Designing with Piezoceramics

Eberhard Hennig
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Tuesday morning, 21 April, will feature a workshop presented by Eberhard Hennig from PI Ceramic, Germany, on **Designing with Piezoceramics Workshop.**

This workshop will present an overview of PI's rule-of-thumb design guidelines for piezoceramics with specific application examples tailored to power ultrasonic transducers and sensors. It will also include an update on PI's latest lead-free piezoceramic materials with detailed comparisons versus leaded materials on their performance and application differences. The workshop will include step-by-step examples on applying the technology along with applications information such as material selection, preload, heat-treatments, electrodes, surface finish/flatness, power handling, autoclave cycling and vibrational life.

Eberhard Hennig

Other presentations on Tuesday include invited speaker Kenji Uchino (see below), Active Needle Technology for Safe Needle Intervention, Intellectual Property Considerations; Sonic and Ultrasonic Measurements in Oil and Gas Well Logging and A Genesis of Commercial Low Frequency High Power Ultrasonics.

Piezoelectric Ceramics known since the end of the 1940's

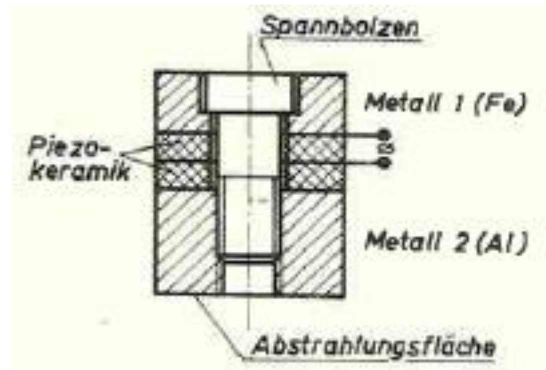
There are no common rules

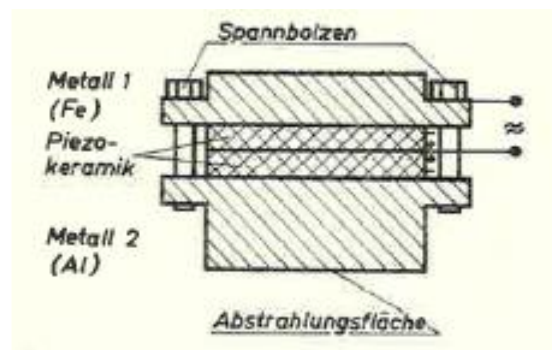
Designing is still based on:

- Theory derived from thermodynamic principles
- Set of Linear equations of state without losses
- Set of linear small signal coefficients
- Knowledge ceramics behavior under different boundary conditions
- Analytical and FEM models
- Trial and error
- IP, not shared with the public

Bolted Langevin-Transducer is a good example to discuss the typical material behavior

- High power application
- High static and dynamic stresses
- Quasistatic direct piezoelectric effect
- Resonant vibration behavior
- Large signal excitation
- 3-D deformation
- Heat dissipation
- Combination of different materials
- Mismatch in the thermal expansion





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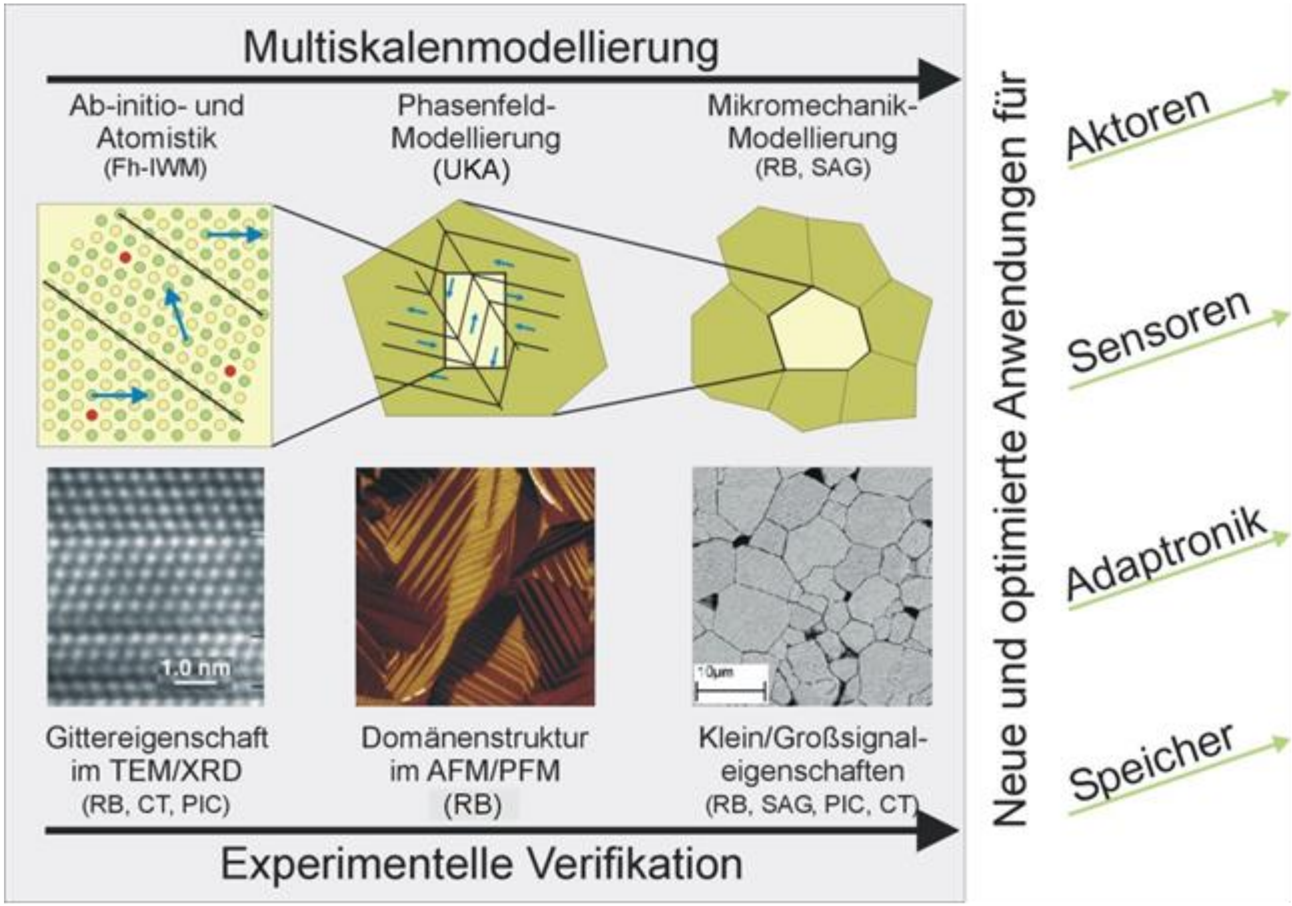
Designing with Piezoceramics

Synthetic polycrystalline materials

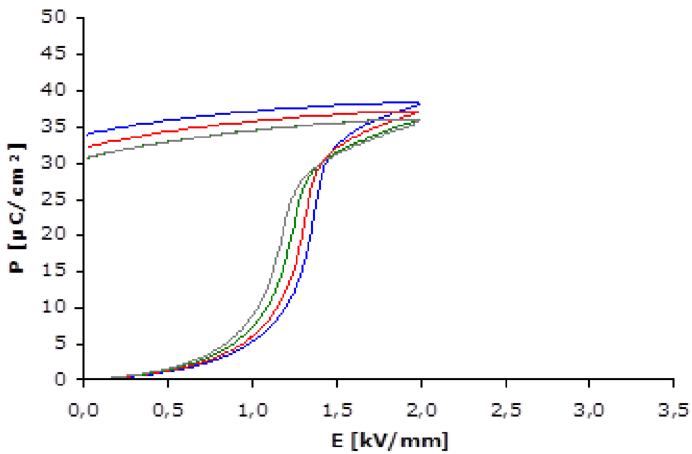
All length scales must be considered

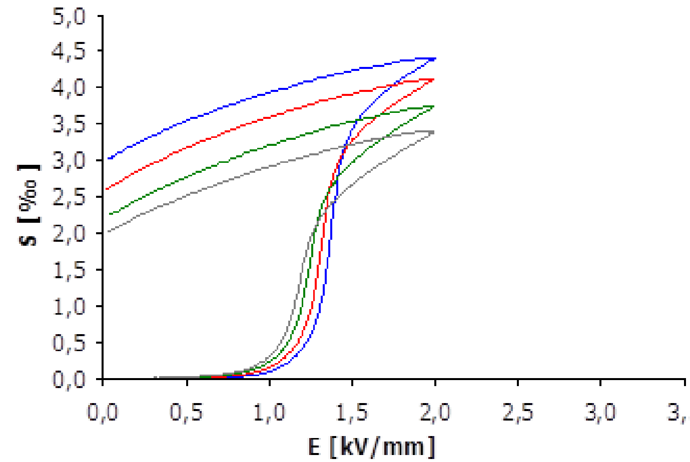


Piezoelectric Ceramics

Why we have a macroscopic piezoelectric effect?

- Ferroelectric material
- Domains can be switched
- After polarization we have a remnant strain and polarization
- Aligned domain structure
- Higher internal energy





Piezoelectric Ceramics

Why we have a macroscopic piezoelectric effect?

Piezoelectricity is the Electrostriction linearized by the remnant polarization

Total strain

$$S_{3t} = Q_{33}(P_r + P_3)^2 = Q_{33}P_r^2 + 2Q_{33}P_rP_3 + Q_{33}P_3^2$$

Remnant strain

$$S_r = Q_{33}P_r^2$$

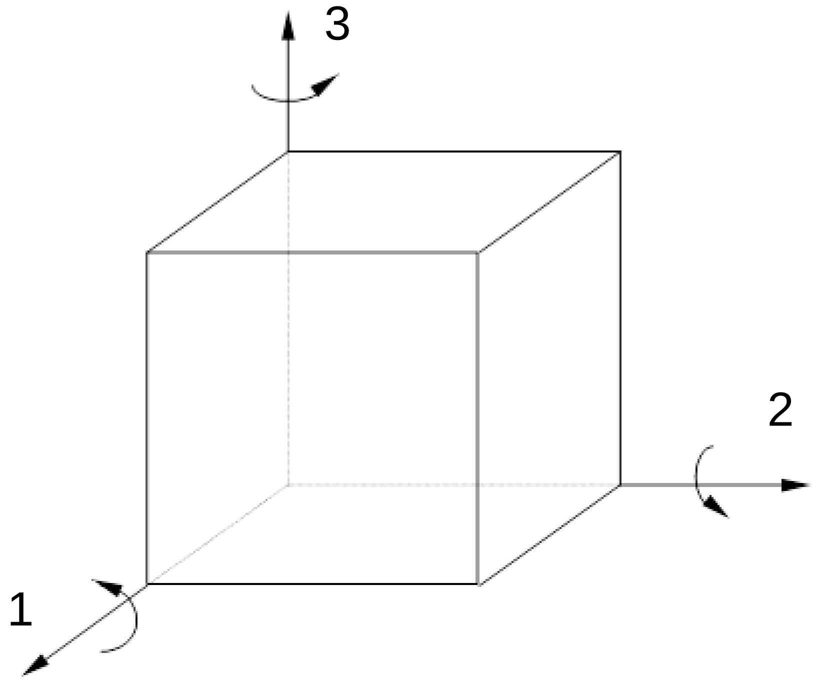
Induced strain

$$S_3 = 2Q_{33}P_rP_3 = g_{33}P_3 = g_{33}\varepsilon_{33}E_3 = d_{33}E_3$$

Piezoelectric Ceramics

Why we have a macroscopic piezoelectric effect?

- Material is considered as homogeneous
- After sintering - isotropic
- After polarizing – anisotropic (symmetry 6mm)
- Polarization direction – 3-axis



Thermodynamic Theory

Piezoelectric Ceramics

Existing piezoelectric, elastic and dielectric coefficients

- Small signal – linear behavior
- Dependent and independent variables
- Boundary conditions (intensive, extensive)
- Real part (do we need the imaginary part?)

