Embedded passives –
Recent Advances and Opportunities

PSMA Phase III Report

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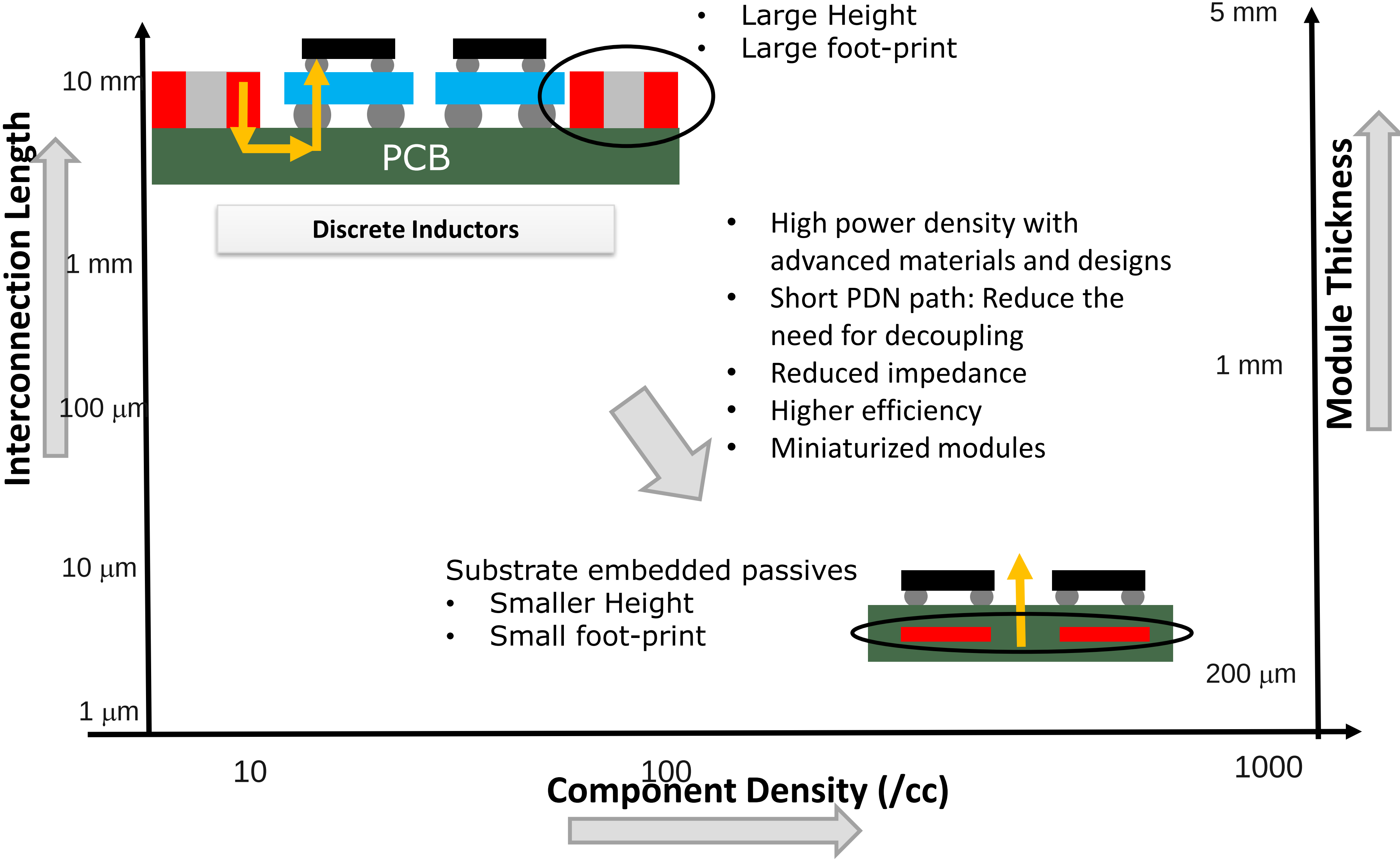
Outline

- Need for embedded passives
- Recent Advances
  - Magnetics:
    - Material advances and options
    - Low-frequency and high-power – nanocystalline and amorphous flakes
    - Medium-frequency – medium power: Integrated metal flake composites
    - High-frequency, high power density – thin nanomagnetic films
    - Emerging opportunities

  - Capacitors
    - Low-voltage, integrated capacitors
    - Medium-voltage integrated capacitors
    - High-voltage, high-temperature capacitors
    - Emerging opportunities

  - LC integrated modules
- Summary

Need for Embedded Passives



SMT Discrete inductors

- Large Height
- Large foot-print

- High power density with advanced materials and designs
- Short PDN path: Reduce the need for decoupling
- Reduced impedance
- Higher efficiency
- Miniaturized modules

Substrate embedded passives

- Smaller Height
- Small foot-print

Magnetic Material Advances and Options

	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

Low-Frequency, High-Power

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

Medium-Frequency, Medium-Power

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

High-Frequency, High Power Density

Low-Frequency - High-Power Magnetics

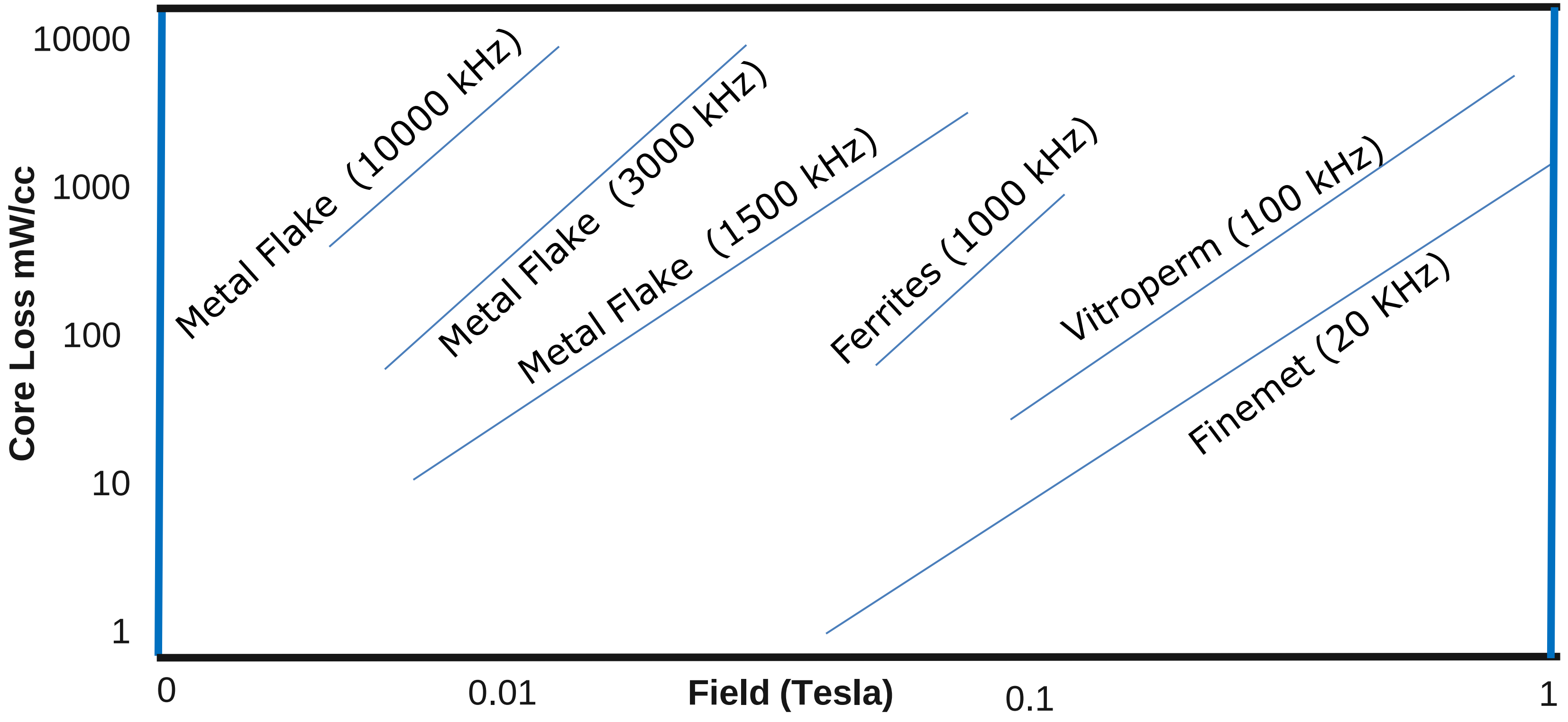
Ferrite 3C90:
- 500 kHz: 0.1 T peak; 700 mW/cc;
- 1 MHz; 0.02 T; 70 mW/cc;

