Emerging high-performance and low-cost power packaging solutions with nanoscale capacitors and inductors

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& Heraeus Inc., Leverkusen, Germany.

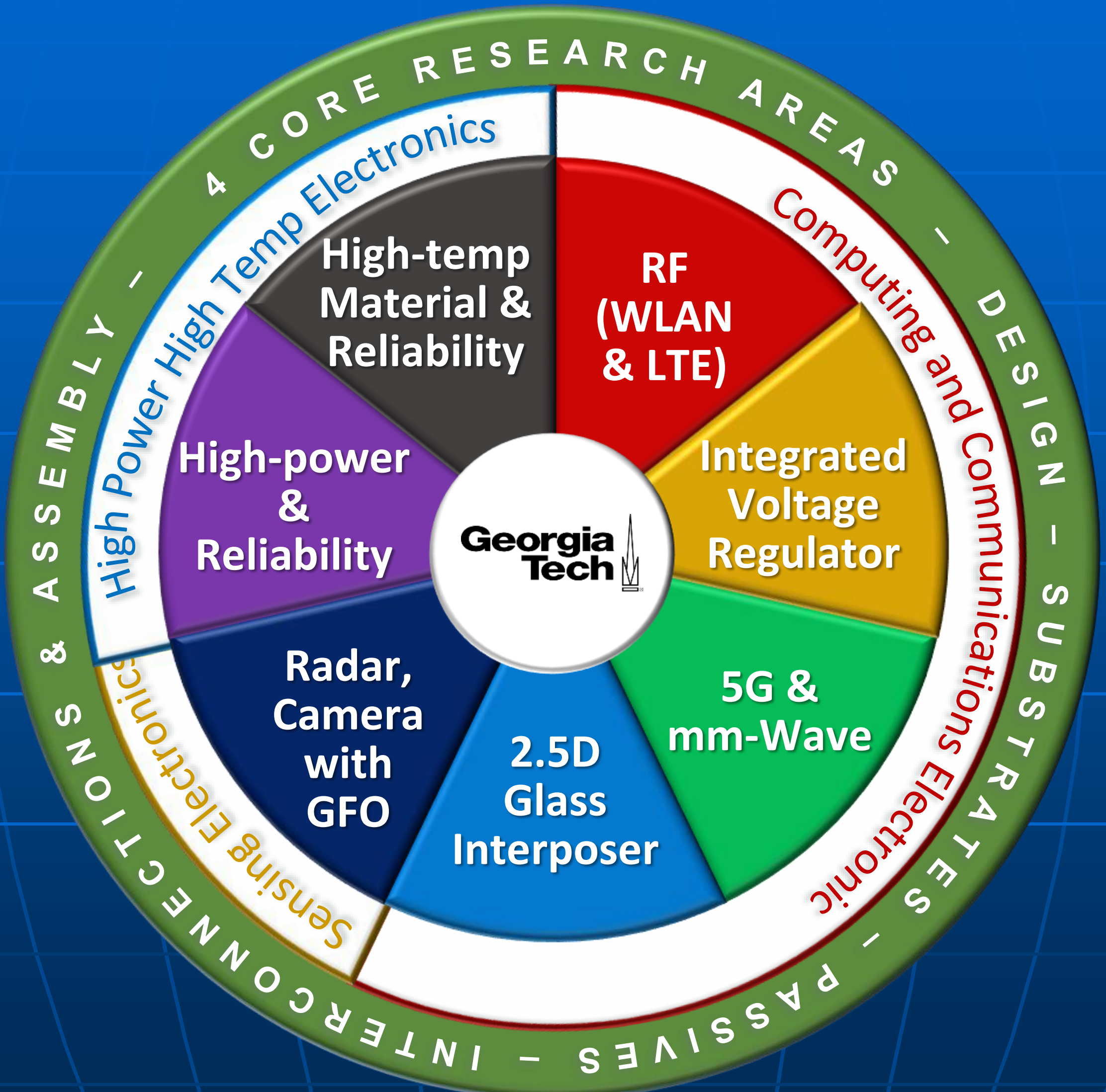
Summary

GT-PRC is innovating power packaging technologies with advanced components and 3D integration,

and also creating an industry ecosystem of material suppliers, component manufacturers and end-users:

- Capacitors in consumer power modules:
  - Silicon-integrated nanoscale tantalum capacitors
- High-temperature and high-voltage capacitors with:
  - Porous copper electrodes
  - Nanoscale inorganic – organic hybrid dielectrics
- Capacitors and inductors in integrated voltage regulators:
  - Low-cost polymer nanomagnetic inductors
  - Panel-scale inductor and capacitor integration
- Shielding:
  - Nanolayered structures for performance beyond copper

Packaging R&D at GT-PRC



Why Collaborate With Georgia Tech PRC

- No. 1 Academic Leader in IC & Systems Packaging
- Technical Vision Consistent with Market Needs
- Co-development of Panel-based Glass Packaging with 50 Global Researchers, Developers, Manufacturers and users
- Explore and Develop Advanced Systems Packaging Technologies Beyond Industry's 3-year Horizon
- Seamless from R&D, Prototype, and Tech Transfer Enabling Commercialization
- Track Record of Technology Breakthroughs
- Only 300mm Cleanroom Panel Facility in the Academic World
- > 50 Person Co-development Team: Full-time Researchers, Manufacturing Industry Partners, Graduate Engineers, Faculty and On-campus Industry Engineers
- Leverage: $8M/100k

Global Industry Partners in Co-development

NORTH AMERICA
- Corning – Glass
- Dow Chemical – Polymers
- Advantech – Deposition
- Coherent – Laser
- ESI – Laser
- K&S – TCB Bonder
- MKS – Plasma Etching
- *Rudolph – Lithography*
- SavanSys – Cost Model
- Tango – PVD Tools
- Veeco – Cleaning
- QualiTau – Assembly
- AMD – 2.5D
- AVX – Passives
- GlobalFoundries
- Intel – Digital
- Johnson Battery – User
- Qualcomm – 5G, Fan-out, RF
- TE – Opto
- TI – Passives

EUROPE
- HC Starck – Capacitors
- Schott – Glass
- Atotech – Plating
- Suss – Laser Via
- Xyztec – Assembly
- TDK-Epcos – RF
- *Valeo – ADAS*

ASIA
- Orbotech – Metrology
- PacTech – Assembly

CHINA
- JCET – Bumping

KOREA
- Gigalane – RF

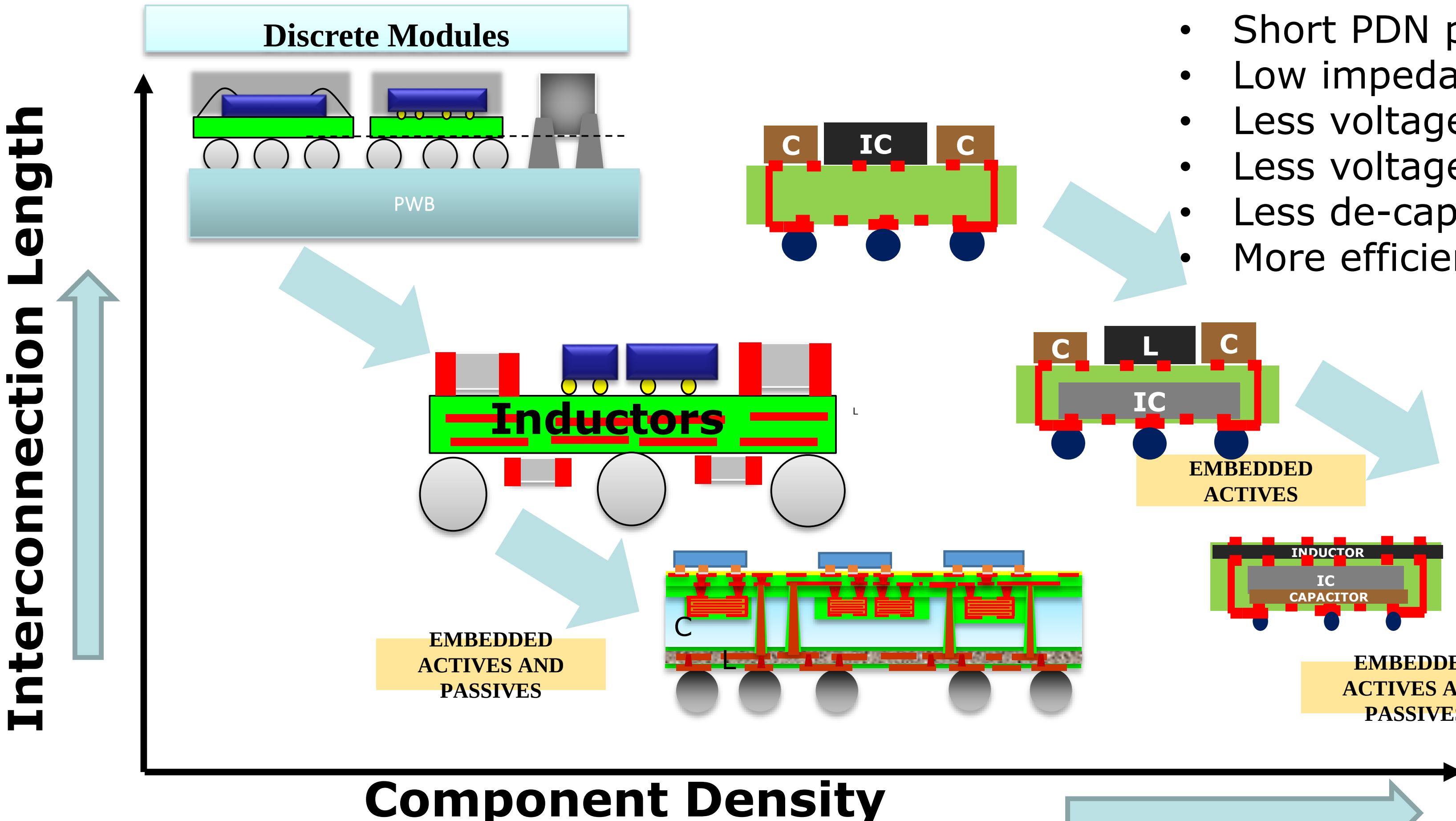
TAIWAN
- Unimicron – 2.5D
- TSMC – User

JAPAN
- Ajinomoto – Dry Film
- Asahi Glass – Glass
- JSR – Low-loss Polymer
- Nitto Denko – Magnetics
- Panasonic – Low-loss Polymer
- *Taiyo Ink – Photopolymer*
- TOK – Photopolymer
- Asahi Glass – TPV
- Disco – Dicing
- Hitachi Metals – 2.5D
- NGK/NTK – 2.5D
- Shinko – 2.5D
- Namics – Underfill
- WALTS – Substrate
- Murata – RF

