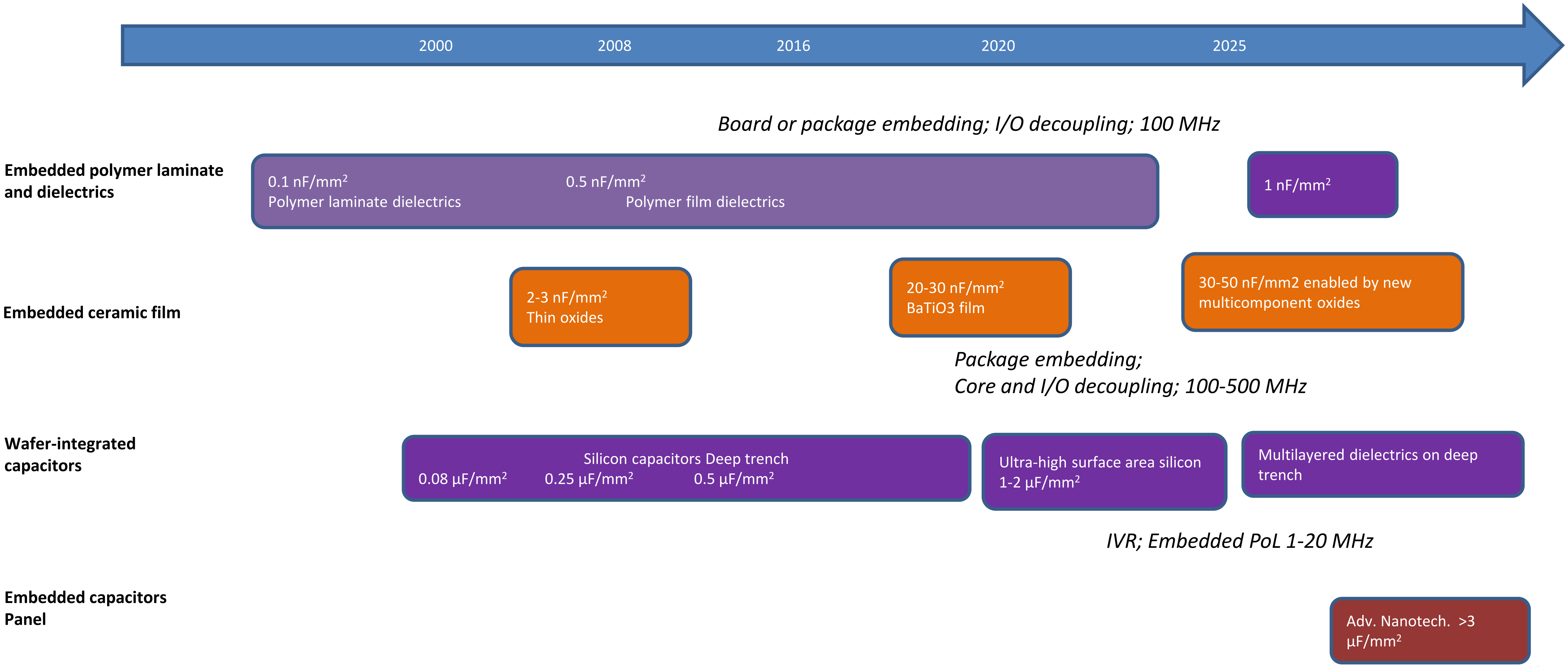






>1µ F/mm^2 up to 1 MHz at 5 V with low ESR, low leakage current, and 100 µm component thickness

Embedded Capacitors Roadmap



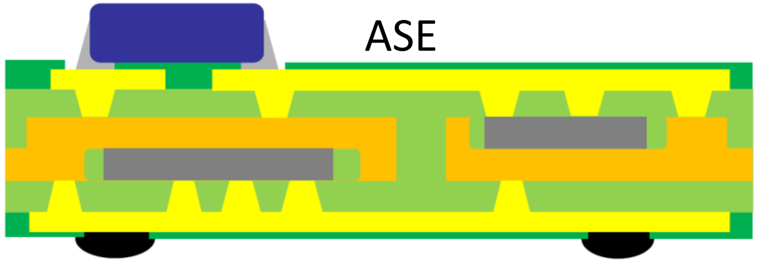
3D Power Packaging

- Multiphysics converter design (topology & hardware co-design)
- Advanced GaN devices & high-temp passives

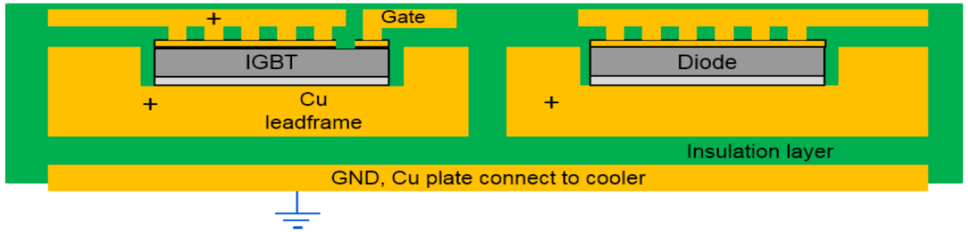
- Structure and process innovations
- Doubleside wafer plating
- Panel-scale embedding of power devices
- High-temperature materials with enhanced interfaces for Hi-Rel

Infineon

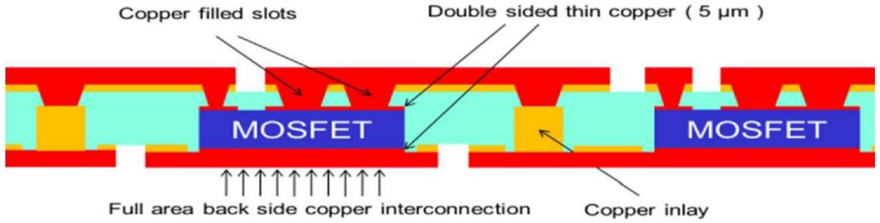
ASE



Schweizer



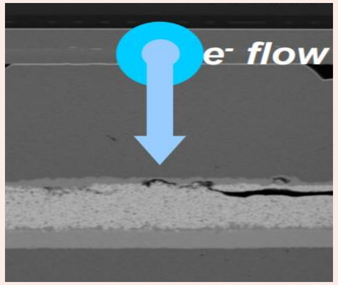
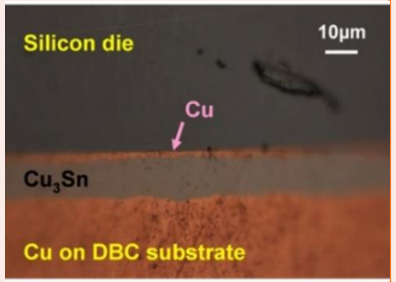
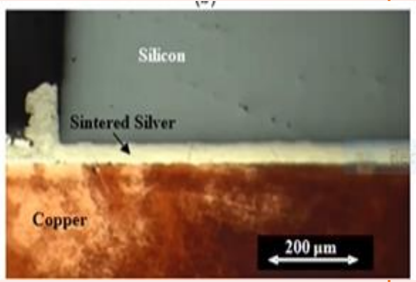
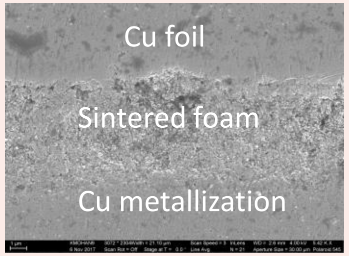
AT&S



- Sintered copper interconnections between devices, IMS or leadframe and PCB
- Barriers for oxygen and moisture
- Advanced encapsulants

- Advanced cooling loop with temp uniformity
- System-level thermomechanical and electrical reliability:

