VOLTAGE AND FREQUENCY DEPENDENCE OF MLCCS

Dr. René Kalbitz

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

BIOGRAPHY / CONTACT DETAILS

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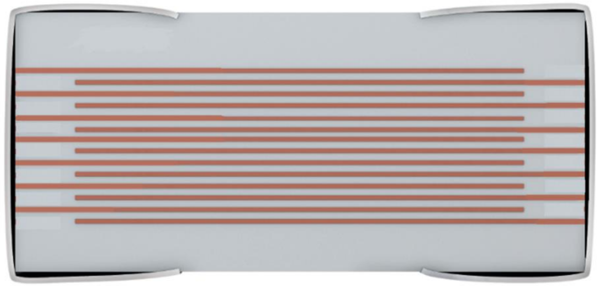
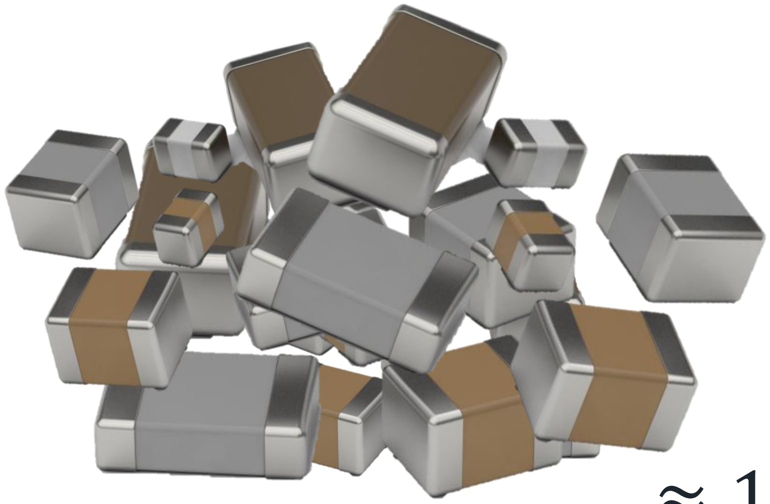
Background:

- Experience in
  - application-oriented research
  - development of organic electronics,
  - polymer analysis
- Responsible for Supercapacitors

MOTIVATION





Multilayer ceramic capacitors (MLCC) most common capacitor

Different classes, defined by material, capacitance/volume, thermal stability

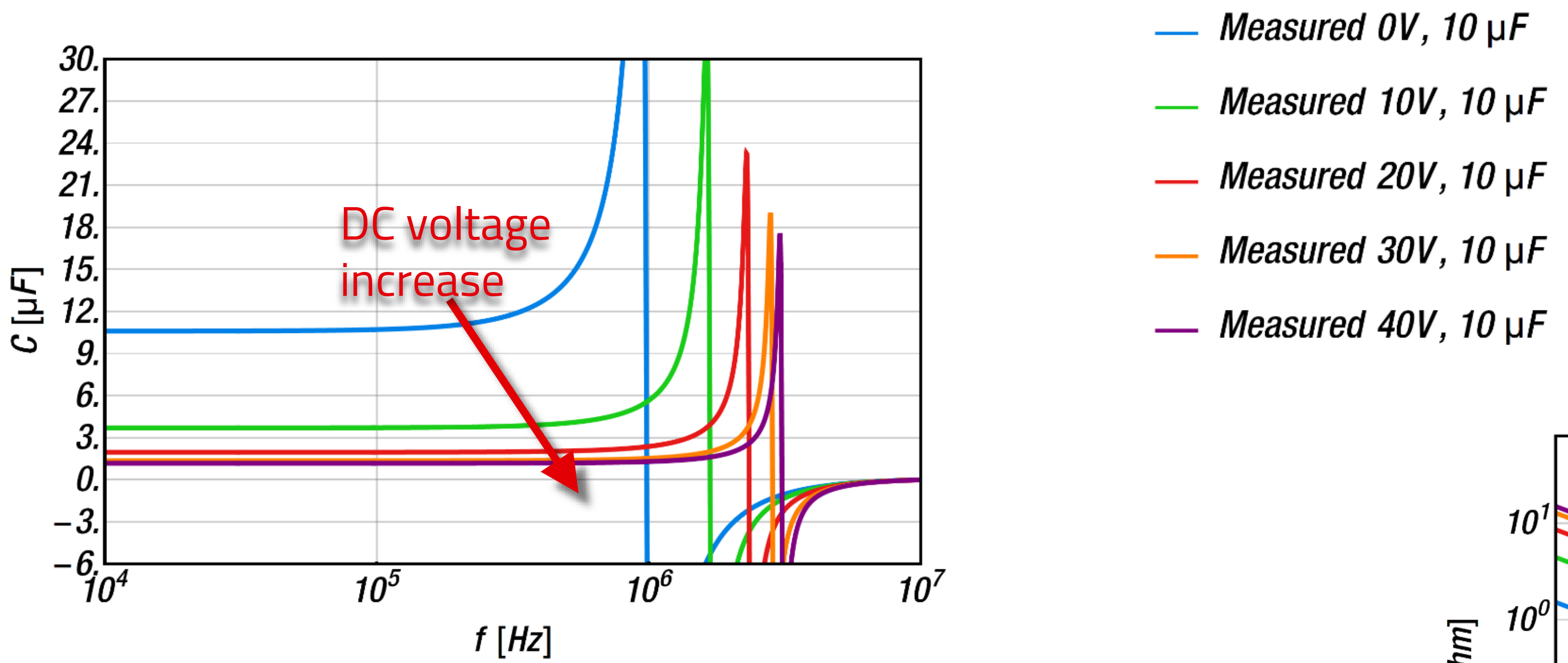
Most prominent: Class 2 Capacitors

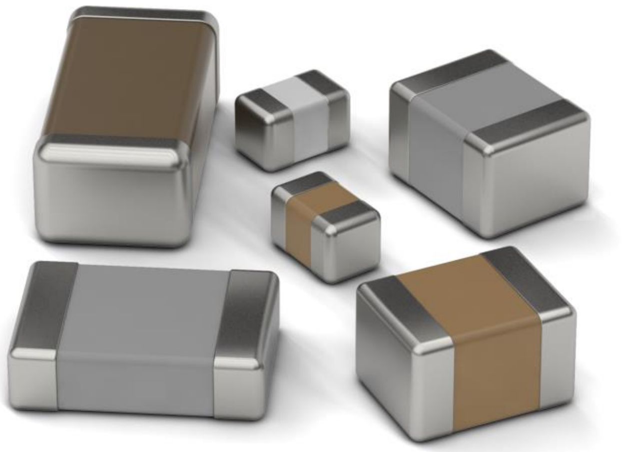
high volumetric capacitance

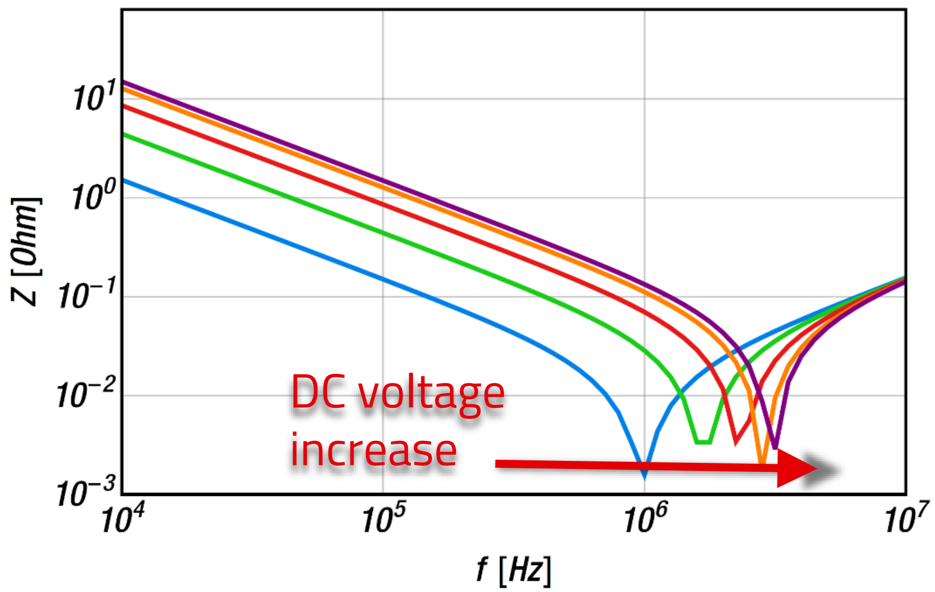
buffer, and coupling applications

$\approx$ 1000 part numbers at WE

MOTIVATION







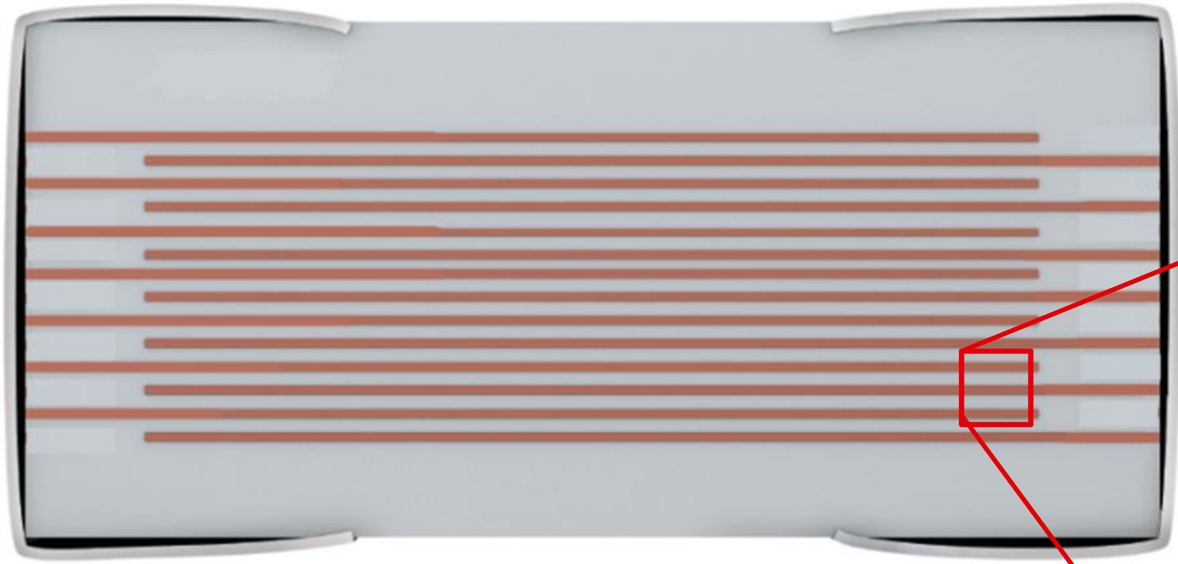
Class 2 ceramic capacitors have high permittivity,

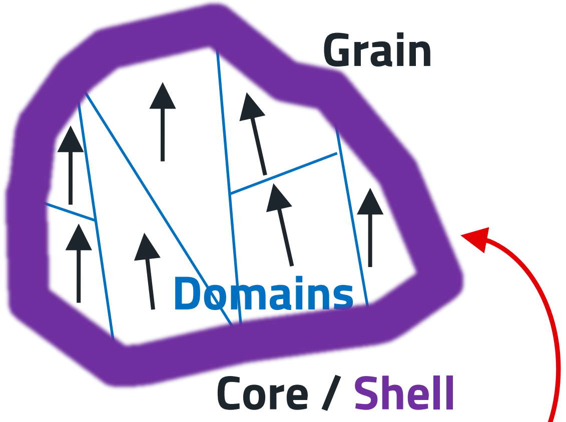
BUT… capacitance decreases with increasing DC Voltage

