Inkjet printing of tunable microwave devices

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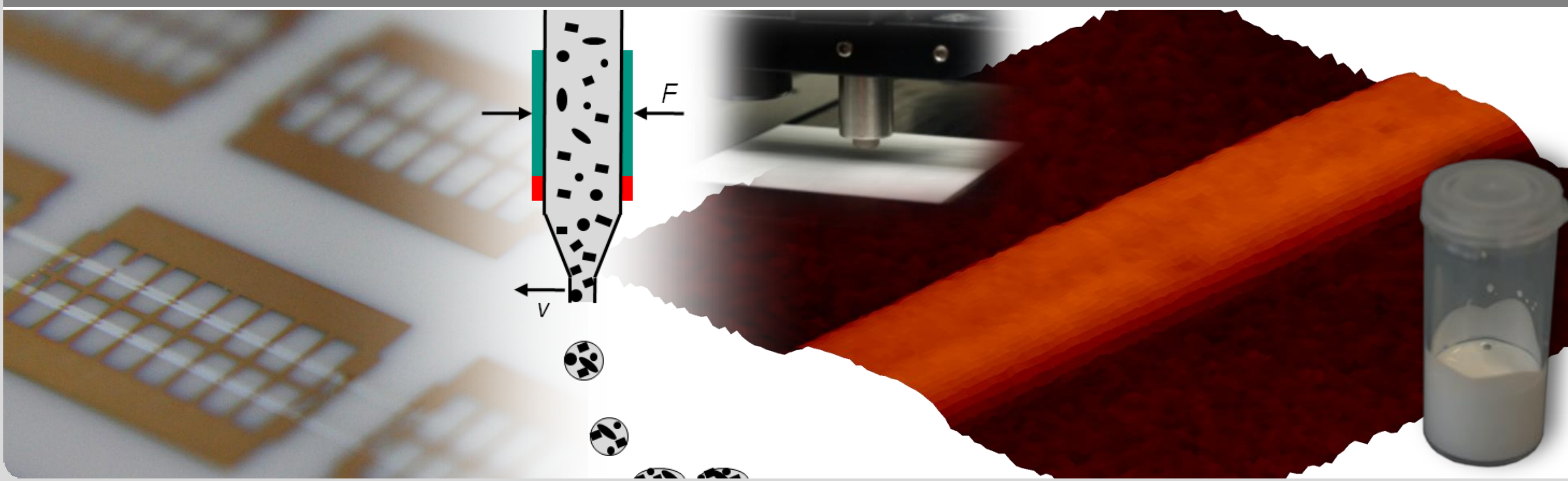
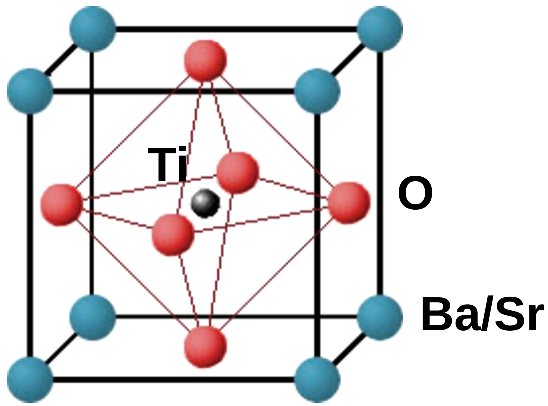


Outline

- Introduction
  - Barium Strontium Titanate
  - Applications
- Development of an inkjet printing process chain
  - ink preparation
  - ink development
- Preparation of tunable microwave devices
  - selective printed devices
  - fully printed devices

Barium Strontium Titanate

- $Ba_xSr_{1-x}TiO_3$ (BST)
  - Solid solution
  - Perovskite structure
  - Ferroelectric, $T_{Curie} = f(x)$

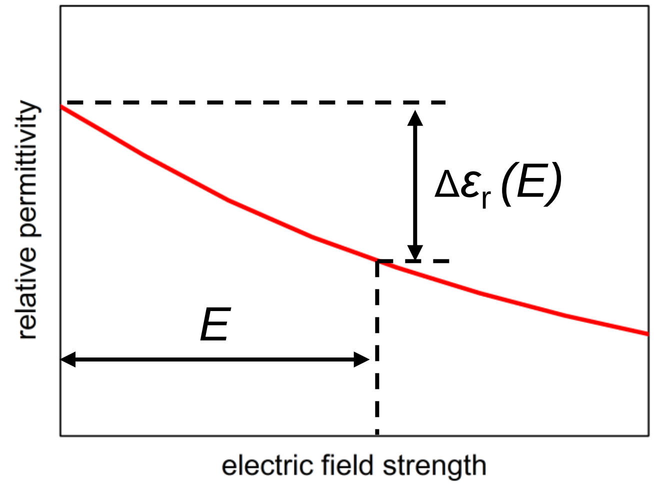


- Material characteristics
  - Dependency of permittivity on electrical field strength, i.e. tunability

