No. 1C-a63 $Pb(Zr_xTi_{1-x})O_3$ (x = 0.5...0.6, lead zirconate-titanate) (PZT)

For general properties of $PbTiO_3$–$PbZrO_3$, see No. 1C-a62.

1a	Large piezoelectric coupling in $Pb(Zr,Ti)O_3$ ceramics was discovered in 1954 by Jaffe et al. The name PZT is a trade mark of Vernitron, Cleveland, Ohio, USA.	54Jaf
3	Unit cell parameters and crystal structure: Table 1C-a63-001.	
4	Thermal expansion: Fig. 1C-a63-001.	
5a	Dielectric properties: Fig. 1C-a63-002...Fig. 1C-a63-008; see also	83Muk, 83Taw, 84Lev, 84Sri, 85Abd
c	Spontaneous polarization: Table 1C-a63-002; Fig. 1C-a63-009.	
d	Pyroelectricity: Table 1C-a63-003; Fig. 1C-a63-010, Fig. 1C-a63-011.	
7	Electromechanical properties: Tables 1C-a63-004...1C-a63-008; Figs. 1C-a63-012...1C-a63-017; see also	82Did, 83Wul1
	Effect of electric field bias: Fig. 1C-a63-018, Fig. 1C-a63-019; see also	74Bar
	Effect of external stress: Fig. 1C-a63-020, Fig. 1C-a63-021; see also	60Ger, 61Kru
	High power level vibration: Fig. 1C-a63-022.	
	Effect of Fe_2O_3 addition: see	69Wes
8	Elastic property: see Fig. 1C-a63-017 and also	83Taw
	Ultrasonic velocity: see Table 1C-a63-008.	
	Surface acoustic wave: see	76Saf
11	Electrical resistivity: Fig. 1C-a63-023, Fig. 1C-a63-024.	
15a	Observation of domains: see	81Goo, 85Luc, 89Luc
16	Thin film:	
	MOCVD:	90Oka
	Laser ablation (pulsed laser deposition):	90Sae, 90Ots
	Sputtering:	90Blo
	Ion-beam sputtering:	92Kru
	Hydrothermal deposition:	91Shi
	Metallo-organic decomposition:	91Spi
	Sol-gel method:	91Toh

Table 1C-a63-001. $Pb(Zr_{0.6}Ti_{0.4})O_3$ (ceramics). Structural parameters [81Ami]. Unit cell parameters and fractional coordinates of atoms are refined by Rietveld profile fitting method for neutron diffraction data. Coordinates are defined as Pb ($1/4 + s$, $1/4 + s$, $1/4 + s$), Zr / Ti (t, t, t) and O ($-e + d$, $1/4 - 2d$, $e + d$) based on the hexagonal cell. Angle of tilt ω is given by $\tan\omega = 4\sqrt{3}\,e$.

T [K]	9	295
Phase	$F_{\alpha LT}$	$F_{\alpha HT}$
Space group	$R3c–C_{3v}^{6}$	$R3m–C_{3v}^{5}$
Unit cell parameters		
a_h [Å]	5.7597(5)	5.7550(4)
c_h [Å]	14.2510(12)	14.2138(11)
Positional parameters		
s	0.0343(3)	0.0310(4)
t	0.0114(5)	0.0108(7)
d	–0.0028(1)	–0.0023(1)
e	0.0105(2)	–
ω [°]	4.2(1)	–

Table 1C-a63-002. Pb(Zr,Ti)O_3. Physical properties of hot-pressed ceramics [70Hae]. 1 psi = 6.895·10^3 Pa.

Zr/Ti ratio	Hot-press conditions *T* [°C]	*t* [h]	*p* [psi]	Grain size [μm]	Virgin *κ* (*f*=1 kHz)	P_r [$\cdot 10^{-2}$ Cm^{-2}]	E_c [$\cdot 10^5$ Vm^{-1}]	k_p
53/47	850	64	4500	1.2	1120	38.6	13.6	0.512
53/47	1300	1	3000	5.5	750	46.5	8.3	0.660
65/35	800	16	4000	0.8	965	34.0	13.1	0.370
65/35	850	2	4000	1.0	910	25.5	12.9	0.200
65/35	850	16	4000	1.5	905	35.7	13.1	0.380
65/35	850	64	4000	1.8	850	39.5	12.6	0.410
65/35	1100	16	1500	2.1	657	43.0	12.6	0.442
65/35	1300	1	3000	5.0	476	42.0	8.7	0.420
80/20	850	16	5000	1.2	692	37.0	15.3	0.272
80/20	875	16	4500	1.5	632	38.5	12.9	0.285
80/20	900	16	4500	2.0	648	39.5	12.4	0.286
80/20	1200	3	1500	7.0	462	41.7	11.8	0.288
92/8	800	16	4500	1.5	563	30.7	18.6	0.162
92/8	800	16	10000	1.8	532	34.4	15.0	0.157
92/8	1200	3	1500	12.0	300	38.9	13.2	0.180

Table 1C-a63-003. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics doped with 2 wt % $Zn(Mn_{1/3}Bi_{2/3})O_3$). Pyroelectric and dielectric properties [79Che].

x	0.30	0.42	0.46	0.50	0.52	0.54	0.56	0.59	0.70
p_i [$\cdot 10^{-5}$ CK^{-1}m^{-2}]	20	26	29	31	37	42	44	38	38
κ	290	490	660	880	1070	940	600	450	310
p_i/κ [$\cdot 10^{-5}$ CK^{-1}m^{-2}]	0.07	0.05	0.04	0.04	0.03	0.04	0.07	0.08	0.12
Θ_f [°C]	430	380	360	350	340	330	320	310	290

Table 1C-a63-004. $Pb(Zr,Ti)O_3$ (ceramics modified with additive of 1 wt % Nb_2O_5). Electromechanical properties [59Kul].

Base composition	ρ_a [$\cdot 10^3$ kg m^{-3}]	Before poling		24 h after poling					
		κ at 1 kHz	tan δ [%] at 1 kHz	κ at 1 kHz	tan δ [%] at 1 kHz	k_p	$f_R \cdot r$ [Hz m]	d_{31} [$\cdot 10^{-12}$ CN^{-1}]	Q_{mech}
$Pb(Zr_{0.50}Ti_{0.50})O_3$	7.38	879	1.5	1041	1.2	0.42	1696	82	81
$Pb(Zr_{0.51}Ti_{0.49})O_3$	7.31	975	1.6	1188	1.3	0.45	1642	97	73
$Pb(Zr_{0.52}Ti_{0.48})O_3$	7.39	985	1.5	1200	1.4	0.45	1640	97	76
$Pb(Zr_{0.53}Ti_{0.47})O_3$	7.43	1092	1.8	1371	1.4	0.53	1547	130	61
$Pb(Zr_{0.54}Ti_{0.46})O_3$	7.44	1051	1.8	1296	1.7	0.54	1549	128	62
$Pb(Zr_{0.55}Ti_{0.45})O_3$	7.40	955	2.4	973	2.0	0.56	1524	117	55
$Pb(Zr_{0.56}Ti_{0.44})O_3$	7.38	818	2.8	745	2.5	0.53	1601	93	56
$Pb(Zr_{0.57}Ti_{0.43})O_3$	7.41	750	3.0	684	2.5	0.50	1636	82	60
$Pb(Zr_{0.58}Ti_{0.42})O_3$	7.41	713	3.0	630	2.8	0.49	1676	75	62

Table 1C-a63-005. $Pb(Zr,Ti)O_3$ (ceramics). Electromechanical constants at RT [60Ber]. f = 1 kHz for κ.