	T_1	T_2	T_3	T_4	T_5	T_6	E_1	E_2	E_3
S_1	s_{11}	s_{12}	s_{13}						d_{31}
S_2	s_{12}	s_{11}	s_{13}						d_{31}
S_3	s_{13}	s_{13}	s_{33}						d_{33}
S_4				s_{44}				d_{15}	
S_5					s_{44}		d_{15}		
S_6						$2(s_{11}-s_{12})$			
D_1					d_{15}		ε_{11}		
D_2				d_{15}				ε_{11}	
D_3	d_{31}	d_{31}	d_{33}						ε_{33}

$\{s_{ij}\}^E$

$\{s_{ij}\}^D$

$\{c_{ij}\}^E$

$\{c_{ij}\}^D$

$\{\varepsilon_{ij}\}^T$

$\{\varepsilon_{ij}\}^S$

$\{g_{ij}\}$

$\{e_{ij}\}$

$\{h_{ij}\}$

Standards
IEC 483 / EN 50324-1,2:1998

Piezoelectric Ceramics
Basic equation of state

- Small signal coefficients (matrix)
- Dependent and independent variables (vectors)
- linear behavior

$$S=s^{E}T+dE$$

$$D=dT+\varepsilon^{T}E$$

$$T=c^{E}S-eE$$

$$D=eS+\varepsilon^{S}E$$

$$S=s^{D}T+gD$$

$$E=-gT+\beta^{T}D$$

$$T=c^{D}S-hD$$

$$E=-hS+\beta^{S}D$$

Material properties

Piezoelectric Ceramics

Data sheet

- Mostly typical values
- Not all coefficients are given
- Not recommended for FEM

Coefficient matrix

- Measured on (a small number of) special samples
- Not representative for normal production variations
- Quality define the simulation results
- Critical interpretation required

Complete material data set PIC181

Coefficient	Unit	Value	Coefficient	Unit	Value
Density	kg/m³	7,85E+03	N1	Hzm	1646
			N3	Hzm	2004
Qm		2200	N5	Hzm	1222
			Np	Hzm	2265
ε 11Tr		1224	Nt	Hzm	2302
ε 33Tr		1135			
ε 11Sr		740	d31	m/V	-1,08E-10
ε 33Sr		624	d33	m/V	2,53E-10
tan δ		3,0E-3	d15	m/V	3,89E-10
k31		0,315	g31	Vm/N	-1,08E-02
k33		0,662	g33	Vm/N	2,52E-02
k15		0,629	g15	Vm/N	3,59E-02
kp		0,551			
kt		0,459	e31	N/Vm	-4,50
			e33	N/Vm	14,70
Poisson (σ)		0,35	e15	N/Vm	11,00
s11E	m²/N	1,175E-11	c11E	N/m²	1,523E+11
s33E	m²/N	1,411E-11	c33E	N/m²	1,341E+11
s55E	m²/N	3,533E-11	c55E	N/m²	2,830E+10
s12E	m²/N	-4,070E-12	c12E	N/m²	8,909E+10
s13E	m²/N	-4,996E-12	c13E	N/m²	8,547E+10
s44E	m²/N	3,533E-11	c44E	N/m²	2,830E+10
s66E	m²/N	3,164E-11	c66E	N/m²	3,161E+10
s11D	m²/N	1,058E-11	c11D	N/m²	1,550E+11
s33D	m²/N	7,930E-11	c33D	N/m²	1,664E+11
s55D	m²/N	2,134E-11	c55D	N/m²	4,686E+10
s12D	m²/N	-5,235E-12	c12D	N/m²	9,182E+10
s13D	m²/N	-2,268E-12	c13D	N/m²	7,061E+10
s44D	m²/N	2,134E-11	c44D	N/m²	4,686E+10
s66D	m²/N	3,164E-11	c66D	N/m²	3,161E+10

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Piezoelectric Ceramics

Data sheet

- Mostly typical values
- Not all coefficients are given

Material selection

- More than100 different compositions on the market
- Most of then classified as PZT 4 or PZT 8 comparable
- Selection is difficult
- Every composition have his own characteristic

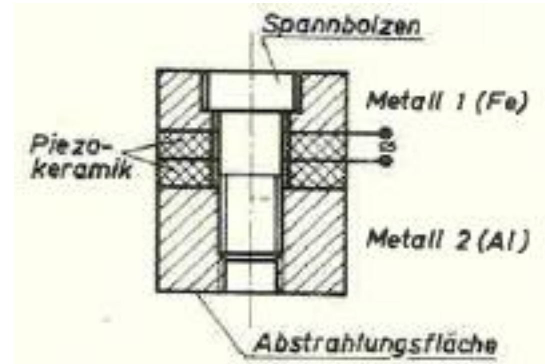
Parameter		Hard PZT	
Common		PZT 4	PZT 8
DOD-STD-1376A		DOD I	DOD III
EN 50324-1		100	300
T_C	[°C]	≥ 310	≥ 290
$\varepsilon_{33} / \varepsilon_0$		1300	1300
tan δ $[10^{-3}]$		6	4
tan δ $[10^{-3}]$ 400 V		40	10
d_{33}	[pm/V]	290	220
k_p		0,56	0,51
Q_m		500	1000

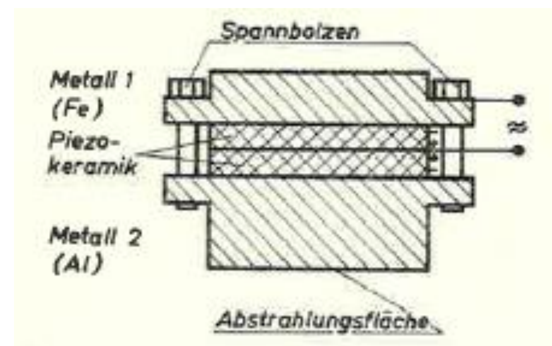
Bolted Langevin-Transducer is a good example to discuss the typical material behavior

- Piezo ceramic elements
- Head and tail mass
- Preload by a Bolt
- Metal shims for electrical connection

- Spring – Mass - Model
- λ / 2 - Resonator

- Problem
- Boundary conditions at the interfaces
- Push no pull





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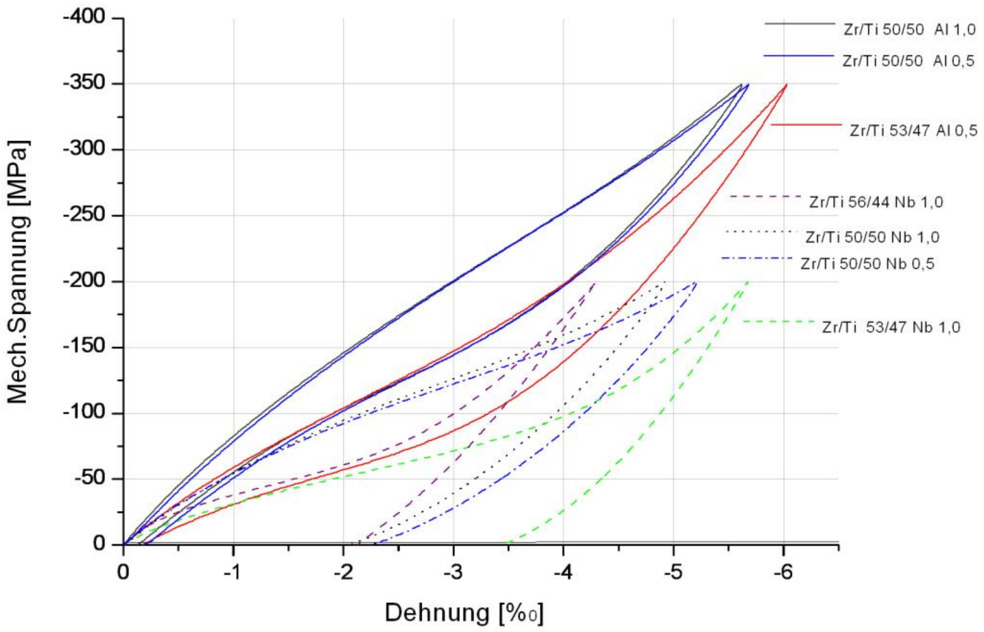
Mechanical stress

Typical behavior

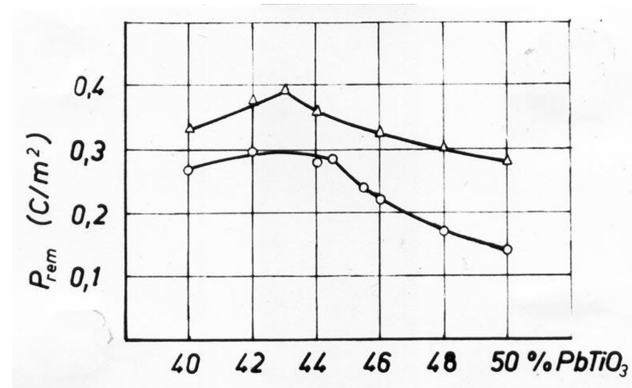
- Ferro elastic hysteresis – non-linear behavior
- Comparison "hard" and "soft"
- Change in remnant strain after load
- "hard" PZT strongly time dependent

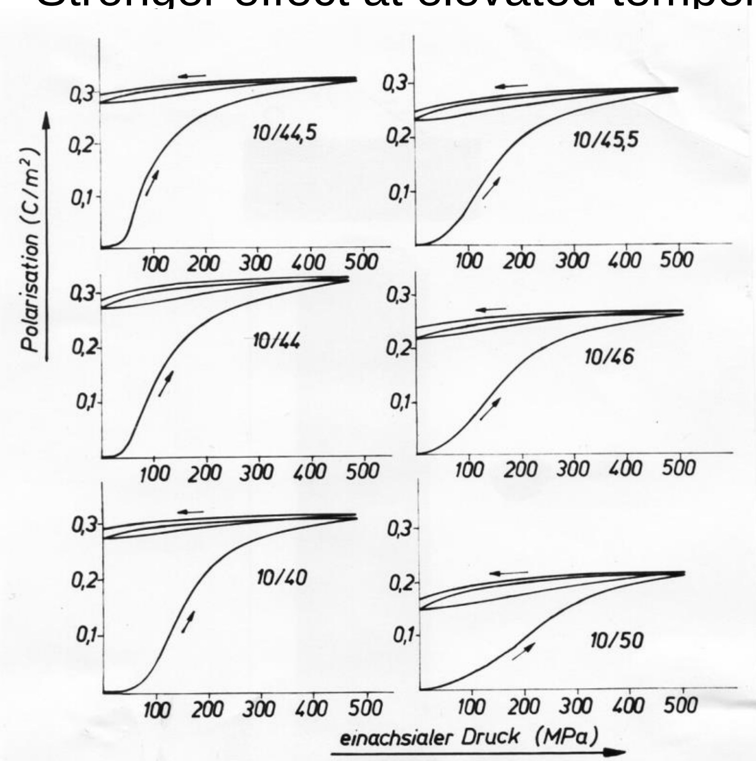


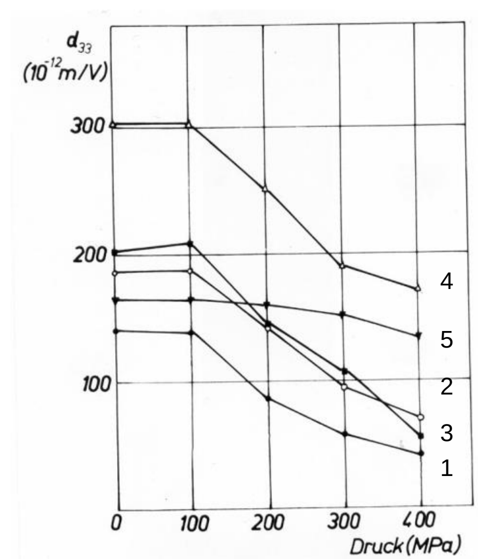
Stress vs. strain

Typical behavior

- Uniaxial compression stress parallel to polarization
- Non-linear charge release
- Change in remnant polarization after load
- Change in piezoelectric properties
- Difference between 1. and 2. cycle
- Stronger effect at elevated temperatures



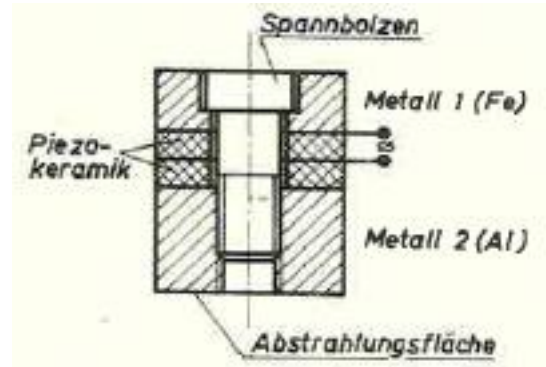




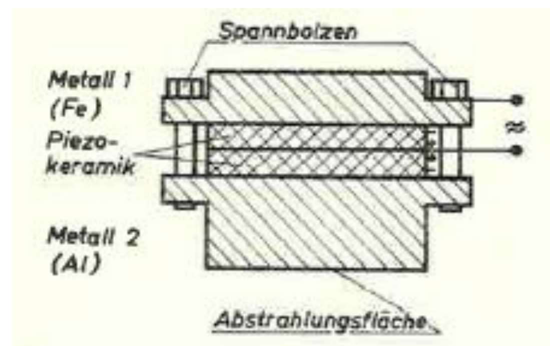
	Mol% $PbTiO_3$
1	40
2	44
3	44,5
4	46
5	50

Bolted Langevin-Transducer is a good example to discuss the typical material behavior

- Preload changes the material properties
- After mounting a settling must be expected
- Big influence from the elasticity of the bolt
- Take into account the real stress distribution



