PI CERAMIC

Lead-Free Piezoceramic Materials

Lead-Free Piezoceramic Development at PI Ceramic

Potassium Sodium Niobate (KNN) & Bismuth Sodium Titanate (BNT)

Lead zirconate titanate (PZT) is the gold standard for performance and reliability in most piezoelectric applications since its invention more than 70 years ago. However, since the early 2000s the European Commission encourages the industry in Europe to look for alternative material systems via the Restriction of Hazardous Substances Directive (RoHS). The aim is to reduce environmental pollution from lead in electronic waste.

One way to get closer to this goal is to develop and use lead-free piezoelectric materials. PI Ceramic has been working on this theme for a long time and is working on alternatives to lead-containing materials. During the development the material systems bismuth sodium titanate (BNT) and potassium sodium niobate (KNN) have proven to be the most promising candidates for industrial use. Ongoing work with regards to different customer applications has resulted in various variants of these material systems with different levels of technological maturity. Our many years of experience enable us to meet most of our customers' requirements in terms of geometries.

Especially in resonant applications, lead-free piezoceramics can be an alternative to lead-containing materials. First positive development results can be demonstrated for ultrasonic nebulizers and power ultrasonic transducers as well as sensors. It is particularly worthwhile testing the performance of lead-free alternatives when designing new or redesigning existing devices.

Read Article:
Lead-Free Ceramics in Prestressed Ultrasonic Transducers

Lead-Free Piezoceramic Development at PI Ceramic

Sample Applications

	Application	PIC700	PIC701	PIC753	PIC758
Medical Technology	Nebulizers			xx	
	Sonication & Lysis				xx
	Mixing & Dispersion				xx
	Therapeutic & Surgical Ultrasound				x
	Air Bubble Detection	xx	x		
	Flow Metering	xx	x		
Industrial Applications	Material Processing				x
	Flow Metering	xx	x		
	Hydro Acoustics			x	x
	Level Sensors			x	
	Ultrasonic Cleaning				x
	Non-Destructive Testing	x	x		
	Ultrasonic Sensors			x	
	Ultrasonic Motors				x

Potassium Sodium Niobate (KNN)

Performance

KNN components can be easily soldered and glued and exhibit superior planar and transversal piezoceramic properties compared to BNT components. As a result, they can serve as an alternative to PZT components in the following applications:

- air ultrasonic sensors
- power ultrasonic transducers
- nebulizer units
- ultrasonic motors

For the production of lead-free piezoelectric components, PI Ceramic uses raw materials with a better environmental footprint than PZT.

Material datasheet: [Ceramic Material Data]

				PIC753[1]	PIC758[2]
Physical & dielectric properties	Density	ρ	g/cm³	4.8	4.8
	Curie temperature	T_c/T_d	°C	300	290
	Coercive field strength	E_c	kV/mm	1.1	1.2
	Relative permittivity ∥ polarization	$\varepsilon_{33}^T/\varepsilon_0$		1341	850
	Relative permittivity ⊥ to polarization	$\varepsilon_{11}^T/\varepsilon_0$		1222	950
	Dielectric loss factor	$\tan\delta$	10^{-3}	13	20
Electro-mechanical Properties	Coupling factor	k_p		0.53	0.43
		k_t		0.45	0.42
		k_{31}		0.3	0.27
		k_{33}		0.59	0.57
		k_{15}		0.58	0.55
	Piezoelectric charge coefficient	d_{31}	10^{-12} C/N	-118	-75
		d_{33}	10^{-12} C/N	241	170
		d_{15}	10^{-12} C/N	316	287
	Piezoelectric voltage coefficient	g_{31}	10^{-3} Vm/N	-9.9	-9.9
		g_{33}	10^{-3} Vm/N	20.0	22.5
Acousto-mechanical properties	Frequency coefficient (fs)	N_p	Hz·m	2869	
		N_1	Hz·m	2065	2296
		N_3*	Hz·m	2445	2582
		N_t*	Hz·m	2739	2803
		N_5*	Hz·m	1555	1315
	Elastic complience coefficient	S_{11}^E	10^{-12} m²/N	12.2	9.8
		S_{33}^E	10^{-12} m²/N	13.6	11.6
	Elastic stiffness coefficient	C_{33}^D	10^{10} N/m²	17.2	17.8
	Mechanical quality factor	Q_m		200	585

Modified materials on request. The materials are not yet approved for full scale production. The reliability of lead-free materials must be re-evaluated in each application case.

