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D. H. Chung

Selected Materials for Use in Microsound Circuits and Components: Their Elastic, Piezoelectric, and Dielectric Parameters

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

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LINCOLN LABORATORY

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D. H. CHUNG, Consultant

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ABSTRACT

Tables are set forth containing a critical compilation of the elastic, piezoelectric, and dielectric properties of crystals that are of potential interest in applications to microsound circuits and components. Elastic constants are provided for the total of 27 crystals, consisting of 10 semiconductors, 6 piezoelectrics, and 11 acoustic materials. Piezoelectric constants are given for 16 crystals, and dielectric constants for 11 crystals of potential interest. All the property constants entered in these tables were taken from the literature. A brief description of each property is provided in the Appendix to assist users of these tables.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

SELECTED MATERIALS FOR USE IN MICROSOUND CIRCUITS AND COMPONENTS: THEIR ELASTIC, PIEZOELECTRIC, AND DIELECTRIC PARAMETERS

The design, manufacture, and evaluation of microsound circuits and components for practical applications demand detailed information on the behavior of surface waves on the various crystalline materials to be used (see, for example, Stern[1]). Successful realization of microsound circuits and components depends, therefore, on intelligent utilization of the well established physical properties of materials that are to be used in the design and manufacture of these circuits and components. The properties of primary interest are of course the elastic constants and density, piezoelectric parameters, and dielectric constants.

The purpose of this memorandum is to present tables containing a critical compilation of the elastic, piezoelectric, and dielectric parameters of selected materials that are of potential interest in applications to microsound circuits and components. Table I presents the elastic constants of 22 crystals along with the crystal density and percent elastic (shear) anisotropy. The piezoelectric strain and stress constants of 16 selected crystals are given in Table II and Table III lists the dielectric constants for 11 crystals. A brief description of each of these properties is given in the Appendix, for the purpose of assisting the users of these tables.

The symbols and units used in the tables are as follows:

Property	Symbol	Unit
Density	ρ	gm/cm^3
Elastic stress	T	dyn/cm^2
Elastic strain	S	None
Electrical field strength	E	
Dielectric displacement	D	
Elastic stiffness constant	$c_{\mu\nu}$	$\times 10^{-11} dyn/cm^2$
Elastic compliance coefficients	$s_{\mu\nu}$	$\times 10^{-12} cm^2/dyn$
Piezoelectric strain constant at constant E	$d_{j\nu}$	$\times 10^{-8}$ estE Ldg./dyn
Piezoelectric strain constant at constant D	$g_{j\nu}$	$\times 10^{-8} cm^2$/estE Ldg
Piezoelectric stress constant at constant E	$e_{j\nu}$	$\times 10^{4}$ estE $Ldg./cm^2$
Piezoelectric stress constant at constant D	$h_{j\nu}$	$\times 10^{4}$ dyn/estE Ldg
Electromechanical coupling factor	$k_{j\nu}$	Numerical
Dielectric permittivity	ϵ_{jm}	Numerical
Dielectric impermeability	β_{jm}	Numerical