D=dT **$Q/A=nd_{33}T_3$**



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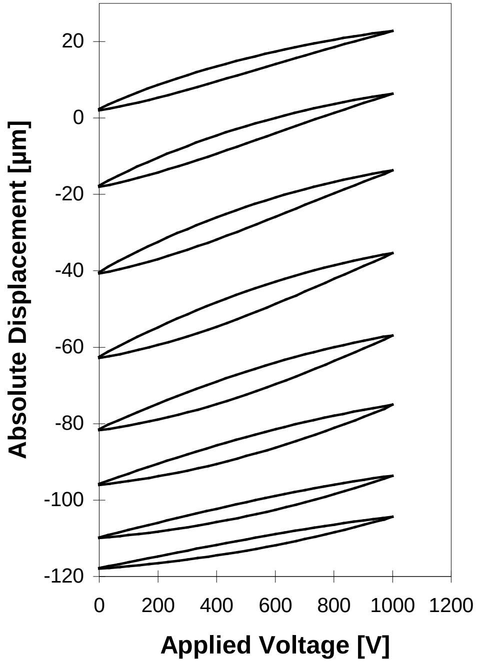
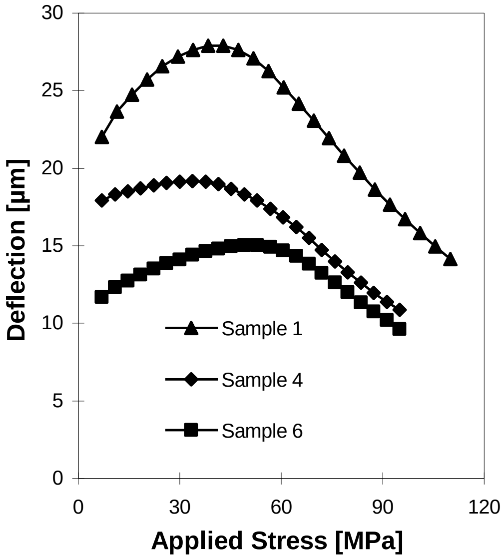
- Preload cannot be measured by the charge
- Good method to control the mounting

- Non-linearity's
- Inhomogeneous stress distribution
- Surface matching at the interfaces
- Time dependence and relaxation

Typical behavior constant load

- Mechanical stress – depolarizing effect (only 90° domains)
- Electrical field – polarizing effect (90° and 180° domains; parallel to P_r)
- Electrical field – depolarizing effect (90° and 180° domains; anti-parallel to P_r)
- Domain contribution increases strain
- Domain contribution increases losses
- Dependent on crystal structure (composition)





Mechanical stress + Electric field

Typical behavior constant load

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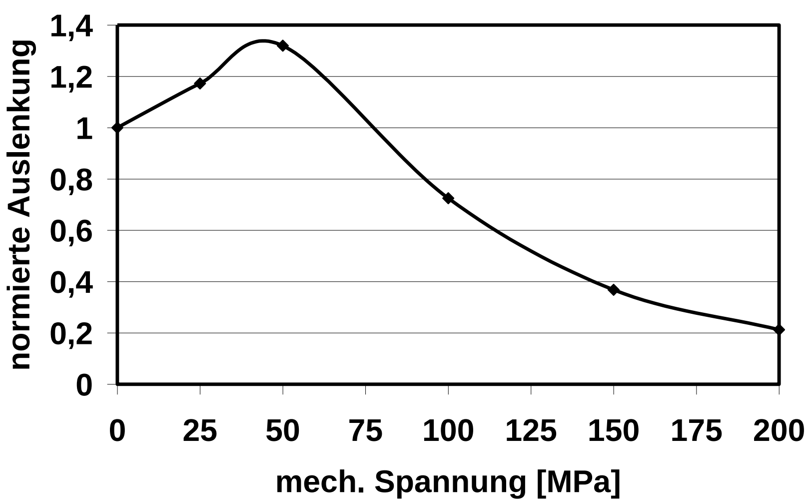
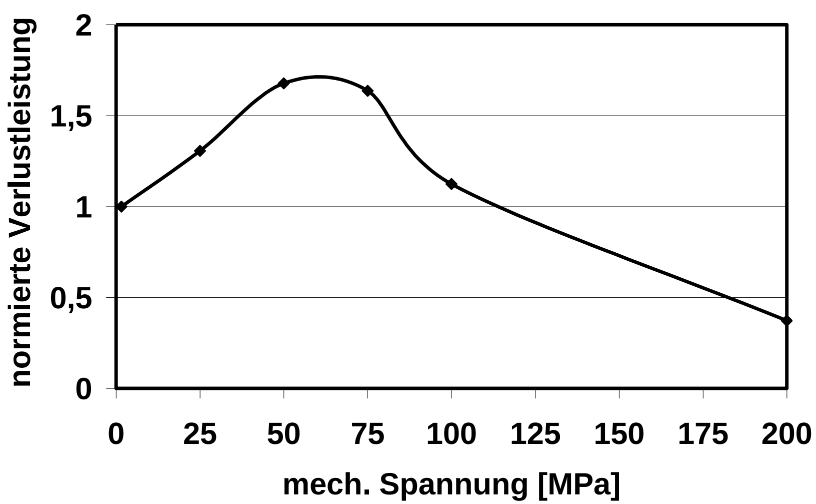




Mechanical stress + Electric field

Typical behavior   Spring load

- Domain reorientation depending on field direction and amplitude
- Changes in the state of polarization (P_r, S_r)
- Changes in the small signal coefficients
- Nonlinear behavior
- Increase of loss power

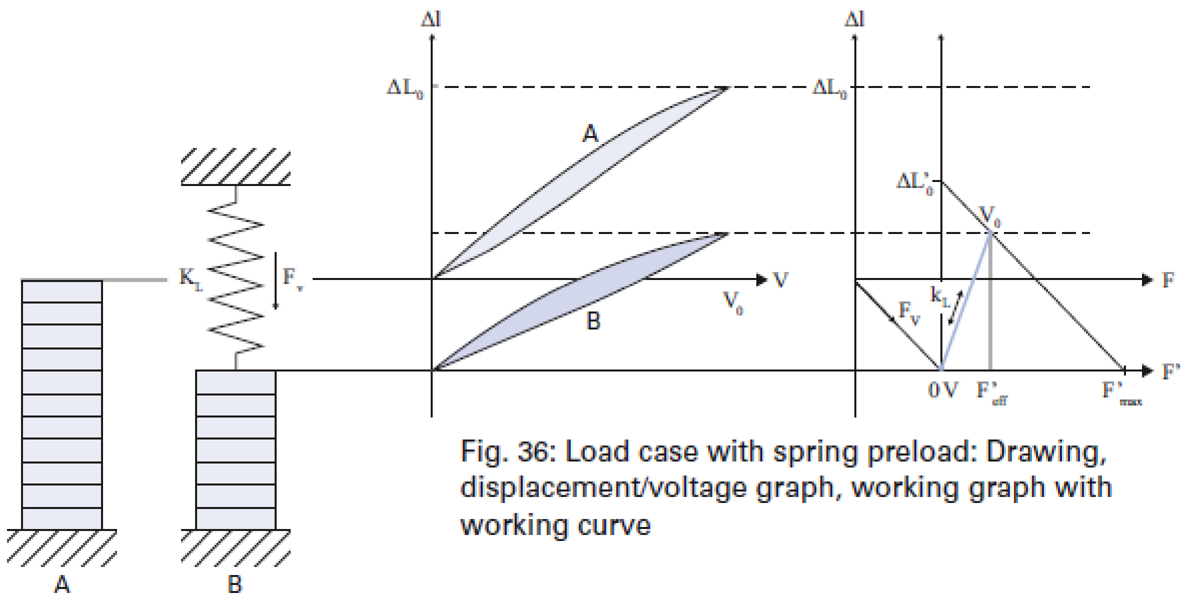
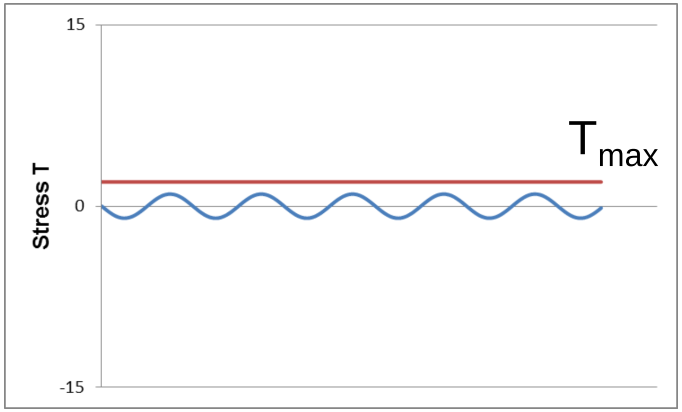


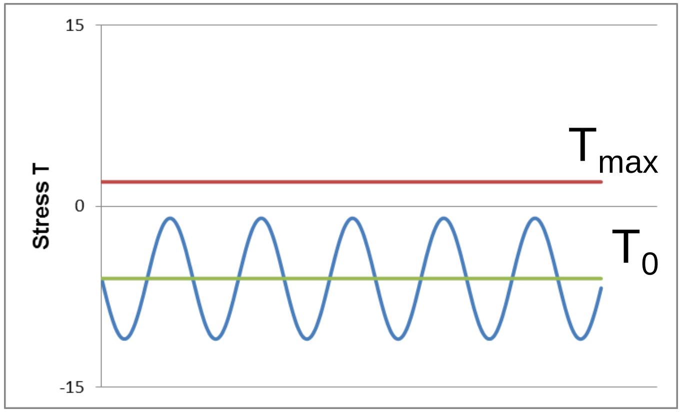
Fig. 36: Load case with spring preload: Drawing, displacement/voltage graph, working graph with working curve

Typical behavior (longitudinal mode)

Without preload amplitude is limited by
•Tensile strength of the ceramic
•*Non-linearity's*
•*Self-heating*
•*Electrical (AC) depolarization*

With preload higher amplitudes are possible
•No tensile stress
•*Non-linearity's*
•*Self-heating*
•*Electrical (AC) depolarization*

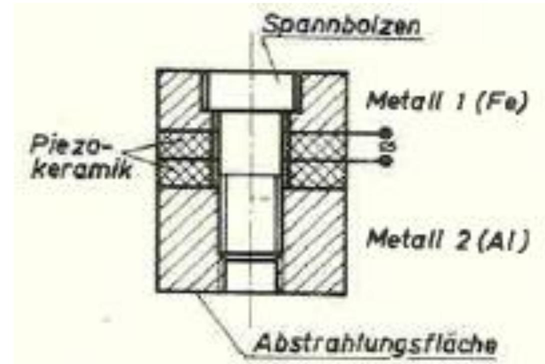




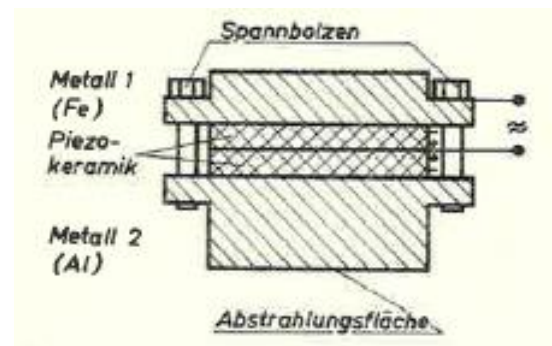
Simplified explanation

Bolted Langevin-Transducer is a good example to discuss the typical material behavior

- Preload changes the material properties
- After mounting a settling must be expected
- Big influence from the elasticity of the bolt
- Take into account the real stress distribution



- Deformation stress dependent
- Preload increases losses
- Expansion – acting against a spring
- Contraction – supported by the spring



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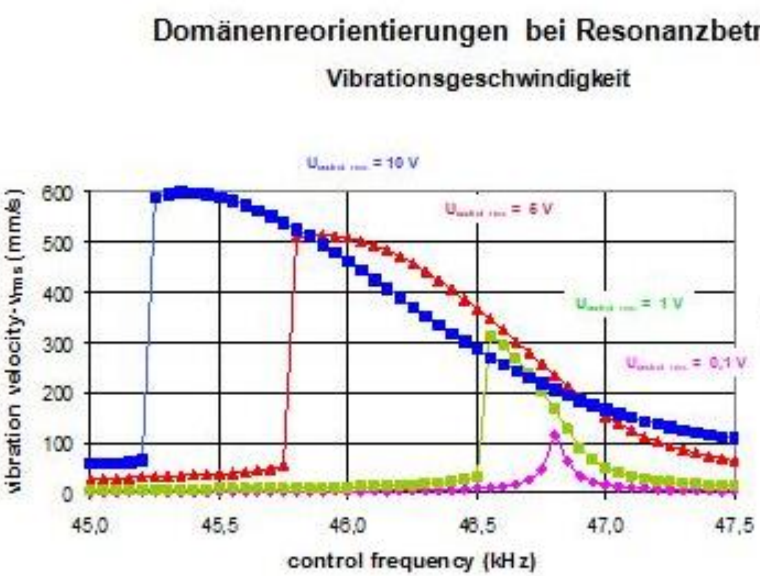
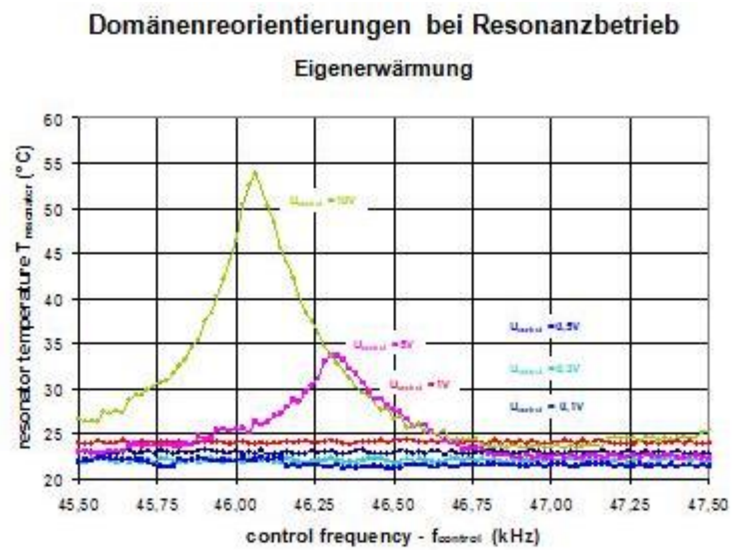
- Non-linearity's
- Inhomogeneous stress distribution
- Surface matching at the interfaces
- Time dependence and relaxation