Zr/Ti ratio	k_{31}	k_p	k_{15}	k_{33}	κ_{11}^T	κ_{11}^S	κ_{33}^T	κ_{33}^S(obs)	κ_{33}^S(calc)
48/52	0.170	0.289	0.408	0.435	663	551	666	540	537
50/50	0.230	0.397	0.504	0.546	855	631	846	585	585
52/48	0.313	0.529	0.694	0.670	1180	612	730	399	389
54/46	0.280	0.470	0.701	0.626	990	504	450	253	268
56/44	0.267	0.450	0.657	0.619	840	477	423	246	258
58/42	0.254	0.428	0.646	0.607	751	437	397	243	246
60/40	0.238	0.400	0.625	0.585	672	410	376	240	245

Zr/Ti ratio	s_{11}^E	s_{11}^D	s_{33}^E	s_{33}^D	s_{44}^E	s_{44}^D	s_{66}	s_{12}^E	s_{12}^D	s_{13}^E	s_{13}^D
	[$\cdot 10^{-12}$ m^2N^{-1}]										
48/52	10.8	10.5	10.9	8.83	28.3	23.6	28.3	–3.35	–3.66	–3.21	–2.40
50/50	12.4	11.7	13.3	9.35	32.8	24.5	32.9	–4.06	–4.72	–4.22	–2.60
52/48	13.8	12.4	17.1	9.35	48.2	25.0	38.4	–4.07	–5.38	–5.80	–2.56
54/46	11.6	10.7	14.8	9.0	45.0	22.9	29.9	–3.33	–4.24	–4.97	–2.68
56/44	11.0	10.2	14.0	8.65	39.8	22.6	28.4	–3.22	–4.01	–4.63	–2.57
58/42	10.5	9.85	12.8	8.10	37.7	21.9	27.1	–3.07	–3.75	–4.12	–2.33
60/40	10.4	9.75	12.05	7.92	36.9	22.5	26.7	–2.96	–3.55	–3.72	–2.17

Zr/Ti ratio	Density ρ	g_{31}	g_{33}	g_{15}	g_{33}–g_{31}	d_{31}	d_{33}	d_{15}	d_{33}–d_{31}
	[$\cdot 10^3$ kg m^{-3}]	[$\cdot 10^{-3}$ m^2C^{-1}]				[$\cdot 10^{-12}$ CN^{-1}]			
48/52	7.59	–7.3	18.7	28.4	26.0	43.0	110	166	153
50/50	7.55	–9.35	23.1	33.2	32.4	70.0	173	251	243
52/48	7.55	–14.5	34.5	47.2	49.0	93.5	223	494	316
54/46	7.62	–15.1	38.1	50.3	53.2	60.2	152	440	212
56/44	7.59	–14.5	37.8	48.0	52.3	54.3	142	357	196
58/42	7.64	–13.9	36.7	48.8	50.6	48.9	129	325	178
60/40	7.60	–13.3	35.2	49.3	48.5	44.2	117	293	161

Zr/Ti ratio	s_{33}^D+ s_{11}^D–2s_{13}^D [$\cdot 10^{-12}$ m^2N^{-1}]	Q_{mech}	Q_E (=1/tanδ)	P [$\cdot 10^{-2}$ Cm^{-2}]	c_{33}^D [$\cdot 10^{10}$ Nm^{-2}]	$-s_{12}^E / s_{11}^E$	$-s_{12}^D / s_{11}^D$	$-s_{13}^E\cdot(s_{33}^E s_{11}^E)^{-1/2}$	$-s_{13}^D\cdot(s_{33}^D s_{11}^D)^{-1/2}$
48/52	24.1	1170	380	17	14.0	0.310	0.349	0.296	0.250
50/50	26.2	950	370	27	13.5	0.328	0.404	0.329	0.249
52/48	26.9	860	360	36	13.4	0.295	0.434	0.376	0.238
54/46	25.1	680	300	42.5	14.8	0.288	0.396	0.380	0.273
56/44	24.0	490	190	48	15.3	0.293	0.394	0.373	0.274
58/42	22.6	500	200	43	15.8	0.292	0.381	0.355	0.261
60/40	22.0	600	210	33	15.6	0.285	0.365	0.332	0.247

Table 1C-a63-006. $Pb(Zr_{0.54}Ti_{0.46})O_3$ (ceramics). Effect of (A) penta- or (B) tri-valent additives on electromechanical constants [59Kul].

Addition	ρ_a	Before poling		24 h after poling						Θ_f
		κ at 1 kHz	tan δ [%] at 1 kHz	κ at 1 kHz	tan δ [%] at 1 kHz	k_p	$f_R \cdot r$	d_{31}	Q_{mech}	
[wt%]	[$\cdot 10^3$ kg m^{-3}]						[Hz m]	[$\cdot 10^{-12}$ CN^{-1}]		[°C]
None	7.41	707	0.3	537	0.4	0.49	1641	71		390
None	7.29	706	0.4	513	0.5	0.50	1687	69		387
A 0.1 Nb_2O_5	7.26	598	0.3	508	0.4	0.38	1643	54		
0.5 Nb_2O_5	6.96	732	2.1	790	2.0	0.46	1443	94		
0.8 Nb_2O_5	7.36	965	1.6	1166	1.5	0.48	1606	105		
1.0 Nb_2O_5	7.36	1064	1.8	1308	1.6	0.53	1563	126	61	
1.0 Nb_2O_5	7.60	1055	2.2	1242	2.2	0.54	1538	125		361
1.2 Nb_2O_5	7.34	1011	2.0	1167	1.7	0.48	1614	104	70	
1.4 Nb_2O_5	7.37	1057	2.2	1218	1.9	0.50	1584	113	69	
1.7 Nb_2O_5	7.39	1058	2.0	1218	1.8	0.47	1594	105		
2.0 Nb_2O_5	7.37	1074	2.1	1202	2.0	0.50	1550	115		344
0.5 Nb_2O_5 } 0.5 La_2O_3	7.39	1169	2.1	1377	2.0	0.57	1491	146	48	369
1.0 Ta_2O_5	7.31	989	1.5	1187	1.5	0.49	1563	111	61	
1.0 Ta_2O_5	7.22	918	2.0	1121	2.1	0.50	1525	114		368
2.0 Ta_2O_5	7.49	1062	2.2	1230	2.1	0.50	1547	115		
2.0 Ta_2O_5	7.40	1077	1.8	1275	1.8	0.48	1581	111		364
2.5 Ta_2O_5	7.23	959	2.7	1112	2.4	0.36	1518	82	28	
5.0 Ta_2O_5	6.75	995	2.5	1052	2.6	0.33	1508	76		
B 1.0 Y_2O_3	7.26	796	0.9	841	1.0	0.34	1547	66		374
1.0 La_2O_3	7.46	1187	1.9	1483	2.0	0.53	1510	138		
1.0 La_2O_3	7.47	1139	2.2	1387	2.1	0.52	1522	130		339
1.0 Nd_2O_3	7.43	1111	1.6	1395	1.8	0.49	1512	123		
1.0 Nd_2O_3	7.37	1101	1.9	1354	1.8	0.48	1511	119		348
1.0 didymia	7.41	1122	2.2	1341	2.2	0.50	1499	125		
2.0 La_2O_3	7.49	1296	2.6	1545	2.3	0.51	1545	132		
1.0 La_2O_3	7.20	1375	2.1	1792	1.7	0.51	1528	147		
1.0 Nd_2O_3	7.35	1362	2.2	1776	1.9	0.49	1558	136		
0.1 La_2O_3	6.75	790	0.4	870	0.6	0.42	1505	88		
0.2 La_2O_3	6.45	686	0.7	735	0.9	0.37	1419	78		
0.4 La_2O_3	6.44	942	1.4	1100	1.5	0.42	1407	109		
0.8 La_2O_3	7.19	1288	1.8	1682	1.8	0.49	1516	139		
1.0 La_2O_3	7.50	1255	2.4	1532	2.4	0.50	1550	128		

Table 1C-a63-007. PZT (commercial modified ceramics). Electromechanical constants at RT [71Ber]. The designations for materials are trademarks of Vernitron Piezoelectric Division. f = 1 kHz for κ.