$$\tau = \frac{\varepsilon_r(E=0) - \varepsilon_r(E)}{\varepsilon_r(E=0)}$$

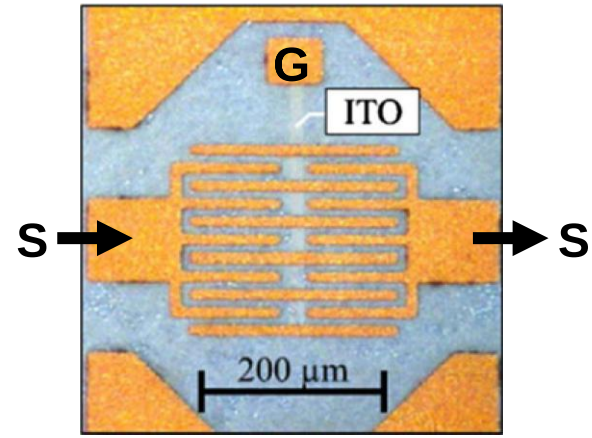
  - Low dielectric losses for $T > T_{Curie}$

$$\tan\delta = \tan\delta(f, T, E, \ldots)$$



Barium Strontium Titanate

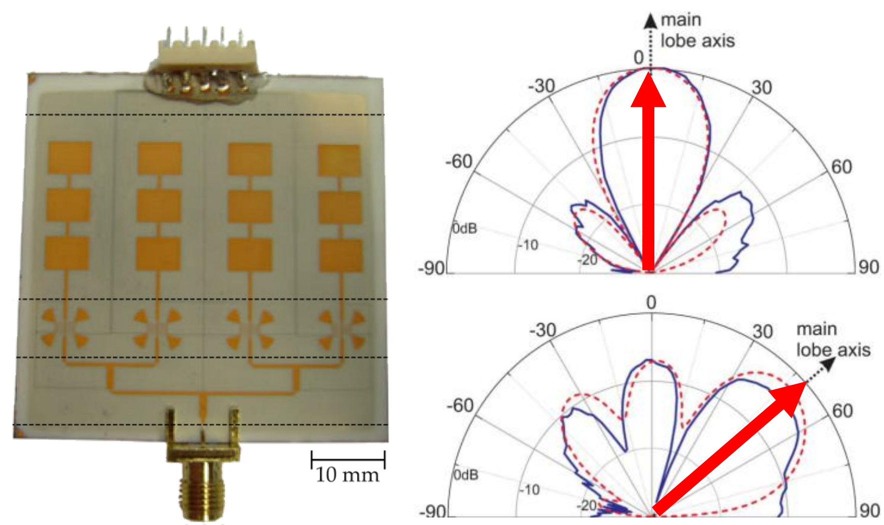
- How can we use it?
  - Capacitor with adjustable capacitance
    → Adjustable phase shift of AC current
    → Adjustable resonance frequency of antennas
    → Adjustable frequency filters



Two stage serial varactor,
Maune et al., *Microsyst. Technol.* 17 (2011)

- Already prepared devices:
  - Tunable antennas
    (swivelling / frequency agile)
  - Phase shifters
  - High frequency filters

on screen-printed
BST thick-films



Phased array antenna on BST thick-film,
Sazegar et al., *IEEE Trans. Microw. Theory Tech.* 59 (2011)

Requirements for tunable microwave devices

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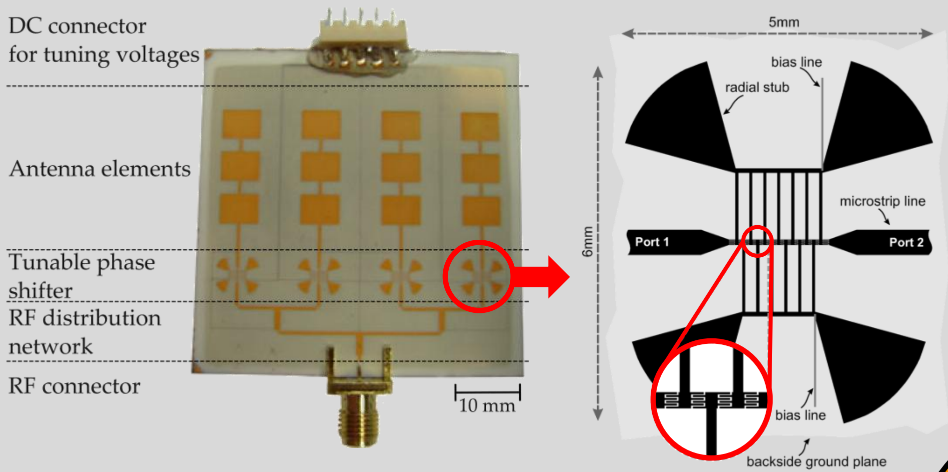
low loss (dielectric and conductive materials)

reproducible material properties

high tunability

high permittivity for miniaturisation

Example:
Tunable phased-array antenna on BST thick-film



Sazegar et al., 2011

narrow lines for miniaturisation

high geometric accuracy (reproducible!)