[1] Preliminary data, subject to change
[2] Material under development

The following values apply approximately for lead-free materials from PI Ceramic:

Specific heat capacity:
WK KNN = approx. 420 J kg^{-1} K^{-1}

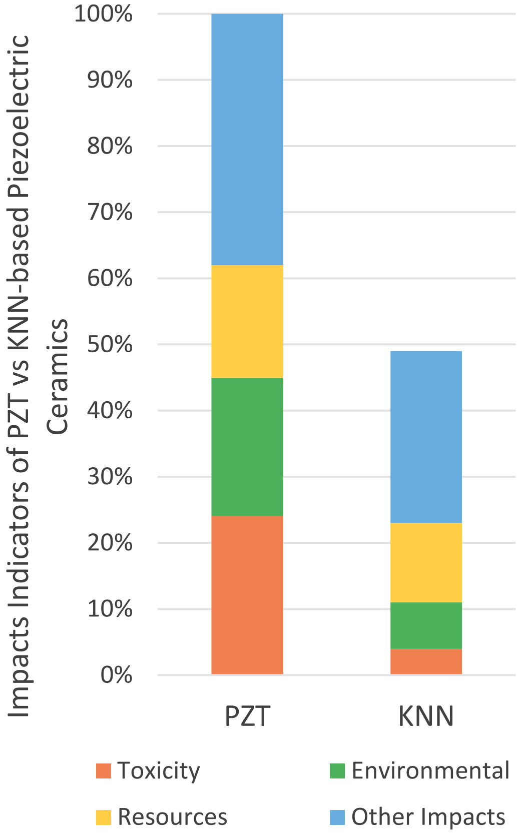
Specific thermal conductivity:
WL KNN = approx. 2.5 W m^{-1} K^{-1}

The data is determined using test pieces with the geometric dimensions laid down in EN 50324-2 standard and are typical values. All data provided is determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ± 2 °C. A complete coefficient matrix of the individual materials is available on request. If you have any questions about the interpretation of the material characteristics, please contact PI Ceramic.

Sustainability of Potassium Sodium Niobate (KNN)

Better than PZT when Choosing the Right Raw Materials

The ecological footprint of KNN has been subject of various discussions in research as well as in companies within in recent years. Initial results have shown an even worser footprint than PZT due to the poor valuation of the raw material niobium oxide when chemically prepared.[1,2] Later studies dealt with the different fabrication methods of niobium oxide. Mining fabrication has been shown to improve the global warming factor as well as human carcinogenic toxicity a lot.[3] Thus, the overall environmental impact of KNN materials is less than half of PZT.[4] This factor could be further improved by advanced fabrication technologies, which are under investigation.



Total impact indicators of PZT and KNN-based piezoceramics.[4]

[1] Ibn-Mohammed. T.; Koh, S.C.L.; Reaney, I.M.; Sinclair, D.C.; Mustapha, K.B.; Acquaye, A.; Wang, D. 2017: *Are lead-free piezoelectrics more environmentally friendly?* MRS Communication 7: 1-7.
[2] Ibn-Mohammed. T.; Reaney. I.M.; Koh. S.C.L.; Acquaye. A.; Sinclair. D.C.; Randall. C.A.; Abubakar. F.H.; Smith. L.; Schileo. G.; Ozawa-Meida. L. 2018: *Life cycle assessment and environmental profile evaluation of lead-free piezoelectrics in comparison with lead zirconate titanate.* Journal of the European Ceramic Society 38(15): 4922-4938.
[3] Da Silva Lima. L.; Alvarenga. R.A.F.; de Souza Amaral. T.; de Tarso Gonçalves Nolli. P.; Dewulf. J. 2022: *Life cycle assessment of ferroniobium and niobium oxides: Quantifying the reduction of environmental impacts as a result of production process improvements*. Journal of Cleaner Production 348(18): 131327.
[4] Wu, Y.; Soon, P-S.; Lu, J-T.; Zhou, J.; Liu, Y-X.; Guo, Z.; Wang, K.; Gong, W. 2024: *Life cycle assessment of lead-free potassium sodium niobate versus lead zirconate titanate: Energy and environmental impacts.* EcoMat 6(5): 12450.