Materials	*Tools*	*Substrates*	*Assembly*	*Users*

Technology Trends and Drivers

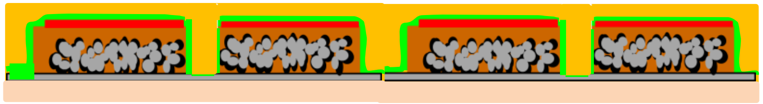
- Higher bus voltage to suppress losses
- Integrated power conversion with the load:
  - Suppress I^2 R losses
  - Minimize the need for decoupling capacitors
- Integration of storage elements – should not offset the benefits or interconnection losses
- Better Power distribution network designs



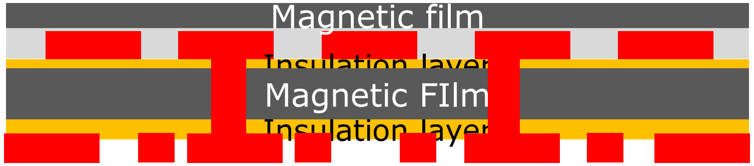
- Short PDN path
- Low impedance
- Less voltage drop
- Less voltage variation
- Less de-caps
- More efficiency

Large-Area Capacitor and Inductor Integration

- Both capacitors are inductors are made as large-area free-standing films
  - Can be pre-tested for yield and performance
- Laminated onto substrate or wafer
- Or diced into IPDs and embedded or surface-assembled

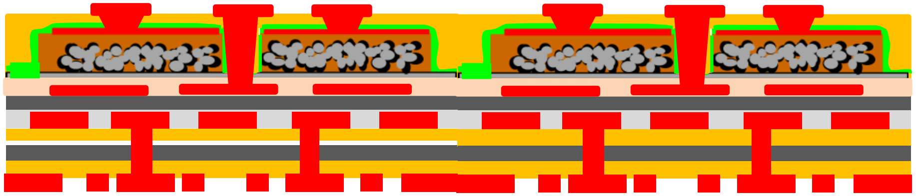


Capacitor Layer at panel scale



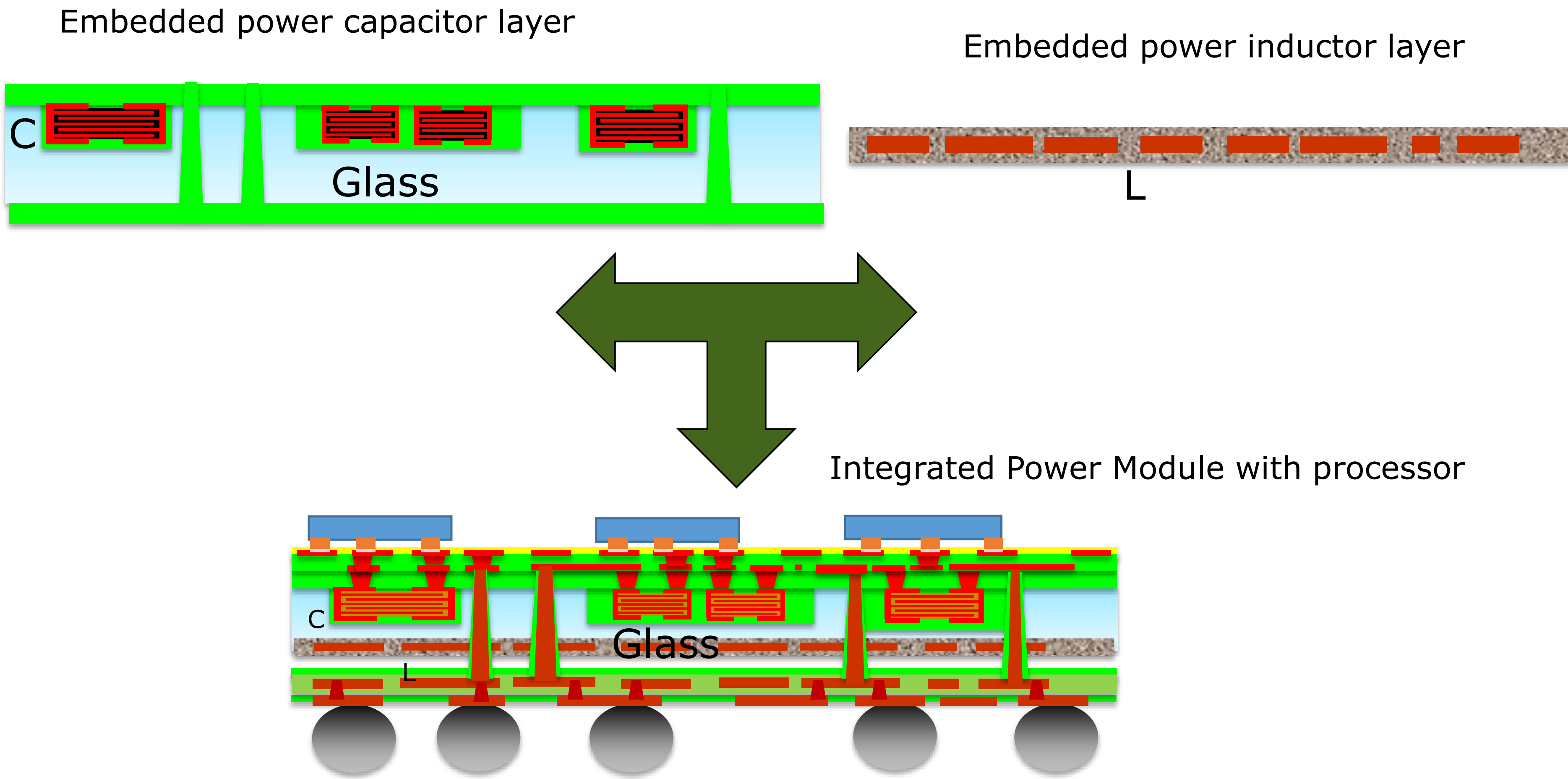
Spiral inductor

Inductor layers at panel scale



Large panel LC integration process

Glass Panel Capacitor and Inductor Integration

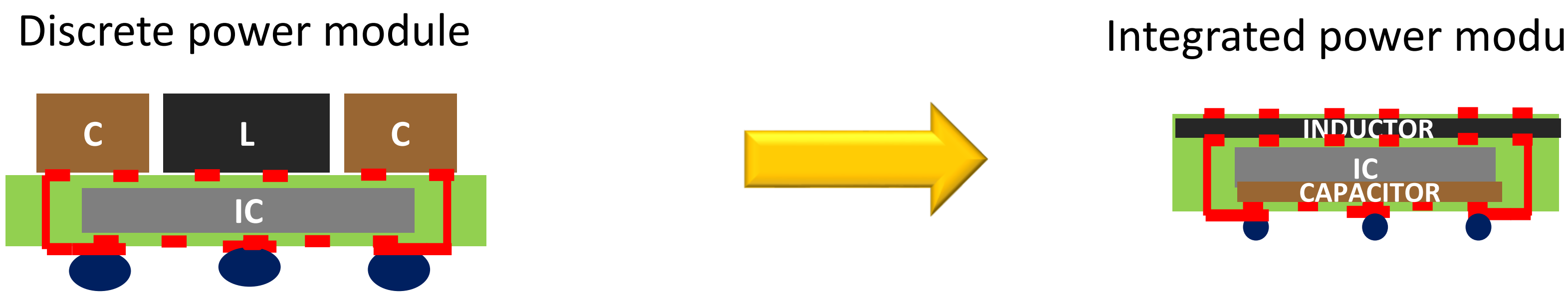


- Glass to support high-density fine-line wiring on large 510 x 510 panel manufacturing
- Currently ongoing, in collaboration with component manufacturers and end-user companies

