Metacapacitors: Printed high-frequency capacitors for electric power conversion

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Eli S. Leland

Power Supply on Chip 2012
November 17, 2012

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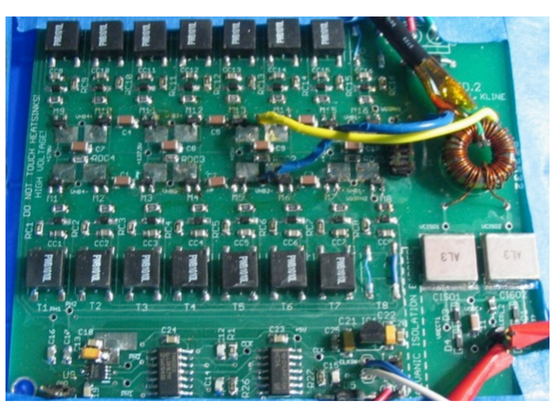
Metacapacitors™: Next-generation power electronics for LED lighting and other applications

What	Why	How	What for
• Better DC-DC converters	• Cheaper • Smaller • More efficient • Longer lasting	• Switched capacitor circuit topologies • Novel high-frequency, low-loss capacitors • Scalable continuous printed fabrication • No transformers or electrolytics	• LED lighting drivers • PV power conversion • Mobile devices • Power supplies

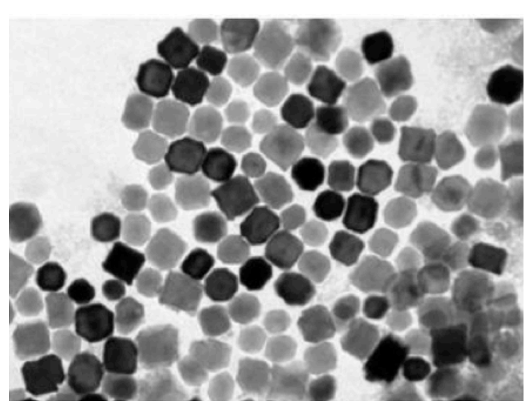
Our multidisciplinary team combines enabling technology and expertise:

Analog power circuits and IC design



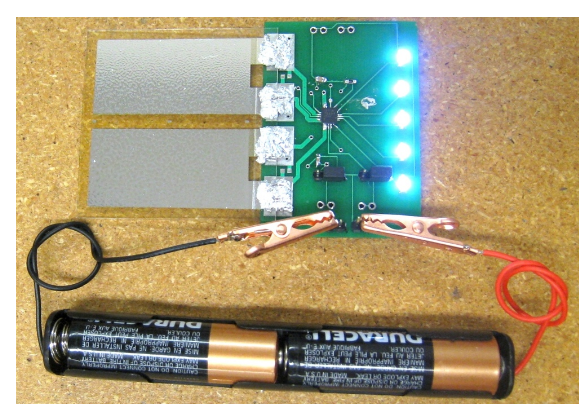
Sanders (Berkeley), Kinget (Columbia)

Self-assembling nanoparticle dielectrics



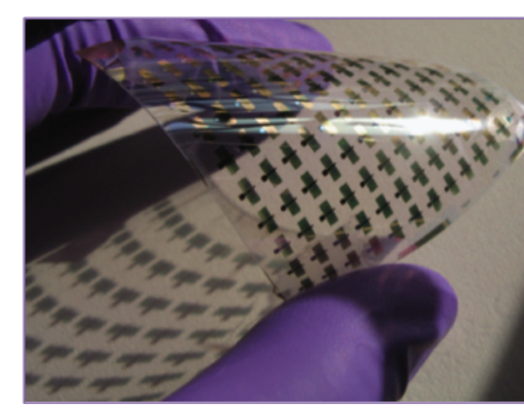
O'Brien, Couzis (CUNY)

Scalable capacitor printing technologies



Steingart, Leland (CUNY)

Flexible substrates and novel device integration



Kymissis (Columbia)

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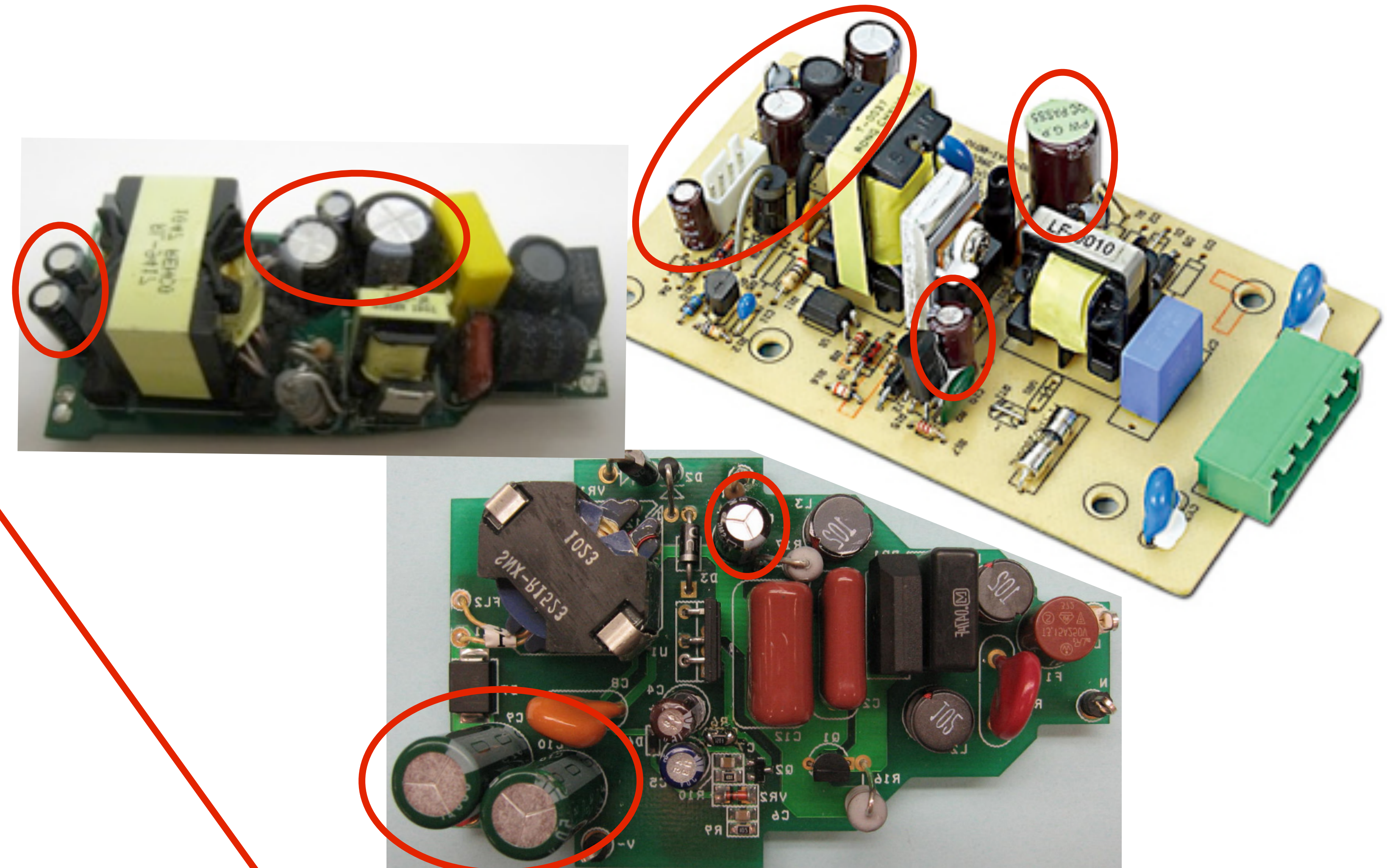
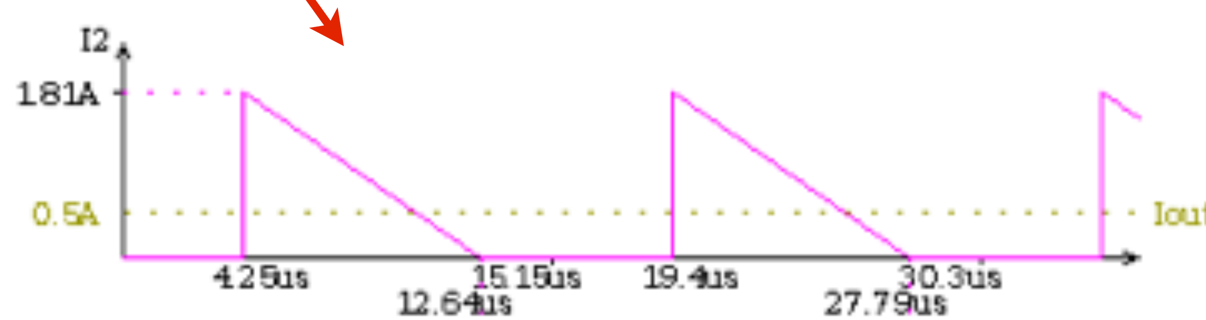
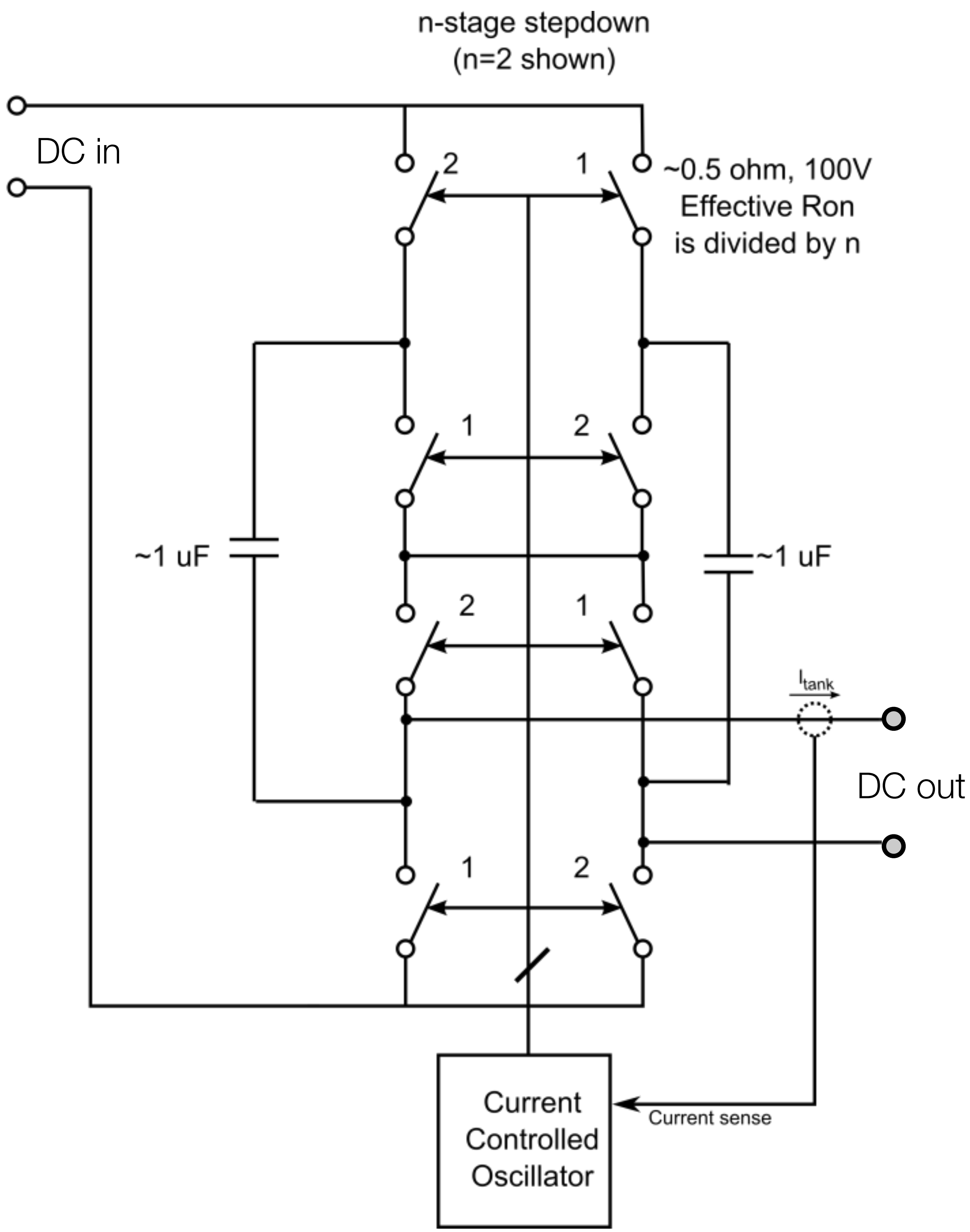
Switched-mode power supplies dominate, but have issues

- Lifetime limited by electrolytic capacitors
- Significant energy storage capacitance is required due to output waveform
- Efficiencies of 70-80% are common. Higher efficiencies are achievable, but at significantly higher cost
- Nonetheless, SMPS developments continue to be slow, evolutionary





Switched capacitor converters offer an attractive alternative



- DC-DC power train is only switches and capacitors, no transformers or inductors
- Switches and capacitors only handle a fraction of the input voltage or total current
- Higher switching frequencies allow for higher power densities, efficiencies of 95% or greater
- **Vision:** A two-component power converter
  - Passives printed on cheap flex
  - Single IC for switching, control