Typical behavior Constant voltage, serial resonance

- Nonlinear behavior
- Current proportional to vibration velocity
- Frequency shift
- Changes in the small signal coefficients
- Increase of loss power





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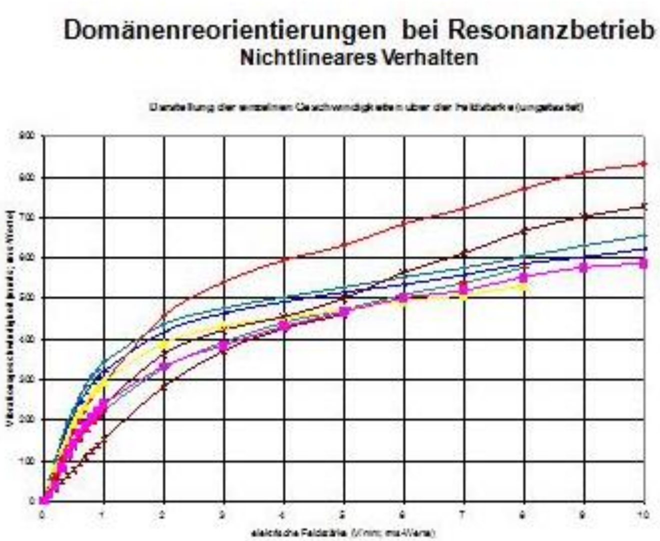
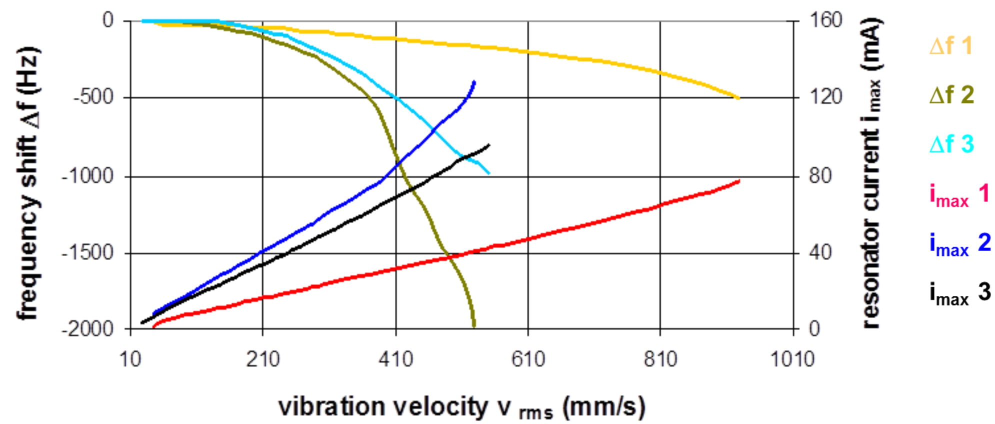
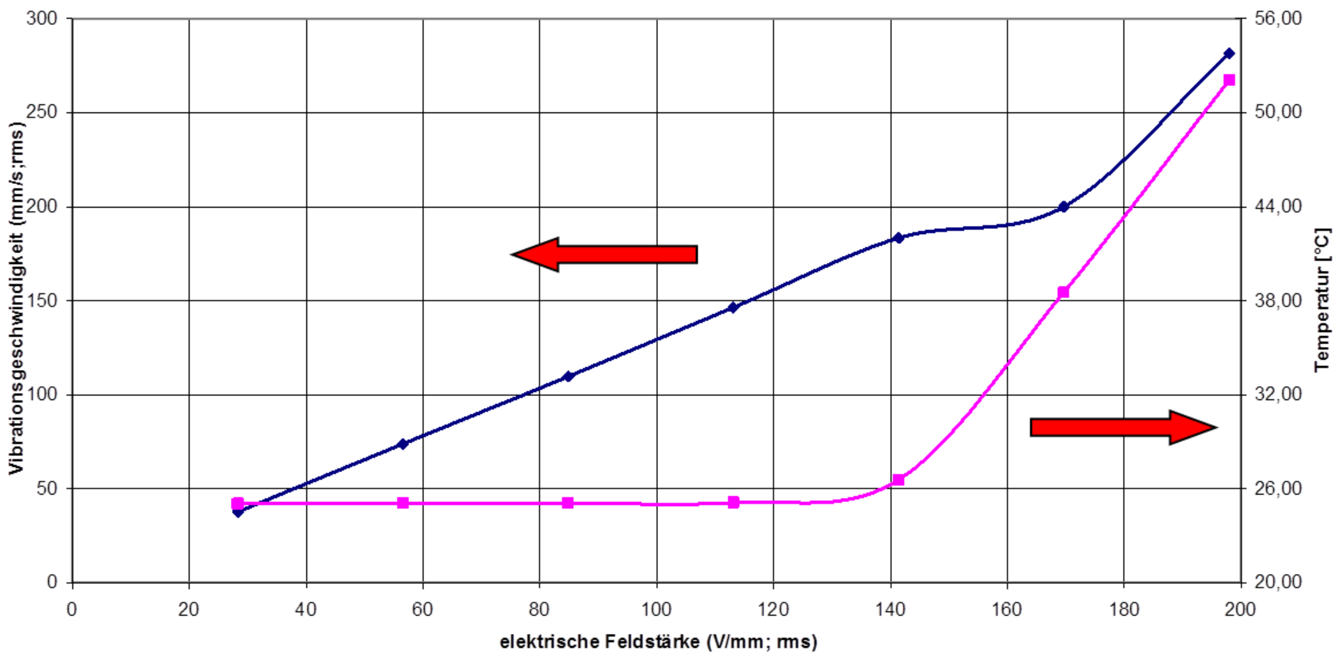




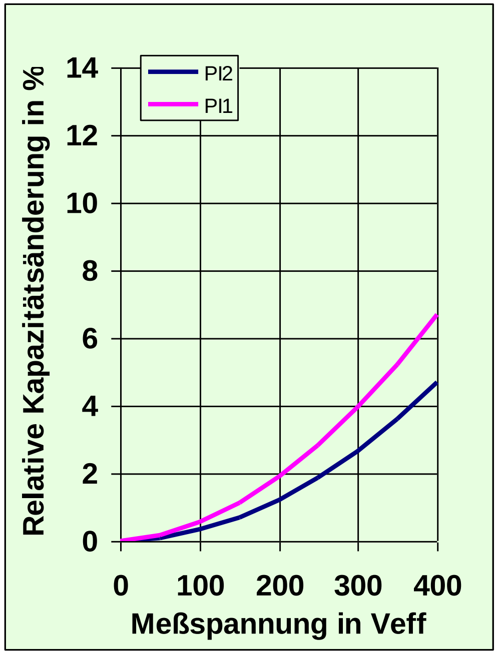
Typical behavior Constant voltage, out of resonance

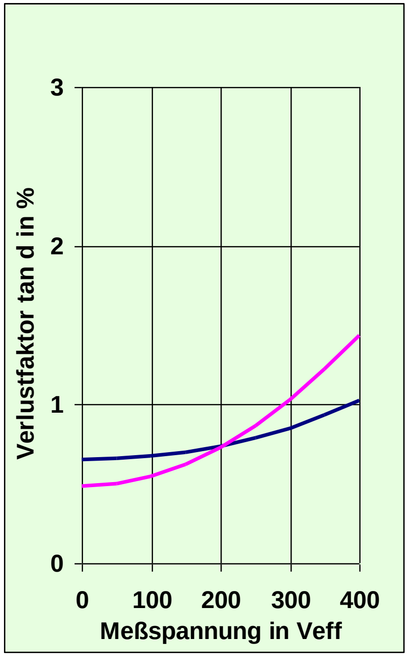
- Nonlinear behavior
- Current proportional to vibration velocity
- Frequency shift
- Changes in the small signal coefficients
- Increase of loss power



Typical behavior Dielectric properties

- Domain reorientation depending on field direction and amplitude
- Changes in the state of polarization (P_r, S_r)
- Changes in the small signal coefficients
- Depending on field strength, temperature, time
- Increase of capacitance and loss tangent and loss power





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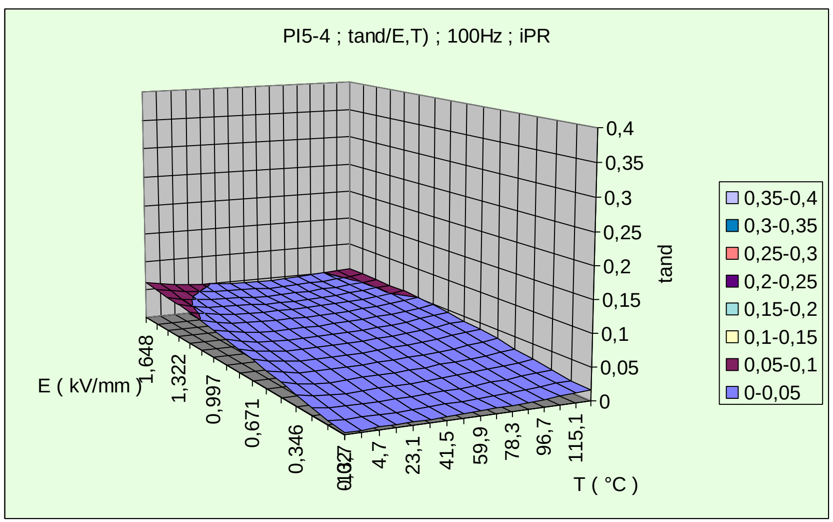
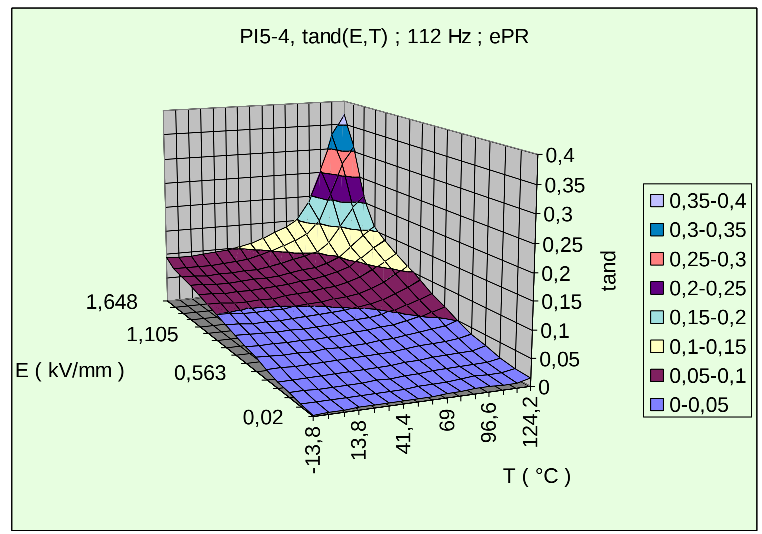


Unipolar
in polarization direction



Unipolar
aigainst polarization direction

AC Electric fields

Typical behavior **Deformation**

- Longitudinal effect
- Transversal effect
- Both effects must be considered

Longitudinal effect

$$S_3 = d_{33} E_3$$

$$\Delta h = d_{33} U$$

Transversal effect

$$S_1 = d_{31} E_3$$

$$S_2 = d_{31} E_3$$

$$\Delta R = d_{31} R / h \; U$$

Radius: R
Thickness: h

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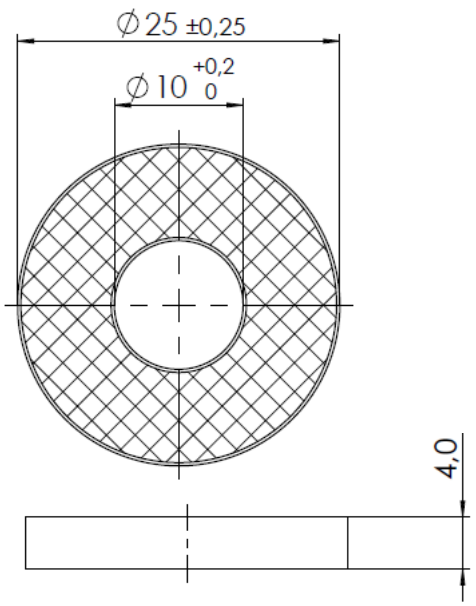
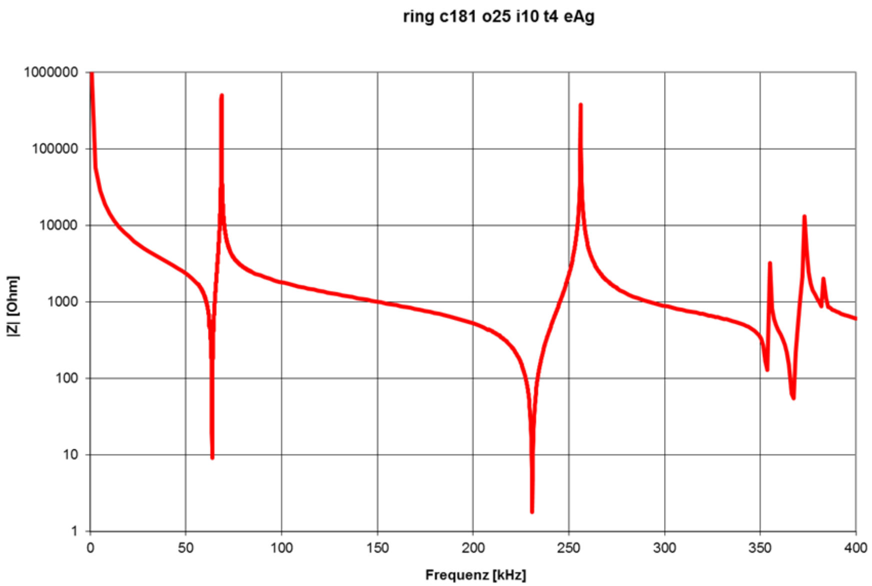
Typical behavior Deformation

