Cold-sprayed aluminum capacitors on leadframes for 3D power packaging

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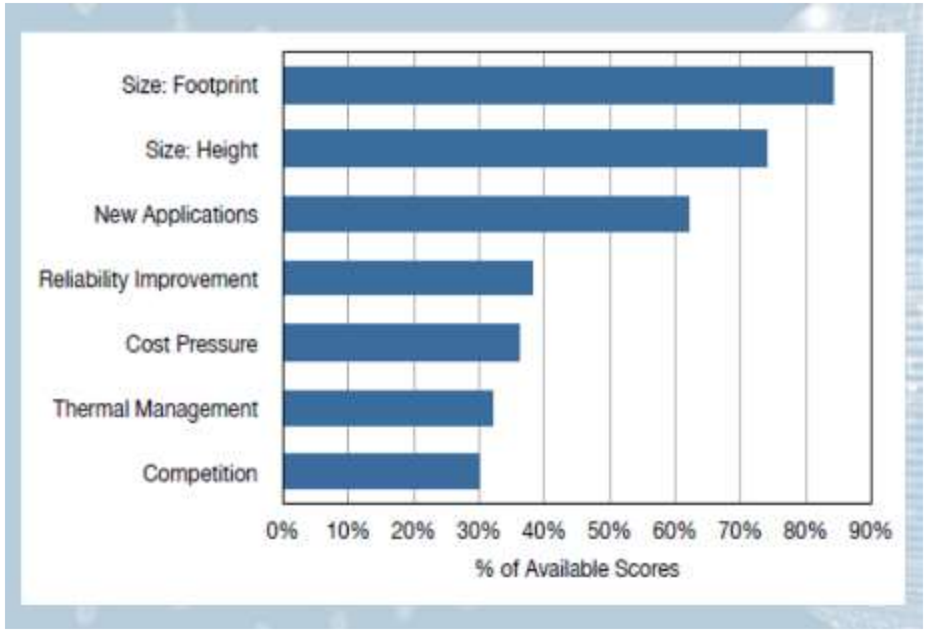
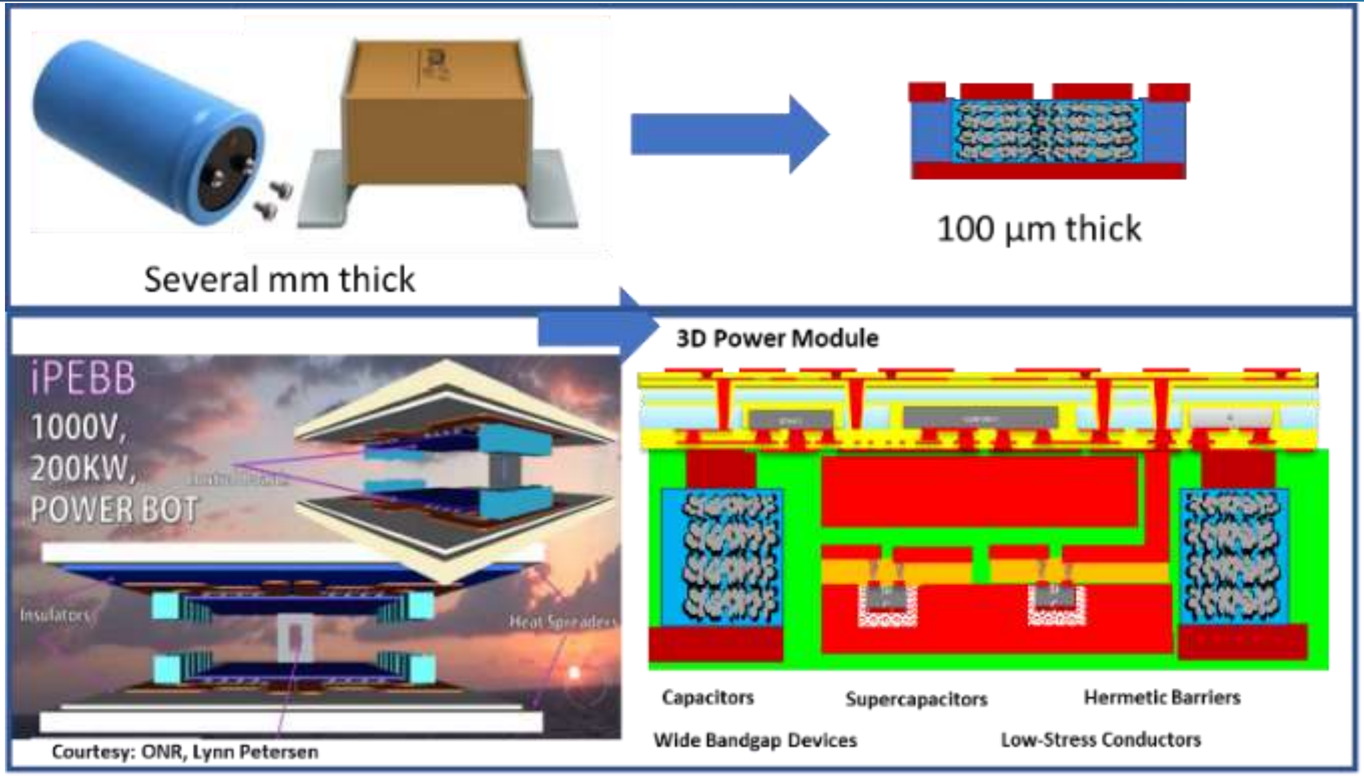
Outline

- Introduction
  - 3D Power Packaging
  - Need for low-profile capacitors
- Cold-sprayed electrode technology
- Porous electrode development and characterization
- Summary

3D Power Packaging



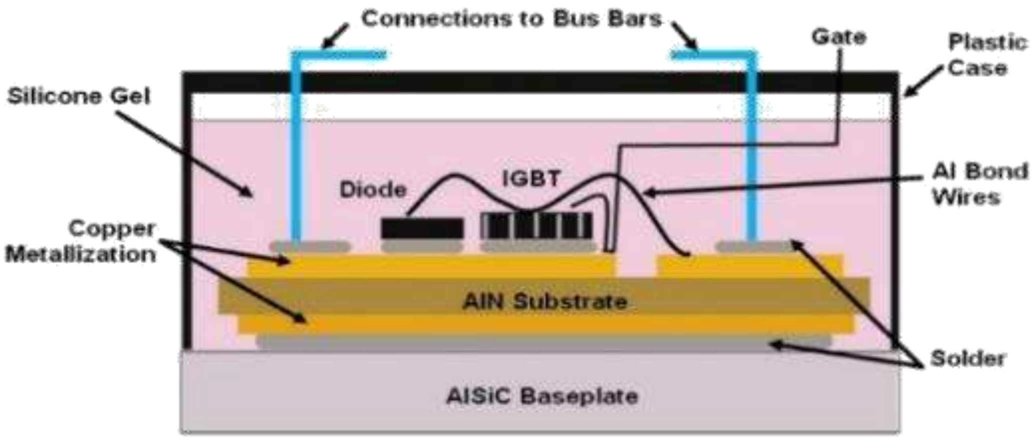
3D Packaging Challenges
Courtesy : PSMA



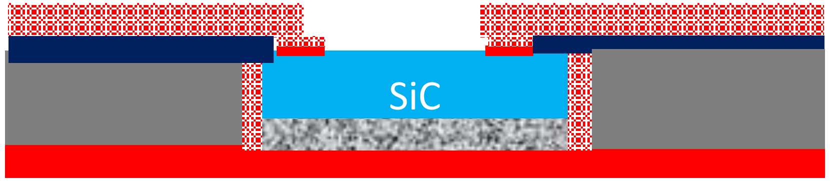
Passive components are key bottlenecks in miniaturization of power module

- Vertically 3D stacked (z axis) power supply
- Reduce footprint
- Increase power density by embedding actives/ passives in substrates