small gap sizes (<10 µm)
→ high tuning field strength at low voltages

high quality materials

exact process

Inkjet printing of BST thick-films

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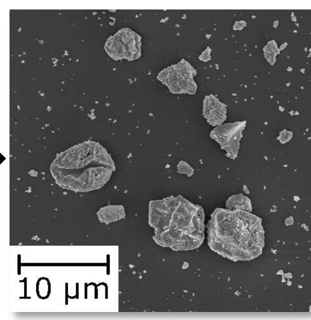
- To establish an inkjet printing process the requirements for inkjet printing must be fulfilled
  - Particle size
  - Viscosity / surface tension
  - Stability

→ **Adapt powder and ink preparation**

- Ink and process conditions must be optimised to obtain homogeneous structures suitable for microwave devices

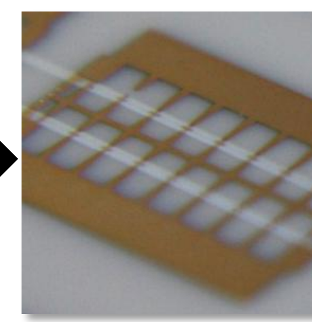
sol-gel synthesis



spray drying + calcination

milling + dispersing

inkjet printing

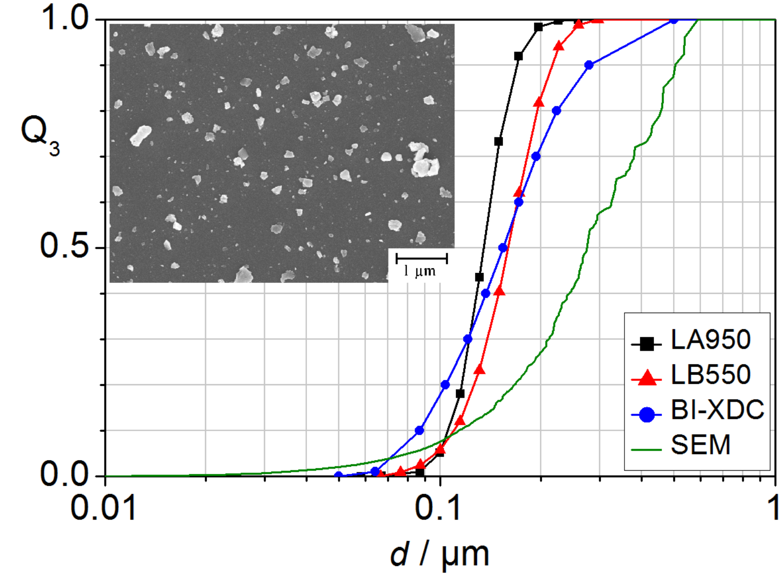


Ink properties

- Particle size:

  $d_{50} \approx 150$ nm

  $d_{100} < 1$ µm



Dilution to 5 vol.% solid content:

- Viscosity:

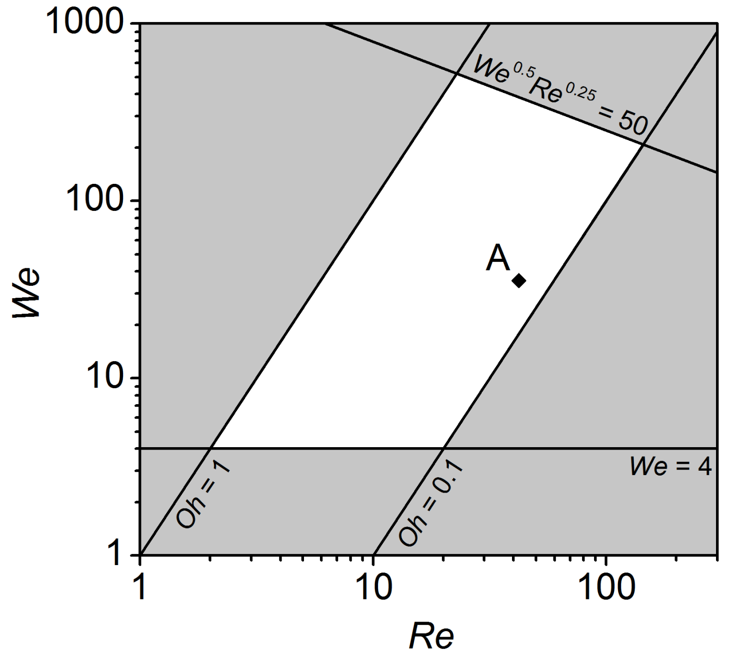
  $\eta = 8.4$ mPas (@ $T = 20°C$, $\dot{\gamma} = 1000\ s^{-1}$)