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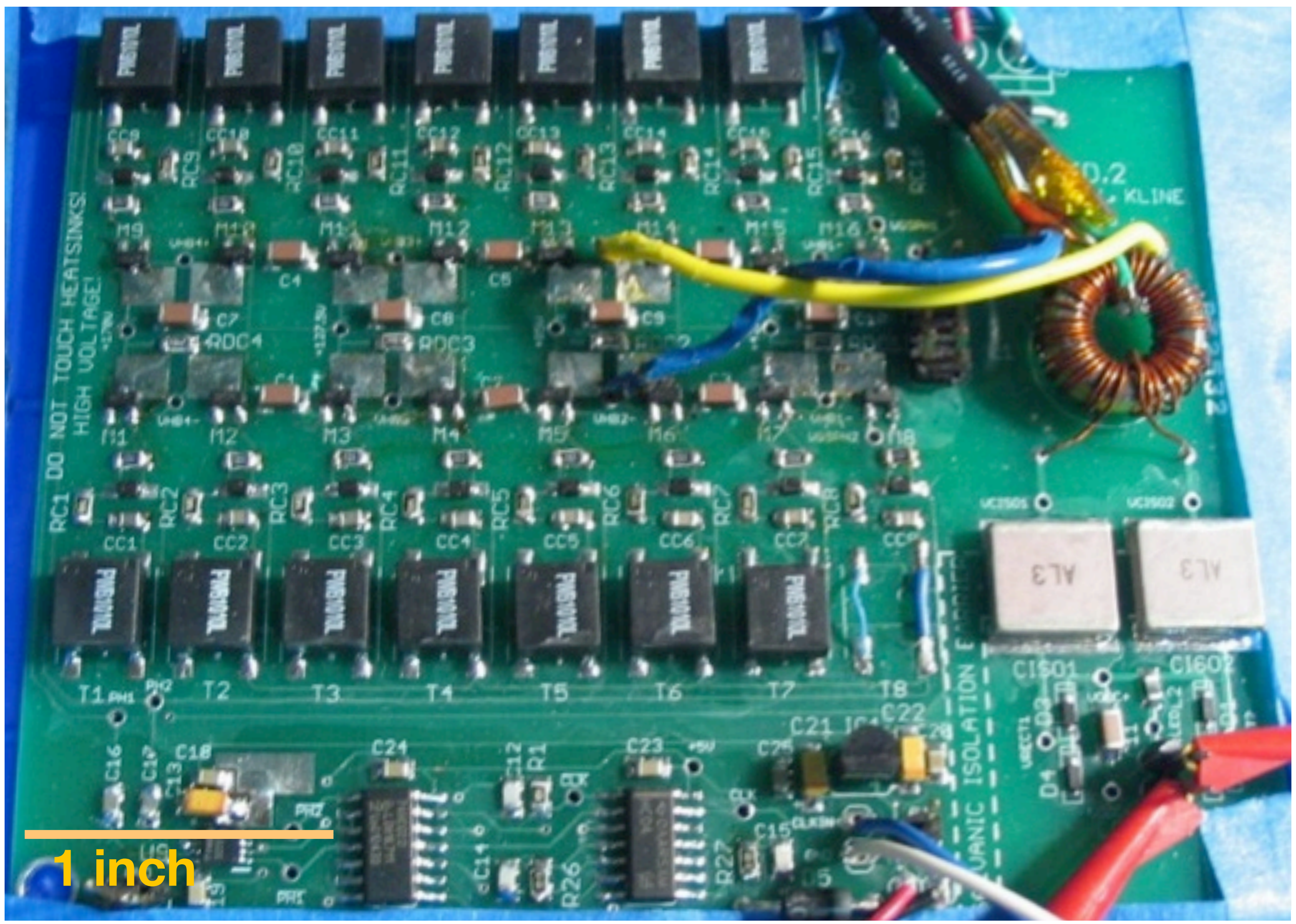
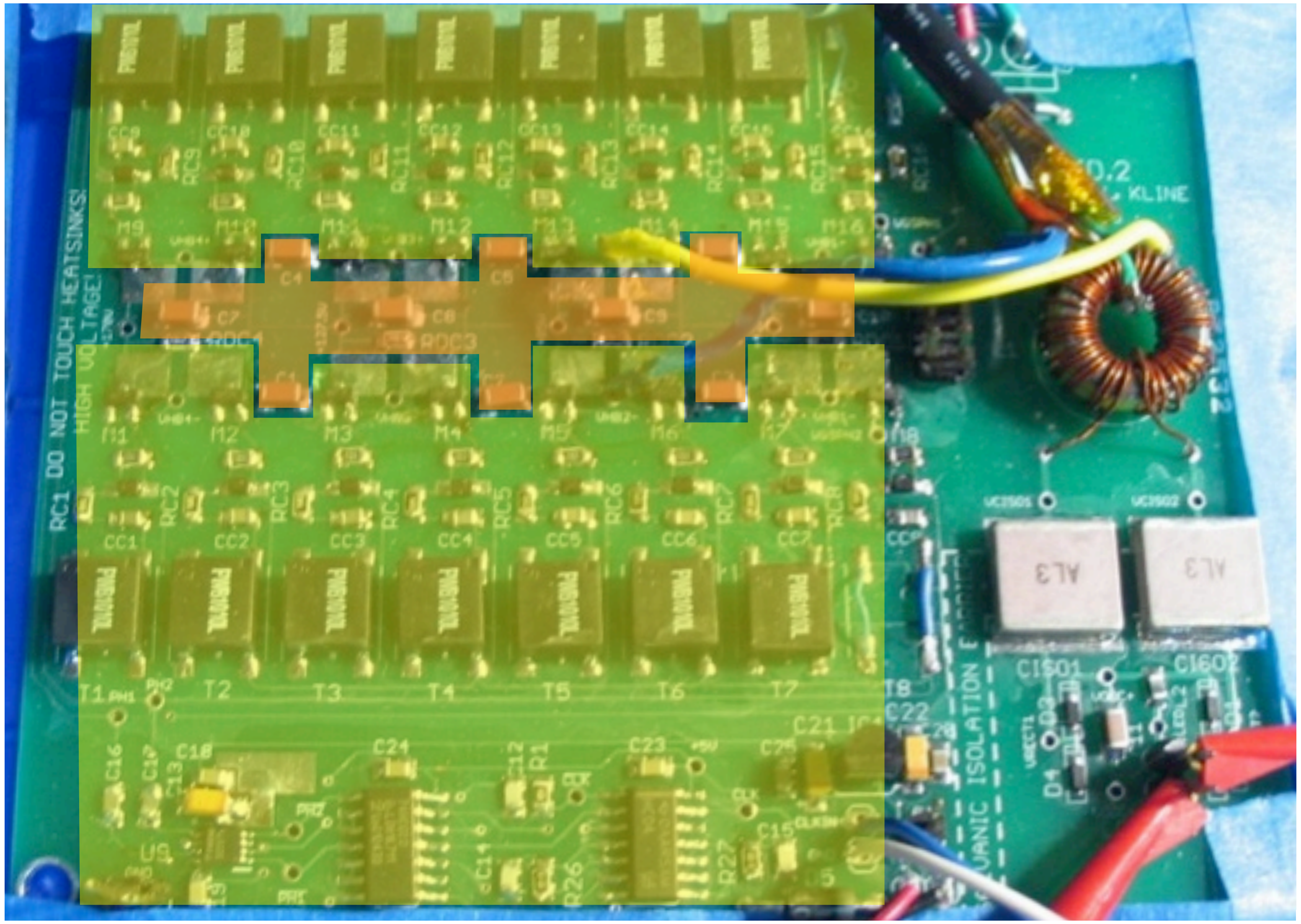
Discrete component proof-of-concept



- Switched capacitor LED driver prototype
- 15.5 W, 425 mA, 2.29 MHz switching frequency
- 92% efficient, achieving DOE goal for 2020
- Input/output isolation
- PWM dimming

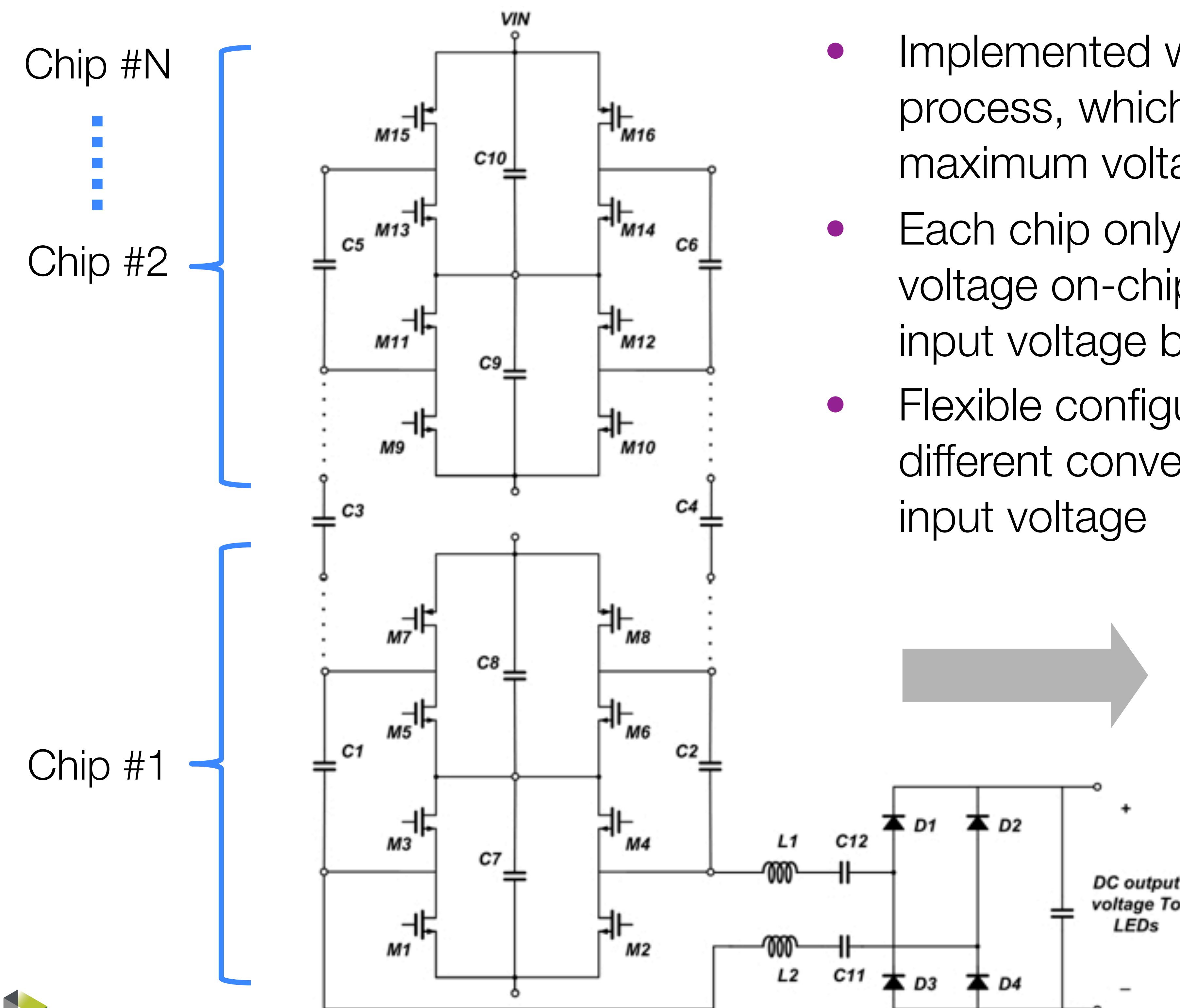
How do we get to our vision?



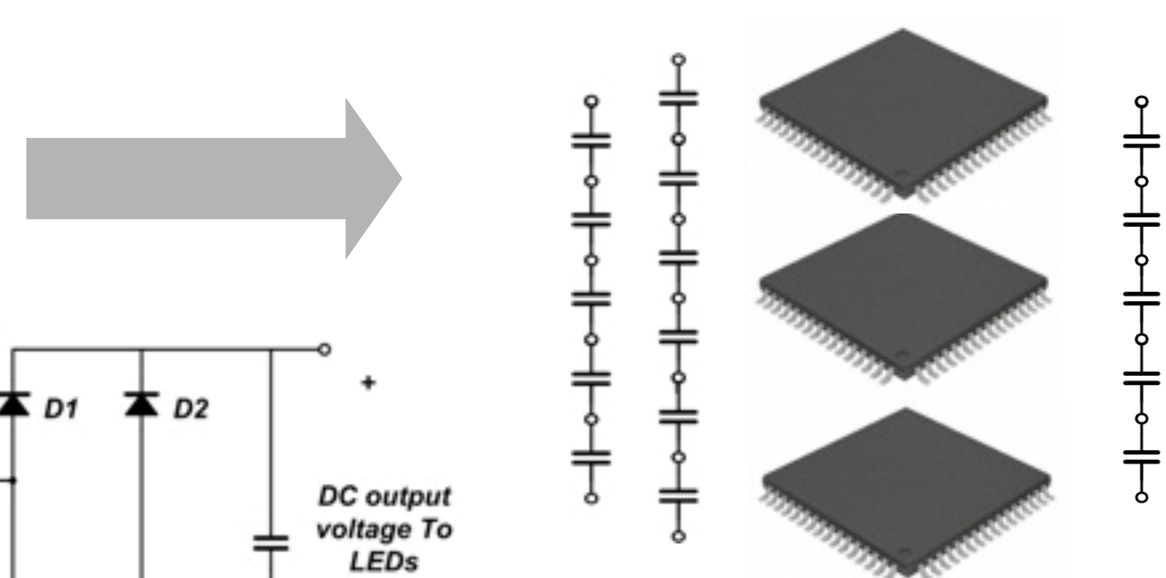
Integrated circuit for switching and control

Powertrain capacitor network printed on flex

Chip-stacking switch capacitor DC-DC converter IC



- Implemented with TI's ABCD5HV process, which can handle 120V maximum voltage on-chip
- Each chip only needs to stand 100V voltage on-chip, can handle higher input voltage by stacking more chips
- Flexible configuration. Can provide different conversion ratios for a given input voltage



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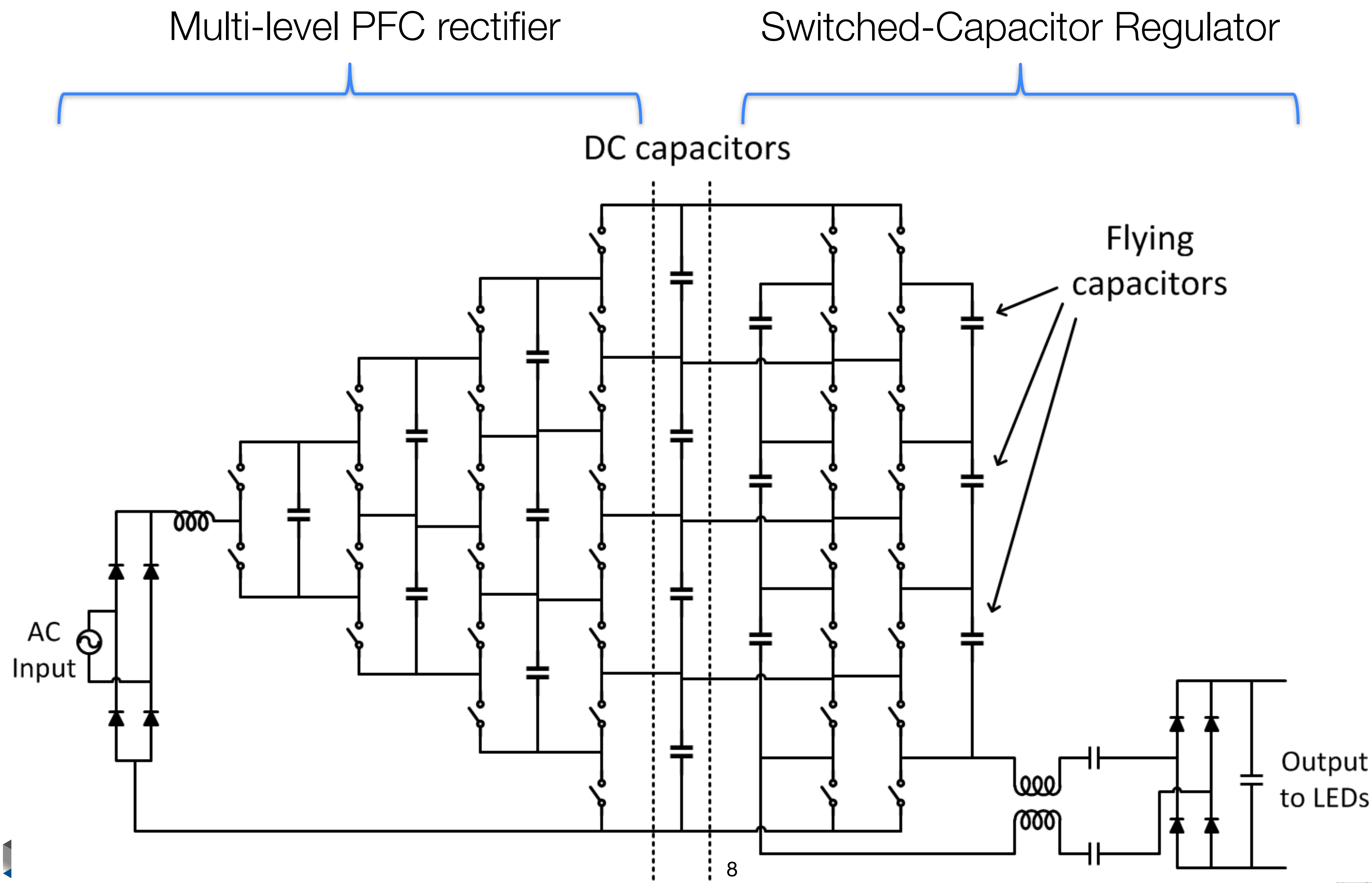
Discrete PFC off-line LED driver prototype



What about the capacitors?