Material	Θ_f [°C]	ρ_a [$\cdot 10^3$ kg m^{-3}]	κ_{33}^T	Q_E	κ_{33}^S	κ_{11}^T	κ_{11}^S	k_p	k_{31}	k_{33}	k_{15}	k_{3t}
PZT–2	370	7.6	450	200	260	990	504	–0.47	–0.28	0.63	0.70	0.51
PZT–4	328	7.5	1300	250	635	1475	730	–0.58	–0.33	0.70	0.71	0.51
PZT–5A	365	7.75	1700	50	830	1730	916	–0.60	–0.34	0.705	0.685	0.49
PZT–5H	193	7.5	3400	50	1470	3130	1700	–0.65	–0.39	0.75	0.675	0.505
PZT–6A	335	7.45	1050	50	730			–0.42	–0.25	0.54		0.39
PZT–6B	≈350	7.55	460	110	386	475	407	–0.25	–0.145	0.375	0.377	0.30
PZT–7A	≈350	7.6	425	60	235	840	460	–0.51	–0.30	0.66	0.67	0.50
PZT–8	300	7.6	1000	250	580	1290	900	–0.51	–0.30	0.64	0.55	0.48

Material	υ_{31} **)	υ_{1s}^D **)	s_{11}^E	s_{33}^E	Q_{mech}	s_{44}^E	s_{66}	s_{11}^D	s_{33}^D	s_{44}^D
	[ms^{-1}]		[$\cdot 10^{-12}$ m^{2}N^{-1}]			[$\cdot 10^{-12}$ m^{2}N^{-1}]				
PZT–2	4410	2400	11.6	14.8	680	45.0	29.9	10.7	9.0	22.9
PZT–4	4600	2630	12.3	15.5	500	39.0	32.7	10.9	7.90	19.3
PZT–5A	4350	2260	16.4	18.8	75	47.5	44.3	14.4	9.46	25.2
PZT–5H	4560	2375	16.5	20.7	65	43.5	42.6	14.1	8.99	23.7
PZT–6A	4570		10.7	13.0	450		27.8	10.1	9.2	
PZT–6B	4820	2340	9.0	9.35	1300	28.2	24.0	8.8	8.05	24.2
PZT–7A	4800	2490	10.7	13.9	600	39.5	27.8	9.7	7.85	21.8
PZT–8	4580	2420	11.5	13.5	1000	31.9	29.8	10.4	8.0	22.6

Material	c_{11}^E	c_{33}^E	c_{11}^D	c_{33}^D	N_1 *)	N_{3t} *)	d_{33}	d_{31}	d_{15}
	[$\cdot 10^{10}$ Nm^{-2}]				[Hz m]		[$\cdot 10^{-12}$ CN^{-1}]		
PZT–2	13.5	11.3	13.6	14.8	1680	2090	152	–60	440
PZT–4	13.9	11.5	14.5	15.9	1650	2000	289	–123	496
PZT–5A	12.1	11.1	12.6	14.7	1400	1890	374	–171	584
PZT–5H	12.6	11.7	13.0	15.7	1420	2000	593	–274	741
PZT–6A		13.1		15.5	1770	2140	189	–80	
PZT–6B	16.8	16.3	16.9	17.7	1920	2225	71	–27	130
PZT–7A	14.8	13.1	15.7	17.5	1750	2100	150	–60	362
PZT–8	13.7	12.3	14.0	16.1	1700	2070	225	–97	330

(continued)

Table 1C-a63-007 (continued)

Material	g_{33}	g_{31}	g_{15}	e_{33}	e_{31}	e_{15}	Change in N_1 per time decade [%]	Change in k_p per time decade [%]	Change in κ_{33}^T per time decade [%]	Change in N_1, –60 to +85 °C [%]
	[$\cdot 10^{-3}$ m^2C^{-1}]			[Cm^{-2}]						
PZT–2	38.2	–15.1	50.1	9.0	–1.9	9.8	+0.6	–1.8	–2.8	1.5
PZT–4	25.1	–10.7	38.0	15.1	–5.2	12.7	+1.5	–2.3	–5.8	4.8
PZT–5A	24.9	–11.4	38.0	15.8	–5.4	12.3	+0.2	–0.2	–1.0	2.6
PZT–5H	19.7	–9.1	26.8	23.3	–6.5	17.0	+0.25	–0.35	–1.5	9.0
PZT–6A	20.4	–8.6		12.5			<0.1	–0.2	–0.6	<0.2
PZT–6B	17.4	–6.6	31.0	7.1	–0.9	4.6	<0.1	–0.2	–0.6	<0.2
PZT–7A	39.8	–15.9	48.8	9.5	–2.1	9.2	–0.08	0.0	+2.0	2.9
PZT–8	25.4	–10.9	29.0	13.2	–4.0	10.4	+1.0	–2.0	–5.0	~2.0

*) N_1 is the frequency constant for extensional vibration of a bar with long axis perpendicular to the polar axis, and N_{3t} is the frequency constant for thickness longitudinal vibration of a plate with thickness parallel to the polar axis.
**) υ_{31} and υ_{1s} are the longitudinal and shear sound velocities parallel and normal to the polar axis, respectively.

Table 1C-a63-008. PZT-4, PZT-5 and PZT-7 (sintered and hot-pressed ceramics). Dielectric and electromechanical properties [86Pat]. υ_p: longitudinal velocity of sound propagated along polarization direction in polarized specimen, υ_u: longitudinal sound velocity in unpolarized specimen.

	PZT–4		PZT–5		PZT–7	
	sintered	hot-pressed	sintered	hot-pressed	sintered	hot-pressed
ρ [$\cdot 10^3$ kg m^{-3}]	7.65	7.99	7.73	8.01	7.45	7.97
tan δ [$\cdot 10^{-2}$]	0.4	0.3	1.8	1.6	1.5	0.6
κ	1100	1250	1550	2100	400	450
k_p	0.54	0.62	0.63	0.72	0.32	0.38
k_{31}	0.32	0.37	0.38	0.43	0.19	0.23
d_{31} [$\cdot 10^{-12}$ CN^{-1}]	–115	–136	–170	–230	–30	–40
g_{31} [$\cdot 10^{-3}$ m^{2}C^{-1}]	–11.8	–12.3	–12.4	–12.4	–8.5	–10.0
υ_p [m s^{-1}]	4420	4820	4510	4850	4620	4940
υ_u [m s^{-1}]	4100	4420	4150	4420	4400	4640
Q_m	450	490	70	80	1025	1180

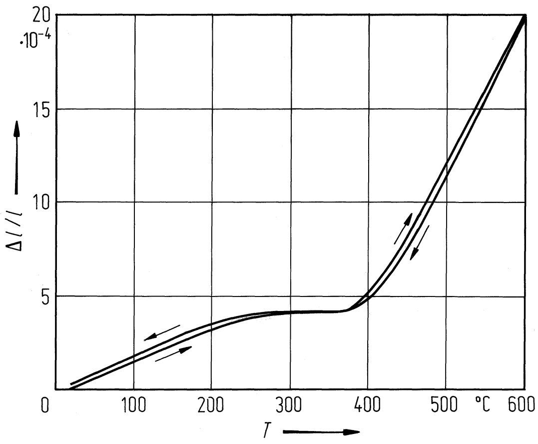

Fig. 1C-a63-001. $Pb(Zr_{0.5}Ti_{0.5})O_3$ (ceramics). $\Delta l/l$ vs. T [79Bis].

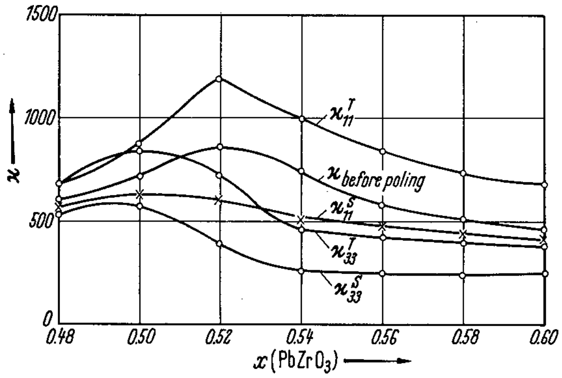

Fig. 1C-a63-002. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics). κ vs. x [60Ber]. f = 1 kHz.