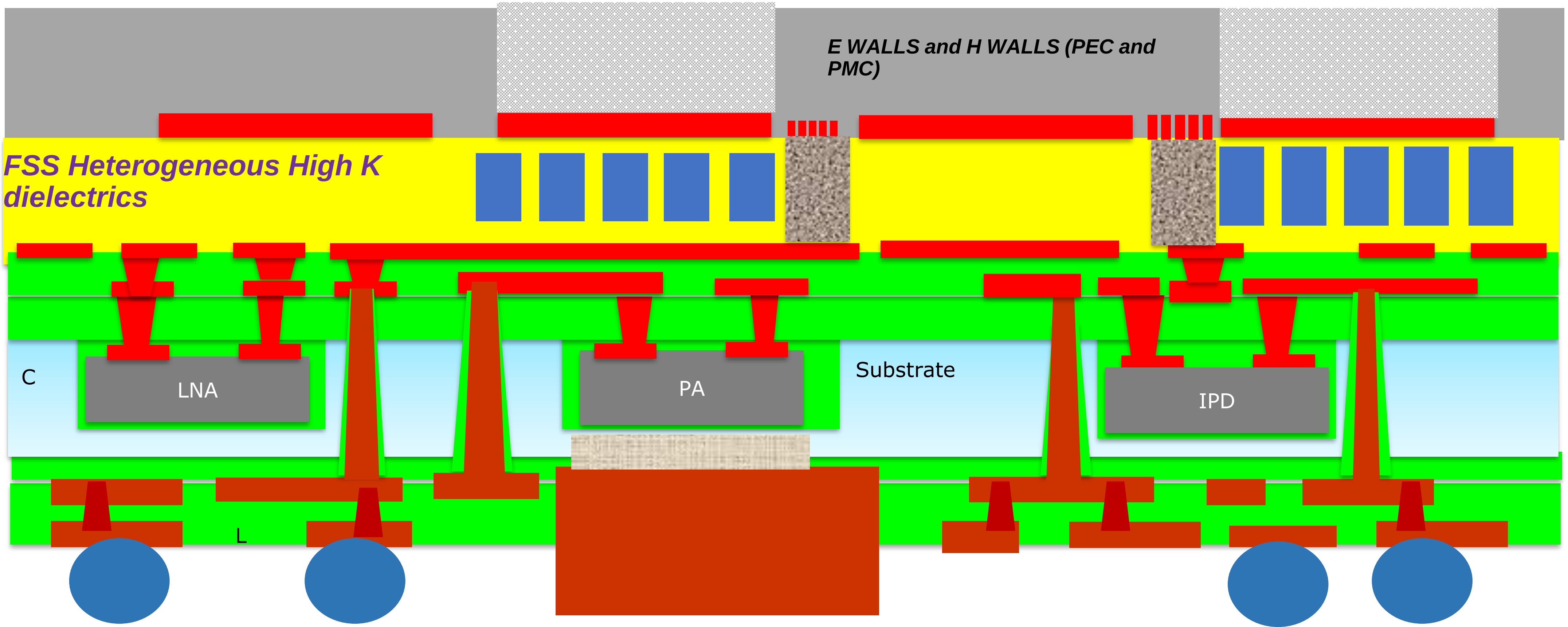
Evolution of Die-Attach Materials

	High-lead solders	Transient Liquid Phase Sintering	Nanosilver	Nanocopper	Nanocopper-microwire-graphene multilayers
	 Koduri, Texas Instruments Current is not needed for lateral GaN die-attach)	 Infineon	 Jiang Li (TI, Virginia Tech)	 Vanessa Smet, Georgia Tech	
Pressureless assembly capability	Pressureless		Requires pressure	Requires more pressure	Pressureless with reactive nanosurfaces
Electrical and thermomechanical reliability performance	Moderate with low homologous temperature	Moderate with kirkendall voids	Microstructural instabilities and diffusion	Die shear strength is low with smooth backside metallization	
Safety	Lead-based				
Cost			High	Moderate	Low, because of design and process flexibility

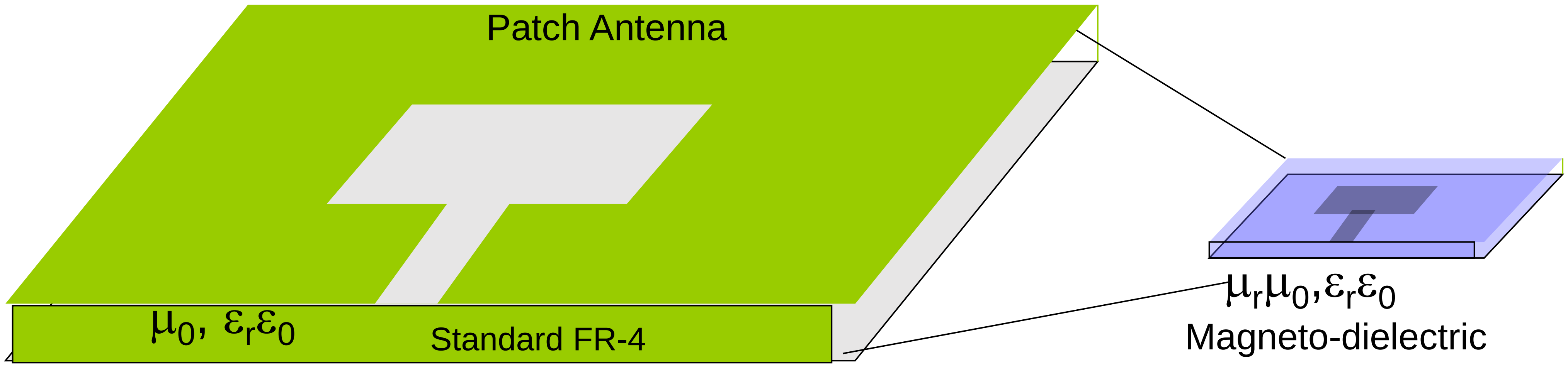
Heterogeneous 5G System Integration

- RF and digital in the same package
- High-density and low-loss transmission lines:
- Ultra-fine vias and TPVs for seamless 3D interconnects
- Precision circuitry for impedance matching
- Smooth surface for low losses
- Package- and board-level reliability
- Large-area panel processing

- Advanced antenna array for wideband and gain
- Embedded FSS for improved performance
  - Heterogeneous high-K superstrates as lenses, E walls, H walls, AMCs



Antennas with Nanoscale Magnetodielectrics

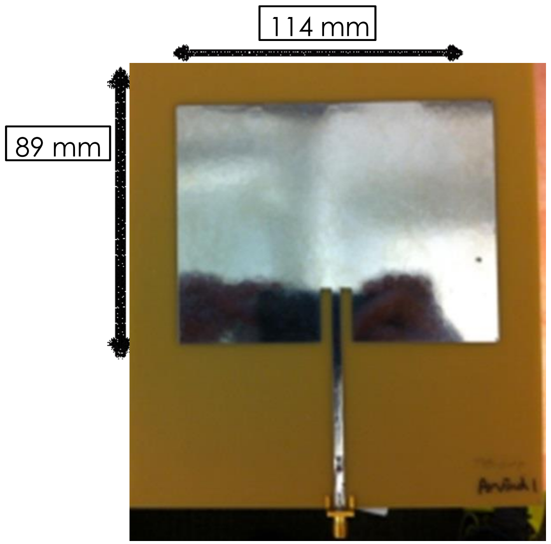


Size is proportional to $1/\sqrt{\varepsilon_r \mu_r}$

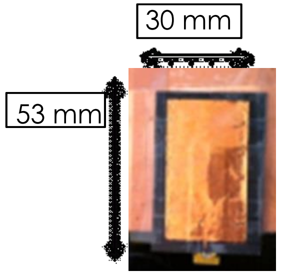
Bandwidth improves with impedance match with air: $\mu_r \sim \varepsilon_r$

Radiation Efficiency: High μ, Low loss tangents

Permeability of 2-2.5
Permittivity of 6-12
Combined effect reduces size by 80 %
Increases bandwidth by 10X
Efficiency remains almost same



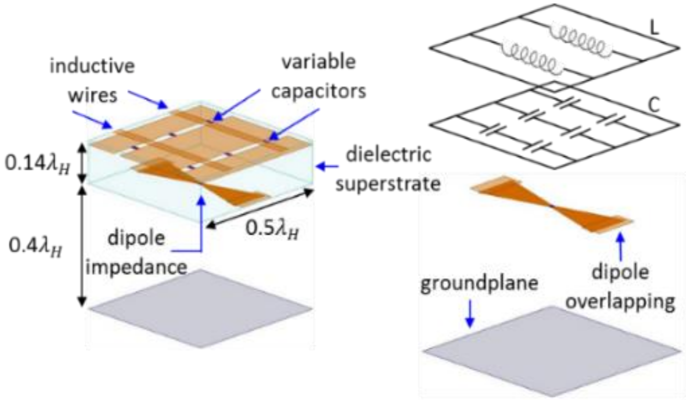
Traditional antenna

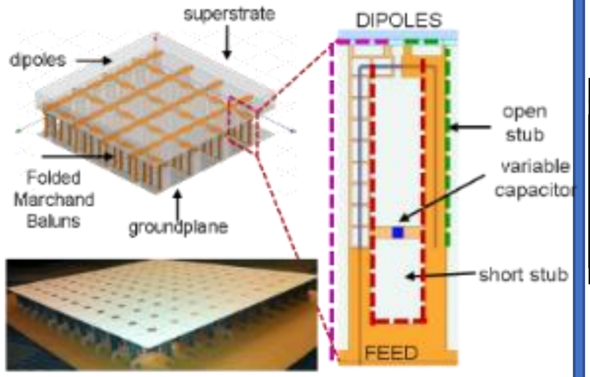


Nanomagnetic antenna

Tunable Nanoscale Superparaelectrics for Beamforming and band rejection

Alwan, Volakis et al., FIU

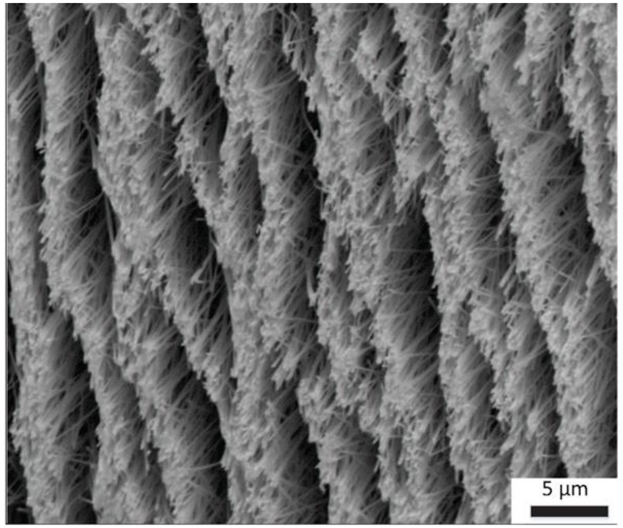


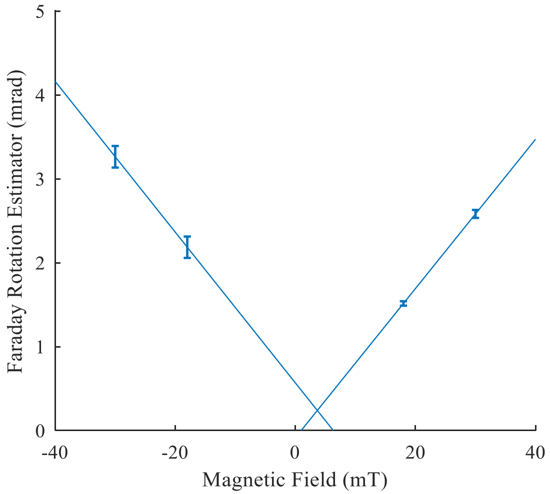


Tunable BSTs can eliminate the PCM switch assembly, interconnect lengths and losses