- Surface tension:

  $\sigma = 29.9$ mN/m (@ $T = 20°C$)

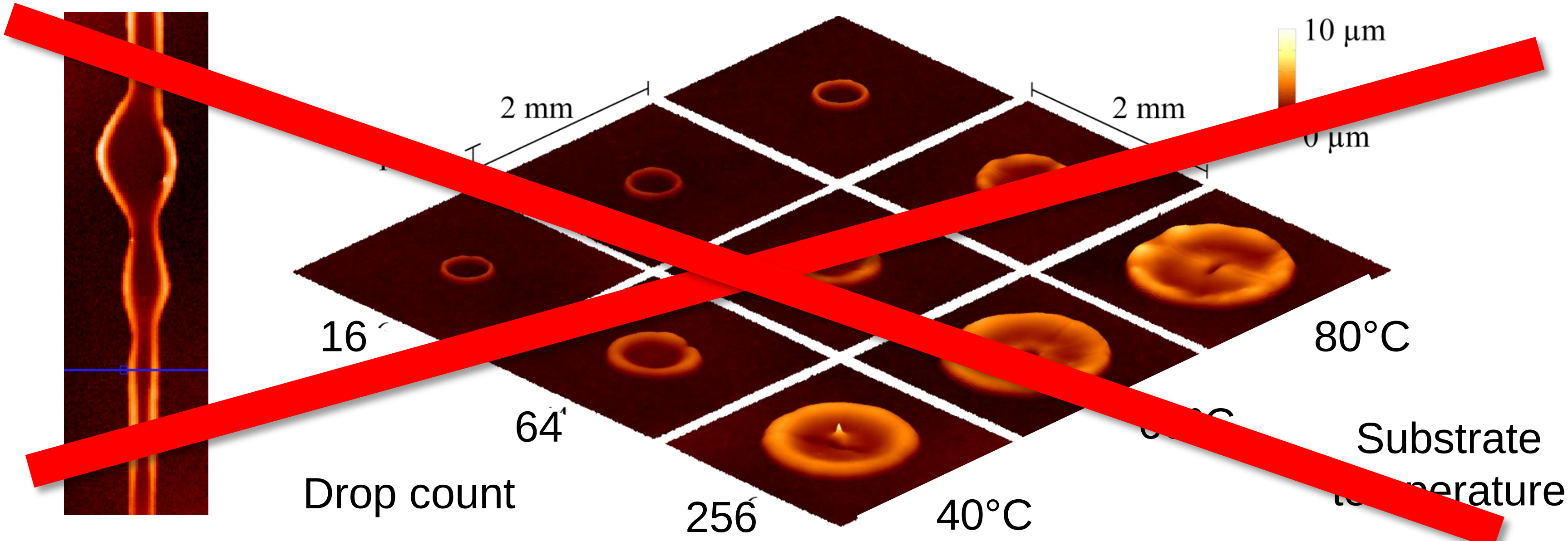
- Ohnesorge number:

$$Oh = \frac{\sqrt{We}}{Re} = \frac{\eta}{(\gamma \rho a)^{1/2}} = 0.14$$



Printed topography (ink A)