Traditional to 3D Power Packaging

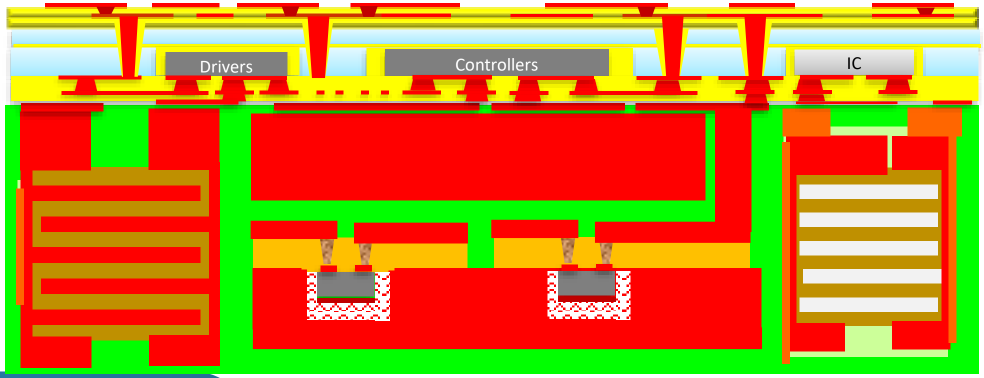


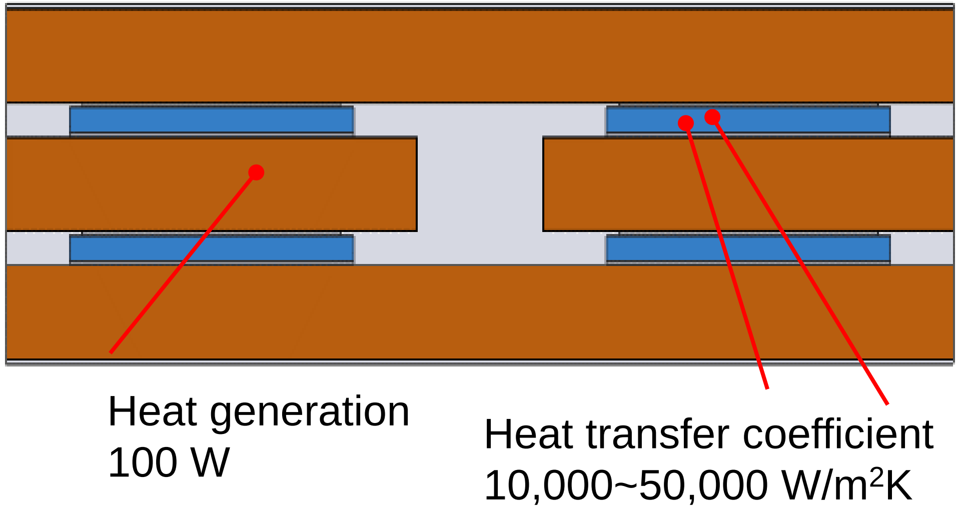
- Large electrical inductance and high thermal resistance
- Reliability challenges with nanocopper and nanosilver
- Thick packages



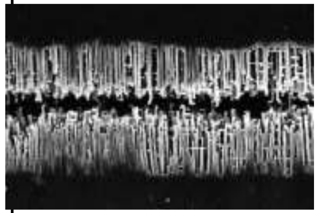
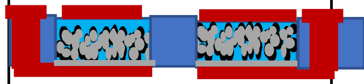
Leadframe Fan-Out Packaging

- **No reliability challenges with nanocopper**
- **Thin packages**
- **Lower electrical inductance and thermal resistance**



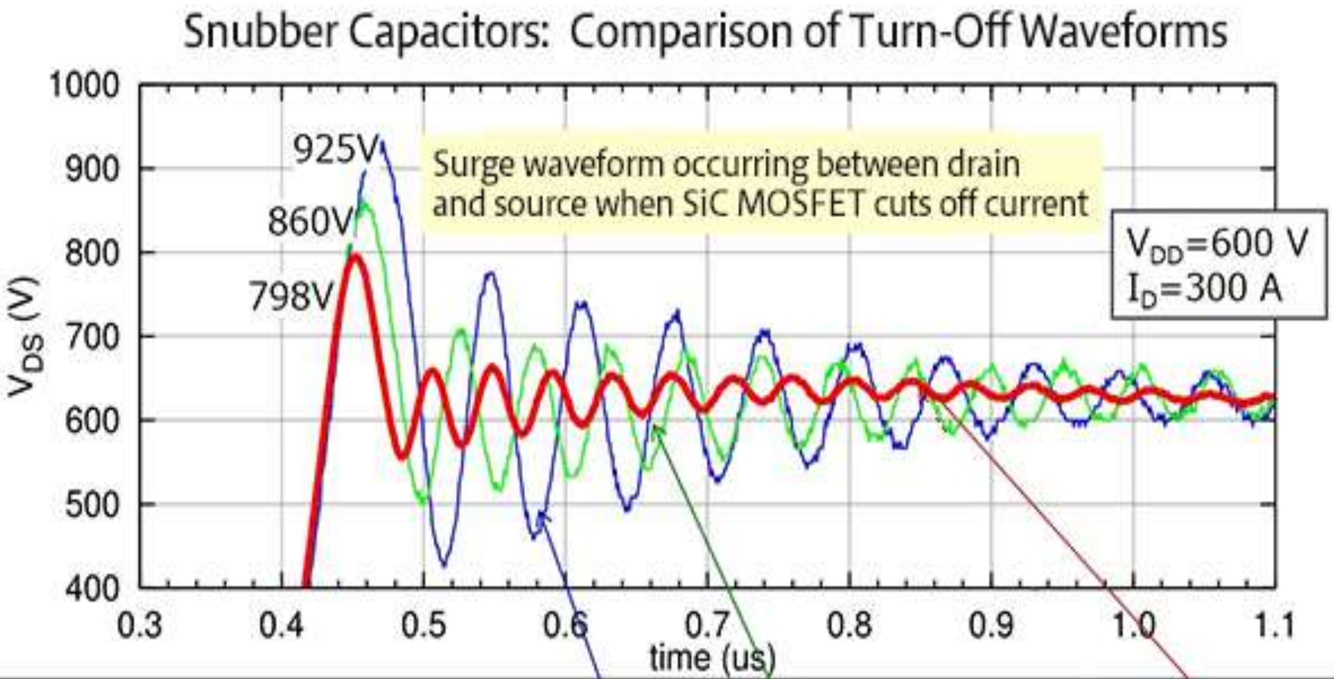


Benchmarking Capacitor Technologies :High-Voltage Capacitors

	Polymer film caps 		Aluminum foil Caps 	Ceramic paraelectric (KEMET, $CaZrO_3$) 		TDK CeraLink® PLZT Ceramic 		High surface area electrodes and dielectrics 
μF/cc	0.7	0.085	>6	1	0.6-0.012	5.5	5.5-2	10
V	400	600-2400	200-500	500	1000-3000	400	500-900	400
ESR mΩ x μF		60	100-228	<1	<1	10-12	10-12	5
Irms A/ μF	1	5.2	5-31	50		12	12.5	
Temp		125-150 C	105	125	125	150		105

Snubber Capacitor

- Connected to a large-current switching node to reduce parasitic inductance of electric wiring.
- Prevents large surges at switch-off (when the current is blocked), so they don't exceed component ratings
- The surge waveforms between drain and source when the SiC MOSFET is turned off and current, surge suppression with sbubbers are shown

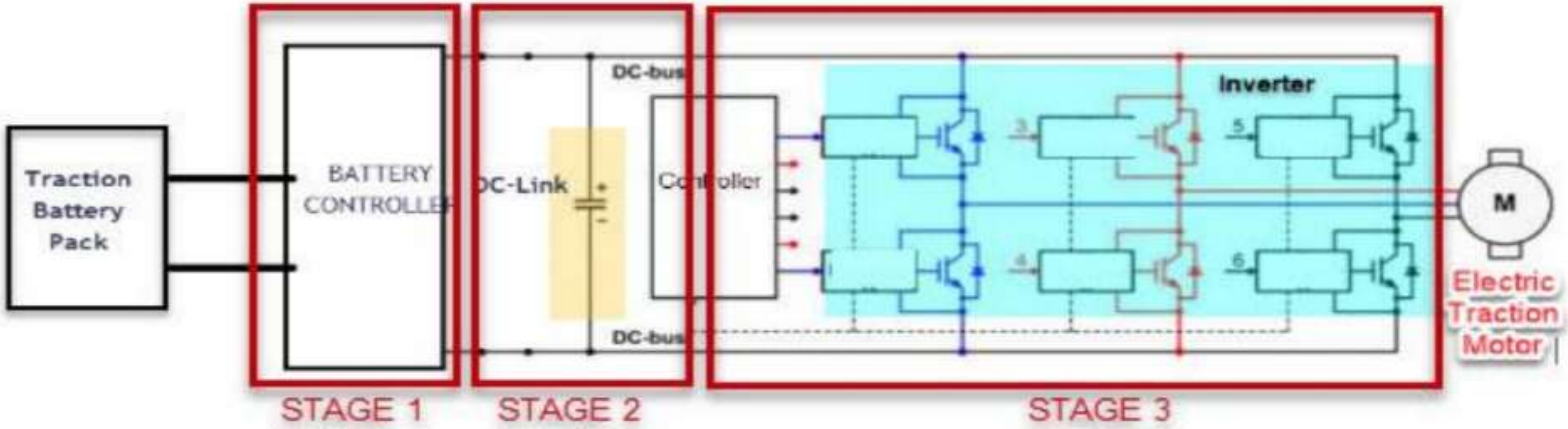


1	Soshin Electric LC78P801D127K-AA + None
2	Soshin Electric LC78P801D127K-AA + Nippon Chemi-Con FHACD1C2V125JTLJZ0
3	Soshin Electric LC78P801D127K-AA + Murata EVSM1D72J2-145MH14 5 parallel 2 series