Cobalt Nanowire NonReciprocal Components (Circulators, Isolators)

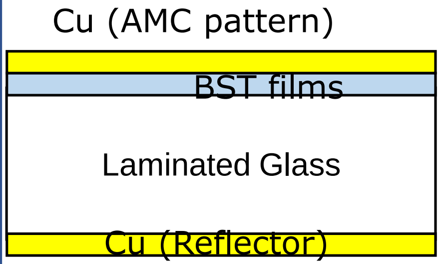
Nitin Parsa, Univ. Toledo

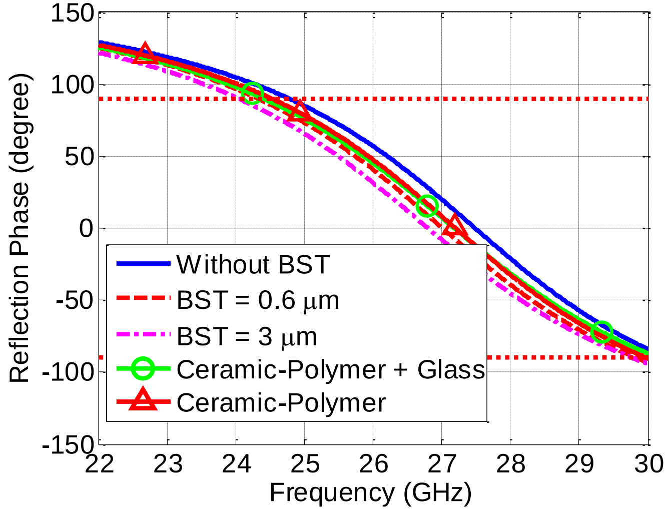




High-K mm wave Superparaelectrics for AMCs

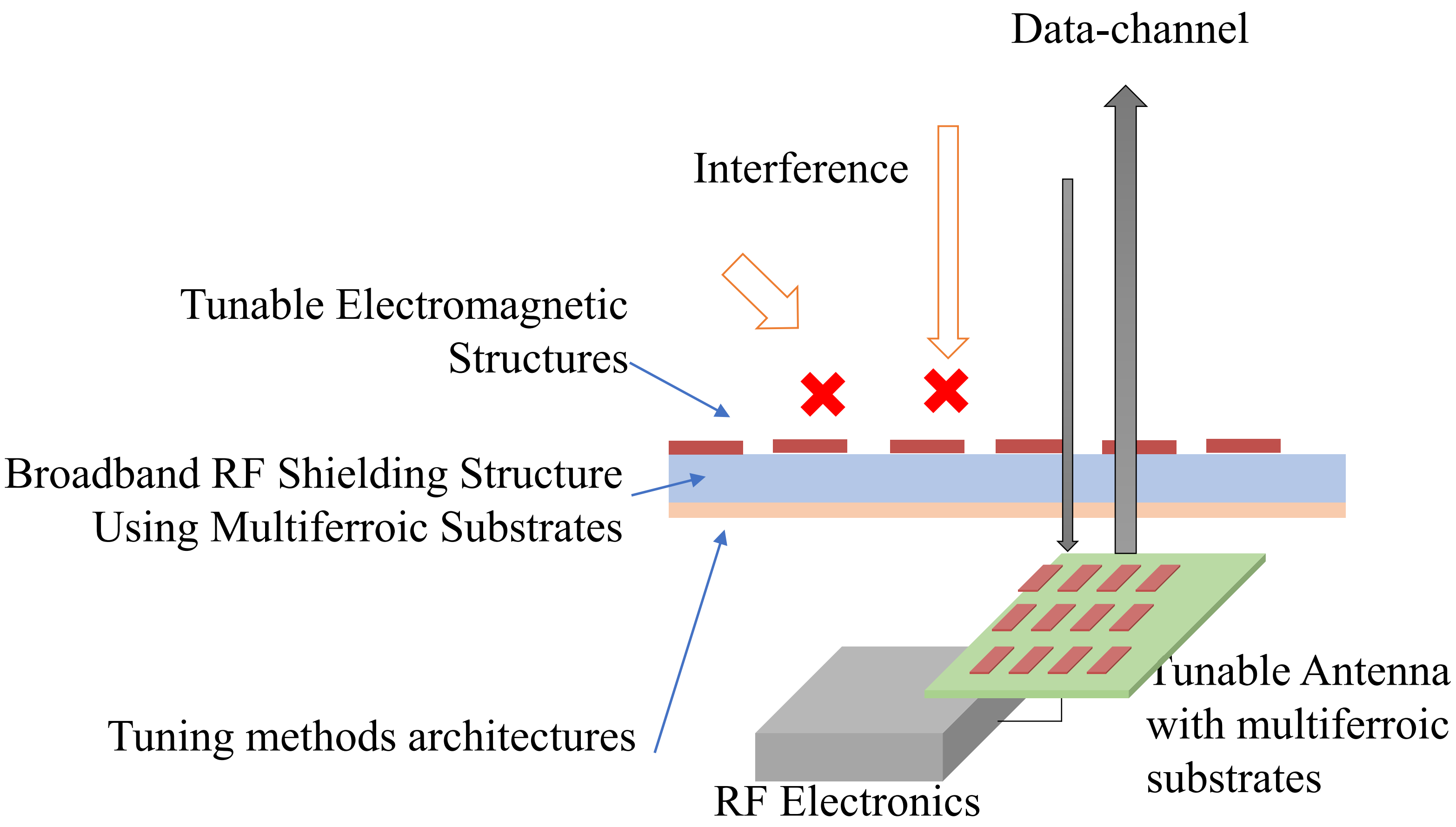
Tong-Hong Lin, GT





	Unit-cell size (mm)	Operational Band (GHz)	FBW (%)	Size Reduction Rate
Without BST	2.42	24.5 ~ 30.4	21.5	
0.6 µm BST	2.24	24.3 ~ 29.8	20.3	14.3 %
3 µm BST	1.7	24 ~ 29.8	21.6	50.6 %
Ceramic-Polymer Composite + Glass	1.5	24.4 ~ 30.2	21.3	61.5 %
Ceramic-Polymer Composite	1.16	24.5 ~ 30	20.2	77 %

Multiferroic Tunable Shields and Filters for Secure RF Electronics



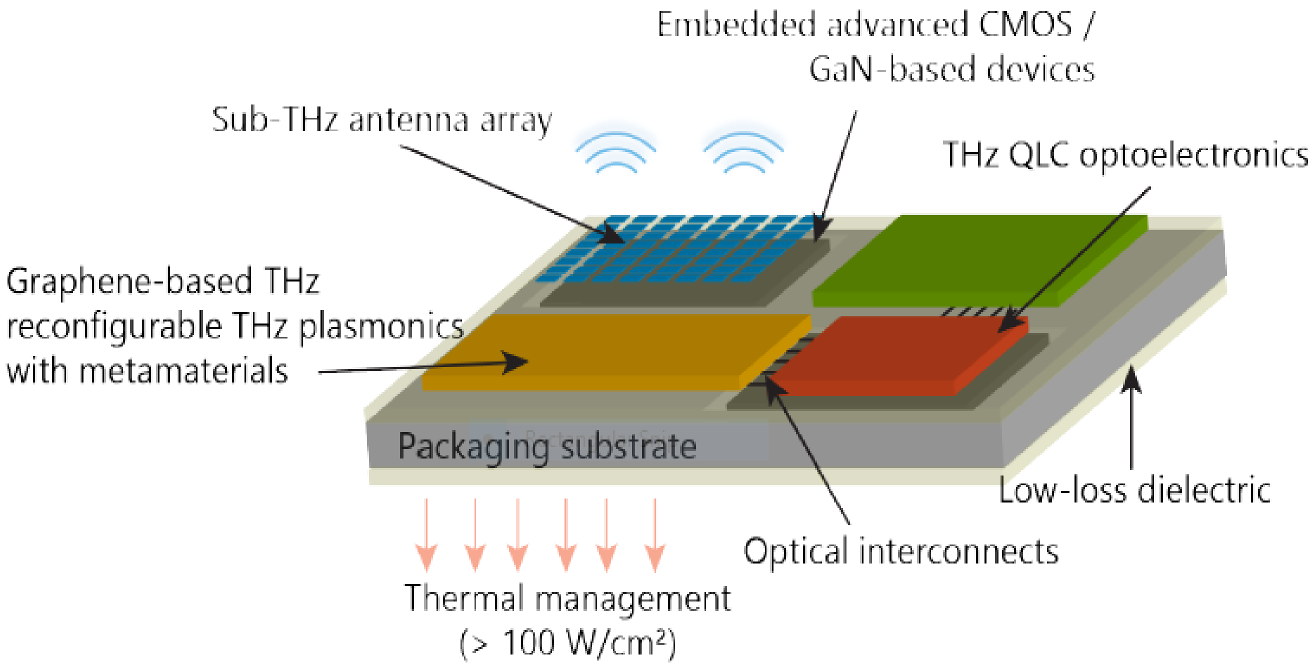
- ❑ *Multiferroic based electromagnetic architectures for smart shielding.*
- ❑ *Planar EM substrate architectures for smart substrates (with tunable permittivity) for antennas.*
- ❑ *Frequency selectivity and direction selectivity for EM blocking.*