Ferrite 3F5 MnZn:
- 1 MHz; 0.02 T; 30 mW/cc

Sumida’s ferrite:
- 1.5 MHz; 0.02 T; 37 mW/cc
- 1 MHz; 0.02 T; 70 mW/cc;
- 200 kHz; 0.1 T; 250 mW/cc

Vitrovac (Co_{67} Fe_4 B_{11} Si_{16} Mo_2) amorphous flakes:
    100 kHz; 0.1 Tesla, 30 mW/cc;
    100 kHz; 0.2 Tesla: 200 mW/cc;

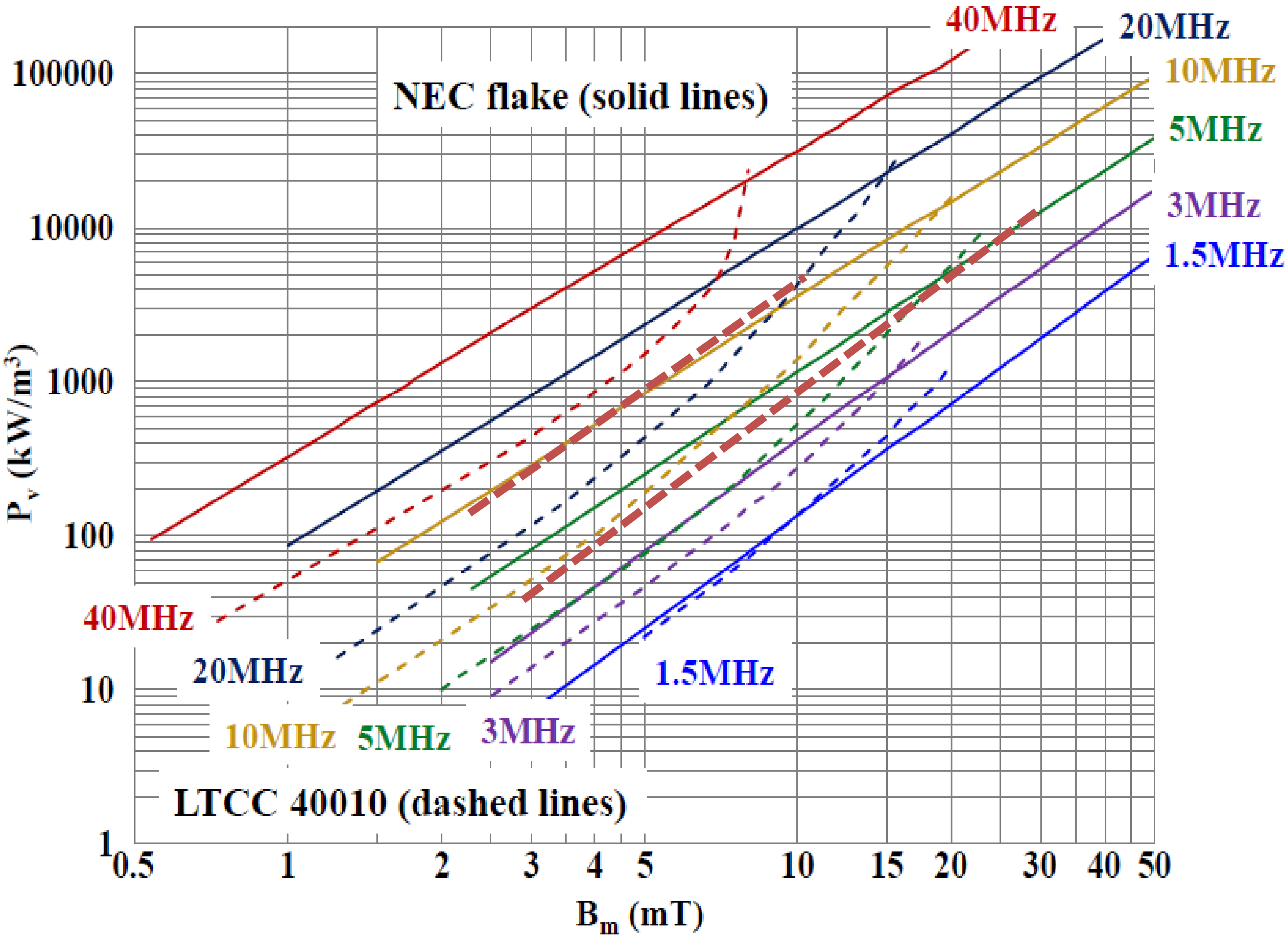
Hitachi metals: Finemet - FT-3L and FT-3M:
    20 kHz; 0.1 Tesla; 2 mW/cc
    20 kHz; 0.2 Tesla; 15 mW/cc
    20 kHz; 1 Tesla; 300 mW/cc



Mid-Frequency - Medium-Power: Metal flake composites:

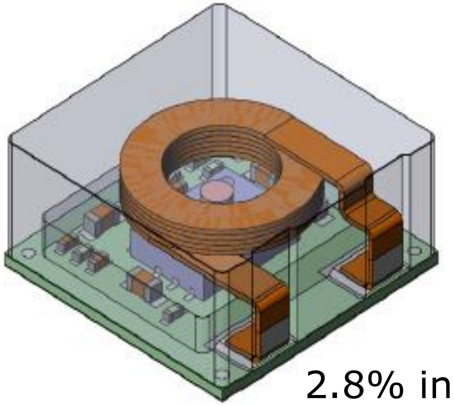
- (Material Class A)
  - 1 MHz; 20 mT; 400 mW/cc
  - 2 MHz; 20 mT; 1000 mW/cc

Material Class B:
3 MHz; 10 mT; 550 mW/cc
10 MHz; 3 mT; 250 mW/cc
10 MHz; 10 mT; 4000 mW/cc