*Apart from the position of capacitor installation, the surge voltage also differs for different parasitic inductances due to the circuit structure

ROHM Electronics

DC Link Capacitor



- Balance fluctuating instantaneous power on the rails injected by activity from the first and third stages
- Stabilizes the "ripple" generated by Stage III's high-frequency power switching circuits.
- The DC-Link capacitor (located in Stage II) must stabilize and smooth out the voltage and current on the rails
  - decoupling spikes caused by switching

$$C_{min} = \frac{I_{out} \times dc \times (1 - dc) \times 1000}{f_{SW} \times V_{P(max)}}$$

where C_{MIN} = required minimum capacitance, I_{OUT} = output current, D_{Cycle} = duty cycle, f_{SW} = switching frequency, $V_{pp(max)}$ = peak-to-peak ripple voltage.

DC Link Capacitor, KEMET

High Density Capacitor Design

Multilayered Electrodes

- Linear capacitance density scaling relative to thickness

Porous electrodes

Increment in surface area corresponding to capacitance density

- Electrochemically etched aluminum foil
  - Electrochemically etching limits scope of power module integration
- Sintered tantalum electrodes
  - Temperatures that typically exceed 1500 ^{o}C under high-vacuum conditions
  - Limitations in power module integration

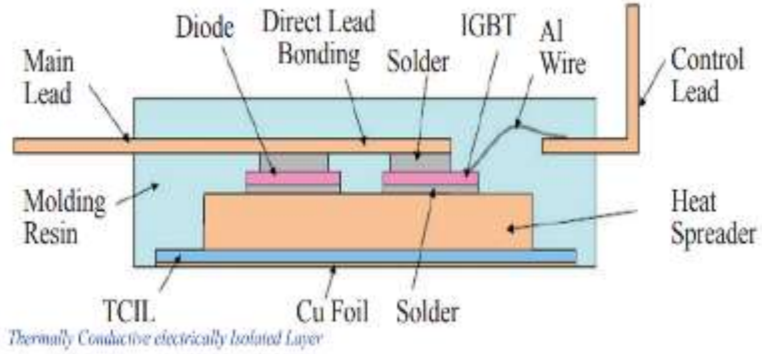
- Unable to compete with Polymer film and MLCCs for high-voltage applications
- The key reason is the high equivalent series resistance (ESR), low voltage and thermal stability of cathodes that are used with such anodes. The high ESR arises from the low conductivity of the cathode materials used in high surface-area capacitors.
- The cathodes are also prone to long-term reliability issues from moisture ingression, temperature and high voltage. The dielectric thickness is also not adequate for kV applications.

Cold Sprayed Aluminum Capacitors

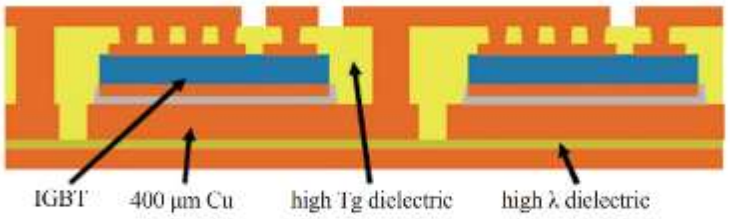
- Eliminates the need for post-patterning the high surface area electrodes and
- Direct integration of electrodes on copper or aluminum lead frames, bus bars and heat-spreaders
- Eliminates the sintering requirement for electrodes
- Selectively deposit the porous aluminum in a direct-patterned format without the need for post-patterning

Opportunities for Cold Sprayed Capacitors

Direct-Lead Bonding (Mitsubishi)

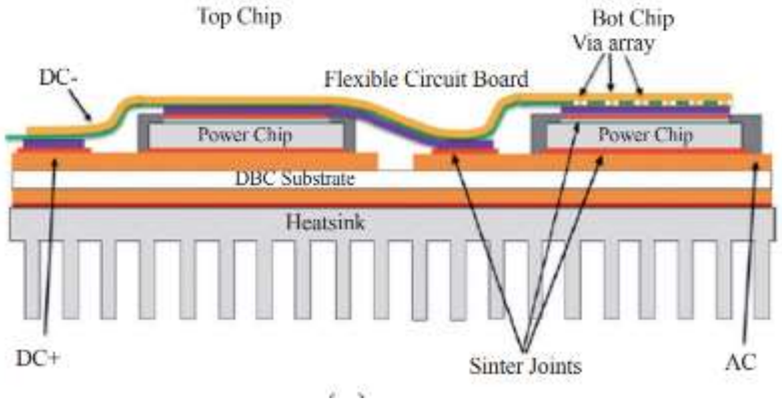


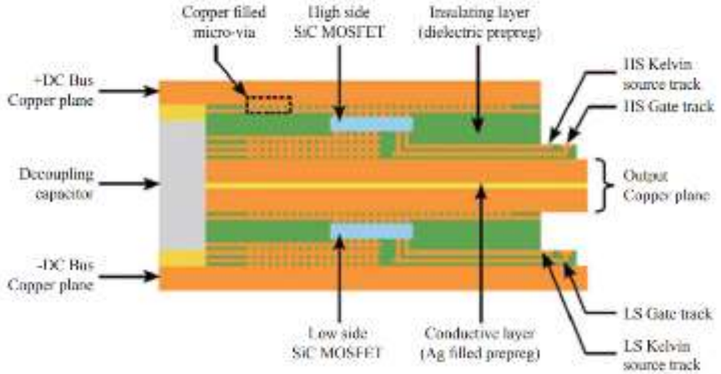
Embedded Module (Boettcher et al., ESTC 2012)



- **Embedded in Lead busbar**
- **Embedded in Flexible circuit board**
- **Embedded in Al ribbon wires**
- **Embedded in the DBC or baseplate**

SKIN Module (Beckedahl, CIPS 2016)



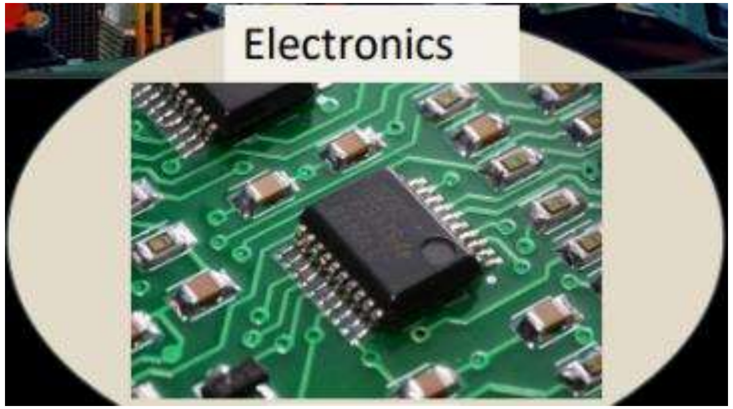


Chip on Chip Module (Regnat et al., ECCE 2015)

Unique Features of Cold Spray for Electronics Applications

3D-PEIM
International Symposium on 3D Power Electronics Integration and Manufacturing