Capacitors in Consumer Power Modules

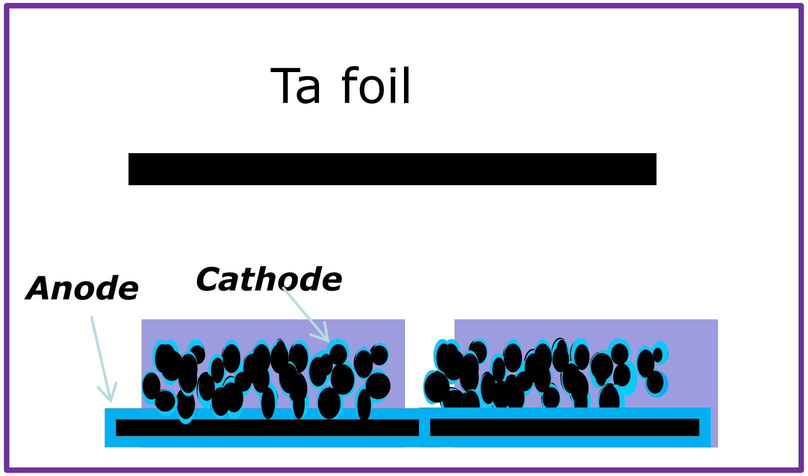
Silicon-integrated nanoscale tantalum capacitors

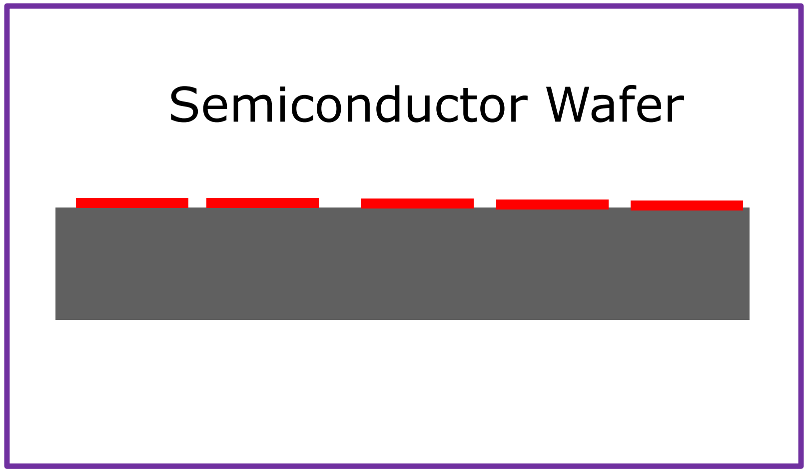
Capacitor Integration in Consumer Power Modules

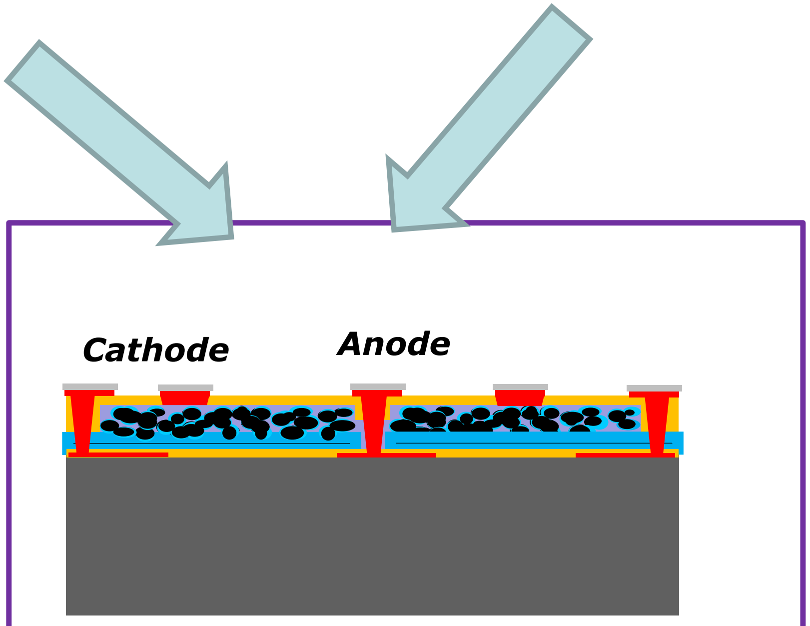


Wafer Integration of Ta Film Capacitors

Component Manufacturer (Ex. AVX)

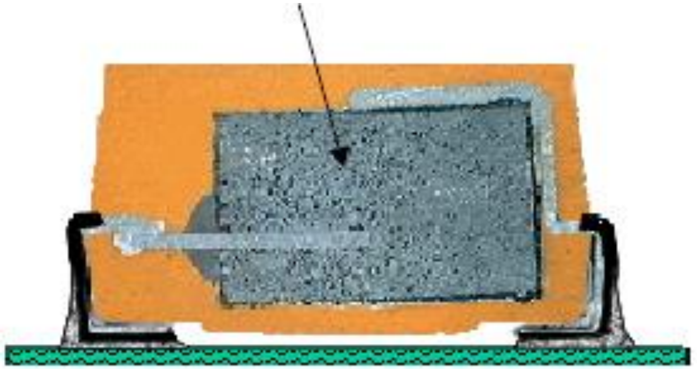


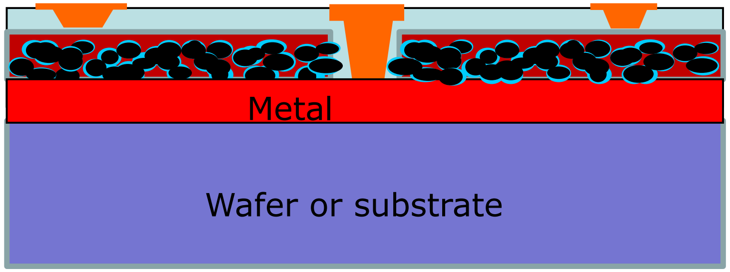




Integrated capacitor on a chip

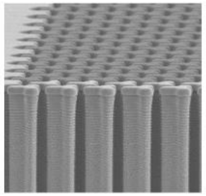
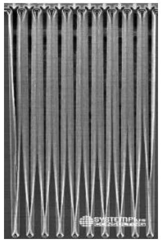
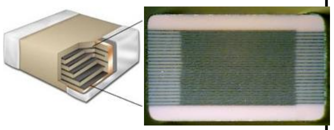
Bulky Ta Vs Ta Film Capacitors



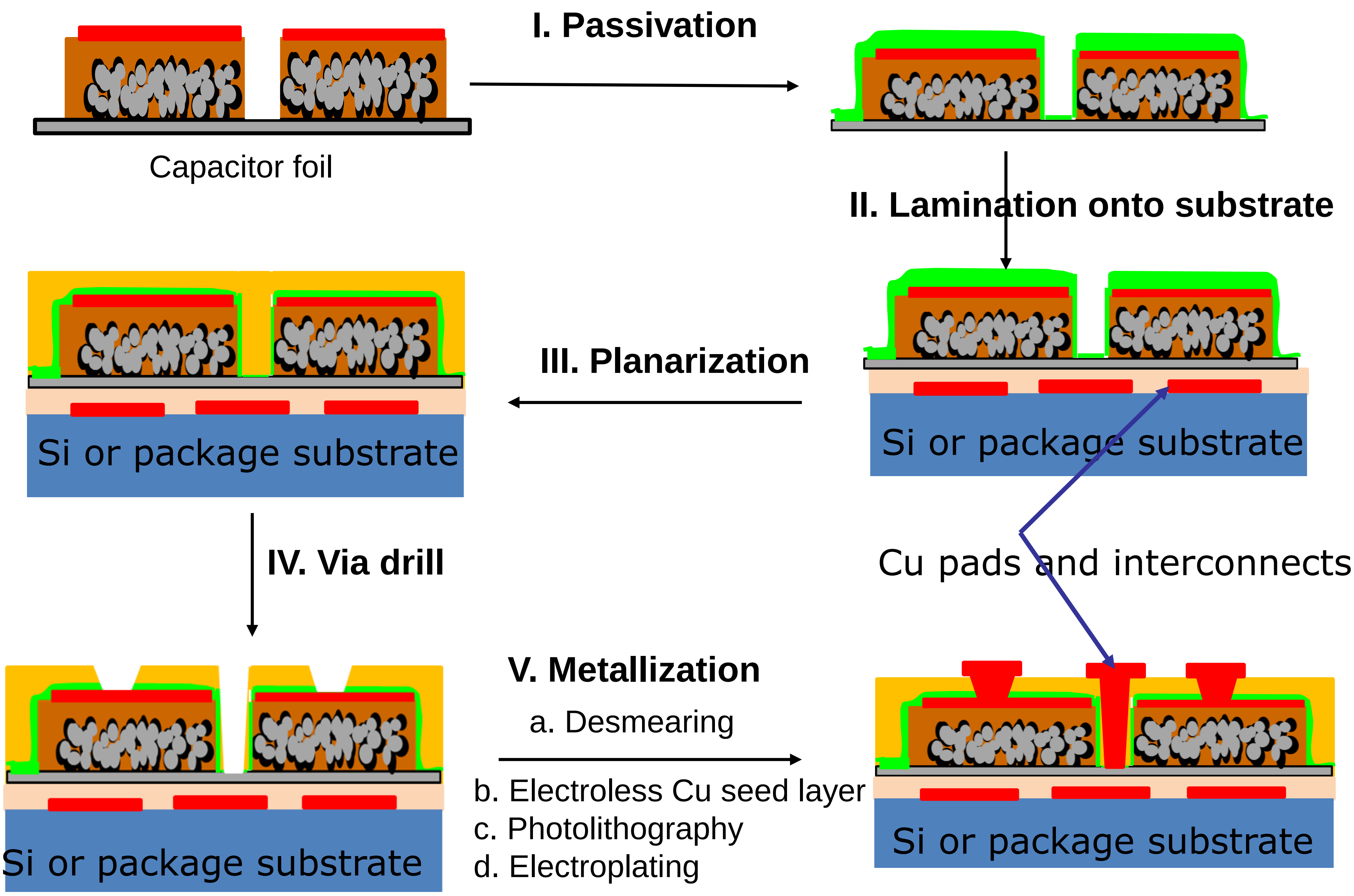


• **Thickness: 500 microns**	• **Thickness: 75 microns**
• 200 micron conducting path	• 50 micron conducting path
• CP/Carbon/Silver paste • Molded in lead-frame • (extra pkg volume)	• Minimal interfaces; • Direct metallization of CP with Cu/Au • (Minimal packaging volume)
• 100 milliohms x microfarad	• 20-50 milliohms x microfarad
• 1-5 MHz	• >10 MHz