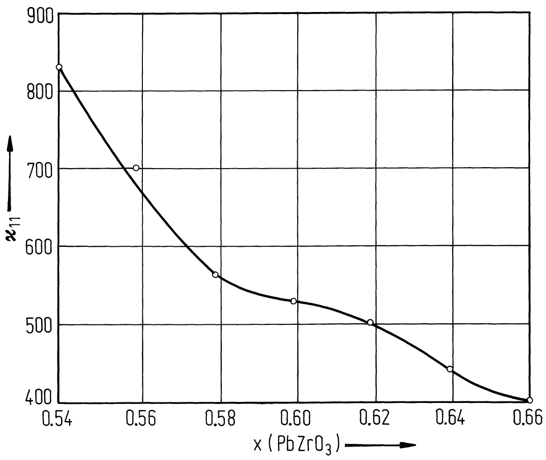

Fig. 1C-a63-003. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics). κ_{11} vs. x [81Kal].

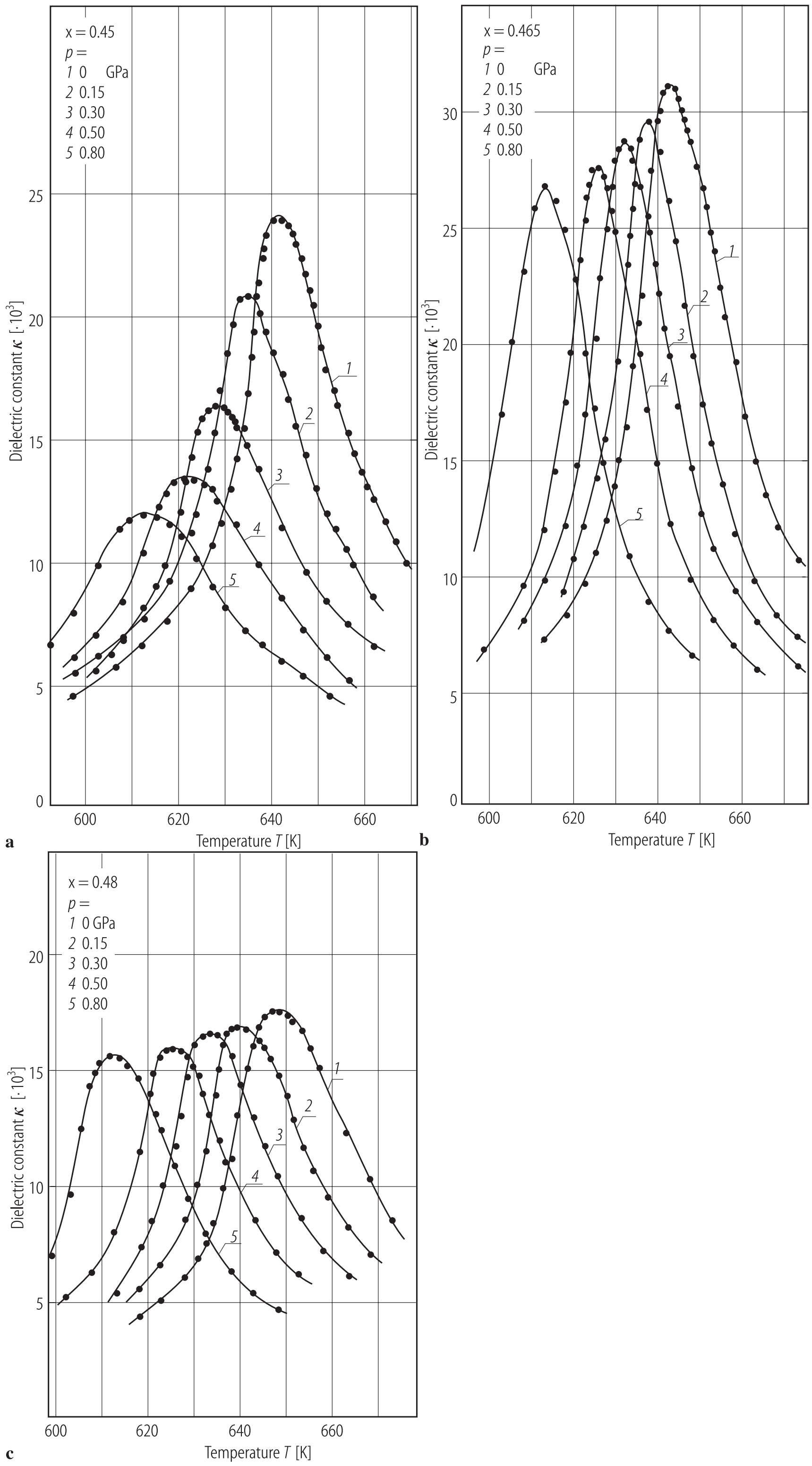

Fig. 1C-a63-004. $Pb(Zr_{1-x}Ti_x)O_3$ (ceramics). κ vs. T [88Pis]. Parameter: p.

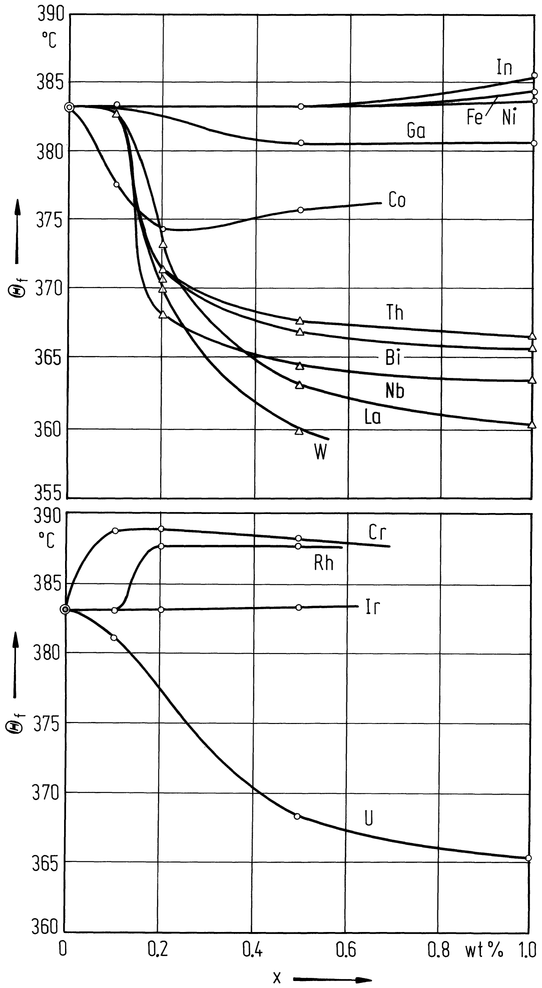

Fig. 1C-a63-005. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramics). Θ_f vs. x_w [82Tak]. Parameter: doped element. x_w: wt % of doped impurity.