Bhardwaj, Venkatakrishnan, FIU

Nanopackaging for 6G and THz

Hybrid front-end for dynamic all-spectrum sensing and communication in 6G

6G System-on-Package



Graphene-based THz radiation sources

Precision THz antenna arrays (ex. 1024 elements in 1 mm^2) and Phase shifters

Lenses and intelligent metasurfaces with space-time-frequency coding

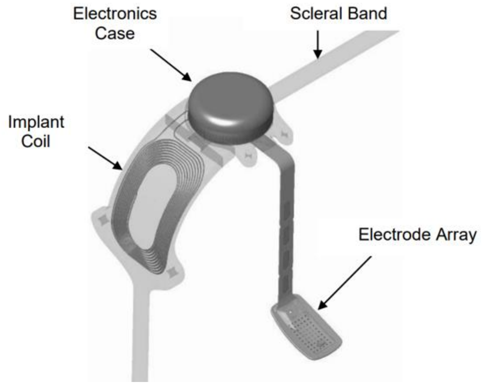
Low-loss interconnects and waveguides

High-responsivity low-noise detectors to surmount the high path-loss at these frequencies

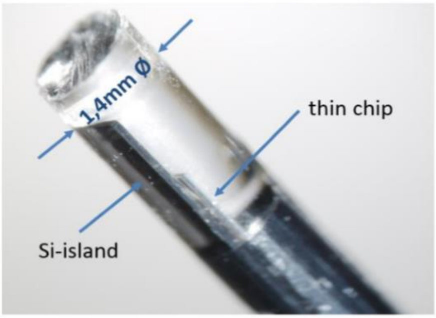
Muhammad Ali, GT

Bioelectronics: Why 3D heterogeneous integration:

Argus Retinal Prosthetics



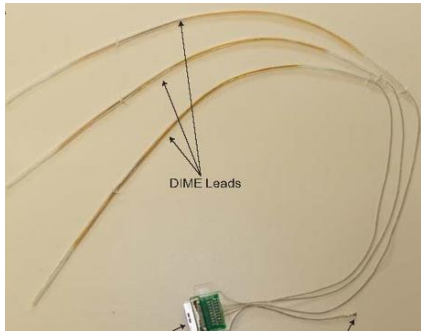
Smart catheters with rolled fan-out flex packages



encapsulated module with assembled thin chips

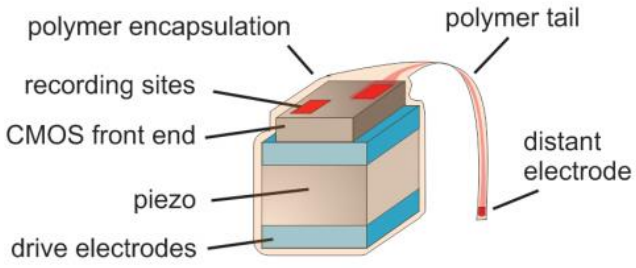
For chronic implants additional layers of encapsulation are required: Parylene C, ALD

Multielectrode arrays from IPGs (FDA approved for human subjects)



Courtesy: Argus Retinal prosthetic system 2013, Ranu Jung and Anil Thota,

Neural Dust for brain-computer interfaces

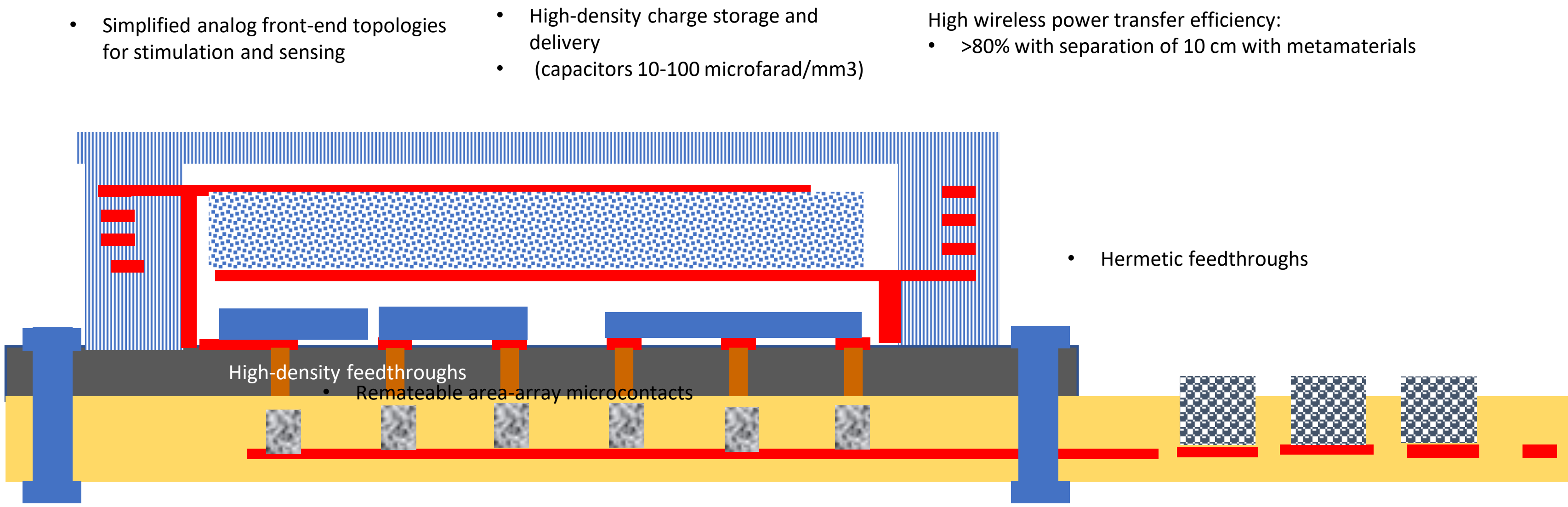


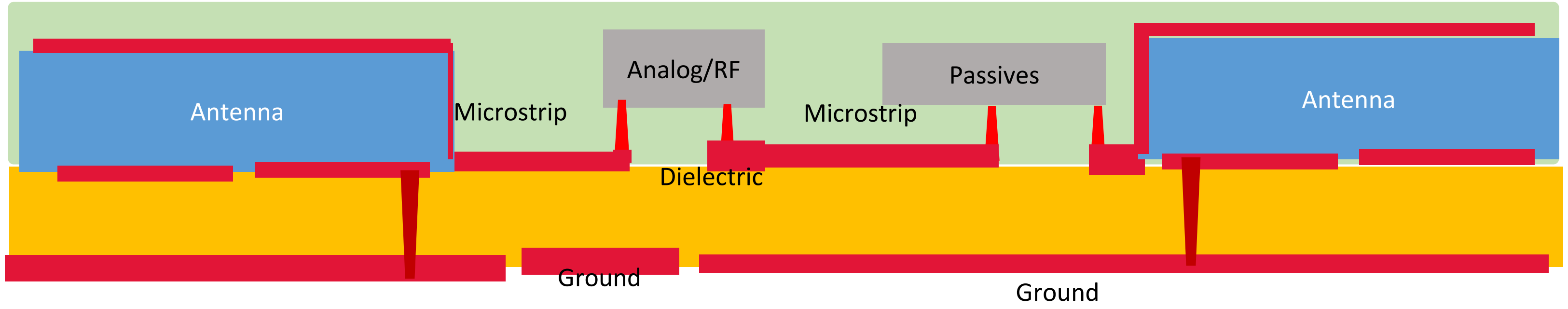
Christine Kallmayer, Fraunhofer IZM
Dongjin Seo, UC Berkley

- Reduce footprint and volume:
  - Vertical integration of power, signal and stimulation functions
- Functionalizing the electrode tip:
  - Chiplets (thin chips) close to the electrode array
- Band-aid patch-like smart sensors and therapies
  - Integrate antennas, RF ICs and electrode arrays
  - Passive neural recording with RF in and out
- Integrate power sources:
  - Tiny telemetry link
  - Tiny flexible conformal capacitors
- Vertical remateable area-array connectors:
- Reduce reliability issues:

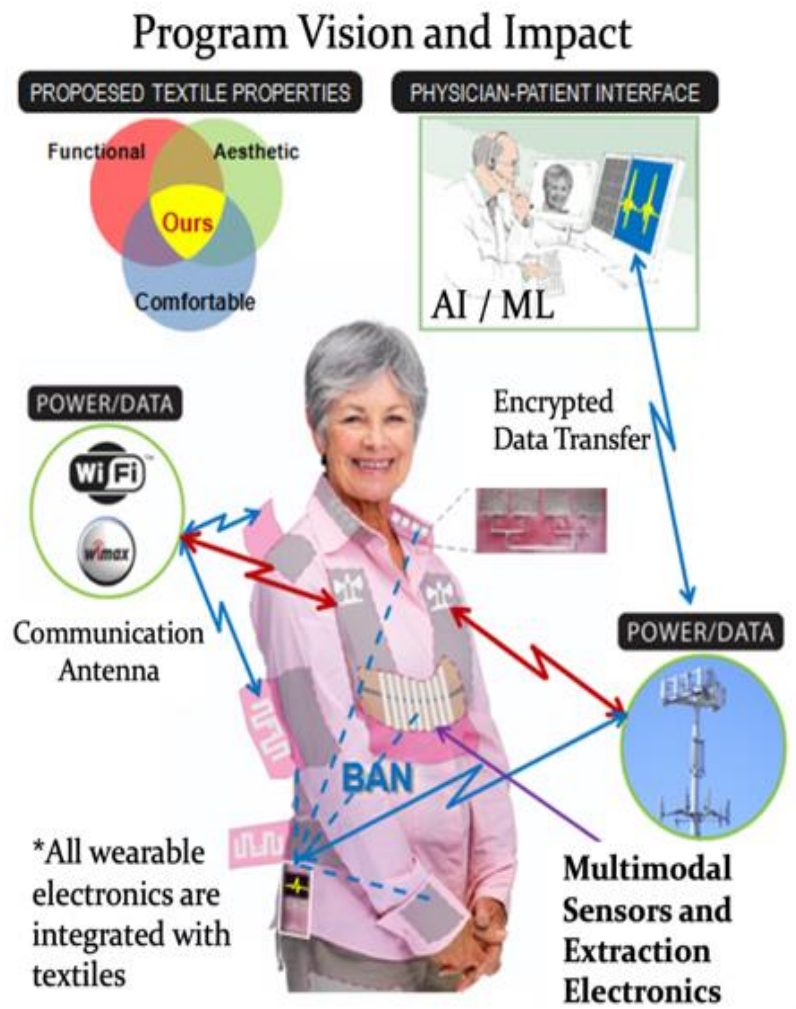
Bioelectronic Packaging Focus at FIU

- Hermetic feedthroughs with remateable interfaces
- Nearfield telemetry
- Wireless neural recording
- Neuroelectrodes
- 3D package integration