- High-frequency
- Cheap!
  - Printable
  - Roll-to-roll process compatible
  - Low-temperature fabrication

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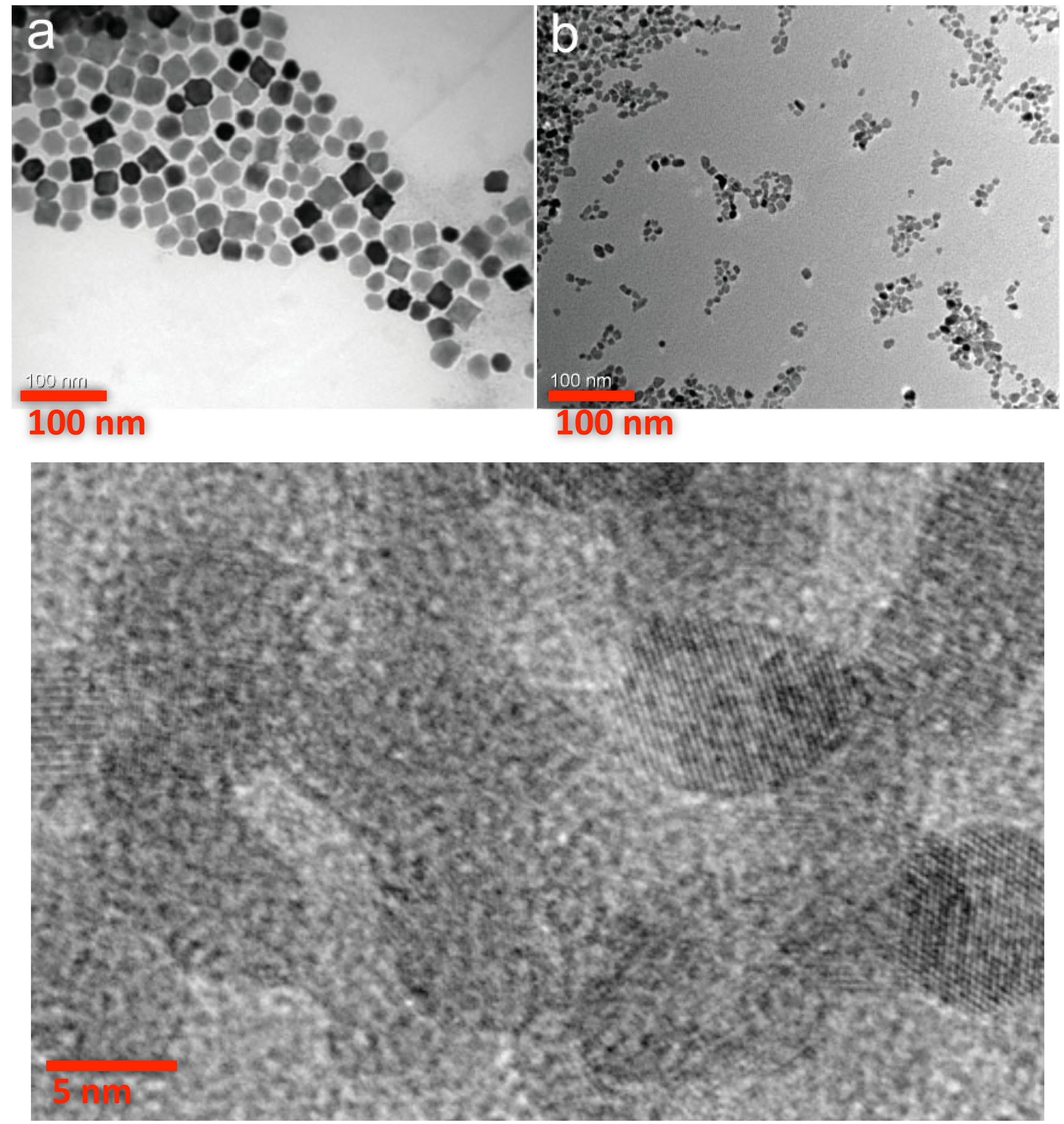
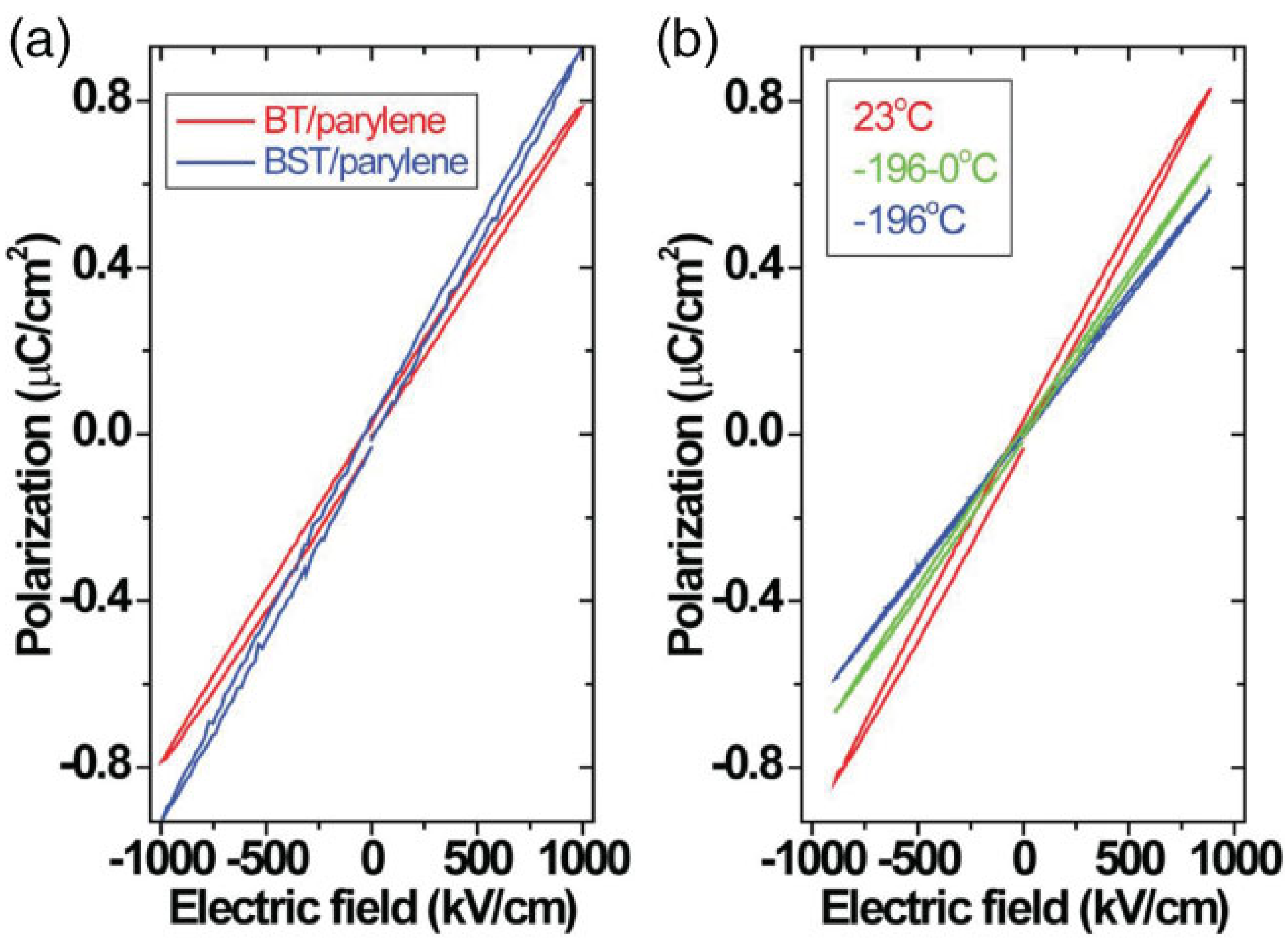
Printable nanoparticle dielectric

- $BaTiO_3$ and (Ba, Sr)TiO_3 nanoparticles, single crystal, size controllable from 5-100 nm
- Low temperature (<100°C), scalable batch synthesis; no HTCC/LTCC processing
- Size, composition determined by solvents (alcohol, water) and metal-organic precursors



O'Brien, S., Huang, L. & Chen, Z. METAL OXIDE NANOCRYSTALS: PREPARATION AND USES. USA patent application 12/566,135

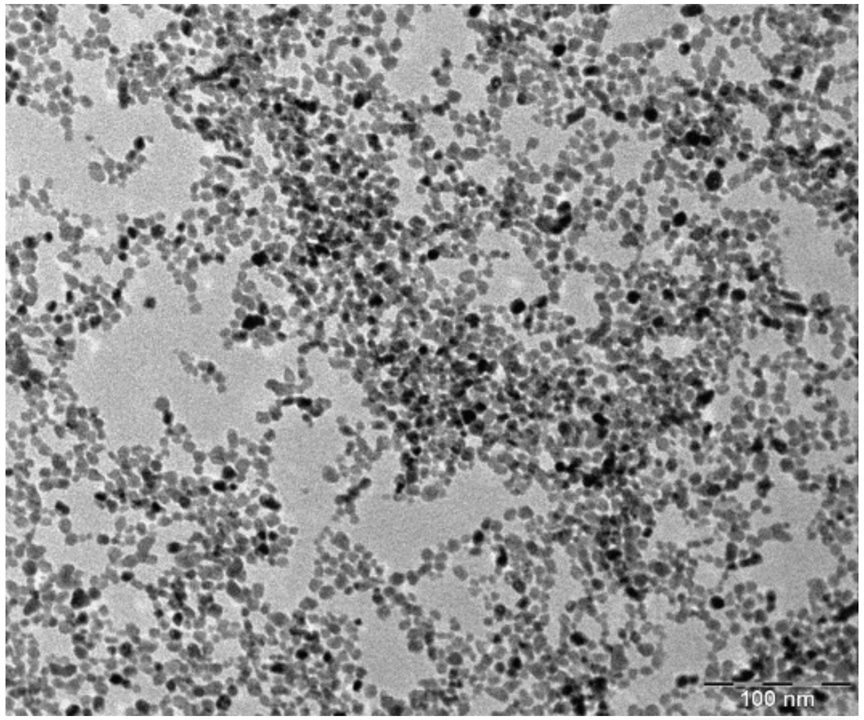
High-frequency capability



- Single crystal particles exhibit no dielectric hysteresis, reducing dielectric switching losses
- Nanoparticle dielectric inks are compatible with printing processes
- Printing process must deliver consistent, functional dielectric films exploiting the low-loss behavior of the dielectric

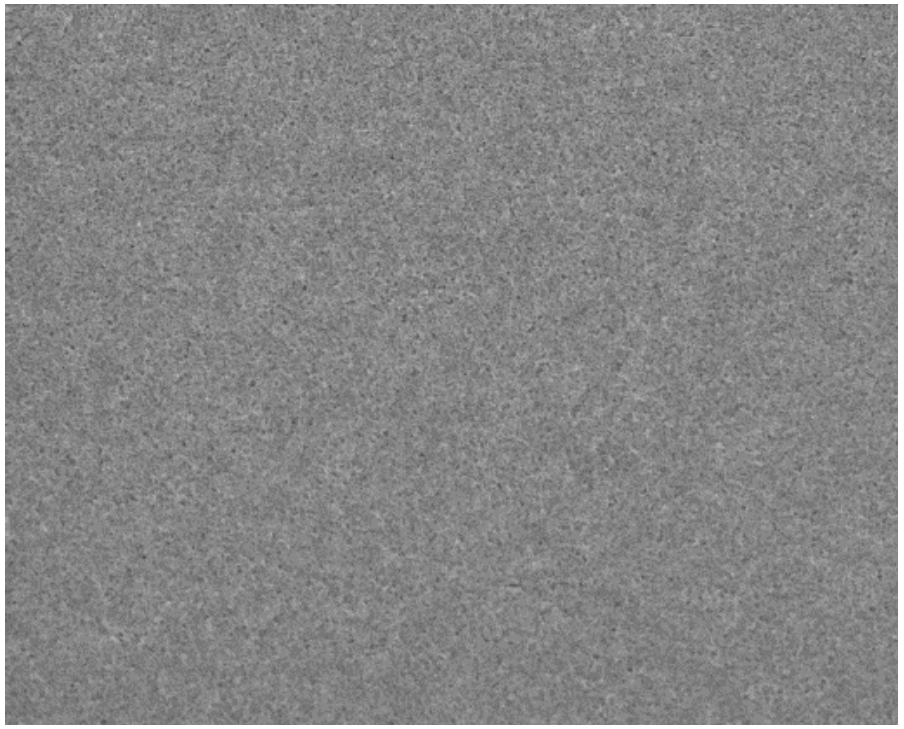
Huang, *et al.,* "High K capacitors and OFET gate dielectrics from self-assembled $BaTiO_3$ and $(Ba,Sr)TiO_3$ nanocrystals in the superparalelctric limit," *Advanced Functional Materials*, 2010