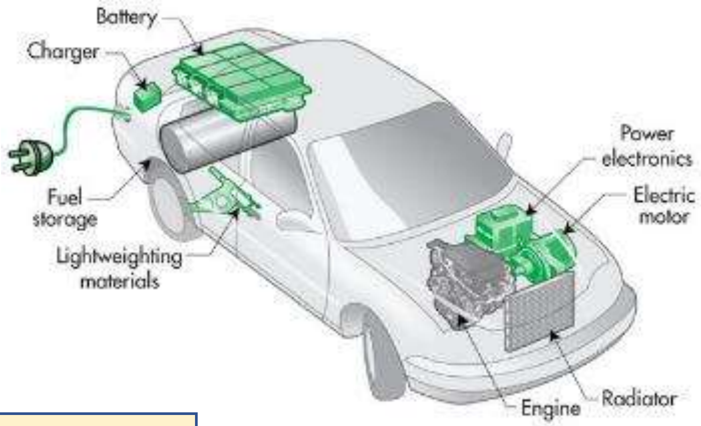
Solid State Process
Eliminates need for heat
Defects due to heat



Coating properties can be predictable

Power Modules in Automotive & Electric Grid Systems

No Oxidation
High Quality Coating



Highly Portable
Cost Effective

Scalable & Light weight Coatings

Retain composition/phases/grain size of initial powder

Tunable Process Parameters for varying porosity

FIU
Florida International University

Research Objective

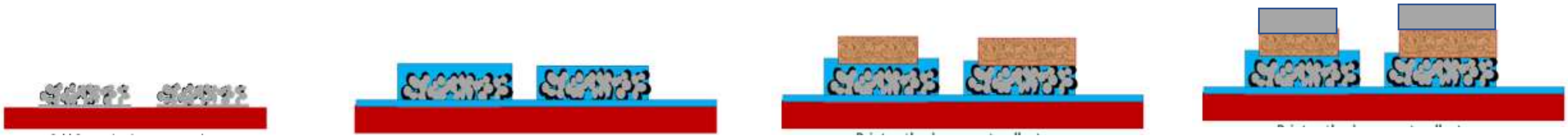
Fabricate aluminum capacitors

- Thin
- High-density
- Package embeddable
- Platform independent integration
    - Traditional leadframe

Parameter	Objective
Capacitance Density	~ 1 μF/cm^2
Electrode Thickness	< 1 mm
Frequency Stability	1 MHz and above
Voltage Stability	100 V operation

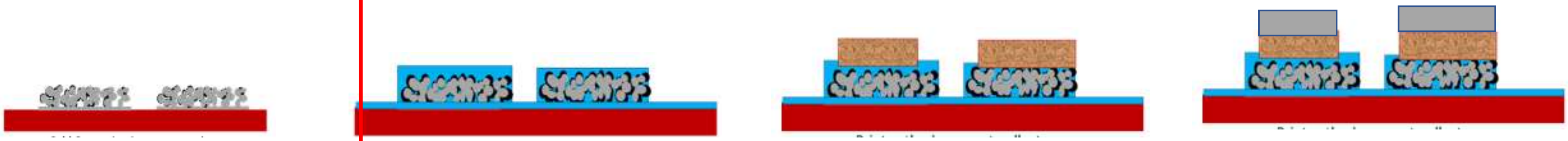
Anodized Aluminum Capacitor fabrication : Overview

Cold Spray deposition on Aluminum substrate → Dielectric formation by Anodization → Counter Electrode deposition → Cathode contact/ Current Collector formation



Anodized Aluminum Capacitors

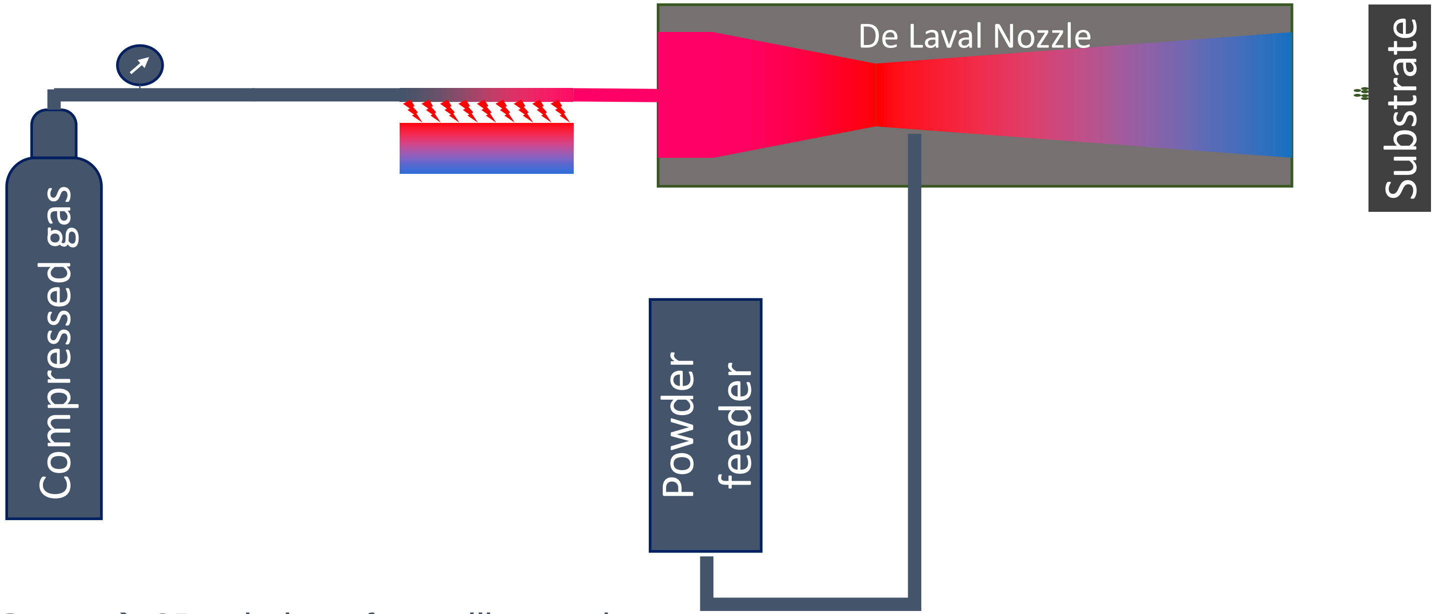
Cold Spray deposition on Aluminum substrate → Dielectric formation by Anodization → Counter Electrode deposition → Cathode contact/ Current Collector formation



Cold Spray Principle

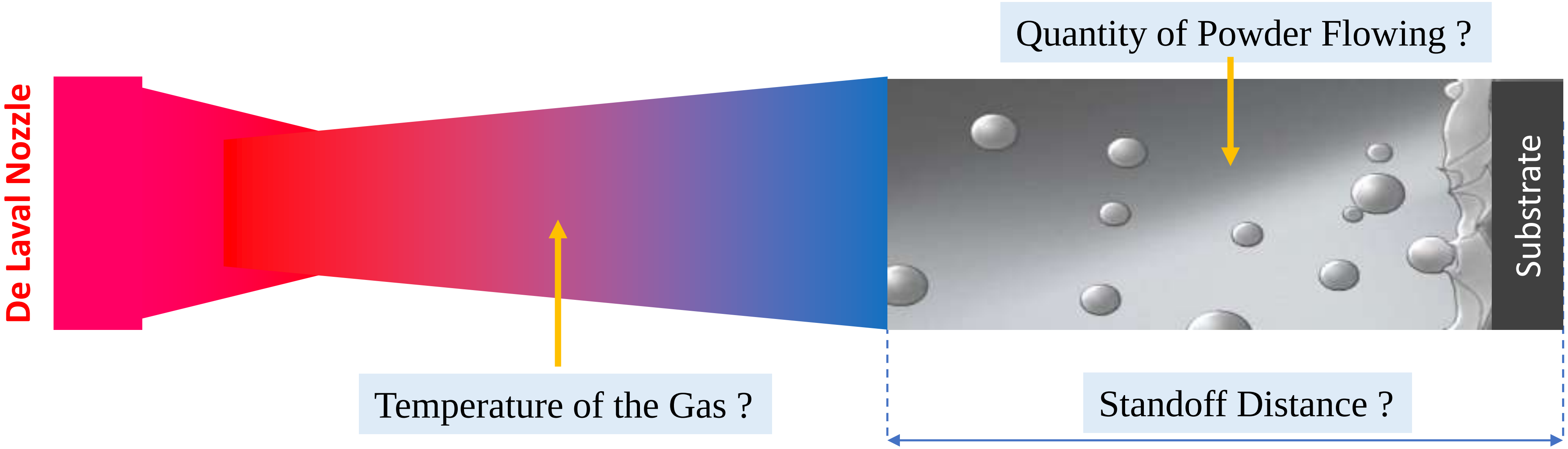
Illustration of CS deposition.
video courtesy: Impact Innovations GmbH