- Printing of lines and drops
- Variation of the drying temperature



Severe coffee staining in all cases and crater-like structures for large drops

Ink development

Detailed information available in:
'J. Am. Ceram. Soc.'
DOI: 10.1111/jace.12385

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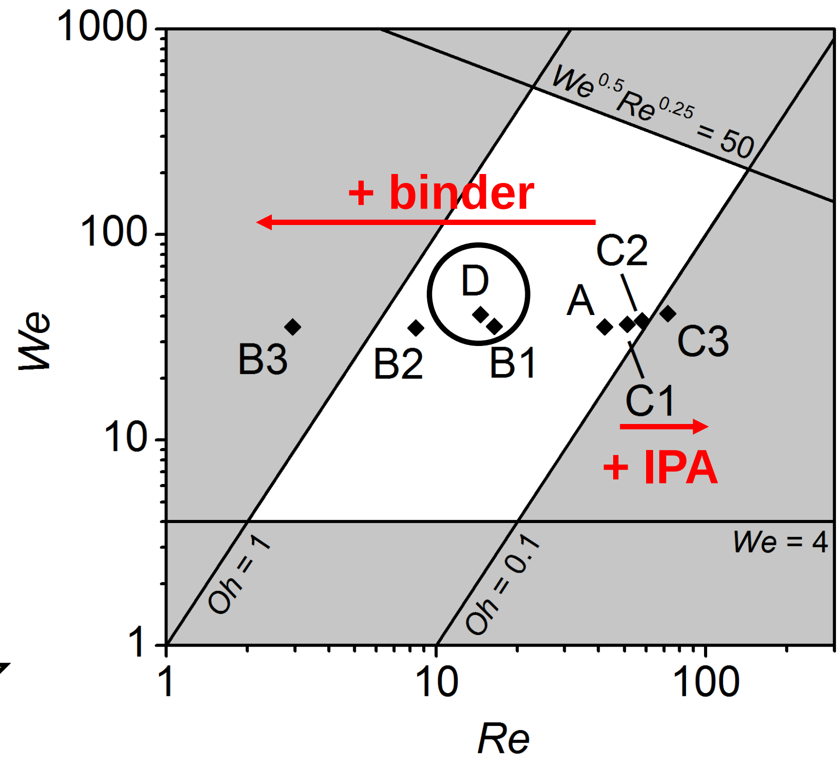
Ink	EC* (vol.%)	IPA** (vol.%)	Viscosity (mPas)
A	-	-	**8.4**
B1	0.62	-	**21.6**
B2	1.25	-	**42.4**
B3	2.50	-	**121.3**
C1	-	12.9	**6.8**
C2	-	25.1	**5.9**
C3	-	50.2	**4.6**
D	1.05	48.7	**22.7**