Competitiveness of GT capacitors

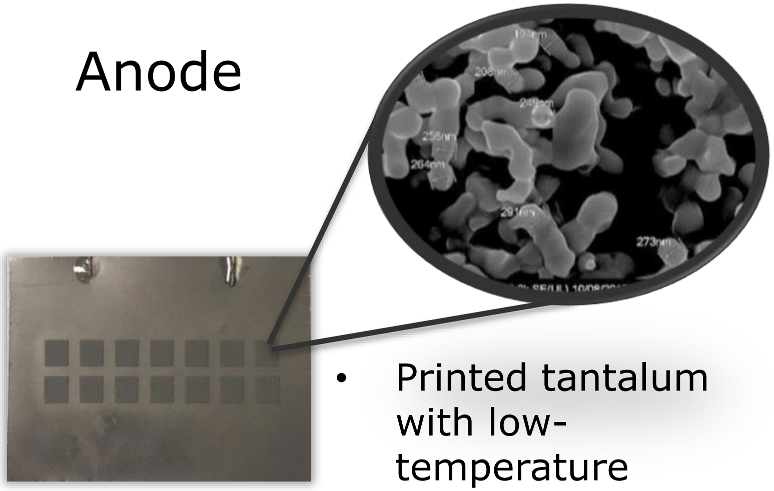
Parameters	**Si deep trench**	**Discrete MLCC**	**Foil Capacitors**
Component thickness (μm)	~ 200-300	200	75
Capacitance (μF/mm²)	1	2-3	1
Frequency (MHz)	-	150	1 - 150
Leakage current (μA/μF)	0.1	0.1	0.1
	 		

Capacitor Integration scheme



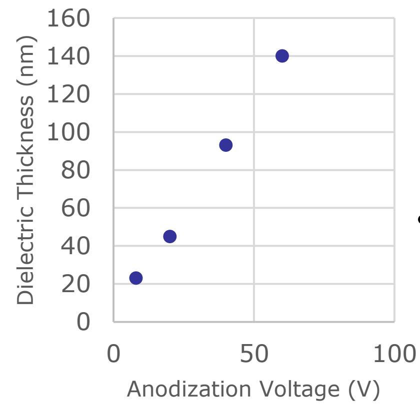
Demo. of Capacitor Integration

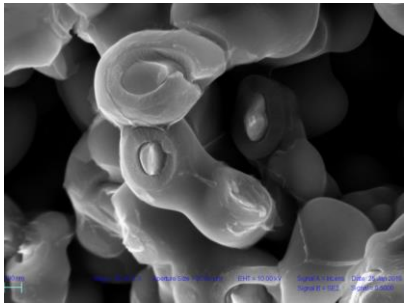
Anode



- Printed tantalum with low-temperature sintering

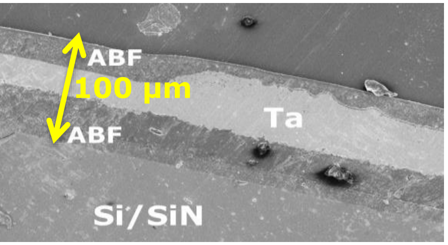
Dielectric





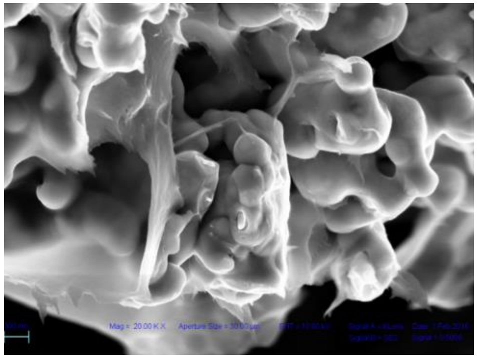
- Anodization for conformal oxide growth with controlled thickness

Component Integration on silicon



- Thin-film design for high volumetric density and frequency stability
- Lamination onto silicon with short copper interconnections

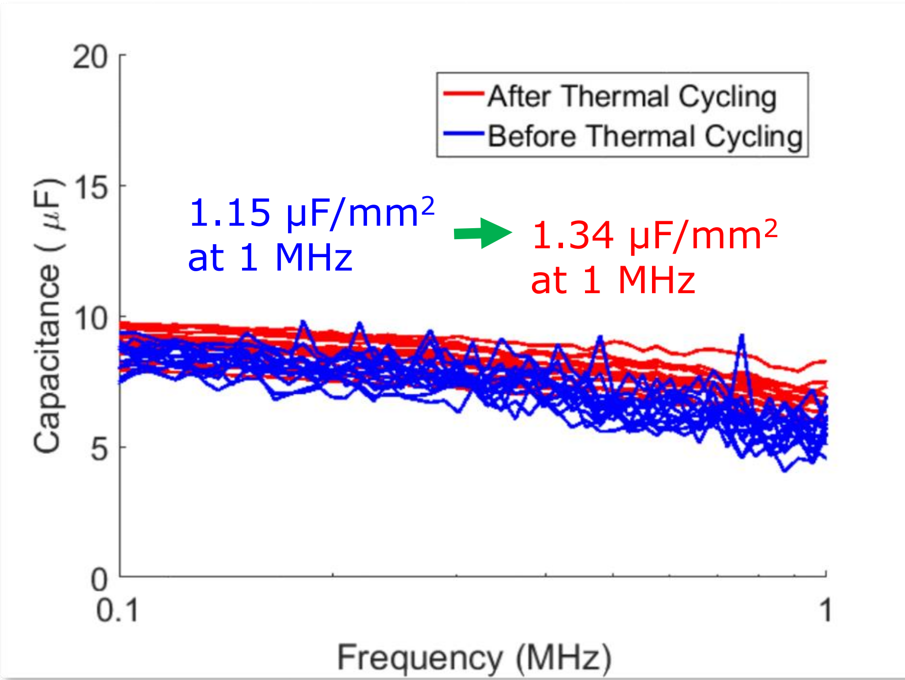
Cathode



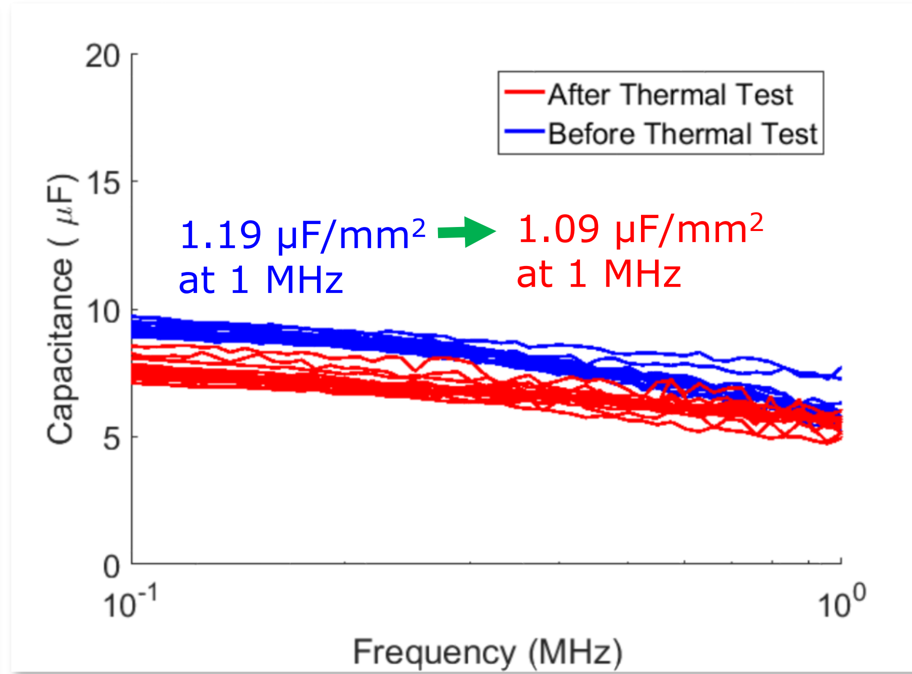
- Cathode dipping process for low ESR and high capacitance density
- Lift-off process for easy cathode patterning

Capacitor Reliability

65°C/95%RH for 500 hours



65°C/95%RH for 1000 hours



- Capacitance response to frequency similar before and after exposure to elevated temperatures and moisture
- Improved ESR after testing
- Near-hermetic seal that removes need for casing

80 kA-8V
200 nm passivation

Georgia Institute of Technology

Manufacturing Ecosystem for Silicon-Integrated Foil Capacitors

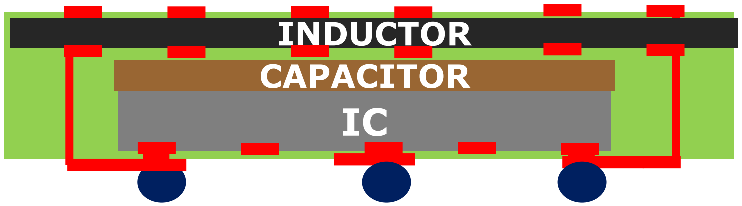
Component Manufacturer
(Ex. AVX)

