Substrate-embedded, magnetic core inductors for Integrated Voltage Regulators

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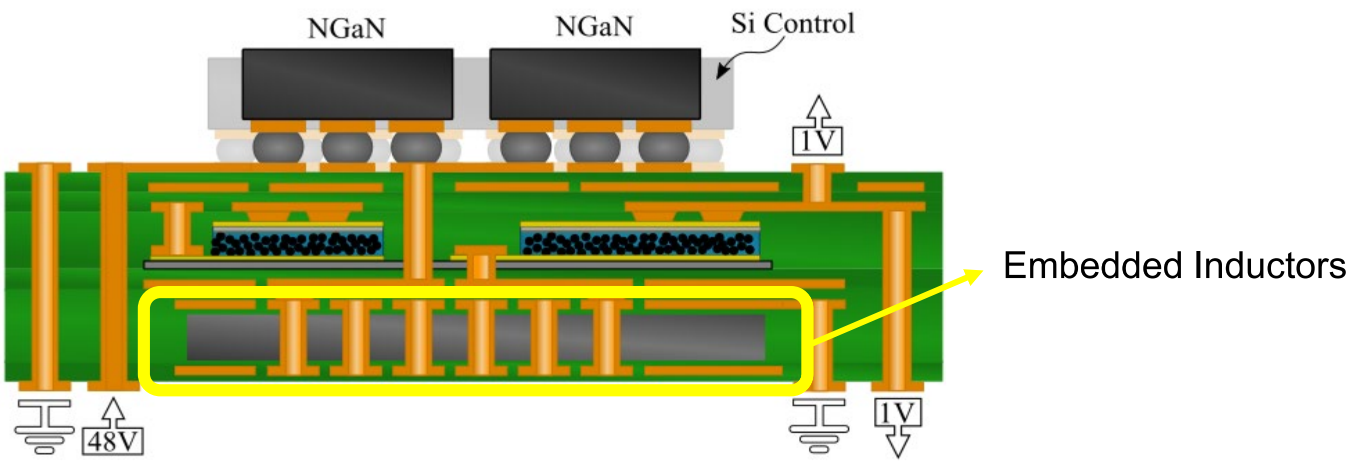
Outline

- Goals & Objectives
- Prior Work
- Technical Approach
- Results & Key Accomplishments
- Comparison with Prior Art
- Schedule
- Summary

Goals and Objectives

Design and demonstrate embedded inductors to yield a low power module with:

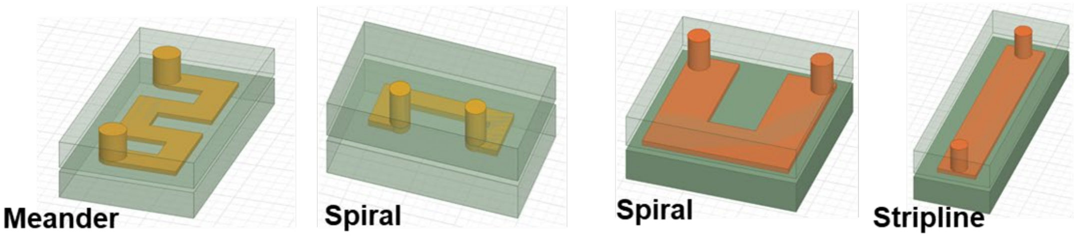
- Power density: 2 A/mm^2
- Miniaturized modules:
  - Inductor thickness < 300 μm
  - Added thickness due to passives ~100 μm
- Single-stage power conversion close to load
- Short PDN path
- Losses (interconnects and passives): < 5%



Metrics	Objectives	Tasks
Inductance (nH/mm^2)	10-20 at 1 - 10 MHz 6 at 100 – 140 MHz	• Model and design magnetic-core inductors with target specifications • Develop new process to fabricate and characterize substrate-integrated inductors • Develop an innovative process to embed LC into substrates
Current handling (A/mm^2)	2	
Thickness (mm)	0.3 – 0.5	