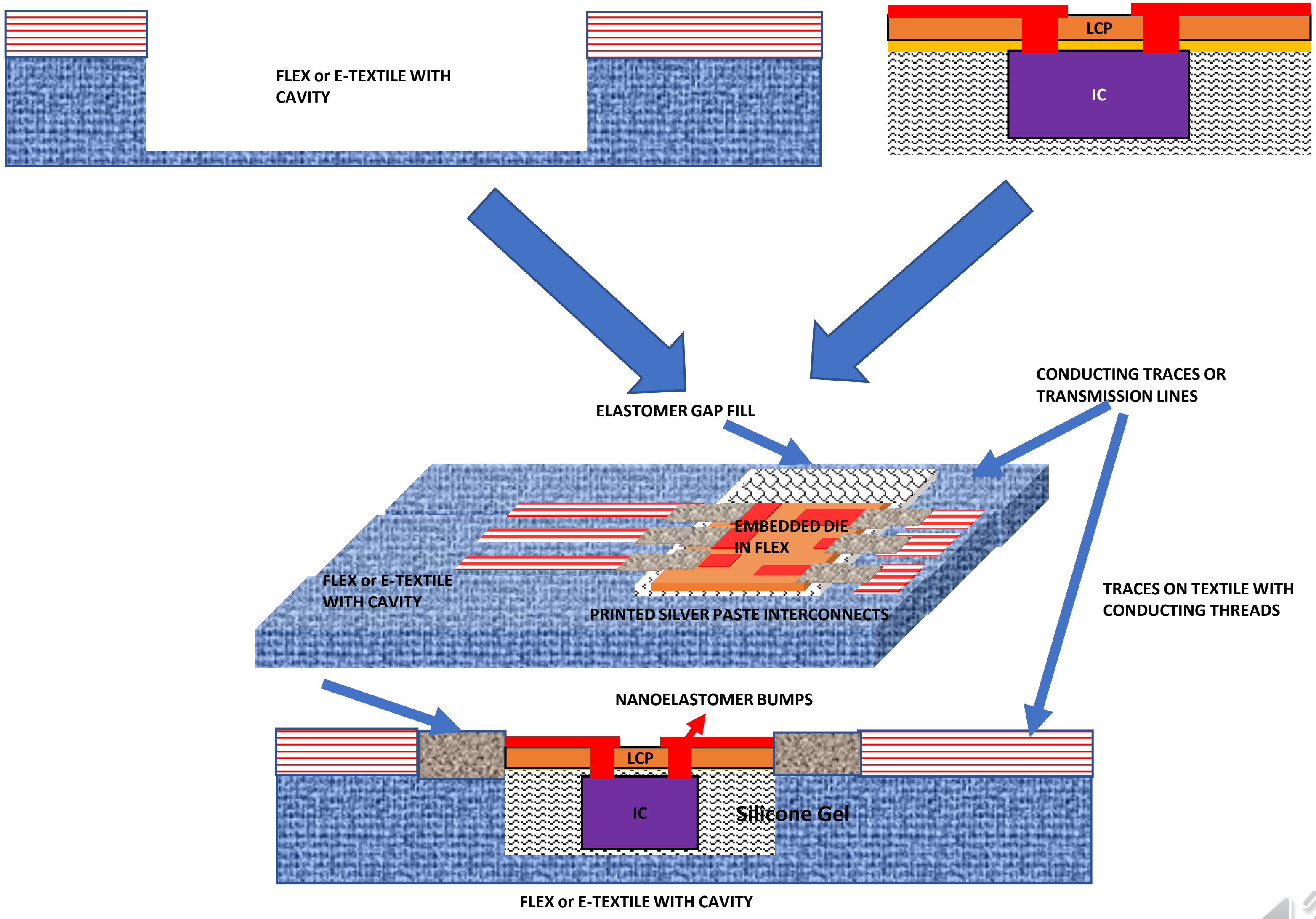




Electronics in Flex – Flex in Textiles



Electronic platform for multimodal sensing.



FLORIDA INTERNATIONAL UNIVERSITY

Packaging for Wireless Neural Recording (Sk Yeahia Been Sayeed, Vignesh Manohar)

<u>Objectives:</u>

Neural recording:

- Wearable on-skin patches
- Implantable for Peripheral Nervous System

Sensitivity of < 30 microvolts

Communication with smartphone

<u>Approach:</u>

RF backscattering technique

Completely-passive: zero-power:

- No active circuits that need voltage bias

Miniaturized antennas with advanced designs

<u>Innovative Packaging:</u>

Design and Integration with physiological inputs

Chip-on-flex or chip-in-flex fan-out packaging

Embedded-chip for

Low –impedance skin or implantable electrodes

Pt or PtIr → Platinum black → Pt/PEDOT-PSS, Au/PEDOT-PSS → Graphene/ PEDOT-PSS

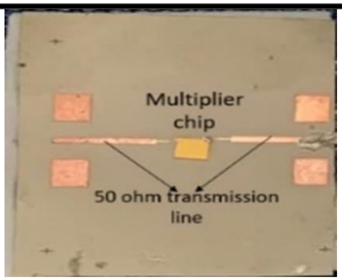
Advanced antennas:

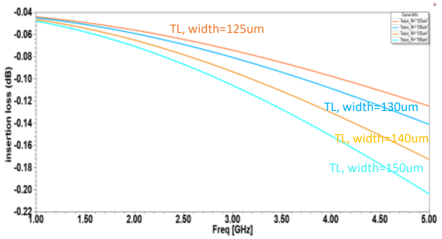
- Dual-band monopole antenna
- Miniaturized patch antenna with high-K

Low-loss flex-compatible interconnects

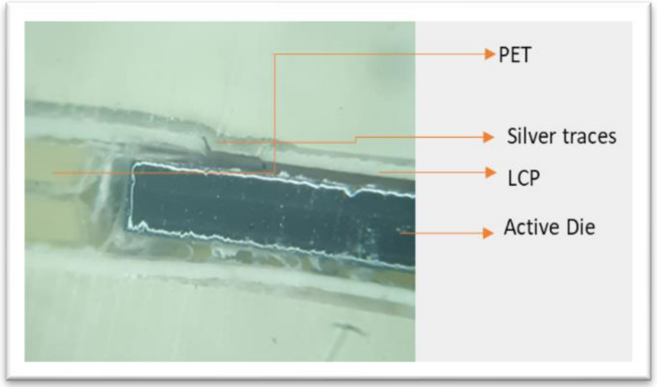
- <0.1 dB end-to-end loss

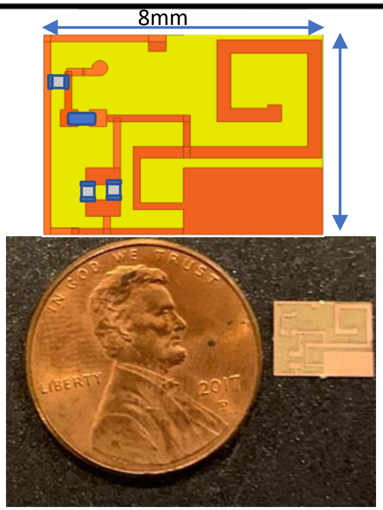
Graphene – PEDOT-PSS electrodes for high-fidelity low-impedance recording





Multiplier chip with RF path





Smallest zero-power wireless neural recording system:

Dual-band antenna

Embedded or backside IC assembly

Thin flex package (100 microns)

Chiplet integration (100 microns)