Bismuth Sodium Titanate (BNT)

Performance

BNT materials are particularly well suited for thickness-mode applications and perform reliably in applications such as air bubble detection and flow sensor technology.

However, they are not suitable for applications that require planar vibration.

The PI Ceramic BNT materials feature a high depolarization temperature. As a result, unlike many other materials on the market, they can be processed by low-melting solders or with thermosetting adhesives.

Read Article:

Lead-Free Ceramics in Prestressed Ultrasonic Transducers

				PIC700	PIC701
Physical & dielectric properties	Density	ρ	g/cm³	5.7	5.7
	Depolarization temperature	T_c/T_d	°C	190	230
	Coercive field strength	E_c	kV/mm	2.8	3.9
	Relative permittivity ∥ polarization	$\varepsilon_{33}^T/\varepsilon_0$		750	542
	Relative permittivity ⊥ to polarization	$\varepsilon_{11}^T/\varepsilon_0$		800	629
	Dielectric loss factor	tan δ	10^{-3}	30	30
Electro-mechanical Properties	Coupling factor	k_p		0.13	0.14
		k_t		0.45	0.39
		k_{31}		0.08	0.09
		k_{33}		0.41	0.37
		k_{15}		0.31	0.32
	Piezoelectric charge coefficient	d_{31}	10^{-12} C/N	-20	-17
		d_{33}	10^{-12} C/N	120	71
		d_{15}	10^{-12} C/N	120	108
	Piezoelectric voltage coefficient	g_{31}	10^{-3} Vm/N	-3.3	-3.5
		g_{33}	10^{-3} Vm/N	15	15
Acousto-mechanical properties	Frequency coefficient (fs)	N_p	Hz·m	3000	3071
		N_1	Hz·m	2270	2302
		N_3*	Hz·m	2240	2403
		N_t*	Hz·m	2340	2503
		N_5*	Hz·m	1470	1535
	Elastic complience coefficient	S_{11}^E	10^{-12} m²/N	8.5	8.3
		S_{33}^E	10^{-12} m²/N	9.1	7.6
	Elastic stiffness coefficient	C_{33}^D	10^{10} N/m²	15.2	13.5
	Mechanical quality factor	Q_m		100	100

Modified materials on request. The reliability of lead-free materials must be re-evaluated in each application case.

Preliminary data, subject to change

The following values apply approximately for lead-free materials from PI Ceramic:

Specific heat capacity:
WK BNT = 101 J kg⁻¹ K⁻¹

Specific thermal conductivity:
WL BNT = 1.4 W m⁻¹ K⁻¹

The data is determined using test pieces with the geometric dimensions laid down in EN 50324-2 standard and are typical values. All data provided is determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ± 2 °C. A complete coefficient matrix of the individual materials is available on request. If you have any questions about the interpretation of the material characteristics, please contact PI Ceramic.