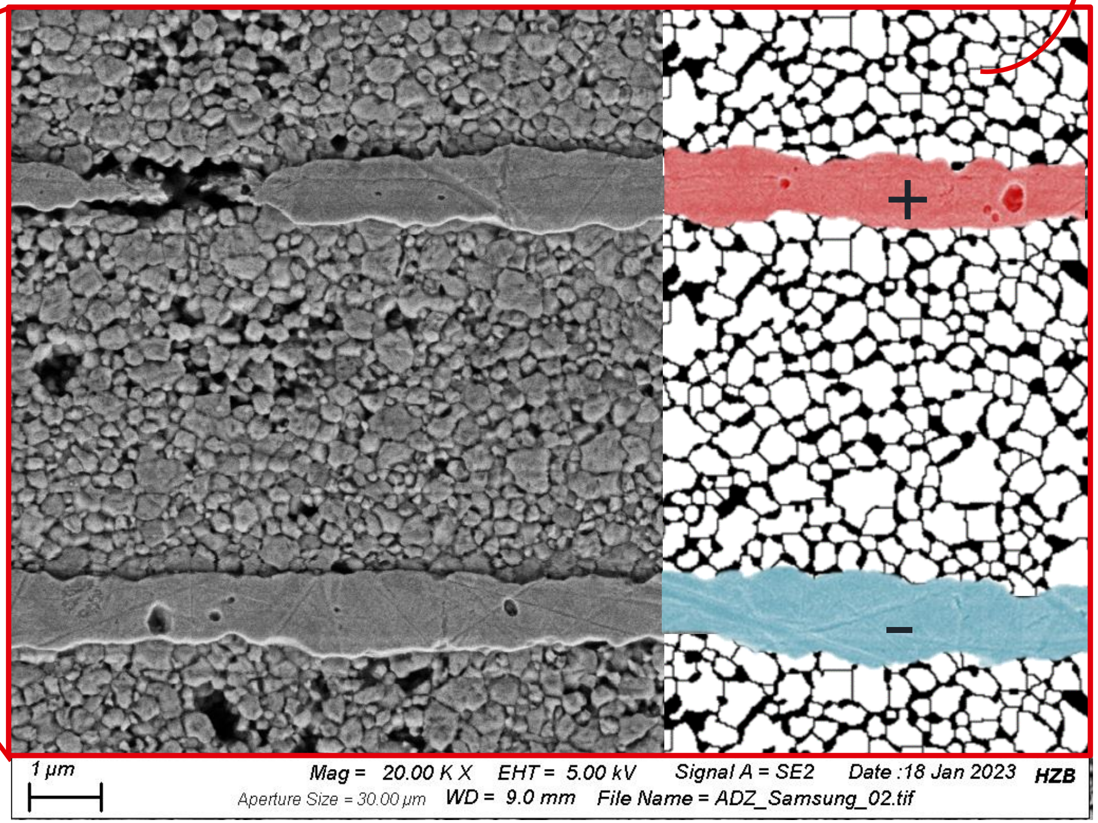
OUTLINE

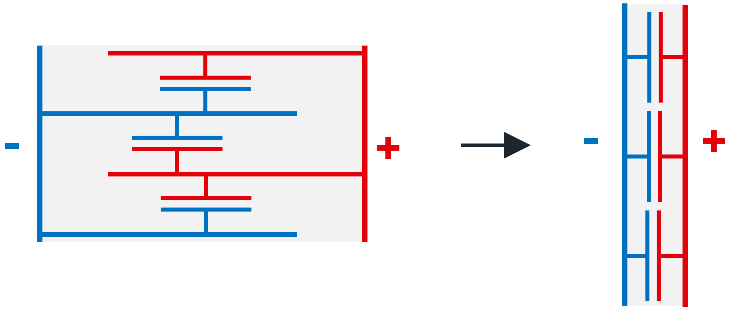
- Structure of MLCCs
- Material analysis of barium titanate
- Long- and short-term polarization
- Effect on capacitance, the memory effect
- Mathematical model of ferroelectric polarization
- frequency and voltage-dependent model
- Implementation: LTSpice

MLCC STRUCTURE, PRINCIPLE



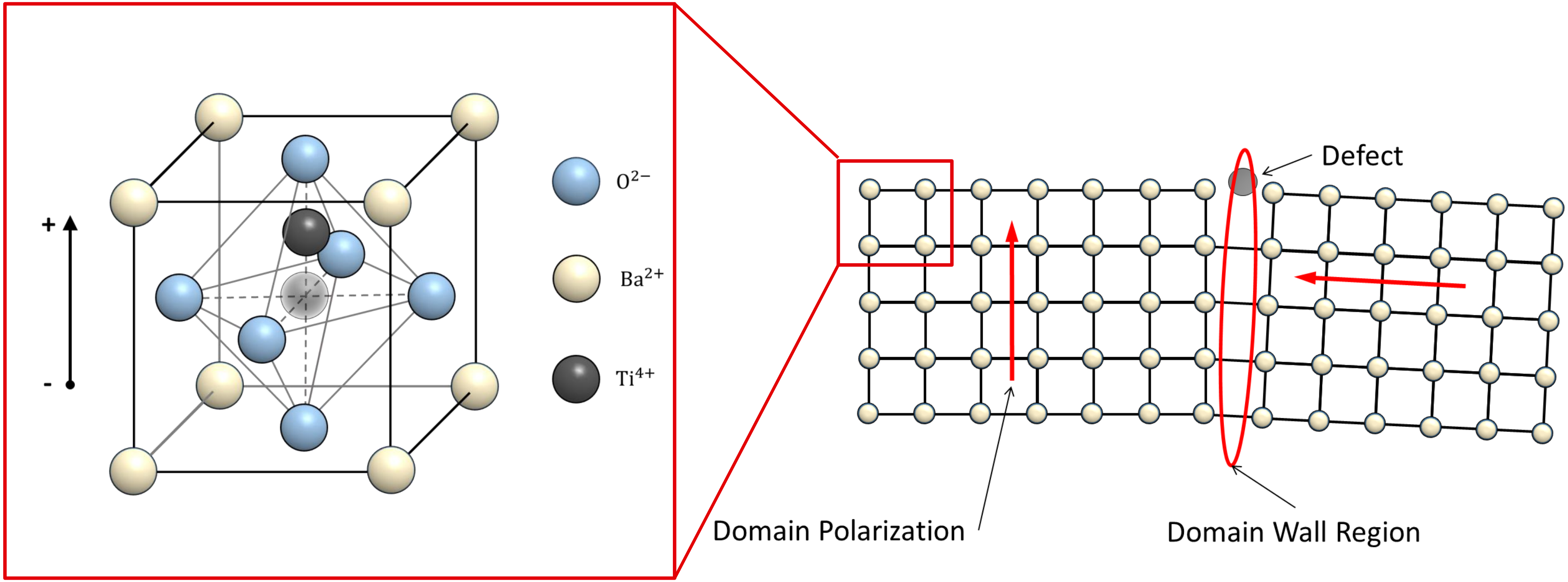






FERROELECTRICS

barium titanate, unit-cell



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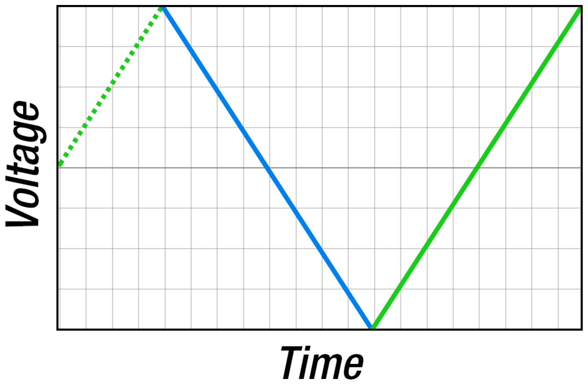
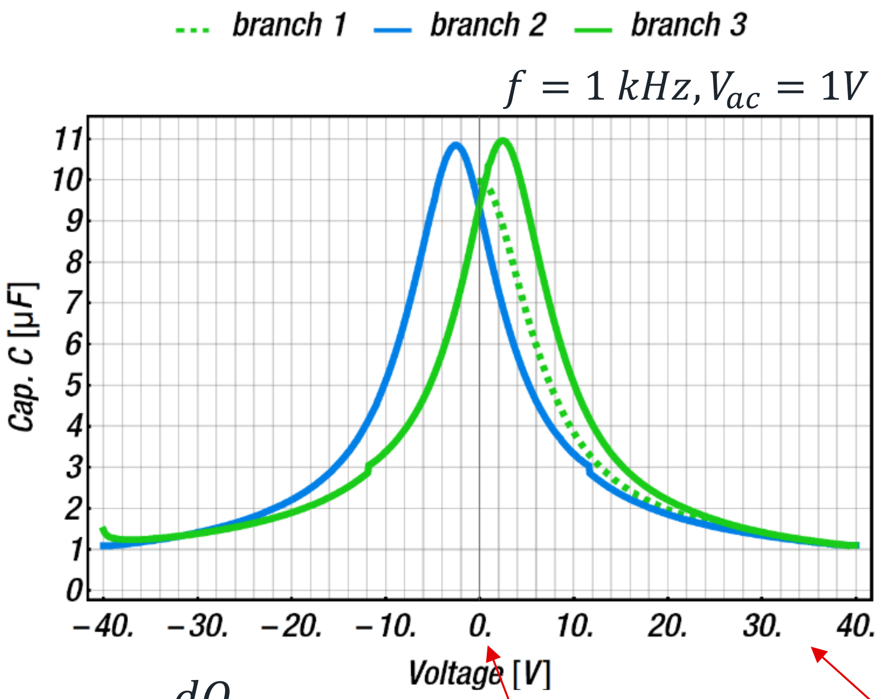
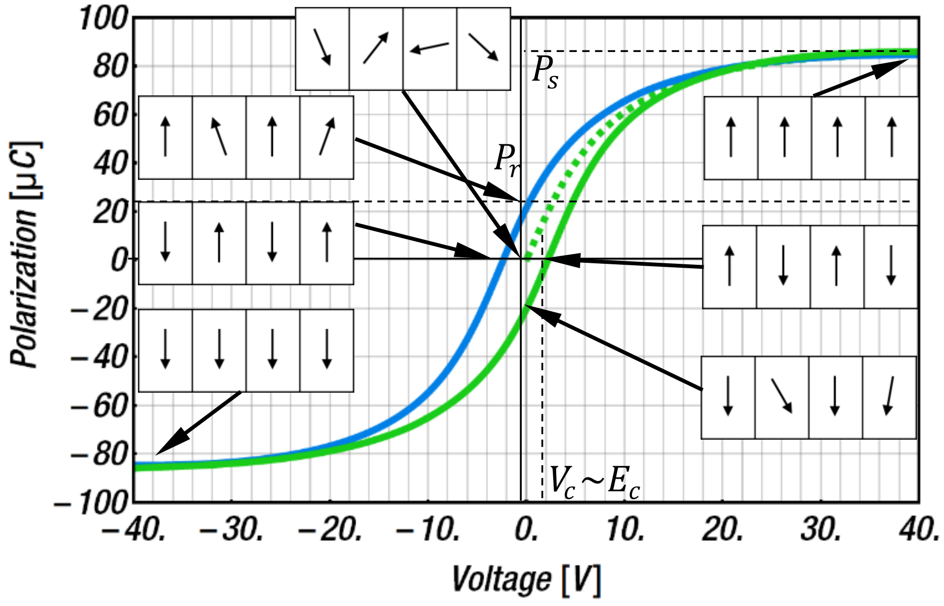
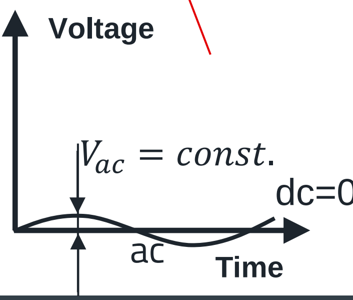
INTERPRETATION OF CAPACITANCE-VOLTAGE MEASUREMENTS