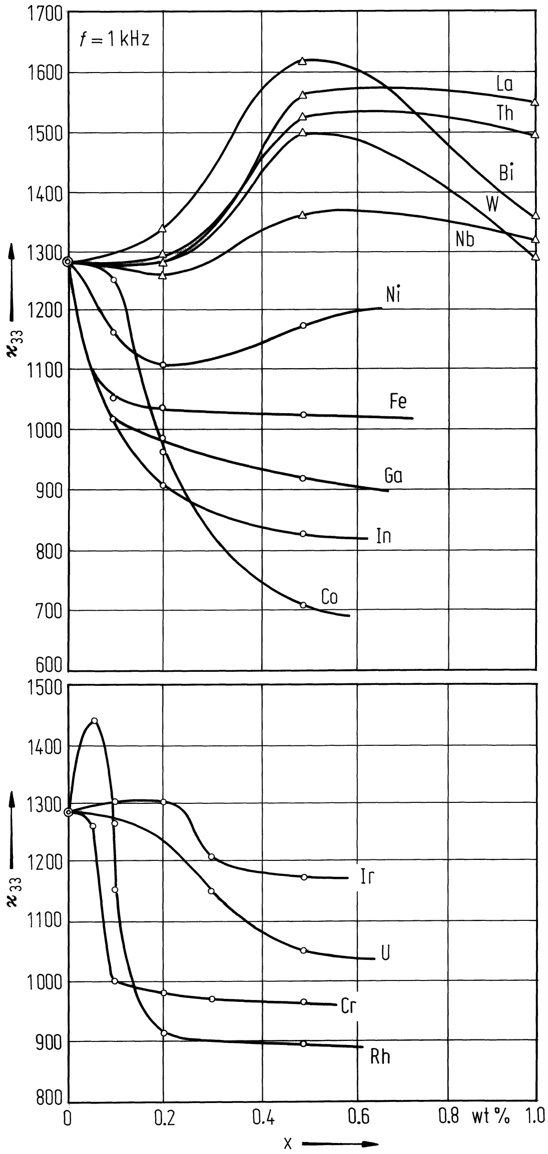

Fig. 1C-a63-006. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramics). κ_{33} vs. x_w [82Tak]. Parameter: doped element. x_w: wt % of doped impurity. f = 1 kHz.

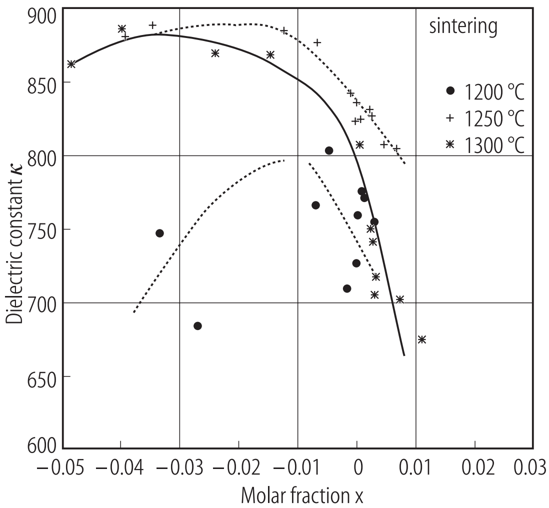

Fig. 1C-a63-007. $Pb_{1+x}(Zr_{0.53}Ti_{0.44})O_{3+x}$ (ceramics). κ vs. x [91Kin]. Parameter: sintering temperature. Influence of excess or deficiency of PbO content.

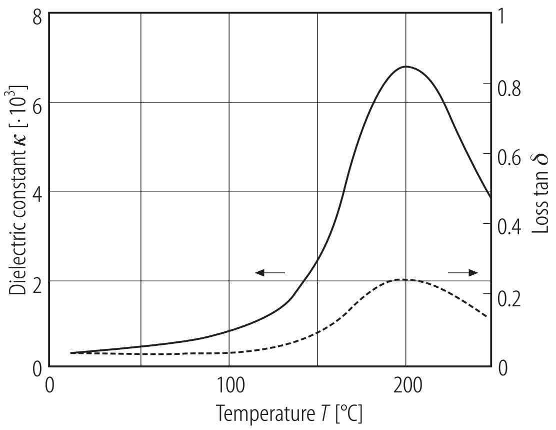

Fig. 1C-a63-008. $Pb(Zr_{1-x}Ti_x)O_3$ (thin film). κ, $\tan\delta$ vs. T [87Ada]. f = 1 MHz. The [111]-oriented film was grown onto Pt-substrate by magnetron sputtering using Pb-enriched PZT (90/10) target.

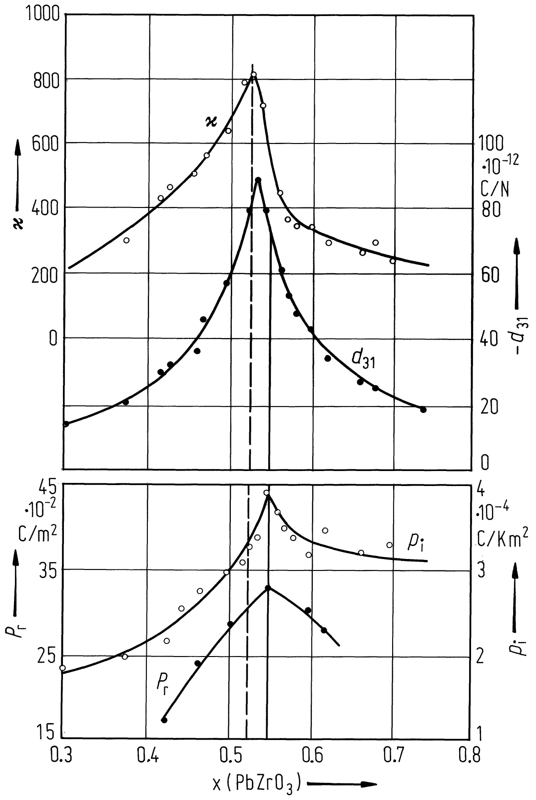

Fig. 1C-a63-009. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics). κ , p_i, d_{31}, P_r vs. x [79Che]. Additive: 2 wt % $Zn(Mn_{1/3}Bi_{2/3})O_3$. p_i: pyroelectric coefficient.

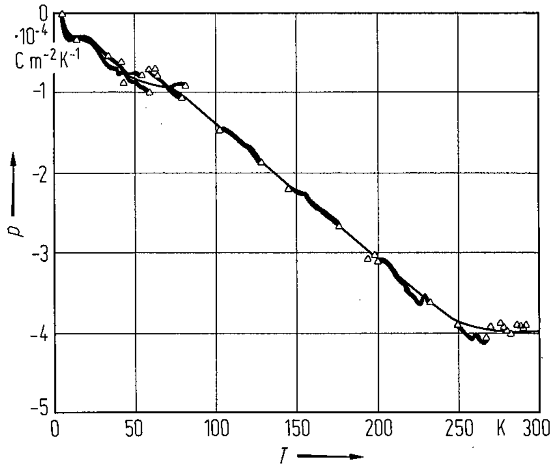

Fig. 1C-a63-010. PZT-5A (ceramics). *p* vs. *T* [69Lan]. *p*: pyroelectric coefficient. Heavy lines indicate areas of dense data points.

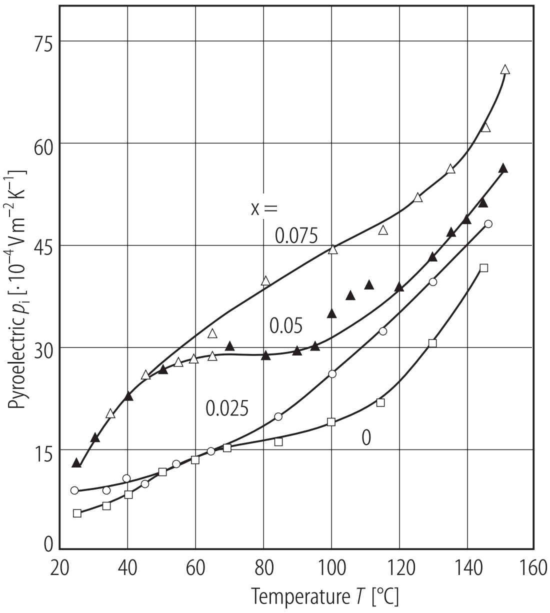

Fig. 1C-a63-011. $(Pb_{1-3x/2}Ga_x)(Zr_{0.6}Ti_{0.4})O_3$ (ceramics). p_i vs. T [94Sha]. Parameter: x. p_i: pyroelectric coefficient.