Prior Work

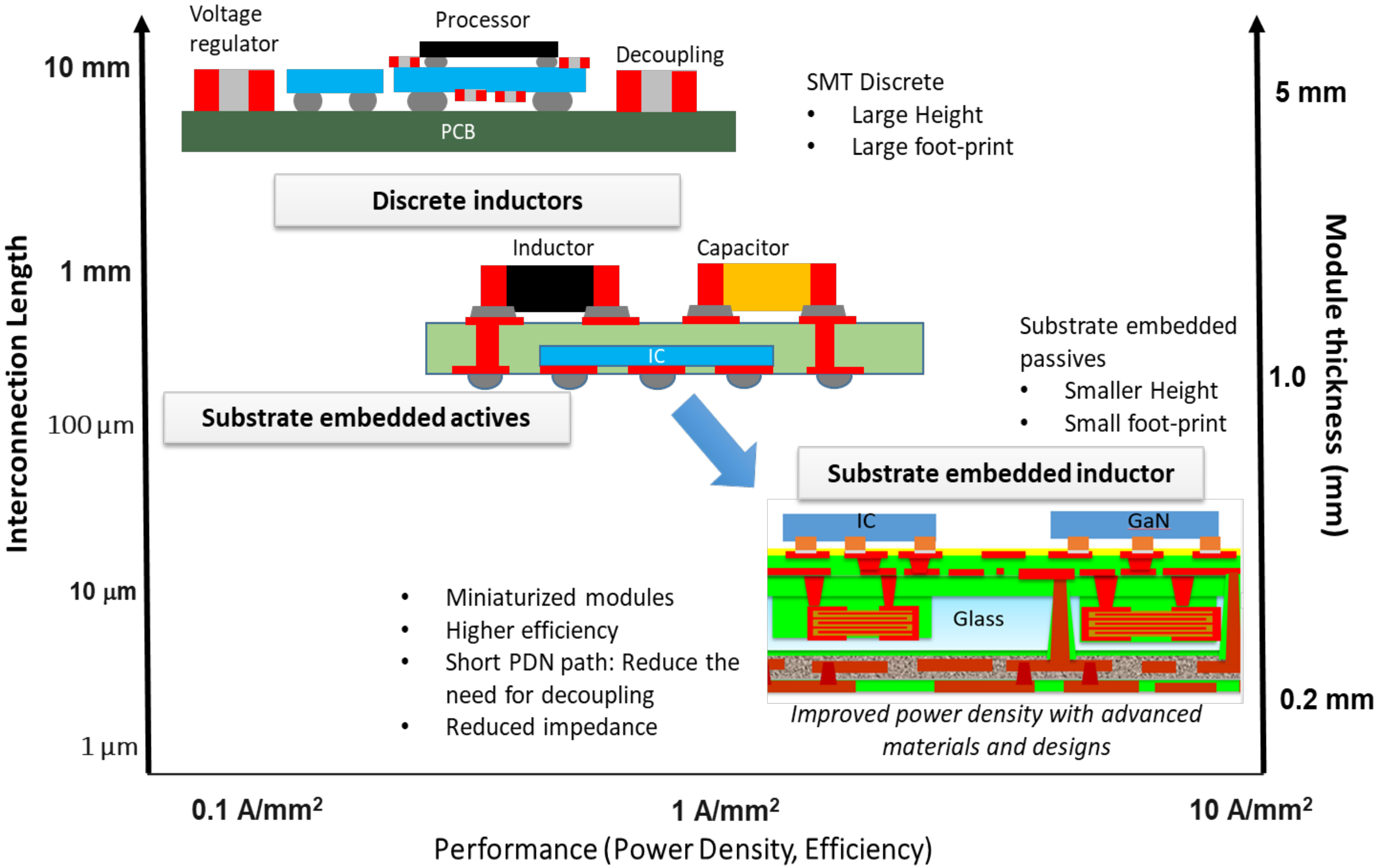
- New magnetic materials with high permeability but high loss:
  - Loss analysis indicated high permeability was critical in energy saving
- Measured electrical parameters and established mechanical performance of the composite:
  - Low-frequency permeability: 140 at 10 MHz, High-frequency permeability: 25 at 140 MHz
  - Good adhesion of composite to ABF (952 g/cm)
  - The magnetic composites were tested for their endurance to different via drilling processes: UV, IR, CO_2
- Modeled different inductor topologies for high permeability cores meeting target objectives



- Embedding process was developed to integrate inductors into the substrate
- Modeled and fabricated spiral (2D) inductors for low-frequency IVRs:

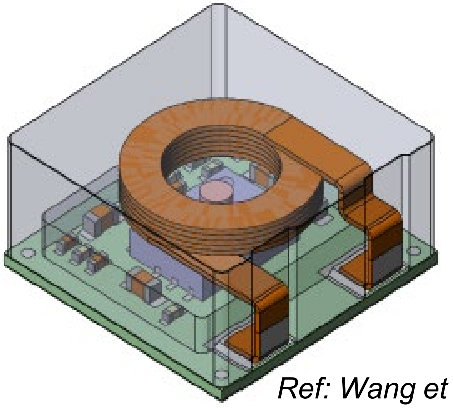
Metrics	Inductance (nH/mm^2)	DC Resistance (mΩ)	Thickness (mm)
Objectives	10	< 10	0.5
Fabricated Performance	12.43	15.2	0.4

Inductor Packaging Evolution



Current Approach for Inductor Fabrication

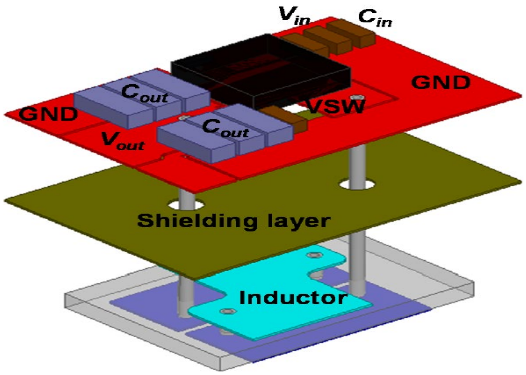
Sumida PSI2: Inductor in package



- 2.8% increase in efficiency with 3-5 Amp current

Ref: Wang et al. ECTC 2016

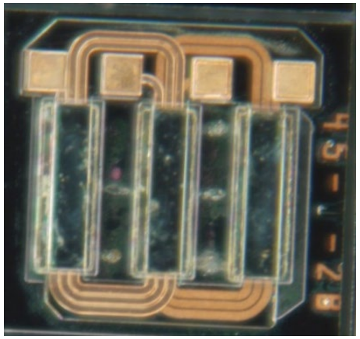
Virginia Tech: Inductor in PCB Substrate