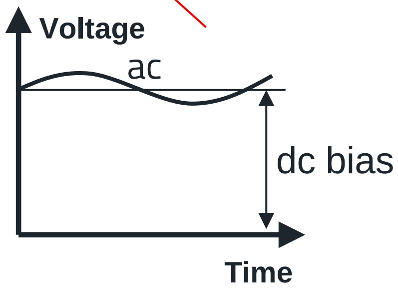






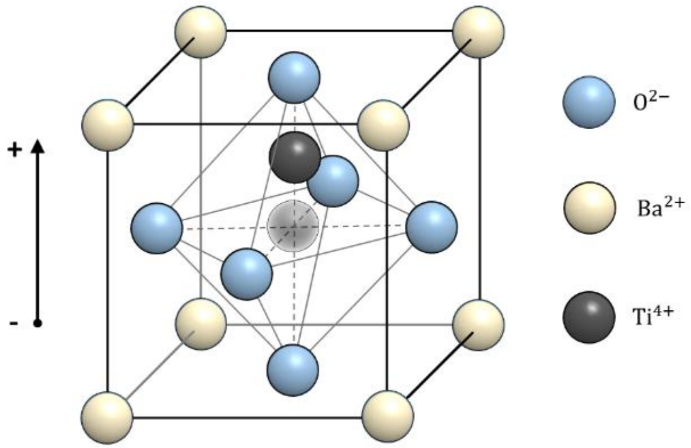
$$C = \frac{dQ}{dV}$$



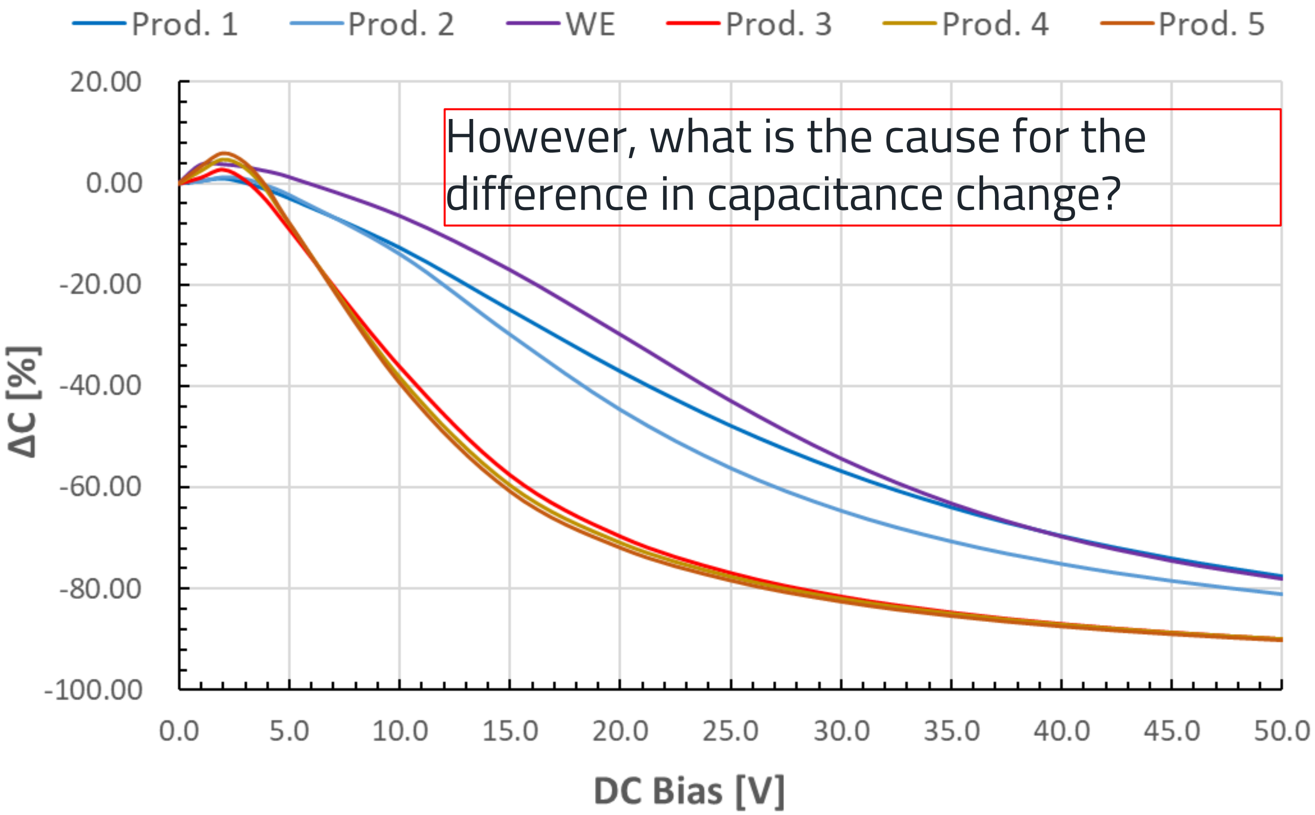


[13, ..., 19]

DC VOLTAGE EFFECT



$BaTiO_3$ based MLCCs show a capacitance dependence upon dc voltage. This is due to ferroelectric properties of $BaTiO_3$.



- Ceramic
  Class 2, X7R
- Capacitance
  10µF
- Rated Voltage
  50V
- Size Code
  1210