- Longitudinal effect
- Transversal effect
- Both effects must be considered
- Rings are driven below the lowest resonance



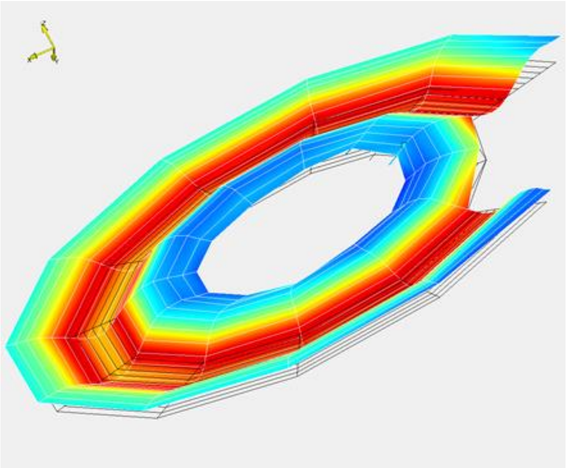


Radius: R_a; R_i
Thickness: h

Typical behavior   Deformation

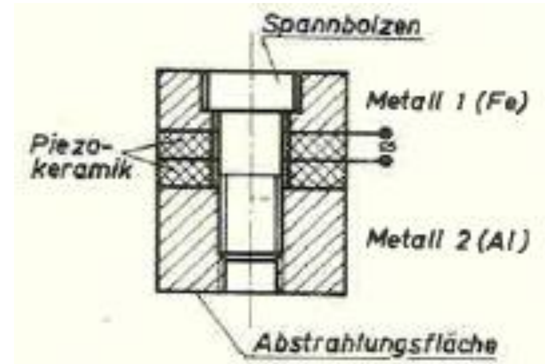
- Longitudinal effect
- Transversal effect
- Both effects must be considered
- Rings are driven below the resonance (example 40 kHz)

New Measuring Equipment – MSA - 100 - 3D



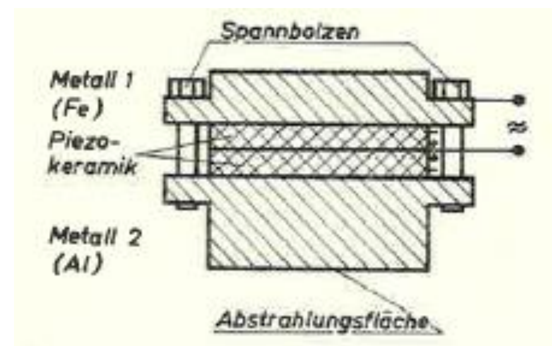
(3 videos)

Bolted Langevin-Transducer is a good example to discuss the typical material behavior



- Preload changes the material properties
- After mounting a settling must be expected
- Big influence from the elasticity of the bolt
- Take into account the real stress distribution

No surface clamping



- Full longitudinal stroke
- Large transversal stroke
- Friction at the interfaces
- Additional (local) heat generation
- Inhomogeneous stress distribution

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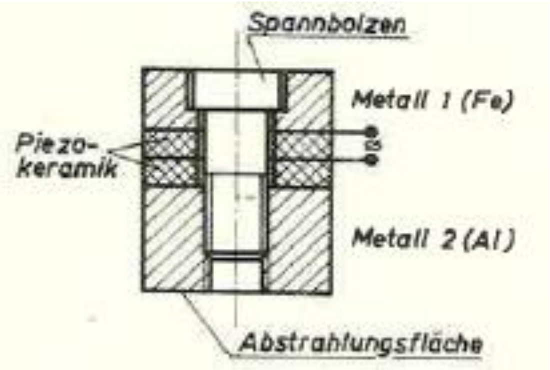
Bolted Langevin-Transducer is a good example to discuss the typical material behavior



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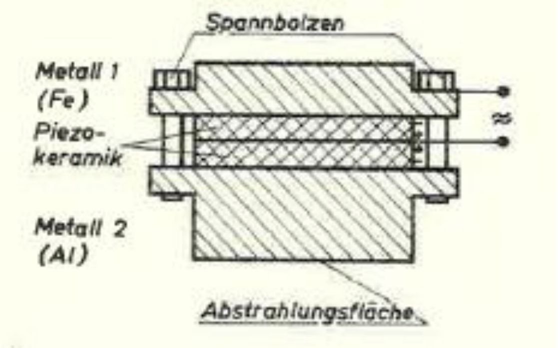
- Take into account the real stress distribution

Full surface clamping



KWH KOMBINAT VEB KERAMISCHE WERKE HERMSDORF

- Reduced longitudinal stroke
- No transversal stroke at the interfaces
- Additional stresses from the clamping
- Inhomogeneous stress distribution
- Exciting of radial resonances

Thermal Properties – Self heating

•Loss power
$P \sim f \tan\delta \, C \, U^2$
effective values must be used for tanδ and C

•Specific heat capacity
Approx. 350 J / kg K

•Thermal conductivity
Approx. 1,1 W / m K

Temperatur distribution in a Stack actuator (Dm=16mm; l=120 mm)

Thermal expansion

Typical behavior

- Nonlinear behavior
- Contraction in poling direction
- Expansion perpendicular to poling direction
- Expansion in poling direction (mechanically de-poled)
- Irreversible change between 1. and 2. cycle

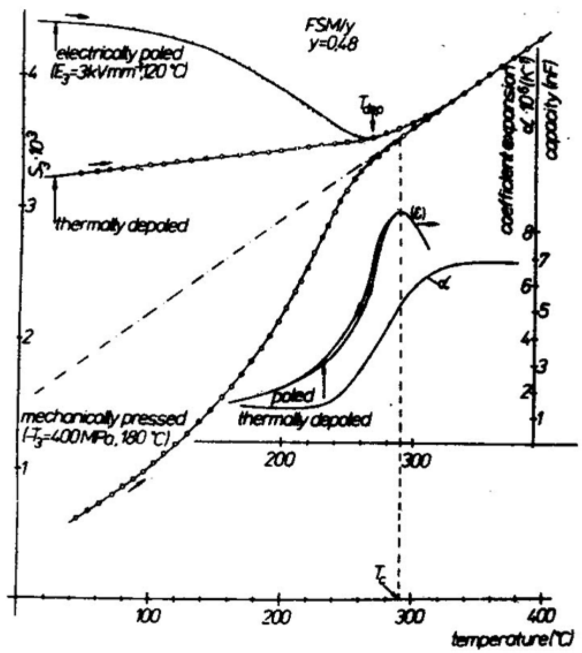


Abb. 3 Temperaturabhängigkeit der thermischen Ausdehnung S_3 und der Probenkapazität C von elektrisch gepolten, mechanisch gedrückten und thermisch depolarisierten Proben der Zusammensetzung y = 0,48

Quelle: H. Arndt, E. Hennig, KTB MLU Halle, Ferroelektrizität 84, 1984

Typical behavior

- •Nonlinear behavior
- •Contraction in poling direction
- •Expansion perpendicular to poling direction
- •Expansion in poling direction (mechanically de-poled)
- •Irreversible change between 1. and 2. cycle

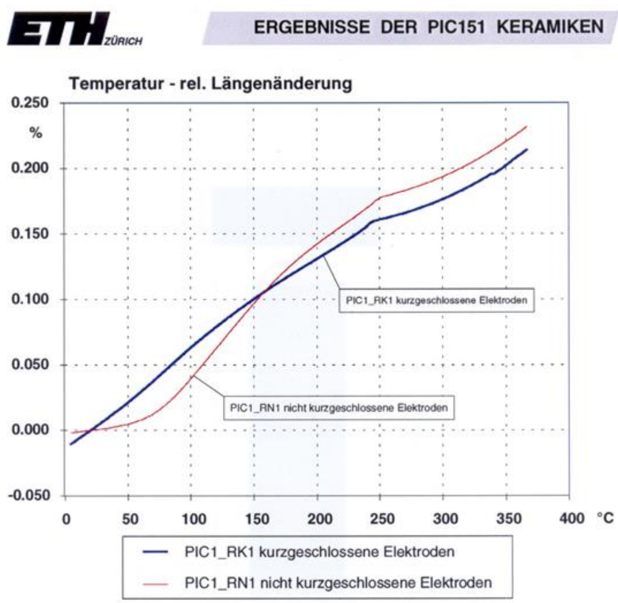


Bild 3. Relative Längenänderung der piezoelektrisch intakten PIC151 Proben bei offenen und kurzgeschlossenen Elektroden.

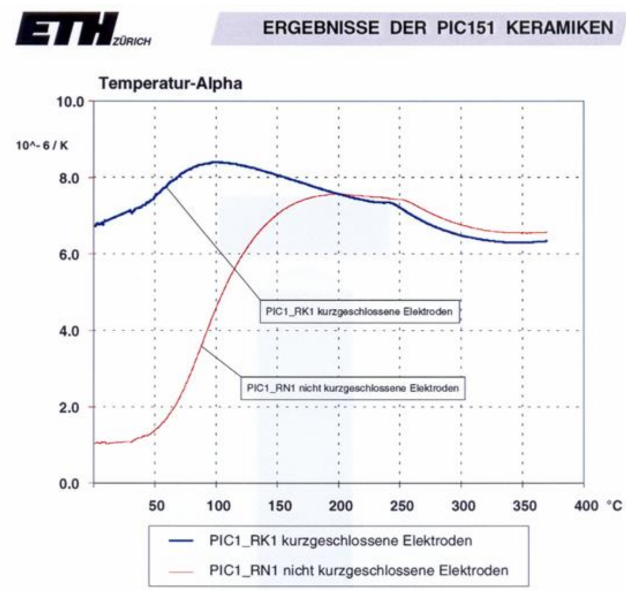
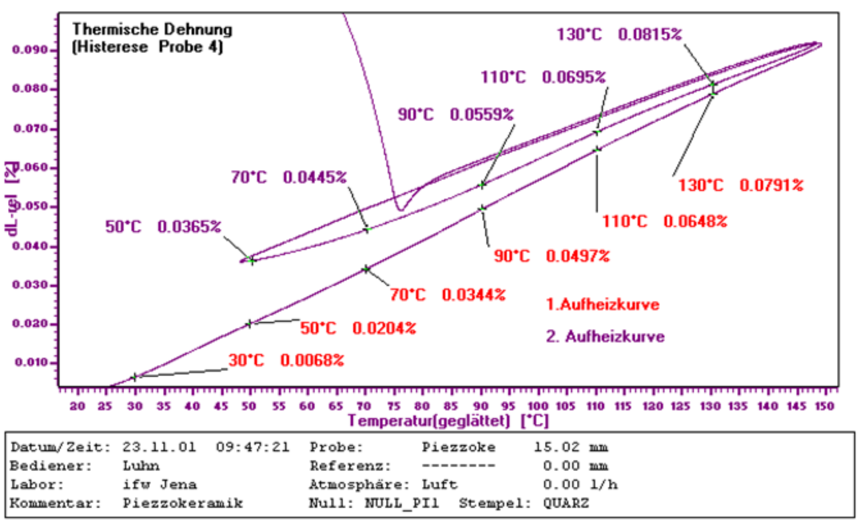


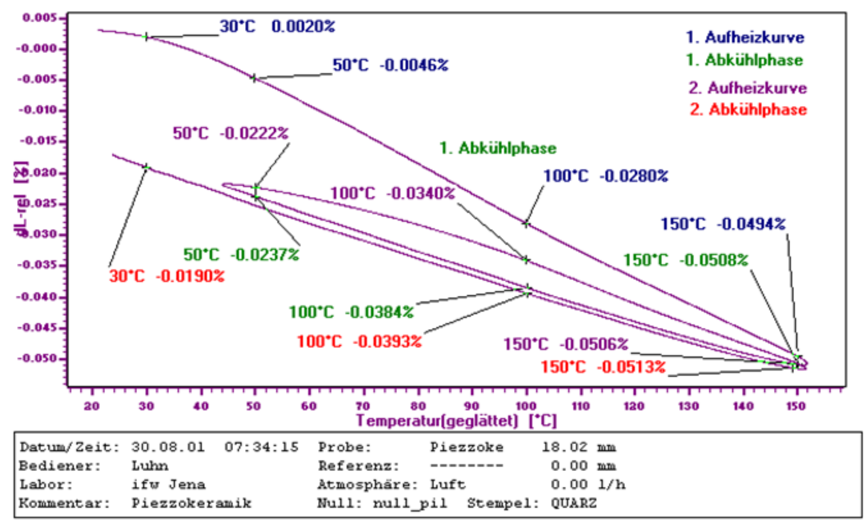
Bild 4. Längenausdehnungskoeffizienten von PIC151 Keramik bei offenen und kurzgeschlossenen Elektroden.