Schematics of Cold Spray System

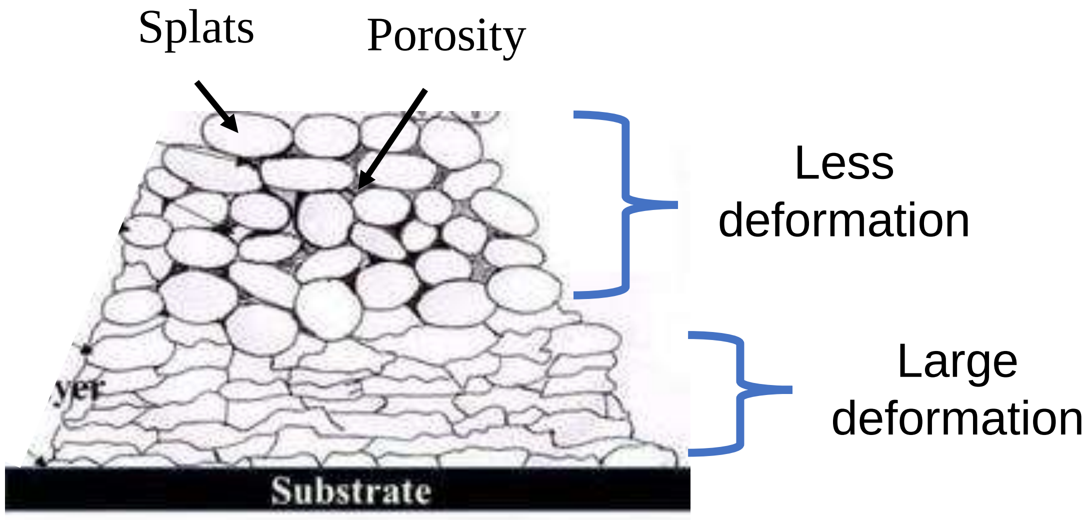


- Cold Spray → 3D printing of metallic powders.
- A compressed gas is heated before entering in a DeLaval Nozzle.
- The gas is accelerated in the nozzle
- Metal powder is injected in gas stream and accelerated
- The powder reaches velocity up to 1200 m/s
- The powder is plastically deformed, and the coating is building up
- **Splats** are the building block of the coating

Porosity Control (Deformation of Splats)



- The temperature of gas translates to the velocity of the metal powder
- When the velocity increases beyond the critical velocity, bonding initiates
- The extent of plastic deformation of powder determines the density/porosity
  - Controlled by varying process parameters



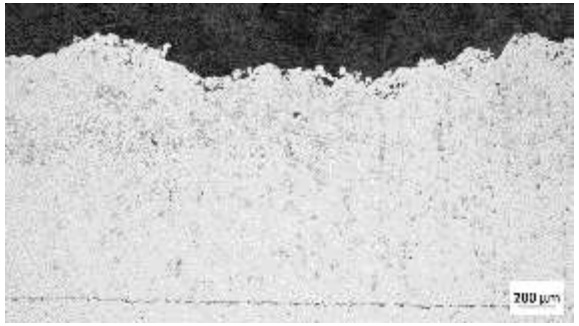
Process Parameter Optimization

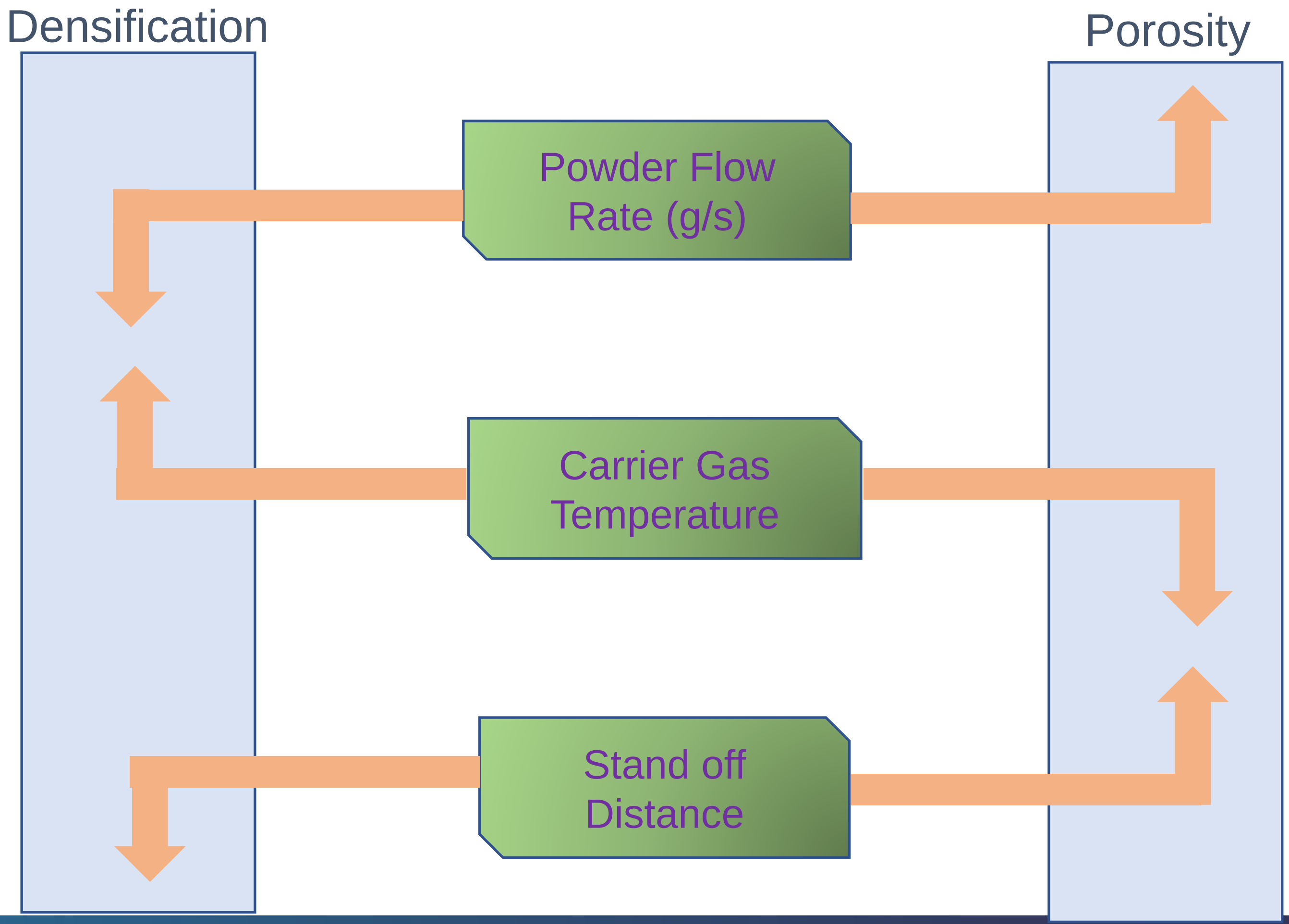
High-velocity process → density is > 99.7%