Scaled-up synthesis, high-quality films



100 nm

Highly uniform BST nanoparticles form void-free films



300 nm

Low temperature synthesis (< 100°C, no HTCC/LTCC) scaled to 200 mL - 1 L batches

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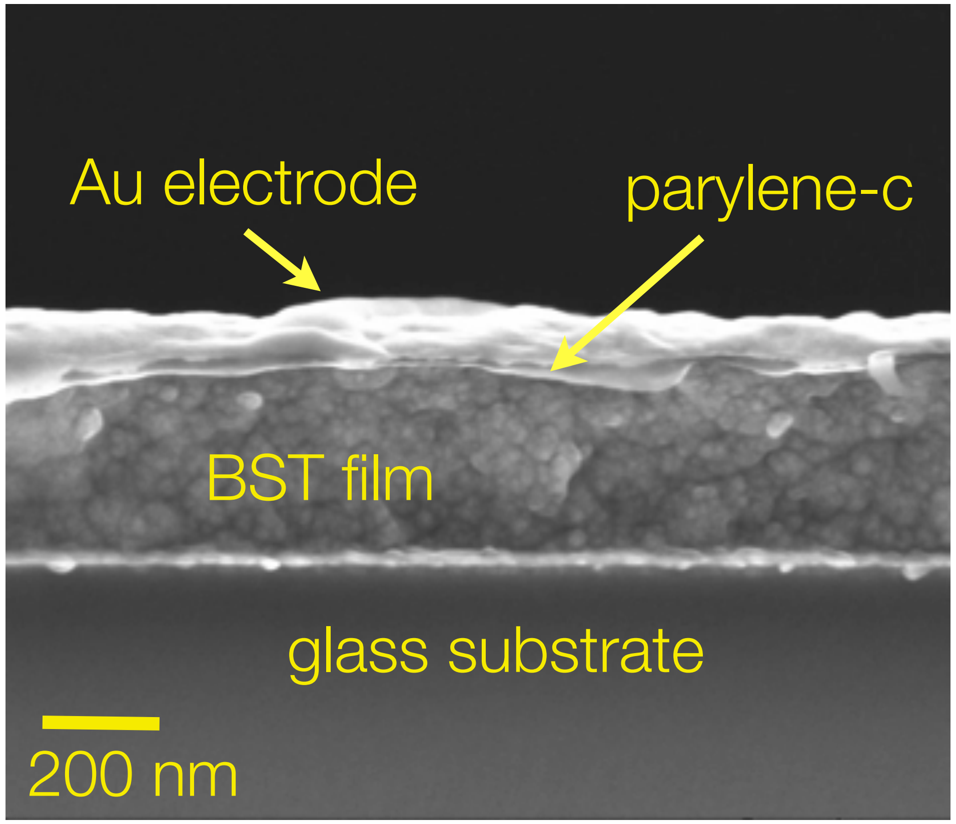
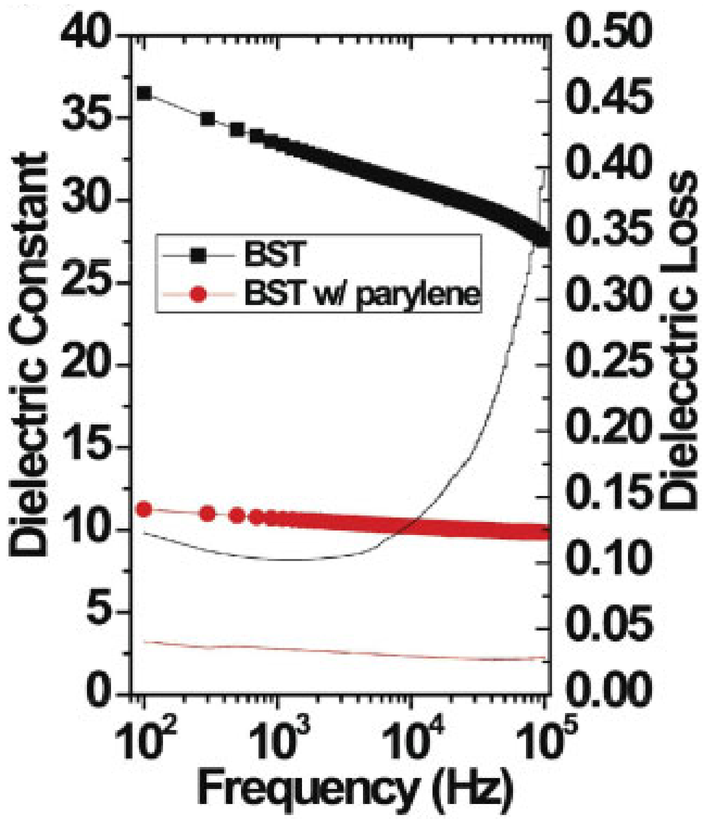
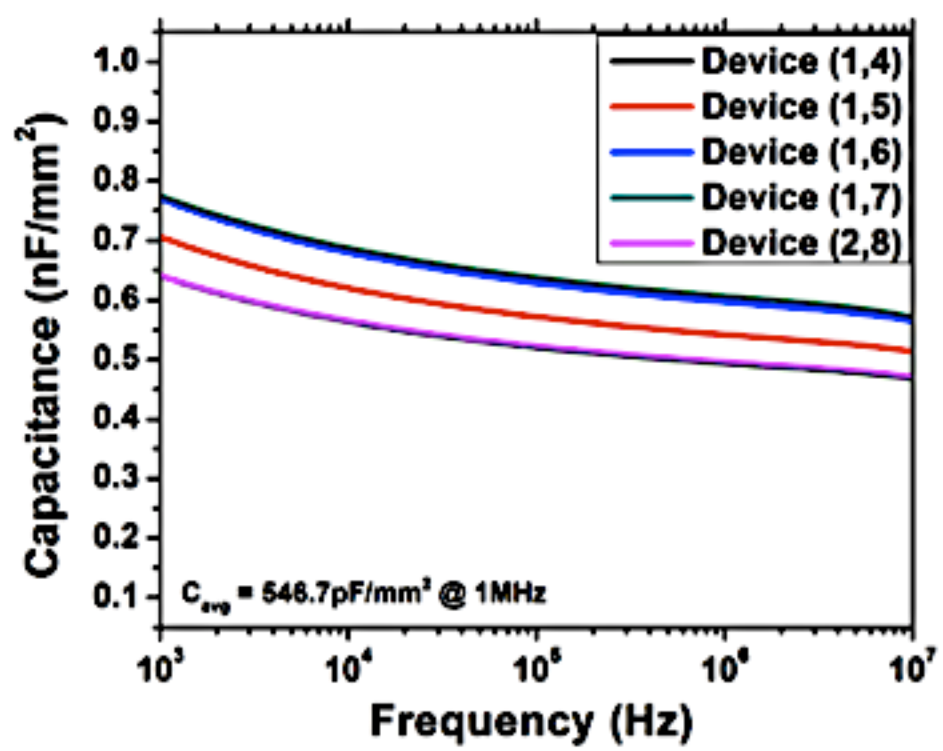
Early prototypes: Spin-coated BST with parylene capping layer

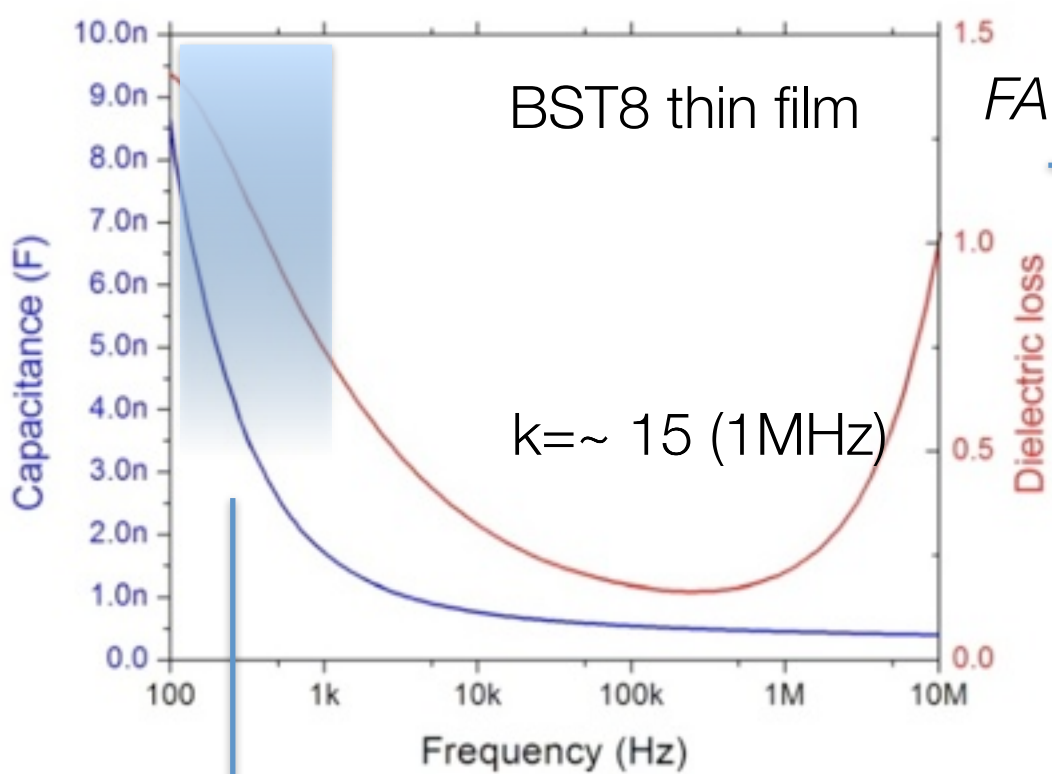




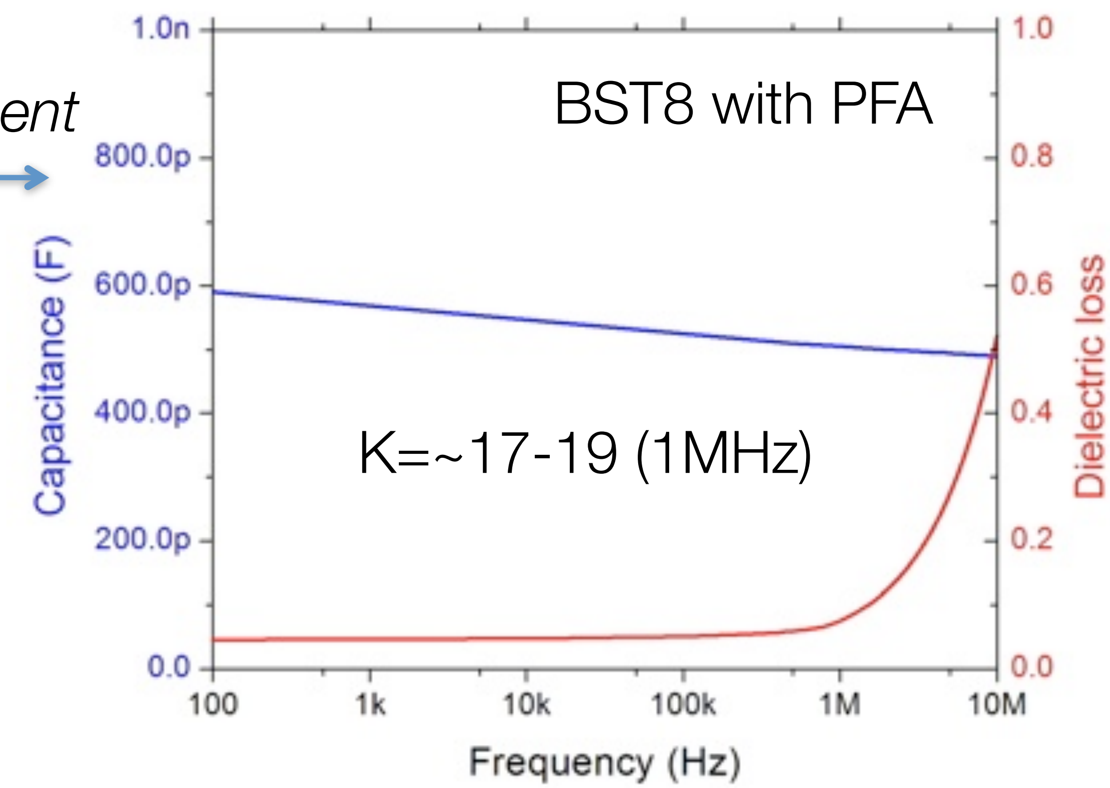


- Spin-coated nanoparticles on glass with thermally-evaporated Au electrodes
- CVD Parylene-C layer to reduce high-frequency loss
- Capacitance flat to 10 MHz, dissipation factor < 0.05 at 1 MHz
- Not roll-to-roll compatible, difficult to scale vertically

Dielectric properties improve with printable polyfurfuryl alcohol (PFA) copolymer



FA treatment

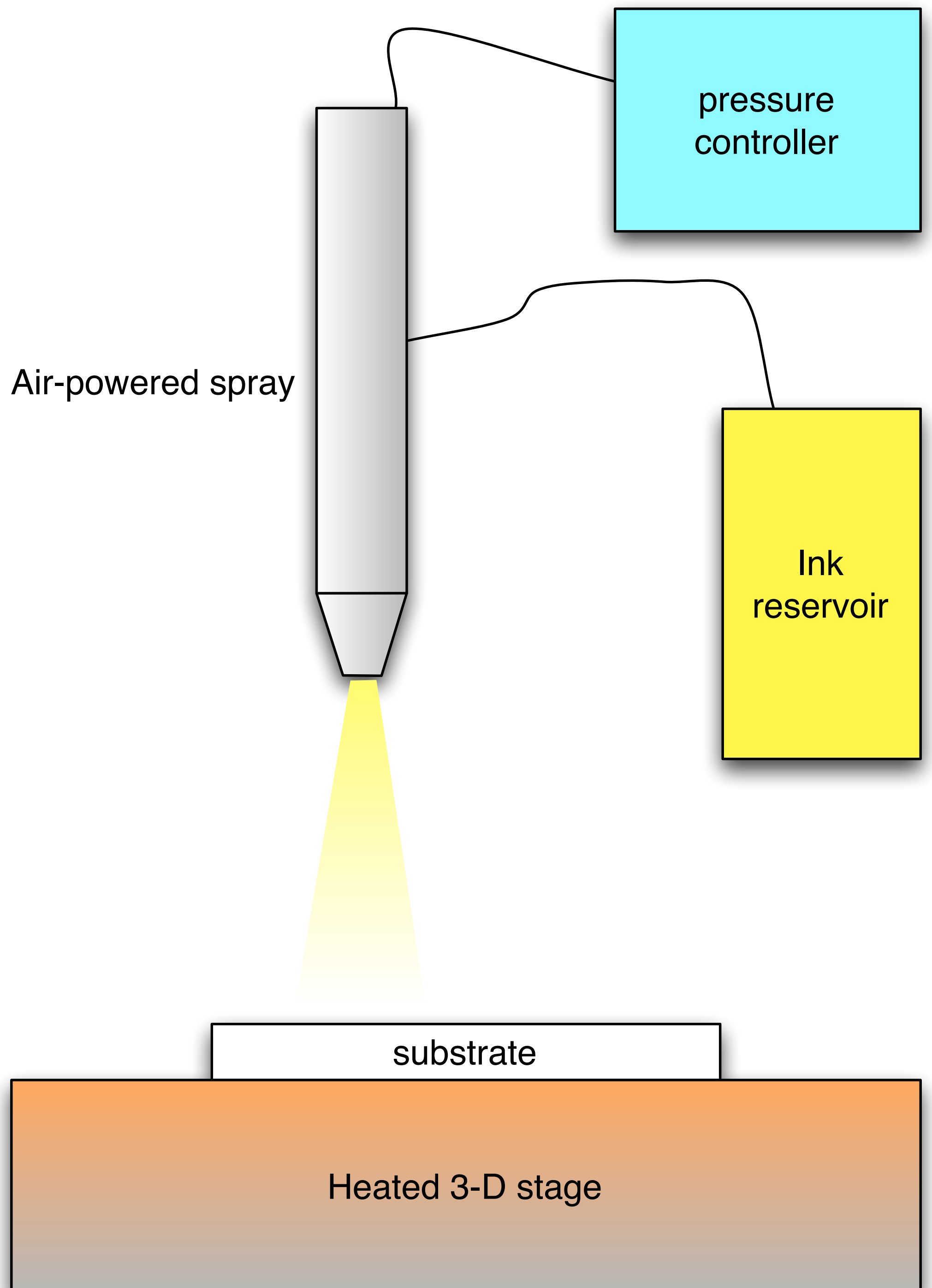


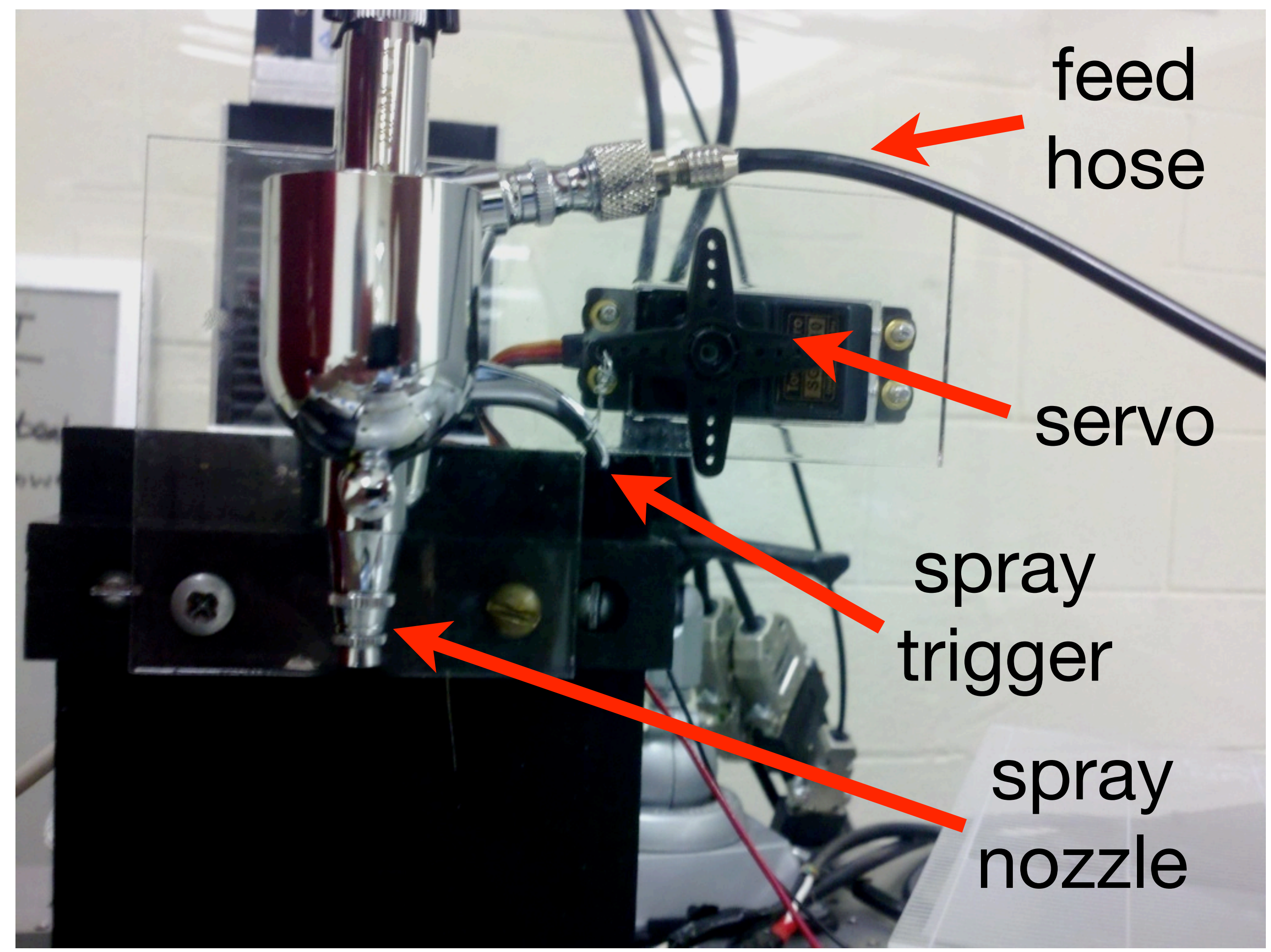
- Much higher capacitance and dielectric loss at low frequency (< 1kHz) due to leakage current (carriers, defects, pinholes)
- Dramatic change in capacitance and dielectric loss with frequency due to different contributions from space charges or water molecules at various frequencies.