PI

Lead-Free Piezo Materials

Parameters of Lead-Free Materials

				BNT materials			KNN materials	
			Unit	PIC700[1]	PIC701[1]		PIC753[1]	PIC758[2]
Physical and dielectric properties								
Density		ρ	g/cm³	5.7	5.7		4.8	4.8
Curie temperature		T_c	°C	190[3]	230[3]		300	290
Coercive field strength		E_c	kV/mm	2.8	3.9		1.1	1.2
Relative permittivity	in polarization direction	$\varepsilon^T_{33} / \varepsilon_0$		680	542		1341	850
	⊥ to polarity	$\varepsilon^T_{11} / \varepsilon_0$		655	629		1222	950
Dielectric loss factor		$\tan \delta$	10^{-3}	30	30		13	20
Electro-mechanical properties								
Coupling factor		k_p		0.14	0.13		0.53	0.43
		k_t		0.41	0.39		0.45	0.42
		k_{31}		0.09	0.08		0.30	0.27
		k_{33}		0.43	0.37		0.59	0.57
		k_{15}		0.25	0.31		0.58	0.55
Piezoelectric charge coefficient		d_{31}	10^{-12} C/N	-20	-17		-118	-75
		d_{33}	10^{-12} C/N	100	71		241	170
		d_{15}	10^{-12} C/N	90	108		316	287
Piezoelectric voltage coefficient		g_{31}	10^{-3} Vm/N	-3.3	-3.5		-9.9	-9.9
		g_{33}	10^{-3} Vm/N	16.0	14.8		20.0	22.5
		g_{15}	10^{-3} Vm/N	14.5	19.4		29.2	34.1
Akustomechanische Eigenschaften								
Frequency coefficient (serial resonance fs)		N_p	Hz · m	2984	3071		2869	
		N_1	Hz · m	2228	2302		2065	2296
		N_3	Hz · m	2420	2403		2445	2582
		N_t	Hz · m	2576	2503		2739	2803
		N_5	Hz · m	1516	1535		1555	1315
Elastic compliance coefficient		S_{11}^E	10^{-12} m²/N	8.8	8.2		12.2	9.8
		S_{33}^E	10^{-12} m²/N	9.1	7.5		13.6	11.6
Elastic stiffness coefficient		C_{33}^D	10^{10} N/m²	15.1	13.5		17.2	17.8
Mechanical quality factor		Q_m		100	100		200	585
Temperature stability								
Temperature coefficient of εT_{33} (in the range of -20 to +125 °C)		TK ε_{33}	10^{-3}/K					
Time stability (relative change of the parameters per decade of time in %)								
Relative permittivity		C_ε						
Coupling factor		C_k	%					

Modified materials on request. The materials are not yet approved for production.

The reliability of lead-free materials must be re-evaluated in each application case. It may differ from the reliability of materials containing lead.

1) Preliminary data, subject to change

2) Material under development, no specifications

3) Depolarization temperature

The following values apply approximately for lead-free materials from PI Ceramic:

Specific heat capacity:
WK KNN = approx. 420 J kg⁻¹ K⁻¹
WK BNT = approx. 101 J kg⁻¹ K⁻¹

Specific thermal conductivity:
WL KNN = approx. 2.5 W m⁻¹ K⁻¹
WL BNT = approx. 1.4 W m⁻¹ K⁻¹

The data is determined using test pieces with the geometric dimensions laid down in EN 50324-2 standard and are typical values.

All data provided is determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ±2 °C.

A complete coefficient matrix of the individual materials is available on request. If you have any questions about the interpretation of the material characteristics, please contact PI Ceramic. Ceramic.

PI Ceramic GmbH
Lindenstraße
07589 Lederhose | Germany
Tel. +49 36604 882-0
Email info@piceramic.de
Web http://www.piceramic.com

Pourous Piezo Materials

Parameters of Porous Materials

			Ferroelectric soft PZT materials		
			Unit	**PIC255P63**[1)]	
Physical and dielectric properties					
Density		ρ	g/cm³	6,3	
Curie temperature		T_C	°C	350	
Coercive field strength (at 25 °C)		E_c	kV/mm		
Relative permittivity	in polarization direction	$\varepsilon^T_{33} / \varepsilon_0$		970	
	⊥ to polarity	$\varepsilon^T_{11} / \varepsilon_0$			
Dielectric loss factor		tan δ	10^{-3}	18	
Electro-mechanical properties					
Coupling factor		k_p		0.35	
		k_t		0.50	
		k_{31}			
		k_{33}			
		k_{15}			
Piezoelectric charge coefficient		d_{31}	10^{-12} C/N		
		d_{33}	10^{-12} C/N	316	
		d_{15}	10^{-12} C/N		
Piezoelectric voltage coefficient		g_{31}	10^{-3} Vm/N		
		g_{33}	10^{-3} Vm/N	37	
		g_{15}	10^{-3} Vm/N		
Acousto-mechanical properties					
Frequency coefficient (serial resonance fs)		N_p	Hz · m	1790	
		N_1	Hz · m		
		N_3	Hz · m		
		N_t	Hz · m	1336	
		N_5	Hz · m		
Speed of sound		v_1^E	m/s		
		v_3^D	m/s		
		v_5^D	m/s		
		v_t^D	m/s	2670	
Elastic compliance coefficient		S_{11}^E	10^{-12} m²/N		
		S_{33}^E	10^{-12} m²/N		
Elastic stiffness coefficient		C_{33}^D	10^{10} N/m²		
Acoustic impedance (pressure wave in polarization direction)		Z^{33}	MRayl (=10^6kg/m²/s)	16.8	
Mechanical quality factor		Q_m		20	
Temperature stability					
Temperature coefficient of εT_{33} (in the range of -20 to +125 °C)		TK ε_{33}	10^{-3}/K		
Time stability (relative change of the parameters per decade of time in %)					
Relative permittivity		C_ε			
Coupling factor		C_k	%		