Medium Frequency – Medium Power: Inductor Advances

Sumida PSI2: Inductor in package molding

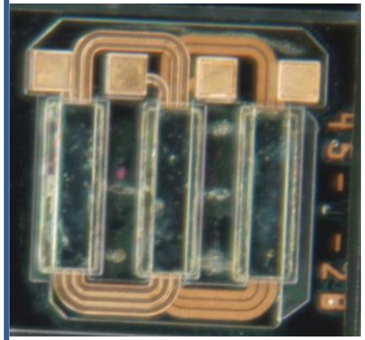


Better thermal, shielding,

High current-handling and efficiency

2.8% increase in efficiency with 3-5 Amp current

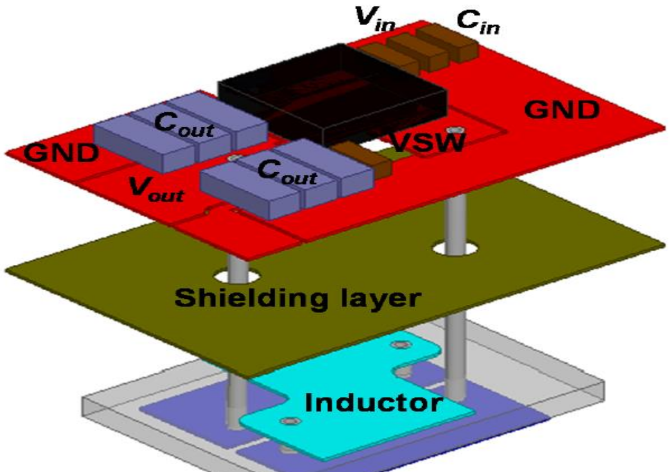
Tyndall



Efficiency of a 61.7% power inductor at 91.7%

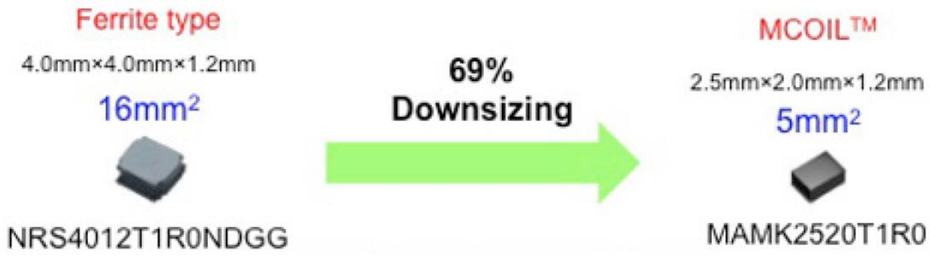
Thin magnetic films and coupled inductor designs