Quelle: ETH Zürich / PI Ceramic, interner Untersuchungsbericht 1996, unveröffentlicht

Typical behavior

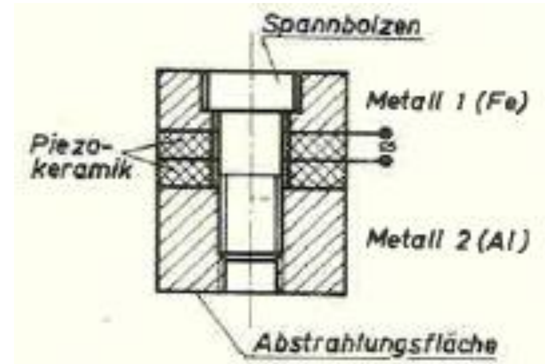
- Nonlinear behavior
- Contraction in poling direction
- Expansion perpendicular to poling direction
- Expansion in poling direction (mechanically de-poled)
- Irreversible change between 1. and 2. cycle





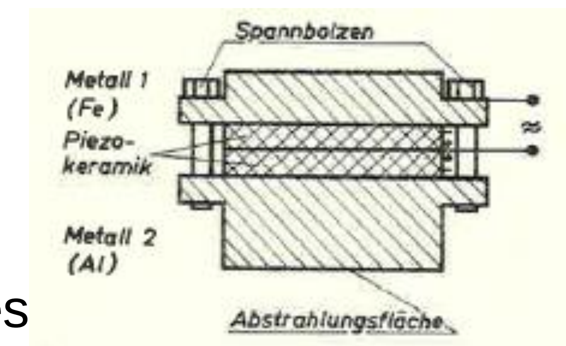
Discussion

Bolted Langevin-Transducer is a good example to discuss the typical material behavior



- Langevin transducer is more than a compromise

- Most heat dissipation in the ceramic volume
- Large temperature gradients
- Risk of overheating
- Temperature control recommended

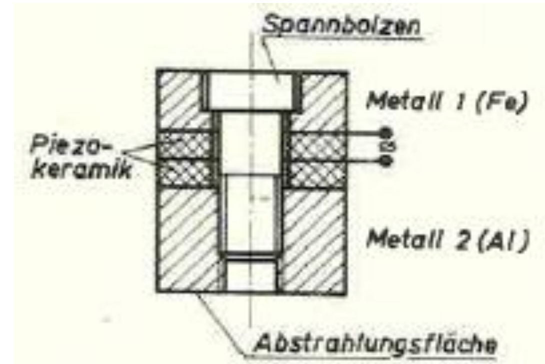


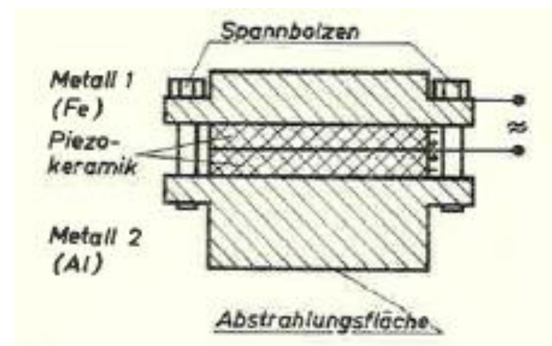
- End masses have a cooling effect
- Additional cooling at the outer and inner surfaces

- Strongest influence from the driving voltage or input power

KWH KOMBINAT VEB KERAMISCHE WERKE HERMSDORF

Bolted Langevin-Transducer is a good example to discuss the typical material behavior





KWH KOMBINAT VEB KERAMISCHE WERKE HERMSDORF

- Difference in the thermal expansion behavior between ceramic and metal parts
- Reduced preload during heating
- Big influence from the expansion of the bolt
- Irreversible change of the ceramic thickness

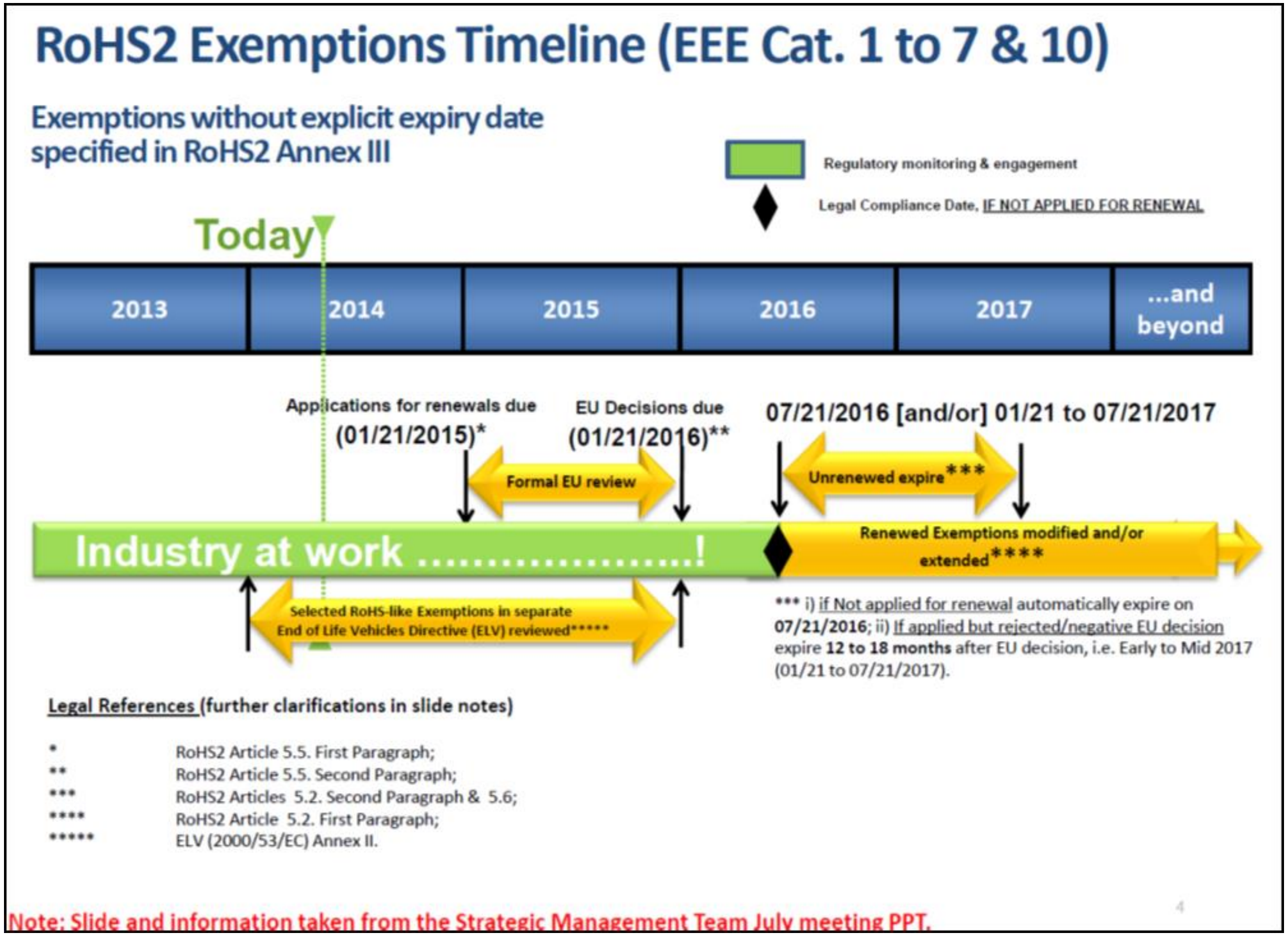
- Relaxation of mounting stresses
- Irreversible change of the ceramic properties

- Temperature cycling is a good method for stabilization
- Control of preload recommended

PIEZOTECHNOLOGY

RoHS – Restriction of the use of certain hazardous substances

Directive 2011/65/EU since 21.07.2011 (RoHS II)



PI Ceramic starts their own R&D activities in 2004

- Investigation of promising compositions
- Working temperature range -40 to 150 °C
- BNT based compositions with MPB
- KNN – LTS and KNN – LT
- Investigation of technological routes

Development focused on:

$(1\text{-}x)(Bi_{0,5}Na_{0,5})TiO_3\text{-}\ xBaTiO_3$	BNBT x
$(1\text{-}x\text{-}y)(Bi_{0,5}Na_{0,5})TiO_3\text{-}\ xBaTiO_3\text{-}\ ySrTiO_3$	BNBST x-y
$(KNaLi)(NbTaSb)O_3$	KNN-LTS, KNN-LT

BNT-based - Sensor and Transducer applications
KNN-based – Actuator, Sensor and Transducer applications

PI Ceramic:
Two patent applications for BNT and KNN based materials

PI Ceramic: since 2011

Technology development

- Conventional mixed-oxide technology (Batch sizes 30 to 50 kg)

Mixing	Reagent grade metal oxide and carbonate powders in **isopropanol** using a disk mill
Calcining	850°C - 950°C
Milling	in **isopropanol** using a disk mill
Granulating	Spray dryer
Pressing	uniaxial press
Sintering	1050°C - 1220°C

PI Ceramic: Pilot production for PIC 700 in 2014

Parameter		PZT	BNT based
		PIC 255	PIC 700
T_C/T_d	[°C]	350	~200
$\varepsilon_{33} / \varepsilon_0$		1750	700
$\varepsilon_{11} / \varepsilon_0$		1650	570
tan δ	[10^{-3}]	20	25
tan δ $_{400\ V}$	[10^{-3}]		70
d_{33}	[pm/V]	400	120
d_{31}	[pm/V]	-180	(-40)
d_{15}	[pm/V]	550	110
k_p		0,62	(0,15)
k_t		0,47	0,4
k_{33}		0,69	0,4
k_{31}		0,35	(0,14)
k_{15}		0,66	0,3

(*) calculated according standard; Correct?

Piezoelectric Ceramics

Data sheet

- Mostly typical values
- Not all coefficients are given

Coefficient matrix

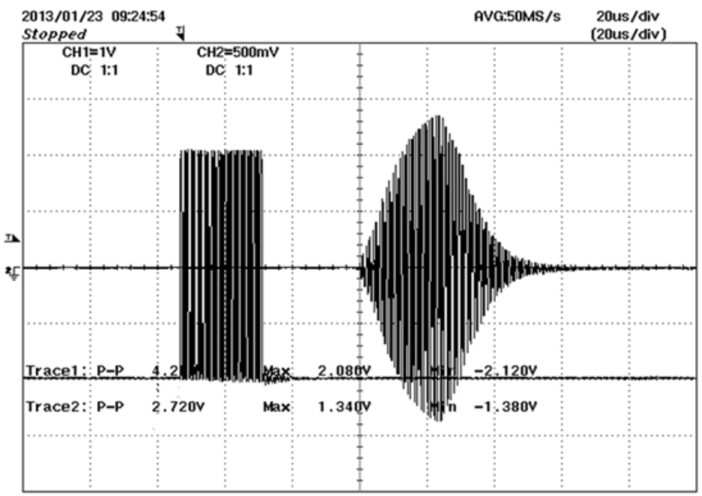
- Measured on (a small number of) special samples
- Not representative for normal production variations

	PI Ceramic GmbH				
	Bearbeiter:	E. Hennig			
	Materialkoeffizienten PIC 700 (small signal)				
	Stand 05.02.2015				
	Änderungen vorbehalten				
Größe	Einheit	Wert	Größe	Einheit	Wert
Dichte	kg/m3	5,65E+03	N1	Hzm	
Q		100	N3	Hzm	2370
			N5	Hzm	1500
eps11T		570	Np	Hzm	
eps33T		700	Nt	Hzm	2600
eps11S					
eps33S			d31	m/V	[-3,60E-11]
tan		0,025	d33	m/V	1,20E-10
			d15	m/V	1,10E-10
k31		[0,14]			
k33		0,4	g31	Vm/N	
k15		0,3	g33	Vm/N	1,94E-02
kp		[0,15]	g15	Vm/N	2,18E-02
kt		0,4			
			e31	N/Vm	
sigma			e33	N/Vm	
			e15	N/Vm	
s11E	m2/N		c11E	N/m2	
s33E	m2/N	9,690E-12	c33E	N/m2	1,580E+11
s55E	m2/N	2,589E-11	c55E	N/m2	3,862E+10
s12E	m2/N		c12E	N/m2	
s13E	m2/N		c13E	N/m2	
s66E	m2/N		c66E	N/m2	
s11D	m2/N		c11D	N/m2	
s33D	m2/N	8,040E-12	c33D	N/m2	1,290E+11
s55D	m2/N	2,352E-11	c55D	N/m2	4,252E+10
s12D	m2/N		c12D	N/m2	
s13D	m2/N		c13D	N/m2	
s66D	m2/N		c66D	N/m2	
Daten [ ]	formal berechnet nach Standard, nicht exakt				