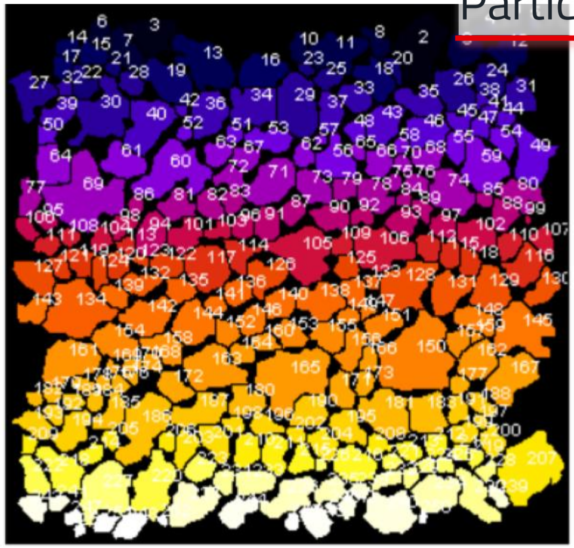
WE, PN: 885012209073

SEM-EDX IMAGE AND ELEMENTAL ANALYSIS

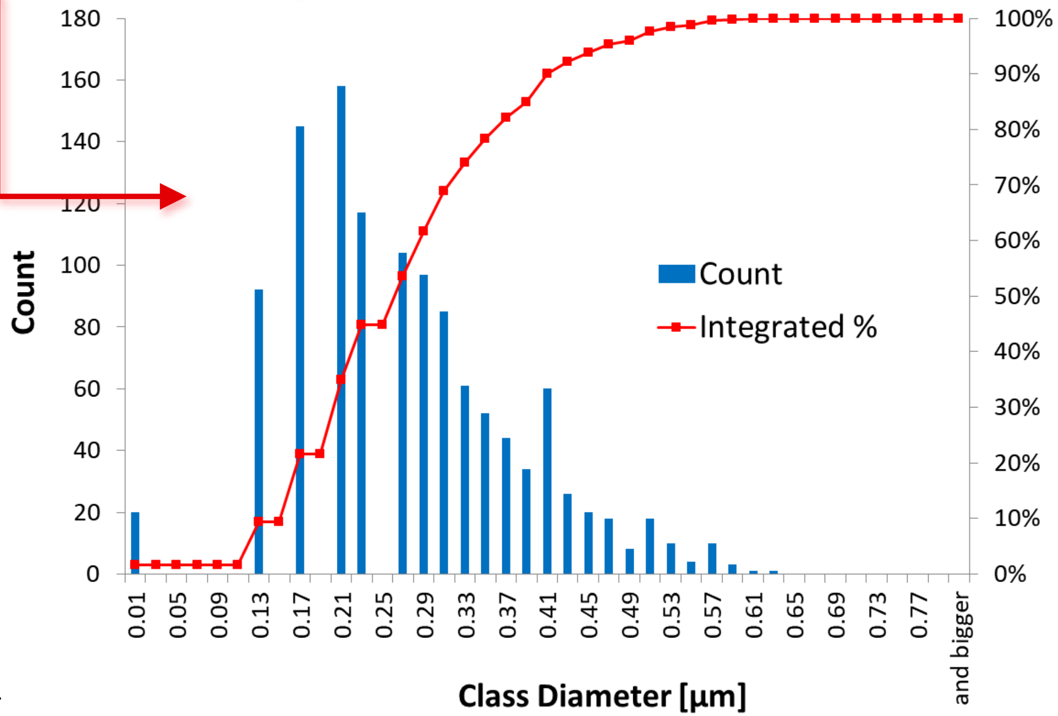
Samples incased in epoxy

Particle size

Chemical Analysis

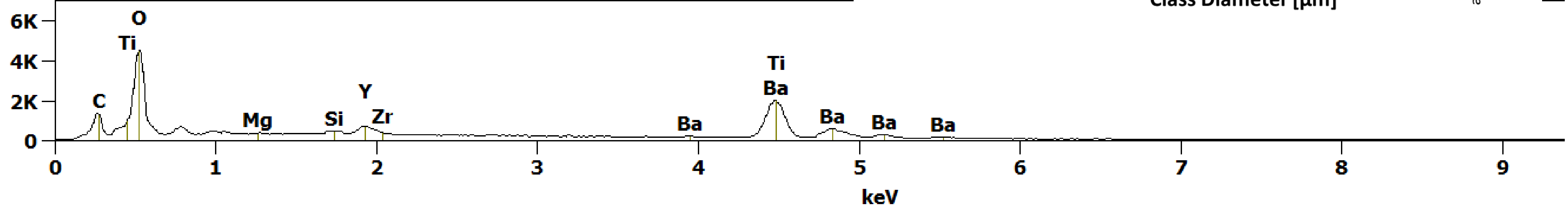


Particle size distribution

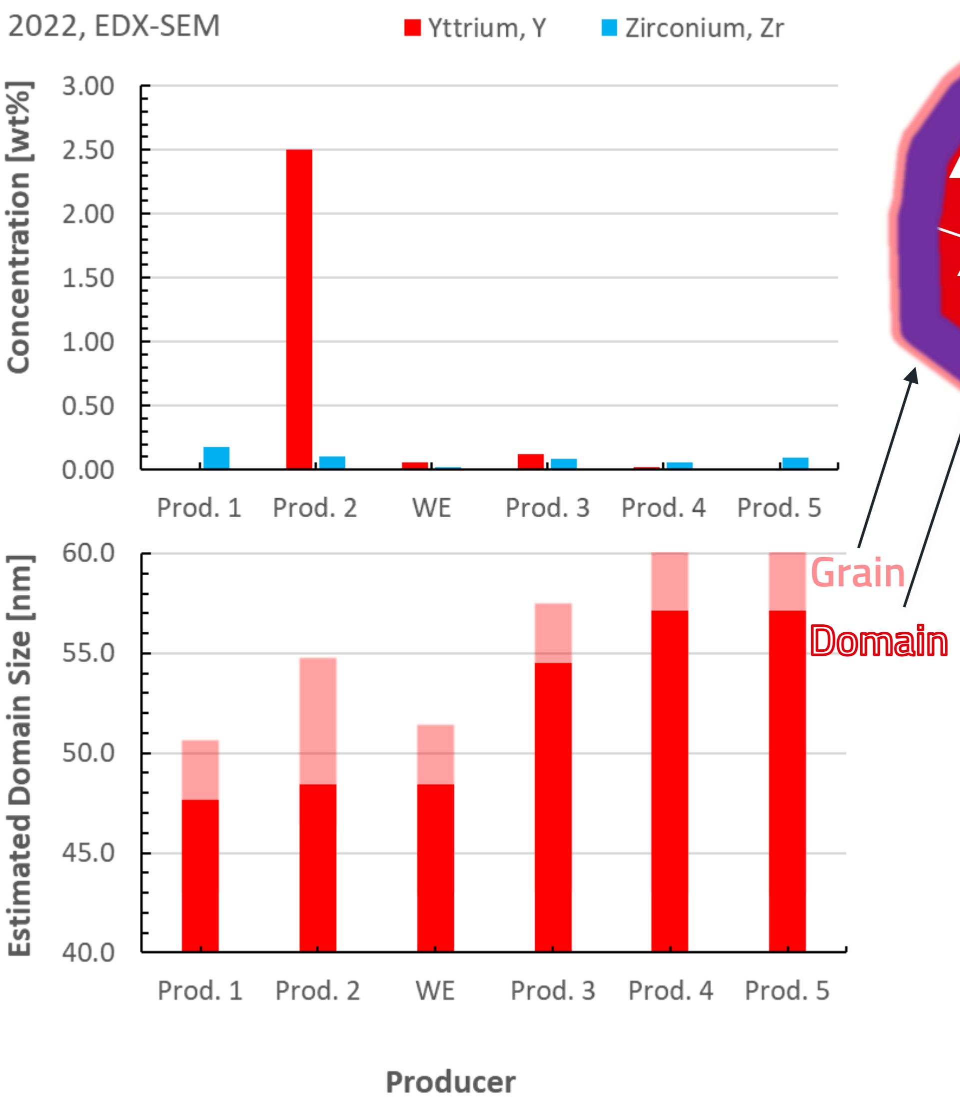


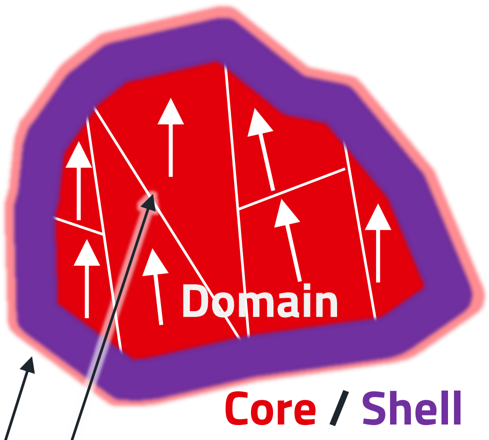
Skalierung, Counts: 4482

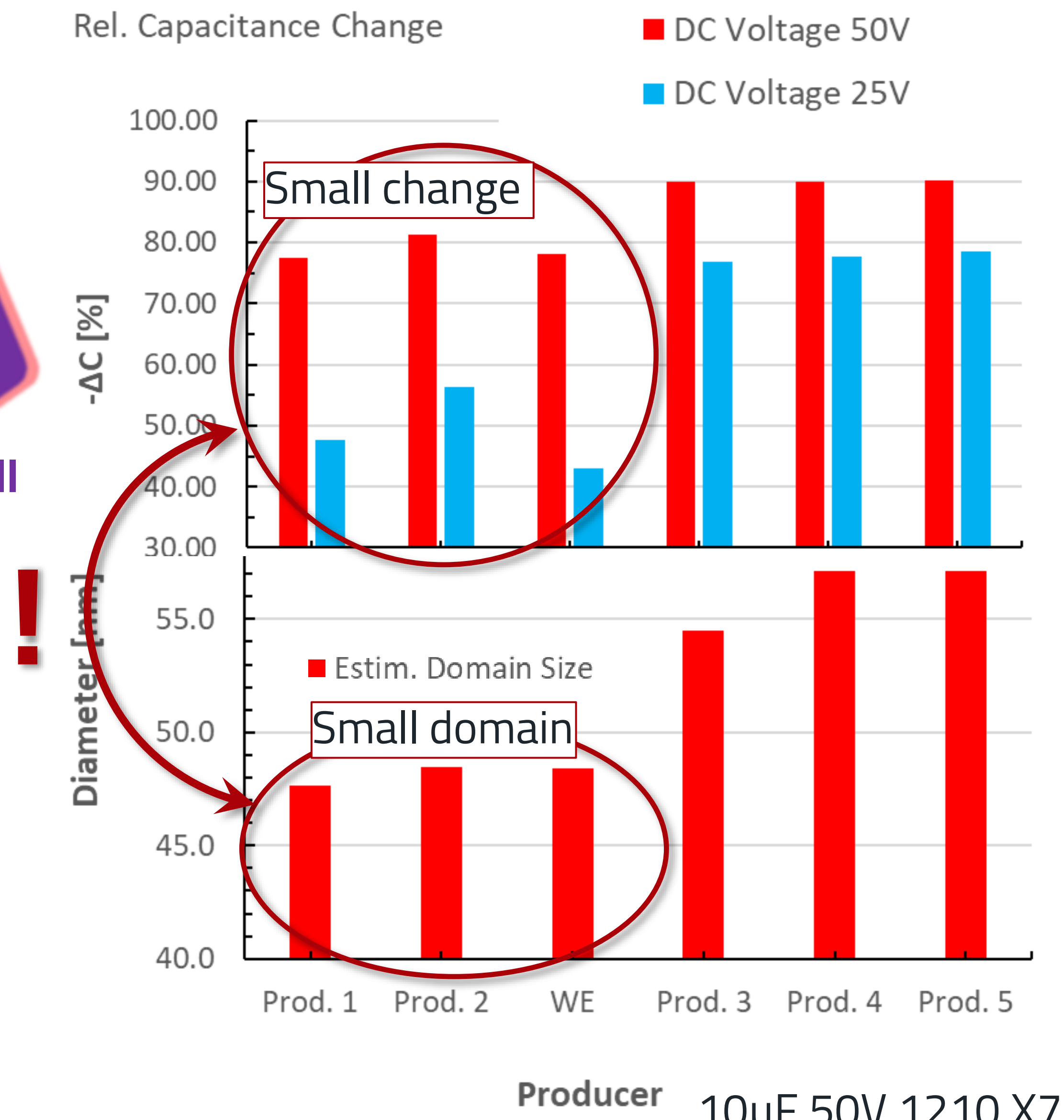
Energy-dispersive X-ray spectroscopy



CORRELATE DOMAIN SIZE WITH CAPACITANCE CHANGE







10µF 50V 1210 X7R

SO FAR...

Introduced MLCC structure, barium titanate

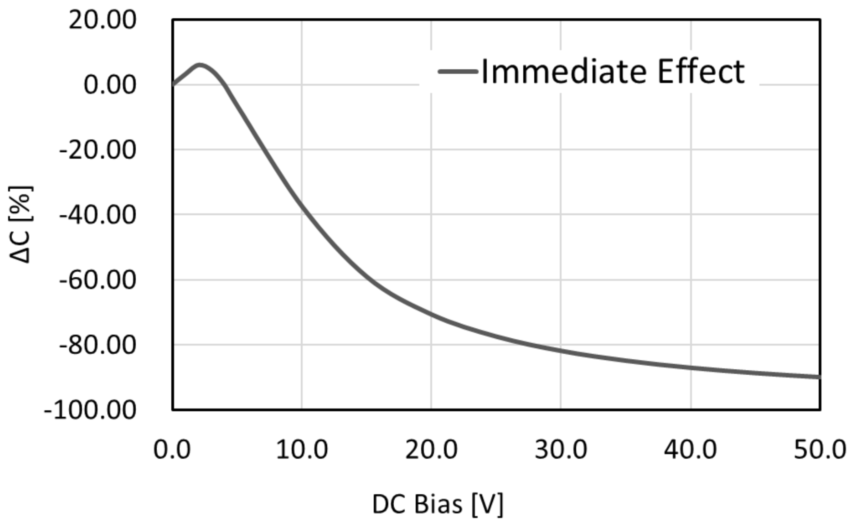
First look at DC-Bias effect and its variations

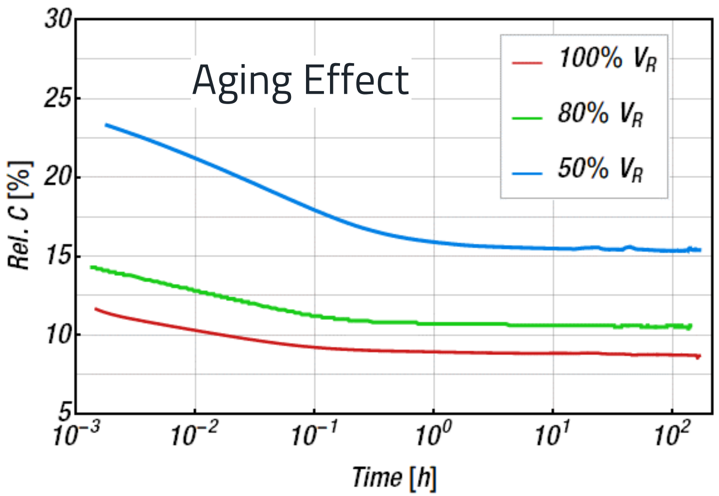
Related ΔC to the domain size

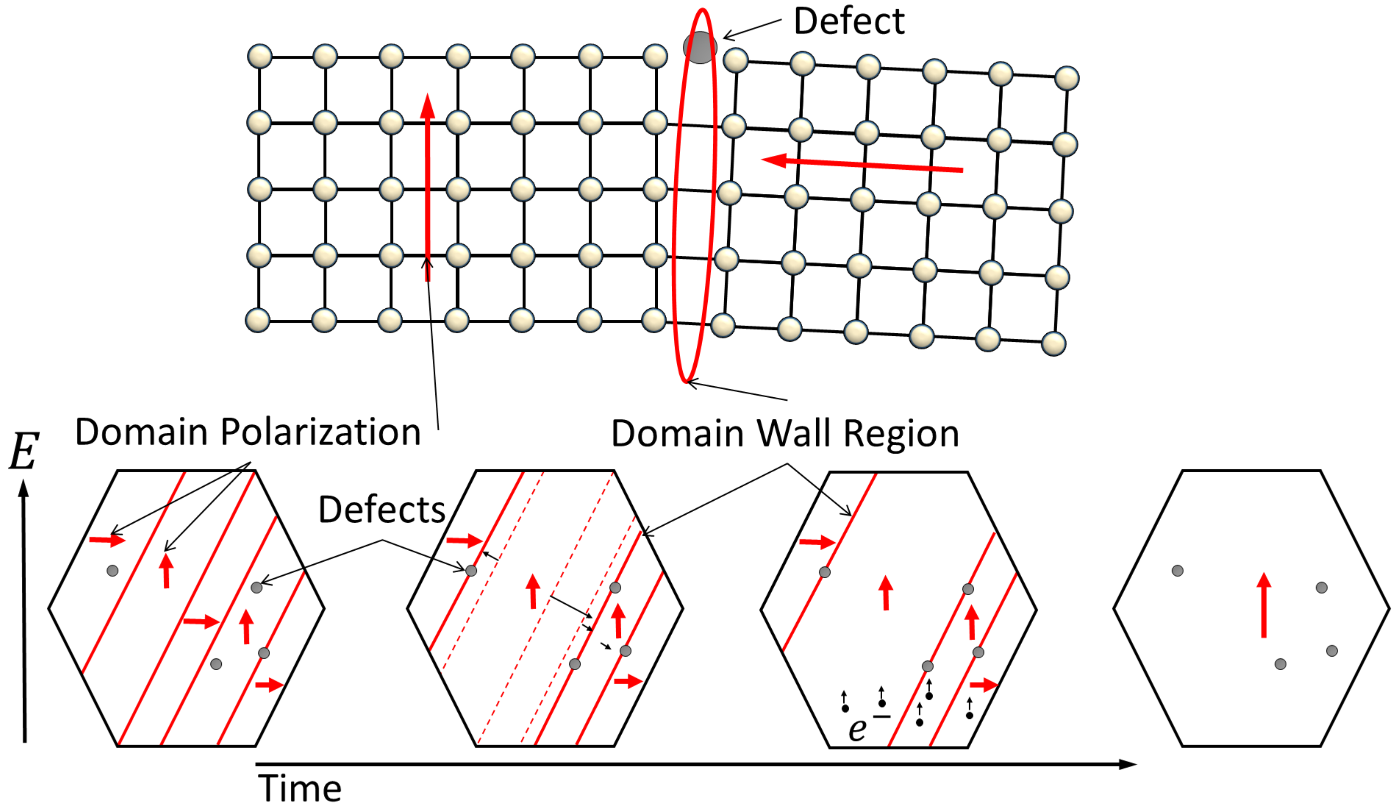
.... However, what is the effect of long-time dc bias exposure?