optimized ink composition

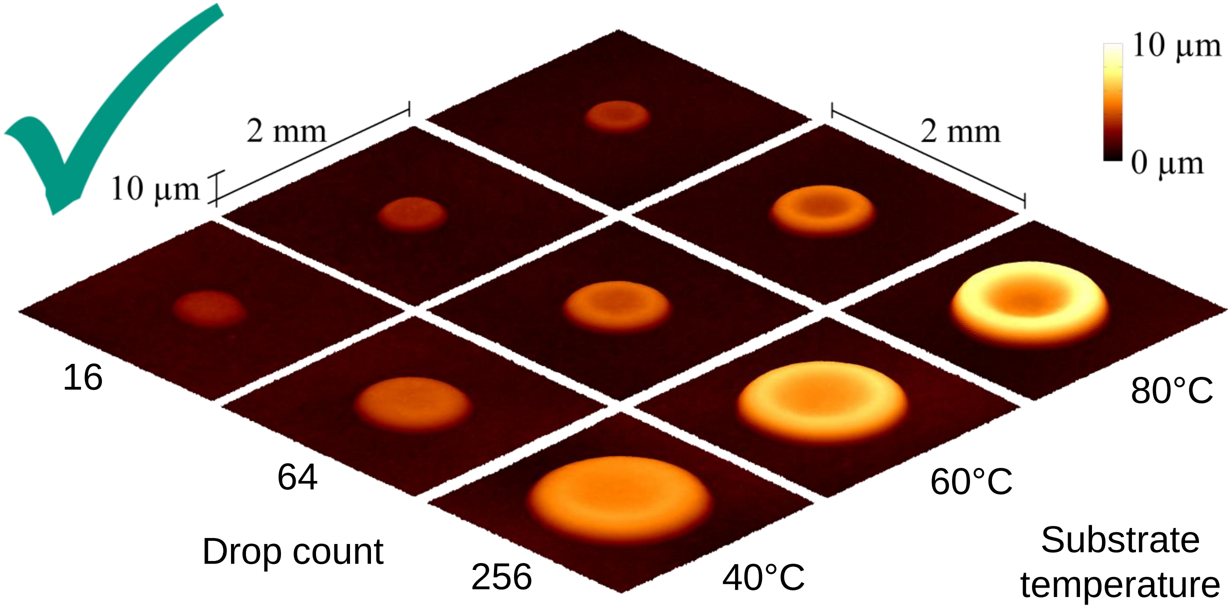


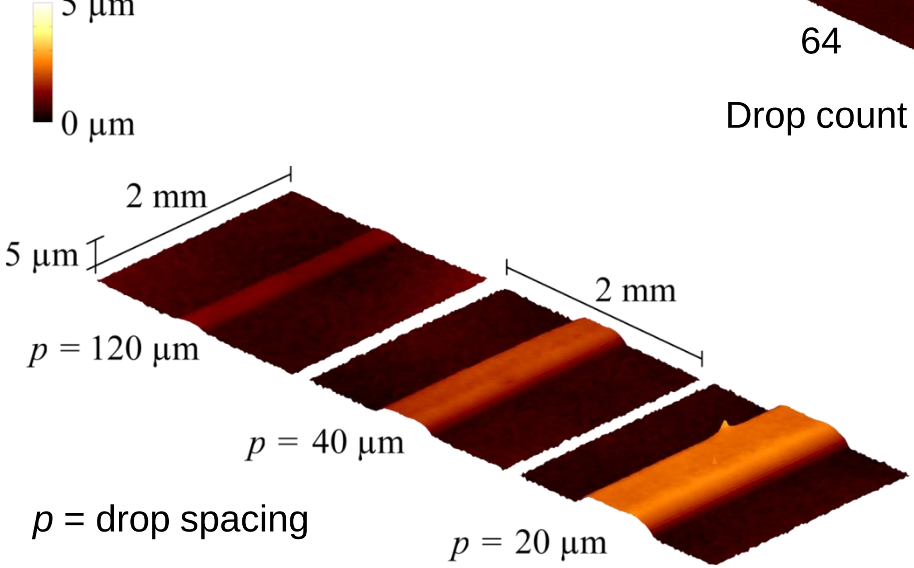
* EC = ethyl cellulose (binder)
** IPA = isopropyl alcohol

All inks:
Surface tension: γ = 24–30 mN/m
(negligible influence on printability)

Topography thick-films printed with the optimized ink composition (ink D)

round structures





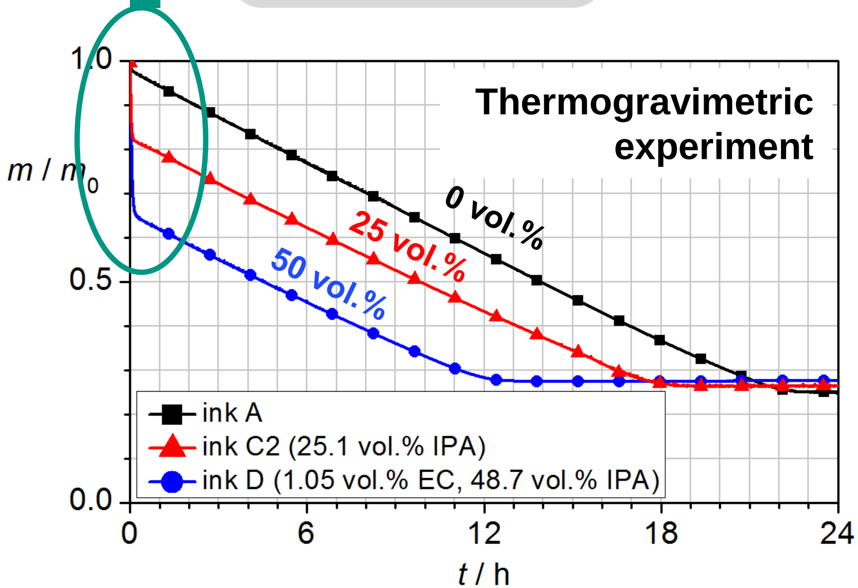
p = drop spacing

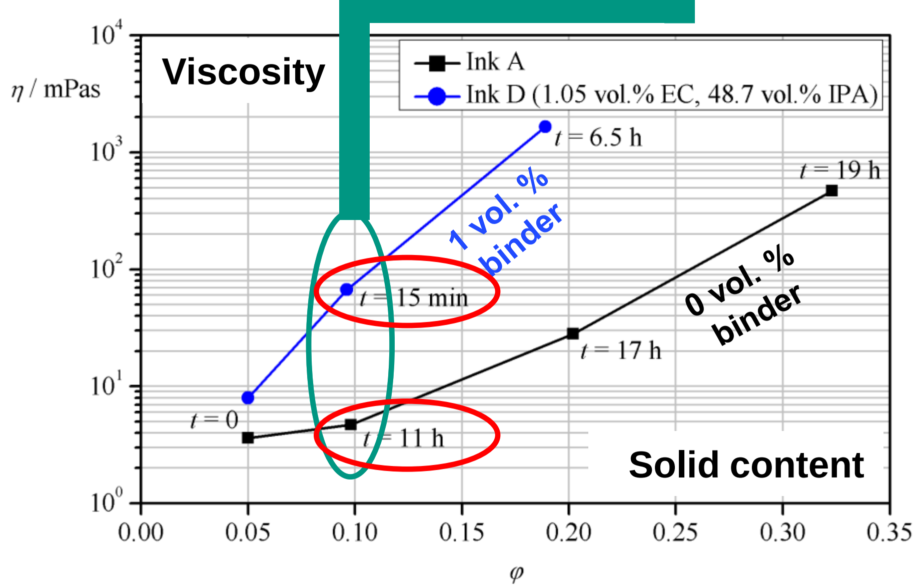
lines

Why does ink D show a better drying behavior?