- PCB-embedded ferrite and metal flake composites

Ref: Su et al. IEEE 2013

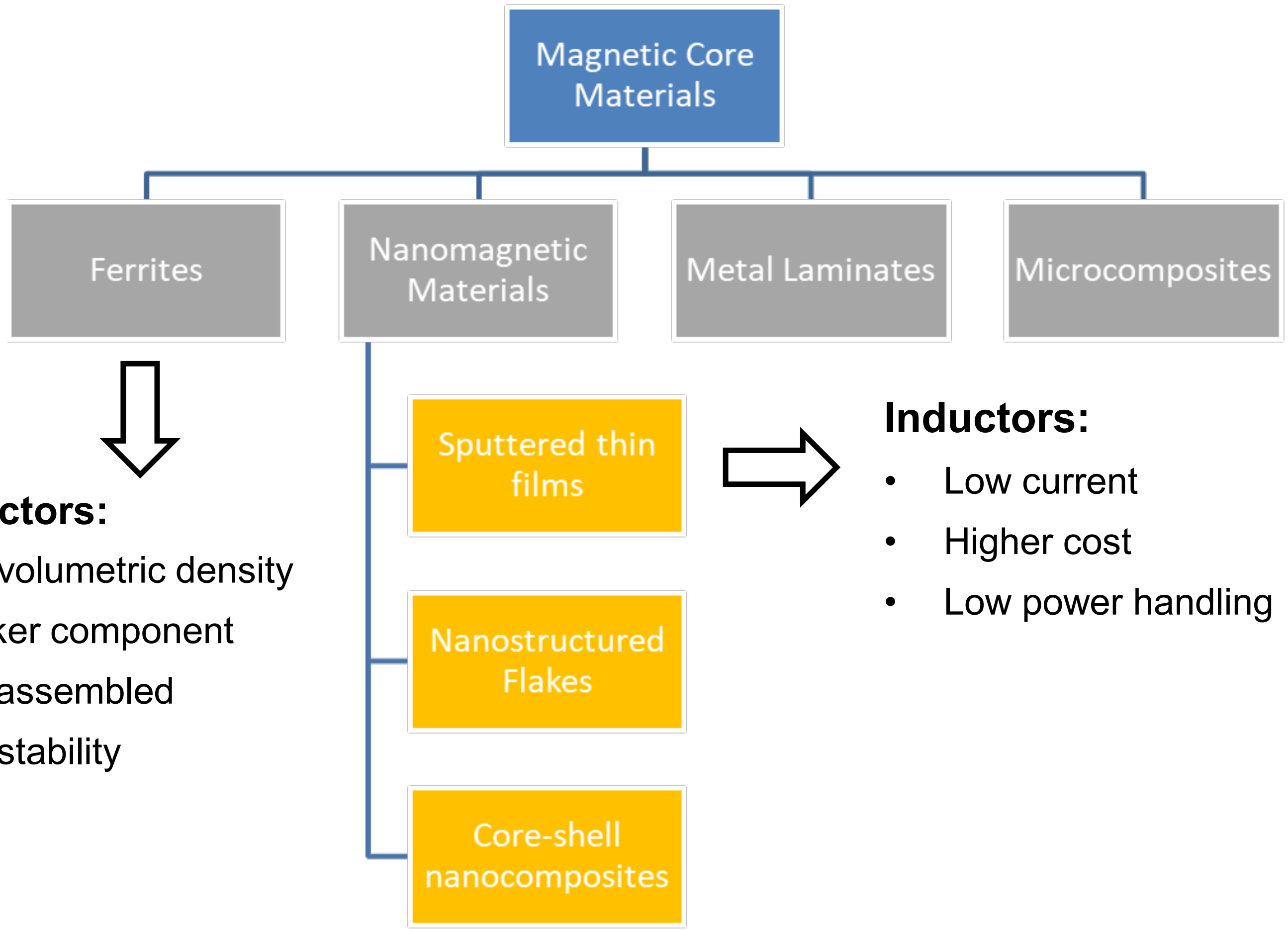
Tyndall: On-chip inductors



- Thin magnetic films; coupled inductor designs

Ref: Wang et al. IEEE 2010

Embedding Challenges



Inductors:

- Low volumetric density
- Thicker component
- Self-assembled
- Low stability

Inductors:

- Low current
- Higher cost
- Low power handling

Substrate Material Selection

Material	Ferrite	Sputtered thin-films	Metal-polymer composites
Freq. stability			
Loss			
Permeability			
Scalability			
Current handling			
Substrate compatibility			

Current focus

- Ferrite, metal-polymer composites and sputtered thin-films are considered as the candidate for magnetic substrate
- Metal-polymer composites provide the best trade-off for density and power-handling

Unique Approach at PRC

Innovative Inductor Designs

Unique inductor designs:

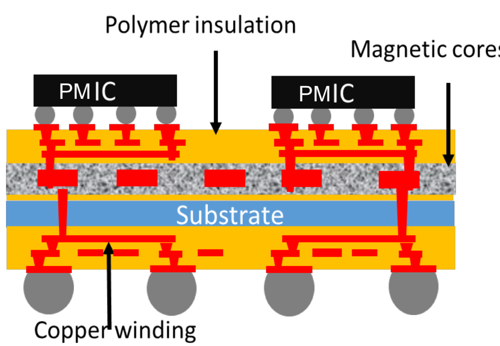
- Spiral inductors (2D)
- Novel toroidal inductors (3D)

Advanced Materials

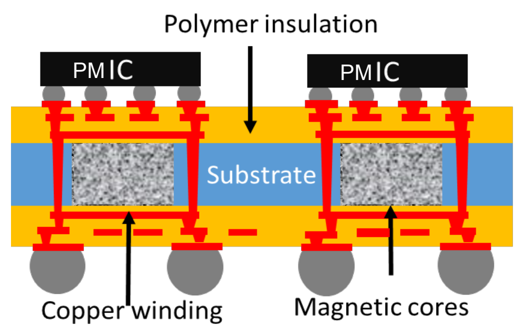
Magnetic composites for high inductance density

- High permeability
- Trade-off high current handling, DC resistance, and inductance density

Spiral



Solenoid



Advanced Integration Process

- Substrate-compatible process to integrate inductor into substrates
- Reliability testing - Thermal cycling and warpage