Virginia Tech: Inductor in PCB Substrate



PCB-embedded ferrite and metal flake composites

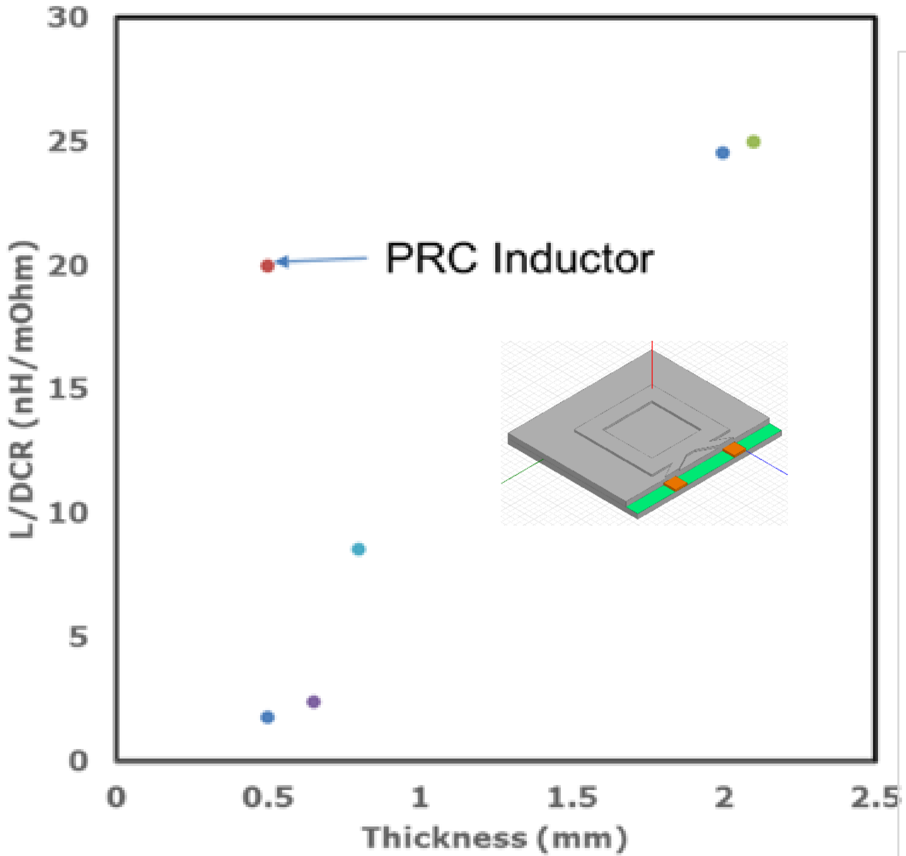
Taiyo-Yuden – Inductor in package

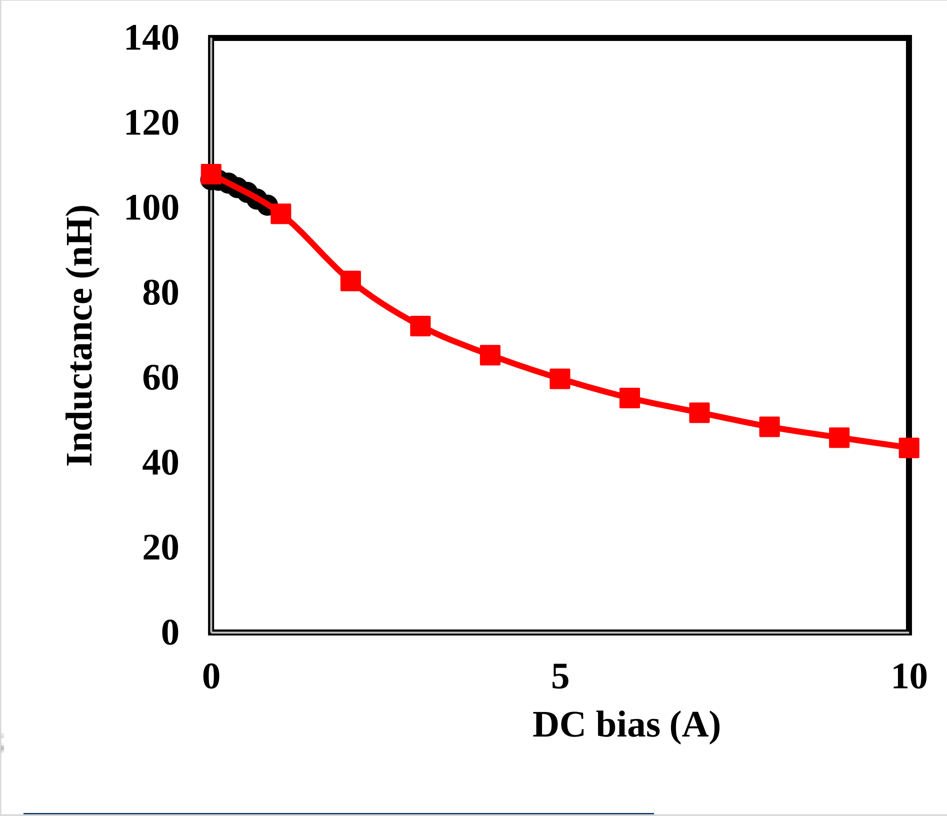


4X increase in current-handling with metal compacts compared to ferrites

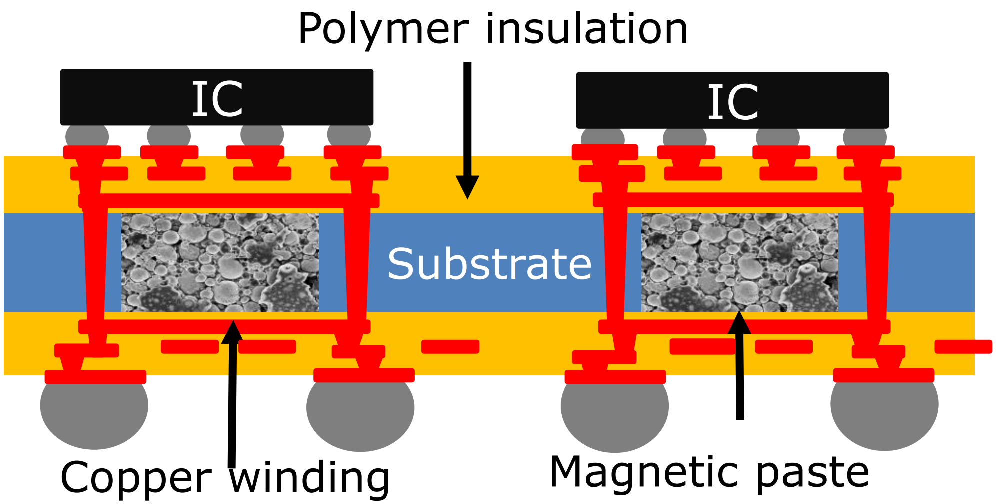
Substrate-Embedded Metal Composite Sheets

Material properties	**A**	**B**
Magnetization (Bs)	~6000 G	~6000G
Initial permeability(B_s/H_k)	464	229
Anisotropic field (Hk)	~10 Oe	~25 Oe





Magnetic Core Inside Substrate Cavities


Polymer insulation

IC

IC

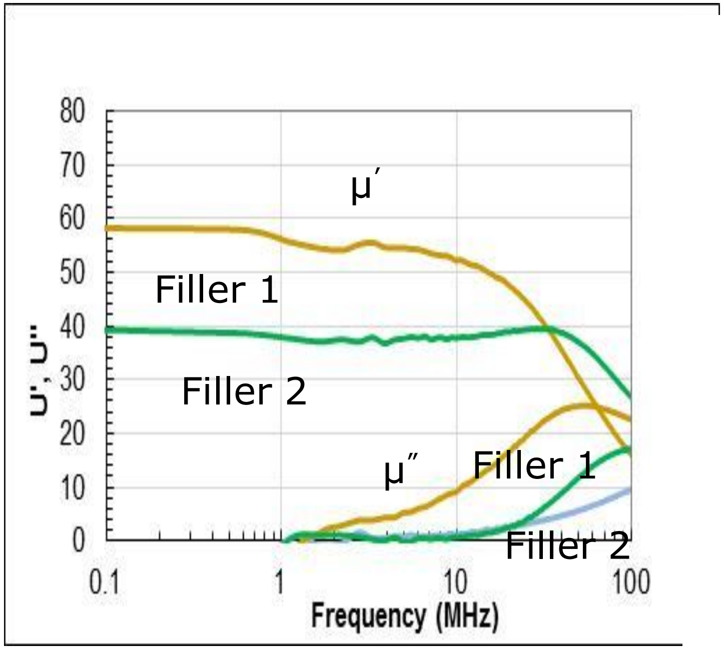
Substrate

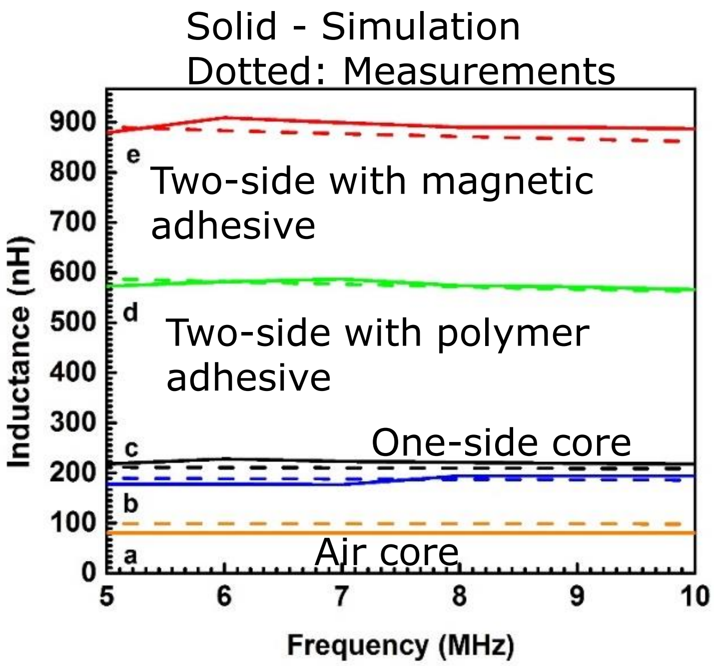
Copper winding

Magnetic paste

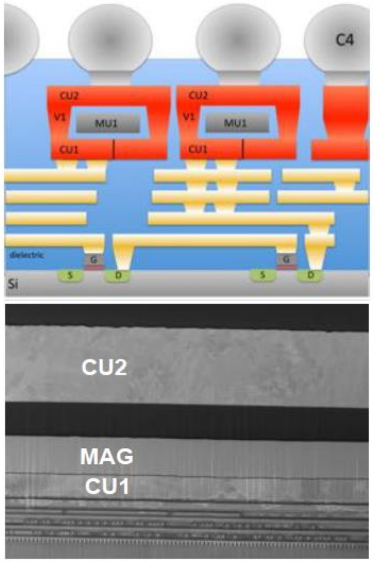
Hot-press magnetic particles or flakes into cavities inside laminate cores;

Wiring plated with standard organic laminate panel processes





High-Frequency – High Power-Density



- Peak Q Factor > 20 @ ~100MHz
- Peak Inductance Density ~300nH/mm2
- L/RDC >200nH/Ω for L > 100nH
- L/RDC of 120nH/Ω for L ~ 10nH
- Current Density exceeding 12A/mm2 for coupled inductors
- Saturation Current exceeding 1.5A for single inductors
- Cross wafer inductance variability σ < 3%
- Other Devices in development:
- Transformers, improved inductor designs

FERRIC

Opportunities for Embedded Inductors

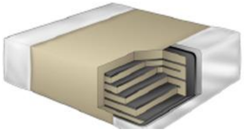
- Thick nanostructured or amorphous films with low coercivity, high resistivity and soft magnetic properties:
    - Sputtered films: Good combination of properties but thin
    - Bulk synthesis approaches: Poor frequency stability
    - New approaches to get nanostructures and low losses but with thickfilms

- Coupled inductors: with multiphase switching topologies, DC currents can be made to flow in opposite directions:
    - Cancel DC magnetic fields
    - Enhance current-handling

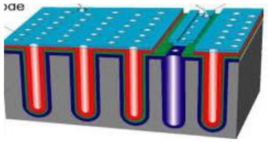
- Introduce permanent DC fields in the opposite direction
    - Create artificial antiferromagnetic materials