P M Raj, John Volakis and Shubhendu Bhardwaj

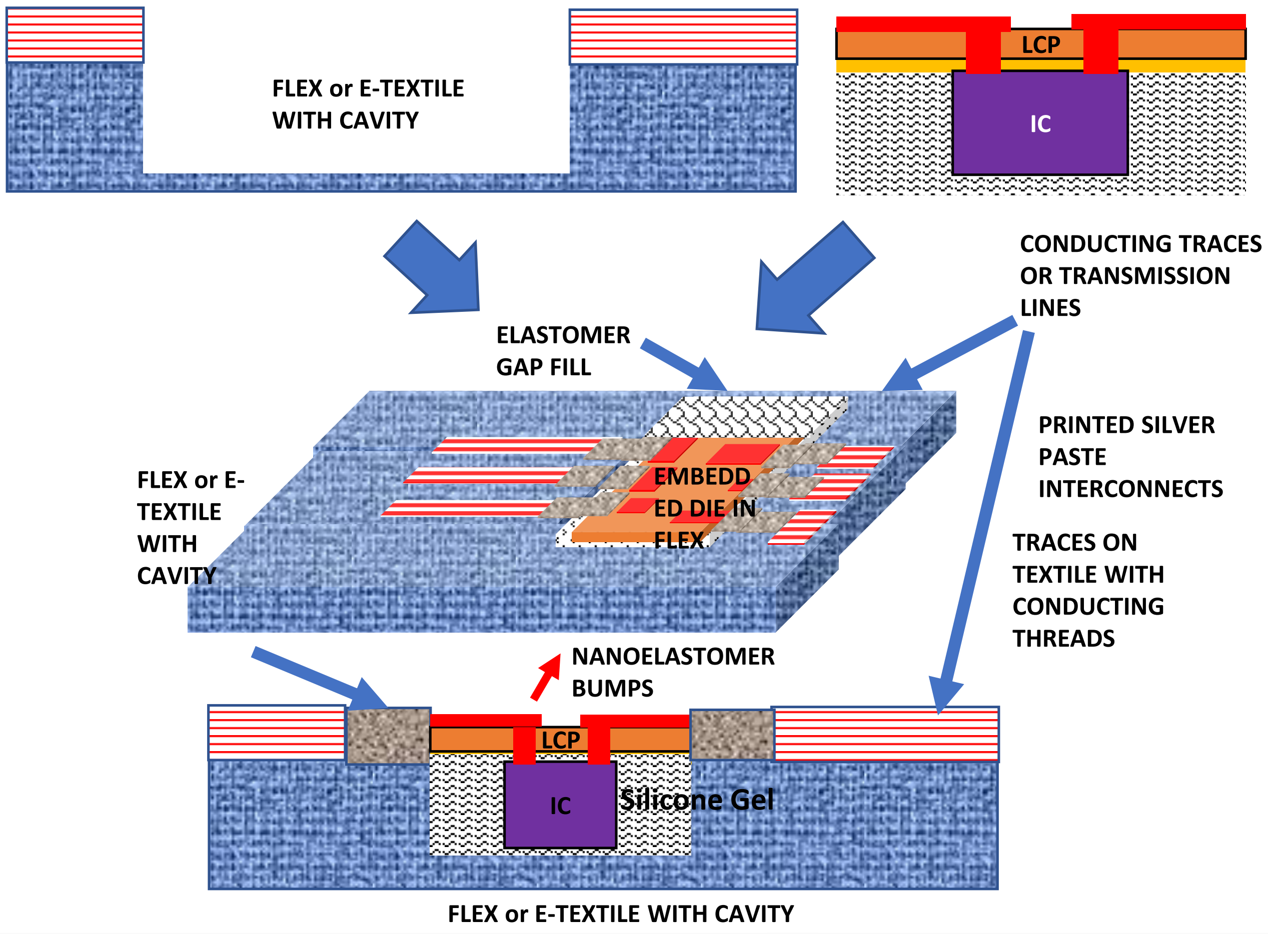
Flex-Textile Hybrid Packaging (Abdal Abdulhameed, Monir Monshi)

1)Packaging of low-power batteryless extraction circuits
    - Simplify the on-site electronics,

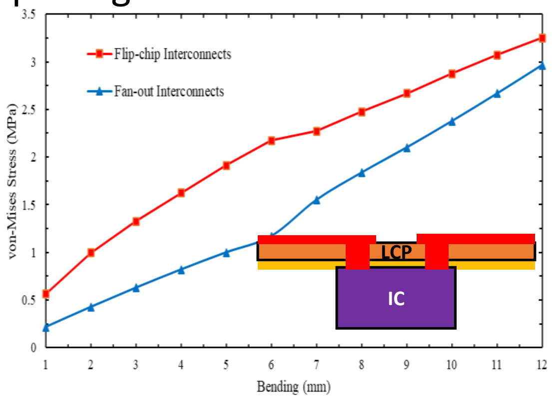
2)Highly planar and unobtrusive integration of RF comm./data interfaces with textiles,

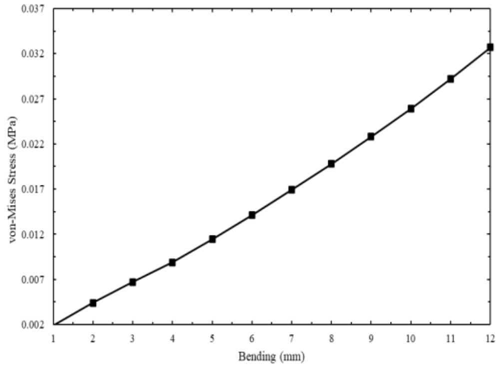
3)Remateable (reconnectable) flex interconnections to modularize sensing electronics and for replacing biofouling parts

4)Integrate with point-of-care centers for eventual diagnosis by practitioners, while ensuring privacy and data security.



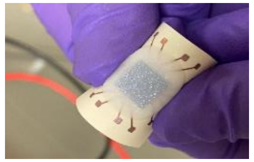
Thermomechanical modeling of flex and textile-embedded packages under flexion



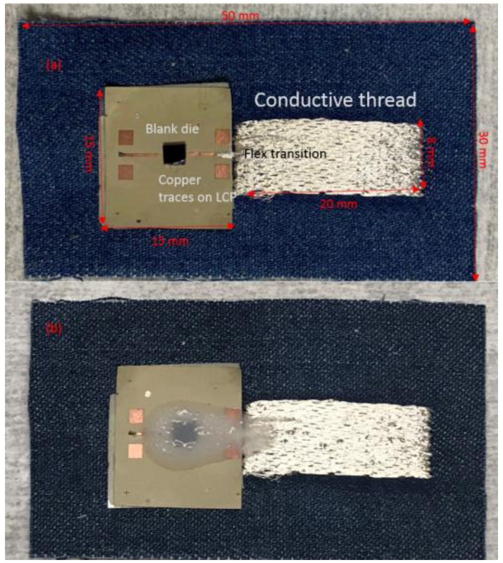


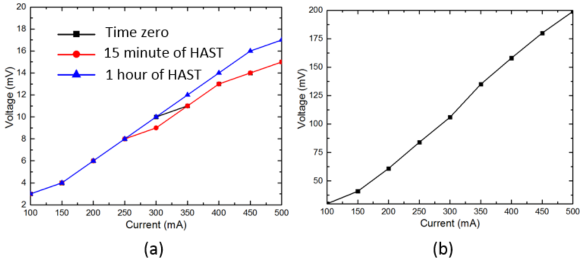
- Lower chip-to-flex Interconnect stresses
- Lower flex-to-textile stresses

Conductive elastomer adhesives



Fluroelastomer encaspulation





Stable resistance under thermal and humidity testing

P M Raj, John Volakis and Shubhendu Bhardwaj

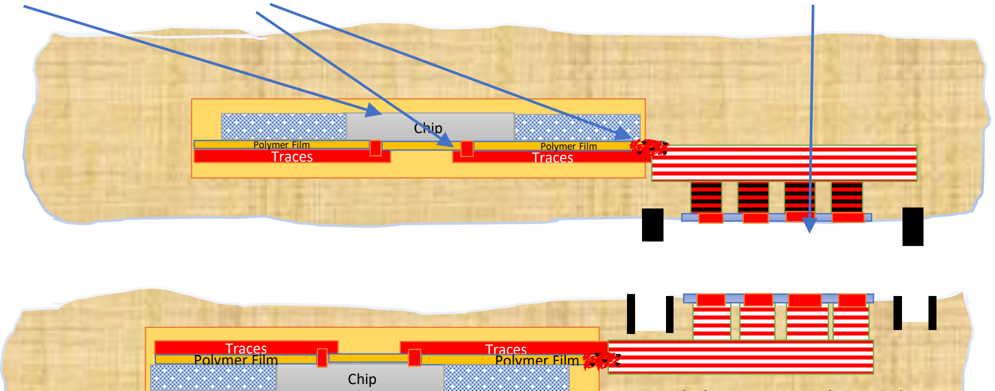
Remateable Connectors Packaging (Jose Solis Camara, Sepehr Soroushiani)

- Remateable flex-to-flex and flex-to-textile Packages
  - End-user or manufacturer can remove and re-assemble
- Examples of use:
  - Power harvesting and RF communication
  - Sensor and communication interfaces
- Fine pitch and area-array
- Low-cost additive manufacturing

Chip in flex

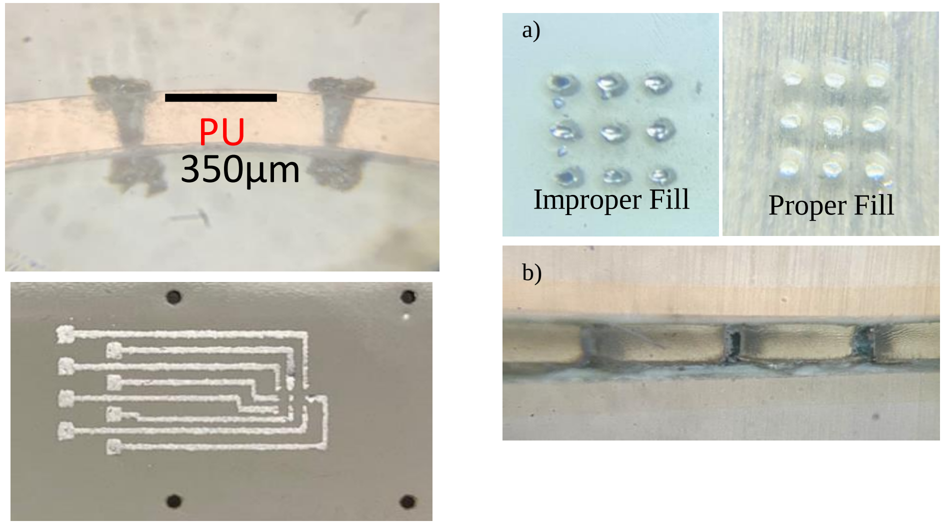
Flex in textile

Remateable Z elastomer interconnect



Push buttons to keep the structures self-aligned, clamped, and under low-resistance contacts