Ta foil

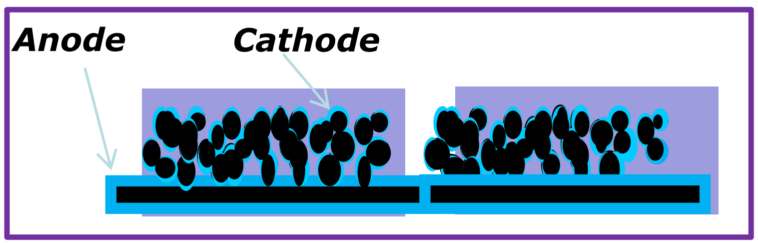
H.C.Starck

Heraeus

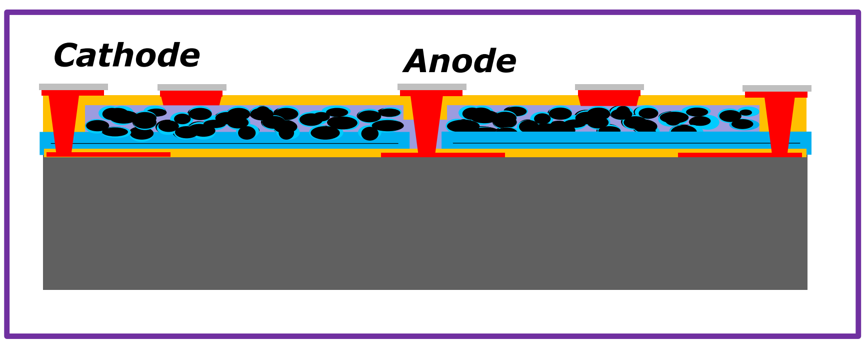
Texas Instruments

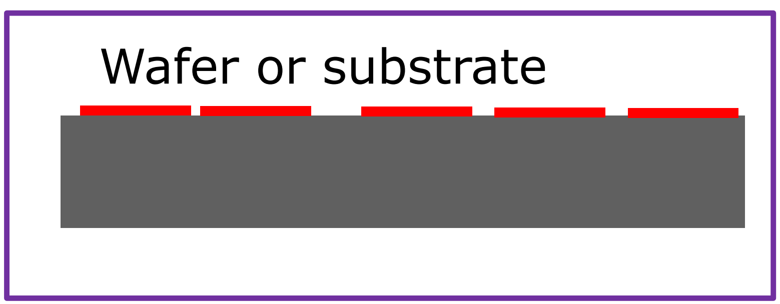


Power modules with passive-active integration



AVX





High-temperature and high-voltage capacitors with nanoscale hybrid dielectrics

High-Temperature and High-Voltage Capacitors

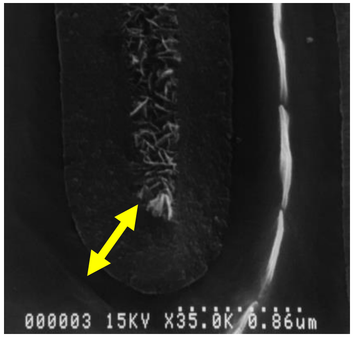
Safron's olymer film capacitors

700 V; 625 A current;
68 mm x 34 mm x 30 mm

AMS' metallized polymer film capacitors

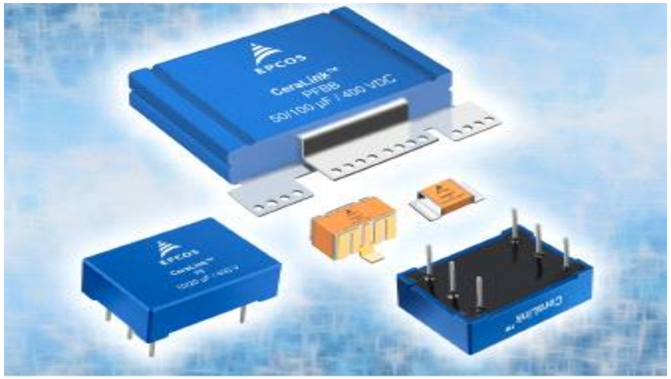
Operating voltage	Capacitance	Case-size (in mm)
400 V	120μF	Diameter: ϕ25 mm Length: 30 mm
400 V	68μF	Diameter: ϕ20 Length: 30 mm