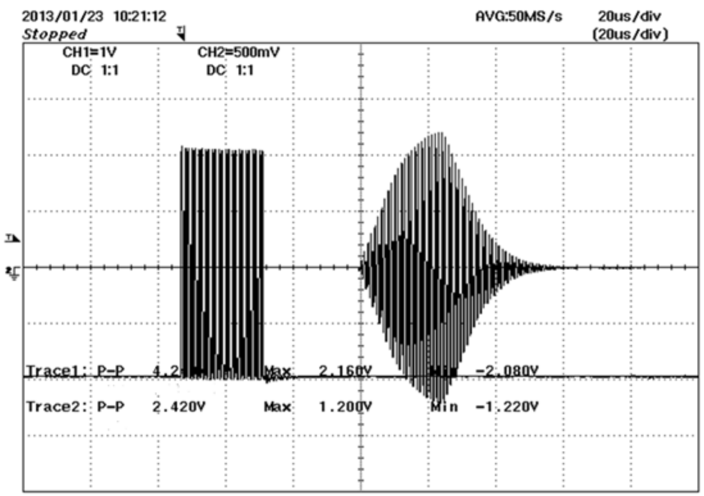
PIC 700 – Sensor Application

- Transmitted and Received Signal (in water without flow, 20°C)

PIC 255 - d7,5 x 2,1



PIC 700 - d7,5 x 2,2



- approx. 90% of signal amplitude has been achieved (PIC 700 vs. PIC 255)
- Functional behaviour of PIC 700 comparable to PIC 255
- BNT based materials have high potential for use in **ultrasonic transducers**

PIC 700 – Transducer Application

Feasibility of lead-free piezoceramic based power ultrasonic transducers

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Abstract

Lead-based piezoceramics are currently the most widely used transduction material in power ultrasonic applications. Directives such as the Restriction of Hazardous Substances (RoHS and RoHS2) [1] regulate the sale of electrical and electronic equipment containing hazardous substances, such as lead, entering the European marketplace. However, lead-based piezoceramics have been exempt due to the lack of a genuine lead-free equivalent. Lead-free piezoceramics were first developed in the 1950s, however their relatively poor properties when compared to PZT left them largely neglected until the implementation of the European directive [2]. This study investigates the incorporation of a modern lead-free piezoceramic, a variant of bismuth sodium titanate (BNT), into a commercial power ultrasonic transducer used in semiconductor wire bonding. It is reported that a device containing BNT was capable of forming wire bonds and that the lead-free transducer exhibited properties that could make them suitable in other power ultrasonic applications.

Piezoceramic elements

TABLE I: AVERAGE PROPERTIES OF THE INVESTIGATED LEAD-FREE AND LEAD-BASED SAMPLES †: SUPPLIED BY PI [5]

	f_r kHz	Z_{fr} Ω	Capacitance pF	tan δ	Q_m
BNT					
Length mode	346.4	1959			
Width mode	529.1	998	195.4	0.024	~100†
Thick mode	2455.1	60			
PZT8					
Length mode	269.1	28			
Width mode	411.4	9	294.8	0.002	≥1000
Thick mode	2197.0	9			

Wire bonding transducers

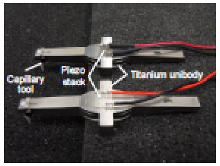


FIGURE I: UNIBODY TRANSDUCERS CONTAINING BNT (NEAR) AND PZT8 (FAR) ELEMENTS

- The transducers are based on a titanium unibody design and contain four piezoceramic plates which are preloaded via a titanium wedge [4].
- The BNT transducer was preloaded to 50 MPa while the PZT8 transducer was preloaded to 95 MPa.
- The transducers were mounted by their support flange, replicating their mounting during wire bonding. A capillary tool, which forms the wire bond, was also fastened to the transducers.

Admittance traces

- The admittance traces indicate that the PZT8 transducer is more responsive than the BNT transducer. From Table II it can also be seen that the BNT transducer exhibits higher losses.
- The body of the transducer and the piezocereamic stack (which contains a high number of mechanical interfaces) dominate the Q_m and the f_r of the transducers.
- The high impedance of the BNT transducer had a negative effect on the phase loop resonant tracking system. This resulted in operational conditions occasionally failing to be achieved.

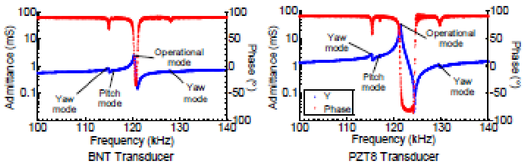


FIGURE II: ADMITTANCE TRACES

Transducer properties

TABLE II: TRANSDUCER PROPERTIES MEASURED 1 HOUR AFTER STACK PRELOADING

	f_r kHz	Z_{fr} Ω	Q_m	Q_e	k_{eff}	Capacitance pF	tan δ	Gain µm/mA	Gain µm/V	Gain µm²/W
BNT Transducer	120.3	412	317	0.3131	0.0999	799	0.035	0.0133	0.0301	0.3745
PZT8 Transducer	119.4	27	375	0.0337	0.2707	1700	0.006	0.0038	0.1296	0.4912

University of Glasgow, charity number SC004401

Transducer ageing

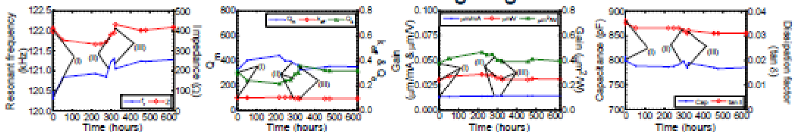


FIGURE III: BNT TRANSDUCER PROPERTIES (I) TRANSDUCER EXPOSED TO OPERATIONAL DRIVE CONDITIONS SHORTLY AFTER PRELOADING, (II) TRANSDUCER EXPOSED TO 70°C FOR 18HRS, AND (III) TRANSDUCER DRIVEN UNDER OPERATIONAL DRIVE CONDITIONS FOR AN EXTENDED DURATION

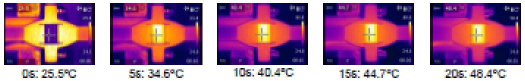


FIGURE IV: INFRA-RED IMAGES OF THE BNT TRANSDUCER DRIVEN AT 2.2µm FOR AN EXTENDED DURATION

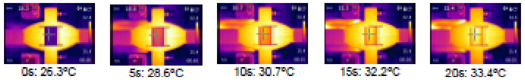


FIGURE V: INFRA-RED IMAGES OF THE PZT8 TRANSDUCER DRIVEN AT 2.2µm FOR AN EXTENDED DURATION

- The BNT transducer properties were measured at different intervals over a duration of a month.
- Figure III illustrates that even with accelerated ageing (exposing the transducer to elevated temperatures and driving it under operational conditions) the properties remained relatively stable.
- Gain and k_{eff} varied very little, while f_r, Z_{fr}, Q_m and Q_e, varied marginally, although settling after (III).
- Figures IV & V illustrate that when driven under operational conditions for a extended duration, the BNT transducer exhibits a larger temperature increase than the PZT8 transducer. This is due to high losses exhibited by the BNT transducer.

Wire bonds

- The bonds are uniform and correctly formed.
- The splash, which is the substrate oxide layer displaced during the bond formation, remains within the pad from which it stemmed. This minimises the likelihood of a short circuit occurring between the pad and neighbouring bonds.
- The feasibility of a lead-free wire bonding transducer was demonstrated.

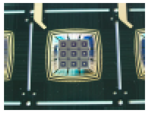


FIGURE VI: WIRE BONDS

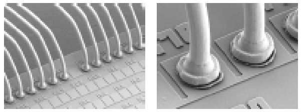


FIGURE VII: SEM IMAGES OF WIRE BONDS

Conclusions

- The successful forming of wire bonds with a lead-free transducer demonstrated the feasibility of incorporating a modern lead-free piezoceramic in to a commercial power ultrasonic transducer.
- The lead-free transducer demonstrated good stability indicating that its properties could be predictable over the lifetime of the device.
- However, the lead-free transducer exhibited significant losses when driven at operational amplitudes of vibration for an extended duration. The lead-free material investigated in this study is therefore unsuitable for power ultrasonic applications that are required to be driven continuously under high voltages. Nevertheless, power ultrasonic processes that utilise short duty cycles and relatively low voltages may suit this material.
- It is likely that before lead-free piezoceramics are widely considered in commercial power ultrasonic applications, properties, such as losses and impedance will have to be competitive to those exhibited by PZT materials.

Acknowledgements

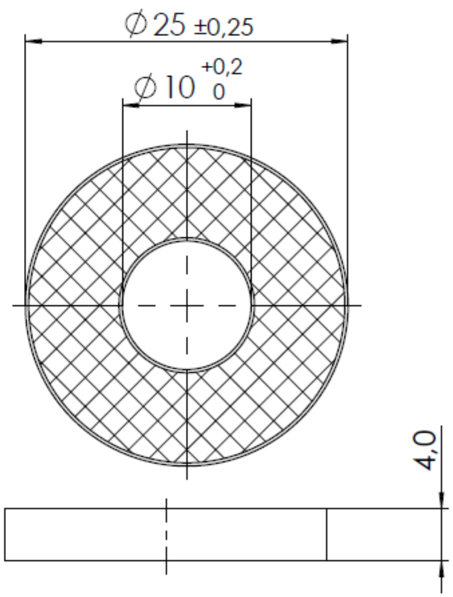
This project was funded by the Glasgow Research Partnership in Engineering (GRPE). Thanks to Eberhard Henning of PI Cermamic GmbH, Germany for supplying the lead-free piezoceramic material. Peter McKenna, University of Glasgow, for his assistance with the graphics, and Jon Brunner, K&S Fort Washington, for configuring the K&S wire bonding machine for the BNT transducer.

References

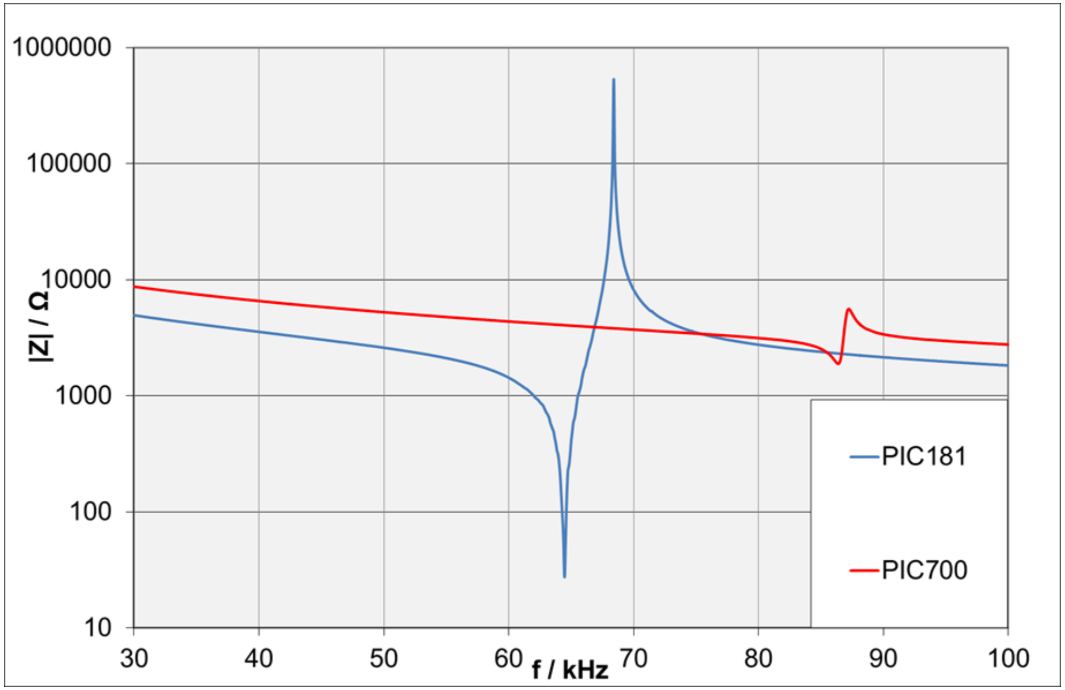
[1] "Directive 2011/65/EU: on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast)," Off. J. Eur. Union, pp. [L174] 88-110, 2011.
[2] J. Rödel, W. Jo, K.T.P. Seifert, E.-M. Anton, T. Granzow, and D. Damjanovic, "Perspective on the Development of Lead-free Piezoceramics," J. Am. Ceram. Soc., vol. 92, pp. 11531177, 2009.
[3] "Directive 2002/96/EC: Waste electrical and electronic equipment (WEEE)," Off. J. Eur. Union, pp. [L37] 24-38, 2003.
[4] D.A. DeAngelis and G.W. Schulze, "Optimizing piezoelectric crystal preload in ultrasonic transducers," Ultrasonic Industry Association (UIA), 38th Annual Symposium, March, 2009, pp. 1-6.
[5] PI Ceramics data sheet [online]. Available: http://piceramic.com Accessed June 2014.