AGING EFFECTS ON CAPACITANCE-VOLTAGE MEASUREMENTS

10µF 50V 1210 X7R







[24]

DETAILS: SHORT- AND LONG-TERM CAPACITANCE-VOLTAGE MEASUREMENTS

Relation of initial and final capacitance

$$C_\infty = C_i \left[1 + \frac{k}{2} \left(\tanh\left(10 \frac{V - 0.7V_r}{V_r} \right) + 1 \right) - \frac{l}{2} \left(\tanh\left(10 \frac{V - 0.25V_r}{V_r} \right) + 1 \right) \right]$$

C_i: immediate capacitance decrease

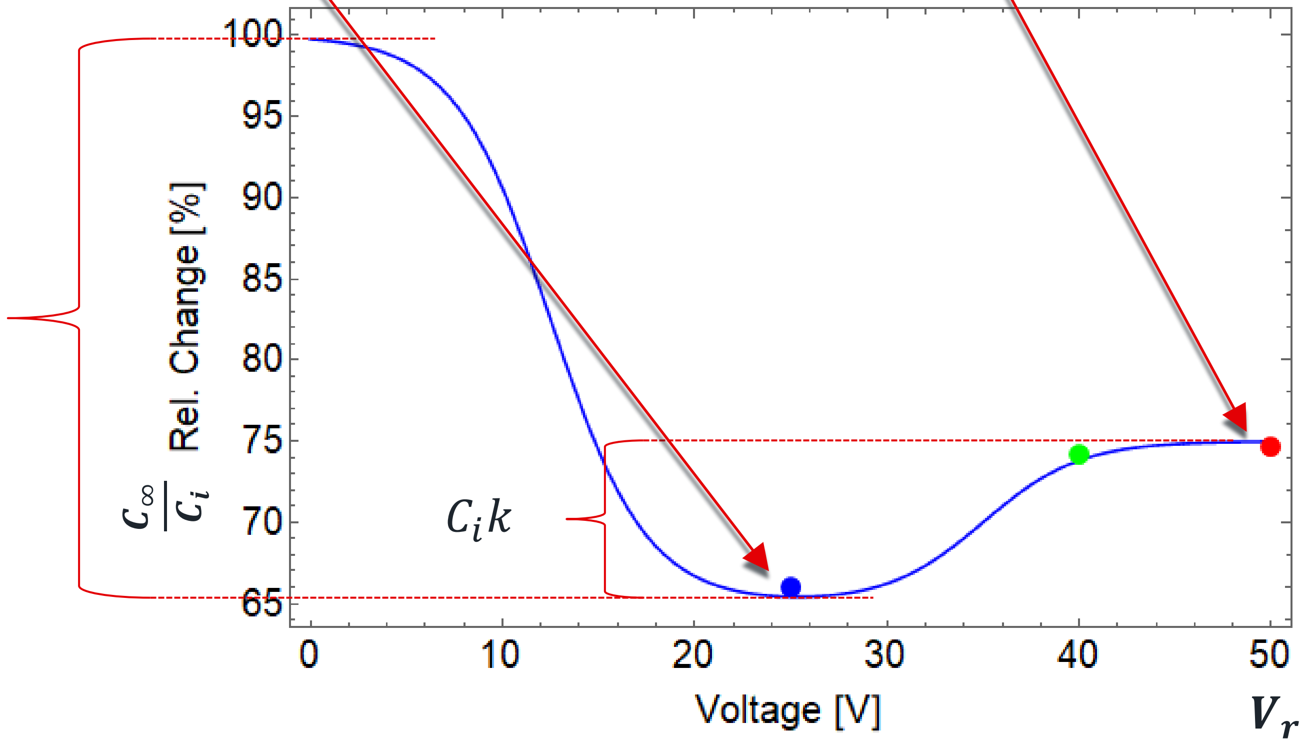
Strong decline at lower voltage

reduced decline high voltage

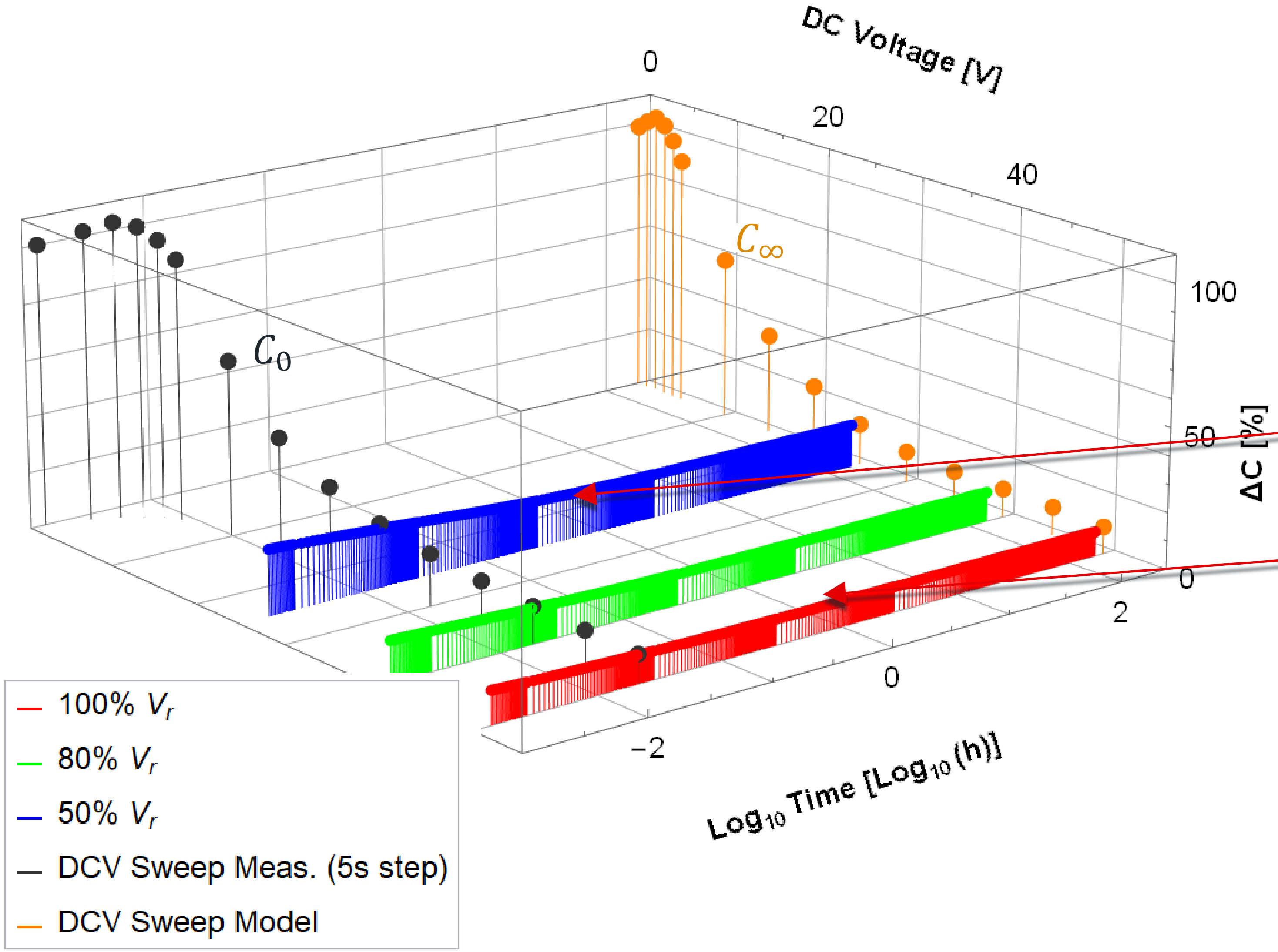
Dynamic of capacitance decline

$$C_l(t) = (C_i - C_\infty) \exp\left[-\left(\frac{t}{\tau} \right)^\alpha \right] + C_\infty$$

$C_i(1 - l)$



SHORT- AND LONG-TERM CAPACITANCE-VOLTAGE MEASUREMENTS



Relative long-time decline:

bit stronger at lower voltage

weaker at high voltage

[24]

SO FAR...

Introduced MLCC structure, barium titanate

First look at DC-Bias effect and its variations

Related ΔC to the domain size

Discussed differences between immediate effect and aging

... What about the model?

MATHEMATICAL MODEL OF FERROELECTRIC POLARIZATION

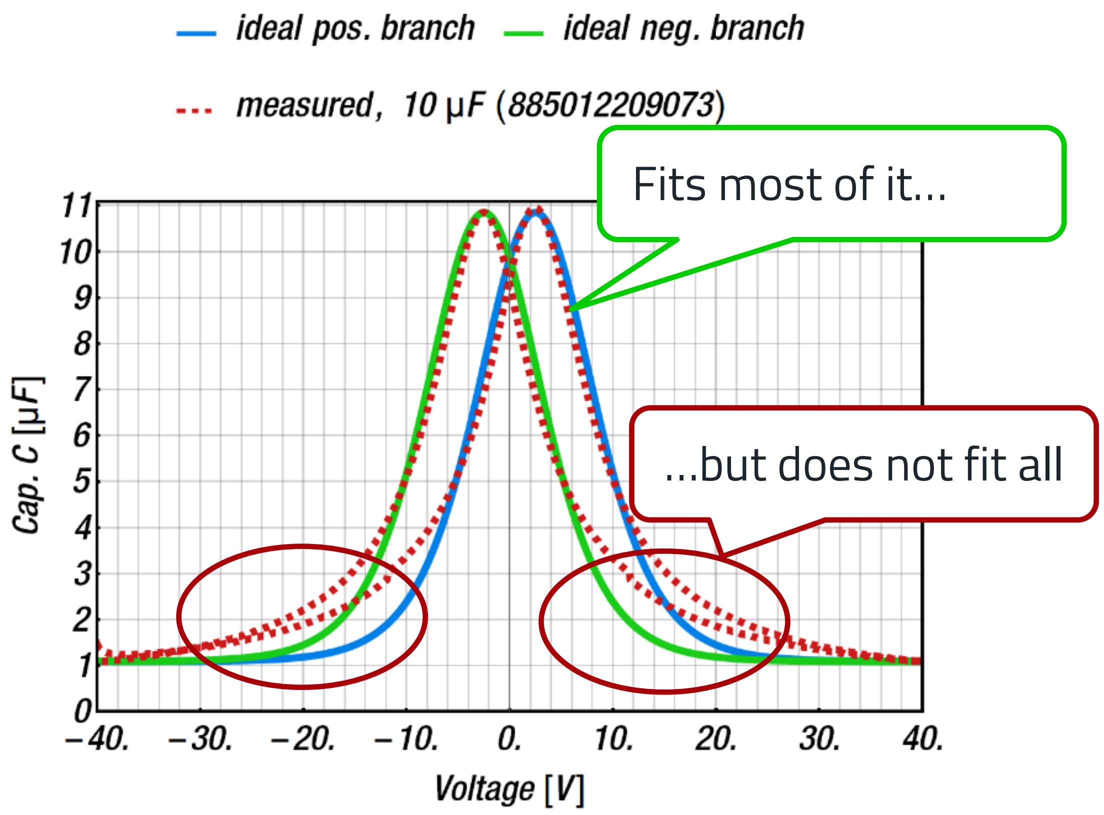
Single fraction

$$P^{-}(E) = P^{+}(-E)$$

$$P^{+}(E) \propto P_s \tanh\left(\frac{E - E_c}{2\delta}\right)$$

$$C_p = \frac{dP}{dV} \propto \operatorname{sech}^2\left(\frac{E - E_c}{2\delta}\right)$$