With in-situ polymerization, nanocrystal surface passivated, defects or pinholes reduced, fewer absorbents:

- stable and increased readings in capacitance;
- low and stable readings in dielectric loss;
- increase of k compared with that for pure BST: indicating that FA and PFA penetrate into voids.

Spray coating for scalability





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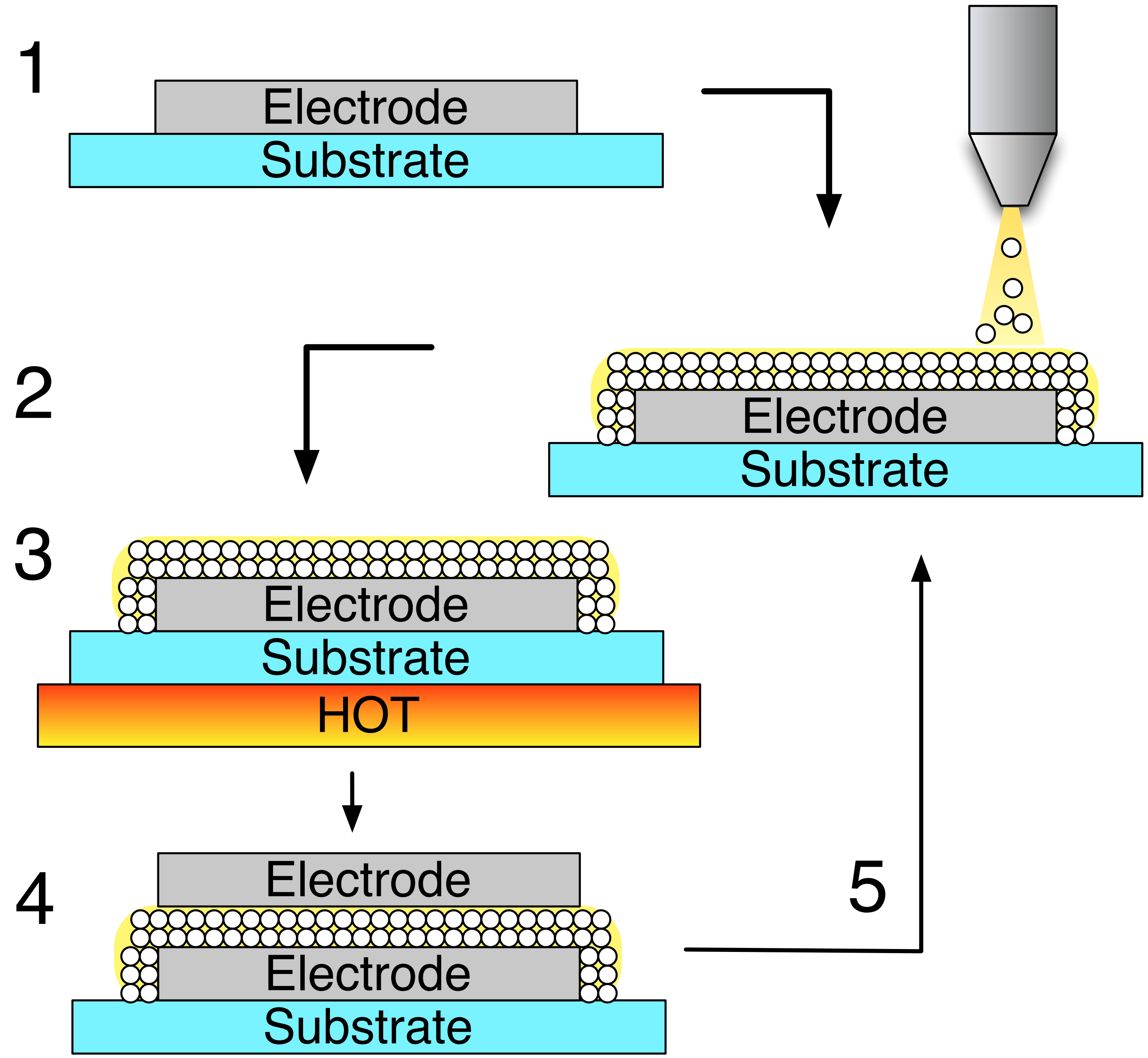
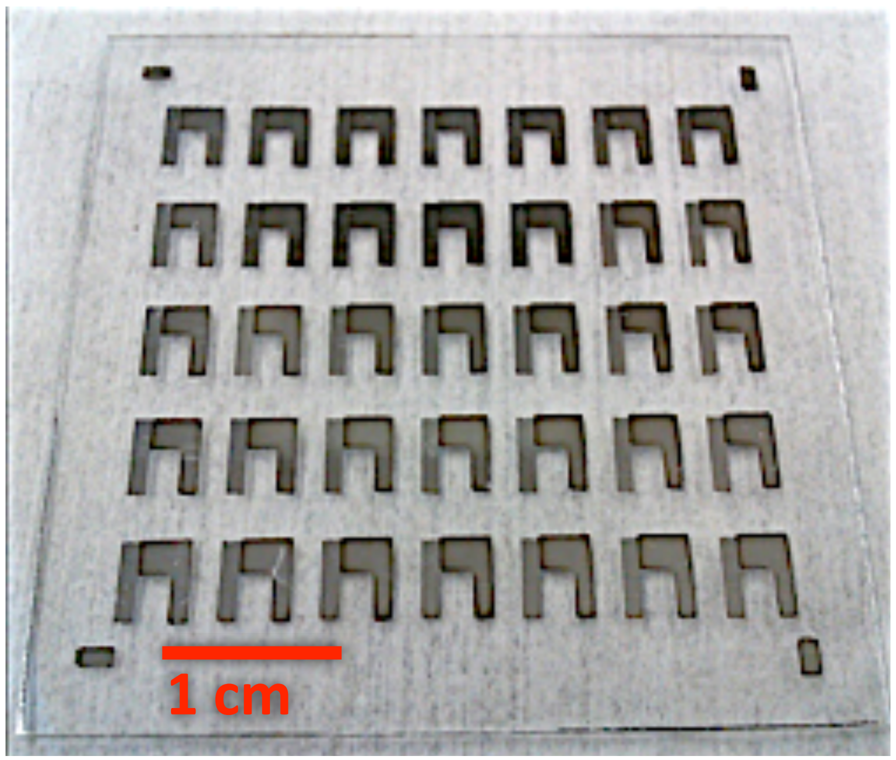
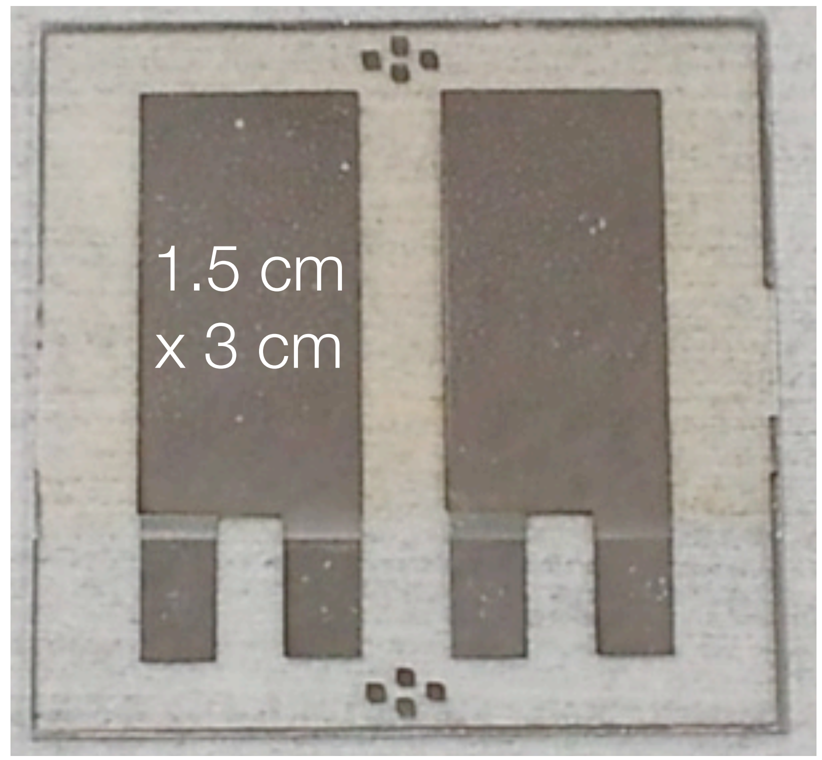
Spray coating process

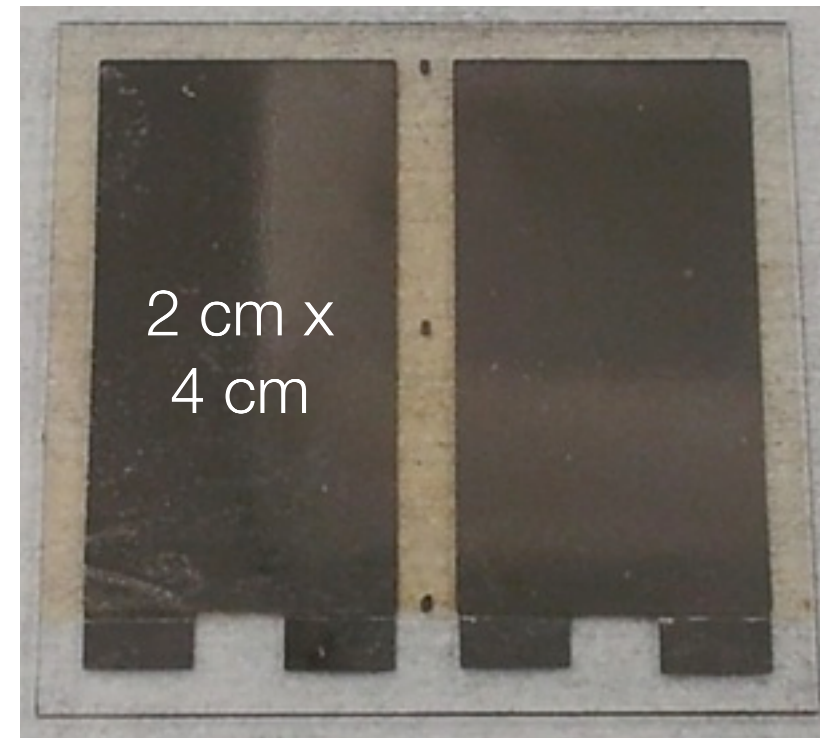
1. Deposit evaporated aluminum electrode
2. Print dielectric layer
3. Heat treatment
4. Deposit next electrode layer
5. Repeat to build multilayer structure