Discrete or Wafer- or Panel-formed capacitors

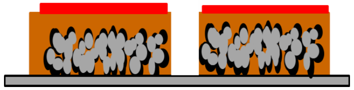
MLCC



Silicon Trench



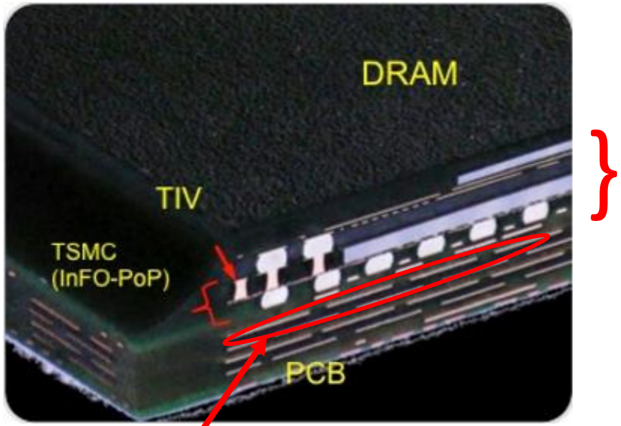
PRC Thin-film Tantalum

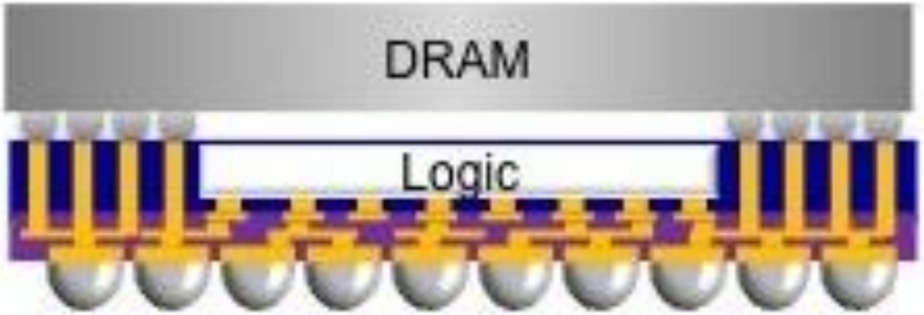


Performance Parameters	MLCC	Silicon Trench	Ta capacitors
Capacitance density	20 μF/mm^3	10 μF/mm^3	20-30 μF/mm^3
Thickness	125 - 500 μm	500 μm	50-75 μm
ESR	5-10 mΩ.× μF	50 mΩ × μF	50 mΩ × μF
Frequency stability	>100 MHz	10-100 MHz	10-100 MHz
Leakage current	0.1 μA/μF	0.1 μA/μF	0.1 μA/μF
Integration	Die-side or landside assembly/embedding	Silicon- integrated	Wafer or package-embedding

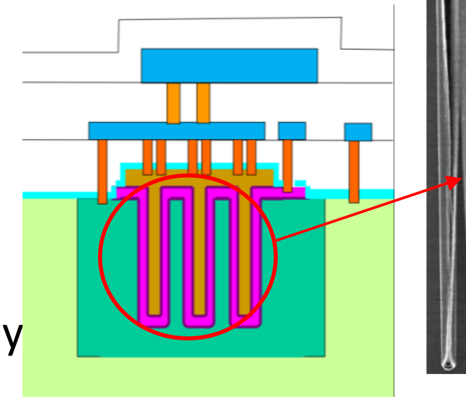
Deep Trench Land-Side Inserted Si Capacitors (TSMC)

Land-side on-Si capacitors for integrated fan-out packaging

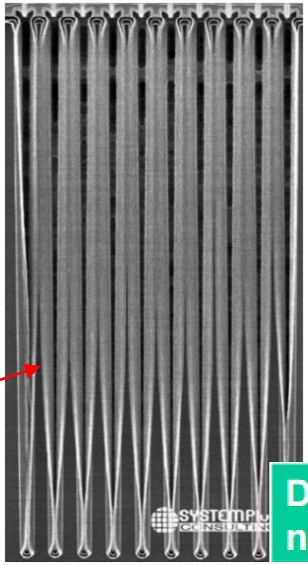




1 × 0.5 mm footprint Located underneath info-POP supported by extra PCB layer



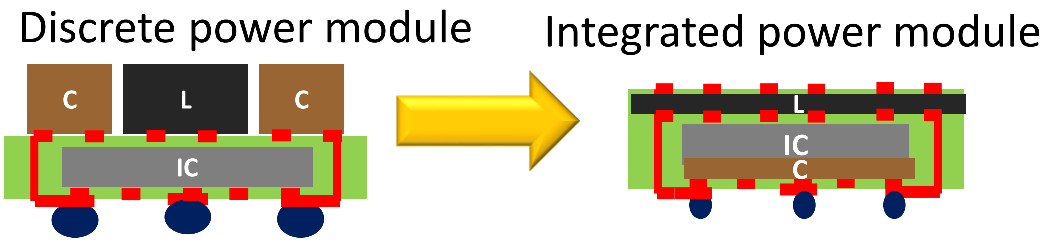
Deep trench capacitor structure

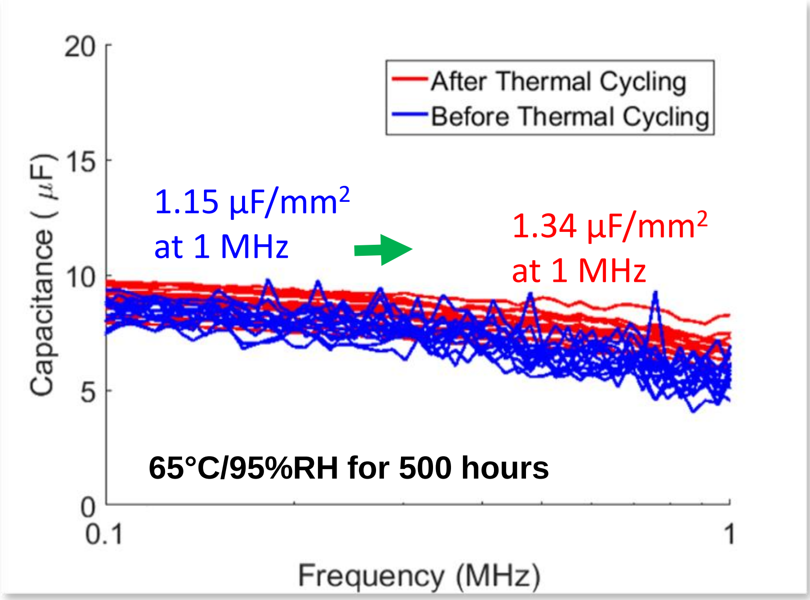


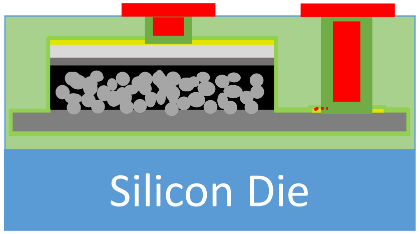
- Up to >500 nF/mm^2 density
- Superior VCC and TCC
- Comparable ESR to MLCCs
- Thickness as low as 100 µm

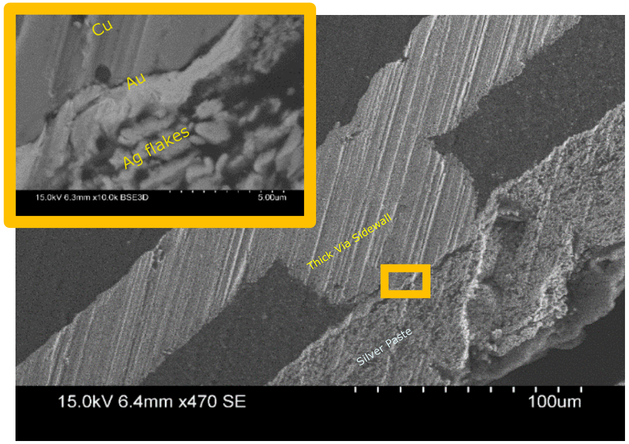
Density, nF/mm2	Breakdown Voltage, V	TDDB, V	Max Voltage rating, V
180	16.1	7.0	4.5
250	14.3	6.8	4.2
500	6.5	4.5	3.2
600-700	4.0	3.8	2.5-1.2