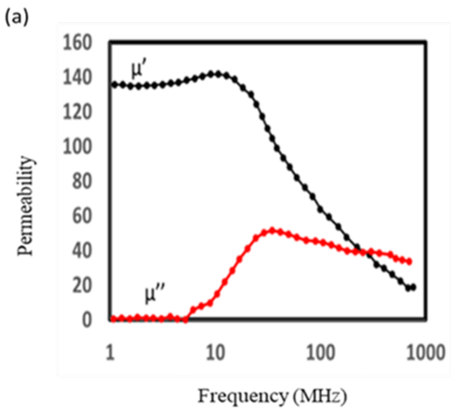
Characterization set-up

Electrical characterization

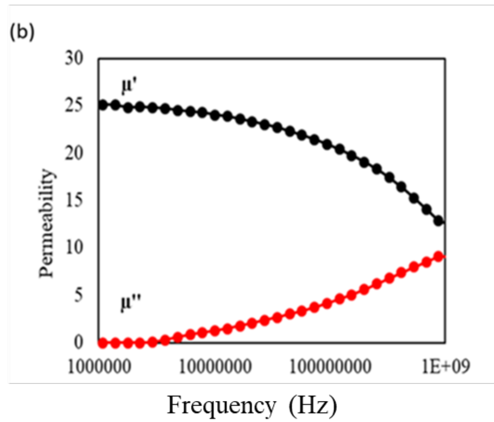
- L vs Frequency
- L vs Current
- DC resistance

Electrical Characterization of Composites

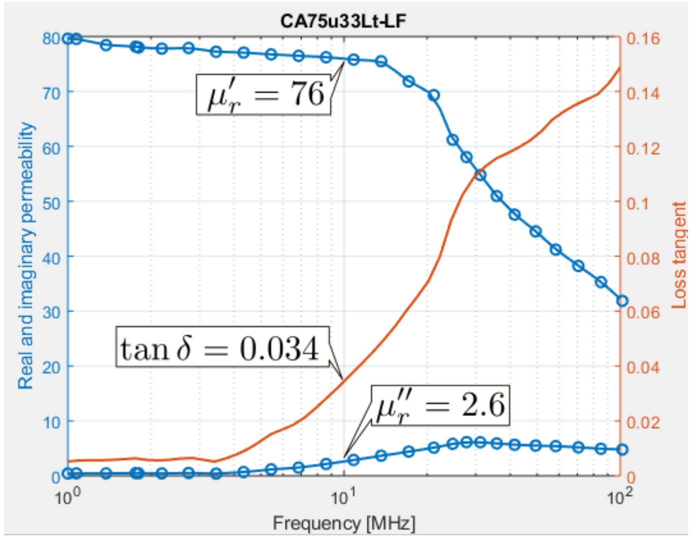
Courtesy: Panasonic



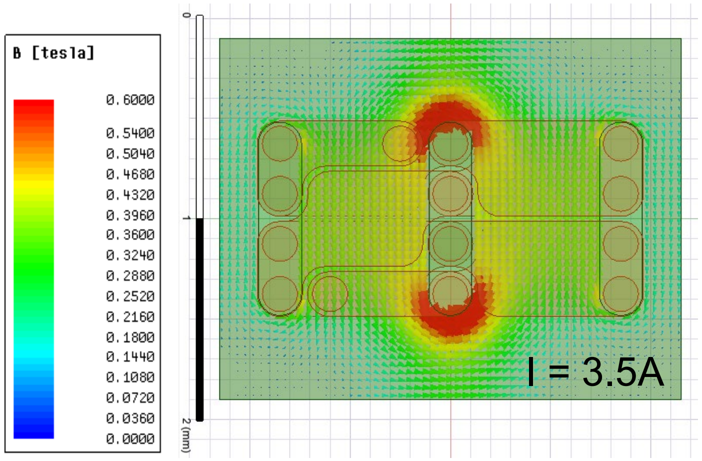
HPE1/GT



HBS1/GT



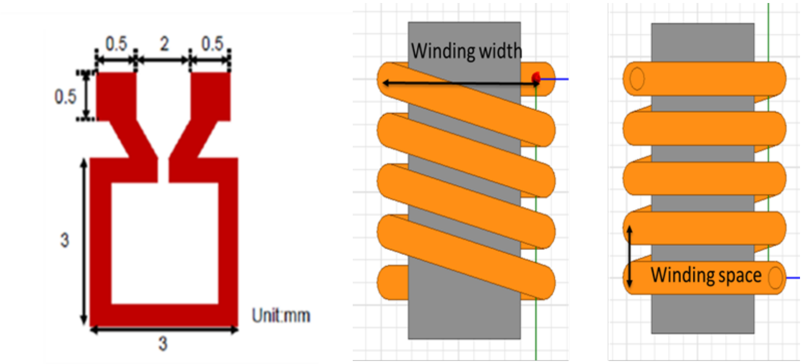
Parameter	Low frequency	High frequency
Permeability (H/m)	150 at 10 MHz	25 at 140 MHz
Loss tangent	0.146	0.230



Required material properties for 96% efficiency:

- The permeability is somewhere in between 50 and 150
- Loss tangent must be less than 0.033
- Magnetic saturation field must be greater than 0.6 Tesla