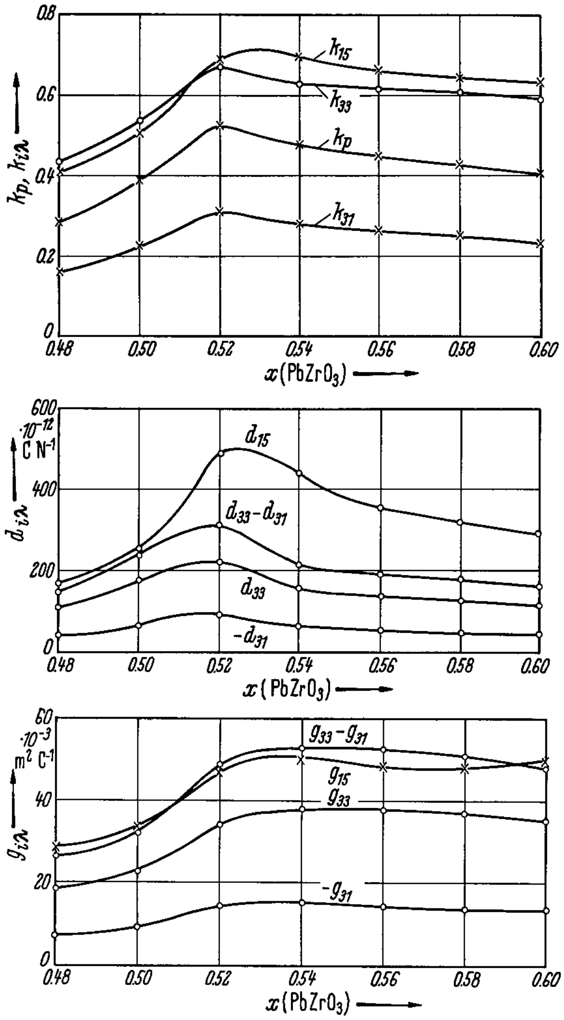

Fig. 1C-a63-012. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics). k_p, $k_{i\lambda}$, $d_{i\lambda}$, $g_{i\lambda}$ vs. x [60Ber].

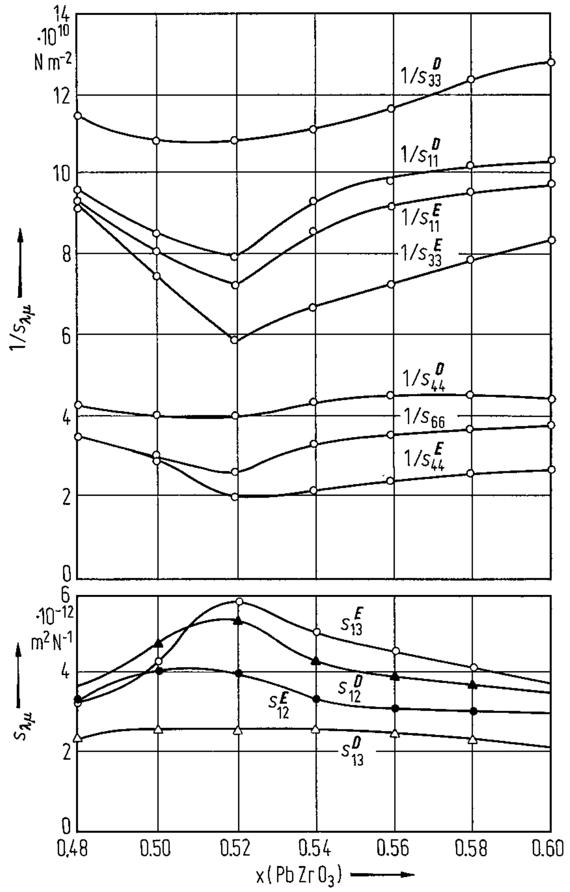

Fig. 1C-a63-013. Pb($Ti_{1-x}Zr_x$)O_3 (ceramics). 1/ $s_{\lambda\mu}$, $s_{\lambda\mu}$ vs. x [60Ber].

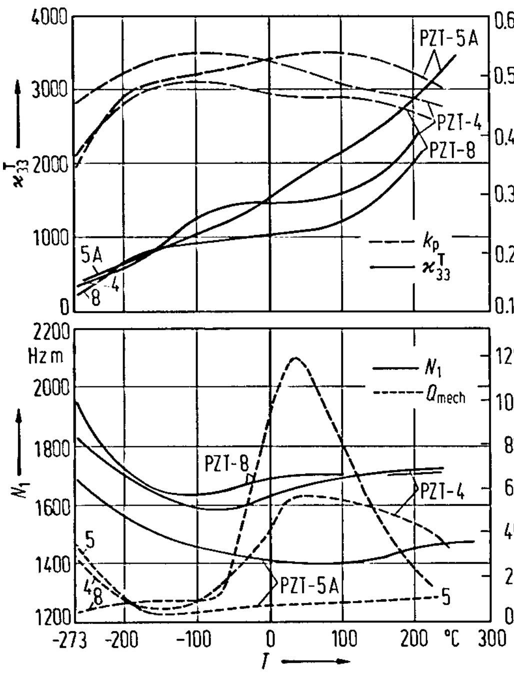

Fig. 1C-a63-014. PZT-4, PZT-5A, and PZT-8 (ceramics). κ_{33}^{T}, k_p, N_1, Q_{mech} vs. T [71Ber]. N_1: frequency constant for transverse-effect extensional vibration of a bar. f = 1 kHz for κ_{33}^{T}.

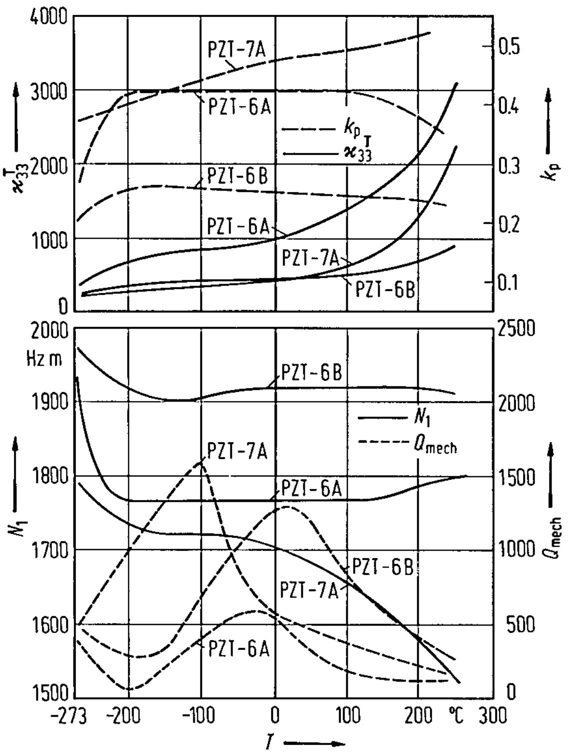

Fig. 1C-a63-015. PZT-6A, PZT-6B, and PZT-7A (ceramics). κ_{33}^{T}, k_p, N_1, Q_{mech} vs. T [71Ber]. See the caption of Fig. 1C-a63-014.

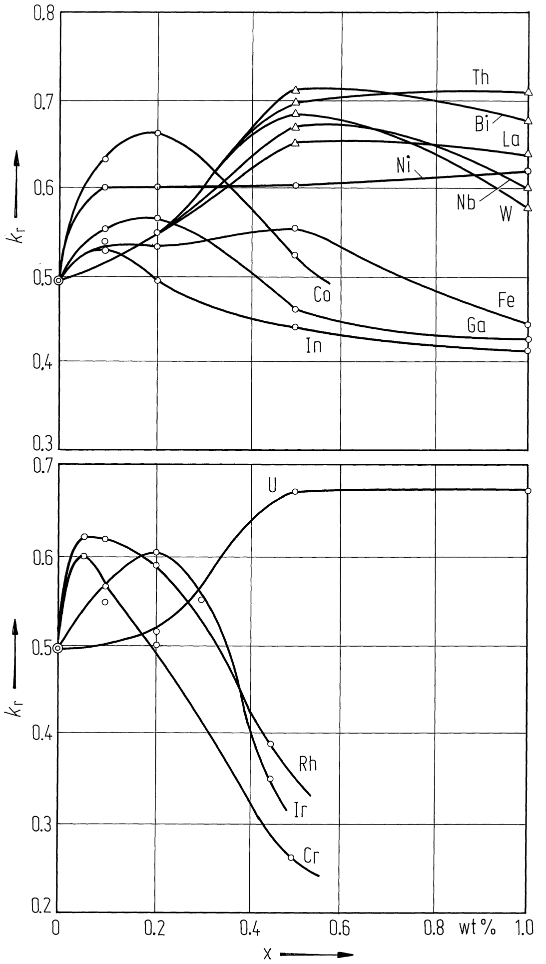

Fig. 1C-a63-016. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramics). k_r vs. x_w [82Tak]. Parameter: doped element. x_w: wt % of doped impurity. k_r: coupling factor of radial mode.