Modified materials on request.

1) Porous ceramic, preliminary data, subject to change

Recommended operating temperature:
up to 50 % of Curie temperature

The following values are valid approximations for all PZT materials from PI Ceramic:

Specific heat capacity:
WK = approx. 350 J kg^{-1} K^{-1}

Specific thermal conductivity:
WL = approx. 1.1 W m^{-1} K^{-1}

Poisson's ratio (lateral contraction):
σ = approx. 0.34

Coefficient of thermal expansion:
$\alpha 3$ = approx. -4 to -6 × 10^{-6} K^{-1}
(in the polarization direction, shorted)
$\alpha 1$ = approx. 4 bis 8 × 10^{-6} K-1 (perpendicular to the polarization direction, shorted)

Static compressive strength:
>600 MPa

The data is determined using test pieces with the geometric dimensions laid down in EN 50324-2 standard and are typical values.

All data provided is determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ±2 °C.

A complete coefficient matrix of the individual materials is available on request. If you have any questions about the interpretation of the material characteristics, please contact PI Ceramic. Ceramic.

PI Ceramic GmbH
Lindenstraße
07589 Lederhose | Germany
Tel. +49 36604 882-0
Email info@piceramic.de
Web http://www.piceramic.com

Standard Piezo Materials

Specific Parameters of Standard Materials

				Ferroelectric soft PZT materials					Ferroelectric hard PZT materials				
			Unit	PIC151	PIC255/ PIC252	PIC155	PIC153	PIC152	PIC181	PIC184	PIC144	PIC241	PIC300
Physical and dielectric properties													
Density		ρ	g/cm³	7.80	7.80	7.75	7.60	7.75	7.85	7.75	7.90	7.80	7.75
Curie temperature		T_C	°C	250	350	340	160	340	330	320	320	270	370
Coercive field strength (at 25 °C)		E_c	kV/mm	1.0	1.5	1.0	0.6	0.8					
Relative permittivity	in polarization direction	$\varepsilon^T_{33} / \varepsilon_0$		2500	1800	1750	4500	1350	1200	1200	1300	1750	1030
	⊥ to polarity	$\varepsilon^T_{11} / \varepsilon_0$		1980	1750	1850	3500	1100	1250	1250	1500	1500	960
Dielectric loss factor		tan δ	10^{-3}	20	20	25	30	15	3	3	3	5	3
Electro-mechanical properties													
Coupling factor		k_p		0.62	0.62	0.62	0.62	0.48	0.56	0.55	0.60	0.55	0.47
		k_t		0.53	0.47	0.48	0.49	0.41	0.46	0.44	0.48	0.45	0.41
		k_{31}		0.38	0.35	0.35	0.33	0.25	0.32	0.30	0.30	0.32	0.27
		k_{33}		0.69	0.69	0.69	0.72	0.58	0.66	0.63	0.66	0.65	0.57
		k_{15}		0.65	0.66	0.65	0.66	0.46	0.63	0.65	0.65	0.63	0.48
Piezoelectric charge coefficient		d_{31}	10^{-12} C/N	-210	-180	-165	-295	-90	-120	-99	-105	-140	-85
		d_{33}	10^{-12} C/N	500	400	360	600	240	265	220	225	300	190
		d_{15}	10^{-12} C/N	610	550	540	780	235	475	421	419	431	248
Piezoelectric voltage coefficient		g_{31}	10^{-3} Vm/N	-10.1	-11.8	-12.8	-7.9	-8.7	-10.6	-10.7	-10.4	-9.2	-9.3
		g_{33}	10^{-3} Vm/N	21.5	25.0	27.9	16.4	23.4	23.0	22.4	23.3	19.9	20.8
		g_{15}	10^{-3} Vm/N	33.9	38.4	46.0	23.3	23.7	37.2	35.8	33.9	33.3	29.3