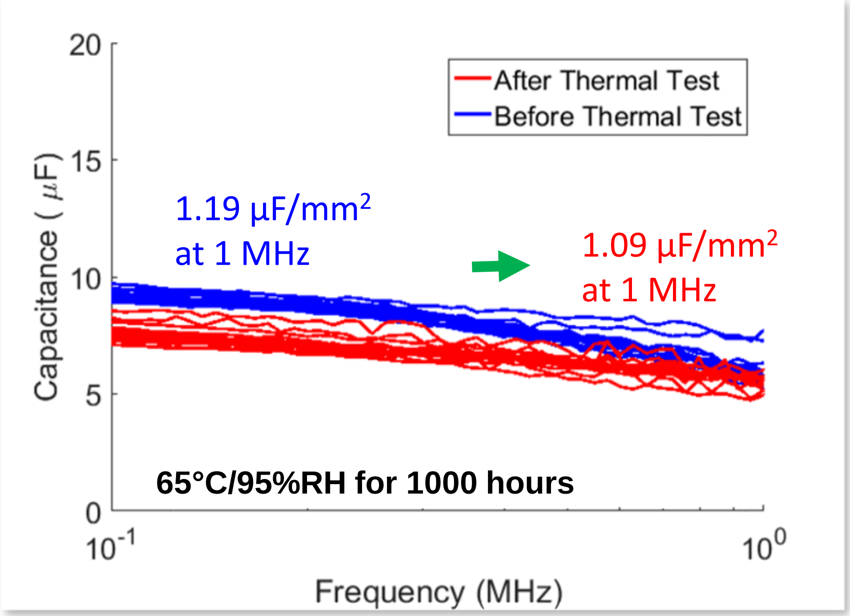
Wafer-Formed Nanoelectrode Capacitors



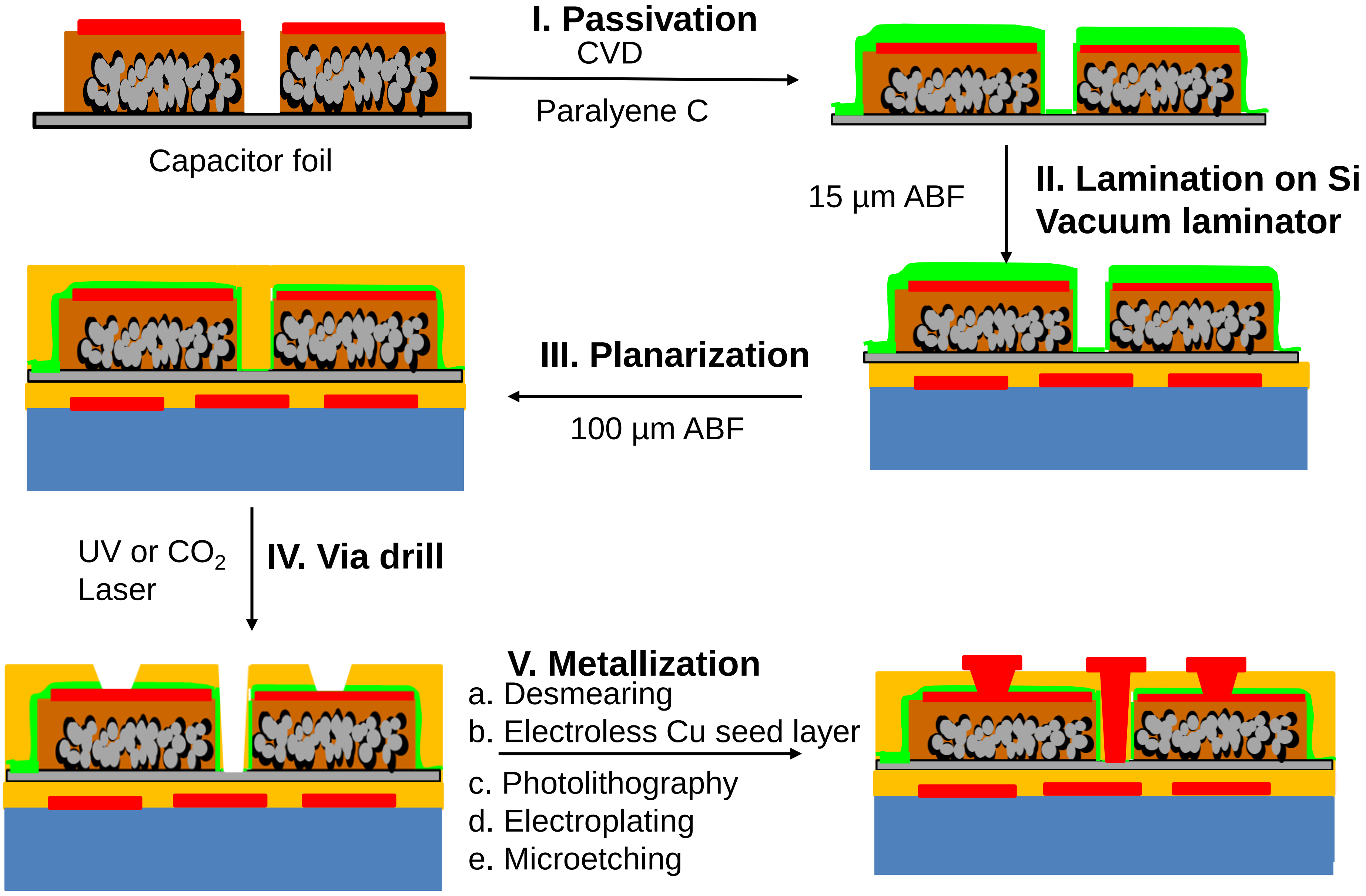








Capacitor Integration Process Flow



Capacitor foil

I. Passivation
CVD
Paralyene C

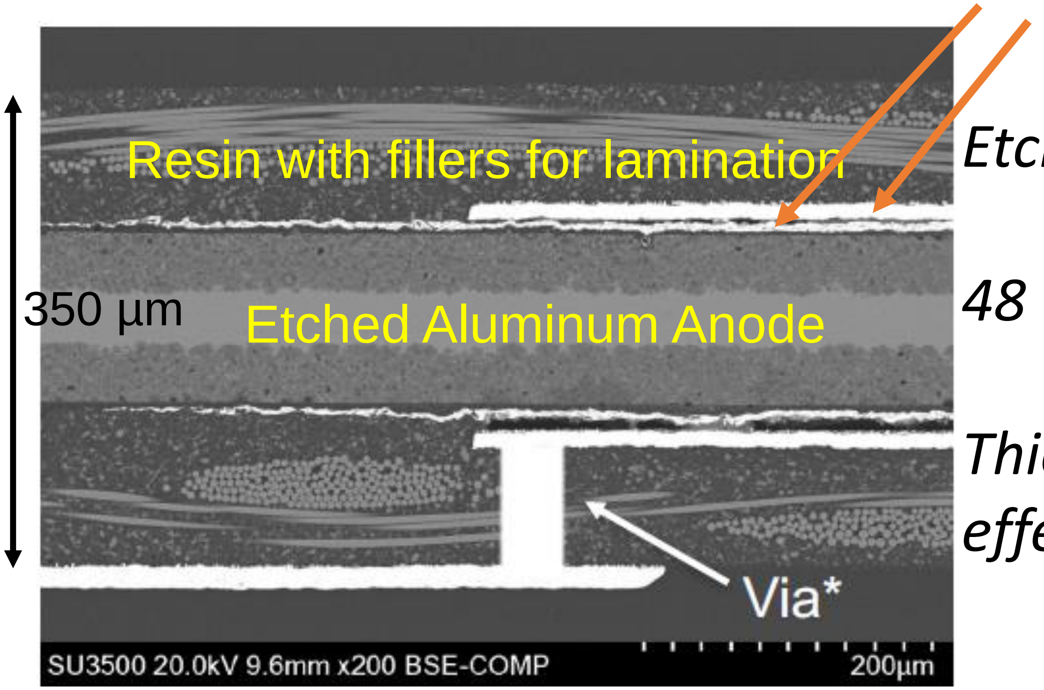
II. Lamination on Si
Vacuum laminator
15 µm ABF