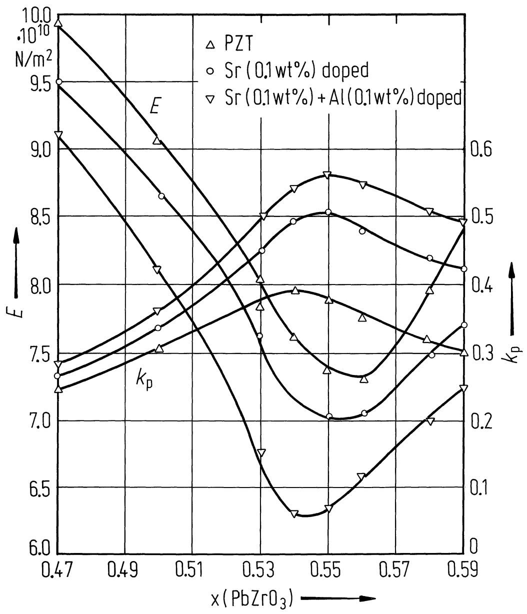

Fig. 1C-a63-017. $Pb(Ti_{1-x}Zr_x)O_3$ (ceramics). k_p, *E* vs. x [85Abd]. Parameter: additives (Sr and/or Al). *E*: Young's modulus.

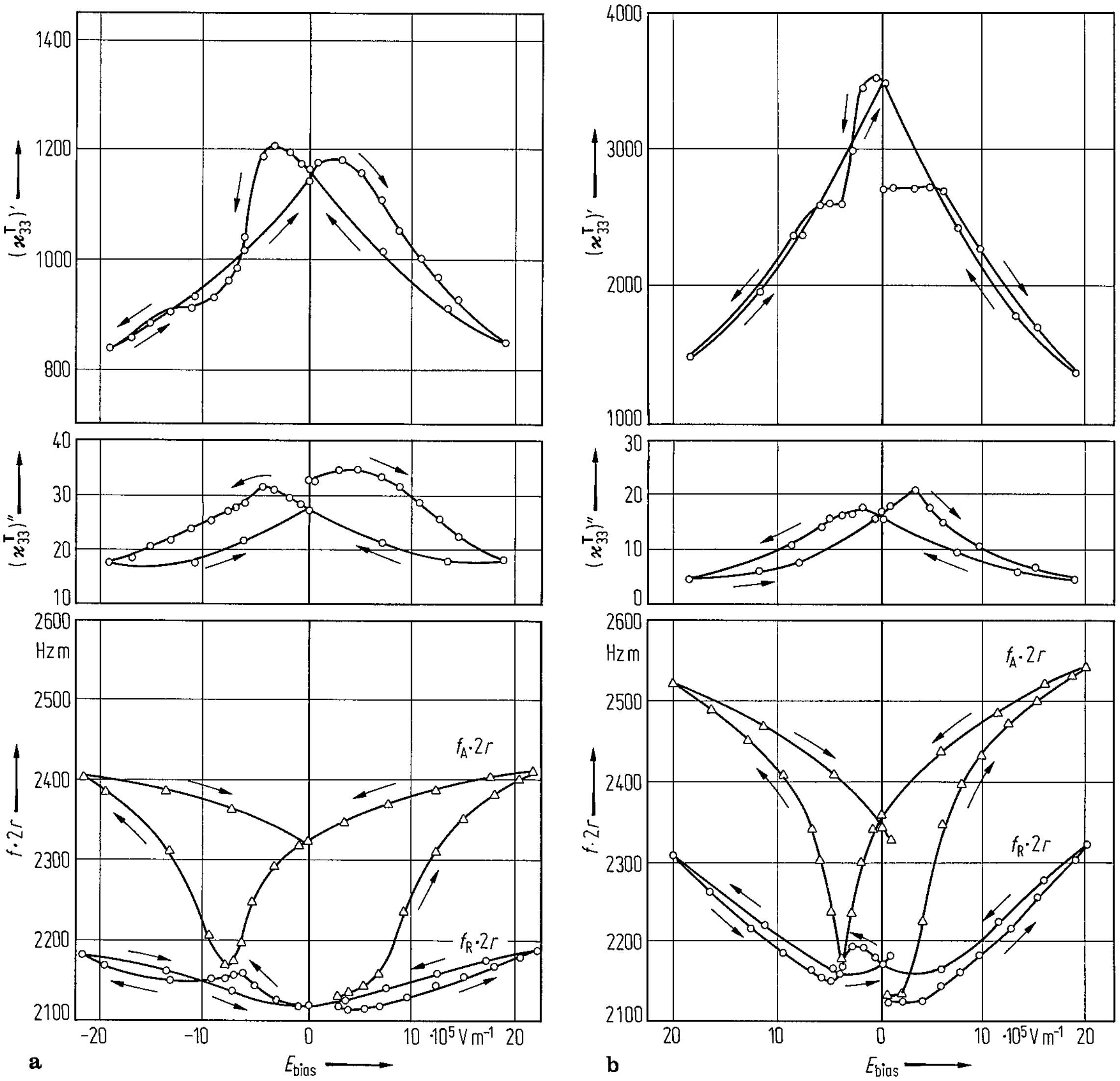

Fig. 1C-a63-018. 0.88 $Pb(Zr_{0.60}Ti_{0.40})O_3$·0.12 $NaNbO_3$ (ceramics). $(\kappa_{33}^{T})'$, $(\kappa_{33}^{T})''$, $f_R\cdot 2r$, $f_A\cdot 2r$ vs. E_{bias} [65Uch]. **(a)** T = 30 °C, **(b)** T = 170 °C. f_R: resonance frequency, f_A: antiresonance frequency. κ at f = 10 kHz.

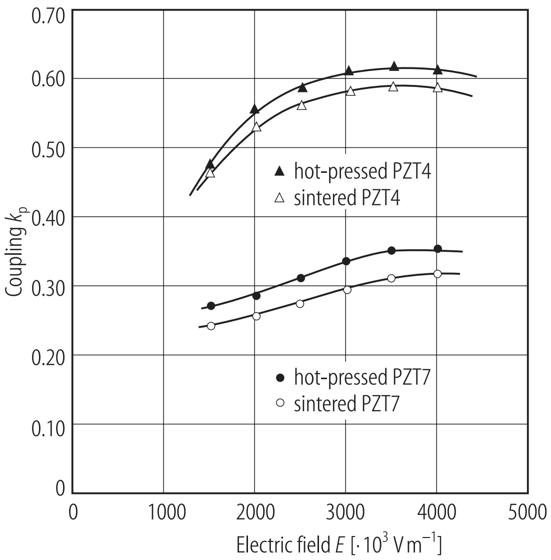

Fig. 1C-a63-019. PZT (ceramics). k_p vs. E [86Pat]. E: poling electric field applied at 120 °C.