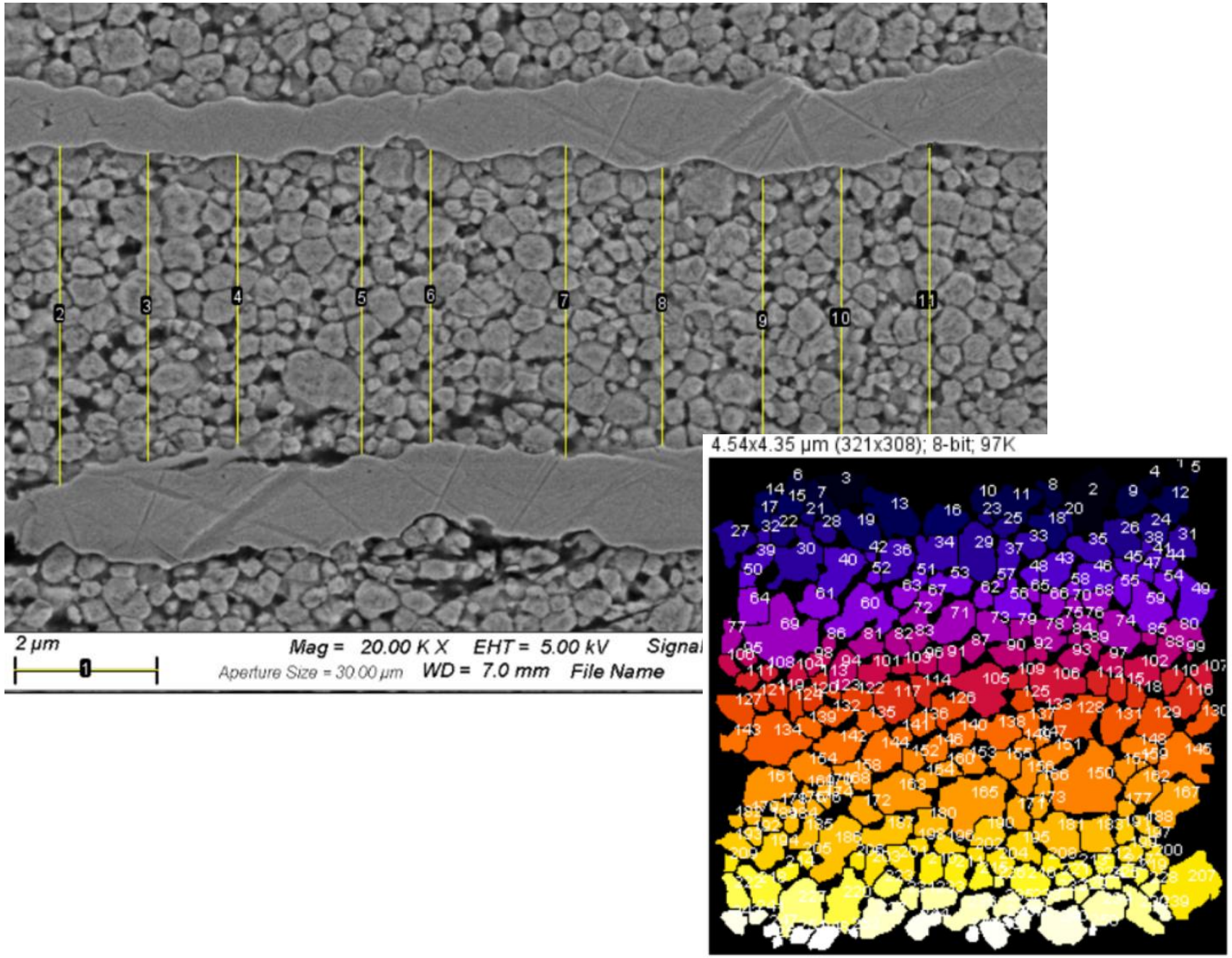
$$C = C_p + C_s$$

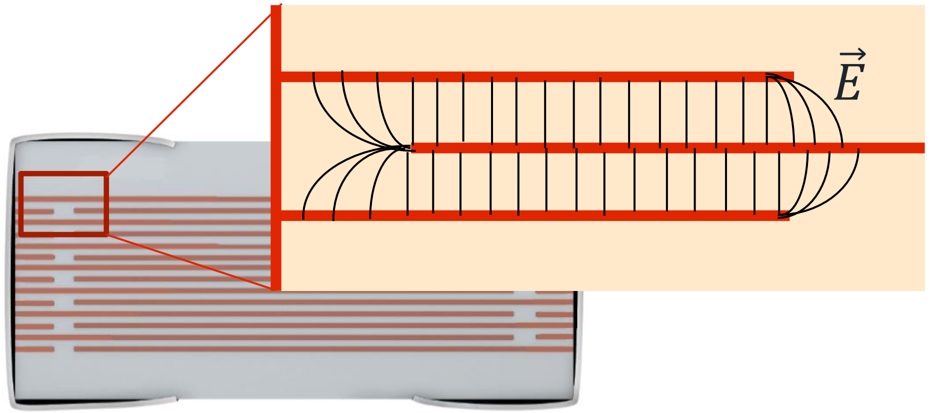


→ **Multiple fractions**

S.L. Miller et al., Modeling ferroelectric capacitor switching with asymmetric nonperiodic input signals and arbitrary initial conditions, Journal of Applied Physics, 70:2849-2860 (1991)

CONSTRUCTION AND COMPOSITION OF MLCC





Material and

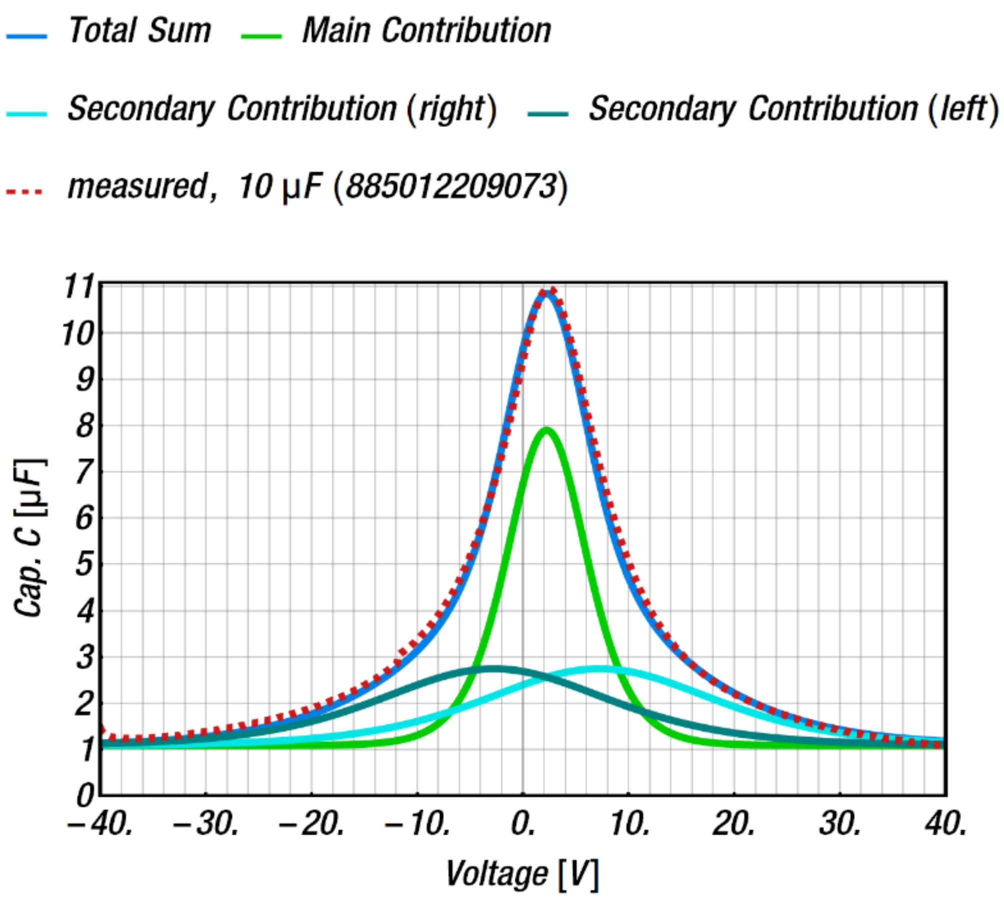
Electrode geometry

... is inhomogeneous

Distribution of voltage dependences

MATHEMATICAL MODEL OF FERROELECTRIC POLARIZATION

Multiple fractions



$$C = C_p + C_s$$

- material fractions and
- inhomogeneous electrodes

... are accounted for by sum:

$$C_P = \sum_i a_i \operatorname{sech}^2\left(\frac{V - V_{Ci}}{b_i}\right) \quad ,$$

… which can be reduced to three summands:

$$C_p = C_{main} + C_{left} + C_{right}$$

[24, 25]

SO FAR...

Introduced MLCC structure, barium titanate

First look at DC-Bias effect and its variations

Related ΔC to the domain size

Discussed differences between immediate effect and Aging

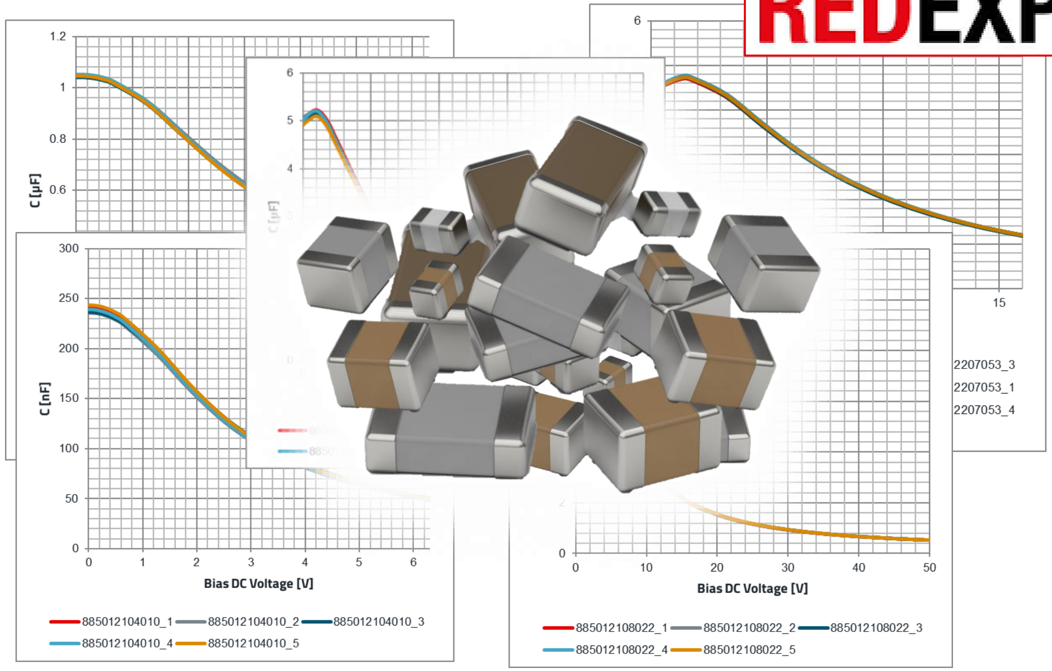
Introduced a model based on measurable and

physically meaningful parameters

.... Well, great, but that is still a complicated calculation.

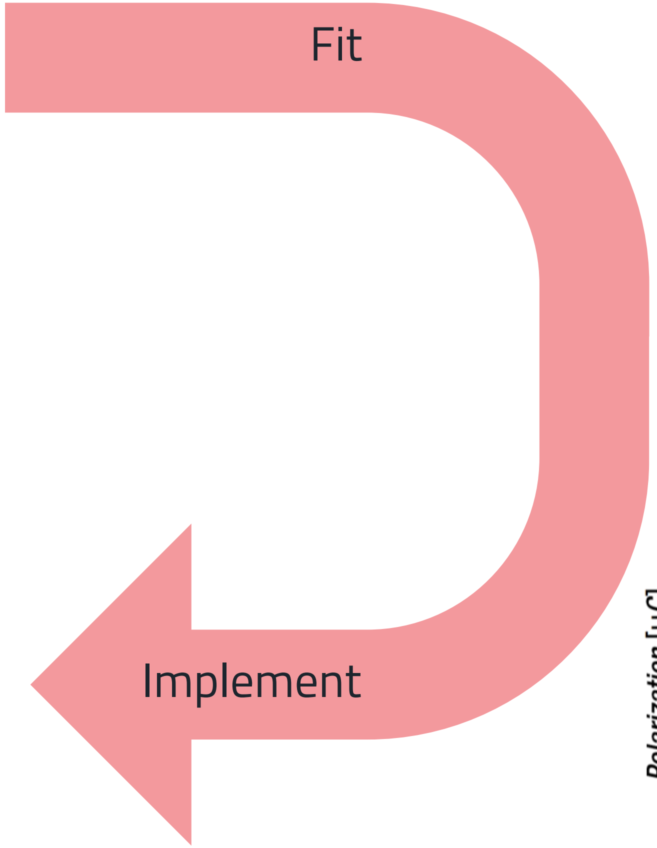
... How is that supposed to help?