TABLE I

ELASTIC PARAMETERS OF SELECTED CRYSTALLINE MATERIALS

Materials	Density (gm/cm^3)	Elastic Stiffness Constants ($\times 10^{11} dyn/cm^2$)							Elastic Shear Anisotropy		Remarks
		c_{11}	c_{12}	c_{13}	c_{14}	c_{33}	c_{44}	c_{66}	A	A (percent)	
GaAs	5.307	11.920	5.986	–	–	–	5.938	–	2.00	5.67	
Si	2.331	16.60	6.40	–	–	–	7.96	–	1.56	2.36	
Ge	5.323	13.00	4.90	–	–	–	6.70	–	1.65	3.01	
InAs	5.672	8.329	4.526	–	–	–	3.959	–	2.08	6.32	
ZnO (hexagonal)	5.676	20.97	12.11	10.51	–	21.09	4.247	4.429	0.96	0.50	
CdS (hexagonal)	4.870	8.16	4.95	4.79	–	8.08	1.43	1.61	0.89	0.23	Semiconductor
InP											
GaP											
Pbs (β)	7.50	12.70	2.98	–	–	–	2.48	–	0.51	5.34	
ZnS (β)	4.079	9.76	5.90	–	–	–	4.51	–	2.34	8.41	
$LiNbO_3$	4.628	2.03	0.53	0.75	0.09	2.45	0.60	0.75	0.80	1.50	
$LiGaO_3$											
$Ba_2NaNb_5O_{15}$											
SiO_2 (α)	2.649	8.680	0.704	1.191	−1.804	10.575	5.820	–	1.46	7.65	Piezoelectric
ZnO (hexagonal)	5.676	20.97	12.11	10.51	–	21.09	4.247	4.429	0.96	0.50	
CdS (hexagonal)	4.870	8.16	4.95	4.79	–	8.08	1.43	1.61	0.89	0.23	
$Bi_{12}GeO_{20}$	9.20	1.20	0.39	–	–	–	0.25	–			
YA1 Garnet	4.55	33.32	11.07	–	–	–	11.50	–	1.03	0.01	
YFe Garnet	5.17	26.80	11.06	–	–	–	7.66	–	0.97	0.01	
YGa Garnet	5.79	29.03	11.73	–	–	–	9.55	–	1.10	0.12	
EuFe Garnet	6.28	25.10	10.70	–	–	–	7.62	–	1.06	0.04	
GdGa Garnet											
Diamond	3.512	107.60	12.50	–	–	–	57.58	–	1.21	0.44	Acoustic
MgO	3.583	29.60	9.51	–	–	–	15.56	–	1.55	2.28	
$MgA1_2O_4$	3.630	30.0	15.2	–	–	–	15.9	–	2.15	6.86	
$A1_2O_3$ (α)	3.986	49.68	16.84	11.09	−2.35	49.81	14.74	–	0.90	1.67	
BeO	3.010	46.06	12.65	8.848	–	49.16	14.77	16.70	1.01	0.44	
TiO_2	4.250	27.3	17.6	14.9	–	48.4	12.5	19.4	0.64	10.86	

TABLE II

PIEZOELECTRIC PARAMETERS OF SELECTED CRYSTALLINE MATERIALS

Material	Crystal Class and Point Group	Density (gm/cm^3)	$k_{j\nu}$ (numerical)	$d_{j\nu}$	$e_{j\nu}$	$g_{j\nu}$	$h_{j\nu}$
$LiGaO_2$	Orthorhombic (mm2)	4.187					
$BaTiO_3$	Tetrahedral (4mm)	6.020		$d_{15} = 1175$			
				$d_{31} = -103.5$			
				$d_{33} = 256.8$			
$BaTiO_3$	Hexagonal (6mm)	5.720	$k_{15} = 0.476$	$d_{15} = -78$	$e_{15} = 11.6$	$g_{15} = 18.8$	$h_{15} = 10.3$
		(at 115°C)	$k_{31} = 0.208$	$d_{31} = -78$	$e_{31} = -4.4$	$g_{31} = -4.7$	$h_{31} = -3.5$
			$k_{33} = 0.493$	$d_{33} = 190$	$e_{33} = 18.6$	$g_{33} = 11.4$	$h_{33} = 14.8$
			$k_p = 0.378$				
Quartz (α)	Trigonal (32)	2.649		$d_{11} = -6.76$	$e_{11} = -4.87$	$g_{11} = -19.3$	$h_{11} = 14.5$
				$d_{14} = 2.56$	$e_{14} = -1.23$	$g_{14} = -6.1$	$h_{14} = -3.47$
$AlPO_4$	Trigonal (32)	2.570		$d_{11} = 10$			
				$d_{14} = 4.65$			
$LiNbO_3$	Trigonal (3m)	4.628		$d_{15} = 6800$	$e_{15} = 111$		
				$d_{22} = 2100$	$e_{22} = 75$		
				$d_{31} = -100$	$e_{31} = 6$		
				$d_{33} = 600$	$e_{33} = 39$		
BeO	Hexagonal (6mm)	3.010	$k_{31} = 0.010$	$d_{31} = -0.36$	$e_{31} = -1.53$		
			$k_{33} = 0.22$	$d_{33} = 0.72$	$e_{33} = 2.76$		

TABLE II (Continued)