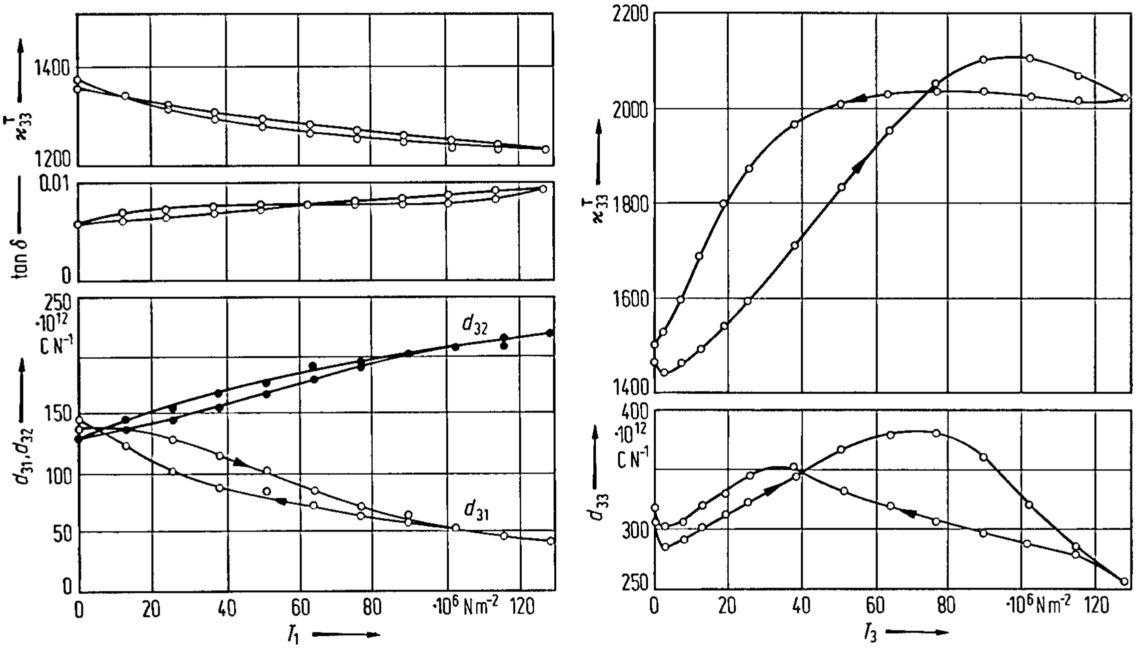

Fig. 1C-a63-020. PZT-4 (ceramics). κ_{33}^T, tanδ, d_{31}, d_{32}, d_{33} vs. T_1, T_3 [67Kru, 68Kru]. T_1: lateral stress, T_3: parallel stress. The stress is repeatedly applied and the results for 4th cycle are shown. κ at f = 1 kHz.

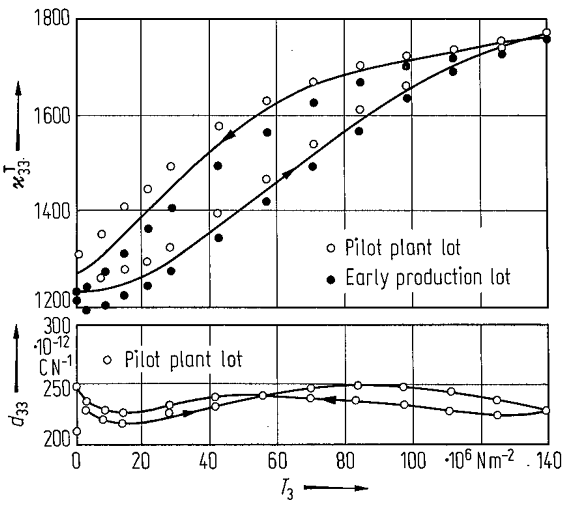

Fig. 1C-a63-021. PZT-8 (ceramics). $\kappa_{33}^{\mathbf{T}}$, d_{33} vs. T_3 [67Kru]. See the caption of Fig. 1C-a63-020.

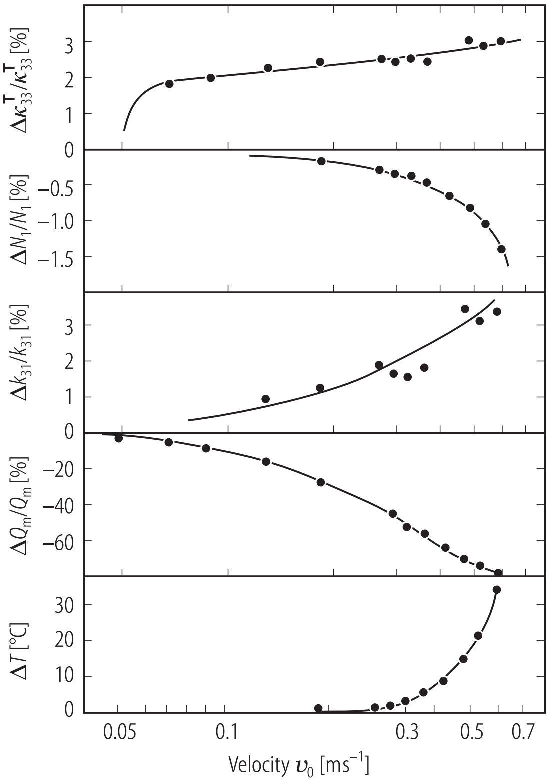

Fig. 1C-a63-022. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramic bar doped with 2.1 atm % Fe). Variation of physical constants under high vibration level [93Tak]. υ_0: effective amplitude of vibration velocity; $\Delta\kappa_{33}^{T}$, ΔN_l, Δk_{31}, ΔQ_m: change of dielectric constant, frequency constant, coupling coefficient, mechanical Q factor from the respective initial values at infinitesimal level; ΔT: temperature rise.

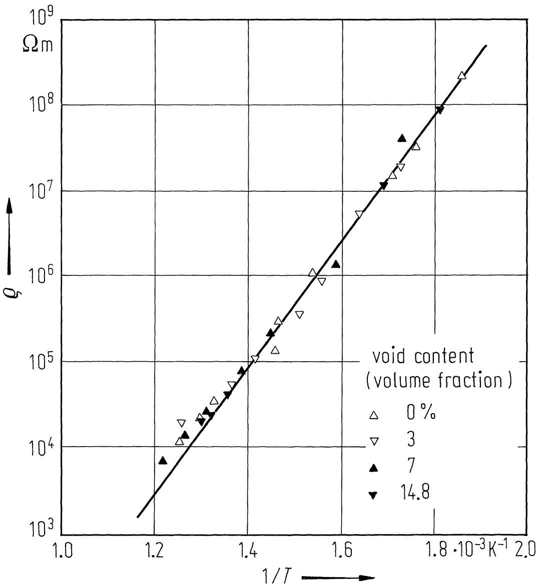

Fig. 1C-a63-023. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramics doped with Nb). ρ vs. $1/T$ [81Dih]. Parameter: void content.

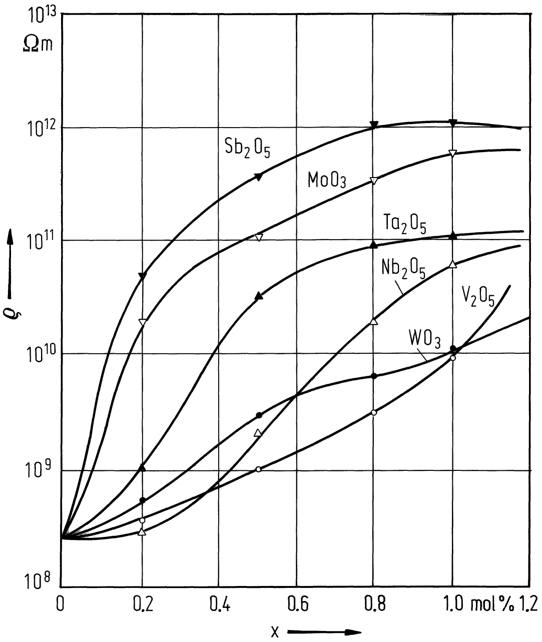

Fig. 1C-a63-024. $Pb(Zr_{0.52}Ti_{0.48})O_3$ (ceramics). ρ vs. x [83Wul2]. Parameter: doped impurity. x: mol % of impurity.

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