IMPLEMENTATION: LTSPICE

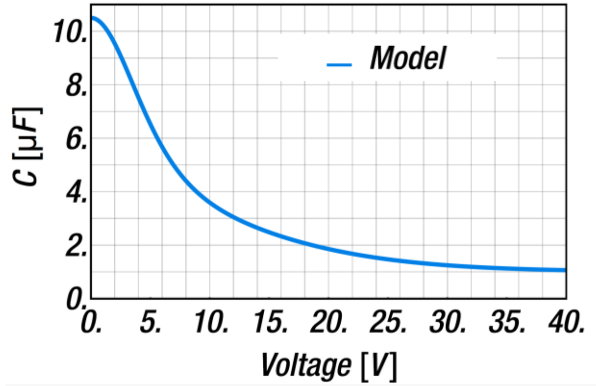


REDEXPERT

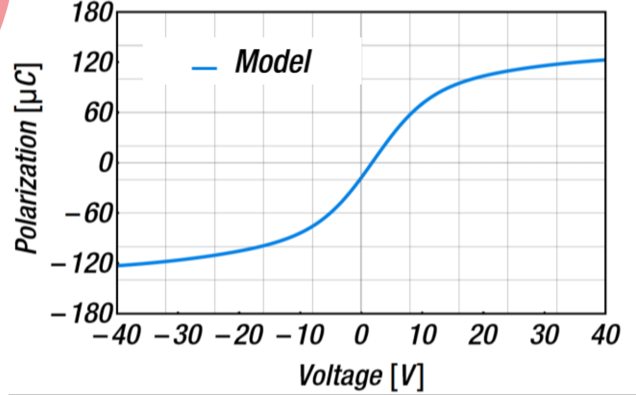
https://redexpert.we-online.com

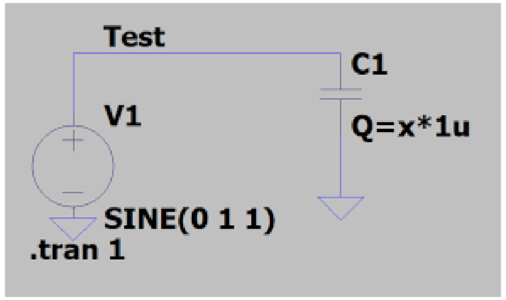


$$C(V) = x_1 \times Sech^2\left(\frac{V - x_2}{3}\right) + \cdots$$



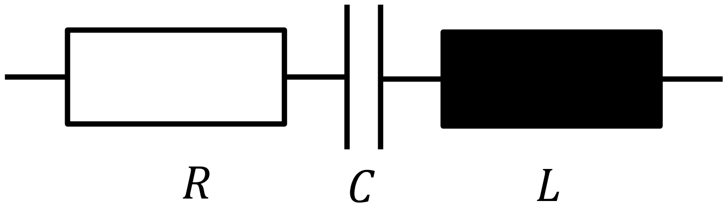
$$P(V) = x_4 \cdot Tanh\left(\frac{V - x_5}{x_6}\right) + \cdots$$