Scaling outward



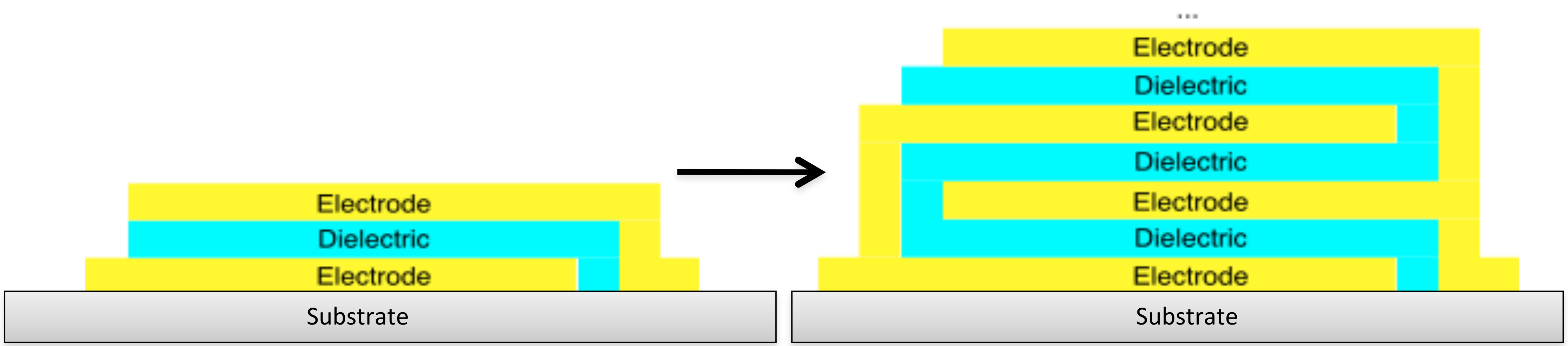




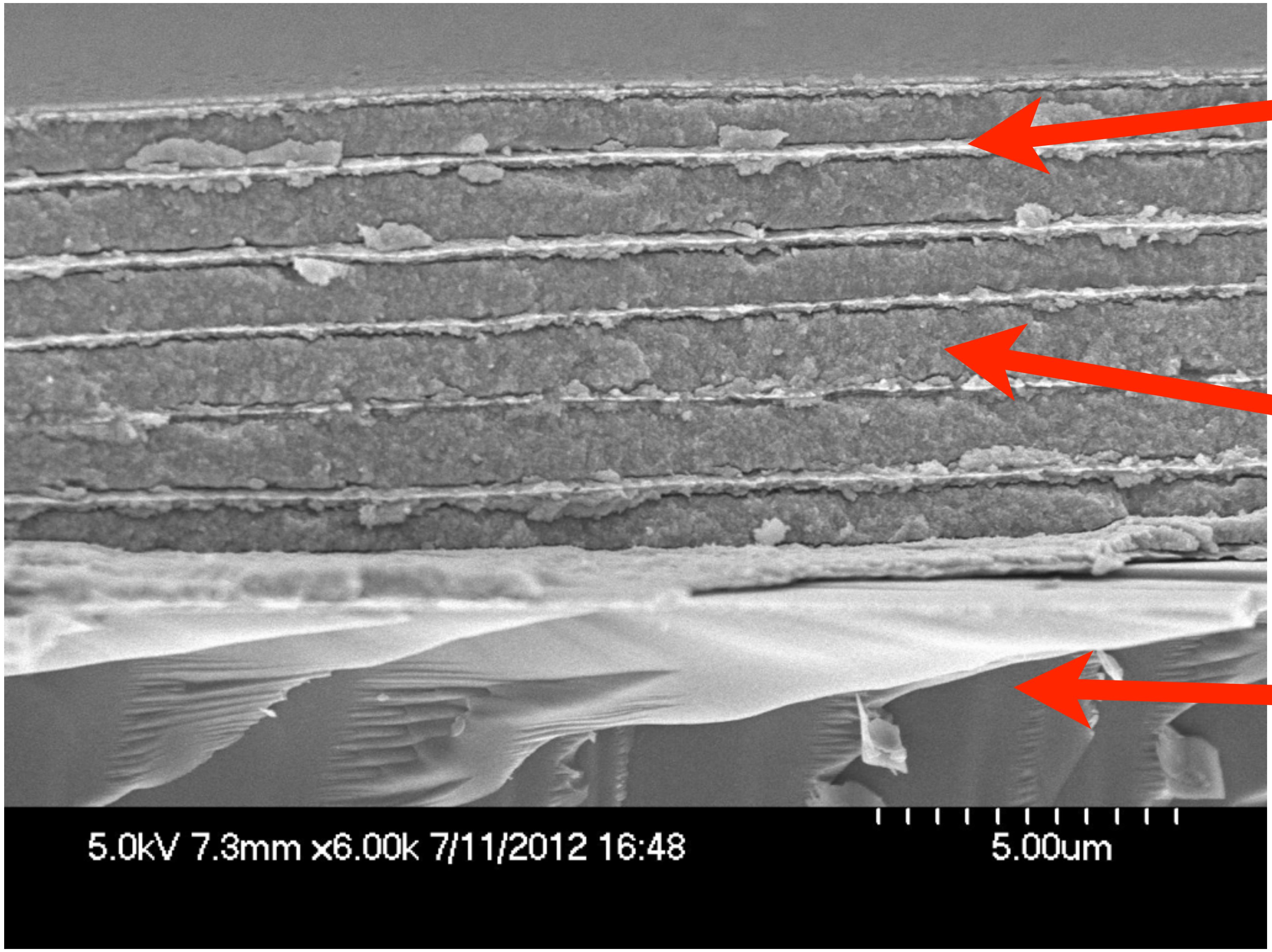
Mid 2011	Late 2011	Mid 2012
4 mm^2	450 mm^2	800 mm^2
2 nF (4 layers)	80 nF	180 nF

Scaling upward

Alternate electrode and dielectric layers, forming interleaved, multilayer capacitor structures



Spray-coated 6-layer capacitor

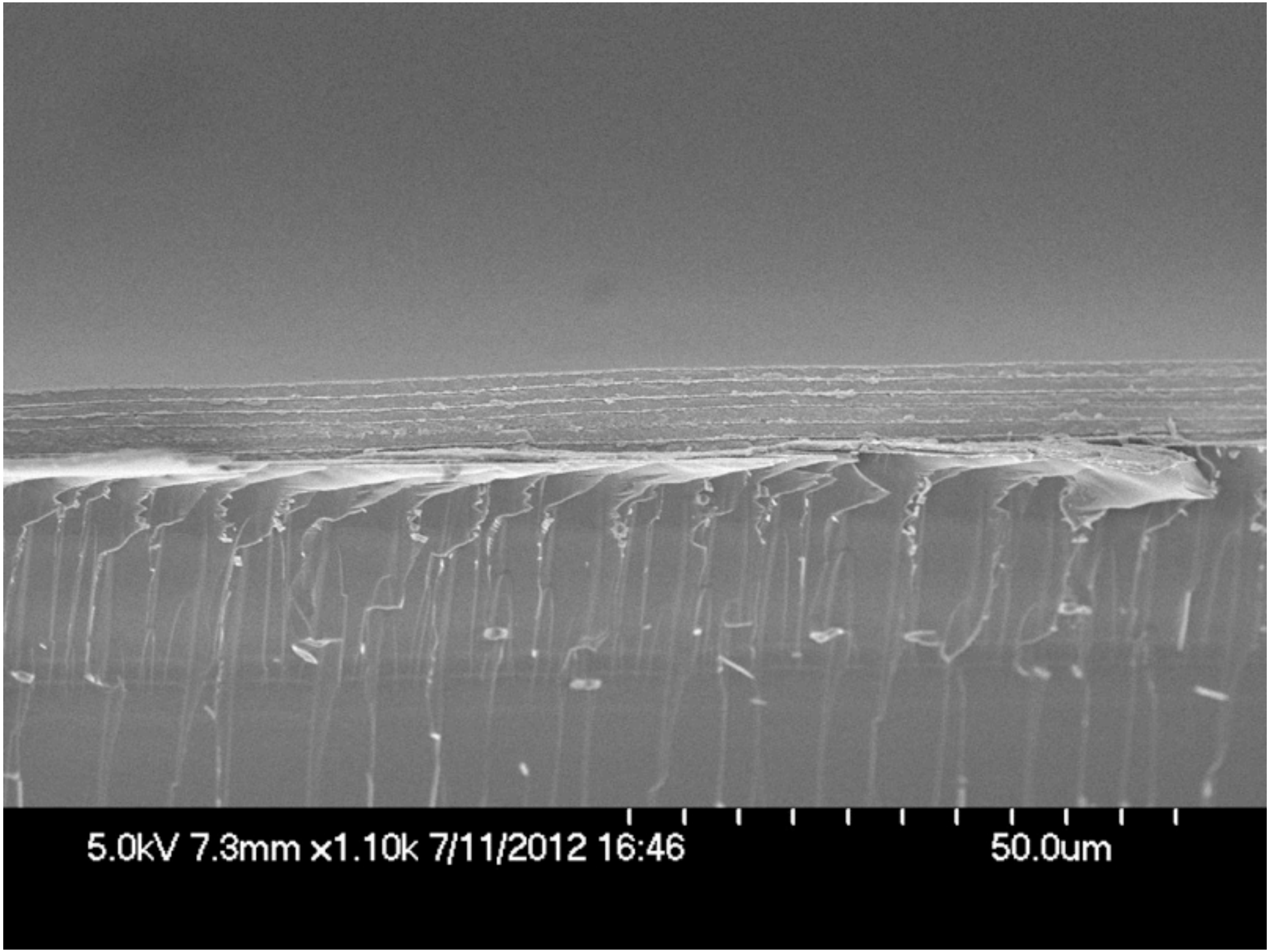


evaporated aluminum electrode

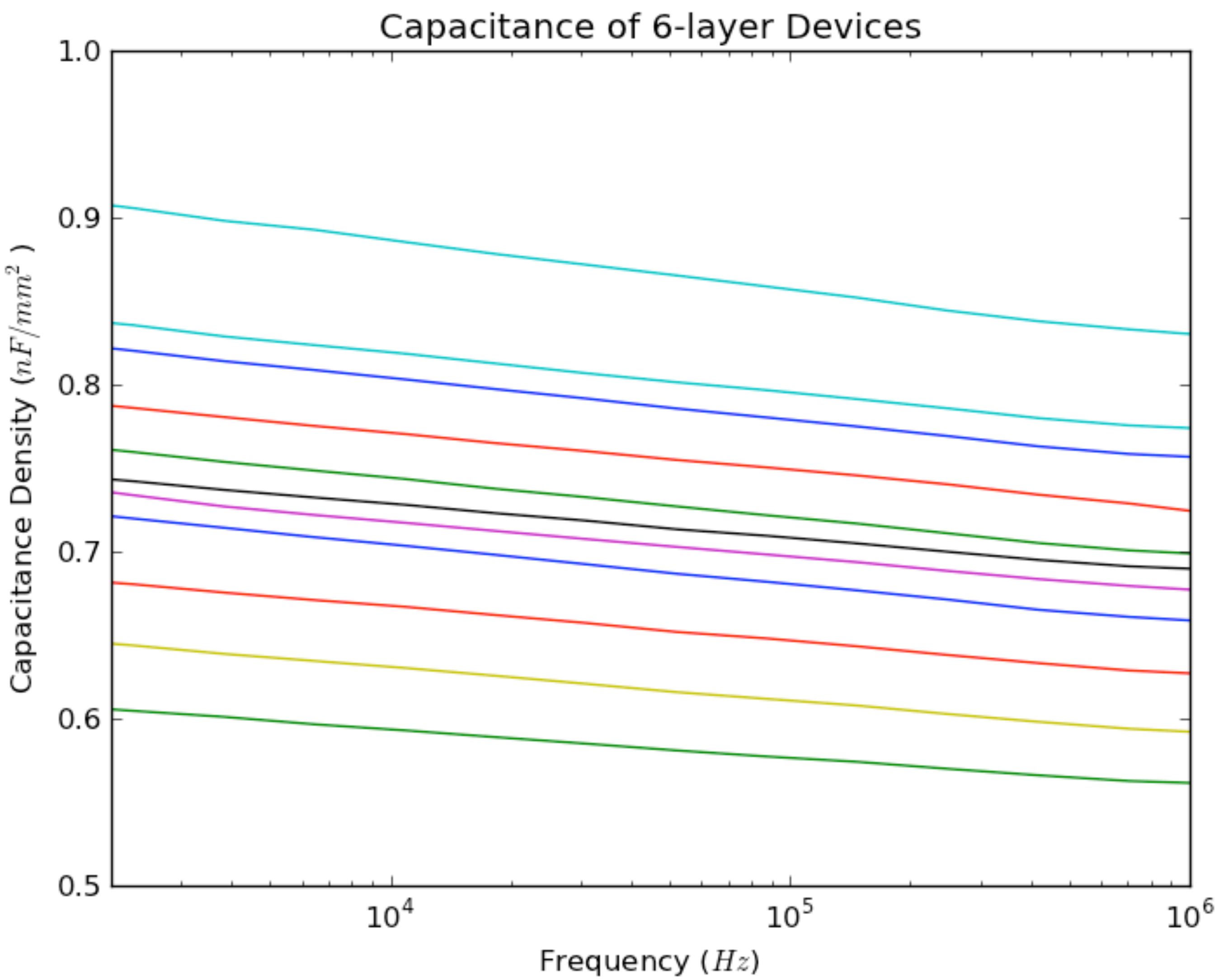
spray-printed dielectric

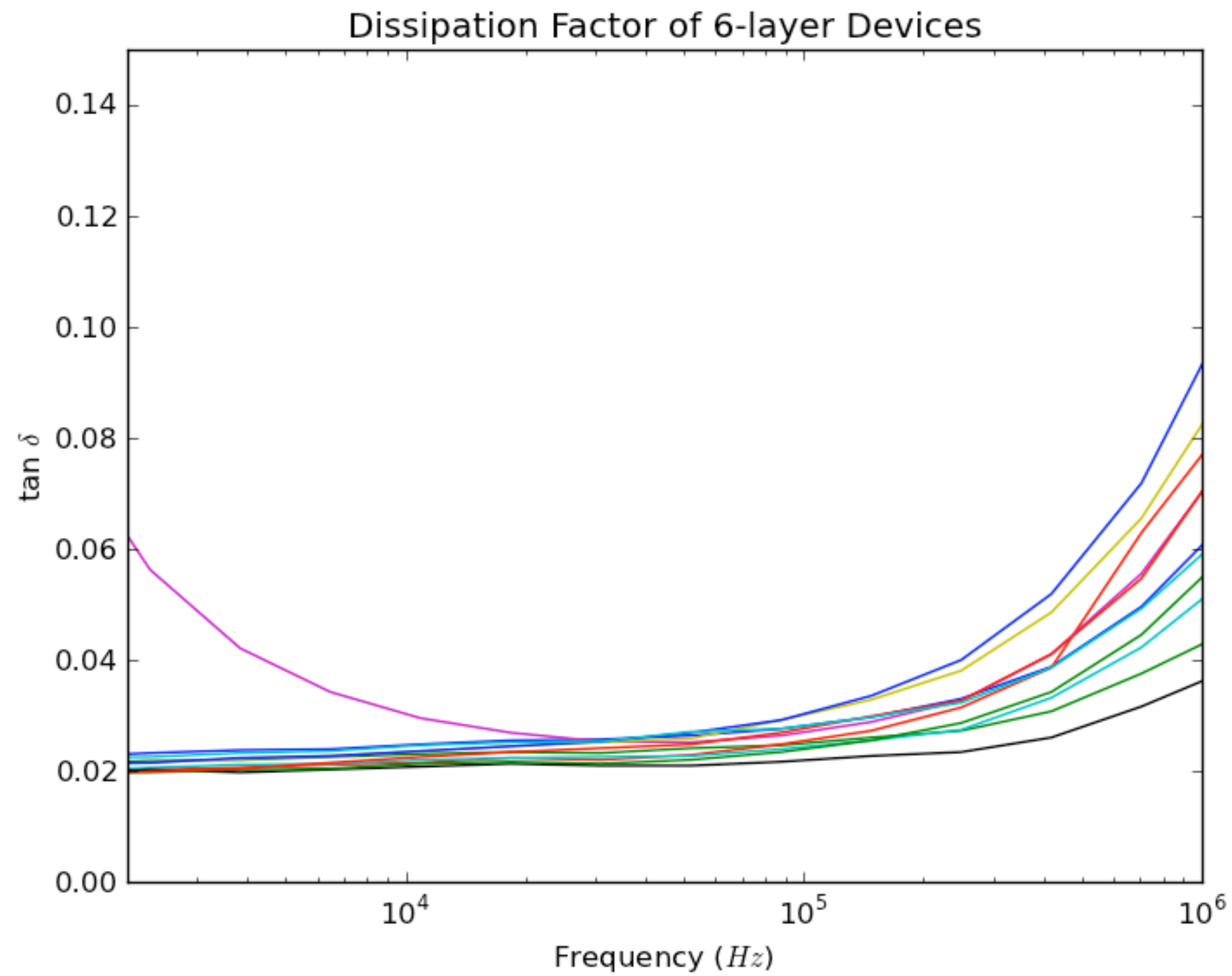
glass substrate

Wide-area dielectric films by spray printing



6-Layer capacitor performance





- Capacitance density = 0.75 nF/mm^2, k ~ 15
- Dissipation factor = 0.06 at 1 MHz
- Leakage current = 1 nA/mm^2 at 40 V