Modeling of Inductor Topologies using Composites



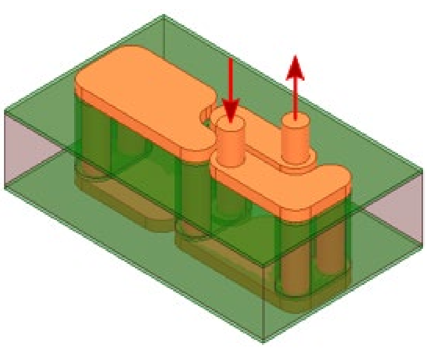
Planar Inductors

Solenoid Inductors

Shown at May 19 IAB

- Planar inductors show lower current handling, but are easier to fabricate
- Solenoid inductors have a comparable inductance but higher current handling

Low-Frequency Material Designed Parameters:

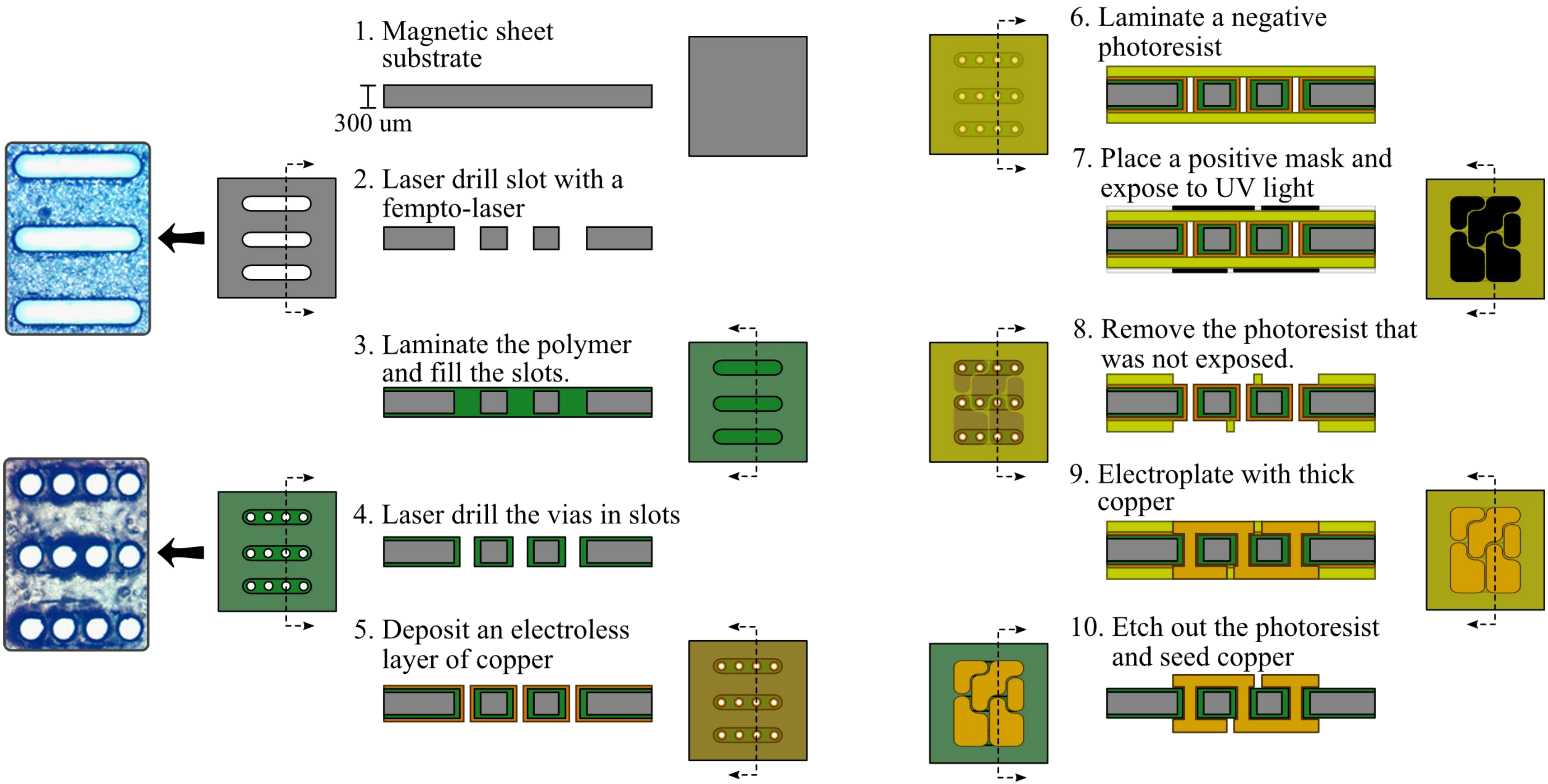


	1	2	3	4
I_{DC} [A]	<1.25	<1.25	<1.00	<1.00
L [nH]	23.8	44.1	66.6	116.9
Inductance Density (nH/mm³)	88.0	101.0	151.6	164.6
R_{DC} [mΩ]	5.5	8.5	9.8	15.7
R_{AC} [mΩ]	227	426	635	1102
R_{AC} [mΩ/nH]	9.6	9.7	9.5	9.4

Novel Toroid Inductors

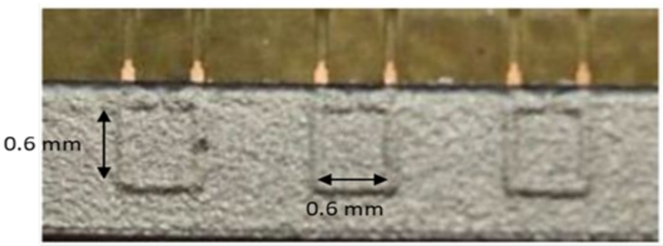
- Toroidal inductors show highest inductance because of closed magnetic loops