EPCOS: MLCCs with PLZT
11 microfarad/cc; 350 V

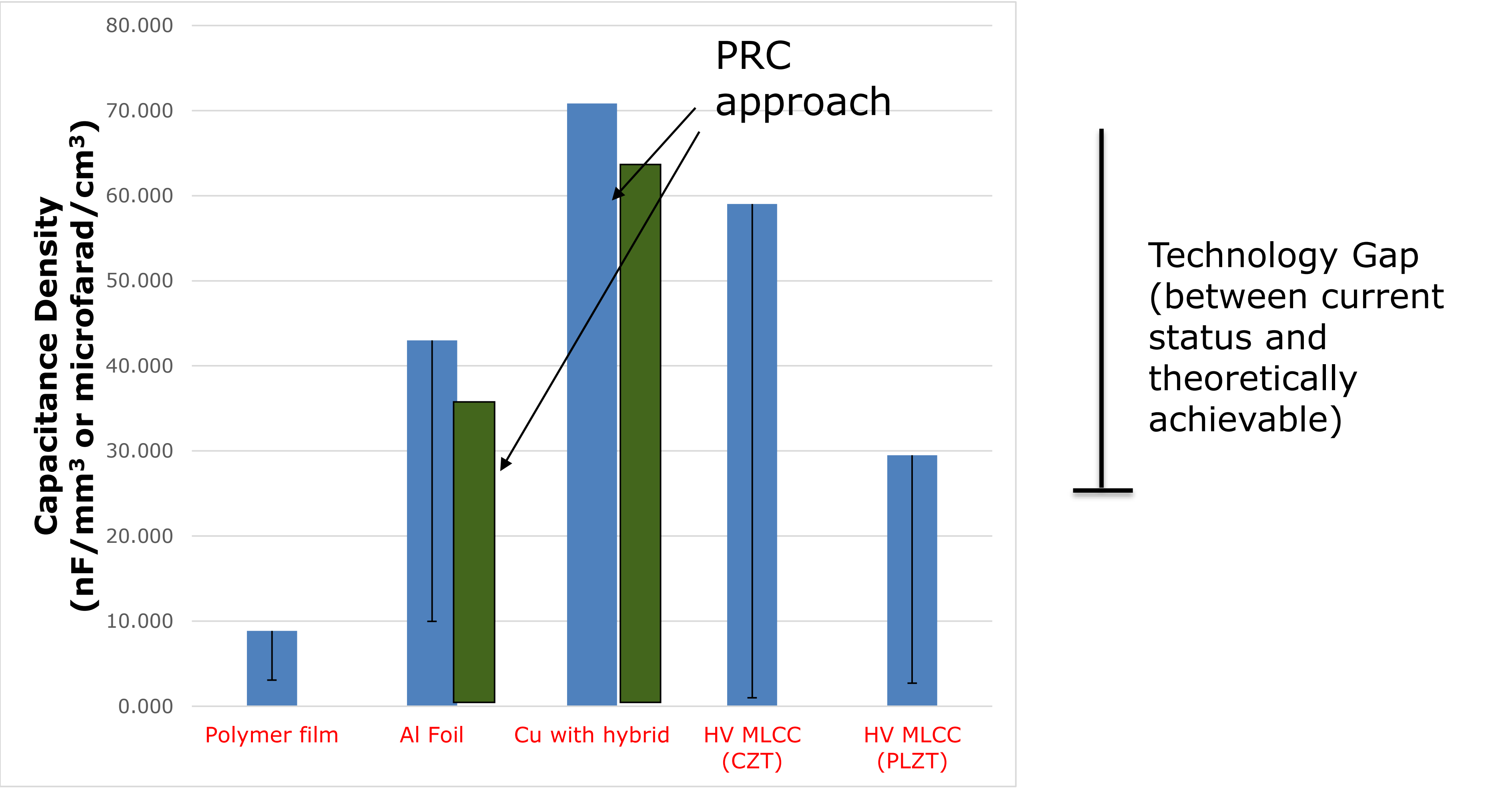


400 V formed dielectric

Electrolytic caps Vishay



Theoretical versus Achieved Volumetric Density for 450 V Applications

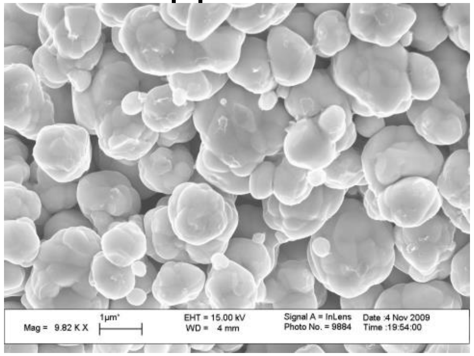


Thin Planar HV and HT Capacitors

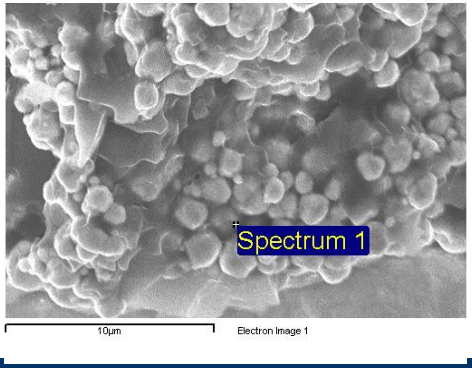
8-9 microfarad/cm^3
450 V
85-115 C

40 microfarad/cm^3
450 V
>175 C

Porous copper Electrode

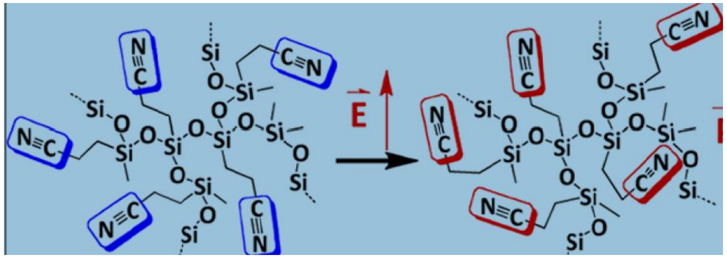


Conformal counter electrode

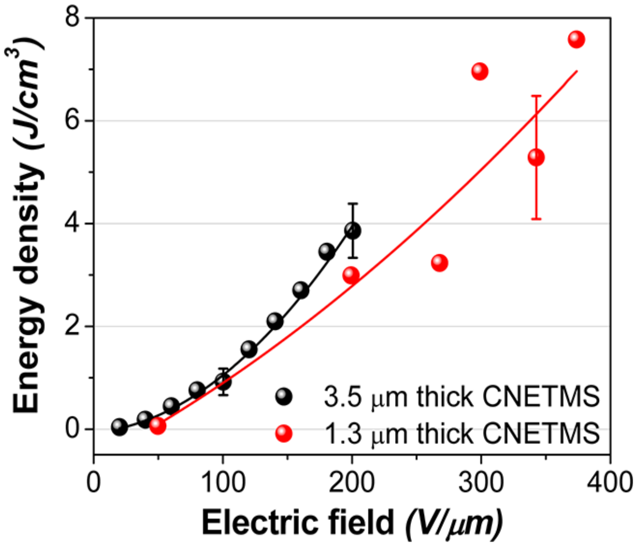


- Porous copper electrodes
- **Inorganic-organic hybrid dielectric**
  - **Permittivity of 20**
  - **BDV of 300 V/micron**
- Layering with high thermal conductivity adhesives
- High thermal-stability adhesives
- Vias and metallization
- Solder termination with through-vias
- 3D stacking for scaling up in capacitance

Inorganic-Organic Hybrid Nanodielectrics (Conformally coated on porous copper electrodes)



Hybrid inorganic-organic dielectric with high permittivity and BDV



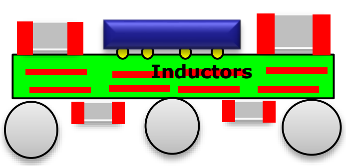
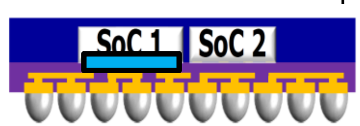
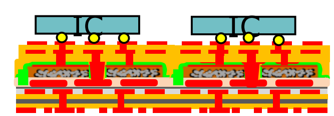
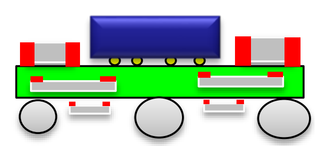
- Temperature stability of 300°C
- Permittivity ~ 20 and high breakdown strength
- Extractable energy density of 40 J/cm3 before packaging

Joe Perry, GT

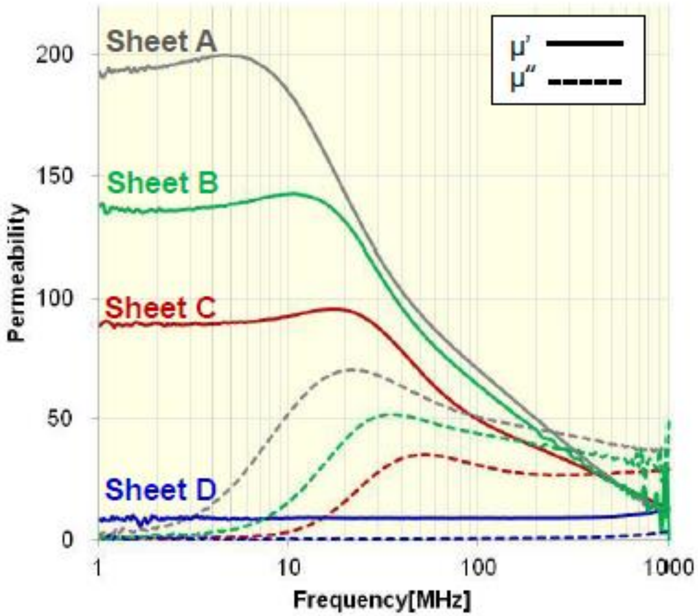
Capacitors and Inductors in Integrated Voltage Regulators

Panel-scale integration

Competitiveness of GT Embedded Inductors

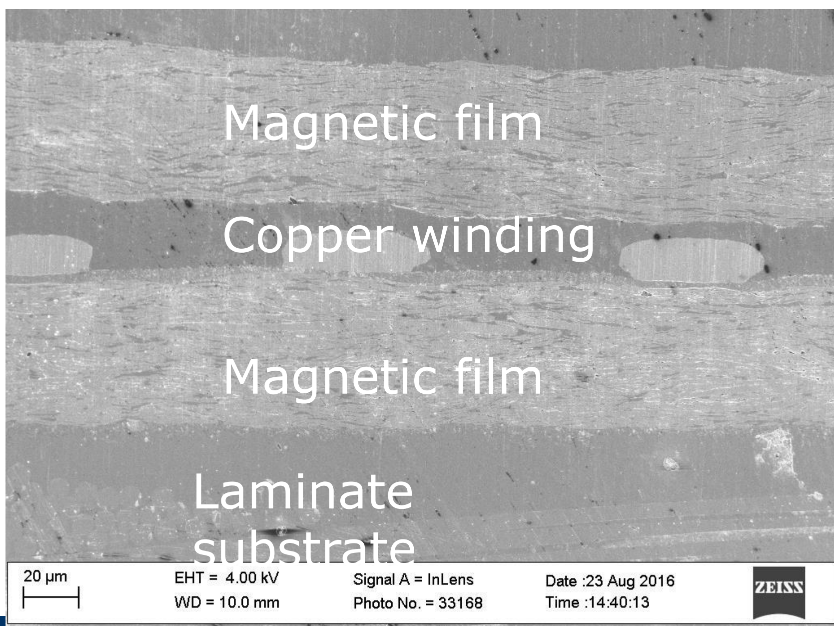
	Air core	Sputtered Thinfilm	Magnetic Composites	Sputtered films as glass IPDs
L/R_{DC} (nH/mΩ)	0.20	0.20	~20	5-10
AC losses (% of total loss)	<1%	<1%	<1%	<1%
Current handling (A/mm^2)	>1	1-2	1-2	1-2
				

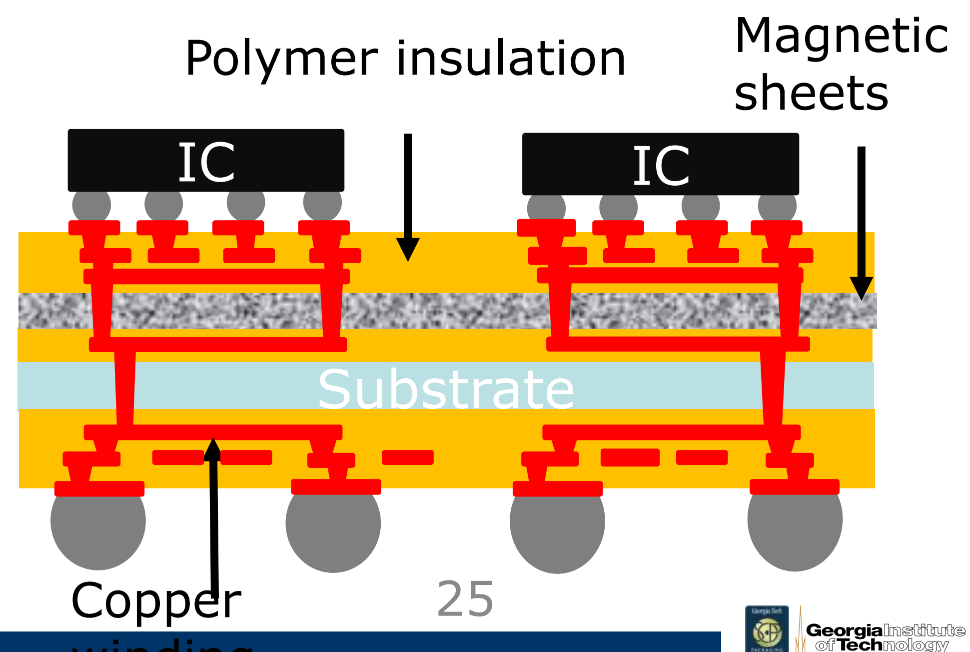
Advanced Magnetic Substrates



Sample		Frequency[MHz] 10	50	100
Sheet A	μ'	182	93	70
	μ"	53	60	51
Sheet B	μ'	141	85	64
	μ"	15	50	44
Sheet C	μ'	92	70	49
	μ"	3	35	31
Sheet D	μ'	9	9	9
	μ"	<0.2	<0.2	0.3