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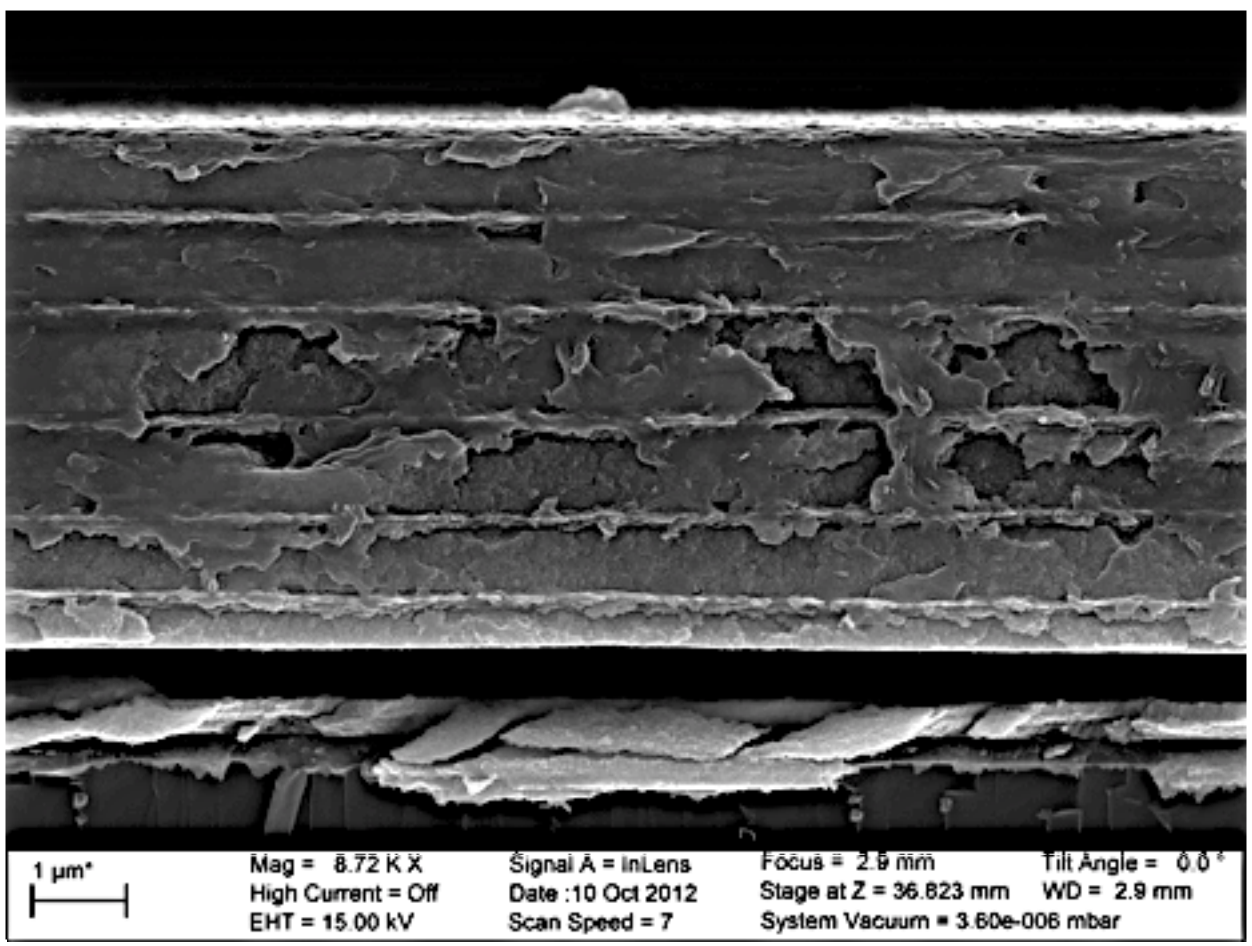
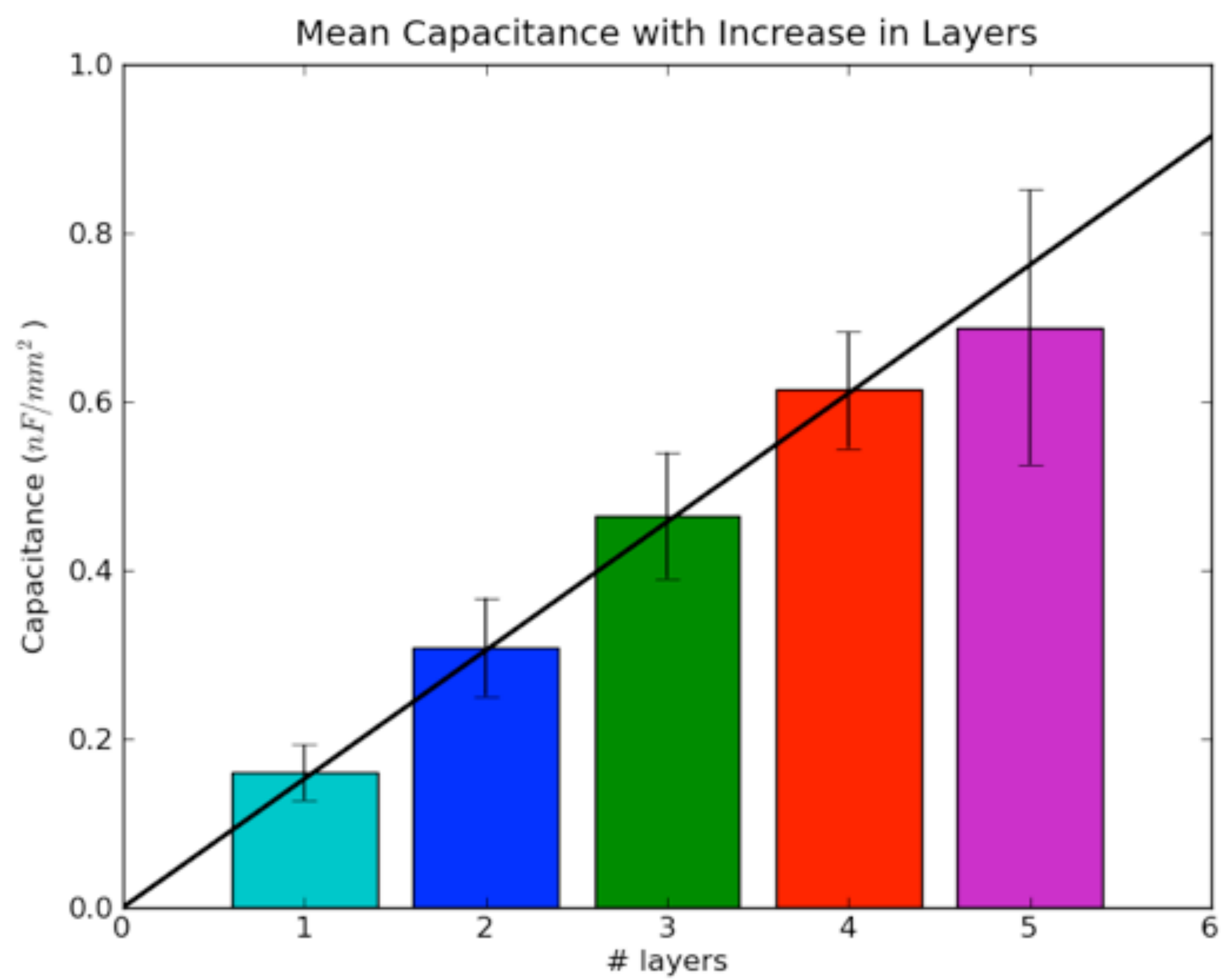
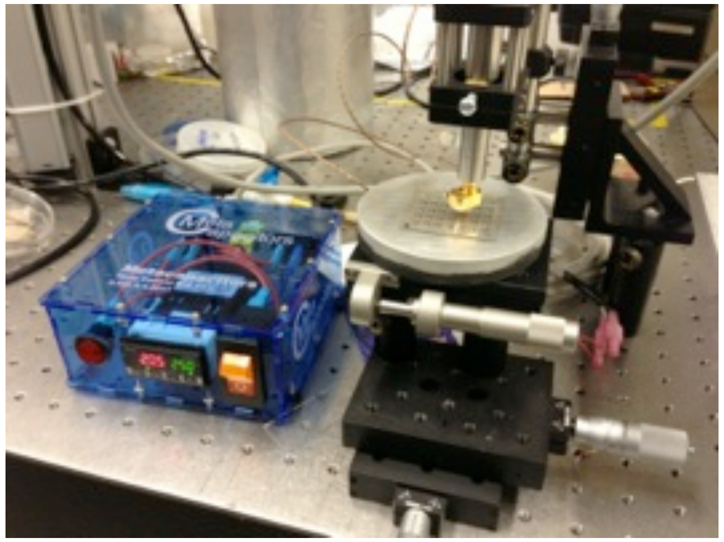
Increasing capacitance layer-by-layer



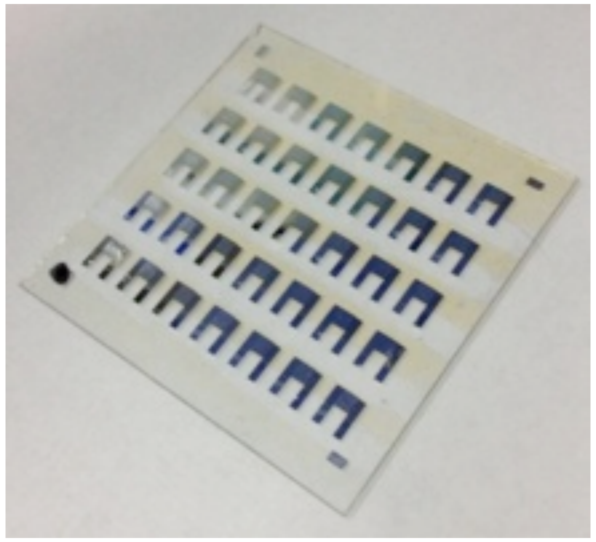


Temperature stability

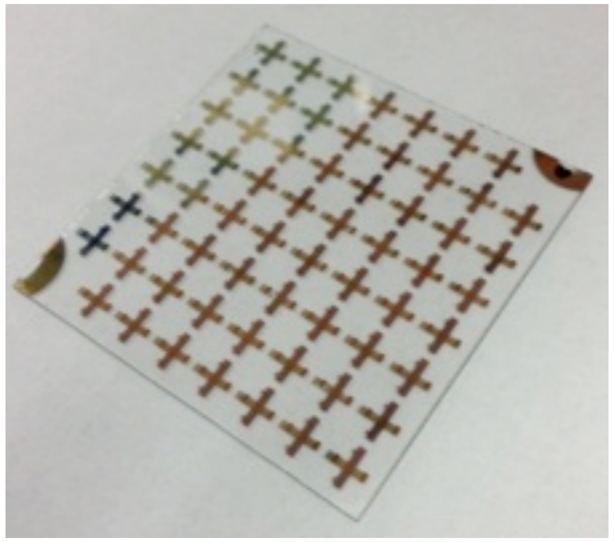
Setup for elevated temperature test



Spay coated sample



Spin coated sample



Temperature stability and age test of spin and spray coated Metacapacitor prototypes

Metrics	*Age test part I (100 hour @125°C)	*Age test part II (1000 hour @125°C)	*Elevated temperature test (25 to 125 °C)
Milestone	< 30 % Δ in capacitance	< 30 % Δ in capacitance	-
Spin coated 1 mm^2 capacitor	6 % Δ	< 1 % Δ	6.5 % Δ
Spray coated 4 mm^2 capacitor	17 % Δ	< 1 % Δ	2.5 % Δ

- All capacitance are measured at 1 MHz
- Age test part 1 and part 2 are continuous test with total of 1100 hours

* Compared to its initial capacitance value at 25C

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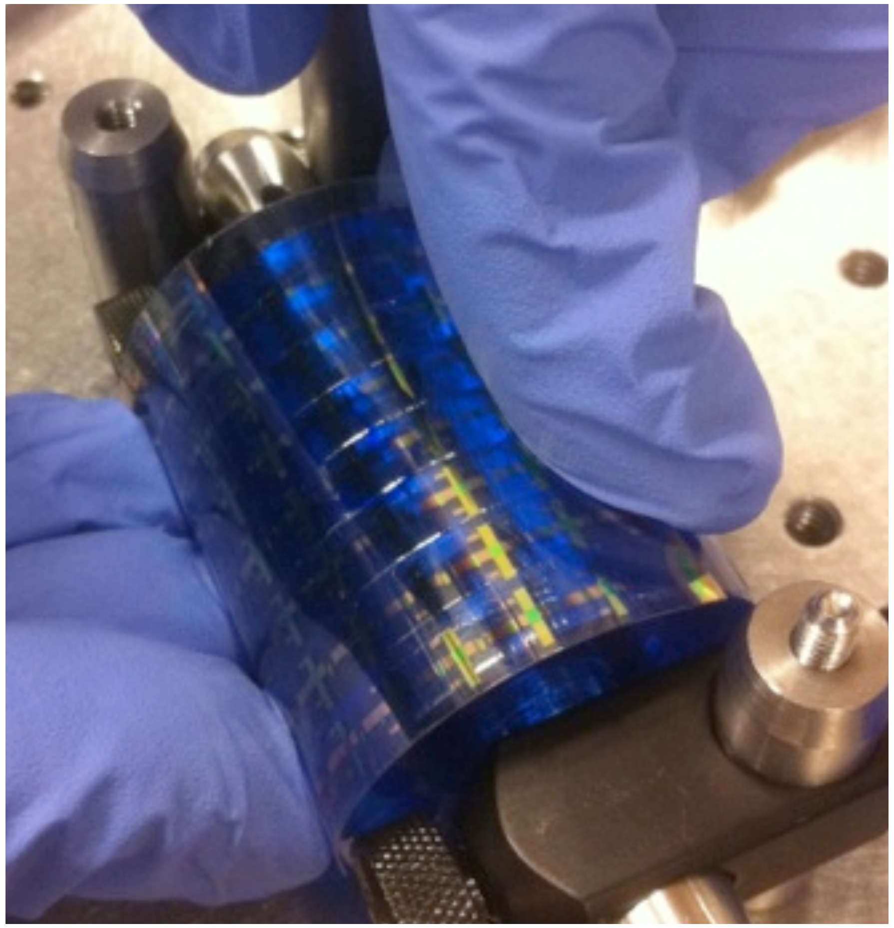
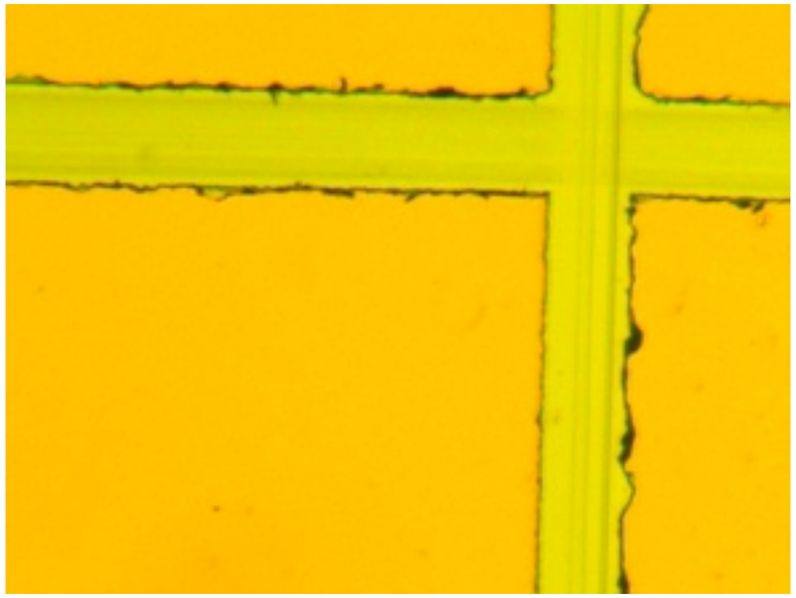
Mechanical testing

- 2 cm radius bending test with no degradation in performance
- Tape test shows excellent adhesion