Fabrication Process Flow

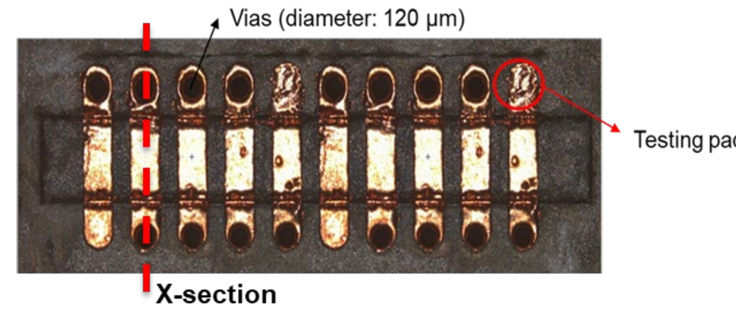


Fabrication of Inductor Topologies

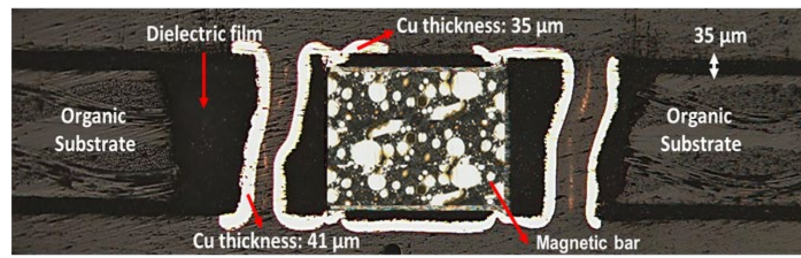
Demonstration of substrate- embedded 2D and 3D inductors for low and high-frequency IVRs



The top view of spiral inductors



Optical view of planar inductor



Metrics	2D Low Frequency Objectives	2D Low Frequency Fabricated Values	2D High Frequency Objectives	2D High Frequency Fabricated Values	Solenoid Low Frequency Objectives	Solenoid Low Frequency Fabricated Values
Inductance Density (nH/mm^2)	10-20	12.38	6	8.21	10-20	To be Measured
DC Resistance (mΩ)	5 - 10	9.83	< 10	7.72	5 - 10	
Thickness (µm)	500	435	200 - 300	315	200 - 300	