III. Planarization
100 µm ABF

IV. Via drill
UV or CO_2
Laser

V. Metallization
a. Desmearing
b. Electroless Cu seed layer
c. Photolithography
d. Electroplating
e. Microetching

Package-Embedded High-Voltage Capacitors (KEMET)

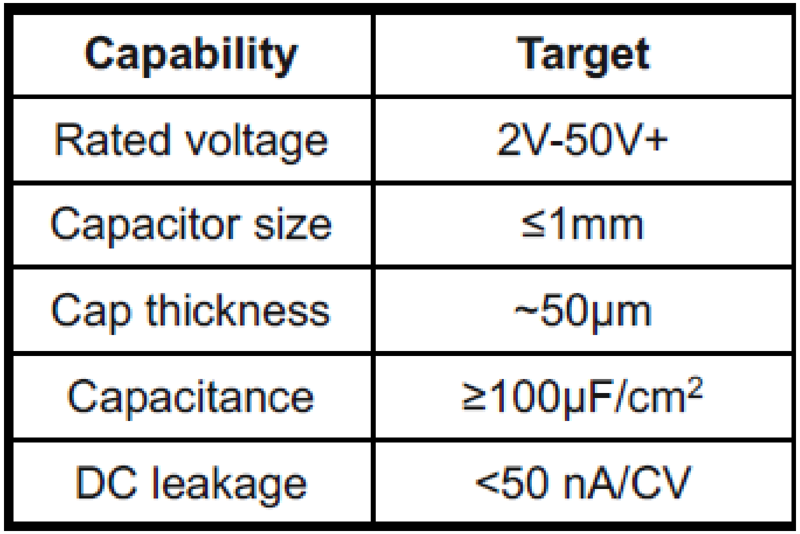


Etched Al foil capacitors to package

48 V Power Converters

Thickness reduction and more effective use of capacitance volume

- Capacitors can be patterned onto transfer release film
    - Arrayed sheets
    - Individual taping
- Terminals formed by copper cladding and plating

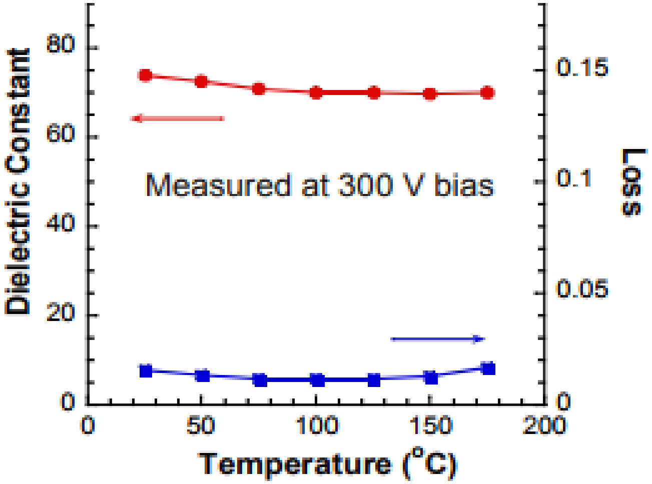


Capability	Target
Rated voltage	2V-50V+
Capacitor size	≤1mm
Cap thickness	~50µm
Capacitance	≥100µF/cm²
DC leakage	<50 nA/CV

Package-Embedded Thinfilm Capacitors

Delphi/Argonne National labs

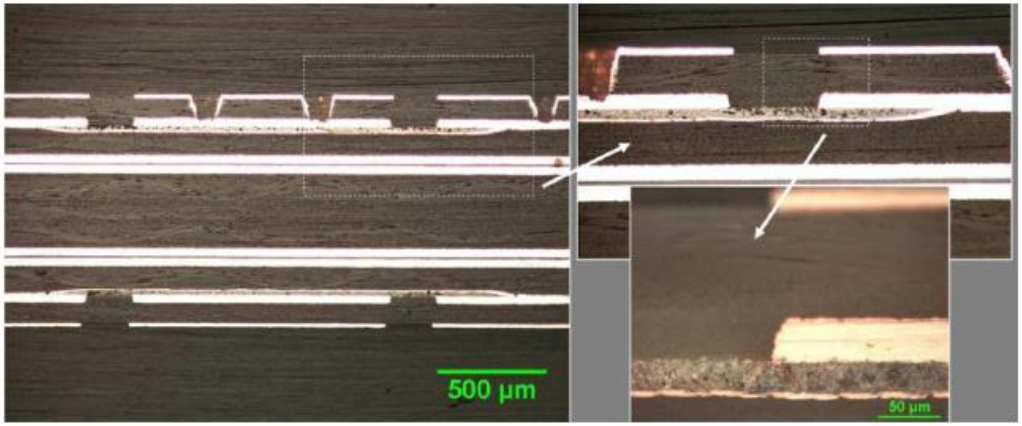
High permittivity compared to film dielectric;
Operation up to 150° C