LTspice®

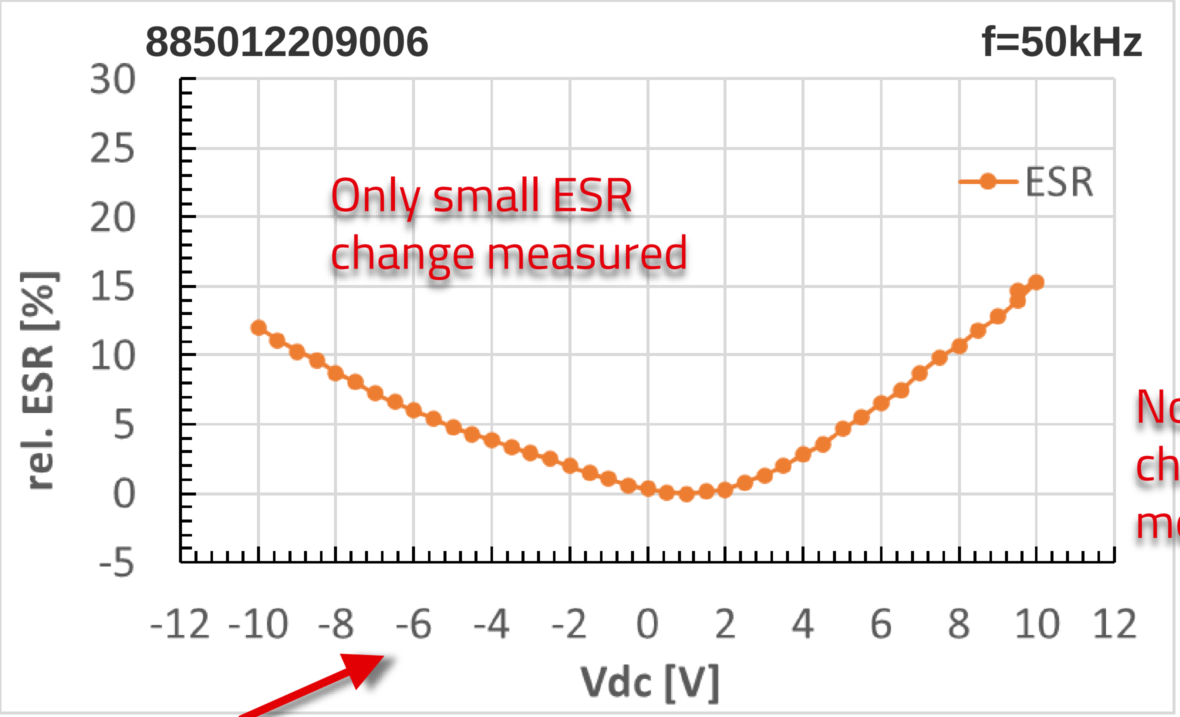
FREQUENCY AND VOLTAGE-DEPENDENT MODEL



$$Z(\omega, V) = R + \frac{1}{i\omega \boldsymbol{C}} + i\omega L$$

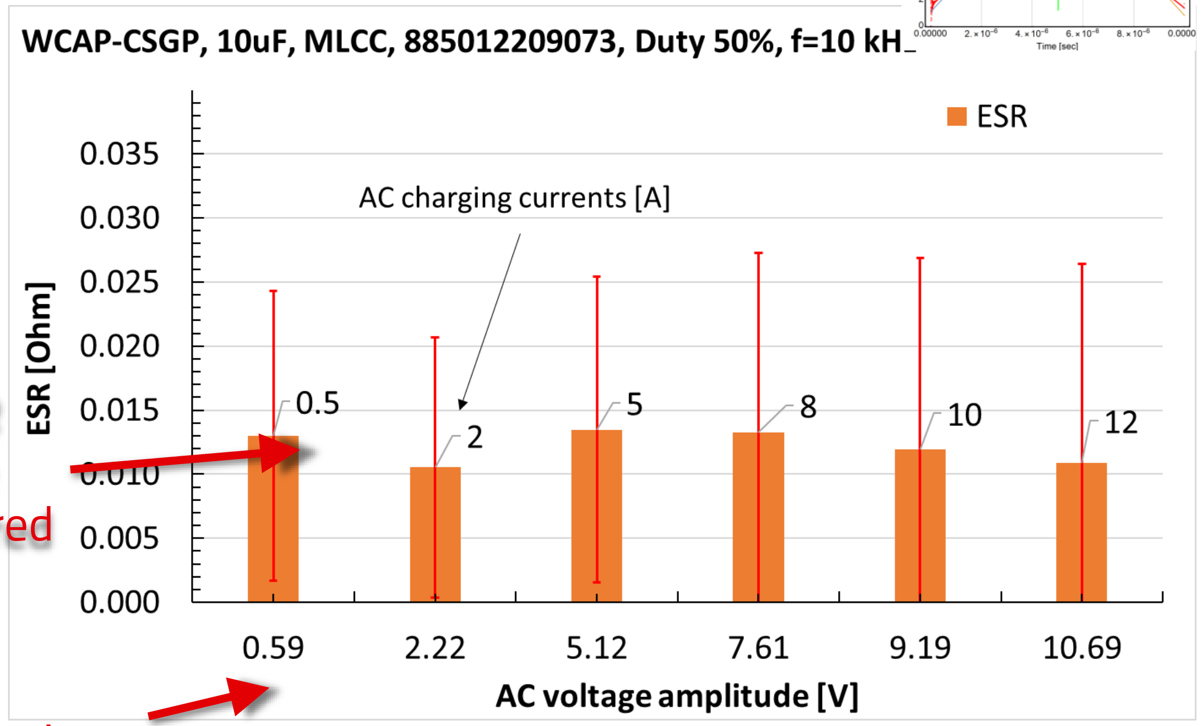
$\boldsymbol{R(V) \approx const.}$

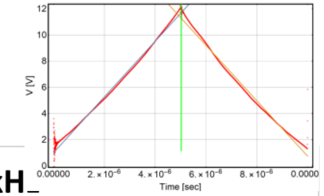
Impedance measurement



DC voltage

Boost converter topology

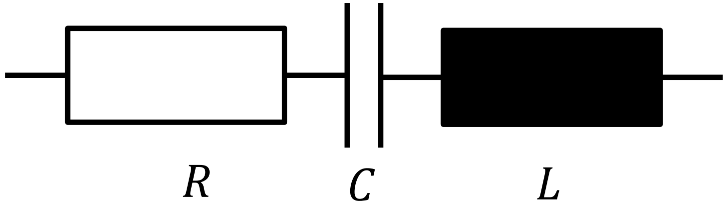




No ESR change measured

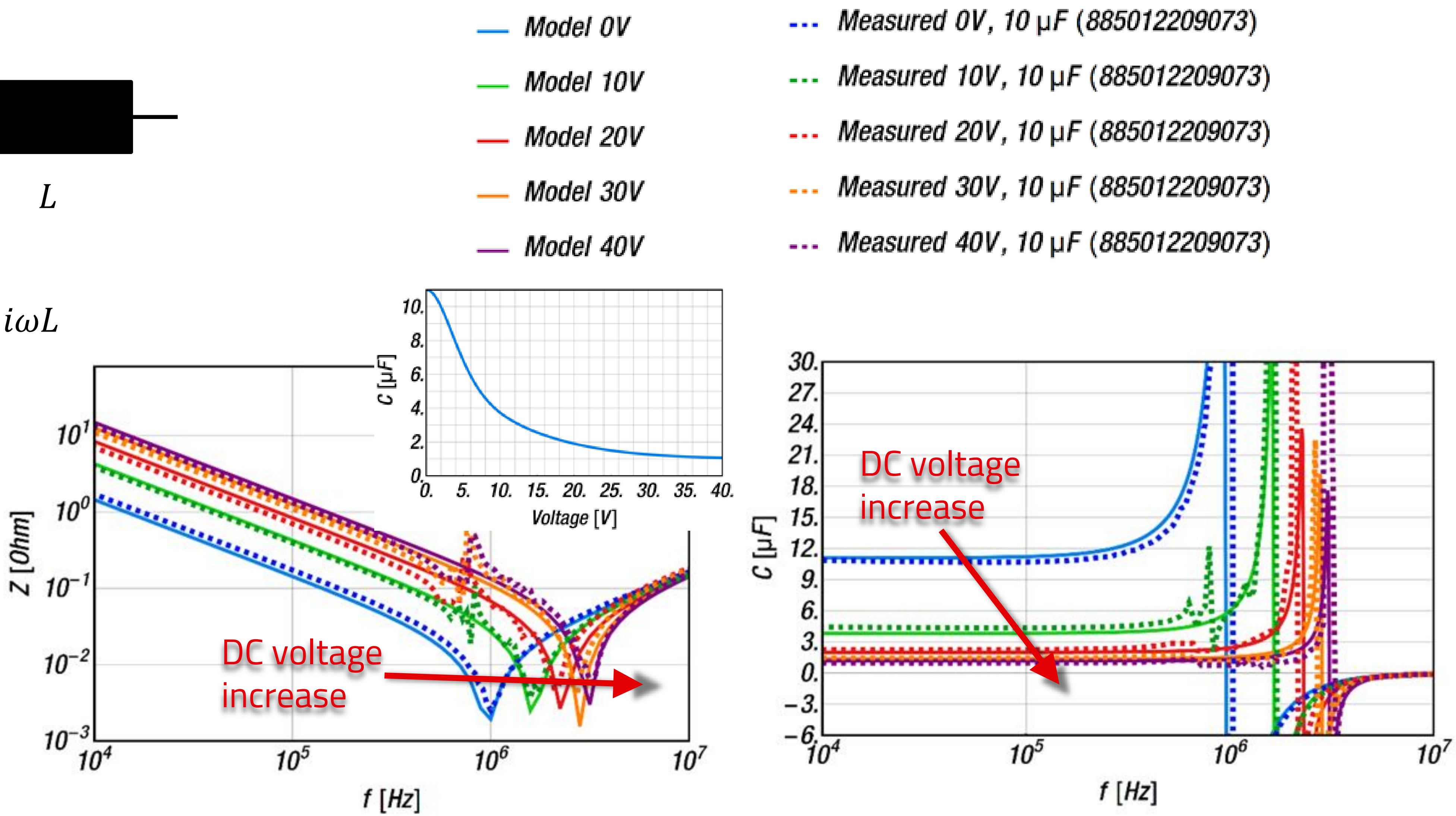
AC voltage

FREQUENCY AND VOLTAGE-DEPENDENT MODEL

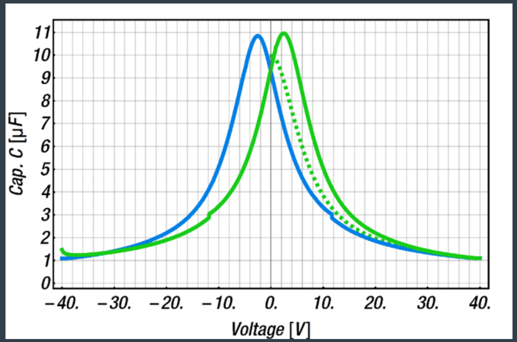


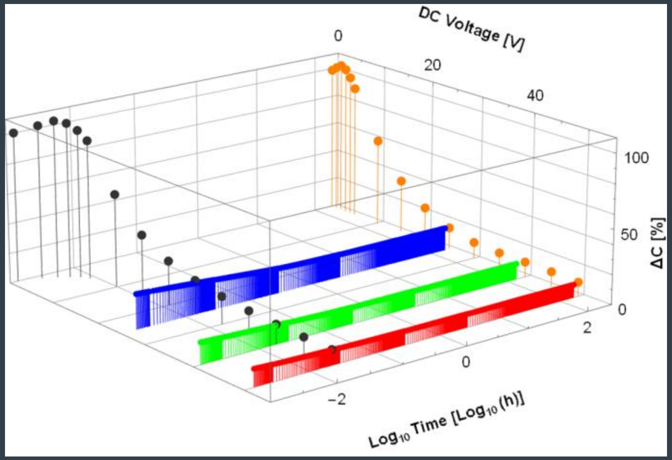
$$Z(\omega, V) = R + \frac{1}{i\omega\, \boldsymbol{C}} + i\omega L$$

$\boldsymbol{C}(\boldsymbol{V})$

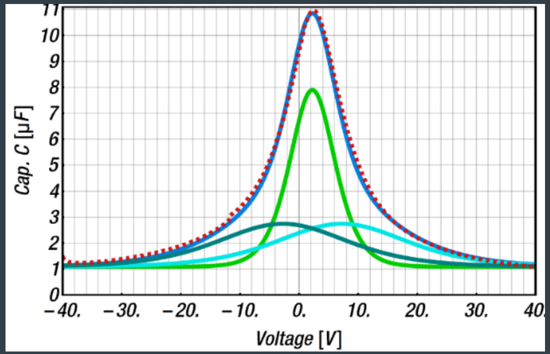


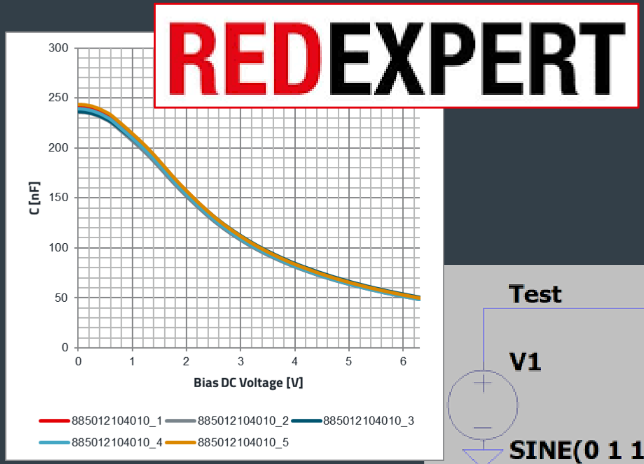
SUMMARY

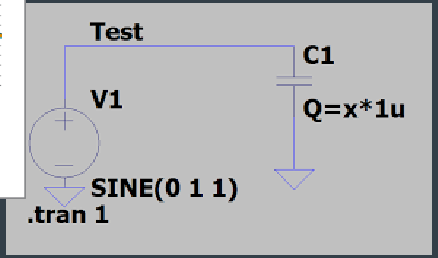




- Introduced ferroelectricity and class 2 MLCCs
- Discussed the long- and short-term polarization effect
- Developed suitable model to fit
  - voltage dependence and
  - frequency spectra
- Implemented the model into LTSpice







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Background:

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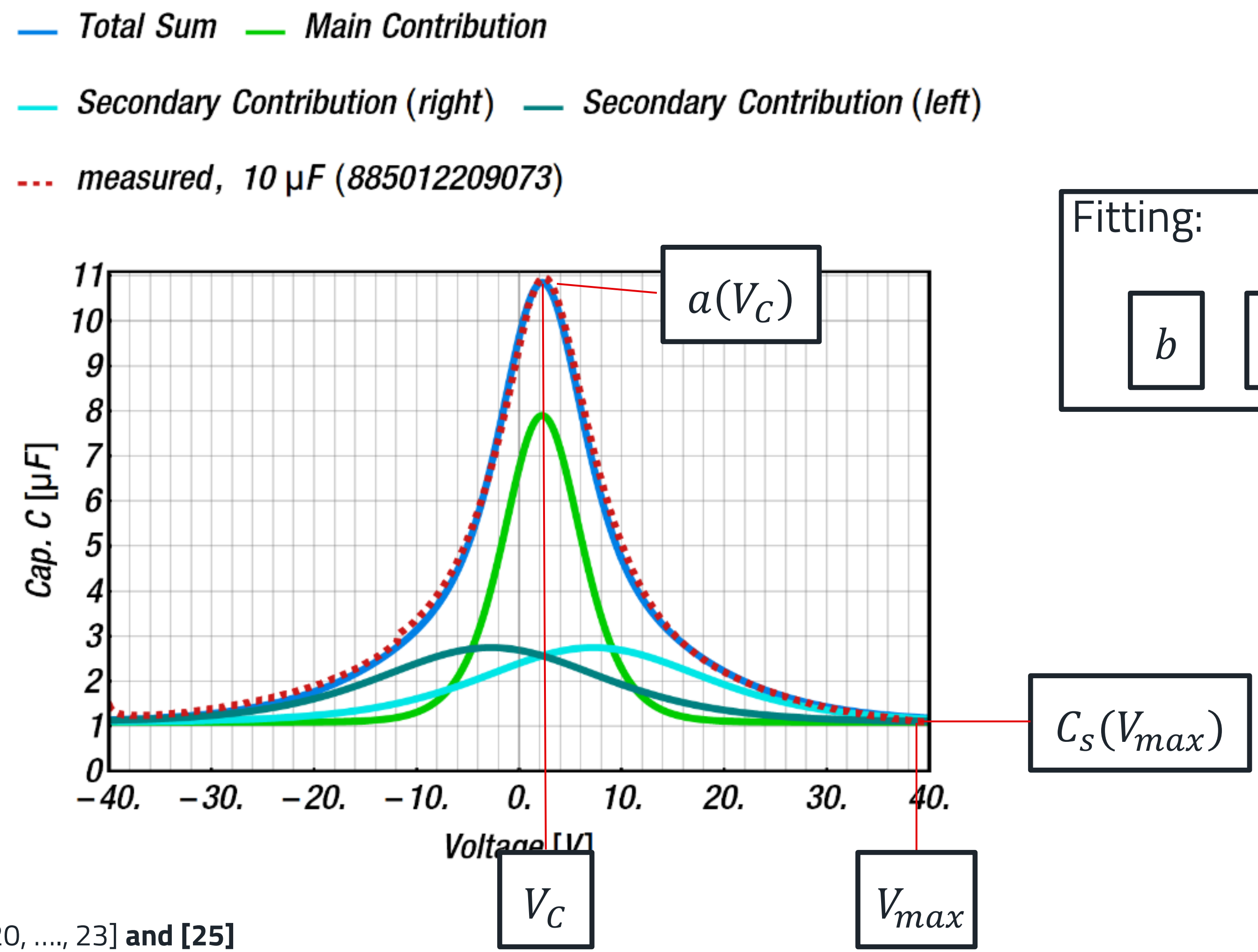
Dr. René Kalbitz studied physics at the University of Potsdam and at the University of Southampton (GB). After completing his diploma degree, he gained is PhD in the field of organic semiconductors and insulators at the University of Potsdam. He was able to gain further experience in the field of applied research at the Fraunhofer Institute for Applied Polymer Research. He has been employed at Würth Elektronik as a product manager for supercapacitors since 2018 and oversees research and development projects in the field of capacitors.

MATHEMATICAL MODEL OF FERROELECTRIC POLARIZATION

Multiple fractions



Fitting: b h

$$C(V) = A(C_s, V_{max} a, b) \times \left[\operatorname{sech}^2\left(10 \frac{V - V_C}{7 \times b}\right) + \frac{b}{30} \operatorname{sech}^2\left(\frac{V - \frac{V_{max}}{8} + V_c}{2 \times b}\right) + \frac{b}{30} \operatorname{sech}^2\left(\frac{V + \frac{V_{max}}{8} - V_c}{2 \times b}\right)\right] - C_s \times \frac{h}{10} + C_s$$

[20, …., 23] **and [25]**

POLARIZATION MODEL

$$C_P = \left(\frac{a^*}{a_0}\right)\left[\operatorname{sech}^2\left(10\frac{V - V_C}{7 \cdot b}\right) + \frac{\mathrm{b}}{30}\operatorname{sech}^2\left(\frac{V - \frac{V_{max}}{8} + V_c}{2 \cdot b}\right) + \frac{\mathrm{b}}{30}\operatorname{sech}^2\left(\frac{V + \frac{V_{max}}{8} - V_c}{2 \cdot b}\right)\right] - C_s \cdot \frac{h}{10}$$

$$a^* = C_s \cdot \left(\frac{h}{10} - 1\right) + a$$

$$a_0 = 1 + 2\frac{\mathrm{b}}{30}\operatorname{sech}^2\left(\frac{\frac{V_{max}}{8}}{2 \cdot b}\right)$$

POLARIZATION CONTRIBUTION TO CAPACITANCE

$$I = A\frac{dP}{dt} + C_s\frac{dV}{dt} + I_0(V)$$

$$C = \left(A\frac{dP}{dt} + C_s\frac{dV}{dt} + I_0(V)\right)\frac{dt}{dV}$$

$$C = A\frac{dP}{dV} + C_s + I_0(V)\frac{dt}{dV}$$

$$C = C_p + C_s + C_V^0$$

$$P^+(E) = P_s\, tanh\left(\frac{E - E_c}{2\delta}\right)$$

$$\delta = E_C\left[\frac{1 + \frac{P_r}{P_s}}{1 - \frac{P_r}{P_s}}\right]^{-1}$$