Comparison with Prior Art

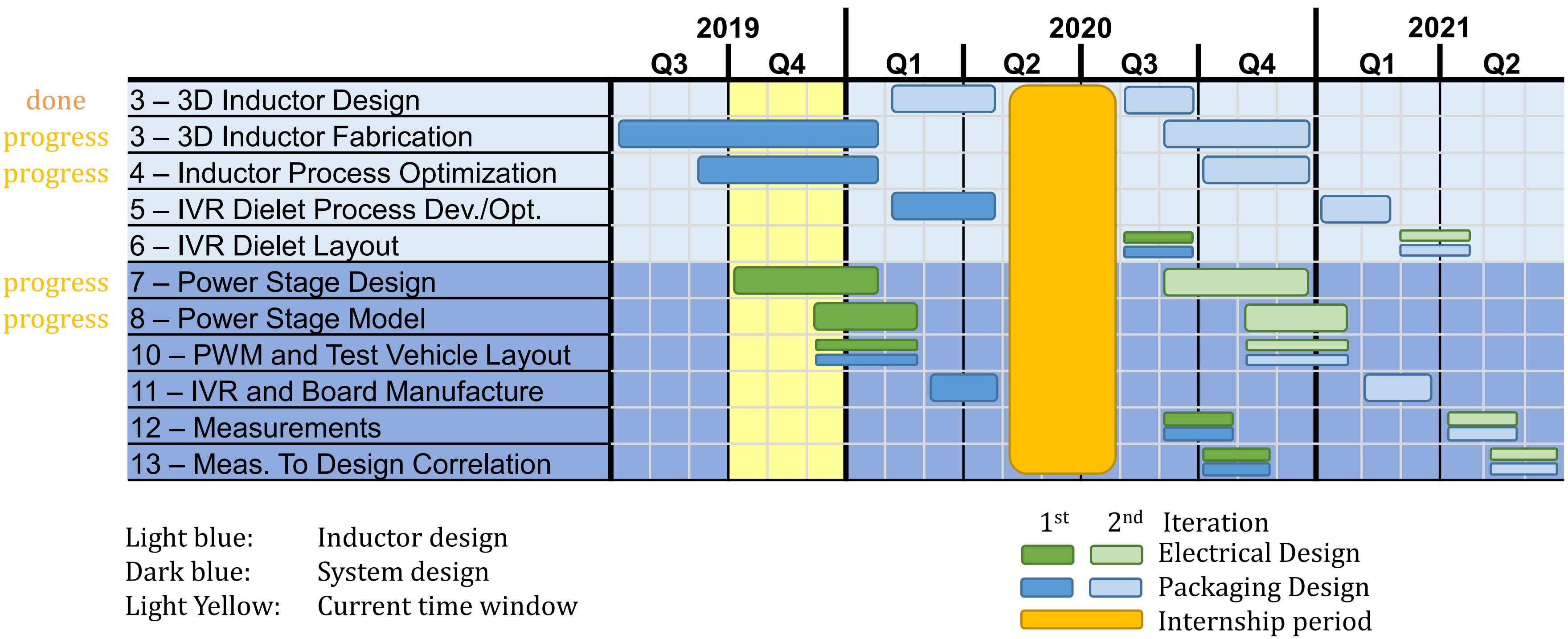
	Inductance	Saturation Current	Process Fabrication	Design Complexity
Solenoid				
Toroid				
Spiral				
Stripline				

- Discrete inductors can accommodate higher thickness which leads to high inductance density with lower resistance
- Low loss tangent materials with moderate permeability have been simulated to show high efficiency embedded inductors with low DC resistance
- There is a trade-off between inductance density and DC resistance

Parameters	Targets	GT-PRC	On-chip inductor	Discrete inductor
L/R (nH/mΩ)	~ 20	**~ 9.6**	0.18	23
Current handling (A/mm²)	2	**2**	3-4	0.6
DC resistance (mΩ)	< 10	**7.72**	1200	5.2

Schedule

- Toroidal single inductor is already designed
- Optimization of fabrication process ongoing
- A single inductor based 4-phase buck converter is in design step
- A Journal paper will be prepared with the analysis results to date
- Next step will be preparing a measurement setup to measure the inductor under DC current bias and with triangular current waveform
- Next iteration will be the design of a tapped inductor-based converter



Summary

- Modeled and designed spiral inductors for target specifications as below.
  - Low-Frequency: L - 10 nH/mm^2 , R – 5 mΩ, thickness – 0.5 mm
  - High-Frequency: L – 6 nH/mm^2 , R – < 10 mΩ, thickness – 0.3 mm
- Developed and optimized process flow for fabricating substrate integrated inductors.
- Fabricated and characterized planar inductors for low and high-frequency applications:
  - Low-Frequency: L – 12.38 nH/mm^2 , R – 9.83 mΩ
  - High-Frequency: L – 8.21 nH/mm^2 , R – 7.72 mΩ
- Fabricated solenoid inductors for low and high-frequency applications
- Modeled novel toroid inductors and currently optimizing the fabrication process

Next Milestones:

- Fabricate toroid inductors and measure the inductance
- Establish effect of undercut on the inductance density
- Lower losses with high L/R_{dc} with filled vias
- Model and fabricate inductors for 48V-1V applications using very low loss materials