Acousto-mechanical properties													
Frequency coefficient (serial resonance fs)		N_p	Hz · m	1940	2000	1930	1940	2280	2270	2175	2170	2200	2400
		N_1	Hz · m	1500	1420	1500	1380	1570	1640	1590	1620	1590	1700
		N_3	Hz · m	1360	1370	1340	1345	1530	1560	1560	1540	1550	1700
		N_t	Hz · m	1950	2000	1990	2020	2100	2110	2035	2035	2020	2100
		N_5	Hz · m	830	870	820	890	1130	1000	960	960	980	1050
Speed of sound		v_1^E	m/s	3000	2840	3000	2760	3140	3280	3180	3240	3180	3400
		v_3^D	m/s	3820	3690	3750	3650	3750	4060	3990	4090	3890	3990
		v_5^D	m/s	2290	2340	2340	2260	2500	2400	2090	2450	2440	2330
		v_t^D	m/s	3900	4000	3980	4040	4200	4220	4070	4070	4040	4200
Elastic compliance coefficient		S_{11}^E	10^{-12} m²/N	16.4	16.0	16.1	17.2	13.1	11.8	12.2	12.4	12.6	11.2
		S_{33}^E	10^{-12} m²/N	19.4	19.0	19.3	20.0	14.8	13.3	13.7	14.3	14.4	12.0
Elastic stiffness coefficient		C_{33}^D	10^{10} N/m²	15.7	15.4	15.8	15.5	16.6	17.0	15.8	16.6	15.5	16.3
Acoustic impedance (pressure wave in polarization direction)		Z^{33}	MRayl (=10^6kg/m²/s)	35.0	34.7	35.0	34.4	35.9	36.6	35.1	36.2	34.9	35.7
Mechanical quality factor		Q_m		100	80	80	50	100	2000	400	1000	500	1400
Temperature stability													
Temperature coefficient of εT_{33} (in the range of -20 to +125 °C)		TK ε_{33}	10^{-3}/K	4	3	4	15	2	3	4		3	2
Time stability (relative change of the parameters per decade of time in %)													
Relative permittivity		C_ε			-1.0	-3.0				-4.0			
Coupling factor		C_k	%		-1.0	-0.5				-2.0			

Modified materials on request.

1) Preliminary data, subject to change

Recommended operating temperature:
up to 50 % of Curie temperature

The following values are valid approximations for all PZT materials from PI Ceramic:

Specific heat capacity:
WK = approx. 350 J kg^{-1} K^{-1}

Specific thermal conductivity:
WL = approx. 1.1 W m^{-1} K^{-1}

Poisson's ratio (lateral contraction):
σ = approx. 0.34

Coefficient of thermal expansion:
$\alpha 3$ = approx. -4 to -6 × 10^{-6} K^{-1}
(in the polarization direction, shorted)
$\alpha 1$ = approx. 4 bis 8 × 10^{-6} K-1 (perpendicular to the polarization direction, shorted)

Static compressive strength:
>600 MPa

The data is determined using test pieces with the geometric dimensions laid down in EN 50324-2 standard and are typical values.

All data provided is determined 24 h to 48 h after the time of polarization at an ambient temperature of 23 ±2 °C.

A complete coefficient matrix of the individual materials is available on request. If you have any questions about the interpretation of the material characteristics, please contact PI Ceramic. Ceramic.

PI Ceramic GmbH
Lindenstraße
07589 Lederhose | Germany
Tel. +49 36604 882-0
Email info@piceramic.de
Web http://www.piceramic.com

Physik Instrumente

PI Ceramic GmbH
Lindenstraße
07589 Lederhose
Germany

Phone +49 36604 882-0
E-Mail info@piceramic.de

Please visit us at: www.piceramic.com