Material	Crystal Class and Point Group	Density (gm/cm^3)	$k_{j\nu}$ (numerical)	$d_{j\nu}$	$e_{j\nu}$	$g_{j\nu}$	$h_{j\nu}$
CdSe	Hexagonal (6mm)	5.684	k_{15} = 0.1305	d_{15} = −31.53	e_{15} = −4.14		
			k_{31} = 0.0836	d_{31} = −11.76	e_{31} = −4.80		
			k_{33} = 0.194	d_{33} = 23.52	e_{33} = 10.41		
			k_t = 0.124				
CdS	Hexagonal (6mm)	4.825	k_{15} = 0.1885	d_{15} = −41.94	e_{15} = −6.30		
			k_{31} = 0.1191	d_{31} = −15.54	e_{31} = −7.32		
			k_{33} = 0.262	d_{33} = 30.96	e_{33} = 13.20		
			k_t = 0.154				
ZnO	Hexagonal (6mm)	5.675	k_{15} = 0.285	d_{15} = −40.0	e_{15} = −9.30		
			k_{31} = 0.182	d_{31} = −15.63	e_{31} = −4.80		
			k_{33} = 0.400	d_{33} = 31.8	e_{33} = 33.0		
			k_t = 0.30				
ZnS (β)	Cubic ($\bar{4}3m$)	4.088	k_{14} = 0.08				
CdTe	Cubic ($\bar{4}3m$)	5.840	k_{14} = 0.026 (at −196°C)	d_{14} = 5.04 (at −196°C)	e_{14} = 1.005 (at −196°C)		
GaSb	Cubic ($\bar{4}3m$)	5.619			e_{14} = 5.4		
GaP	Cubic ($\bar{4}3m$)	1.337		d_{14} = 7.80	e_{14} = 6.3		
InSb	Cubic ($\bar{4}3m$)	5.789			e_{14} = 2.7		
InAs	Cubic ($\bar{4}3m$)	5.700			e_{14} = 3.0		
ZnSe	Cubic ($\bar{4}3m$)	5.262	k_{14} = 0.026		e_{14} = 1.47		
ZnTe	Cubic ($\bar{4}3m$)	5.636	k_{14} = 0.017	d_{14} = 2.73	e_{14} = 0.852		

TABLE III DIELECTRIC PARAMETERS OF SELECTED CRYSTALLINE MATERIALS				
Materials	Crystal Class and Point Group	Density (gm/cm^3)	ϵ_{jm}	β_{jm}
$BaTiO_3$	Tetragonal (4mm)	6.020	ϵ_{11}^{T} = 2920, ϵ_{33}^{T} = 468	
			ϵ_{11}^{S} = 1970, ϵ_{33}^{S} = 109	
$BaTiO_3$	Hexagonal (6mm)	5.720 (at 115°C)	ϵ_{11}^{T} = 1450, ϵ_{33}^{T} = 1700	
			ϵ_{11}^{S} = 1115, ϵ_{33}^{S} = 1260	
$AlPO_4$	Trigonal (32)	2.570	ϵ_{11} = 6	
Quartz (α)	Trigonal (32)	2.649	ϵ_{11}^{T} = 4.52, ϵ_{33}^{T} = 4.64	β_{11}^{T} = 0.2213, β_{33}^{T} = 0.2155
			ϵ_{11}^{S} = 4.435, ϵ_{33}^{S} = 4.640	β_{11}^{S} = 0.2255, β_{33}^{S} = 0.2155
$LiNbO_3$	Trigonal (3m)	4.628	ϵ_{11}^{T} = 84 ϵ_{33}^{T} = 30	β_{11}^{T} = 0.0119 β_{33}^{T} = 0.030
			ϵ_{11}^{S} = 44 ϵ_{33}^{S} = 29	β_{11}^{S} = 0.023 β_{33}^{S} = 0.034
BeO	Hexagonal (6mm)	3.010	ϵ_{33}^{T} = 7.66	β_{33}^{T} = 0.131
CdSe	Hexagonal (6mm)	5.684	ϵ_{11}^{T} = 9.70, ϵ_{33}^{T} = 10.65	β_{11}^{T} = 0.103, β_{33}^{T} = 0.094
			ϵ_{11}^{S} = 9.53, ϵ_{33}^{S} = 10.20	β_{11}^{S} = 0.107, β_{33}^{S} = 0.098
CdS (α)	Hexagonal (6mm)	4.825	ϵ_{11}^{T} = 9.35, ϵ_{33}^{T} = 10.33	β_{11}^{T} = 0.107, β_{33}^{T} = 0.097
			ϵ_{11}^{S} = 9.02, ϵ_{33}^{S} = 9.53	β_{11}^{S} = 0.111, β_{33}^{S} = 0.105
ZnO	Hexagonal (6mm)	5.675	ϵ_{11}^{T} = 9.26, ϵ_{33}^{T} = 11.0	β_{11}^{T} = ? β_{33}^{T} = 0.122
			ϵ_{11}^{S} = 8.33, ϵ_{33}^{S} = 8.84	
CdTe	Cubic ($\bar{4}$3m)	5.840	ϵ_{11}^{T} = 9.65	β_{11}^{T} = 0.104
			ϵ_{11}^{S} = 9.65	β_{11}^{S} = ?
ZnSe	Cubic ($\bar{4}$3m)	5.262	ϵ_{11}^{T} = 9.12	β_{11}^{T} = 0.110
			ϵ_{11}^{S} = 9.12	β_{11}^{S} = 0.110
ZnTe	Cubic ($\bar{4}$3m)	5.636	ϵ_{11}^{T} = 10.10	β_{11}^{T} = 0.099
			ϵ_{11}^{S} = 10.10	β_{11}^{S} = 0.099