Tune process parameters for increasing porosity

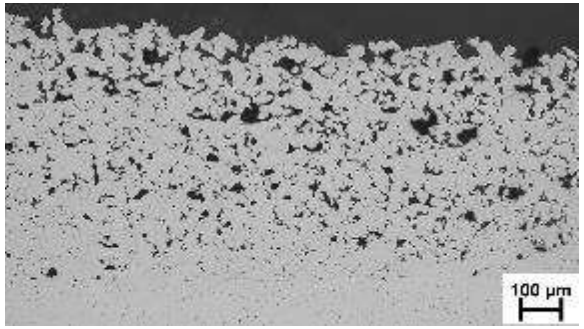
Process Parameters

Dense Coatings



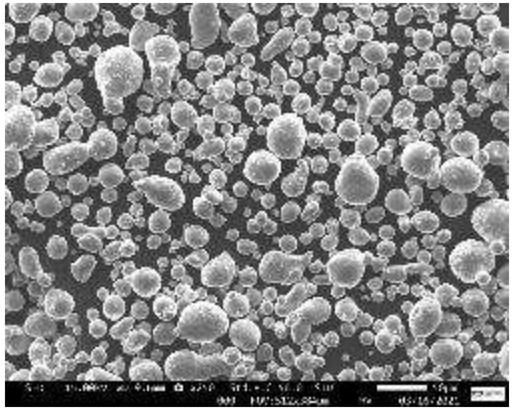


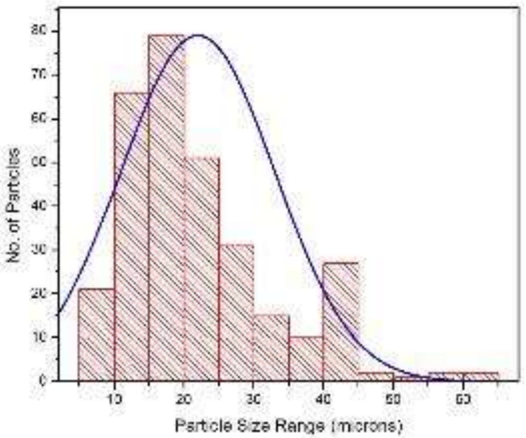
Porous Coatings



Porous cold-sprayed layer deposition

Pure Aluminum Powder

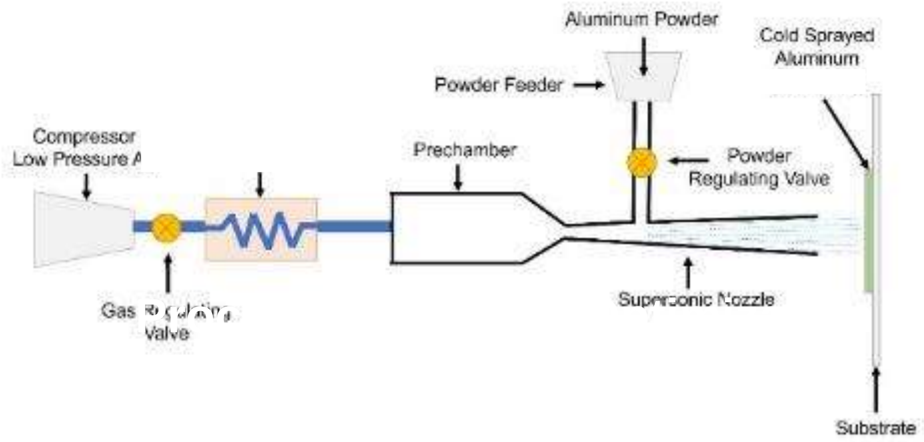




- Spherical Al powder
- 99.5% pure Al
- Mean Diameter: 21.97±11.01 µm

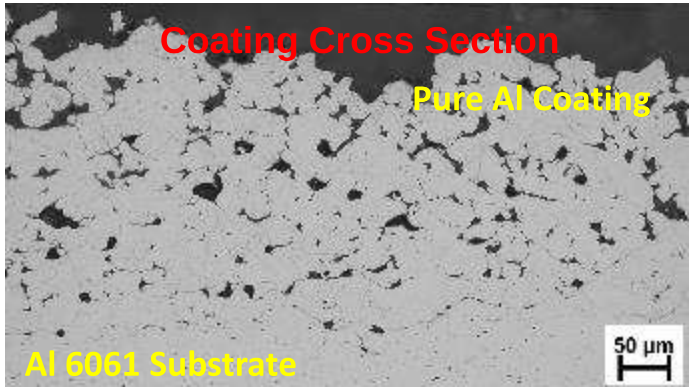
Powder Feed : 1:1 (Pure Aluminum (Al 1100) : HS Aluminum alloy (Al 6061))

Al 1100 restricts the rate of plastic deformation leading to unique uniformly distributed pore formation

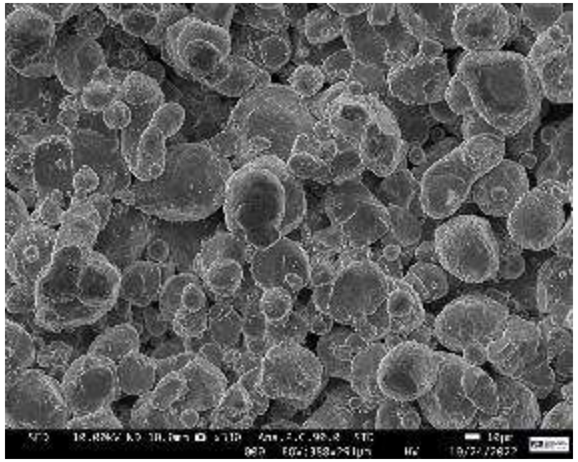


Spray Parameters	
Gas Type	Air
Gas Temperature	400 °C
Gas Pressure	6 bar
Stand-off Distance	15 mm

Porous Aluminum Coating



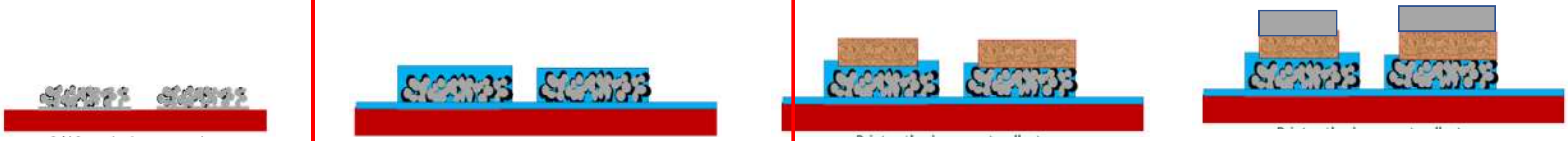
Coating Top Section



Thickness ~ 150 µm
Continuous and uniform porosity

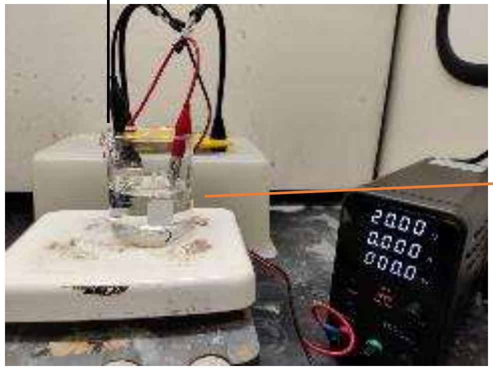
Anodized Aluminum Capacitors

Cold Spray deposition on Aluminum substrate → Dielectric formation by Anodization → Counter Electrode deposition → Cathode contact/ Current Collector formation



Anodized Alumina – Process Characterization

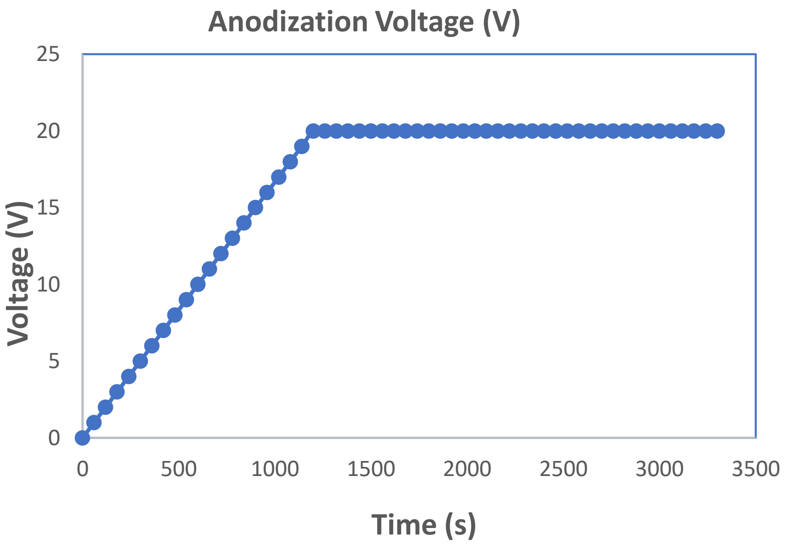
Cathode (Reduction):
$$6H_2O + 6e^- \rightarrow 3H_2 + 6H_2O$$