IPA:
Extremely fast evaporation

Binder:
Much higher viscosity at same volume content

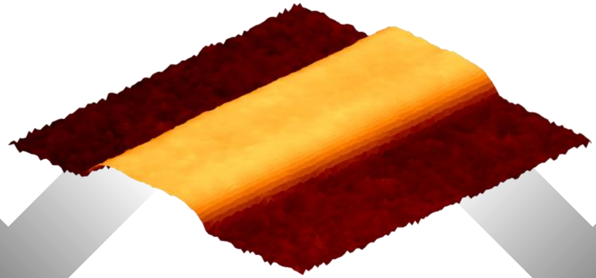




Combination of IPA and binder:
Fast viscosity increase in a very short time

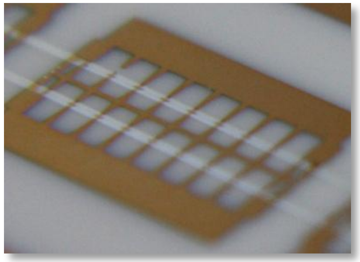
V = 10 µl (approx. 20,000 drops), T = 60°C

BST ink printable ✓ – What‘s next ?



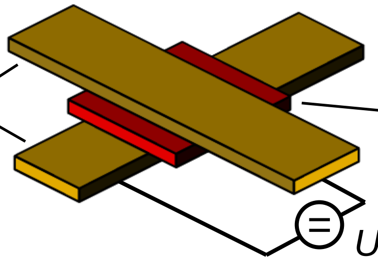
combine printing with other techniques

‚selective printing‘ + lithographic metallisation



use the high vertical resolution for new device layouts

‚fully printed‘



Inkjet printed BST lines

- Material characterisation

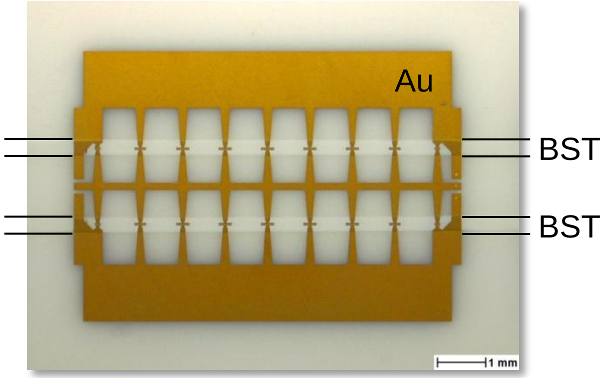
	Measured values	Literature*
Relative permittivity	270 ± 20	285
Dielectric loss	0.09 ± 0.02	0.07
Tunability (@ E = 6.7 V/µm)	25 ± 1 %	27 %

All values at f = 10 GHz

Literature values:* **screen printed BST thick-films; Zhou et al., *J Electroceram.* 24 (2010)