APPENDIX

The macroscopic properties of crystals such as elasticity, piezoelectricity, and dielectric behavior are functions of their crystal symmetry. From a macroscopic point of view, the crystals are divided into 32 crystal classes with seven crystal systems (see, for example, Kittel).[2] The symmetry properties are described by symmetry elements, such as symmetry axes, symmetry planes, etc. A standard text such as one written by Nye[3] gives a detailed description of these symmetry elements and their properties with respect to reference coordinates. In all cases, the material constants are related to the main orthogonal coordinate system X, Y, Z which for the crystal systems of orthorhombic and cubic symmetries is uniquely determined by the crystallographic axes a, b, c. X is parallel to a, Y is parallel to b, and Z is parallel to c. Different notations are used in the monoclinic crystal system for the principal crystallographic axes. According to the Institute of Radio Engineers,[4] the main coordinate system is defined as follows: the Y axis is parallel to the symmetry axis b, and the angle between the crystallographic axis a and c is always obtuse. The c axis is then chosen as the shorter axis. The Z axis is parallel to c, and the X axis together with the Y and Z axes form a rectangular coordinate system. These notations are used throughout this memorandum.

In general, the elastic and electric quantities of state are related to each other by 21 elastic, 18 piezoelectric, and 6 dielectric constants for the lowest symmetry crystals, as, for example, in a triclinic crystal. The number of independent constants decreases as crystal symmetry becomes greater. For example, a cubic crystal has only 3 elastic constants and 1 piezoelectric and 1 dielectric constant. Table A-1 summarizes the number of independent constants of a given crystal property, and lists the 20 crystal classes in which the piezoelectricity exists.

In piezoelectric crystals, the elastic and electrical properties are related to each other. If the components of the elastic stress tensor T_μ and those of the strain tensor S_μ are chosen as elastic variables, and the components of the electric field vector E_j and the dielectric displacement vector D_j are chosen as electric variables, where the tensor components are indicated by Greek letters (ranging from 1 to 6) and the vector components by Latin letters (ranging from 1 to 3), then four different piezoelectric equations of state exist according to the choice of the independent variables. In the most general case, e.g., a triclinic crystal, these equations of state in rationalized units are given as follows:

Elastic equations (converse piezoelectric effect):

$$S_\mu = \sum s^E_{\mu\nu} T_\nu + \sum d_{m\mu} E_m \tag{1}$$

$$T_\mu = \sum c^E_{\mu\nu} S_\nu - \sum e_{m\mu} E_m \tag{2}$$

$$T_\mu = \sum c^D_{\mu\nu} S_\nu - \sum h_{m\mu} D_m \tag{3}$$

$$S_\mu = \sum s^D_{\mu\nu} T_\nu + \sum g_{m\mu} D_m \tag{4}$$

TABLE A-1

SEVEN CRYSTAL SYSTEMS (20 CRYSTAL CLASSES)
IN WHICH THE PIEZOELECTRIC EFFECT IS EXPECTED

Crystal System	Crystal Class	Symmetry Symbol*	Number of Independent Constants		
			Elastic	Piezoelectric	Dielectric
Triclinic	1	1	21	18	6
Monoclinic	3	2	13	8	4
	4	m	13	10	4
Orthorhombic	6	222	9	3	3
	7	mm2	9	5	3
Tetragonal	9	4	7	4	2
	10	$\bar{4}$	7	4	2
	12	422	6	1	2
	13	4mm	6	3	2
	14	$\bar{4}2m$	6	2	2
Trigonal	16	3	7	6	2
	18	32	6	2	2
	19	3m	6	4	2
Hexagonal	21	6	5	4	2
	22	$\bar{6}$	5	2	2
	24	622	5	1	2
	25	6mm	5	3	2
	26	$\bar{6}m2$	5	1	2
Cubic	28	23	3	1	1
	31	$\bar{4}3m$	3	1	1

*This symmetry symbol is according to the Hermann-Mauguin scheme.