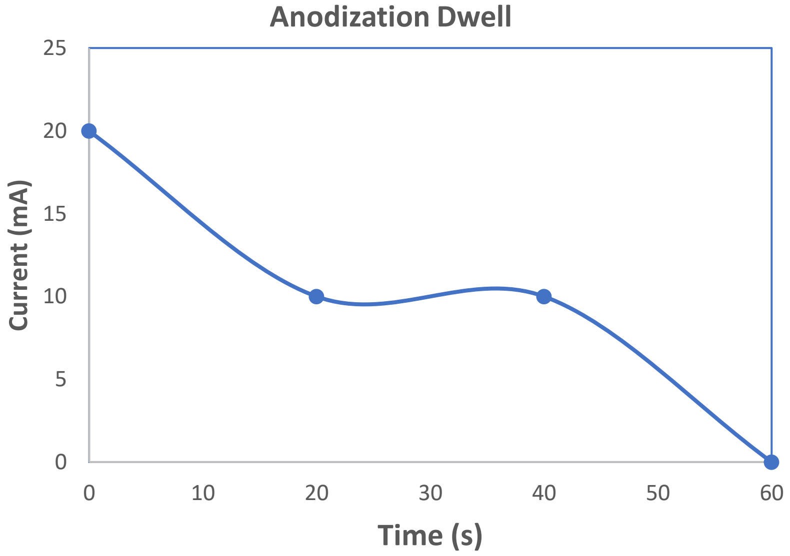
Anode (Oxidation):
$$2Al \rightarrow 2Al^{3+} + 6e^-$$
$$2Al^{3+} + 9H_2O \rightarrow Al_2O_3 + 6H_3O^+$$

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$$

Parameter	Value
Electrolyte	0.15 M Ammonium Pentaborate ((NH4)B_5O_8)
Anodization Temperature	Room Temperature
Anodization Voltage	20 V (ramp @ 1V/min)
Dwell Time	35 minutes
Mode	Constant Voltage



~ 40 nm suitable for 30V application



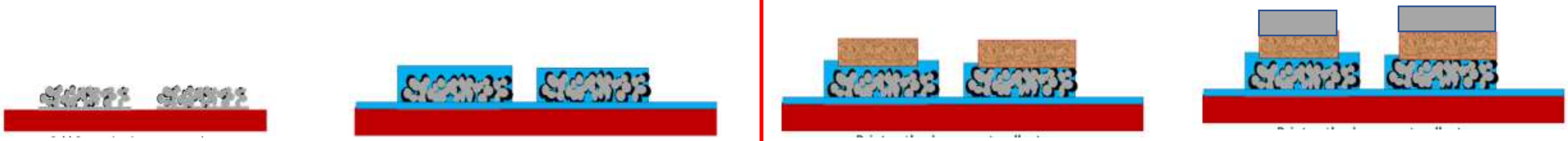
Anodized Aluminum Capacitors

Cold Spray deposition on Aluminum substrate

Dielectric formation by Anodization

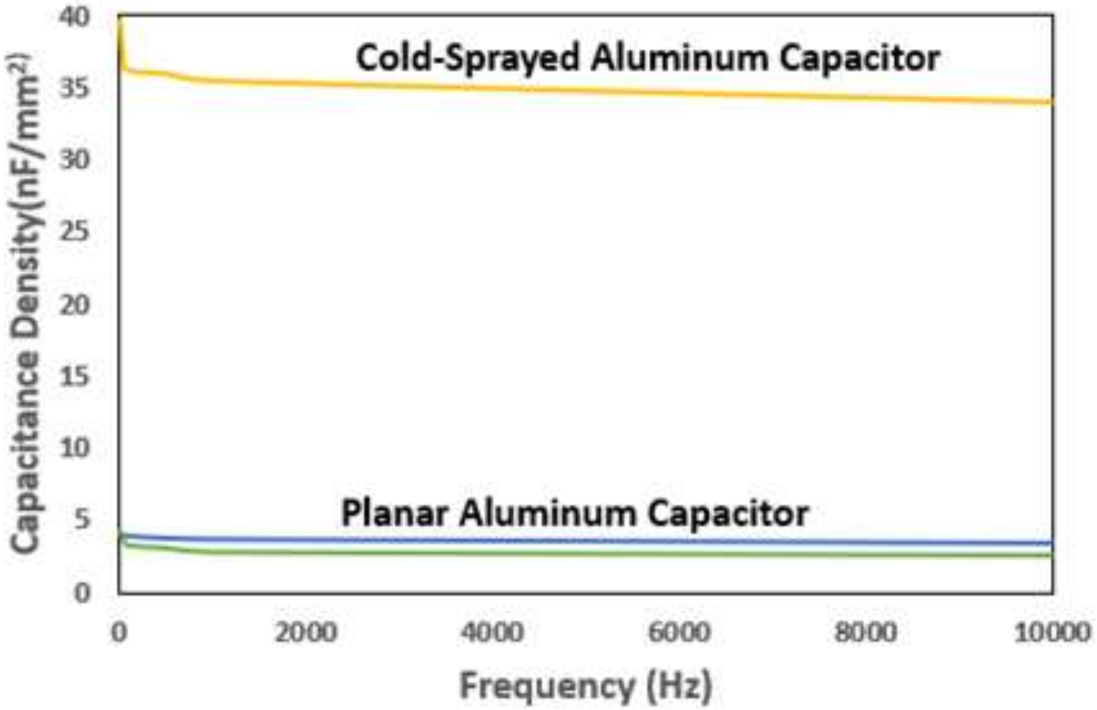
Counter Electrode deposition

Cathode contact/ Current Collector formation



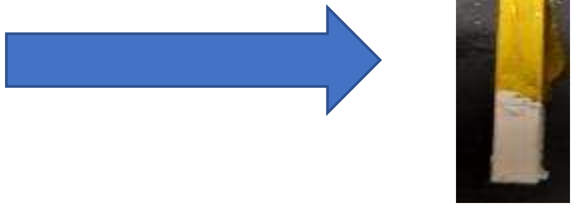
Anodized Alumina: Liquid Electrolyte Cathode

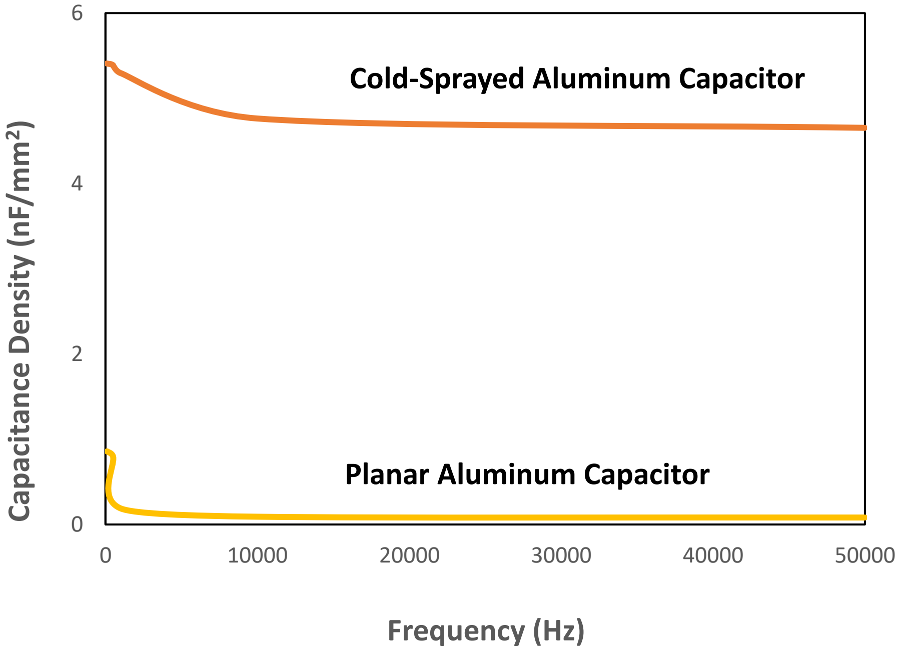
Parameter	Value
Electrolyte	0.5 M Potassium Sulfate (K_2SO_4)
pH	~ 10 -11
Temperature	Room Temperature
Freq Range	20 Hz – 10k Hz
Equivalent Circuit Mode	Cs , Rs, Cp, Rp