→ **similar properties to conventional screen printed thick-films** ✓

- First high frequency phase shifters on inkjet printed BST thick-films



→ **Device characteristics:**

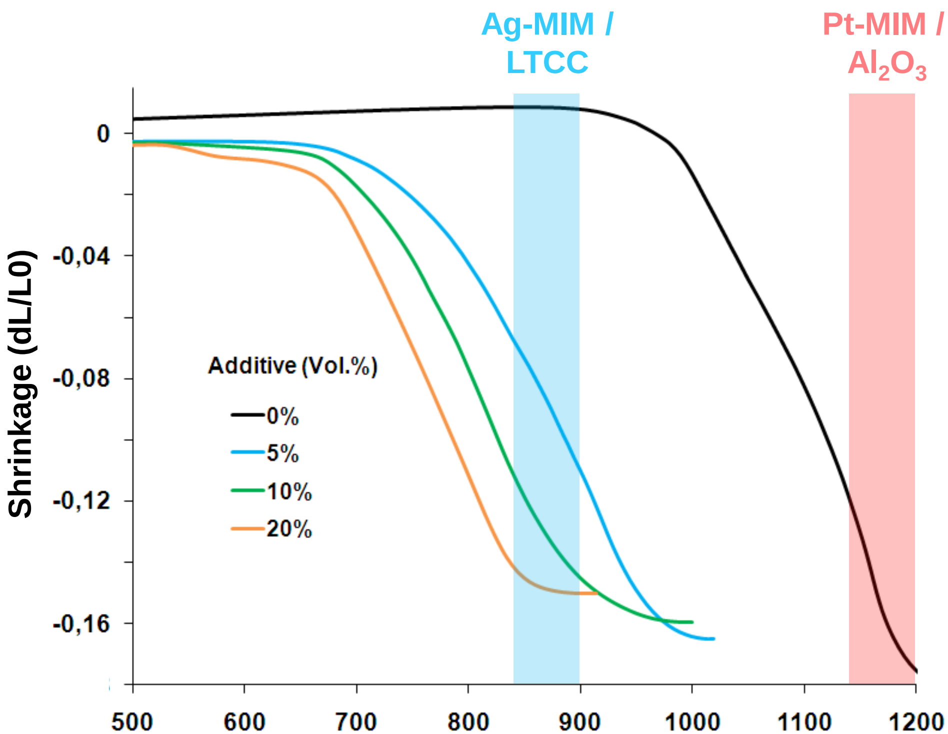
Phase shift: $\Delta\varphi$ = 170°

Figure of Merit. FoM = 20°/dB @ 10 GHz

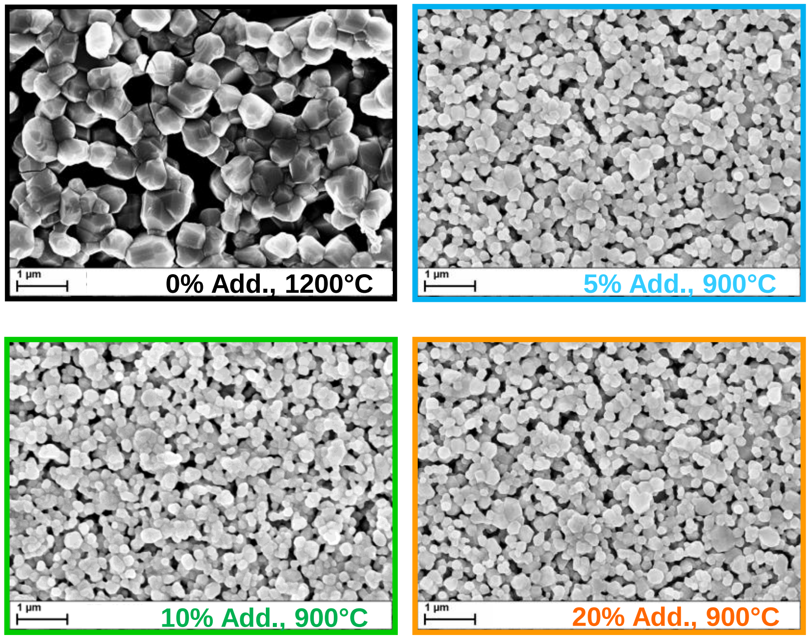
Fully printed devices?

First lower the sintering temperature!

Sintering behaviour of BST pellets



Microstructure of BST thick-films



***T* < 900°C achieved**

Detailed information available:
Int. J. Appl. Ceram. Technol.
DOI: 10.1111/ijac.12116

Low temperature sintered BST thick-films

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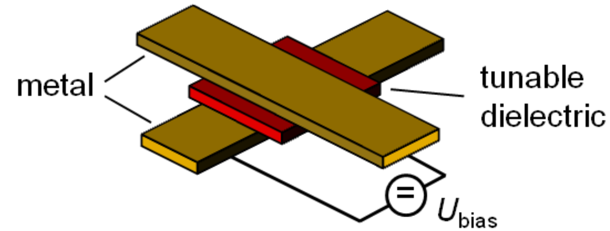
	850°C	1150°C (optimum tunability)
Relative permittivity	125 ± 5	200 ± 35
Dielectric loss	0.07 ± 0.01	0.10 ± 0.02
Tunability (@ E = 10 V/µm)*	21.4 ± 0.5 %	32 ± 1 %

* U_{bias} = 100 V

! tunability poorer at low sintering temperatures

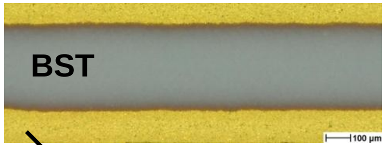
In theory:
Easily compensated through a multiplanar layout



✓ **comparable tunability at a considerably lower voltage**

Printed Ag thick-film

BST thick-films sintered at 850°C



Evaporated Au film

BST on printed Ag thick-film

Tunability:
τ = 30 % (@ U_{bias} = 40 V)

Quality factor:
***Q* = 20** (@ 3 GHz)

next step:
MIM device preparation

Outlook

- Further investigations on printing and co-firing of BST with metal electrodes
- MIM test structures and components
- Thick-film preparation on different substrates, e.g. LTCC
- Printing of tailored material compositions, e.g. through in-situ mixing

Thank you for your attention!