Large-area polymer or metal roll-to-roll compatible process

Applications:
- Isolators
- Embedded decoupling capacitors

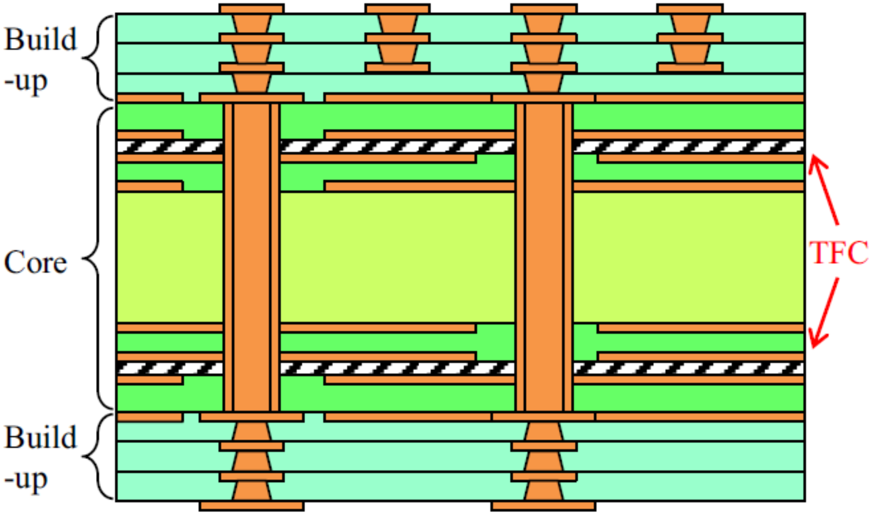
GT-PRC DuPont



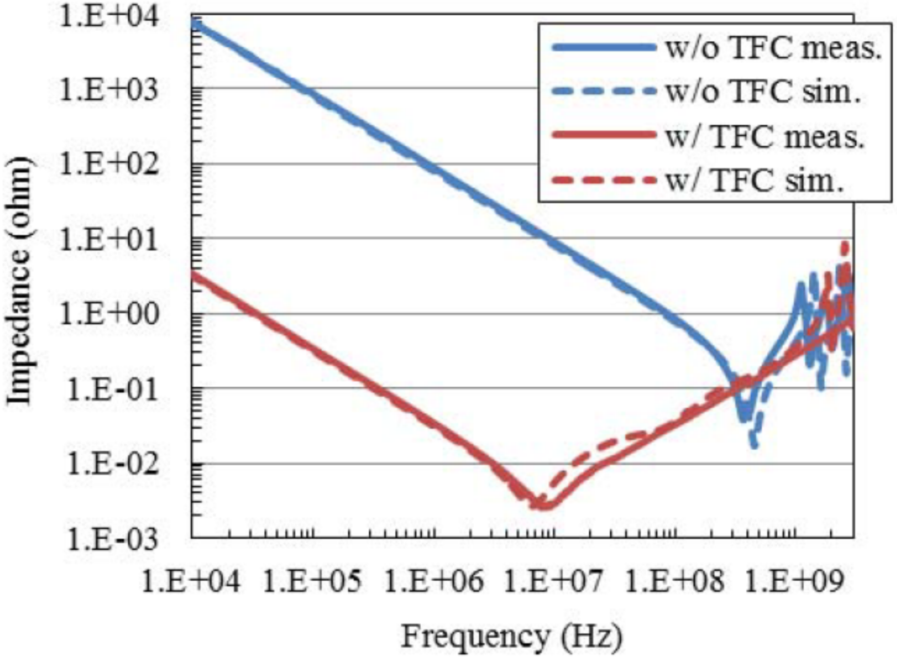
Thin ceramic film decoupling capacitors in organic package substrates;

1-1000 MHz
20 nF/mm^2

Package-Embedded Thinfilm Capacitors (TFC)



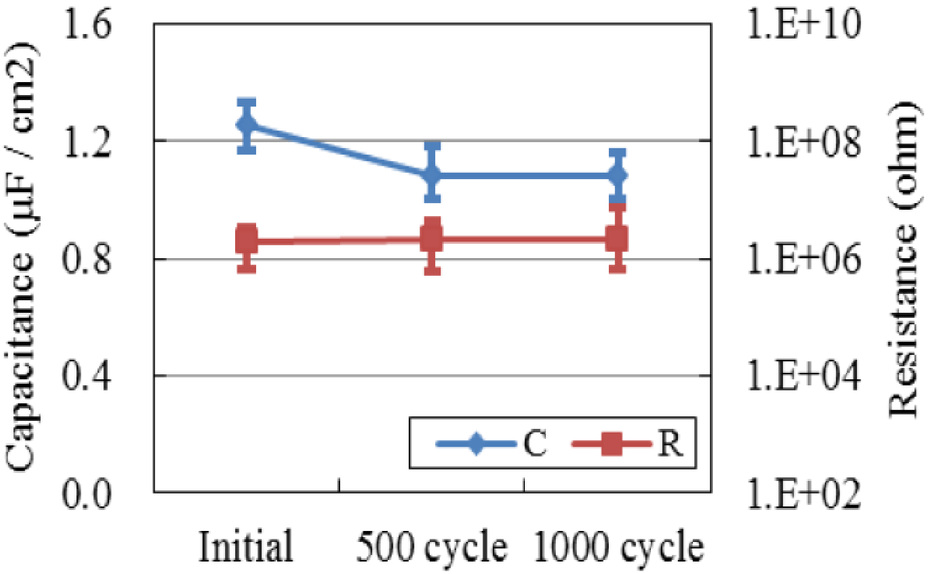
Fujitsu



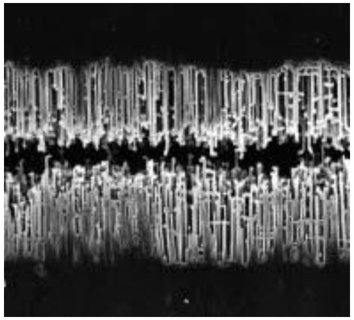
Doubleside integration of decoupling capacitors;

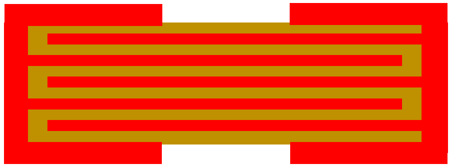
High-frequency noise suppression

Integration and reliability characterization



High-Voltage Capacitors

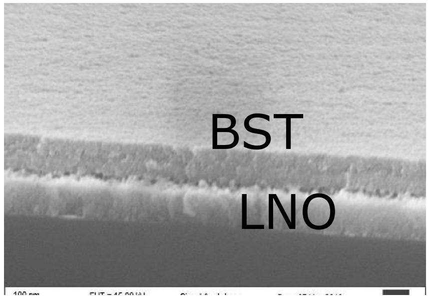




	Polymer film caps ECI HT1	**CDE 550C Aluminum Caps**	**KEMET Ni BME C0G (Comm. Grade)**	**TDK CeraLink PLZT Ceramic**	**Advanced electrodes and dielectrics**
µF/cc	0.085-	>6	0.6-0.012	5.5-2	10
V	600-2400	200-500	500-3000	500-900	500-1500
ESR mΩ	60	16-228	5	4	5
Irms	5.2	5-31	24	12.5	25
Temp	125	105	125	150	105

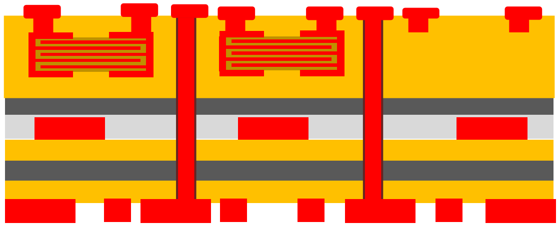
Opportunities for Embedded Capacitors

- High-voltage isolation:
  - High-permittivity and high-voltage dielectrics: PLZT, calcium zirconate
  - 5000 V isolation with power transfer

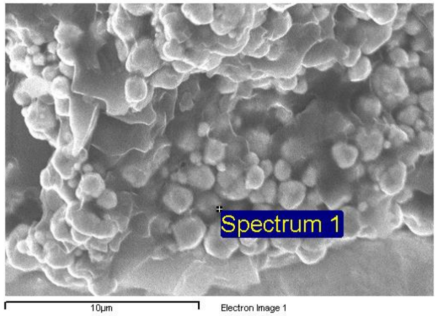


High-density Thinfilm capacitors on Si

- Embedded film and discrete capacitors:
  - MLCC that power processor chips with power module right under the chip (200 W in 100 mm^2 or 2 W/mm^2)

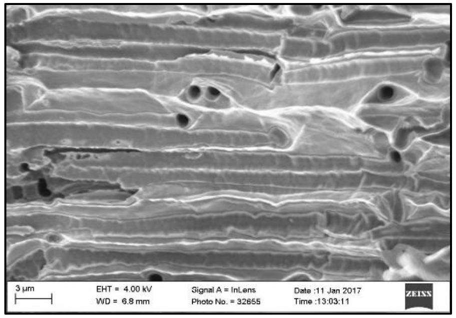


Embedded capacitors and film inductors



High-surface area electrodes with conformal dielectrics

- High-density wafer- or package-integrated capacitors (3 – 400 V):
  - Tantalum film capacitors with porous electrodes
  - Etched foil capacitors
  - Copper film capacitors with porous electrodes



Etched foil Capacitors

Summary

Magnetics:

- Advanced materials and designs leading to higher volumetric densities and smaller form-factors
    - Amorphous and nanocrystalline ribbon flakes - low frequency
    - Metal-flake composites – medium frequency
    - Sputtered and thin plated films – high frequency

Capacitors:

- Advanced large-area fabrication of high-density film capacitors
- Thin and area-integrated - eliminate pick-and-place

LC-integrated substrates for panel-embedded IVRs