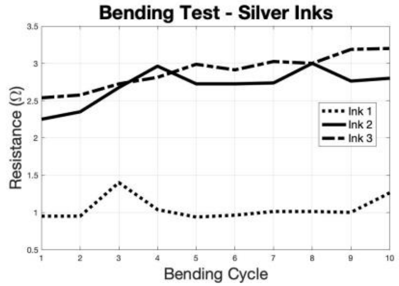
Area-array fine-pitch for flex-to-flex connectors



Via-fill of metal-elastomer nanocomposites in elastomer polymer films;

Can be scaled down to 200 micron pitch

Via Filling and Interconnect Layer Assembly



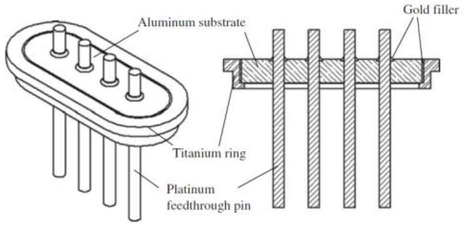
Screw clamps are used for the first demonstration;

Push-button or micro-Velcro assembles are currently investigated

Initial remateability demonstrated with multiple bending cycles, assembly and re-assembly

P M Raj, John Volakis and Shubhendu Bhardwaj

Hermetic Packaging:
Feedthroughs and Remateable Area-Array Connectors



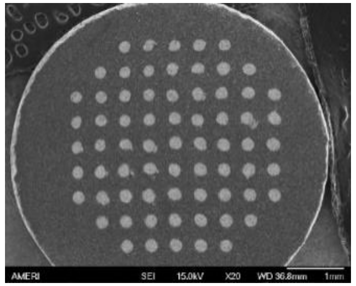
Cofired ceramic and Pt

85 micron vias

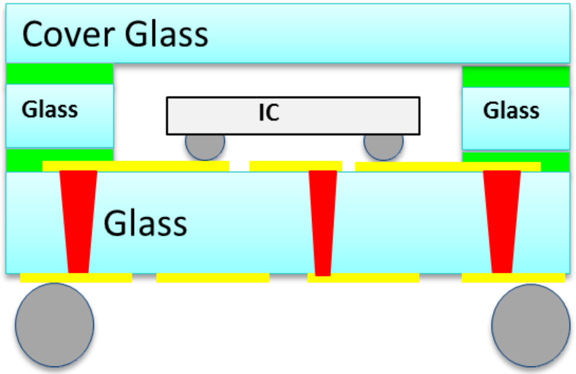
332 feedthroughs in 7 mm

Area-array Pt bonding with sintered Pt nanoink

Karbasi, Jones, FIU



1 X 10.$^{-9}$ cc He atm/sec

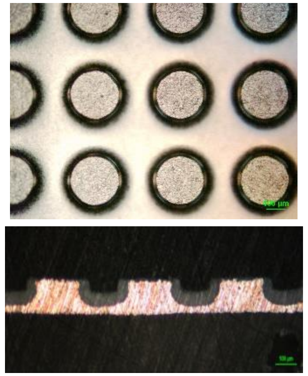


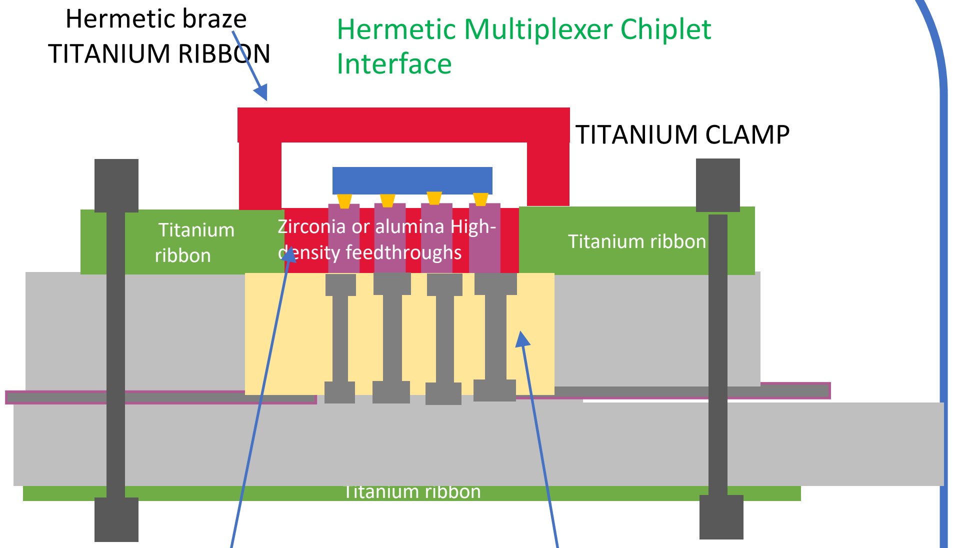
LCP with metal feedthroughs

(Pd-coated copper)

75 micron vias

Sundaram, GT-PRC





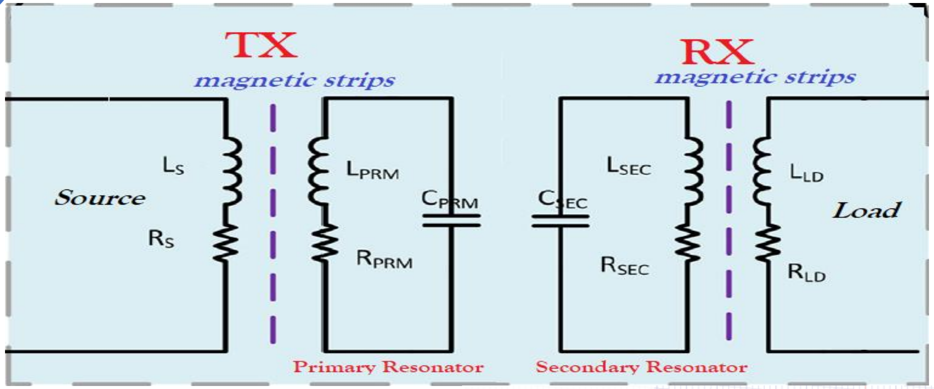
https://www.integer.net/

Hermetic feedthroughs with titanium flange

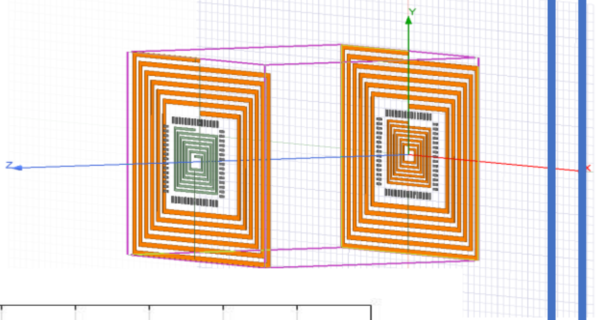
Z elastomer interconnect

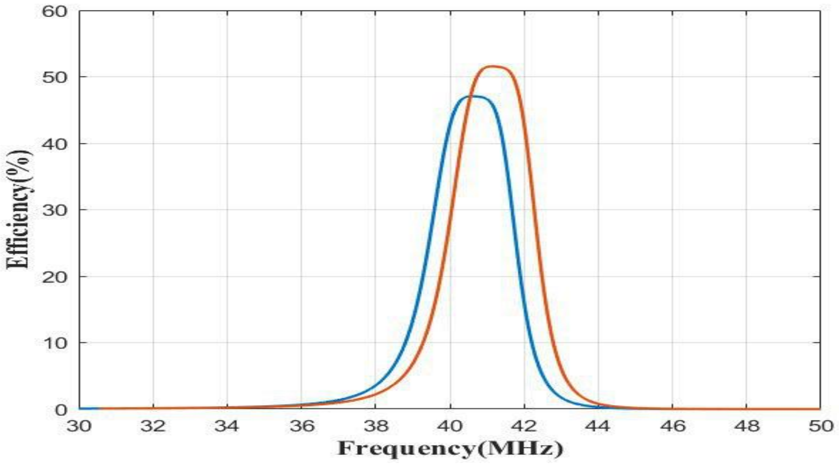
Sepehr Soroushiani, FIU

3D Wireless Power Delivery and Capacitive Storage

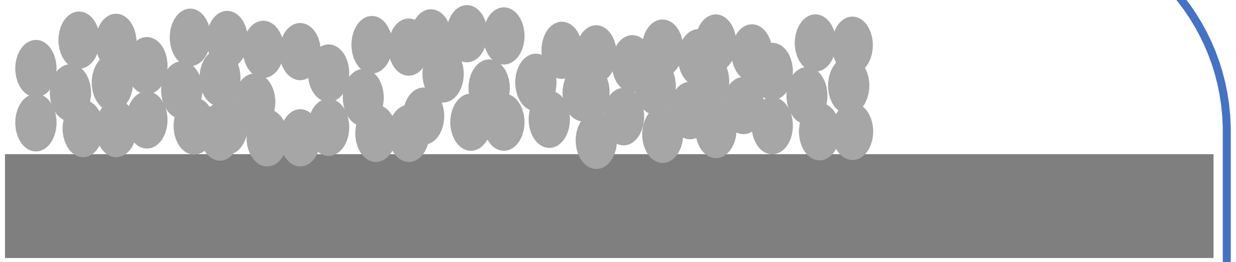


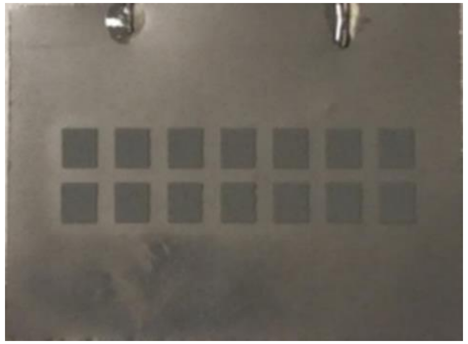
Magnetic flux concentration or metmaterials for better power transfer efficiency