Electric equations (direct piezoelectric effect):

$$D_j = \sum d_{j\nu} T_\nu + \sum \epsilon^T_{jm} E_m \tag{1a}$$

$$D_j = \sum e_{j\nu} S_\nu = \sum \epsilon^S_{jm} E_m \tag{2a}$$

$$E_j = -\sum h_{j\nu} S_\nu + \sum \beta^S_{jm} D_m \tag{3a}$$

$$E_j = -\sum g_{j\nu} T_\nu + \sum \beta^T_{jm} D_m \tag{4a}$$

Each system of the above equations consists of nine equations, six of which are the elastic equations (since the suffix $\mu = 1, \ldots, 6$) and three of which are the electric equations (since the suffix $j = 1, 2, 3$). The addition of the superscripts E, D, and occasionally the elastic charge density σ to the elastic constants, and T and S to the dielectric constants in the above equations, refer to boundary conditions and indicate the quantity which should be kept constant in each case.

Table A-2 gives the definition of each property constant in its rigorous mathematical form. The descriptive definition of these constants appeared in Eqs. (1) through (4) and also in Eqs. (1a) through (4a) (see Ref. 5).

TABLE A-2
MATHEMATICAL DEFINITION OF PROPERTY CONSTANTS

Physical Property	Symbol	Definition
Elastic stiffness constants	$c^E_{\mu\nu}$ or $c^D_{\mu\nu}$	$\left.\frac{\partial T_\mu}{\partial S_\nu}\right)_{E \text{ or } D}$
Elastic compliance coefficients	$s^E_{\mu\nu}$ or $s^D_{\mu\nu}$	$\left.\frac{\partial S_\mu}{\partial T_\nu}\right)_{E \text{ or } D}$
Piezoelectric stress constants (at constant E)	$e_{j\nu}$	$-\left.\frac{\partial T_\nu}{\partial E_j}\right)_S = \left.\frac{\partial D_j}{\partial S_\nu}\right)_E$
Piezoelectric stress constants (at constant D)	$h_{j\nu}$	$-\left.\frac{\partial T_\nu}{\partial D_j}\right)_S = -\left.\frac{\partial E_j}{\partial S_\nu}\right)_D$
Piezoelectric strain constants (at constant E)	$d_{j\nu}$	$\left.\frac{\partial S_\nu}{\partial E_j}\right)_T = \left.\frac{\partial D_j}{\partial T_\nu}\right)_E$
Piezoelectric strain constants (at constant D)	$g_{j\nu}$	$\left.\frac{\partial S_\nu}{\partial D_j}\right)_T = -\left.\frac{\partial E_j}{\partial T_\nu}\right)_D$
Dielectric permittivity	ϵ^T_{jm} or ϵ^S_{jm}	$\left.\frac{\partial D_j}{\partial E_m}\right)_{T \text{ or } S}$
Dielectric impermeability	β^T_{jm} or β^S_{jm}	$\left.\frac{\partial E_j}{\partial D_m}\right)_{T \text{ or } S}$

It is of value to note the following more important inter-relationships between the two types of piezoelectric parameters:

$$\sum \beta_{jt} \epsilon_{mt} = \delta_{jm} \quad \text{(for both constants, T and S)} \tag{5}$$

where

$$\delta_{jm} = \begin{cases} 1 & \text{if } j = m \\ 0 & \text{if } j \neq m \end{cases}$$

$$d_{m\lambda} = \sum e_{m\nu} s^{E}_{\nu\lambda} = \sum \epsilon^{T}_{tm} g_{t\lambda} \tag{6}$$

$$g_{m\lambda} = \sum h_{m\nu} s^{D}_{\nu\lambda} = \sum \beta^{T}_{tm} d_{t\lambda} \tag{7}$$

$$s^{D}_{\mu\nu} - s^{E}_{\mu\nu} = - \sum g_{t\mu} d_{t\nu} \tag{8}$$

$$\epsilon^{S}_{jm} - \epsilon^{T}_{jm} = - \sum e_{j\nu} d_{m\nu} = - \sum e_{m\nu} d_{j\nu} \tag{9}$$

In the literature dealing with piezoelectric materials, we often find quantities designated by $k_{j\nu}$, the static electromechanical coupling factors (see, for example, Ref. 5 for a working definition). For a resonance element, however, a distinction must be made between the static and dynamic coupling factors; the dynamic coupling factor should be smaller than the static.

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13. ABSTRACT

Tables are set forth containing a critical compilation of the elastic, piezoelectric, and dielectric properties of crystals that are of potential interest in applications to microsound circuits and components. Elastic constants are provided for the total of 27 crystals, consisting of 10 semiconductors, 6 piezoelectrics, and 11 acoustic materials. Piezoelectric constants are given for 16 crystals, and dielectric constants for 11 crystals of potential interest. All the property constants entered in these tables were taken from the literature. A brief description of each property is provided in the Appendix to assist users of these tables.

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