Typical behavior

- Longitudinal effect
- Transversal effect
- Both effects must be considered
- Rings are driven below the lowest resonance



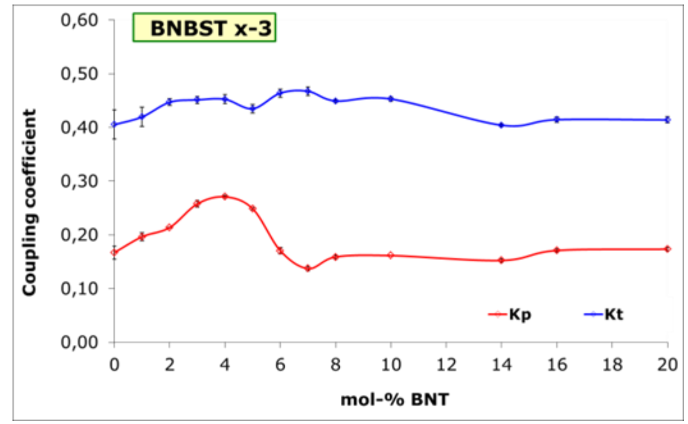
Radius: R_a; R_i
Thickness: h

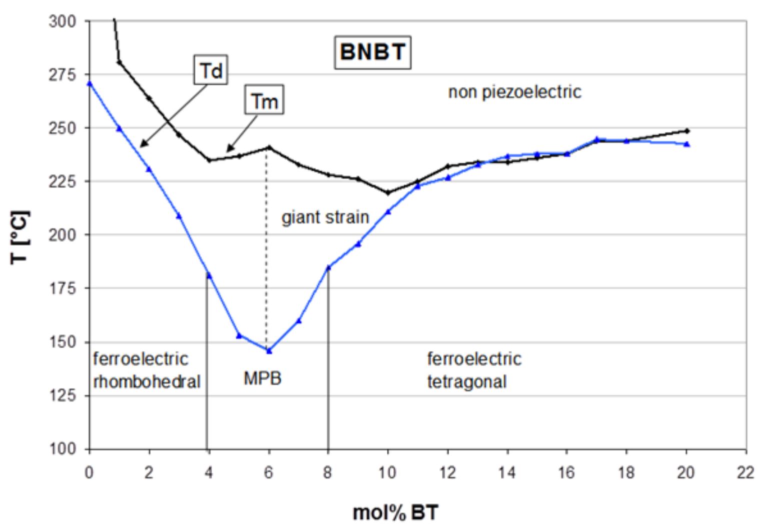


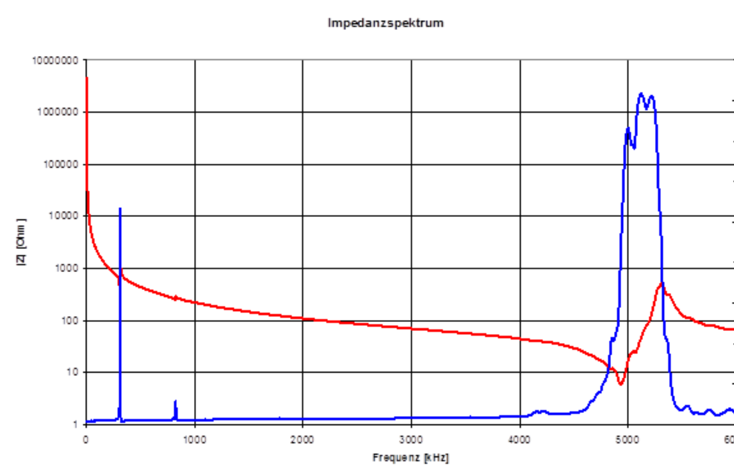
(3 videos)

Typical material behavior

- T_d depolarization temperature
- T_m temperature of max. capacitance
- Piezoelectric effect stable below T_d
- Anisotropic behavior

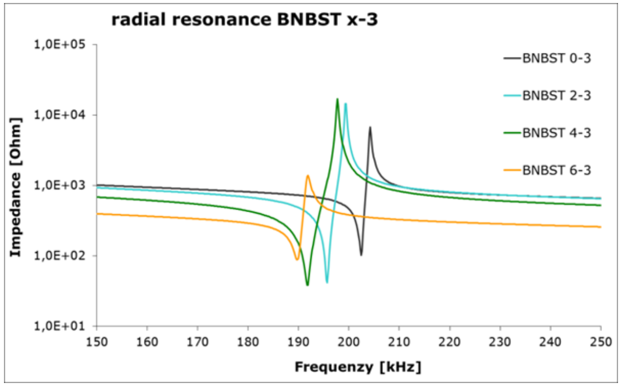


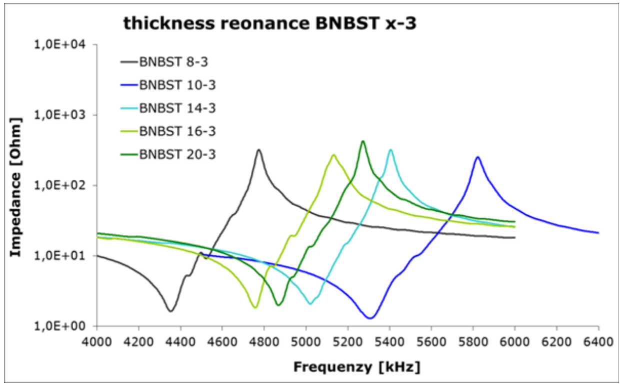


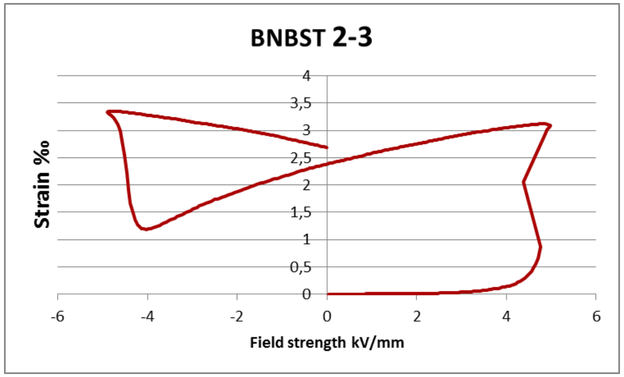


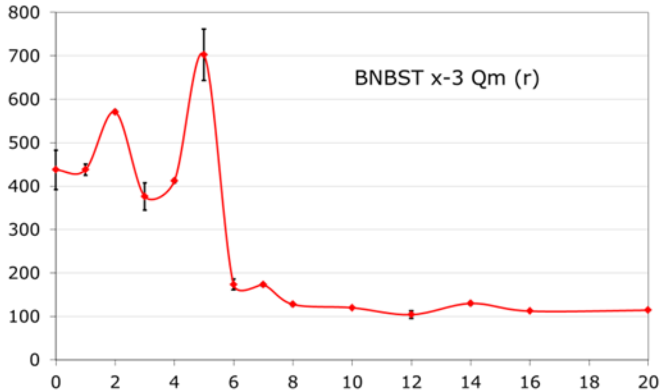
Typical material behavior

- Stronger planar coupling for rhombohedral compositions
- Strong anisotropic behavior for tetragonal compositions
- Low quality factor for tetragonal compositions
- Higher quality factor for rhombohedral compositions
- High coercive fields



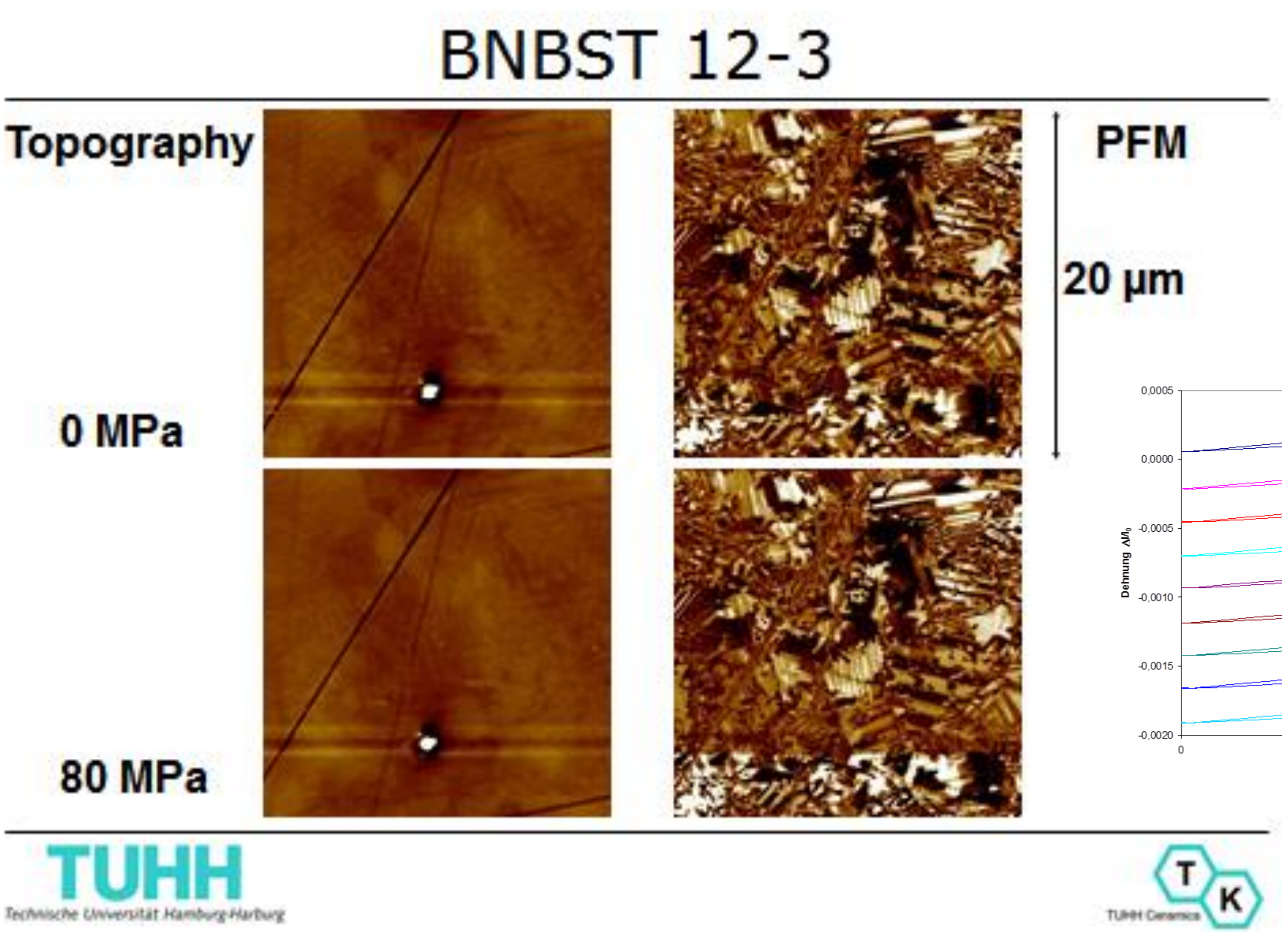


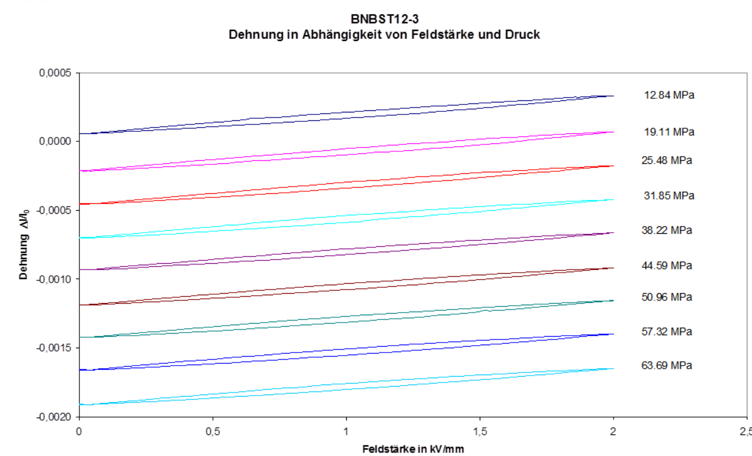




PFM analysis of BNBST x-y

- No ferroelastic switching up to 80 Mpa
- On Microscopic as well as on macroscopic scale





Modifications of BNT-based compositions

Next targets

Parameter		BNBT based			BNBST based		
		BNBT 2	BNBT 3	BNBT 15	BNBST 2-3	BNBST 3-3	PIC 700
T_d	[°C]	195	190	235	180	180	200
$\varepsilon_{33} / \varepsilon_0$		340	360	500	380	430	700
tan δ	[10^{-3}]	10	12	20	10	17	25
k_p		(0,18)	(0,19)	(0,14)	0,22	0,25	(0,15)
k_t		0,42	0,39	0,42	0,45	0,42	0,40
Q_m (radial)		570	540	110	570	380	100
Q_m (thickness)		350	300	70	220	290	65

(*) calculated according standard; Correct?

Similar behavior of PIC 700 compared to PIC 255

BNT based materials are promising Lead-free alternatives to PZT

BNT based materials have high potentials for ultrasonic transducers

Learn, how the materials behave in real applications

Input and strategies for modifications necessary

At PI Ceramic the two systems will be investigated further:

$(1\text{-}x)(Bi_{0,5}Na_{0,5})TiO_3\text{- }xBaTiO_3$	**BNBT x**
$(1\text{-}x\text{-}y)(Bi_{0,5}Na_{0,5})TiO_3\text{- }xBaTiO_3\text{- }ySrTiO_3$	**BNBST x-y**
$(KNaLi)(NbTaSb)O_3$	**KNN-LTS, KNN-LT**

Thank you for your attention!

Questions?

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