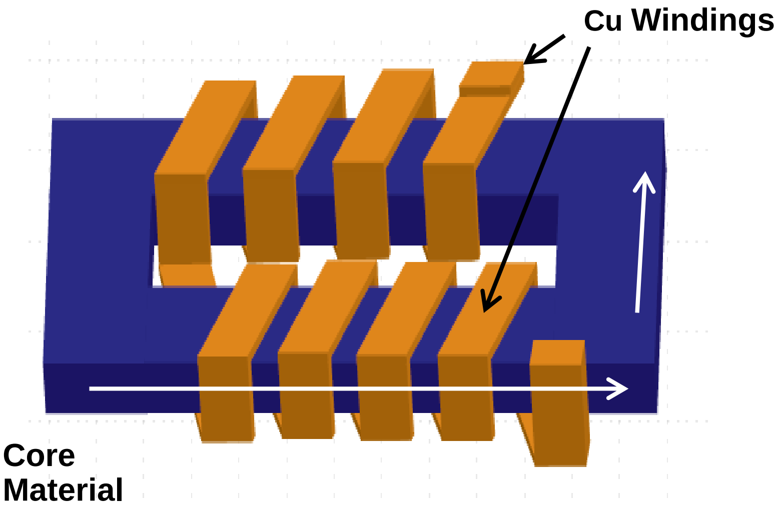
Nitto Denko Corporation

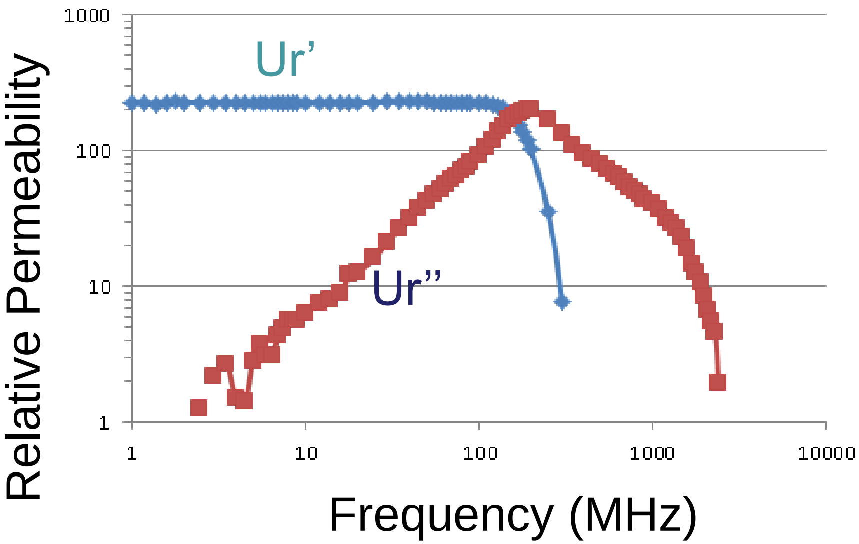




Nanomagnetic High-Sat, Soft Magnetic Core Material

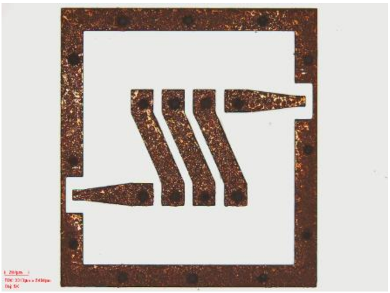
- Material sample thickness = >40um
- High deposition rate – high throughput and low cost
- IC or glass substrate- compatible
- Deposition thickness capability up to 50um demonstrated
- μ_r= 200, Bsat= 1.3 T, Q @ 5 MHz>90, Q@ 20 MHz=30
- 0.5 microhenries; Isat of 2 Amp demonstrated on 6 inch;
- Toroid and solenoid inductors demonstrated

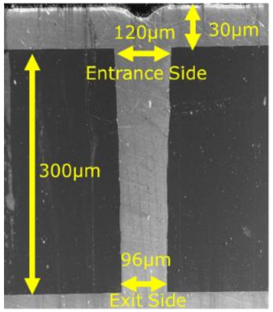


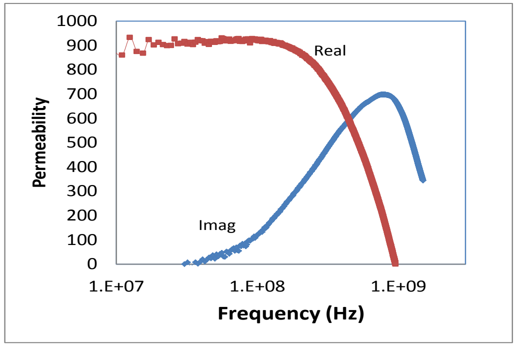


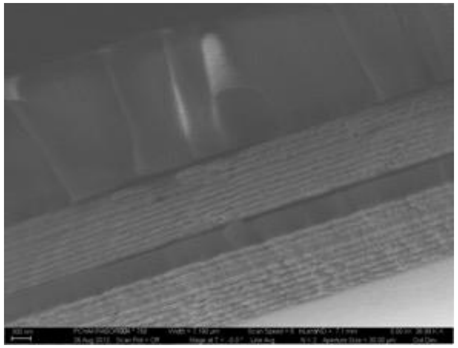
Inductors IPDs with Nanomagnetic Films on 50 microns glass