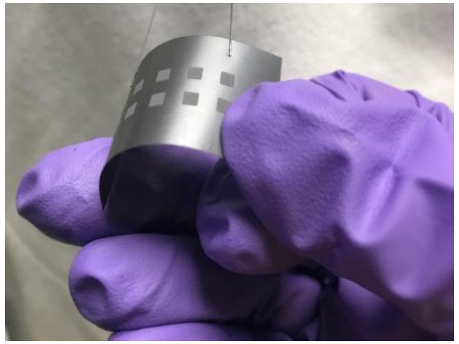


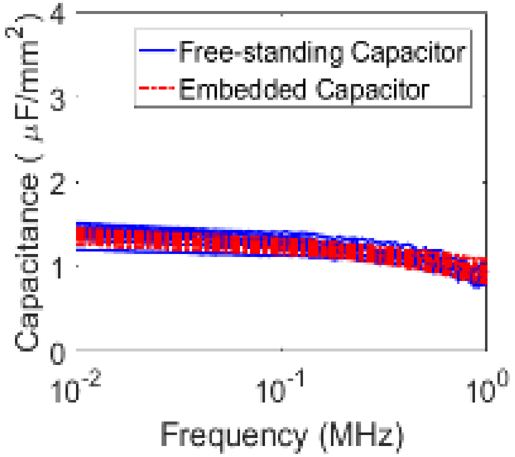


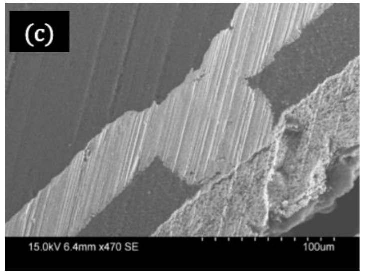
Mahmoud Sharafi, FIU

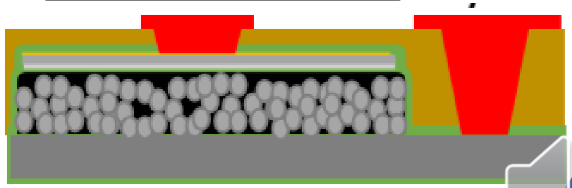












Grant Spurney, GT

Implanted Electrodes

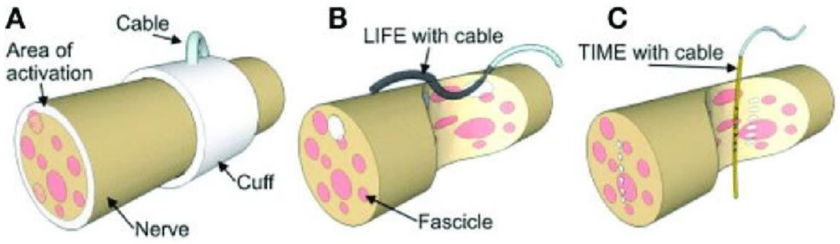
Pt or PtIr

Platinum black

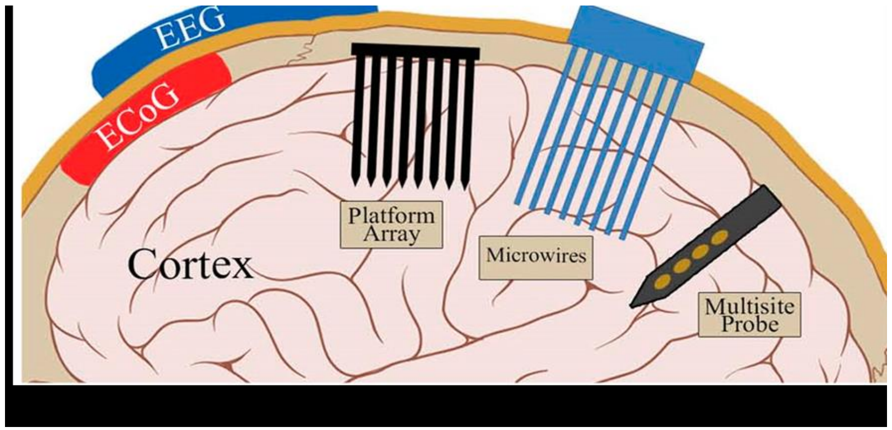
Pt/PEDOT-PSS
Au/PEDOT-PSS

Graphene/
PEDOT-PSS

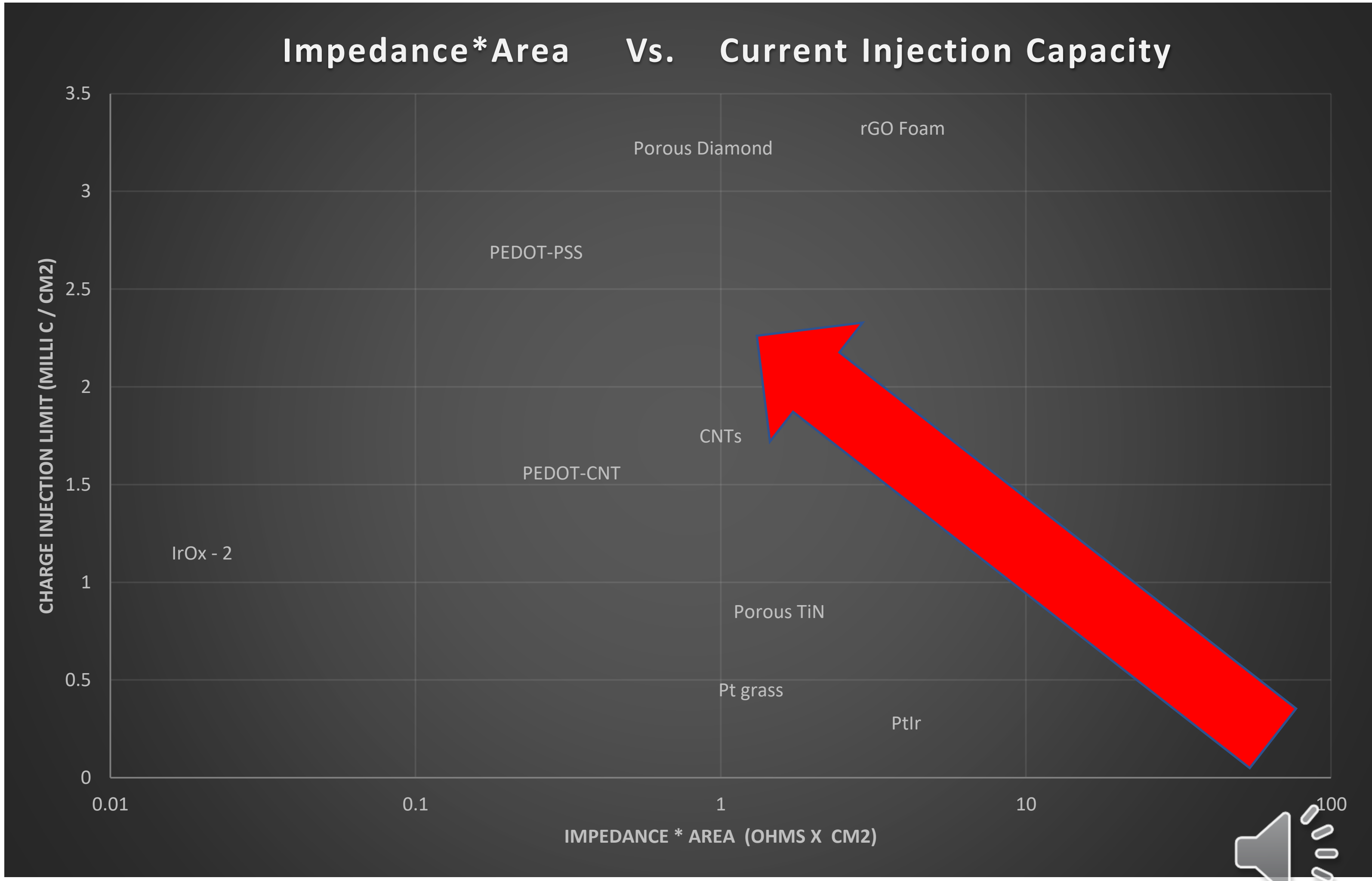
- Biocompatibility
- Charge injection: >5 mC/cm2
- Low impedance: < 0.1 ohms x cm2
- Mechanical tissue compatibility



Boretius, Biosens. Bioelec 2010



Fattahi, Advanced Materials, 2014



Redrawn from data reported in Kosteralos, Advanced Materials 2018.

Kelly Rojas, FIU

Summary

- Heterogeneous package integration for future systems

- Power Modules:
  - Passive components with high storage densities; 3D packaging
  - Diamond-like heat-spreaders; low thermal impedance bonding interfaces

- RF:
  - Nanodielectrics and nanomagnetic films for passives, antennas
  - Nanowire arrays for circulators, isolators
  - THz array – integration of sources, detectors with antenna arrays and waveguides

- Bioelectronics:
  - Electrode arrays with pulse generators or recording units
  - High-efficiency power and date telemetry
  - Zero-power data telemetry
  - Remateable interfaces

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