Capacitance Density using Liquid Electrolyte

Anodized Alumina: Solid Electrolyte Cathodes



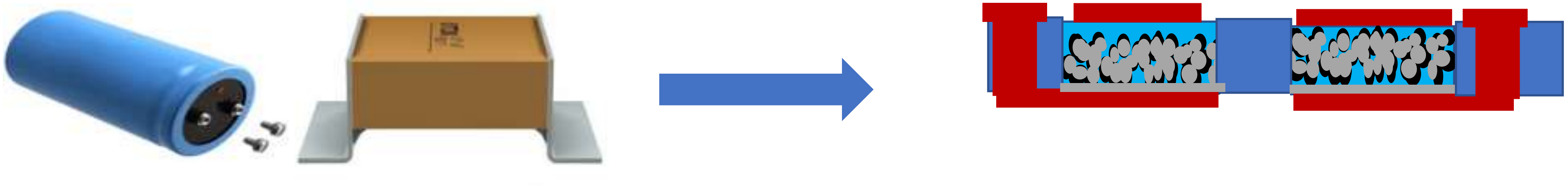


Capacitance Density using Conductive Polymer Cathode

Parameter	Value
Counter Electrode	Conductive Polymer (Pedot: PSS)
Temperature	Room Temperature
Freq Range	20 Hz – 50kHz
Equivalent Circuit Mode	Cp , Rp, Cs, Rs

Result Summary and Next Steps

Demonstrate thin high-density aluminum capacitors for >100 V at 1 MHz operation with the following attributes:



Parameter	**Objective**	**Opportunities for Improvement**	**Strategies for Improvement**
Capacitance Density	~ 1 µF/cm^2	Optimizing anode-dielectric structure and infiltration of polymer cathode	Usage of conformal cathode
Electrode Thickness	< 1 mm	Design optimization	Introduce sacrificial material during cold spray
Frequency Stability	1 MHz	Ripple current handling of cathode	Inorganic Conductive cathode (ALD)
Voltage Stability	100 V operation	Thicker, conformal dielectric with few defects	Eventually 100-200 V anodization

Summary

- Innovative low-temperature additive manufacturing process developed to form capacitors
  - Electrode formation at room temperature on any metal frames
  - Can be integrated on wires, leadframes, busbars, and other innovative 3D architectures
- Proof-of-concept results showed
  - Initial enhancement in surface area
  - Projected to reach higher area enhancement with more process enhancement
- Ideal for high-voltage and high-temperature capacitors

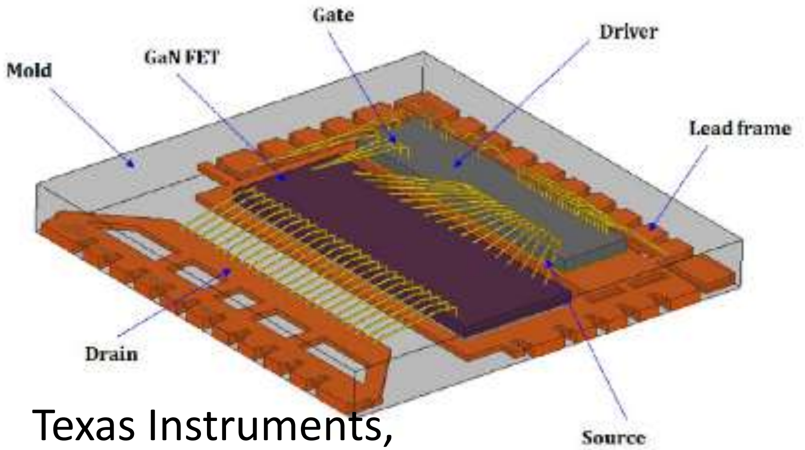
Thank you !

Back-Up Slides

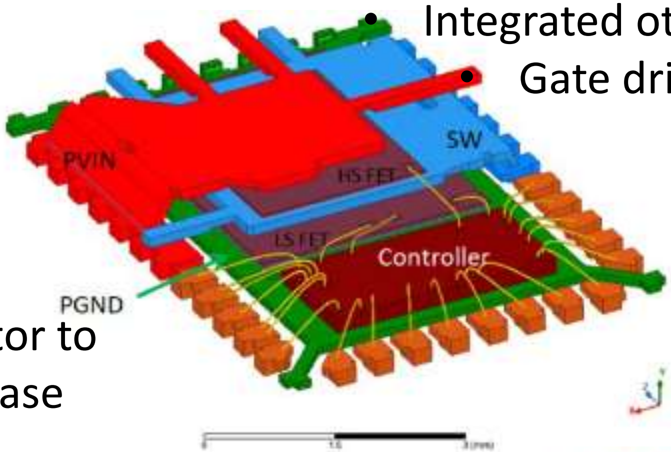
Capacitors in Discrete Power Modules

Why:

- Miniaturize footprint and thickness
- Eliminate Bill-of-Material burden for the customer
- Reduce parasitic inductances from 10s of nH to sub-5 nH
- Reduce thermal resistance (>30 C/W to 10-20 C/W to <1 C/W)
- Integrated other functions:
    - Gate driver isolation, sensors, EMI isolation



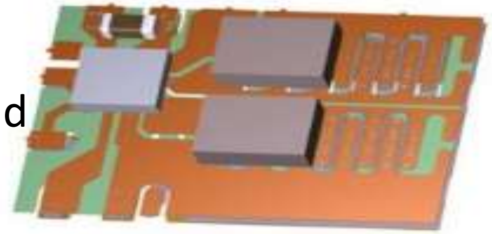
Texas Instruments,
Rajen Murugan et al.,



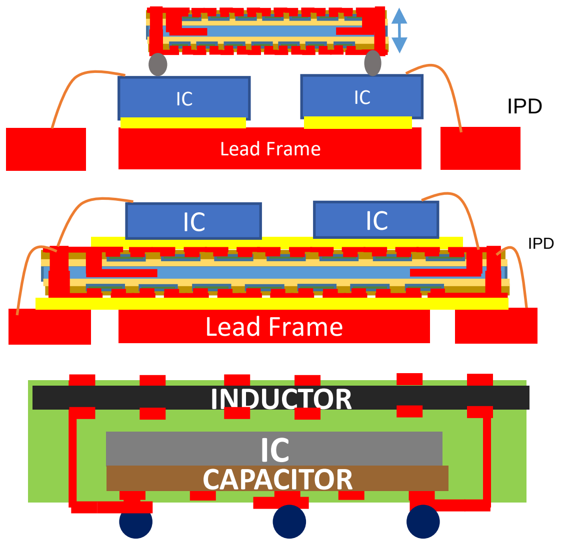
As topologies migrate from switching regulator to resonant/hybrid with multilevel and multiphase conversion: more passives are needed

What causes delays:

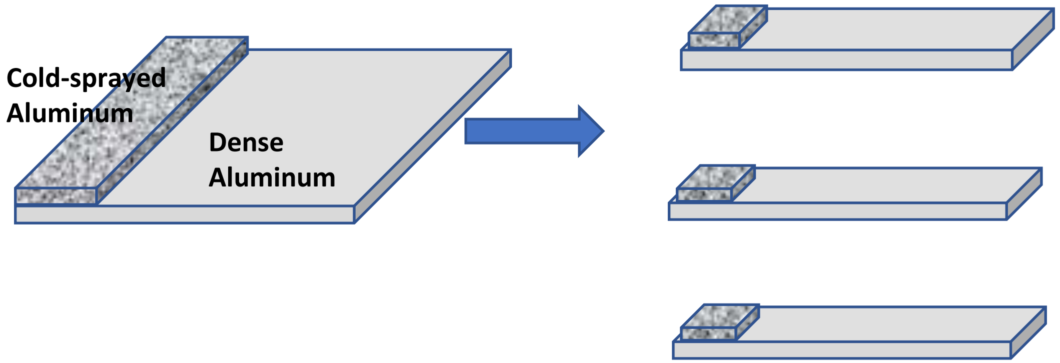
- Need system co-design for thermal, mechanical, electromagnetic and material considerations
- Supply-chain and manufacturing readiness
- Market pull



Texas Instruments,
Mishra et al.,



Power modules with passive-active integration


Cold-sprayed
Aluminum
Dense
Aluminum