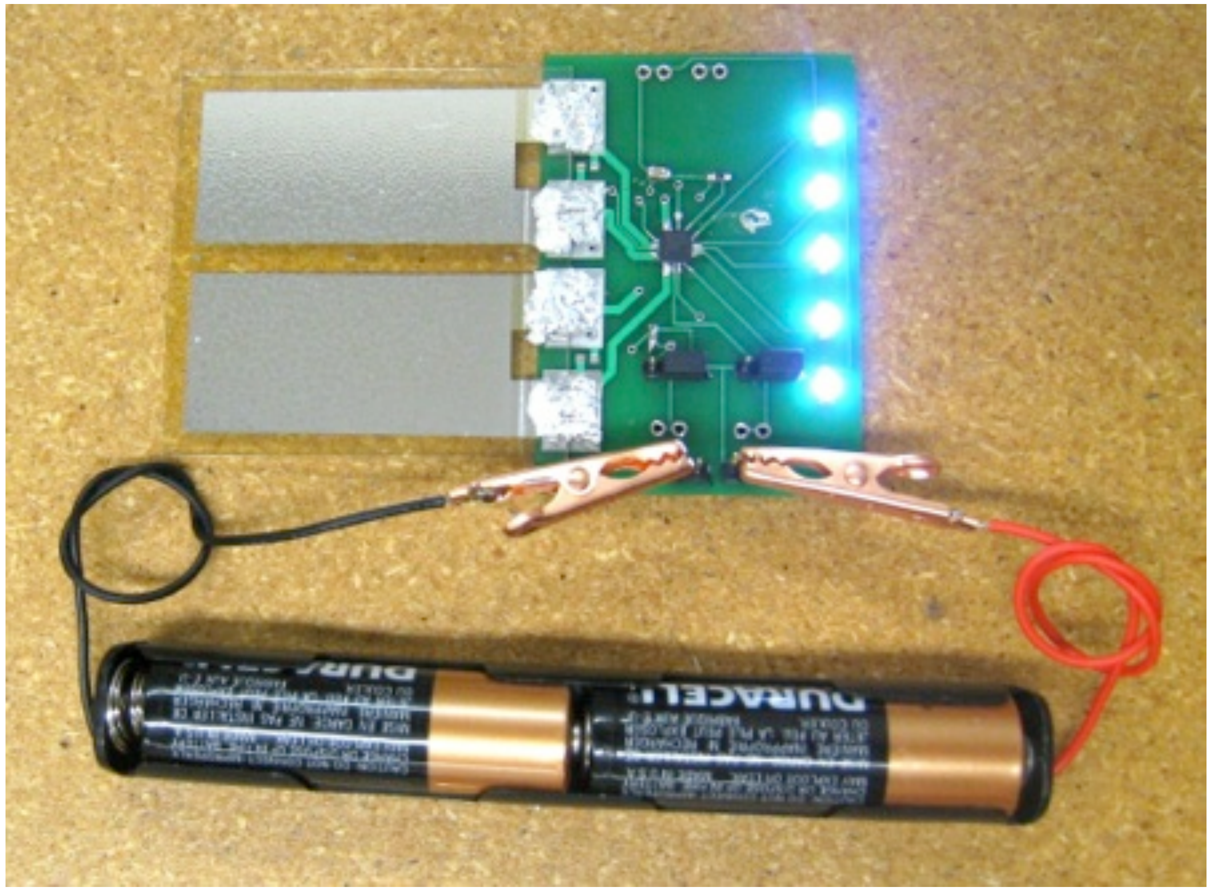
Before Tape Test

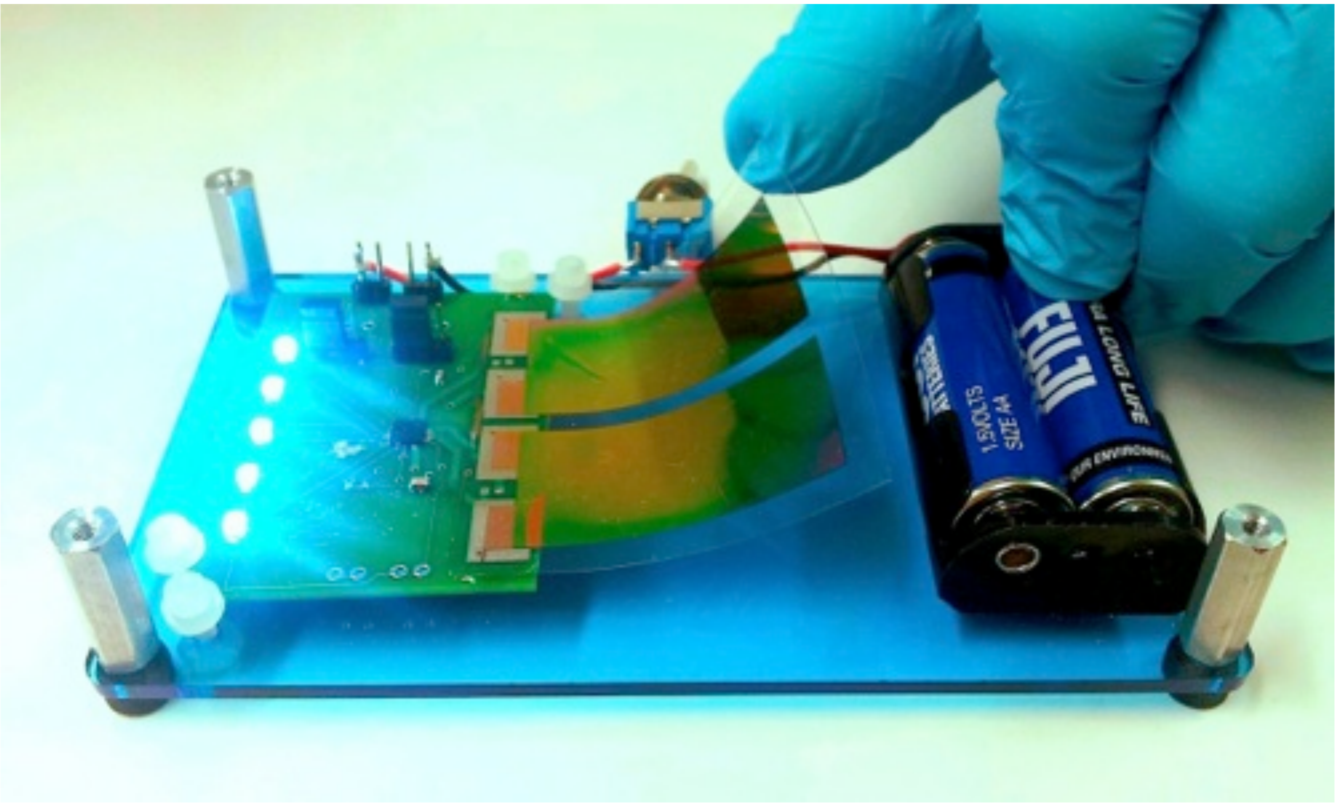
After Tape Test



Integration to a power circuit

Metacapacitors in a 1 MHz LED driver regulator circuit





- Spray-coated caps on glass
- Spin-coated caps on flex

Thanks!

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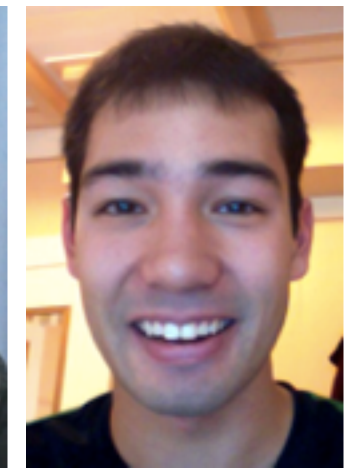

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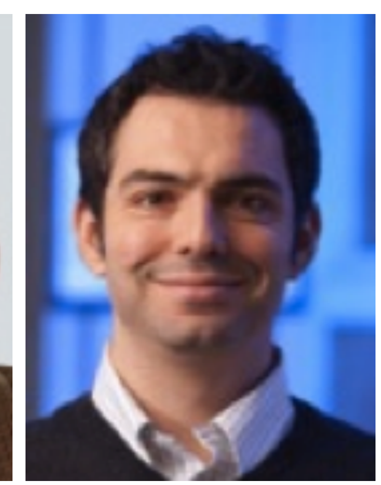

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backup

Moving forward

- Integrating spray-coating process on flexible substrates
- Testing custom power IC with printed capacitors
- Integrated LED driver prototype on flex!

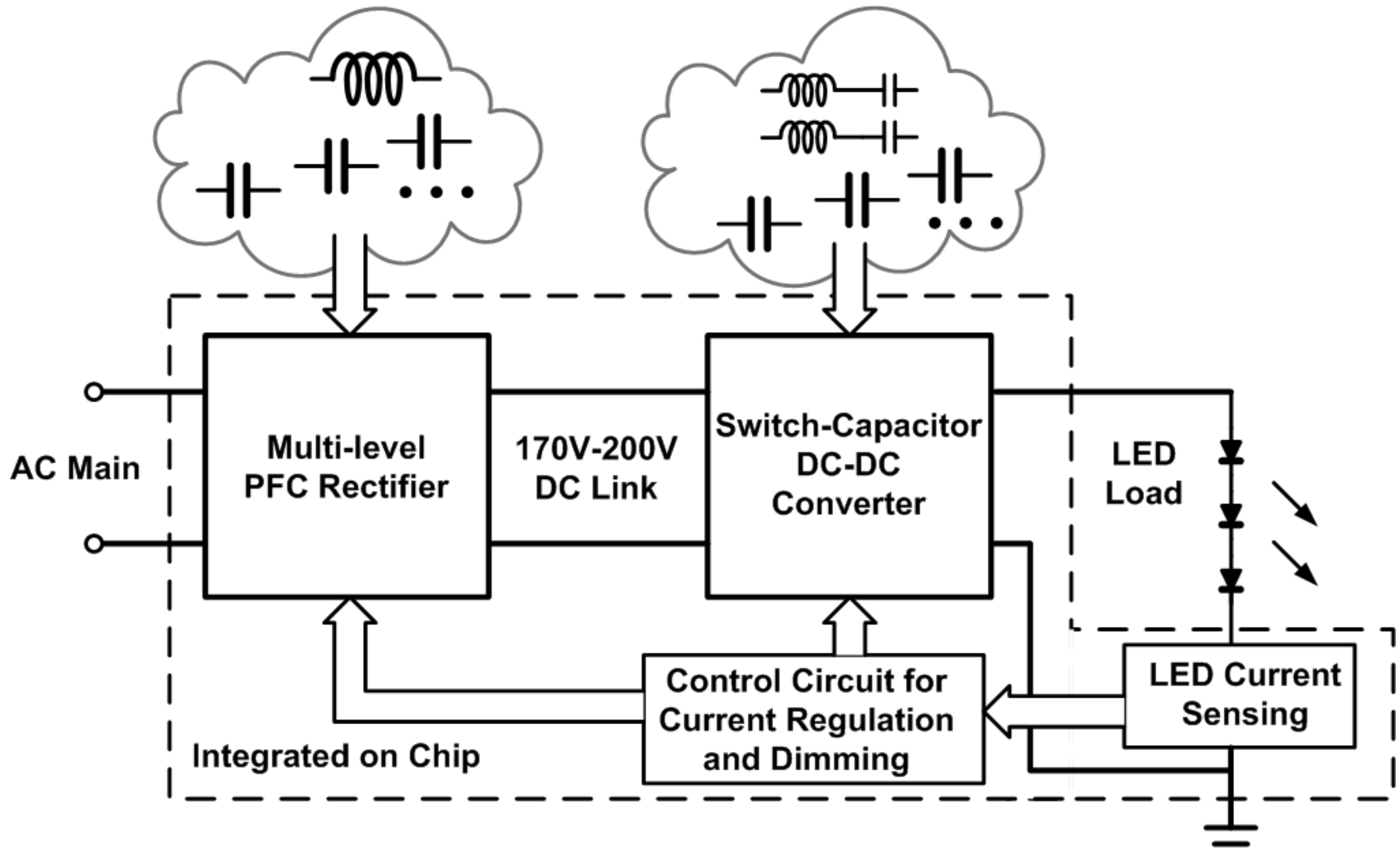
Why capacitors instead of inductors?

Type	Manufacturer	Capacitance, Voltage rating	Dimensions (mm)	Energy density ($\mu J/mm^3$)
Ceramic Cap	Taiyo-Yuden	22μF @4V	1.6 x 0.8 x 0.8	**172**
Ceramic Cap	Taiyo-Yuden	1μF@35V	1.6 x 0.8 x 0.8	**598**
Tantalum Cap	Vishay	10μF@4V	1.0 x 0.5 x 0.6	**267**
Tantalum Cap	Vishay	100μF@6.3V	2.4 x 1.45 x 1.1	**518**
Electrolytic Cap	Kemet	22μF@16V	7.3 x 4.3 x 1.9	**47**
Electrolytic Cap	C.D.E	210mF@50V	76ϕ x 219	**264**
Shielded SMT Inductor	Coilcraft	10μH @ 0.21A	2.6 x 2.1 x 1.8	**0.022**
Shielded SMT Inductor	Coilcraft	100μH @ 0.1A	3.4 x 3.0 x 2.0	**0.025**
Shielded inductor	Coilcraft	170μH @ 1.0A	11 x 11 x 9.5	**0.074**
Shielded inductor	Murata	1 mH @ 2.4A	29.8ϕ x 21.8	**0.189**

>1000x

Capacitors have >1000x higher energy density than inductors for power handling applications

Metacapacitors™
High-level LED driver architecture



- Output regulation is accomplished using frequency modulation of switching converter

Update on materials synthesis

Scalable, low T “gel-rod” method for BST and novel Oxides

precursor gel

r. t. --55^{o}C

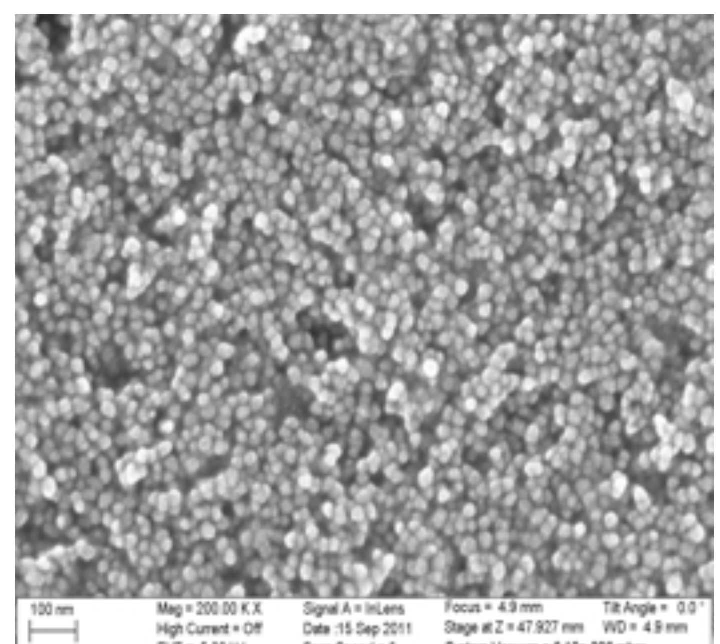
BST nanocrystal gel rod

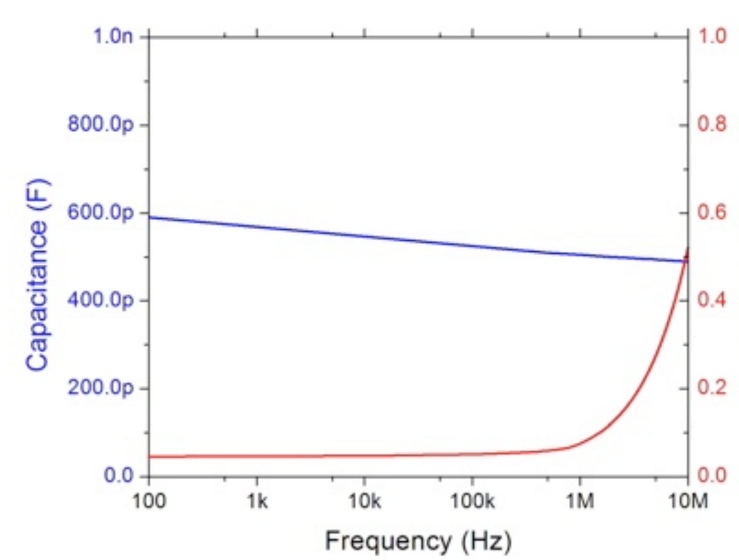
sonication with various solvents

BST/ethanol 40 mg/ml

BST/furfural alcohol 50 mg/ml

The method is being used for all BST experiments, multilayers and for development of new oxides with potentially higher dielectric constant





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