Solenoid inductors

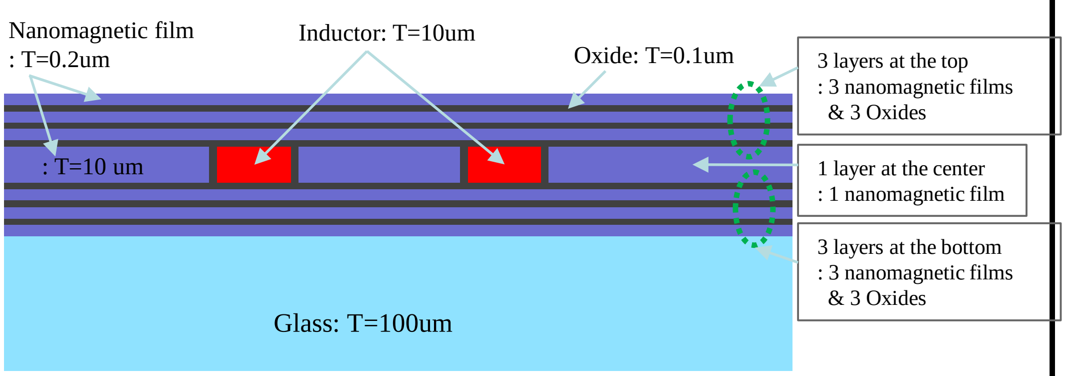


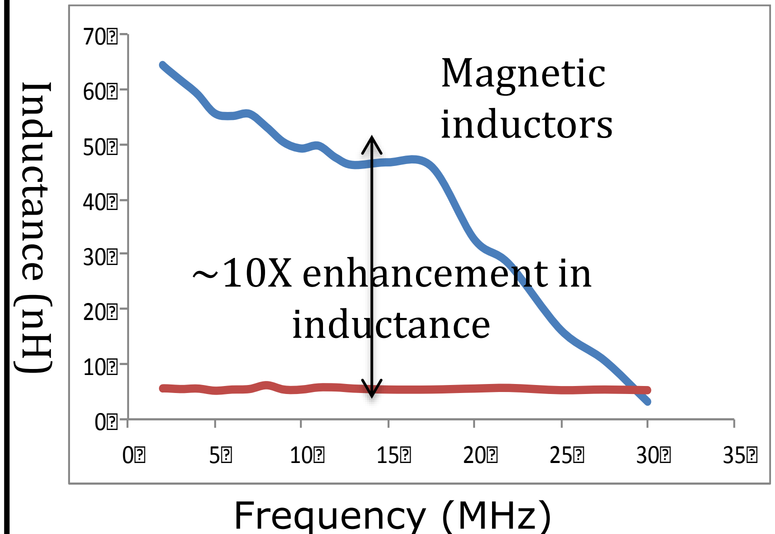






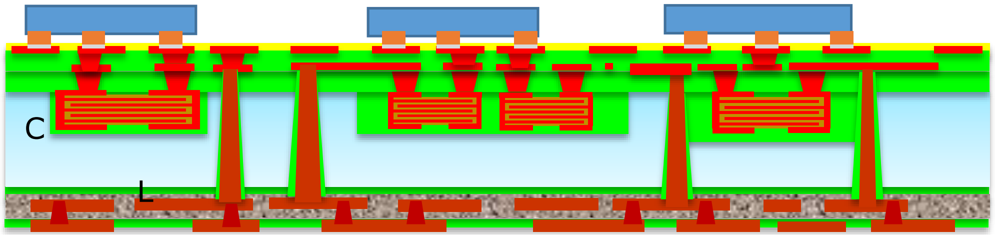
Potcor or racetrack inductors

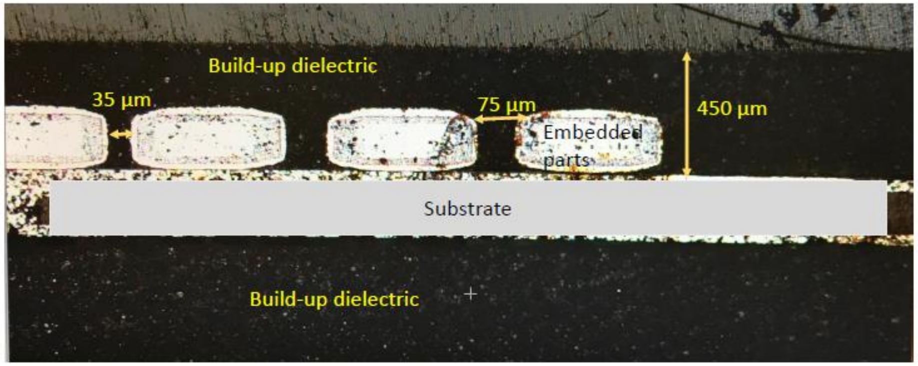




LC-Embedded Power Substrate

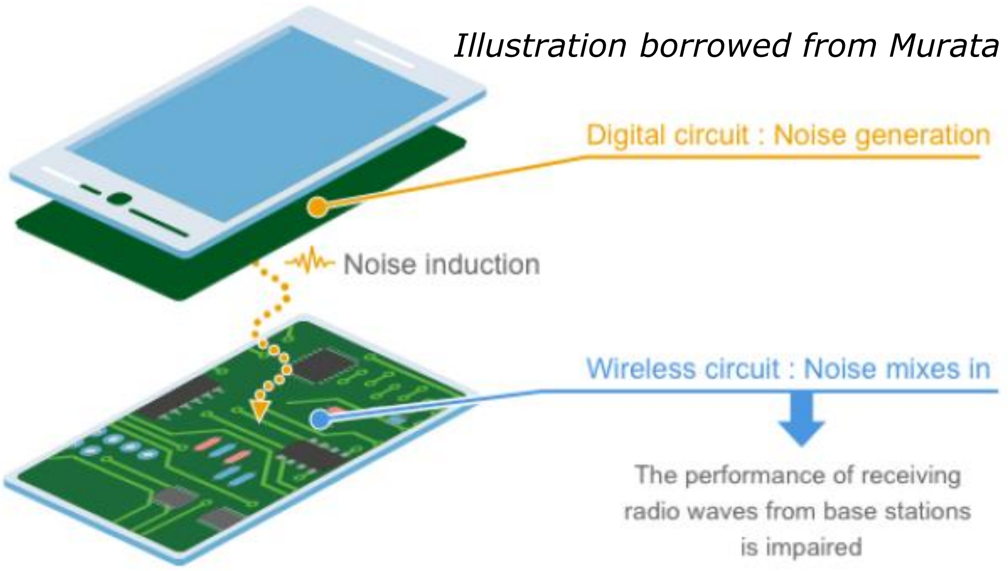
- Pre-manufactured capacitors fan-out embedded in organic laminate panels
- Magnetic components as large-area substrates
- Vertical through-via interconnections
- Ability to support redistribution layers on the top for routing
- Fine-pitch processor or other logic ICs on the topic





Component- and Package-Level Shielding

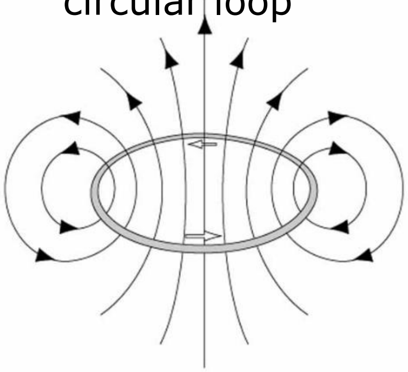
Parameter	Objectives
Shielding	60 - 120 dB
Frequency	1 MHz – 40 GHz
Distance of separation	0.1 – 10 mm
Shield metal thickness	~5-50 um



Component-level shielding:
- Plated copper
- Multilayered metallic structures

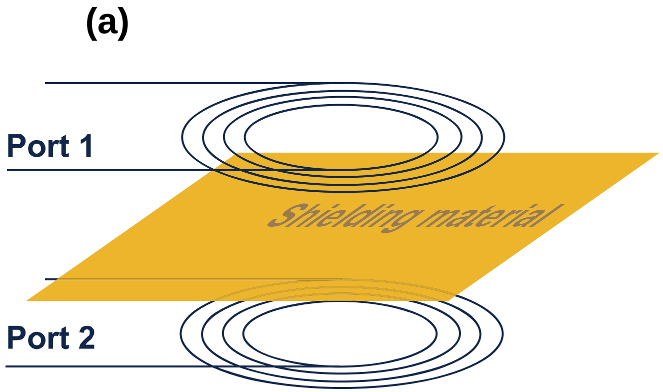
External shielding:
- Spray-coated, plated, sputtered

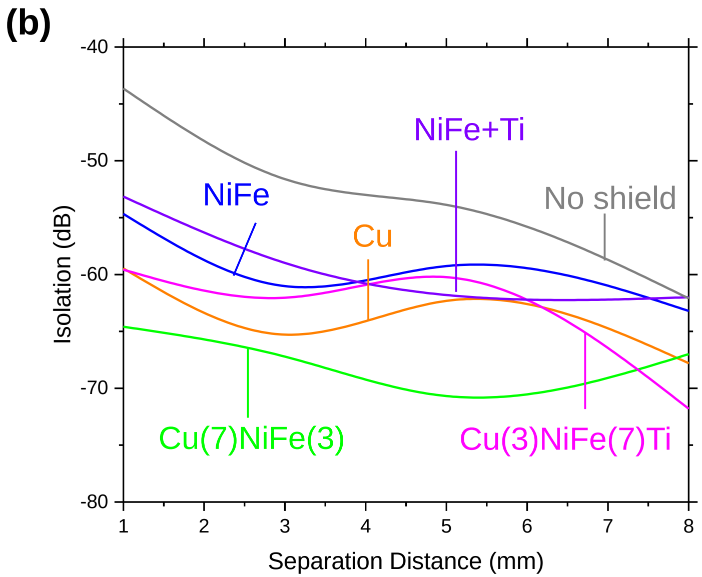
Field patterns for circular loop

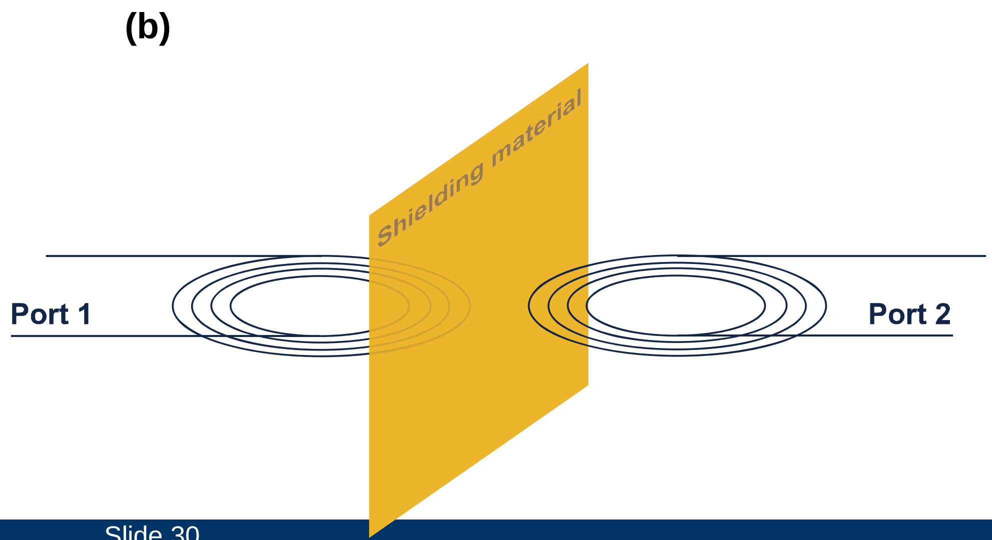


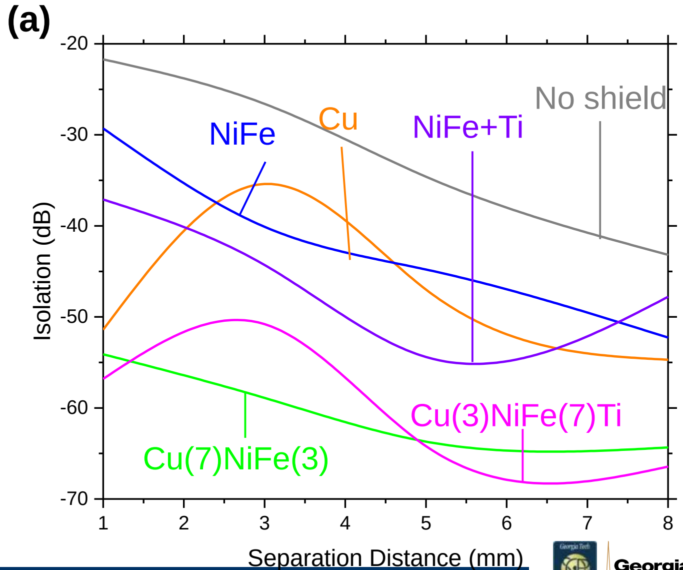
Materials beyond copper are needed to shield magnetic fields

Better EMI isolation Over Cu with Cu-Magnetic structures









Summary

GT-PRC is innovating power packaging technologies and also creating an industry ecosystem of material suppliers, component manufacturers and end-users:

- Capacitors in consumer power modules:
  - Silicon-integrated nanoscale tantalum capacitors
- High-temperature and high-voltage capacitors with:
  - Porous copper electrodes
  - Nanoscale inorganic – organic hybrid dielectrics
- Inductors and capacitors in integrated voltage regulators:
  - Low-cost polymer nanocomposite inductors
  - Panel-scale inductor and capacitor integration
- Integrated shielding at component and package-level
  - Materials beyond copper